NASA-CR-193010

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CENTER FOR Space Construction

Campus Box 529
University of Colorado
Boulder, CO 80309

Second Annual Symposium

Hotel Boulderado
Boulder, Colorado
October 17–19, 1990

(NASA-CR-193010) SECOND ANNUAL SYMPOSIUM (Colorado Univ.) 733 p

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CENTER FOR Space Construction

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Boulder, CO 80309

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UNIVERSITY OF COLORADO
AT BOULDER

CENTER FOR SPACE CONSTRUCTION

Second Annual Symposium

Hotel Boulderado Conference Center
Boulder, Colorado

October 17 - 19, 1990

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5 MIT.

Session One

OVERVIEW OF THE CENTER FOR SPACE CONSTRUCTION

Donald P. Hearth
Director, Center for Space Construction

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P-10

OVERVIEW OF THE CENTER FOR SPACE CONSTRUCTION

Donald P. Hearth

The purpose of the overview is to summarize the objectives and structure of the Center. The Center is a major element of the University's initiative to upgrade space-related research and education on the Boulder campus. With the support of NASA's University Space Engineering Research Centers Program, we provide a mechanism for interdisciplinary and system-level space engineering research and training. Twenty faculty members and 56 students from seven academic units are associated with the Center and are interacting with each other and with the CSC Associates. As a result of feedback from the 1989 symposium, we have focused the efforts of the Center during the past several months on Lunar Base construction. This included a system level study of a Lunar Base in an Independent Study Project by a group of students from across the Center during the spring semester. This project is being continued this fall. During the two-year history of the Center, 13 students previously affiliated with the Center have graduated and there have been 55 publications from the Center.

CENTER FOR SPACE CONSTRUCTION

- ONE OF NINE "NASA UNIVERSITY SPACE ENGINEERING RESEARCH CENTERS" SELECTED IN 1988
- PROGRAM FOCUS IS CONSTRUCTION & ITS INFLUENCE ON DESIGN
- FACULTY AND STUDENTS FROM 7 DEPARTMENTS -- DISCIPLINES:
  - STRUCTURES
  - MATERIALS
  - CONTROLS
  - FLUIDS
  - ROBOTICS
  - HUMAN PERF.
  - AI
  - COMMAND & CONTROL
  - SOIL MECHANICS
  - STR./SOIL INTERACTION
  - IN-SITU MATERIALS
  - SYSTEM ANALYSIS
  - COMPUTER AIDED MODELS
- INCLUDES MAJOR EMPHASIS ON EDUCATION AT BOTH UNDERGRADUATE AND GRADUATE LEVELS
- INCLUDES CENTER ASSOCIATES FROM INDUSTRY, GOV. LABS, AND OTHER UNIVERSITIES
- IN CONTEXT OF $20 TO $25 M/YR "SPACE PROGRAM" AT UNIVERSITY
- MEETS IMPORTANT NEEDS AT UNIVERSITY
  - TO CREATE "T PEOPLE"
  - TO ENHANCE DISCIPLINARY SPACE ENG. PROGRAMS

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90-11

CSC TEAM

DIRECTORS OFFICE

D. Hearth,Dir.
C. Osborne, Admin

STRUCTURES

S. Datta, M. Mikulas
M. Balas, W. Rogers
C. Farhat, H. Snyder
L. Yang
18 Students

OPERATIONS

E. Hansen, J. Faber
J. Avery, C. Lewis
F. Barnes, R. Su
R. Davis
16 Students

EXTRATERRESTRIAL

S. Sture
H. Ko
3 Students

SYSTEMS

G. Morgenthaler
J. Diekmann
F. Glover
U. Racheli
19 Students

ASSOCIATES

- Ball
- BDM
- Bechtel
- CTA
- Colorado School of Mines
- EG&G
- Explosive Fab.
- External Tanks
- Fluor-Daniel
- HP
- Johnson Eng.
- Lockheed
- Martin Marietta
- McDonnell Douglas
- NASA GSFC
- NASA JPL
- NASA JSC
- NASA Langley
- NASA MSFC
- Robotool
- Space Studies Inst.
- Stearns-Roger

OTHER CU CENTERS

- Astrodynamics Research
- Applied Parallel Processing
- Geo-Technical Eng.
- Cognitive Sciences
- Atmos. & Space Physics
- Space Structures & Control

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89-10

A NASA Space Engineering Research Center at the University of Colorado

CSC ASSOCIATE PROGRAM

1. TO PROMOTE COLLABORATIVE ACTIVITIES WITH INDUSTRY, GOV. LABS., AND OTHER UNIVERSITIES
2. MAY INCLUDE JOINT RESEARCH PROJECTS AND
   - USE OF CSC/ASSOCIATE FACILITIES W/O COMPENSATION
   - PERSONNEL EXCHANGES
   - JOINT PROPOSALS
3. NO MEMBERSHIP FEE FOR ASSOCIATES
4 CSC AND ASSOCIATES PAY OWN COSTS
5. ASSOCIATES HAVE PRE-PUBLICATION REVIEW RIGHTS TO PREVENT PUBLICATION OF ASSOCIATE PROPRIETARY INFO.
6. INTELLECTUAL PROPERTY RIGHTS SHARED, AS APPROPRIATE

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89-25

CSC OUTPUT - AS OF OCT. 1,1990

STUDENTS

- 13 STUDENTS AFFILIATED WITH CENTER HAVE GRADUATED

  3-PHD 5-MS 5-BS

- 56 STUDENTS NOW AFFILIATED WITH CENTER

  17-PHD 18-MS 21-BS

PUBLICATIONS

- 55 THESES, JOURNAL ARTICLES, PROCEEDINGS
- ALL AVAILABLE AS CSC REPORTS

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89-21

ACADEMIC ADVISORY COMMITTEE

COMMITTEE

MAX PETERS, CHAIR
PROF. EMERITUS, CHEM ENG
DEAN EMERITUS, ENG COLLEGE

SUSAN K. AVERY
ASSOCIATE PROF., E&CE
ASSOCIATE DEAN, ENG COLLEGE

GEORGE H. BORN
PROF., AEROSPACE
DIRECTOR, CCAR

WILLIAM J. HANNA
PROF., ELEC & COMP. ENG

NGUHEN X. XINH
ASSOCIATE PROF., AERO.

A. RICHARD SEEBASS
PROF., AEROSPACE
DEAN, ENG. COLLEGE

CHARTER

"TO ASSESS THE IMPACT OF CSC ON THE ACADEMIC PROGRAM"

CONCLUSION OF DEC. 1989 REVIEW: "THERE HAVE BEEN SUBSTANITIAL CONTRIBUTIONS FROM CSC ACTIVITIES TO THE UNDERGRADUATE & GRADUATE CURRICULA."

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90-1

CSC SYMPOSIUM

OCTOBER 12 & 13,1989

FEEDBACK - EXCELLENT SYMPOSIUM
VERY GOOD INFLUENCE ON EDUCATION
EXCELLENT STUDENTS
SUPPORT INTER-DISCIPLINARY APPROACH, DO MORE
NEED "CRISPER" DEFINITION OF SPACE "CONSTRUCTION"
SOME ASPECTS OF CONSTRUCTION NOT INCLUDED
LOOK BEYOND SPACE STATION FREEDOM
EXCELLENT OPPORTUNITY FOR OUTSIDE INTERACTION, DO MORE
"AMAZING PROGRESS FOR FIRST YEAR"

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89-27

LUNAR BASE CONCEPTUAL DESIGN STUDY

- PURPOSE
  - EXAMINE CONSTRUCTABILITY OF CURRENT DESIGN CONCEPTS
  - PROVIDE CONSTRUCTION BASELINES & QUESTIONS TO RESEARCH CLUSTERS
- INDEPENDENT STUDY PROJECT DURING SPRING SEMESTER 1990
  - STUDENTS FROM ALL CLUSTERS
  - TEAM LEADER FROM CSC ASSOCIATE
  - OVERSIGHT BY FACULTY
  - DESIGN REVIEW BOARD COMPOSED OF SIX CSC ASSOCIATES
- WILL PROBABLY CONTINUE

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90-12

CSC PROGRAM GUIDELINES - JULY 1990

- EMPHASIS FOR CENTER WILL BE SEI
- FOCUS ON CONSTRUCTION OF LUNAR BASE (INCLUDING ORBITAL ASSEMBLY REQUIRED TO ESTABLISH LUNAR BASE)
- CENTER DESIGN REF. MISSION WILL BE 90 DAY STUDY AS UPDATED
- CONTINUE CENTER-WIDE LUNAR BASE CONCEPTUAL DESIGN STUDY
- "CATALOG" SPACE CONSTRUCTION TECHNOLOGY STATE OF THE ART
- EXAMINE/UPDATE SPACE CONSTRUCTION TECHNICAL ISSUES
- UNDERSTAND HUMAN CAPABILITIES BUT NO RESEARCH ON IMPROVEMENT (WILL CONDUCT RESEARCH ON HUMAN-MACHINE INTERFACE)
- IDENTIFY DEVELOPMENT NEEDS FOR "REGOLITH MOVING EQUIP."
- INCREASE CENTER EMPHASIS ON EXPERIMENT - DEVELOP TESTBED(S)

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90-13

CSC SYMPOSIUM - 1990

SESSION	CONCEPTS	CONST. SUPPORT	OPS. & TOOLS	STRUC. & CONTROL	SYSTEM ANALYSIS MODELS	ORBITAL ASSEMBLY	LUNAR SURFACE CONST.
WED.							
1. BASE CONCEPTS	✓						
2. LOGISTICS		✓					
3. CONSTR. WORKFORCE			✓				
4. TROTERS			✓				
5. C 3			✓				
6. HUMANS & THEIR TOOLS			✓				
THURS.							
7. STRUCTURES & ASSEMBLY	✓		✓	✓		✓	
8. TEST & VERIFICATION		✓					
9. CAE TOOLS					✓		
FRI.							
10. LUNAR REGOLITH				✓			✓
11. CONSTR. OF LUNAR BASE	✓		✓	✓	✓		✓

POSTER SESSIONS

WED. & THURS.

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90-14

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OMIT TO P16

Session Two

LUNAR BASE CONCEPTS

George W. Morgenthaler,
Chair

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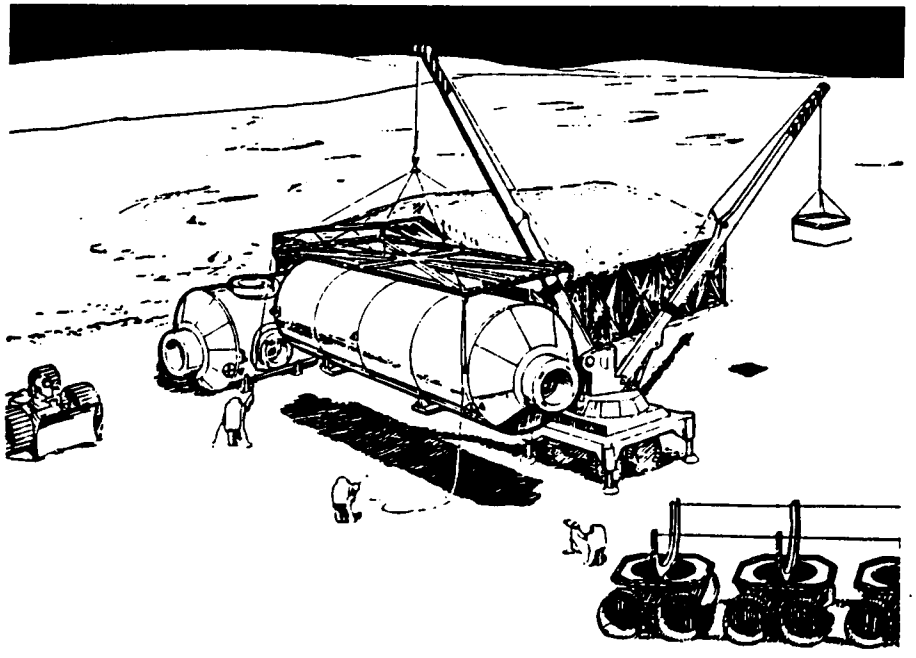
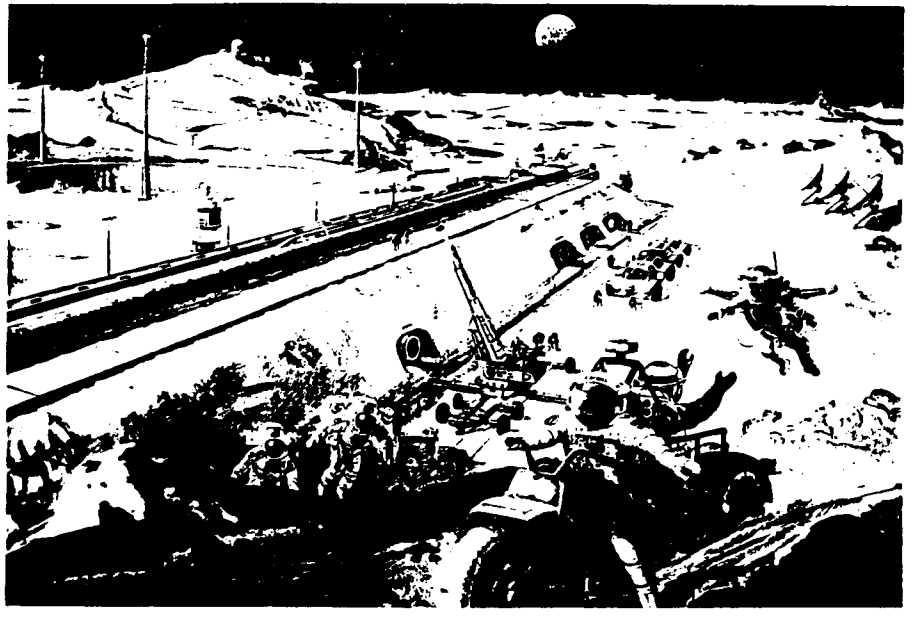
CSC Symposium
Lunar Base Concepts Session
Wednesday, October 17, 1990, 9:15 – 10:30 a.m.
George W. Morgenthaler, Chair





—What kind of Lunar Base Construction?

Lunar Base Session Philosophy and Agenda

George W. Morgenthaler, Chair (5 min)

- Prefabricated Lunar Base Concepts – Charles King, Bionetics (15 min)
  - Begin permanent Lunar activities with a pre-fabricated, fully tested Lunar habitat – minimal space construction
  - Modified Shuttle External Tank as one possibility

- Inflatable Lunar Base Approach – Stuart Nozette, LLNL (20 min)
  - LLNL's "Great Exploration Plan"
  - Use of inflatable "First-Step" technology leads to earlier bases.
  - Pre-fabricated, pre-packaged
  - Unique development - test program

- Current NASA Lunar Base Approach – Barney Roberts, NASA/JSC (20 min)
  - Prefabricated first habitat
  - Add SSF habitat and logistic modules

- Evaluation/Selection of Lunar Base Approach – Janet Gleave, CSC (15 min)
  - What kind of model needed?
  - Inclusion of risk analysis, space logistics, and cost
  - Inclusion of future SEI needs

Omit

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N94- 70985

A Single Launch Lunar Habitat Derived from an NSTS External Tank

Charles B. King

Bionetics, Hampton Engineering

A concept for using the spent External Tank from a National Space Transportation System (Shuttle) to derive a Lunar habitat is described. The concept is that the External Tank is carried into Low-Earth Orbit (LEO) where the oxygen tank-intertank subassembly is separated from the hydrogen tank, berthed to Space Station Freedom and the subassembly outfitted as a 12-person Lunar habitat using extravehicular activity (EVA) and intravehicular activity (IVA). A single launch of the NSTS Orbiter can place the External Tank in LEO, provide orbiter astronauts for disassembly of the External Tank, and transport the required subsystem hardware for outfitting the Lunar habitat. An estimate of the astronauts' EVA and IVA is provided.

The liquid oxygen tank-intertank modifications utilize existing structures and openings for human access without compromising the structural integrity of the tank. The modification includes installation of living quarters, instrumentation, and an air lock. Feasibility studies of the following additional systems include micrometeoroid and radiation protection, thermal-control, environmental-control and life-support, and propulsion.

The converted Lunar habitat is designed for unmanned transport and autonomous soft landing on the Lunar surface without need for site preparation. Lunar regolith is used to fill the micrometeoroid shield volume for radiation protection using a conveyor. The Lunar habitat concept is considered to be feasible by the year 2000 with the concurrent development of a space transfer vehicle and a Lunar lander for crew changeover and resupply.

CONCEPT FOR A LUNAR HABITAT

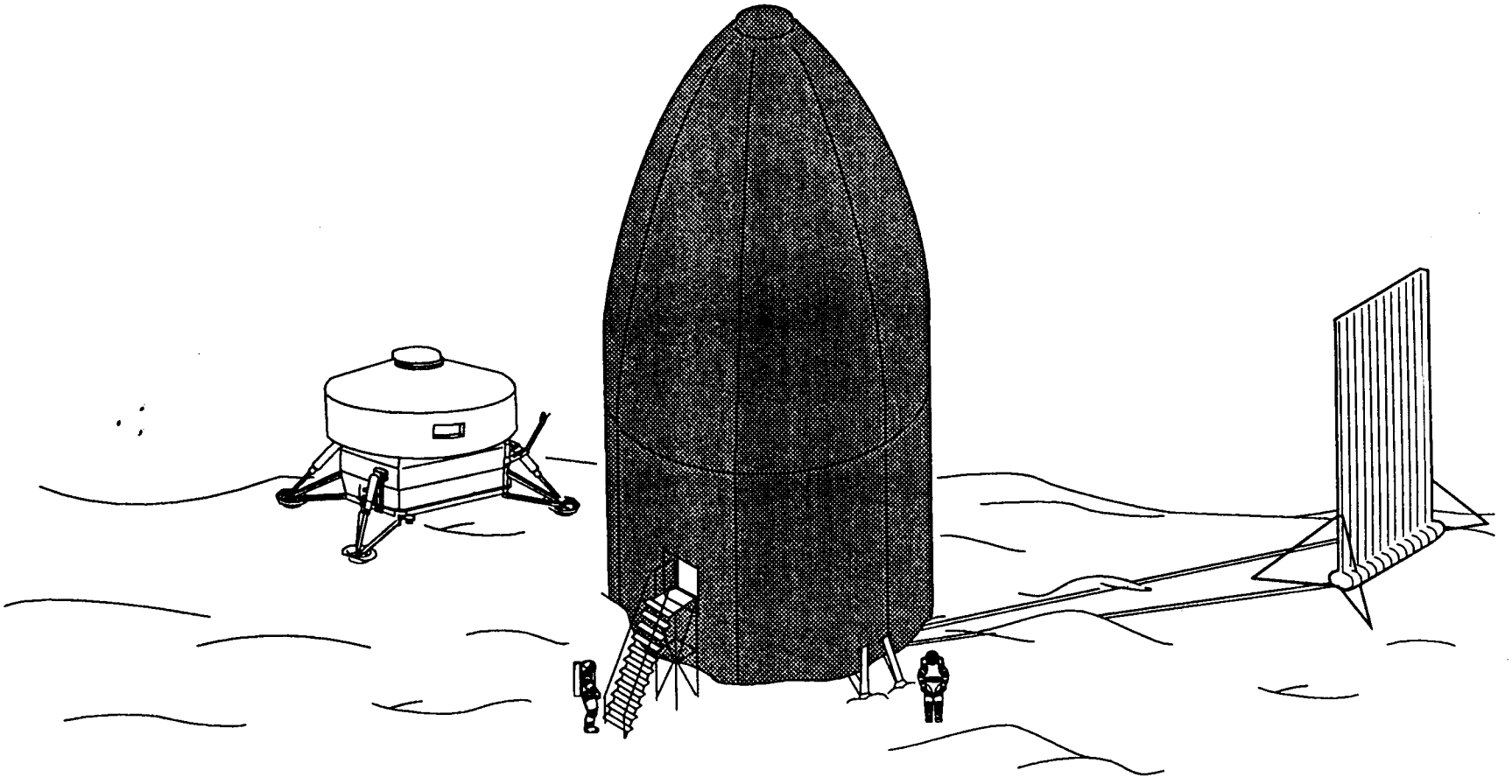
Charles B. King, Ansel J. Butterfield, Warren D. Hypes,

John E. Nealy and Lisa C. Simonsen

Presented at the Center for Space Construction
Boulder, Colorado
October 17, 1990

CONCEPT FOR A LUNAR HABITAT

12-MAN 70-DAY RESUPPLY CYCLE



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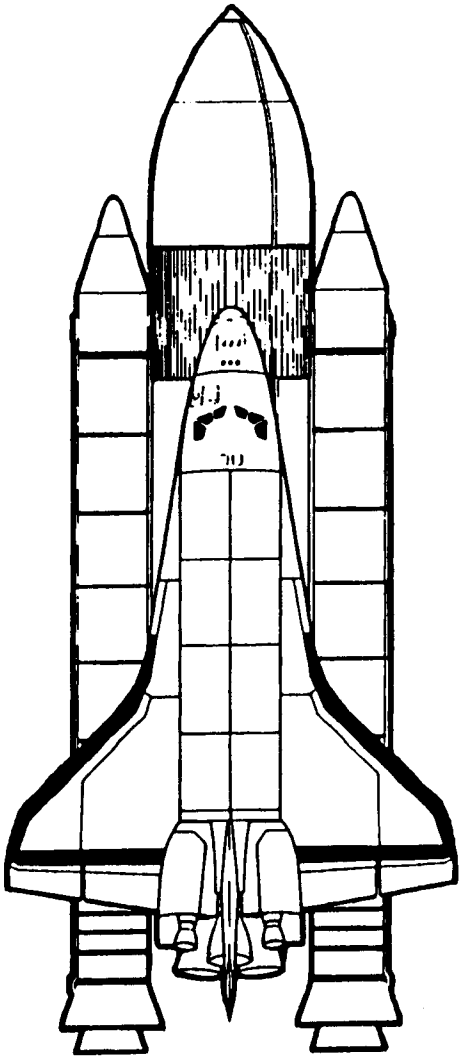
INTRODUCTORY OUTLINE

- NSTS External Tank
- Outfitting the LO_2 Tank-Intertank
  - On Earth
  - At Space Station Freedom (OMV, ELV)
- Packaging Constraints
- Quantity and Mass of Outfitting Items
- Habitat Internal Arrangement
- Air Lock
- Propellant Tankage
- Micrometeoroid Sheath
- Radiation Shielding
- Summary

5/10/89 CBK-02

NATIONAL SPACE TRANSPORTATION SYSTEM (NSTS)



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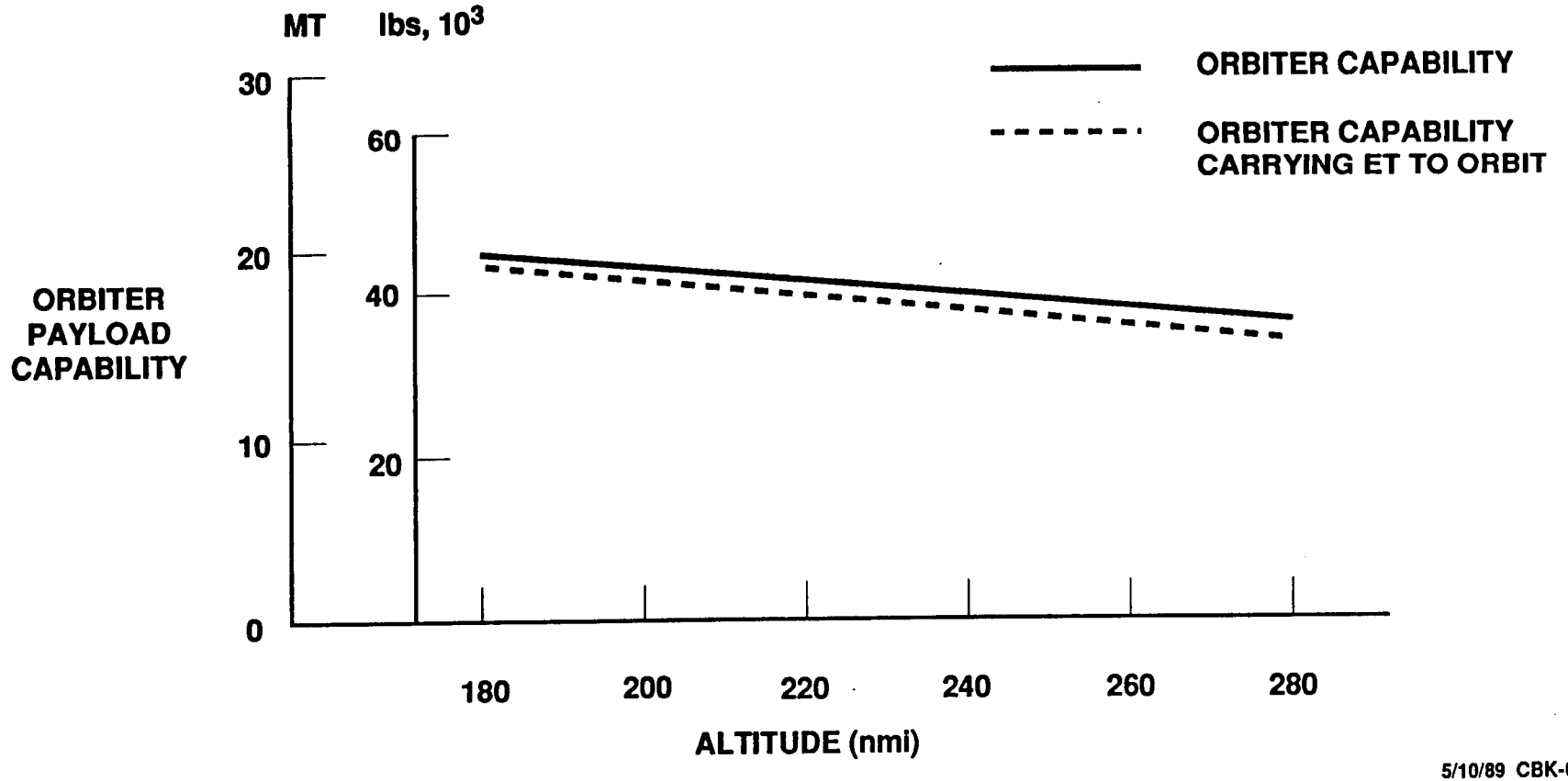
NSTS CAPABILITY vs ALTITUDE
EXTERNAL TANK UTILIZATION



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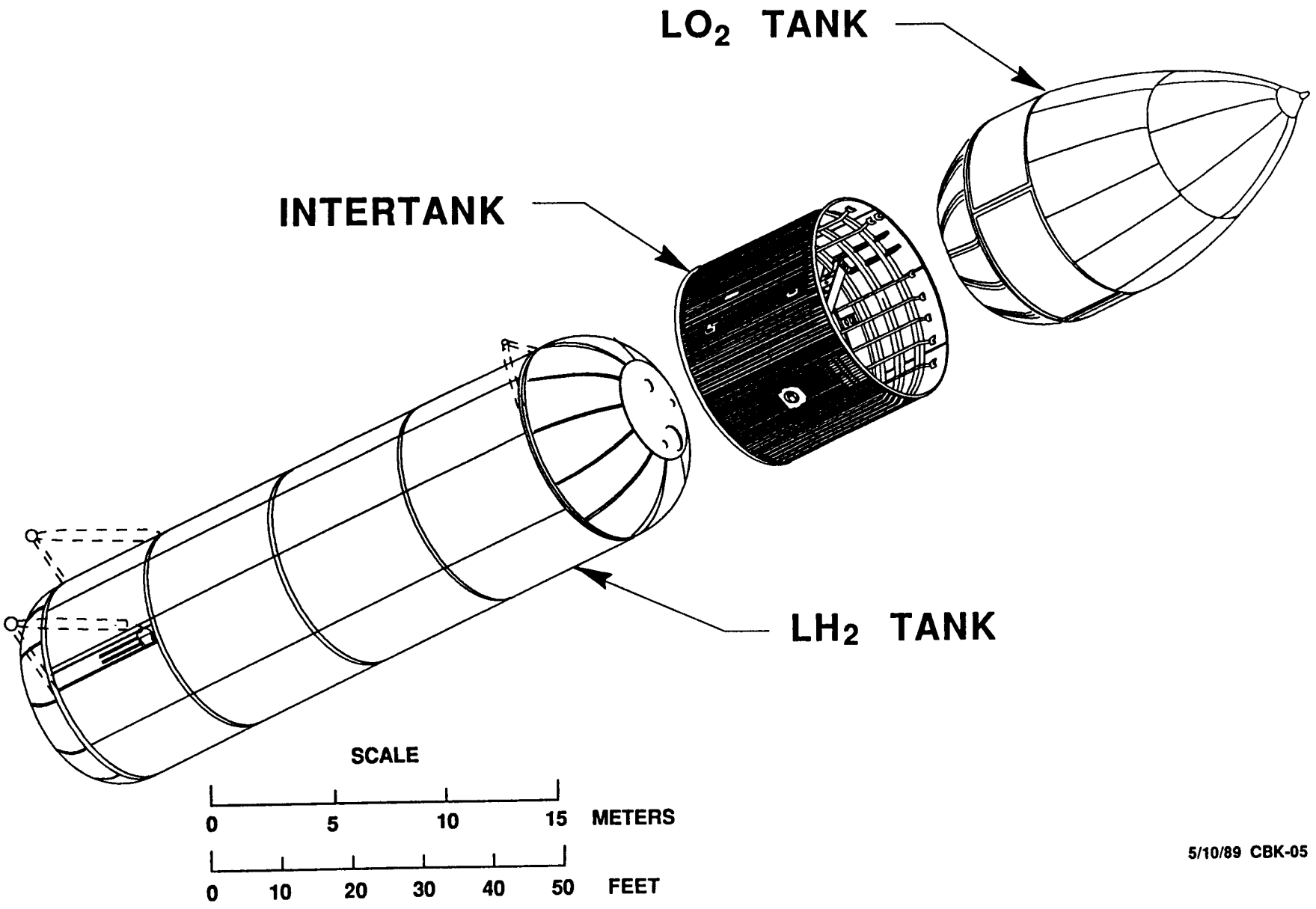
NSTS EXTERNAL TANK STRUCTURE



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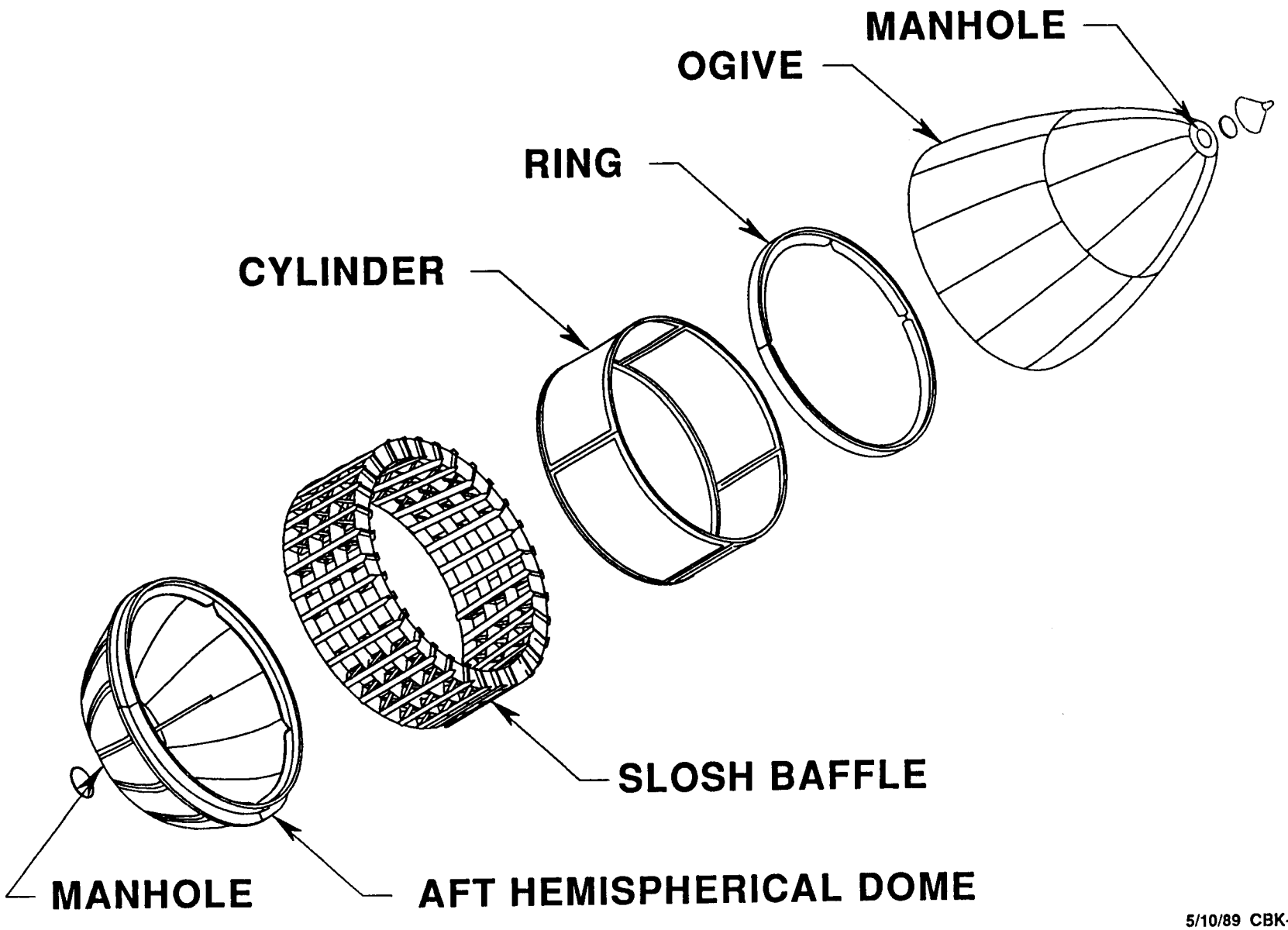
LO_2 TANK STRUCTURE



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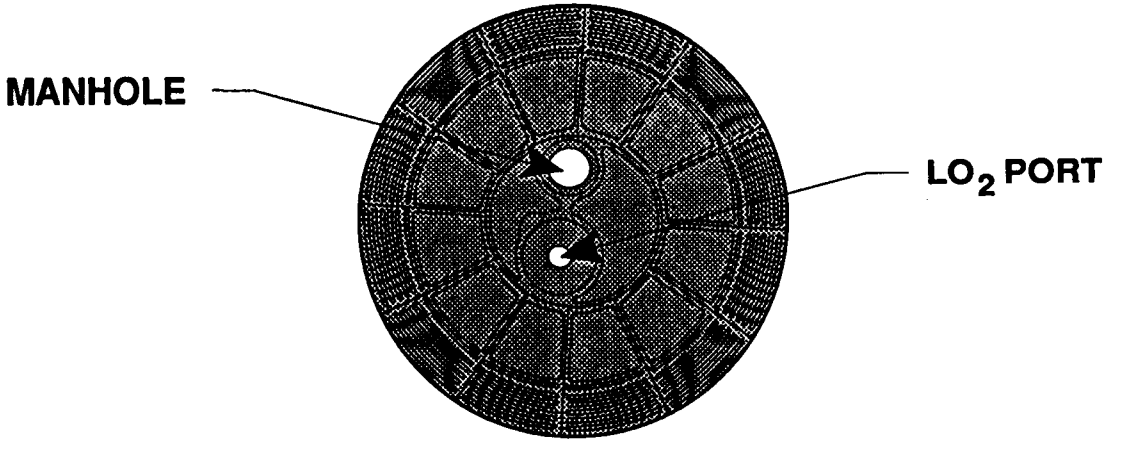
LO_2 TANK PROFILE



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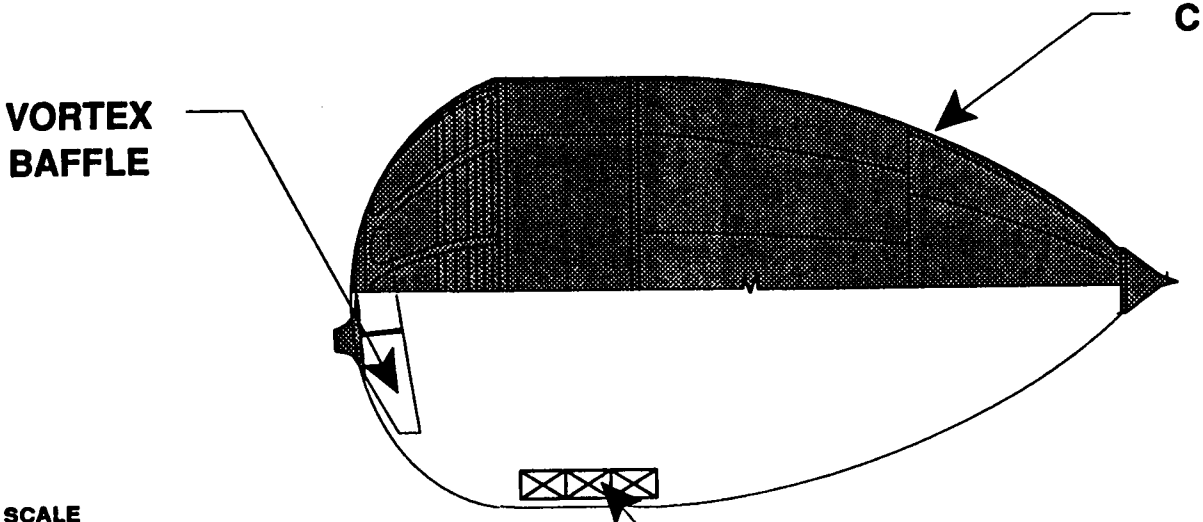


SCALE

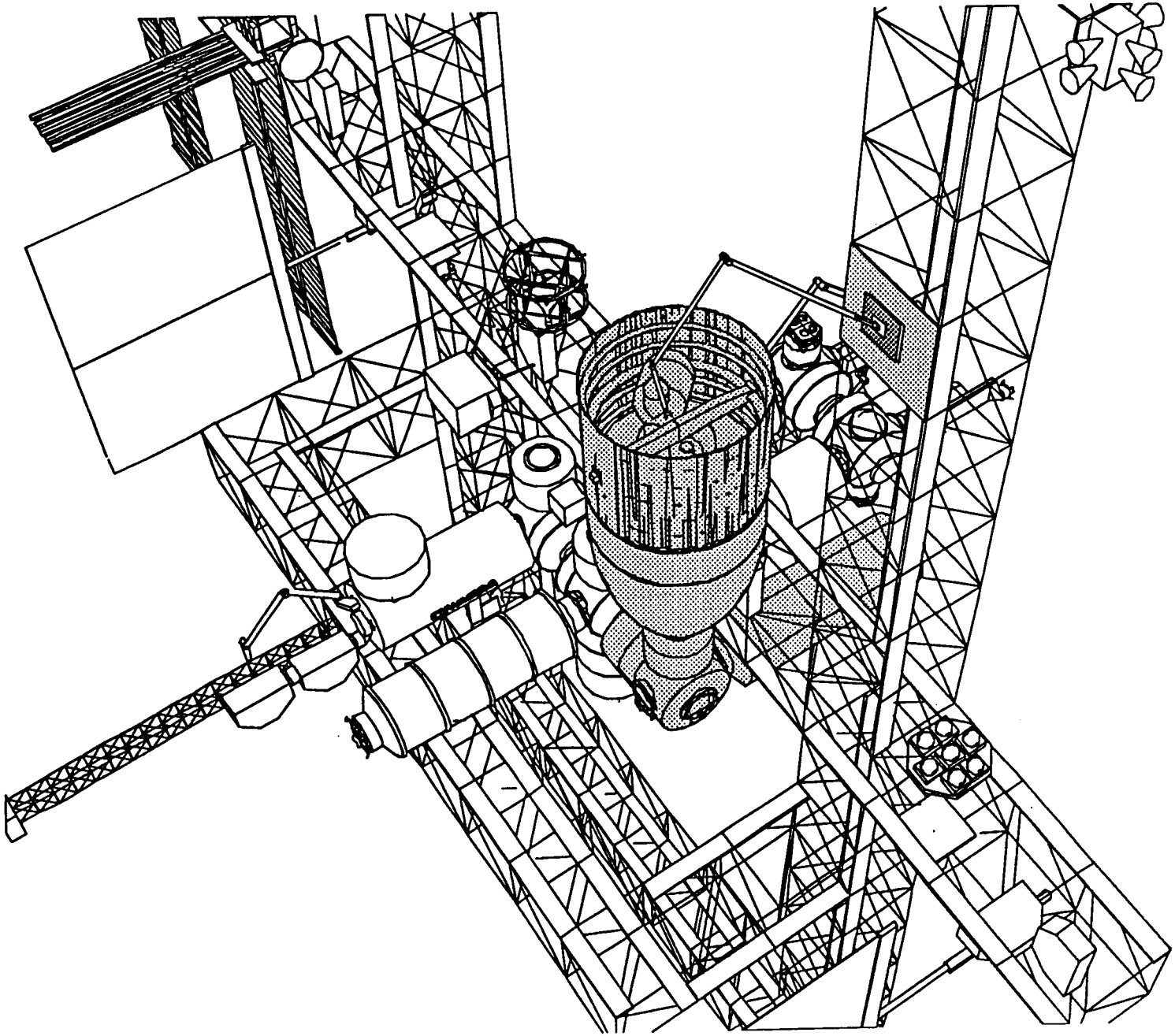
0 5 10 METERS

0 10 20 30 FEET

CUTAWAY VIEW

5/10/89 CBK-07

LUNAR HABITAT ASSEMBLY AT SPACE STATION FREEDOM



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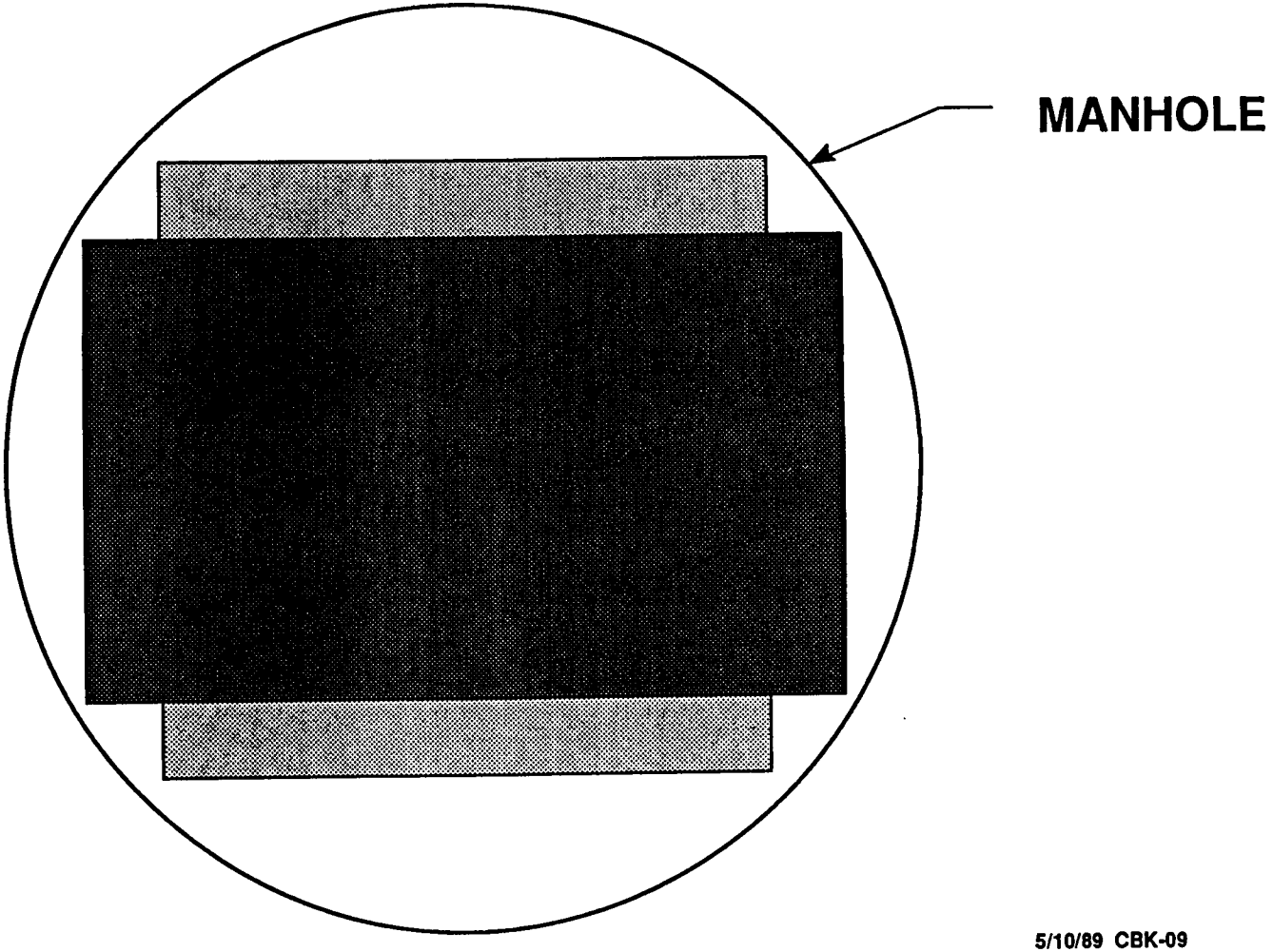
MANHOLE PASS-THROUGH CAPABILITIES



5/10/89 CBK-09

OUTFITTING THE LUNAR HABITAT IN LEO

SYSTEM	CONTAINERS/ITEMS INSTALLED IN LEO					
	LO_2 TANK INTERIOR			LO_2 TANK EXTERIOR		
	QUANTITY	MASS kg (lbs)		QUANTITY	MASS kg (lbs)	
STRUCTURES						
• Flooring and struts	33	2,500	(5,500)			
• Air lock				1	800	(1,770)
MICROMETEOROID PROTECTION						
• Sheath				16	3,550	(7,830)
ECLS						
• Habitability	20	820	(1,800)			
• Water management	14	1,030	(2,260)			
• Air revitalization	19	730	(1,600)	12	3,450	(7,600)
• Integration equipment	2	160	(350)			
• Food, storage, and preparation	25	2,500	(5,500)			
• Waste management	4	350	(770)			
Subtotal	84	5,590	(12,280)	12	3,450	(7,600)
THERMAL CONTROL						
• Acquisition						
– Internal thermal control	9	1,130	(2,500)			
– ATHC	13	750	(1,650)			
• Transport				11	320	(700)
• Rejection						
– Heat pump				1	80	(180)
– Radiator assembly				25	480	(1,060)
Subtotal	22	1,880	(4,150)	37	880	(1,940)
POWER, COMMUNICATIONS, AND GUIDANCE, NAVIGATION, AND CONTROL	40	600	(1,330)	30	600	(1,330)
PROPULSION						
• Tanks within intertank				10	2,000	(4,400)
• Tanks outside intertank				16	3,270	(7,200)
• RL - 10 O_2 - H_2 engines				4	2,400	(5,300)
Subtotal				30	7,670	(16,900)
TOTALS	179	10,570	(23,260)	126	16,950	(37,370)

5/10/89 CBK-10

OUTFITTING THE LUNAR HABITAT IN LEO

- Position and attach
  - ~ 180 items inside the LO_2 tank
  - ~ 125 items outside the LO_2 tank

- Projected mass on orbit

– LO_2 tank-intertank	11.1 MT
– Outside attached mass	16.9 MT
– Inside attached mass	10.5 MT
TOTAL	38.5 MT

- Projected mass as landed ~ 32 MT

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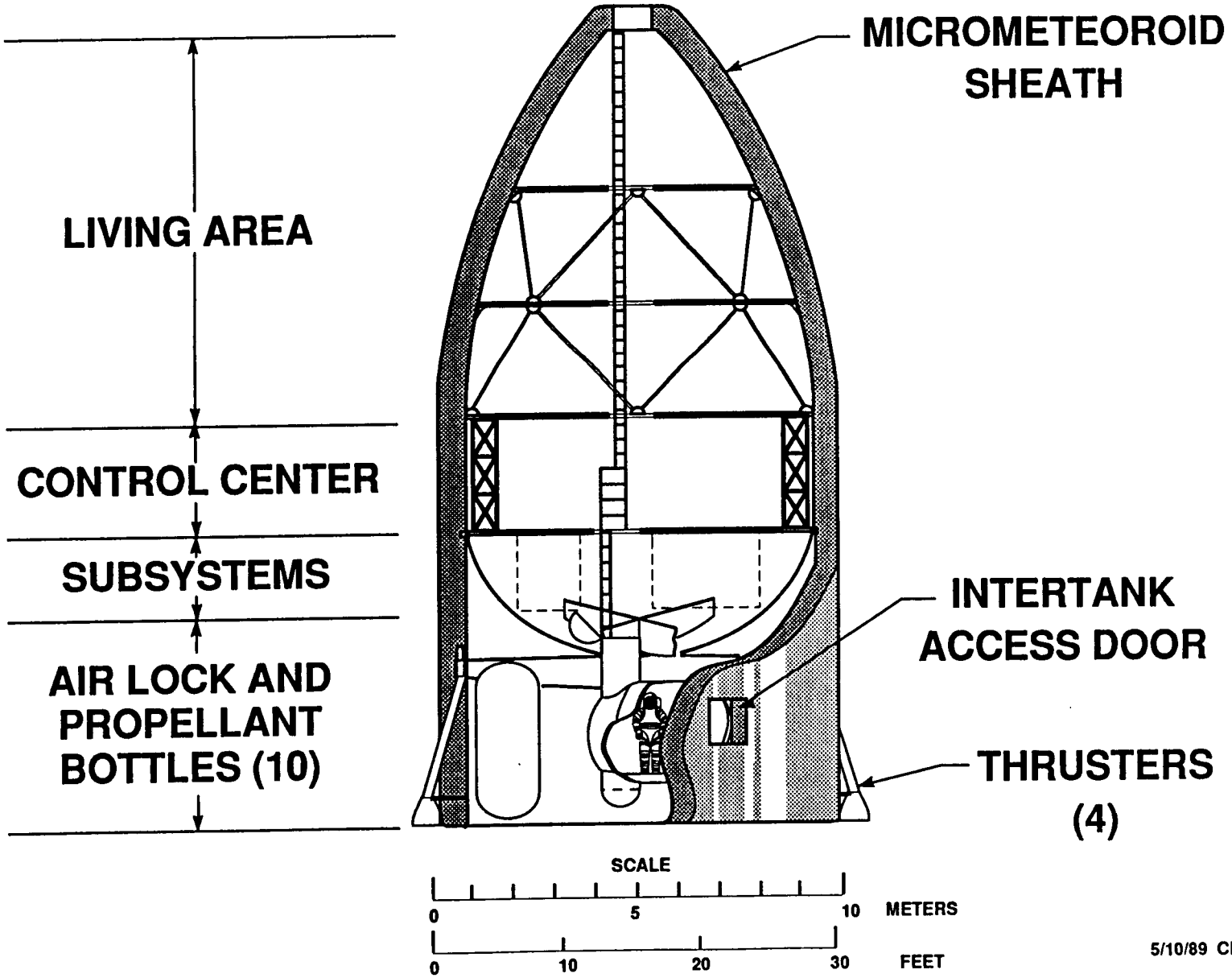
LUNAR HABITAT INTERNAL ARRANGEMENT



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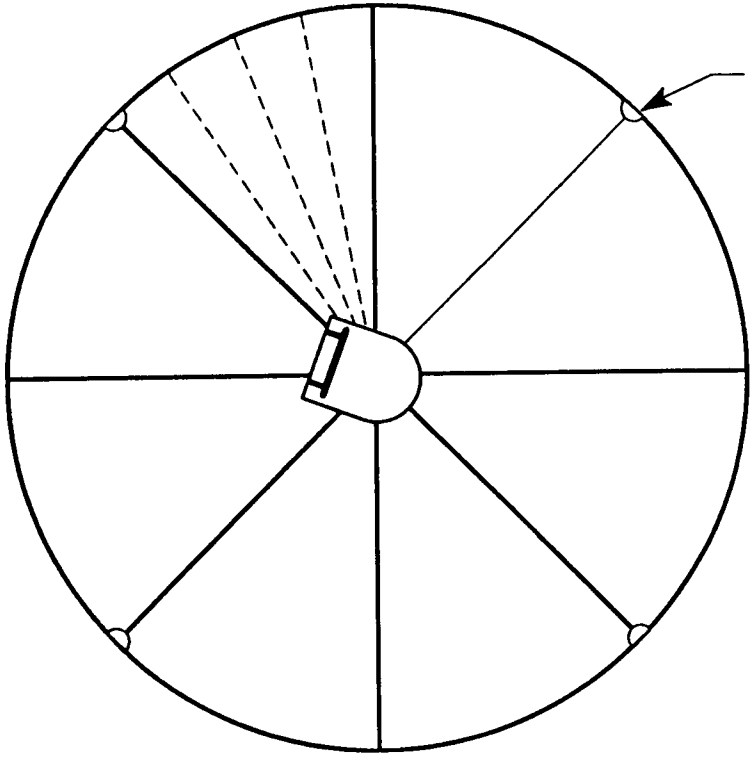
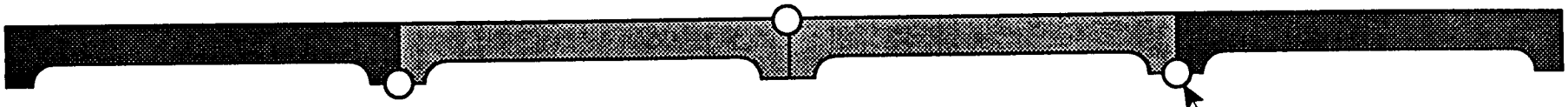
HABITAT FLOOR



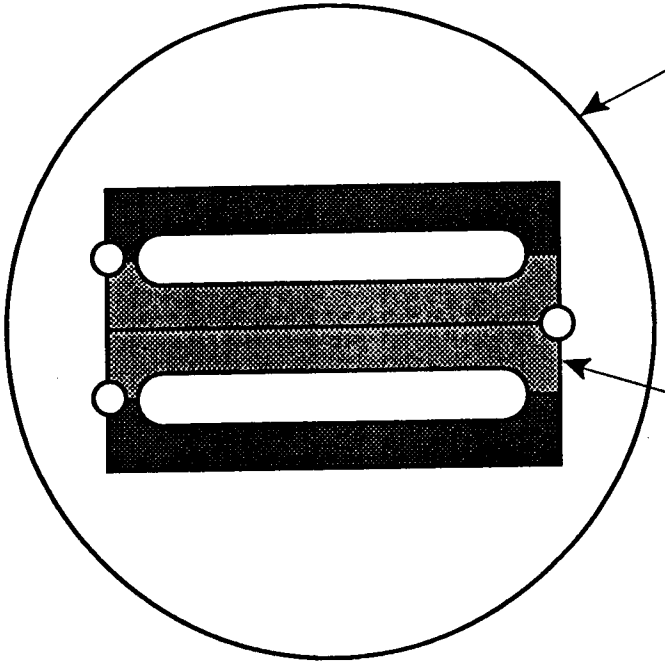
TRUSS NODES
(8 places,
4 each side)

5/10/89 CBK-13

FOLDING FLOOR PANELS

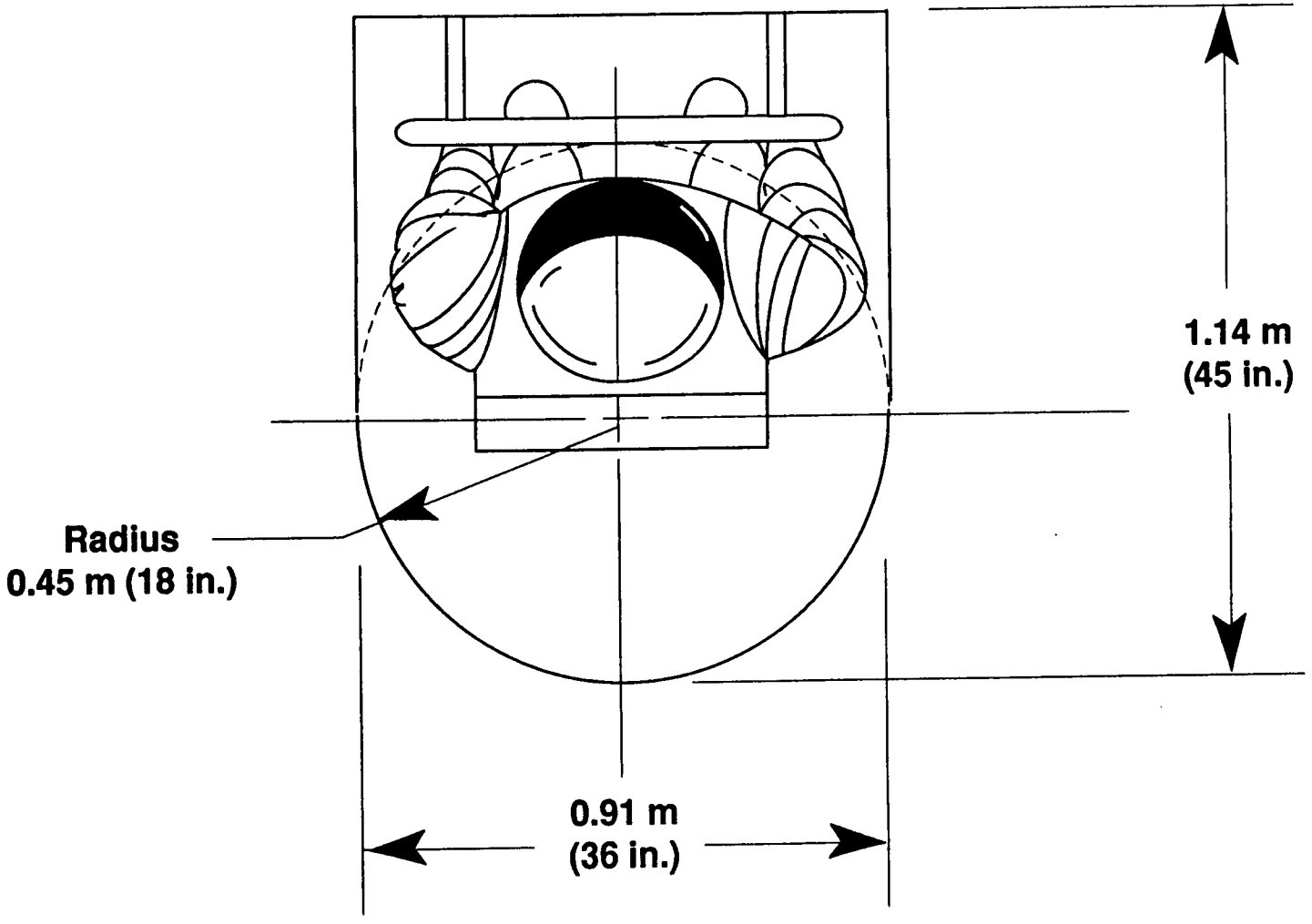


FLOOR OCTANT CROSS SECTION
(EXTENDED)



5/10/89 CBK-14

TYPICAL ACCESS OPENING IN HABITAT FLOORING



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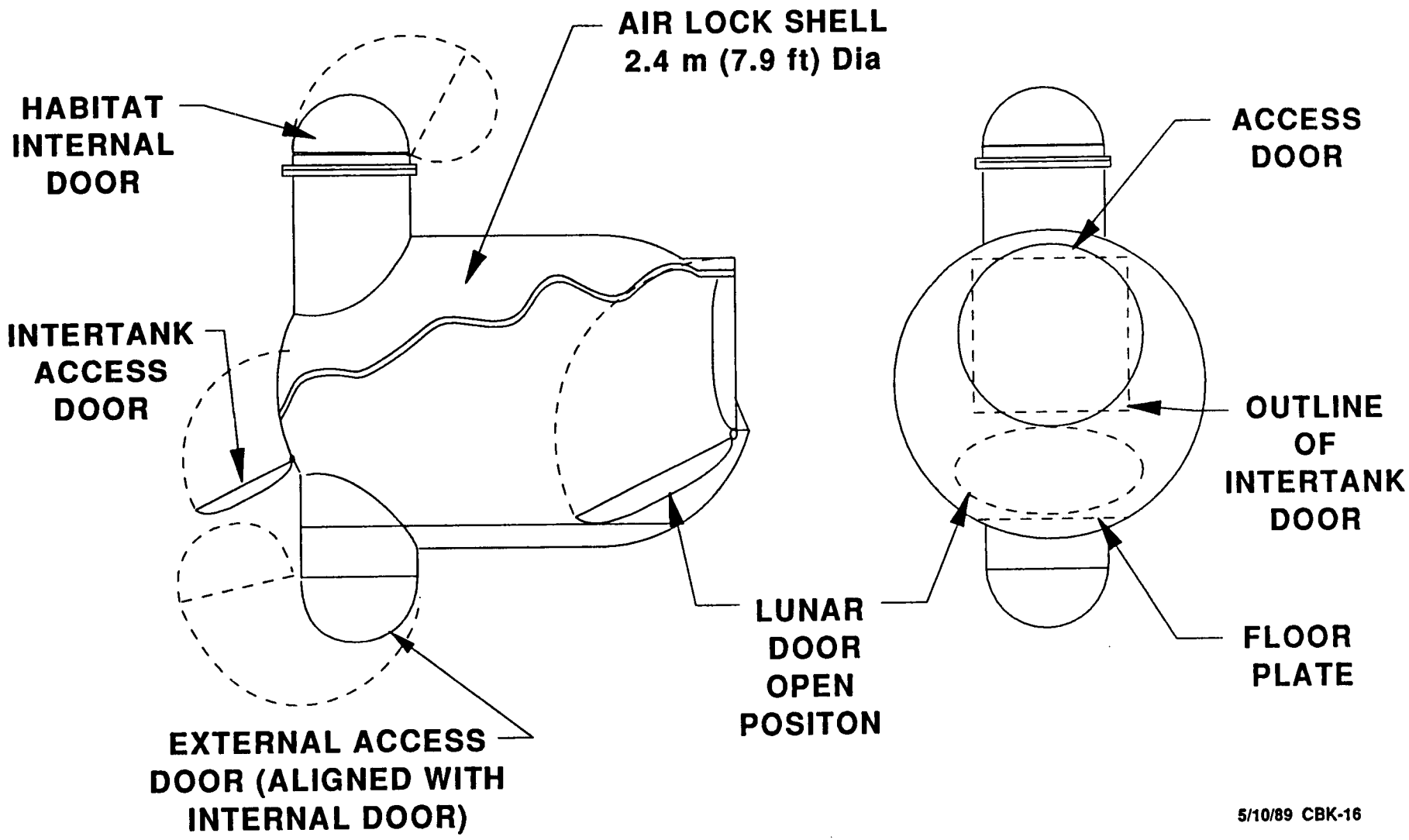
AIR LOCK CONCEPT



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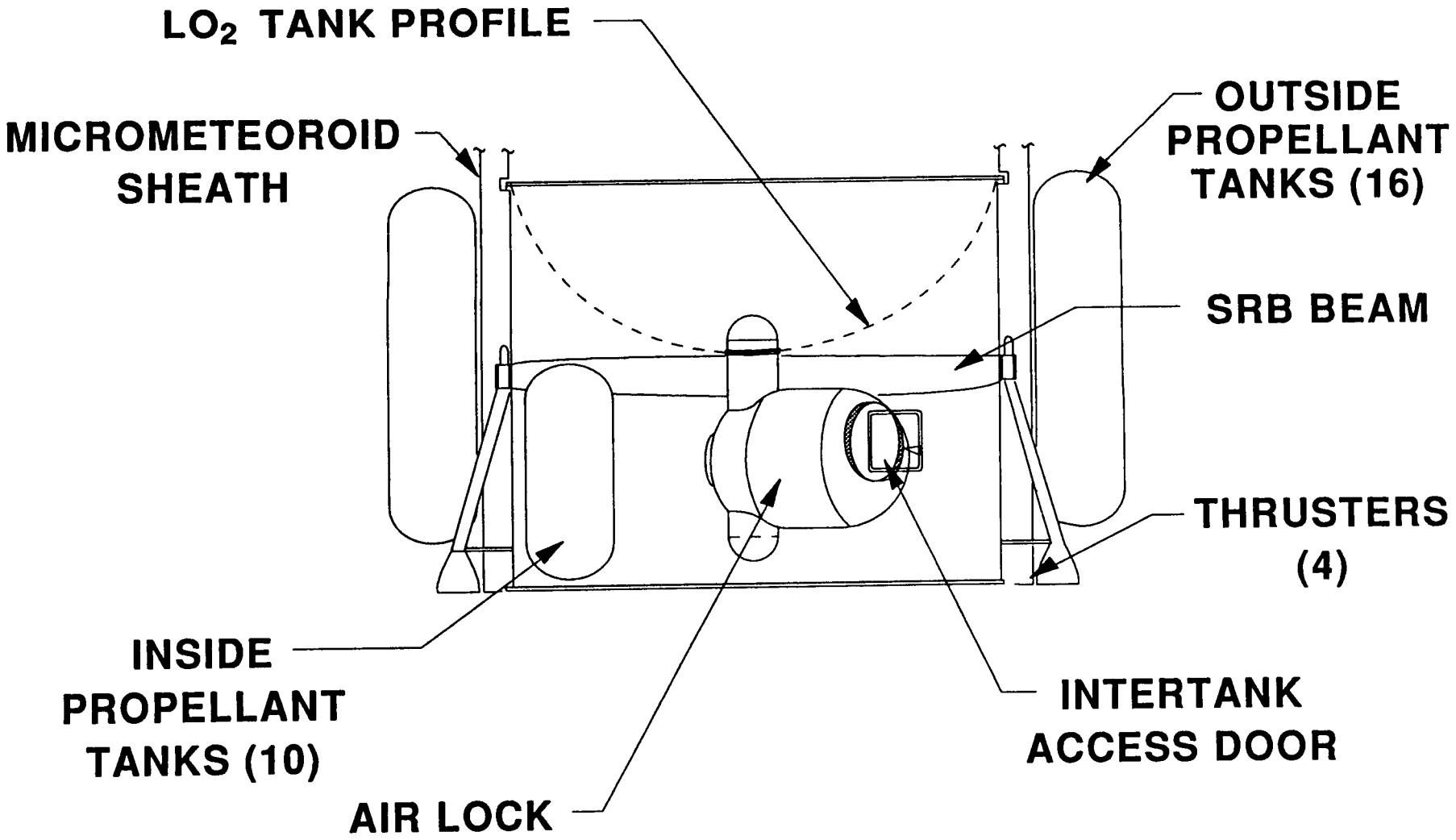
INTERTANK WITH AIR LOCK INSTALLED



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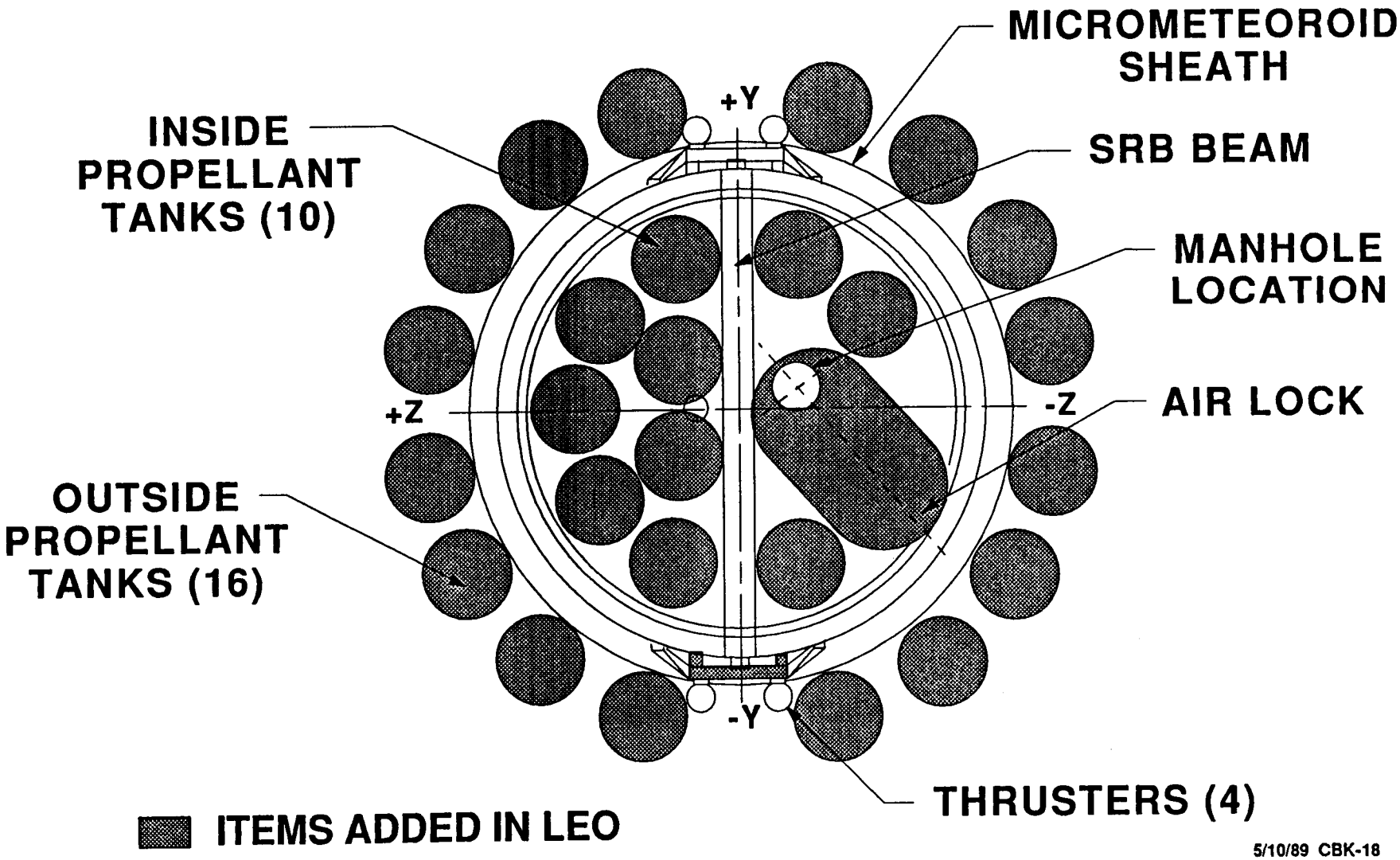
INTERTANK WITH AIR LOCK AND PROPELLANT TANKAGE



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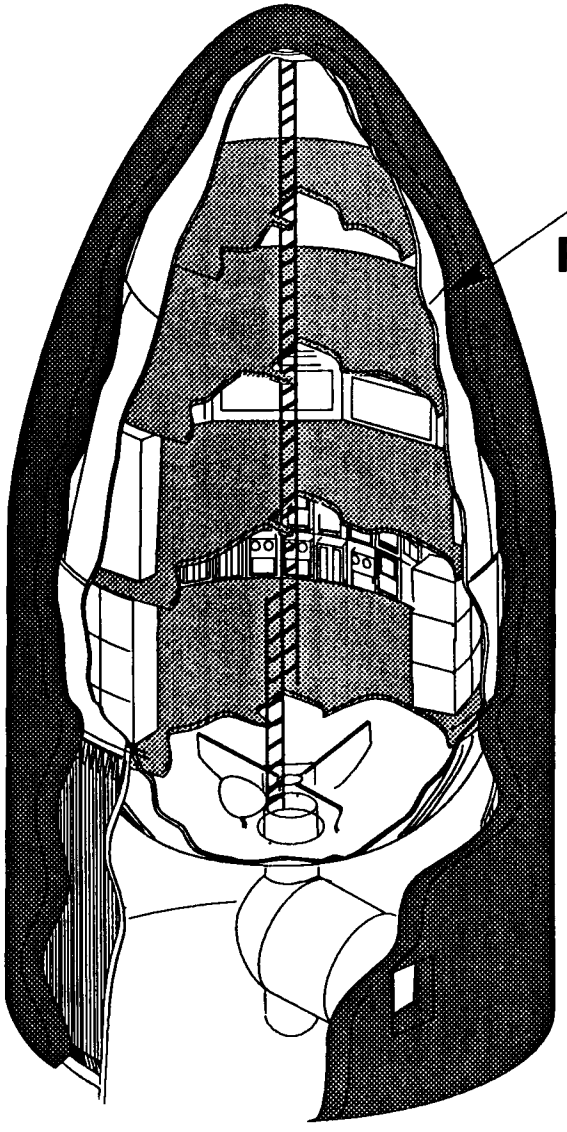
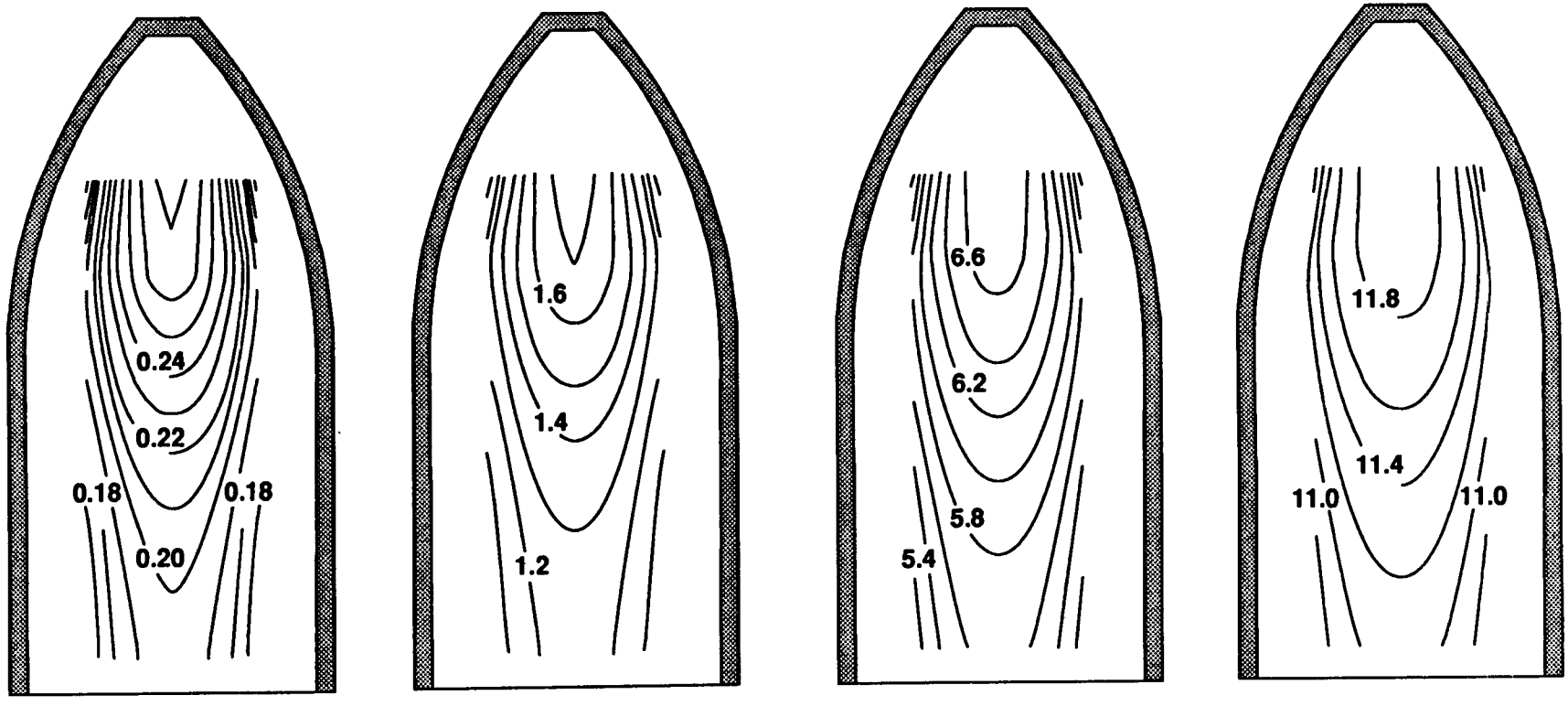
CUTAWAY VIEW OF HABITAT



50 cm
REGOLITH SHIELDING
(SEP AND GCR)

5/10/89 CBK-19

LUNAR HABITAT
BFO DOSE PREDICTIONS (rem)
(50-cm Regolith Shield)



(a) 8/72 Flare

(b) 11/60 Flare

(c) 2/56 Flare

(d) Annual GCR

5/10/89 CBK-20

SUMMARY

- Can reuse LO_2 tank-intertank without prior modification to the pressure vessel.
- Utilize existing and near term technology developments.
- Space suits for NSTS and Space Station Freedom are suitable for ET manhole entry.
- Space transportation infrastructure requires:
  - NSTS
  - ELV
  - OMV
  - Manned cargo lander with cislunar transportation
- Lunar site preparation is not required.
- Lunar Habitat is ready for occupancy after assembly of the radiator and addition of regolith.
- Can house 12 men on a 70-day resupply cycle.

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N94- 70986

An Initial Lunar Outpost Based on Deployable Inflatable Structures

S3-54
160783
p. 11

Dr. Stewart Nozette

Lawrence Livermore National Laboratory

The Great Exploration Plan (GEP) has been proposed as an alternative approach for achieving the Space Exploration Initiative (SEI) objectives stated by President Bush on July 20th, 1989. The GEP is an evolutionary, end-to-end approach for the establishment and settlement of an orbiting Earth Station, and permanent bases on the Moon and Mars. The GEP deviates from most other proposed SEI architectures by its extensive use of inflatable structures, and by its emphasis on Earth-based assembly and test of all components.

The following presentation focuses on the design, development and implementation of an inflatable/deployable Lunar outpost as part of the GEP. Programmatic and technical issues associated with this concept are also addressed.

GREAT EXPLORATION PROGRAM DETERMINANTS

Dr. Stewart Nozette - Lawrence Livermore National Laboratory

How to choose among the variables of each axis in the program specifying parameter space?

- Ground rules
  - "New heaven, new Earth", e.g., use past/present space investments exactly as appropriate
    - Future resource allocations don't go to buying from wish lists of times past
  - Minimize *a priori* choosing of winners and losers, e.g., scientists choose science endeavor directions as opportunities present themselves during the *Great Exploration* — and then propose allocation of resources, relative to other options
  - Human Exploration Initiative: man at the leading edge of all *Great Exploration* endeavors
    - Adequate robotic (Surveyor, Viking) and human (Apollo) site surveys are already in hand
  - Moon, then Mars
    - Technically sensible track
    - Political specification
  - "And this time, back to stay" — permanency of human bases, from the beginning
    - Expand horizontally from initial slender end-to-end capability
    - Local environments, needs and opportunities drive horizontal expansions — scientists/settlers' "annual Christmas wish list" determines contents of next re-supply mission
    - *Great Exploration* crews are career scientists/explorers of the Admiral Perry type — they establish and man bases and do scientific exploration

BASIC POINTS OF DEPARTURE

- Minimum essential R&D
  - Basic Thesis: We already have in-hand what we need for the Great Exploration of the inner solar system
  - Innovative-but-prudent use of off-the-shelf technologies everywhere
    - Technology advance is often pricey, always risky and usually time-consuming
    - No new heavy launch vehicle R&D, rocket engine creation, zero-gee equipment, bio-support systems, ...
      - Here-and-now, on-Earth technology used pervasively
    - Adapt space and planetary environments maximally to human-familiar ones
  - Answer all open questions minimally and as late as possible, e.g., physiological consequences of sustained hypogravity
- Thrust is swift exploration, settlement and infrastructure creation — science happens as scientists follow
  - The "American standard" approach — the American West, the polar expeditions, undersea exploration
- Assemble and test everything on the Earth
  - No construction or assembly in orbit, in deep space, on the Moon, on Mars — or anywhere else
    - Exception: work that can be executed completely in shirt-sleeves
    - In-space EVA as rare luxury: a mission-enhancing, not mission-critical, activity
  - Space Stations, Lunar Bases, Mars Expeditions are launched from Earth whole
    - Exploitation of cheap, near-term heavy-lift expendable vehicles-based launch services, e.g., Titan VI's/HL Delta's 50-70 tonnes to LEO
  - "Fleshed out" with propellants loaded in Earth or lunar orbit — remotely supervised
    - Inflatable Common Modules employed for habitation and propellants
    - Exploit, e.g., "small parcel" launch technologies for (proto-)propellant delivery to LEO
      - Major private enterprise "wedge"
  - Earth Station, Lunar Base, Mars Base all staffed after Station/Base is deployed and basically functional
    - Shirt-sleeved staff does internal unpacking, assembly and final check-out of Station/Base sub-systems
  - Comprehensive on-the-ground testing and staff training of all Station/Base components, sub-systems and total system
    - Realistic conditions, e.g., Earth-surface gravity
    - "No major surprises in space" — intelligent risk management
    - "Emergency return to Earth is always available, anywhere in cislunar space
  - All testing is "all up", all the way
    - Leverage all successes maximally; accept occasional failures/partial successes

BASIC POINTS OF DEPARTURE, cont'd.

- Systematic base-building
  - Each major step meaningfully prototypes equipment and procedures for next step
    - Earth Station hypogravity physiological check-out, propellant generation and storage
    - Lunar Fuel Factory, Fuel Ferry and LLO Gas Station cost-minimize subsequent Great Exploration
    - Lunar and Mars Bases prototype the more challenging Bases on Mercury, Jovian Moons, asteroids
  - Each step leaves major operational legacies — and commitments
    - "Drive bolts into the rock at each rest stop"
    - E.g., Lunar and Martian Bases, once manned, never need be unmanned thereafter
      - Self-sustainability as "organizing principle" of all the Great Exploration Bases — minimum of one-decade manned durability after initiation
- Minimal changes from terrestrial technologies and practices
  - Adapt space environment to humans and their practices, not vice versa
  - E.g., artificial gravity, standard terrestrial machinery and equipment, long-duration station-manning
- "Manned space exploration as though it were a profit-seeking business enterprise"
  - "Business plan" — long-term strategy and "getting there" tactics specified at outset
  - Rational expectations of generating specified return on early capital investment — not requiring ever more capital
    - Knowledge product, delivered on-time, on-spec, on-budget
    - Early self-sustaining point, relative to Earth-generated consumables, for all Bases — enlist pioneers, not junketeers, as the Great Explorers to found and staff the Great Exploration Bases, to accumulate expertise
      - Minimize transportation accidents
  - Purposeful generation of supplier network, customer base, ...
  - Prudent risks taken with all types of resources
  - Dispatch — "Time is money"

MAJOR GREAT EXPLORATION LOCI

- ***Earth Station***
  - Test and qualify crews and equipment for deep space and planetary surfaces operations
  - Receive, store, convert-as-necessary and transfer cryogenic propellants to Deep Space Vehicles

- ***Lunar Base***
  - First site of permanent human habitation of the Moon
    - Primary test-and-evaluation site for lunar colonization-enabling technologies
  - Test-and-evaluation of planetary surface equipments and procedures
    - E.g., Rovers, Hop-Abouts
    - "Dry" asteroid Base technologies test-and-evaluation

- ***Mars Base***
  - First site of permanent human habitation of Mars
    - Primary test-and-evaluation site for Martian-specialized terraforming technologies
  - Test-and-evaluation of Deep Space Vehicle in Base establishment, re-supply
  - Test-and-evaluation of equipment, procedures for Bases on "wet" asteroids, Jovian (Galilean) Moons

INFLATABLE HABITATION MODULES

- "Community-sized space suits" — with centrifugal pseudogravity along long axes
- Right circular cylinders with hemi-domed ends: nominally 5 m diameter x 15 m long
  - Ends bear interface flanges — interconnect to other Modules or Hub
  - All vacuum walls are bi-layers; each layer is full pressure-rated; separated by 3 cm of low-pressure atmosphere
    - Special MLI or thermal radiator surface covers all exposed vacuum wall — meteor bumper <u>and</u> thermal/UV functions
  - Axisymmetric Central Corridor (1 meter diameter) terminates on end flanges — vacuum-rated wall
    - Axial load-bearing, as well as radial
  - Five "floors" segment Module into two hemispherical Utility Regions and four 2.5 m high Living/Working Regions
    - Each Region accesses Central Corridor via vacuum-rated door with manual spill valve
    - Floors terminate on vacuum wall and corridor wall; light-load-bearing (radially stressed)
      - Install 'radial wedge' flooring modules in each Region, as required for full load-bearing
    - Loss-of-pressure in any Region doesn't affect other Regions
- Central Corridor functions/features
  - Provides crew ready access to all Regions via side-wall ladder and Module-long power hoist (Hub-deployed)
  - Emergency escape/refuge if a Region undergoes rapid loss-of-pressure
  - General utility corridor
    - Minimum essential cabling/plumbing in flexible form, Earth-installed
    - Full facilitization cabling/plumbing installed by shirt-sleeved crew in LEO (post-spin-up)
    - Vacuum-rated penetrations through Corridor wall into 6 Regions
    - Inter-Region transport of unpacked equipments/furnishings during facilitization
- Hub functions/features
  - Station spin axis through center
  - Connects Modules on each side through pressure doors
  - Mounts ACS, drag make-up units; stores monopropellant; back-up power generation/distribution
  - Mounts Airlock (on Station spin axis), Astronaut Dispatch/Retrieval Unit (adjacent to Airlock entrance)
  - Deploys comm antennae and transceivers
  - Interfaces to Return-to-Earth Module

BASE SITE SELECTION: APPROACH AND RATIONALE

- Leverage maximally the existing planetary surface data base
  - Luna: Surveyor, Apollo, Luna series
  - Mars: Viking series
    - More detailed data than we had about Luna as of July '69
- What do we need to know about Apollo and Viking sites as Base candidates that we don't already know?
  - But are they the most "interesting" spots to site the first Bases?
    - Whose criteria re "interest"?
    - How long to search for more "interesting" sites?
- ***Great Exploration*** approach is to establish Bases and <u>then</u> explore planetary surfaces
  - Rovers around primary Base site
    - All-planet Rovers possibly feasible on Luna
      - Maintain ~15 kph speed on equator, stay in sunlight on circum-lunar trips
    - Supplemented with free-flyers, as feasible, on Mars
  - Hop-Abouts to "interesting" remote locations, with local exploration by Rovers
    - Frequency-of-use depends on success in water-winning locally
      - Materials Recovery Unit on Luna; Water Plants on Mars
  - Site follow-on Bases at "fascinating" locations characterized at Apollo intensity by early explorers
- First ***Great Bases*** go at Apollo (15-17) sites, Viking (1,2) sites
  - Well-characterized surface temperature, composition, mechanical properties, topography on Luna
  - Well-characterized surface/air temperature, basic composition and mechanical properties, local topography on Mars
  - Full minute of local hovering/maneuvering capability provide for touchdown in Landers
    - Real-time, radar-assisted, computer-supported detailed site selection
  - Earth-side testing provides pessimal data base for post-landing Base deployment
    - Higher wind and gravitational loadings readily available, Earth-side
    - As-nasty-as-desired local topographies readily available — bounding exercises
      - Radar/computer data base generation for Lander use

LUNAR BASE

- Implemented with standard inflatable Habitation Modules
  - Inter-netted with 6 Hubs for convenience, safety-related redundancy
  - Basic interior partitions reflect lunar gravity bias (vs. axial pseudo-gravity in Earth Station)
- Base launches from Earth as already-interconnected Modules
  - Single ELV carries payload-integrated Lunar Base and un-fuelled Lunar Transit Vehicle into LEO — 70 T
  - Transit Vehicle fuels up at Earth Station, soft-lands 60 T Base on Moon
- Base deploys from Transit Vehicle by air-bag ejection, followed by sequential inflation of Modules
  - Recapitulation of Earth Station deployment
  - Crew occupies Base from Earth Return Module
    - Modules then soil-covered with "snow-blower"; solar power unit deployed
    - Crew assembles, deploys Modules' furnishings and equipment, in shirtsleeves
- Enhanced from Columbus Project plan
  - Grows out of 35 → 60 T soft-landed mass budget
    - Benefit of heavy-lift ELV, leveraging off Earth Station fuelling of Lunar Transit Vehicle
  - Probably retain initial Base population of 6
  - Add low-rate but omnicompetent materials recovery unit — ~5 T
    - Supplement with materials-forming and -machining facility — ~3 T
  - Add greenhouses — ~5 T
    - Close Base's carbon and nitrogen cycles; provide soil-derived feedstream points to Base ecosystem
  - Add ~5.8 T of essential nutrient/pharmaceutical reserves
    - 0.4 kg/person-day of amino acids, fats, micronutrients, antibiotics, ... : 'C' rations for space
    - 0.4 person-century of bio-sustainability
  - Add RL-10-centered "lunar hop-about" — 1.1 T
    - All-planet exploration capability: RL-10 propulsion package + 2 crew compartment + Rover
      - Loads 5 T LH_2/LO_2 for 7.5 km/sec Δv capability
- Plausible to declare Base indefinitely self-sufficient
  - Spartan life style
  - "This time to stay"

'FIRST STEP' PROGRAM GOALS

- Demonstrate major technologies of Great Exploration proposal
  - ASAP
  - Inexpensively
  - Compellingly
- Inflatable Habitation Module — community-sized space suit in LEO
  - Erectability/collapsability/packability/stowability
  - Basic structural features: atmosphere retention, rigidity, thermal isolation, ...
  - Shirt-sleeves facilitization: deployability of stowed equipments/furnishings
  - Homeostasis system capabilities: ACS, drag make-up, spin/de-spin, thermal and power management
  - Life support system operation in various modes: fully open; half-&-half; mostly closed
  - Habitability/utilizability
- Inflatable Cryogenic Propellant Tankage — super-strength balloon storage for propellant cryogens
  - *Isobaric* filling, storing, accelerating and emptying — constant configuration at low gee
  - Multi-layer insulation (MLI) compatibility — heat leak quantification in vacuum
  - Collapsability/packability/stowability/inflatability
  - Operability envelope determination
- Water → Cryogenic Propellants Conversion/Storage — "LEO Gas Station"
  - Water acquisition/conditioning/electrolysis
  - Liquefaction/storage
  - Power generation/conditioning
  - Control/monitoring
- Lunar Soil Roaster — oxygen/water/(C,N) recovery; photovoltaic, then nuclear, powered
  - Traction and soil lofting/sieving
  - Soil intra-Roaster transport; heating and cooling
  - Volatiles recovery, separation, storage and delivery
  - Teleoperability
- Planetary Base — community-sized space suit on the Lunar surface
  - Hypogravity effects (limited LEO Earth Station test-&-evaluation)
  - Temperature-cycled soil
  - Galactic cosmic ray/anomalously large solar storm biohazard consequences
  - Teleoperability (if initially unmanned option is chosen)

PROGRAMMATICS

- Conducted as fast-paced National Lab-centered RDT&E operation
  - Streamlined Government oversight (SDIO Delta style); MIPRed NASA or DoE 189 funding
  - Extensive university personnel participation — ideas, shock troops, leading-edge technologies, ...
  - Most major modules streamline-contracted to industry
    - Lab designs, contracts-for-implementation, integrates, tests-and-flies with contractors
- Determined in near-term by bootstrap-from-zero requirements
  - Bare-bones FY'90 costing; uncertain ability to obligate for FY'91 costing
  - Modest FY'91 costing
- Oriented to fiscal year-end reviews, determining
  - Costing authority for first out-year
  - Budget request for second out-year
- Within basic constraints, aimed at
  - Technology-limited pace of demonstrations
  - Operational legacies, to greatest extents feasible, e.g.
    - LEO manned space facilities: small Earth Station and LEO Gas Station
    - Lunar Soil Roaster performance-validated in Earth operation
    - Man-rated small Lunar Base

PROGRAM TIMELINE SUMMARY

- CY'90
  - Design and simulation
  - Sub-scale prototyping of key elements
  - Test systems creation
- CY'91
  - Full-scale prototyping
  - Test and validation
    - Realism limited only by sustained one-gee, limited AMO thermal/vac environment
- CY'92
  - Testing completion, for both small Earth Station <u>and</u> small Gas Station
  - Launch vehicle integration and launch-to-LEO, with Delta II/Atlas
    - Small-scale versions of *Great Exploration* Earth Station and Gas Station — low-cost launcher limitation
      - Two Module-with Hub, two-crew member Earth Station, with minimal reserves
      - Third-capacity Gas Station
    - Teleoperated deployment/operation
    - Shuttle astronaut visit option
      - Habitability/utilizability validation
- CY'93
  - Completion of small Lunar Base major modules/systems
  - First delivery of 20 T of H_2O or H_2/O_2 to Earth Station (Titan IV)
- CY'94
  - Completion of small Lunar Base testing
  - Second and third 20 T H_2O or H_2/O_2 deliveries to LEO
- CY'95
  - Launch to Earth Station of small Lunar Base, propellant-loading, lunar landing and Base deployment
    - Propellant loading of Lunar Lander
    - Landing on Moon of small Lunar Base — teleoperated or crew-bearing
    - Trade crew's always-abort-to-Earth capability against Base "richness"

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Current NASA Lunar Base Concepts

Barney B. Roberts,
John F. Connolly
NASA Johnson Space Center
Houston, Texas

The NASA Office of Aeronautics, Exploration, and Technology has completed a Systems Engineering and Integration effort to define a point design for an evolving lunar base that supports substantial science, exploration, and resource production objectives. This study addressed systems level design; element requirements and conceptual design; assessments of precursor and technology needs and operations concepts. The central base is assumed to be located equatorially on the lunar nearside north of the crater Moltke in Mare Tranquilliatis. The study considers an aggressive case with three main phases. The initial Man-Tended Phase establishes basic enabling facilities that include a modular habitat that periodically houses a crew of four. During the Experimental Phase the base becomes permanently manned with the construction of a larger habitat that provides augmented workshop and laboratory volumes and housing for crew. The Operational Phase expands base capabilities to a substantially mature level while reducing reliance on Earth. The analysis classifies base characteristics into several major functional areas: Human Systems; Assembly and Construction; Energy Management; Launch and Landing; Surface Transportation; In-Situ Resources Utilization; User Accommodations; and Telecommunications, Navigation, and Information Management. Results of various NASA-sponsored studies were synthesized to meet requirements. The system level architecture was determined, the physical layout was developed from a set of proximity criteria and related functions, and the evolutionary path of the base was analyzed. Conclusions include a summary of technology needs, design drivers, high leverage items, and important issues.

PLANET SURFACE CONSTRUCTION REQUIREMENTS

2nd ANNUAL SYMPOSIUM OF THE CENTER FOR SPACE CONSTRUCTION

Barney B. Roberts, Manager
NASA - Johnson Space Center
Planet Surface Systems Office

U.S. Gov't

NASA

THE SPACE EXPLORATION INITIATIVE (SEI) NASA/PLANET SURFACE SYSTEMS OFFICE PERSPECTIVE

SEI IS A LONG-TERM, LARGE-SCALE PROGRAM WHICH WILL REQUIRE THE COOPERATION OF NASA, DOD, DOE, ACADEMIA AND INDUSTRY. INTERNATIONAL COOPERATION IS ALSO POSSIBLE.

NASA WILL LEAD THE COORDINATION OF THE EFFORTS. TOP-LEVEL REQUIREMENTS WILL BE FORMULATED AND HANDED DOWN. NASA WILL CONTROL HIGH-LEVEL INTEGRATION.

THE SCOPE OF SEI IS MUCH BROADER THAN ANY OTHER "SPACE PROGRAM" TO DATE; IT WILL REQUIRE EXPERTISE IN DISCIPLINES PREVIOUSLY NOT ASSOCIATED WITH THE SPACE PROGRAM:

- ARCHITECTURE
- CIVIL ENGINEERING
- CONSTRUCTION
- MINING
- CHEMICAL ENGINEERING

OUTPOST BUILD-UP, TECHNOLOGY VALIDATION, INFRASTRUCTURE DEVELOPMENT

↓

- UTILITIES
- MANUFACTURING
- TRANSPORTATION

TRANSITION TO PRIVATE ENTERPRISE

DIVISION OF RESPONSIBILITIES WITHIN NASA

LMEPO (LEVEL II):

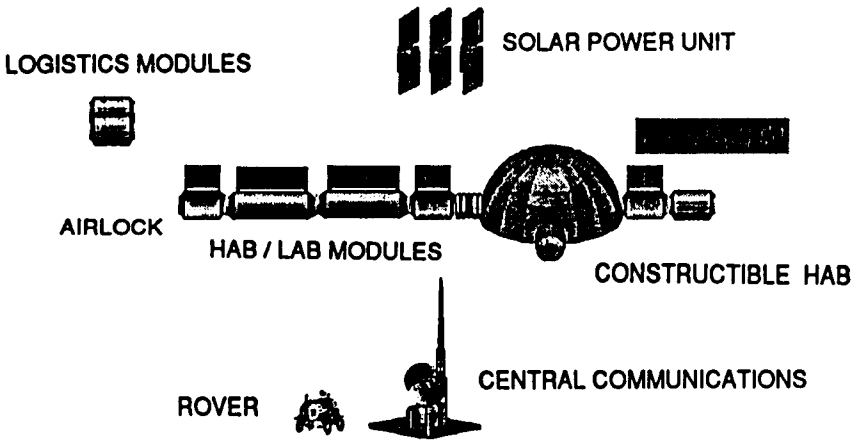
- OVERALL MANAGEMENT OF THE SEI PROGRAM
- DEVELOPMENT AND OPERATION OF THE SPACE TRANSPORTATION SYSTEMS
  - -HEAVY-LIFT LAUNCH VEHICLES
  - -TRANSPORTATION NODE AT SPACE STATION FREEDOM
  - -LUNAR AND MARS TRANSFER VEHICLES
  - -LUNAR AND MARS EXCURSION VEHICLES
  - -PRECURSOR MISSIONS AND SATELLITE NETWORKS

PSS (LEVEL III):

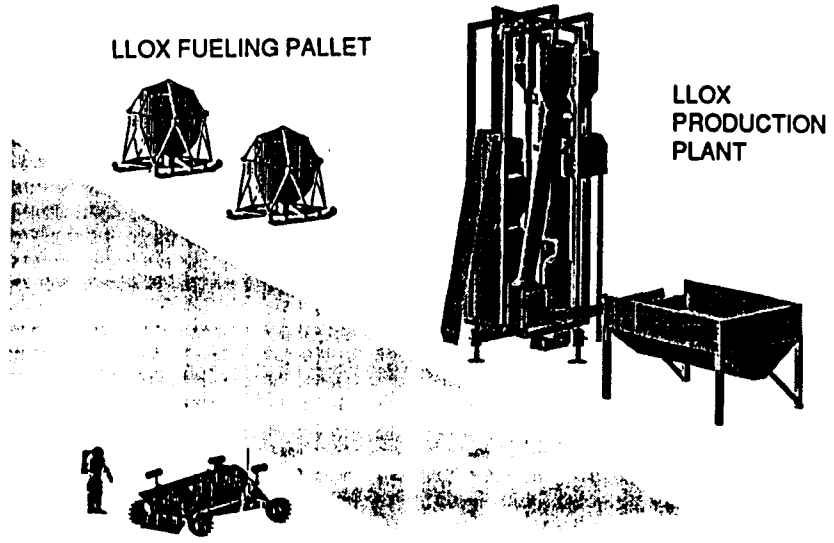
- OVERALL MANAGEMENT OF ANY ELEMENTS OR SYSTEMS WHICH CONTACT THE PLANET SURFACE (WITH THE EXCEPTION OF EXCURSION VEHICLES).
  - -HABITATS
  - -SURFACE VEHICLES
  - -POWER SYSTEMS AND UTILITIES
  - -IN-SITU RESOURCE UTILIZATION
  - -OPERATIONS

U.S. Gov't

NASA



Crew Habitation



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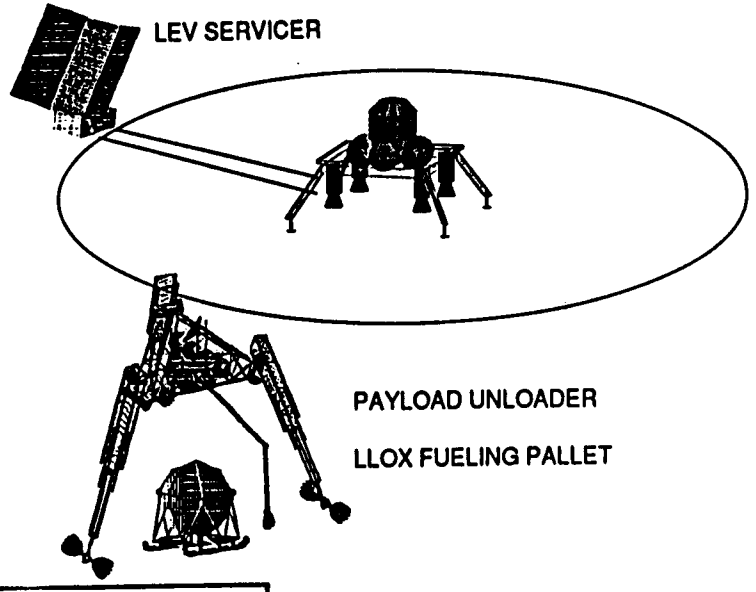
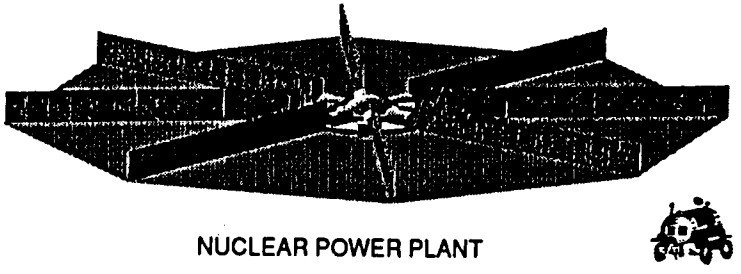


Launch & Landing



Power Production

Planet Surface Systems

Bear-BARRIOS/BRoberts/Synthesis Group Input/GJF-9/24/90 --1

SURFACE CONSTRUCTION REQUIREMENTS

1. SITE SELECTION AND MAPPING

- ORBITAL INFORMATION - SLOPES, TOPOGRAPHIC INFORMATION TO 20cm RESOLUTION, REGOLITH CHARACTERISTICS (SPECTROMETER DATA). WILL ALLOW THE SELECTION OF A NUMBER OF CANDIDATE SITES.

2. SITE SURVEYING AND SUBSURFACE ANALYSIS

- MEASURED FROM A GROUND-BASED UNIT (SUCH AS A ROBOTIC ROVER) - DETAILED SLOPES AND TOPOGRAPHY FOR FINAL SITE SELECTION. SUBSURFACE DRILLING AND TESTING FOR DETAILED DATA. ANALYSIS OF SOIL MINERALOGY.

3. UNLOADING CONSTRUCTION EQUIPMENT FROM LANDER

- SITE SURVEYING EQUIPMENT AND SOME CONSTRUCTION EQUIPMENT MAY PRECEDE ALL OTHER EQUIPMENT TO THE SURFACE - MUST BE SELF-DEPLOYING FROM THE LANDING VEHICLE

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SURFACE CONSTRUCTION REQUIREMENTS

4. ROAD BUILDING

- LEVEL PATHWAYS WILL OPTIMIZE TRANSPORT OF CARGO AND CREW. FILLING CRATERS, SMOOTHING BUMPS AND ELIMINATING ROCKS WILL GREATLY IMPROVE VEHICLE SPEEDS. HARDENING THE SURFACE, SUCH AS BY MICROWAVE SINTERING, WILL REMOVE DUST CONTAMINATION PROBLEMS IN BEARINGS AND WEARING SURFACES.

5. SITE LEVELLING, LANDING PAD PREPARATION

- LEVEL SITES IN THE HABITATION, POWER AND LAUNCH/LANDING AREAS WILL IMPROVE OPERATIONS IN THOSE AREAS. SIMILAR TO ROAD BUILDING, LEVELLING AND GRADING OFFER IMPROVED MOBILITY, BUT HARDENED SURFACES PROVIDE MAXIMUM BENEFITS

6. EXCAVATION AND TRENCHING

- TRENCHING REQUIRED FOR UTILITIES. EXCAVATION REQUIRED FOR HABITAT EMPLACEMENT, NUCLEAR REACTOR EMPLACEMENT, BERMS AT LAUNCH/LANDING AREAS AND REGOLITH SHIELDING FOR HABITATS.

U.S. GOV'T

SURFACE CONSTRUCTION REQUIREMENTS

7. OFFLOADING CARGO FROM LANDER

- CARGO WILL BE DELIVERED ON LANDERS IN ANY NUMBER OF CONFIGURATIONS - ATOP LANDER (FLATBED CONCEPT), ON FIXED SIDE CARGO PLATFORMS, OR ON CARGO PLATFORMS WHICH CAN BE LOWERED TO THE SURFACE. CARGO MASSES FROM 50 KG TO 15 MT MUST BE ACCOMMODATED, AND COULD POSSIBLY BE AS HIGH AS 5M ABOVE THE FOOTPADS

8. TRANSPORTING CARGO ON SURFACE

- OFFLOADED CARGO MUST BE TRANSPORTED TO IT PLACE OF USE. CURRENT DESIGNS INDICATE A MAXIMUM TRAVEL DISTANCE OF 2KM. (NUCLEAR PLANT ELEMENTS).

9. EMPLACING ELEMENTS ON SURFACE

- DELIVERED ELEMENTS MUST BE PROPERLY POSITIONED AND ALIGNED (eg, THERMAL RADIATOR PACKAGES MUST BE PLACED ON AN EAST-WEST AXIS, AND PVA's MUST BE PLACED ON A TRUE NORTH-SOUTH AXIS)

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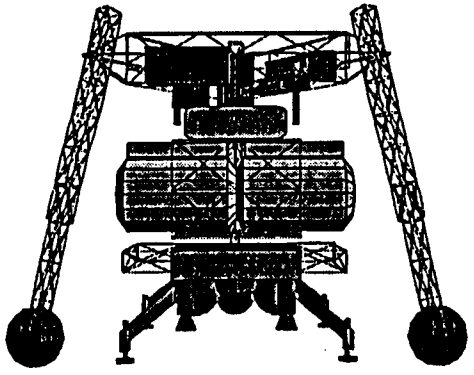
Lander Unloading



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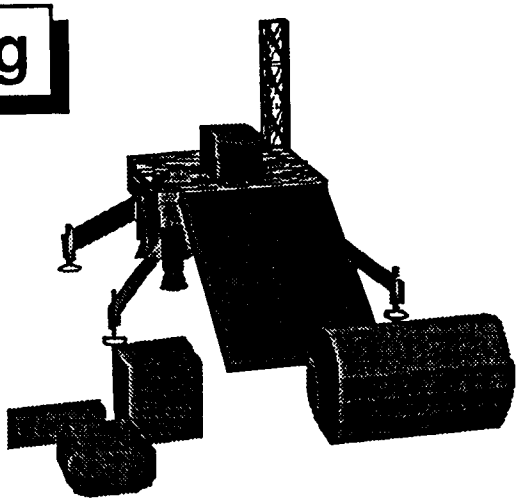
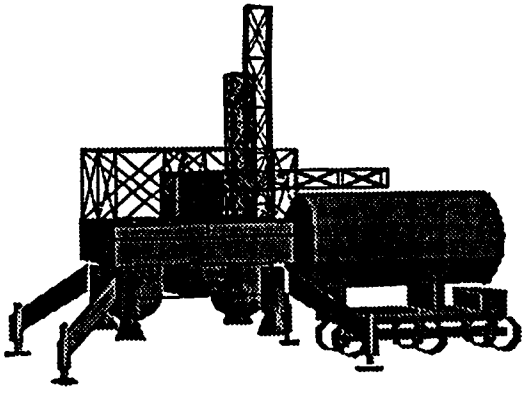
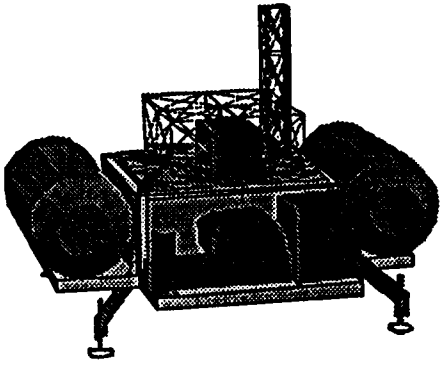


Ramp Integral to Lander



Self-Unloading (Crane on Lander)



Lowering Platform Integral to Lander

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SURFACE CONSTRUCTION REQUIREMENTS

10. DEPLOYING ELEMENTS

- ONCE POSITIONED CORRECTLY ON THE SURFACE, MANY OF THE SURFACE ELEMENTS REQUIRE DEPLOYMENT:
  - PHOTOVOLTAIC ARRAYS
  - NUCLEAR REACTORS
  - THERMAL RADIATORS
  - COMMUNICATION TOWERS
  - LAUNCH PAD MARKERS

11. ELECTRICAL AND FLUID CONNECTIONS

- ELECTRICAL AND FLUID LINES WILL BE PLACED IN A TRENCH FOR THERMAL STABILITY. CONNECTIONS MUST BE MADE FROM THE POWER GENERATION EQUIPMENT TO HABITATS, ISRU FACILITIES, SCIENCE PACKAGES, AND ALL OTHER ELEMENTS REQUIRING POWER. THERMAL FLUID CONNECTIONS AND COMMUNICATION EQUIPMENT CONNECTIONS ARE MADE LIKEWISE.

12. CHECKOUT, TROUBLESHOOTING AND REPAIR

- ONCE THE SYSTEMS ARE INTERCONNECTED, THEY MUST BE CAPABLE OF BEING TESTED AND REPAIRED

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SURFACE CONSTRUCTION REQUIREMENTS

13. REGOLITH SHIELDING OF HABITATS

- TO PROVIDE THE PROPER AMOUNT OF RADIATION SHIELDING TO THE CREW, THE HABITATS MUST BE SHIELDED IN APPROXIMATELY 1M OF REGOLITH. THE REGOLITH CAN BE BERMED AGAINST THE HABITATS, PLACED ON A STANDOFF STRUCTURE, OR PLACED IN BAGS WHICH SHROUD THE HABITAT. THE REGOLITH MUST BE EXCAVATED TRANSPORTED TO THE HABITAT SITE AND EMPLACED TO SUFFICIENT DEPTH AND COMPACTION.

14. LANDER SERVICING

- FOR CREW SURFACE STAYS EXCEEDING 30 DAYS, THE LANDING VEHICLE MUST BE SERVICED ON THE SURFACE TO PROVIDE ELECTRICAL POWER CONDITIONING, THERMAL CONTROL, MICROMETEORITE PROTECTION, AND CRYOGENIC FUEL CONDITIONING.

15. NUCLEAR REACTOR DEPLOYMENT

- NUCLEAR REACTORS ARE DELIVERED IN PACKAGES WHICH MUST BE ASSEMBLED. THE REACTOR CORE IS PLACED IN A HOLE EXCAVATED IN THE PLANET SURFACE, AND THE THERMAL CONTROL SYSTEMS AND POWER MANAGEMENT SYSTEMS ARE DEPLOYED NEARBY.

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SURFACE CONSTRUCTION REQUIREMENTS

16. SCIENCE PACKAGE TRANSPORT AND DEPLOYMENT

- SCIENCE PACKAGES ARE OFFLOADED FROM THE LANDER AND TRANSPORTED TO THE SCIENCE AREA OF THE OUTPOST. SCIENCE PACKAGES CAN RANGE FROM 50 KG SELF-CONTAINED RETROREFLECTORS TO 2MT TELESCOPE ASSEMBLIES.

17. REMOVAL OF EXPENDED LANDERS

- LANDERS ARE DESIGNED EITHER TO BE EXPENDABLE OR TO BE REUSED FOR A SPECIFIC NUMBER OF MISSIONS. THE LANDER WHICH ARE EXPENDED ON THE SURFACE MUST BE TRANSPORTED OFF THE LAUNCH/LANDING PAD AREA TO AN AREA WHERE THEIR COMPONENTS CAN BE RE-USED. AN EXPENDED LANDER COULD BE IN THE RANGE OF 10 MT.

18. ISRU PLANT DEPLOYMENT

- LIKE THE NUCLEAR PLANT, THE FACILITY FOR PRODUCING USEFUL PRODUCTS FROM PLANETARY RESOURCES WILL BE DELIVERED IN PARTS AND CONSTRUCTED, EARLY ISRU (IN-SITU RESOURCE UTILIZATION) FACILITIES MAY MANUFACTURE LIQUID OXYGEN (FOR LIFE SUPPORT AND TO FUEL LANDERS) FROM REGOLITH. A BY-PRODUCT OF THE HIGH-TEMPERATURE MELTING PROCESS MAY BE CAST BASALT STRUCTURAL ELEMENTS OR PAVERS.

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SURFACE CONSTRUCTION REQUIREMENTS

19. MINING - EXCAVATING AND HAULING

- DIFFERENT ISRU PROCESSES REQUIRE VARYING AMOUNTS OF FEEDSTOCK. THE PRODUCTION OF A MINIMUM OF 5 MT OF LLOX PER YEAR COULD CONSUME 30 TO 1500 MT OF REGOLITH PER YEAR. THE PRODUCTION OF A SINGLE MT OF 3He WOULD REQUIRE THE MINING OF 75,000,000 MT OF REGOLITH.

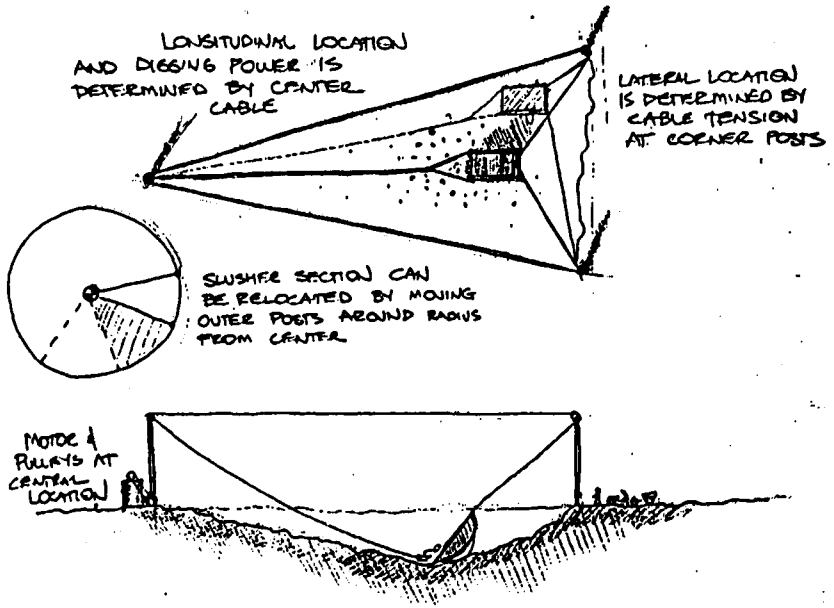
20. ISRU OPERATIONS

- THE REGOLITH MUST BE EXCAVATED AND TRANSPORTED TO THE ISRU FACILITY. THE BY-PRODUCTS OF THE PROCESS MUST BE EITHER STOCKPILED OR RETURNED TO RECLAIM THE EXCAVATION SITE.

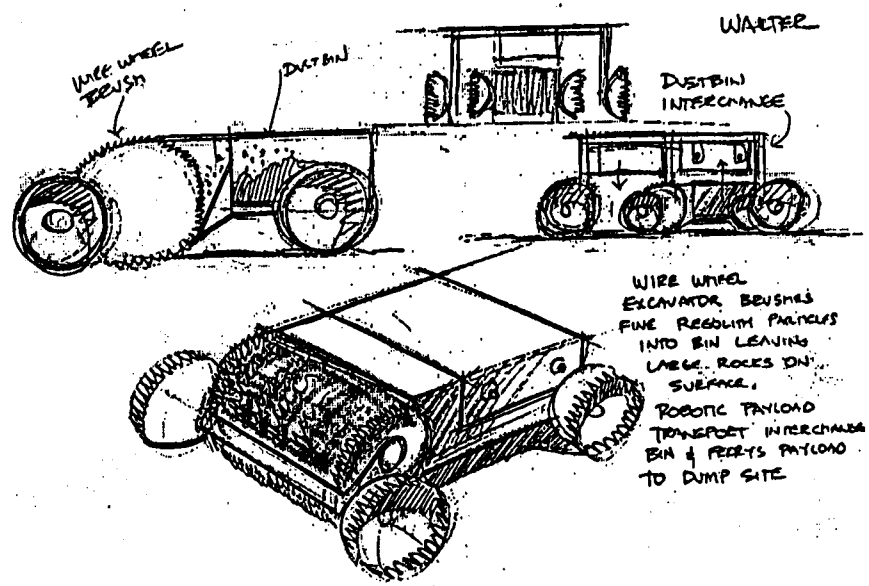
21. MODULAR HABITAT CONSTRUCTION

- IN ORDER TO GAIN SIGNIFICANT LIVING VOLUME WITH MINIMUM MASS AND VOLUME DELIVERED TO THE SURFACE, MODULAR CONSTRUCTIBLE HABITATS WILL BE CONSTRUCTED. CONSTRUCTIBLE HABITATS MAY BE PANEL CONSTRUCTION OR INFLATABLE TECHNOLOGY, BUT MUST BE ERECTED ON SITE USING EARTH-FABRICATED MATERIALS. THE HABITATS MUST PROVIDE A PRESSURE SHELL, RADIATION PROTECTION AND ENVIRONMENTAL CONTROL, AND MAY BE INTERNALLY OUTFITTED IN SHIRT-SLEEVES AFTER THE PRESSURE SHELL IS CERTIFIED

Regolith Excavation



"Slusher" Excavator



Wire Brush Regolith Excavator

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SURFACE CONSTRUCTION REQUIREMENTS

22. ISRU-DERIVED HABITAT CONSTRUCTION

- ONCE ISRU OPERATIONS HAVE BEEN PROVEN AND ISRU-DERIVED MATERIAL PROPERTIES ASSESSED, CONSTRUCTION MAY COMMENCE ON STRUCTURES WHICH UTILIZE ISRU-DERIVED STRUCTURAL MEMBERS, PANELS, etc. INITIAL ISRU-DERIVED STRUCTURES WILL BE NON-CRITICAL BUILDINGS SUCH AS STORAGE FACILITY OR VEHICLE GARAGES. ONCE PRESSURE CERTIFICATION CAN BE MADE, A LOW PRESSURE STRUCTURE SUCH AS A GREENHOUSE CAN BE CONSTRUCTED. FINALLY, A FULL-PRESSURE HABITAT CAN BE CONSTRUCTED USING INDIGENOUS MATERIALS.

NASA

TECHNOLOGY DEVELOPMENT

TECHNOLOGY DEVELOPMENT PROGRAMS ARE THE FIRST STEP TO DEVELOPING THE SYSTEMS WHICH PROVIDE OPTIMUM SOLUTIONS FOR THE PROJECT REQUIREMENTS

TECHNOLOGY DEVELOPMENT AREAS INCLUDE:

- CONSTRUCTIBLE/ERECTABLE/INFLATABLE HABITATS-
  - MATERIALS, PACKAGING, STRUCTURE, ASSEMBLY, UTILITIES, OUTFITTING, VERIFICATION AND MAINTENANCE.
- HABITAT HANDLING, FOUNDATION AND LEVELLING
- CONSTRUCTION -
  - ASSEMBLY AND TOOLS, SITE PLANNING, SITE PREPARATION, MATERIAL TRANSPORT
- PYROTECHNIC EXCAVATION
- CONSTRUCTION AND MINING VEHICLES-
  - STRUCTURAL MATERIALS, BEARINGS/FRICTION SURFACES, THERMAL CONTROL, MOBILITY SYSTEMS
- CONSTRUCTION AND MINING OPERATIONS-
  - OPTIMUM METHODS FOR OFFLOADING, TRANSPORTATION, SITE SURVEYING, REGOLITH EXCAVATION AND TRANSPORTATION, SITE LEVELLING, ROAD BUILDING.
- AUTOMATION AND ROBOTICS-
  - JOINT ACTUATORS, SENSOR TECHNOLOGY, MACHINE VISION, ARTIFICIAL INTELLIGENCE, MAN-MACHINE INTERFACES, END EFFECTORS, MODULAR SOFTWARE, IMPROVED COMPUTER ARCHITECTURE, STRUCTURAL DYNAMICS AND KINEMATICS, HIGH-RATE COMMUNICATIONS

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Lunar Mission Architecture Evaluation Using a Decision Analysis Approach

Janet Gleave

Center for Space Construction, Systems Cluster

President Bush's call for a return to the Moon, followed by the human exploration of Mars, has spawned numerous ideas for implementing what has been called the Space Exploration Initiative (SEI). Because a return to the Moon has been designated as the first step of SEI, the time is rapidly approaching to select one of the many mission architectures proposed for the exploration, settlement, and exploitation of the Moon. The evaluation of alternative architectures, and the subsequent selection of the "best" alternative will be critical to the success of this, and other, space programs.

The following presentation discusses the application of *systems analysis* to the evaluation and selection of a Lunar outpost mission architecture. The role of a *decision model* in the evaluation/selection process is discussed, and different types of decision models are presented. These models are analyzed and discussed in terms of their applicability to the selection of a Lunar outpost mission architecture.

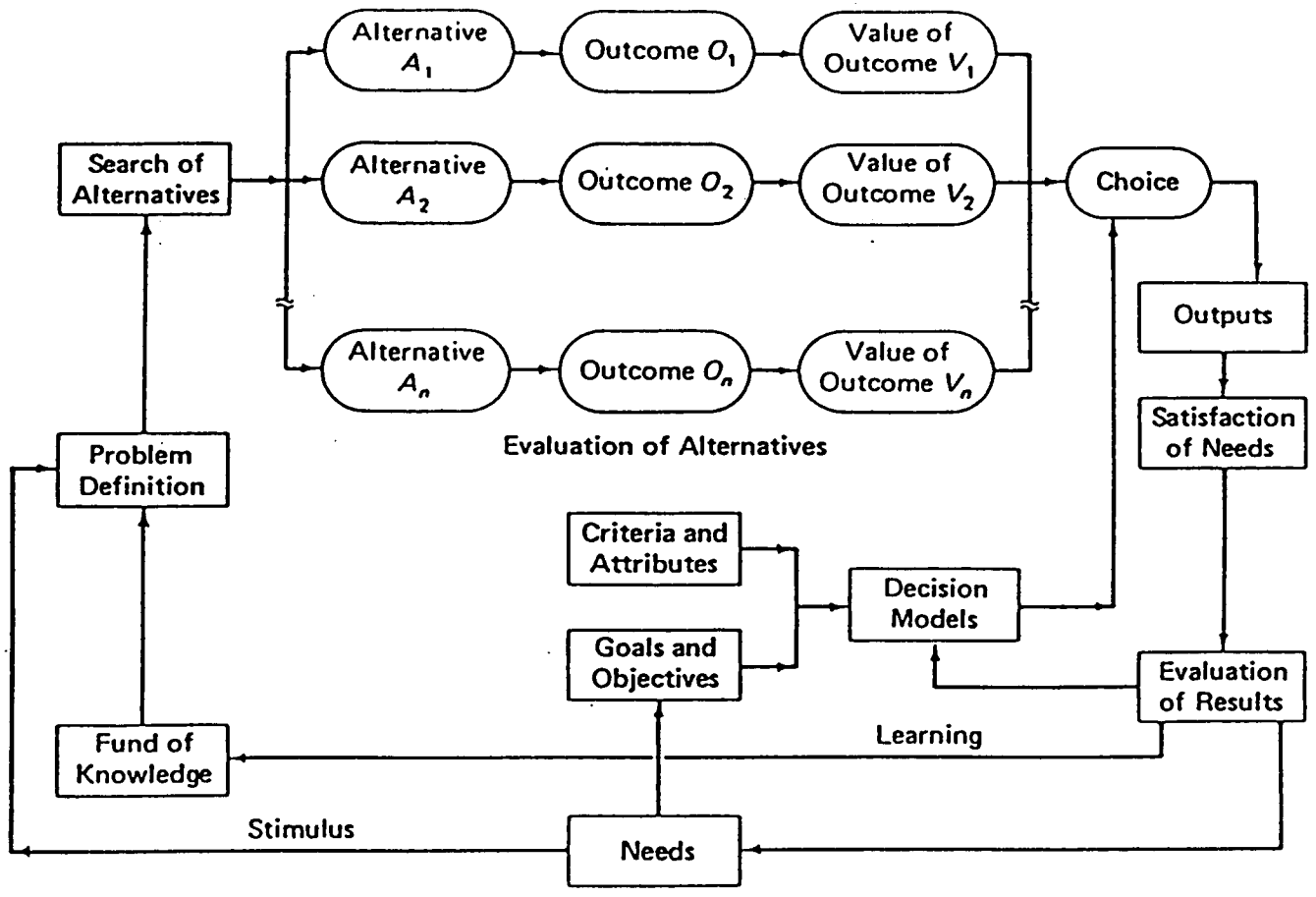
LUNAR MISSION ARCHITECTURE EVALUATION USING A DECISION ANALYSIS APPROACH

CSC Symposium, 17 October 1990

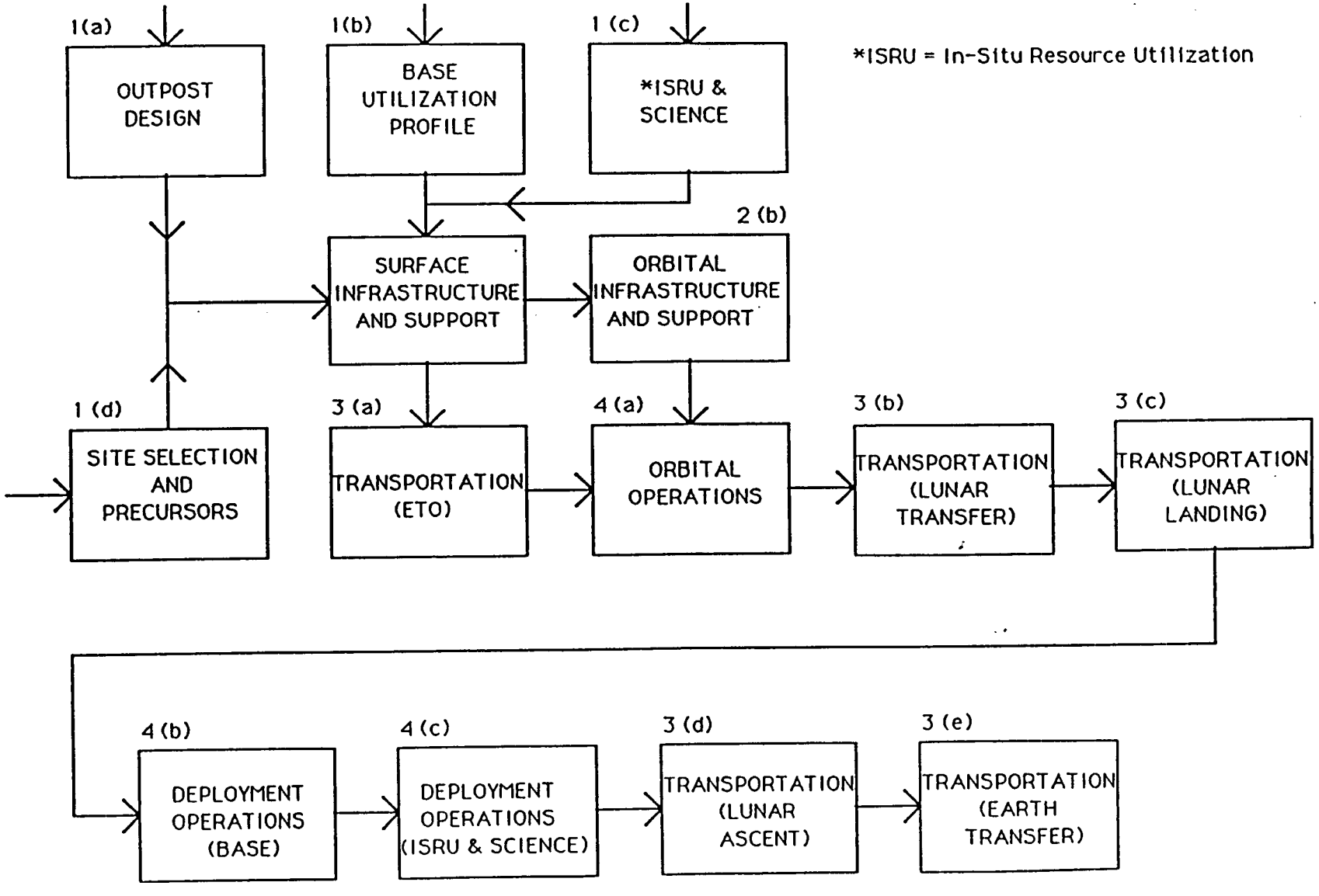
Janet Gleave

CSC Systems Cluster

The Systems Approach to Decision Making



A Lunar Outpost Mission *Architecture* "System"



Decision Model Summary

- *Delphi Approach* **(Judgmental/Qualitative)**
  - Based on Expert Opinion
  - Critical Parameters are Identified and Scored
- *Probability of System Success Model* **(Quantitative)**
  - Derived from Reliability Theory
  - System and Subsystem Networks are Defined
  - Probability Measures are Determined
- *Decision Analysis (Risk Assessment) Techniques* **(Quantitative)**
  - Decision Tree Structure (Branch and Bound)
- *Monte-Carlo Simulation* **(Quantitative)**
  - Used for Multi-level/Multi-variable Systems
  - Permits a Probabilistic Simulation of the Entire System
- *SIMCON (CAE)*

An Example of the Delphi Approach:
*Evaluation of Six Extraterrestrial Building Systems

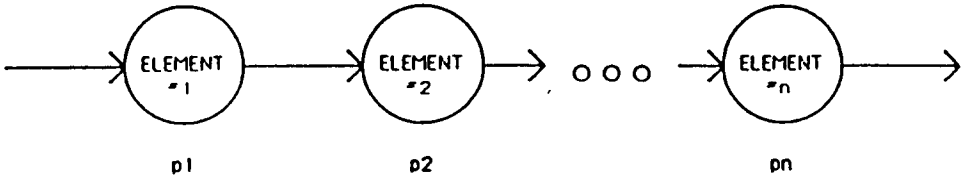
CHARACTERISTIC	CONCEPT					
	A	B-1	B-2C	C	D-1	D-2
Total Weight	5	4	2	1	3	3
Size Limitations	2	3	3	5	2	4
Size Expandability	4	4	5	5	1	2
Space Utilization Efficiency	2	2	4	5	3	4
Ease of Internal Rearrangement	2	3	4	5	2	5
EVA Time for Construction	4	4	2	5	2	2
Erectability	5	4	3	4	2	3
Modularity	3	3	4	5	2	2
Connection of Modules	3	3	4	5	1	2
Adaptable to Automated Tech	5	4	2	3	2	2
Connection of Components	5	4	1	3	2	2
Failure Modes-Safety	2	3	4	5	2	2
Simplicity	5	3	4	4	1	2
Reliability	2	4	3	5	3	4
Maintainability	2	4	4	5	3	4
Transportability of Components	4	4	4	4	3	3
Technology Development State	3	2	4	4	3	3
Redeployability	3	3	4	4	1	1
Terrestrial Analog	2	2	2	3	2	2
Support of Internal Components	2	4	5	5	5	4

A-Inflatable
B-1-Framed/Rigidized Foam
B-2-Polygonal Framed
C-Prefabricated Modules
D-1-Spherical Hybrid
D-2-Semi-spherical Hybrid

5 is most favorable -- 1 is least favorable

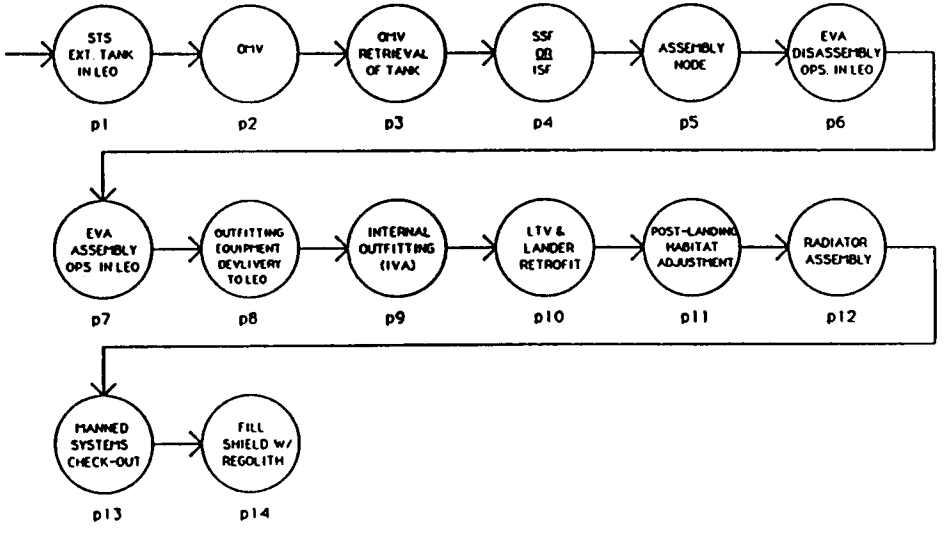
*Courtesy of Phillip J. Richter,
Director of Structural Engineering, Fluor Daniel, Inc.

The "Probability of System Success" Model Applied to a Series System



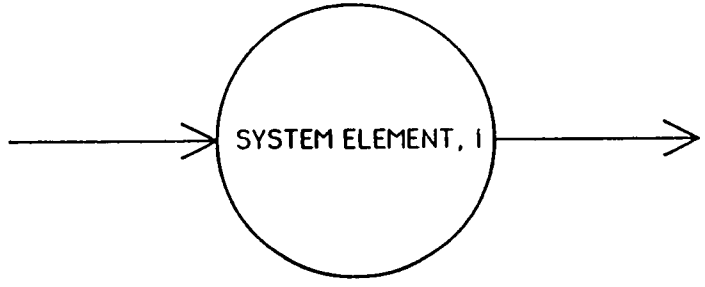
p_i = probability of success for element i

$R(p_1, p_2, \ldots, p_n)$ = reliability of the series system

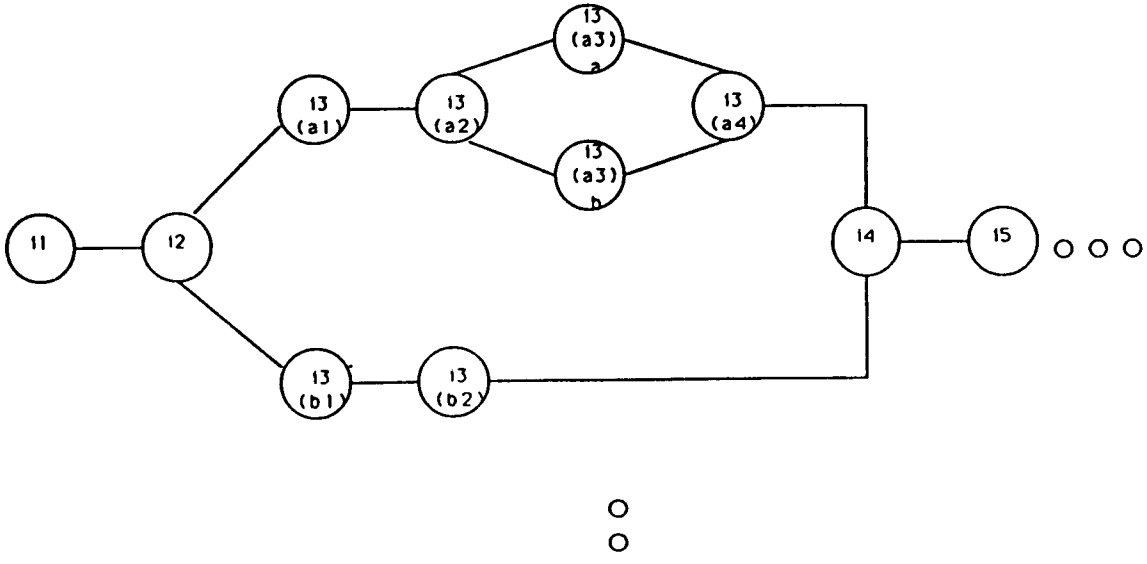


The series model adapted to "A Single-Launch Lunar Habitat Derived from an NSTS External Tank" Lunar outpost mission architecture.

The "Probability of System Success" Model: An Example of a Series System Sub-network



SYSTEM ELEMENT, i
SUBSYSTEM ELEMENTS



A Brief Discussion of the "Levels" of Probabilities

Probability assessment is a function of available information.

Subjective Probabilities

Information:	Little or none available
Analysis Methods:	Judgment (Expert Opinion, Delphi Technique)

Objective Probabilities

Information:	Historical and/or current
Analysis Methods:	Mathematical models derived from existing probability model and/or the statistical analysis of data

Bayesian Probabilities

Incorporate New Information
to Move from Subjective to Objective Probabilities

Conclusions: A General Statement of Decision Model Requirements

- *Multiple Figures of merit*
  (transportation and manpower requirements, technology development, cost, schedule, etc.)
- *Model structure*
- *Constraints* (space logistic limitations, etc.)
- *Uncertainty Modeling and Sensitivity Analysis Capabilities*
- *Feedback* for updating network structure and probabilities based on future information.

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Session Three

LOGISTICS CONSIDERATIONS

George W. Morgenthaler,
Chair

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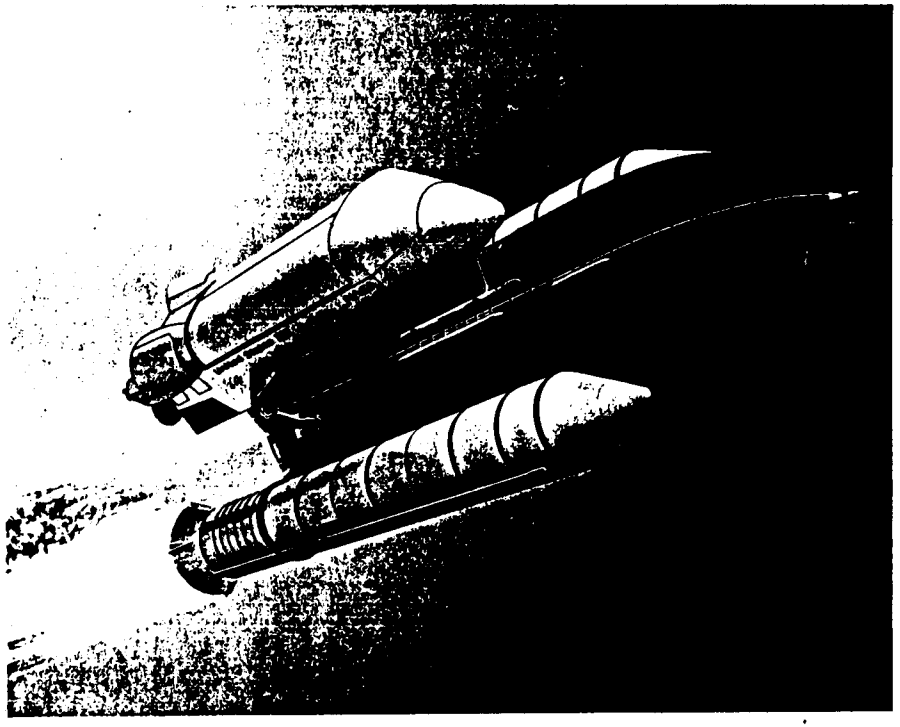
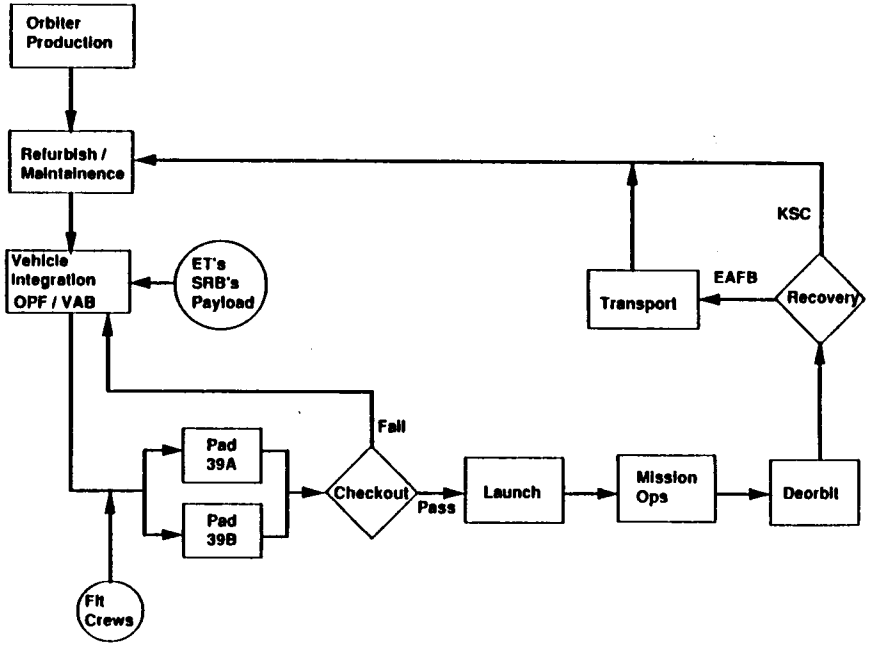
Center for Space Construction
Space Construction Logistics Considerations Session
Wednesday, October 17, 1990, 10:45 a.m. – 12:00 noon
George W. Morgenthaler, Chair



SIMULATION FLOW LOGIC



—Construction Options are limited by logistics capability!

Space Construction Logistics Considerations
Philosophy and Agenda

George W. Morgenthaler, Chair (5 min)

- Launch Vehicle Selection - Alex Montoya, CSC (14min)
- Space Logistics Simulation: Launch-On-Time - Kendall M. Nii, CSC (14min)
- The Application of Depot Transfer/Rendezvous in Space Based Cyclic Orbit Missions - Randall E. Coffey, Ball Aerospace (14min)
- Combining Near-Term Technologies to Achieve a Two-Launch Manned Mars Mission - David A. Baker and Robert M. Zubrin, Martin Marietta Astronautics (14min)
- Assessing the Feasibility of a Mars Cycling Transportation System -Michael E. Loucks, CSC (14min)

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LAUNCH VEHICLE SELECTION MODEL

Alex J. Montoya
Center for Space Construction, Systems Cluster

Over the next 50 years, man will be heading for the Moon and Mars to build scientific bases to gain further knowledge about the universe, and to develop rewarding space activities. These large scale projects will last many years and will require large amounts of mass to be delivered to Low Earth Orbit (LEO). It will take much planning to complete these missions in an efficient manner. The preferred selection of a transportation fleet to move these large masses to LEO and beyond becomes necessary, because of the trade-offs and the vast differences in cost depending upon which vehicle fleet is chosen. Furthermore, the planning of a future Heavy Lift Launch Vehicle (HLLV) will significantly impact the overall multi-year launching cost for the vehicle fleet, depending upon when the HLLV will be ready for use.

It is desirable to develop a model in which many trade studies can be performed. In one sample multi-year space program analysis the total launch vehicle cost of implementing the program reduced from 50% to 25%. This indicates how critical it is to reduce space logistics costs. A linear programming model has been developed to answer such questions. The model is now in its second phase of development and this paper will address the capabilities of the model and its intended uses.

The main emphasis over the past year was to make the model user friendly and to incorporate additional realistic constraints that are difficult to represent mathematically. We have developed a methodology in which the user has to be knowledgeable about the mission model and the requirements of the payloads. We have found a representation that will cut down the solution space of the problem by inserting some preliminary tests to eliminate some infeasible vehicle solutions. The paper will address the handling of these additional constraints and the methodology for incorporating new costing information utilizing learning curve theory. The paper will review several test cases that will explore the preferred vehicle characteristics and the preferred period of construction, i.e., within the next decade, or in the first decade of the next century. Finally, the paper will explore the interaction between the primary mission model (all payloads going from Earth to low Earth orbit (LEO), and the secondary mission model (all payloads from LEO to Lunar and LEO to Mars and return).

Launch Vehicle Selection Model

CSC Systems Cluster

Alex J. Montoya

Issues:

- Approach to Space Construction depends upon reliable Space Logistics
- SEI demands a new Heavy Lift Launch Vehicle (HLLV)
- Define the characteristics of HLLV
  - Consider a Total National Needs Mission Model
  - Multi-year Space Program
  - Funding Limitations
  - Realistic Constraints
  - Development Lead Times

CSC Systems Cluster
2nd Annual NASA
Symposium
October 17-19,1990

Launch Vehicle Selection Model

Model Definition:

Minimize Cost= $$\sum_i \sum_j \sum_k \frac{X_{ijk}}{p_{ijk}} \cdot C_{ijk}$$

Where:
i= mission
j= year
k= vehicle type

Subject to:

- Weight
- Volume
- Man-rated
- Quality of Ride
- Limited Launch Rate
- Budgetary Limitation
- Facility Availability
- Maximum P/L to Destination
- Resupply Needs

. . . etc . . .

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October 17-19,1990

Development:

Phase I: August, 1988 - October, 1989

Initial Data Collection
Prove Technique
Preliminary Results to LEO only

Phase II: October, 1989 - October, 1990

User - Friendly Environment
Vehicle Decision Theory
Case Studies
- Build new HLLV now or later?
- Sensitivity of payload size - 6 cases

Secondary Mission Model
- Preliminary Results
- Interaction of Primary and Secondary Models

Launch Vehicle Selection Model

Development Continued:

Phase III: November 1990- October 1991

- Launch on Time Simulation
- Ground Operations Simulation
- Combining LOT Simulation and Ground Operations Simulation and Develop Scheduling Theory
- Primary and Secondary Model Interface

- LOT Simulation Team- Kendall Nii, Kadett Chan, Alex Montoya and Dr. Morgenthaler-- All CSC Members

- Ground Operations Simulation Team- Jeryl Voegtly , Steve Sasso Dave Ernst-- Martin Marietta Astronautics Group, Alex Montoya, Dr. Morgenthaler-- CSC Members

- Scheduling Theory Team- Alex Montoya, Dr. Morgenthaler

Current Model Needs:

- **Cost Analysis**
  - Cost Database
  - Cost Estimating Relationships (CER's) -- See Poster

- **Mission Model (35 years)**
  - Decision Making on Which Payloads Can Fly on Which Vehicles
  - Include SEI Missions, Non-SEI Missions, Commercial?
  - Model Needs to be Representative in Size, Complexity, Frequency, not Accuracy

- **Vehicle and Operations Database**
  - Probabilities
  - Times
  - Compatabilities (man-rated, etc)

Launch Vehicle Selection Model

Examples:

Phase II: Case Studies- Sensitivity of Payload Size

a. 30k - 50k - 70k Class Payloads
b. 30k - 70k - 90k Class Payloads
c. 30k - 90k - 120k Class Payloads
d. 50k - 90k 120k Class Payloads
e. 30k - 50k - 120k Class Payloads
f. 50k - 120k - 200k Class Payloads
g. Build another vehicle now or later?

Results:

a. $3.05 billion/year
b. $2.65 billion/year
c. $2.20 billion/year
d. $2.15 billion/year
e. $1.30 billion/year
f. $1.80 billion/year
g Save approx. 30% - 50% if HLLV built now

Secondary Mission Model

- Moves payloads form LEO to final destination (Lunar, Mars)
- Resupply/Crew Rotations Considered
- Assumes Vehicles and propellant are at the destination, if needed.

Interaction Between Secondary and Primary Mission Models

- Secondary Model Transportation Rqmts. become additional Primary Model payloads

Launch Vehicle Selection Model

Conclusions:

- Concerning SEI and the Space Program
  - Need HLLV built now
  - US Costs non-competitive - because of reliability/operability
  - Select Balanced Fleet (Including, perhaps, a PLS)

- Concerning Space Construction
  - Availability of Low-Cost, Reliable Space Logistics Support Constrains Construction Approaches
  - Mixture of Vehicles Needed (Start w/ Existing Systems)

- Concerning Models and Selection Processes
  - Industry now utilizing formal selection models
  - Improve Primary and Secondary Model Interface

- Future Model Needs
  - Exact Payload Requirements: How many, Which Vehicles?
  - CERs and Availability Time Schedules
  - Exact Secondary Mission Model Requirements

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Space Logistics Simulation: Launch-On-TIme

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Kendall M. Nii

During 1989-1990 the Center for Space Construction developed the Launch-On-Time (L-O-T) Model to help asses and improve the likelihood of successfully supporting space construction requiring multi-logistic delivery flights. The model chose a reference by which the L-O-T probability and improvements to L-O-T probability can be judged. The measure of improvement was chosen as the percent reduction in $E[S_N]$, the total expected amount of unscheduled "hold" time. We have also previously developed an approach to determining the reduction in $E[S_N]$ due to reducing some of the causes of unscheduled holds and increasing the speed at which the problems causing the holds may be "fixed". We provided a mathematical (binary linear programming) model for measuring the percent reduction in $E[S_N]$ given such improvements.

In this presentation we shall exercise the model which was developed, and draw some conclusions about: methods used, data available and needed, and make suggestions for areas of improvement in "real world" application of the model.

We will also explore the seasonal effects on, $\overline{X}$, the average number of holds per launch. Using Statistical hypothesis testing techniques we find that there is a statistically significant variation of $\overline{X}$ for different seasons.

We explore the "learning curve" effect. That is, as a launch vehicle system becomes more mature, does $\overline{X}$, the average number of holds, decrease? The "Learning Curve" theory suggests that as one accumulates more experience, one should become more adept at doing a certain job. It seems that $\overline{X}$ is not decreasing with time as we might expect from the theory of "Learning Curves". We test the hypothesis that there is no statistical evidence of a learning curve for launch operations, and seek to determine why this might be so.

Space Logistics Simulation: Launch-On-Time

Kendall M. Nii

CSC Symposium Presentation
October 17-19, 1990
Center for Space Construction, Systems Cluster.

Reasons for Investigating Launch-On-Time Probability

Interruptability and Logistic Support Problems of Space Construction

Avoid interruption of the assembly schedule of space construction projects, such as Space Station Freedom, Lunar base, Mars base. Also maintain adequate logistic supply for finished projects.

Commercial Competition

Improve the U.S. bid capture rate in severe international competition to launch commercial and scientific payloads.

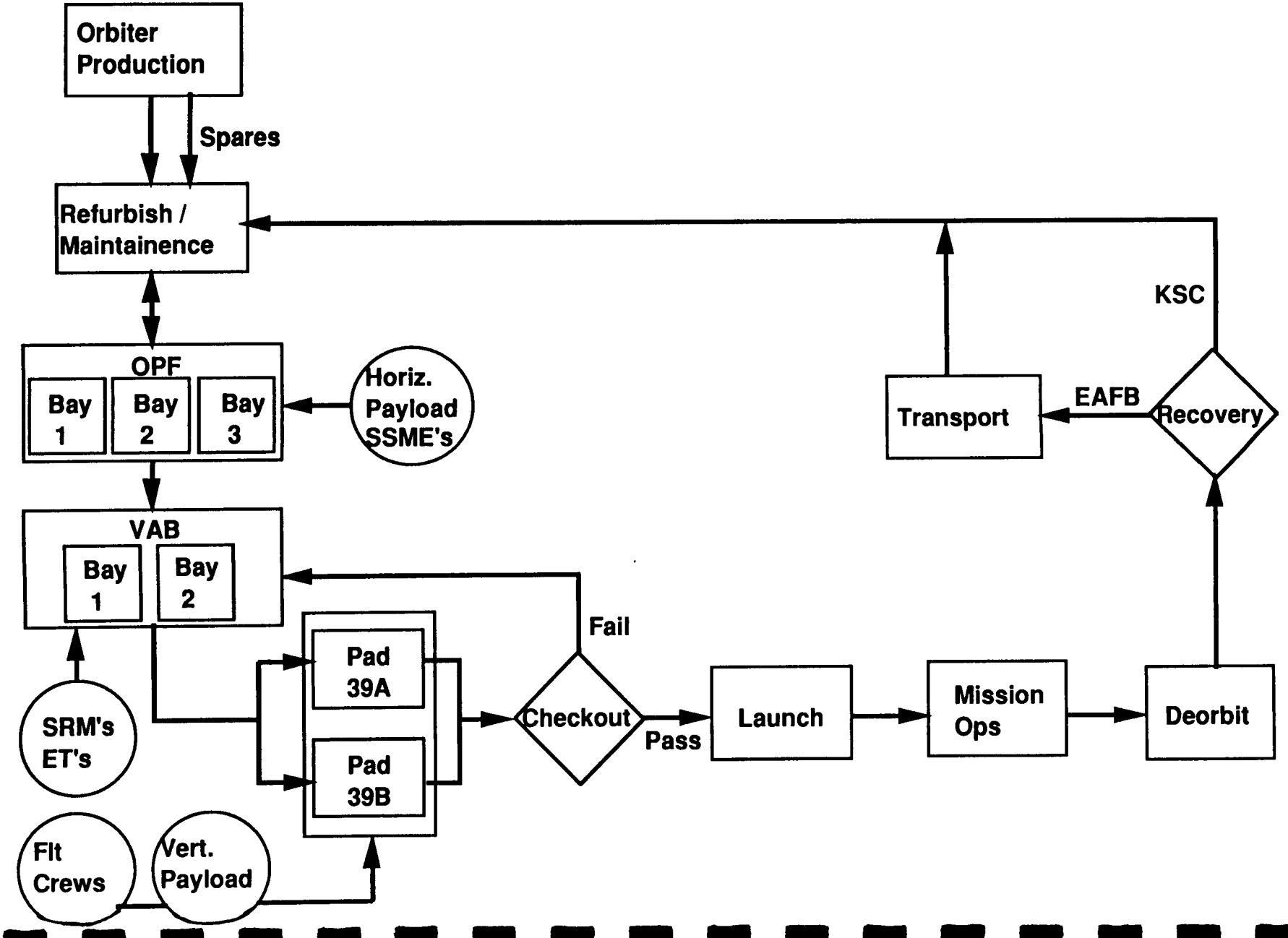
Meeting Space Launch Windows

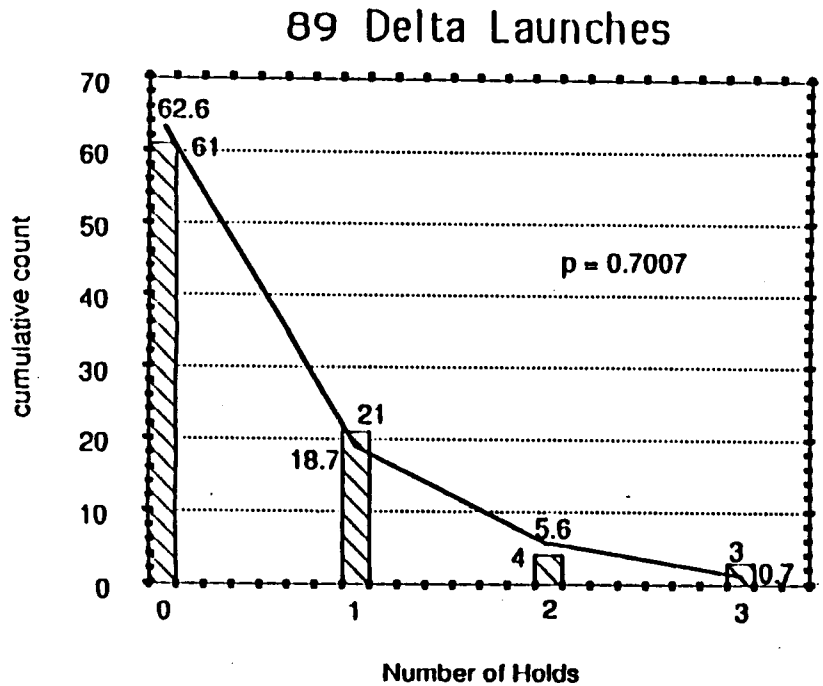
Improve the probability of meeting constrained launch windows such as Voyager II. In 1975 Viking payloads were switched in order to achieve the 30 day launch window.

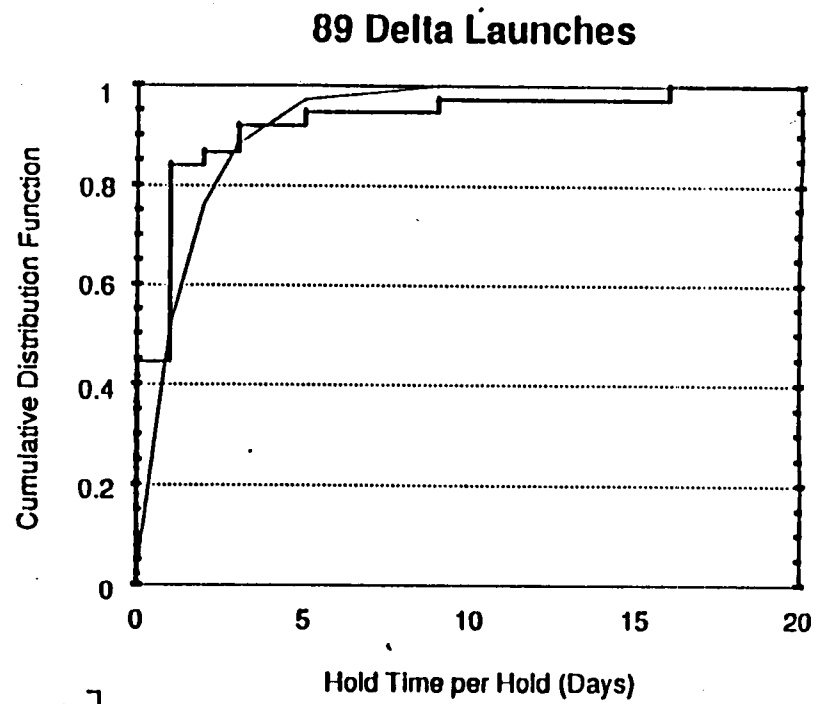
Space Rescue and Police Action

As space activity becomes more widespread, the necessity for precision rescue missions and police action will be present.

SIMULATION FLOW LOGIC







$$\frac{dE[S_N]}{E[S_N]} = -\left[\frac{dp}{p} + \frac{d\lambda}{\lambda}\right]$$

From this formula we derive the

Binary Linear Programming Model

$$\frac{dE[S_N]}{E[S_N]} = -\sum_{i=1}^{h}\left[\frac{1}{p_i}\sum_{j=1}^{N_i} X_{ij}\, s_{ij}\, dp_{ij} + \alpha_i\left(\frac{\lambda}{\lambda_i}\right)\sum_{k=1}^{M_i} Y_{ik}\, t_{ik}\, d\lambda_{ik}\right]$$

$$\sum_{i=1}^{h}\left[\sum_{j=1}^{N_i} X_{ij}\, c_{ij} + \sum_{k=1}^{M_i} Y_{ik}\, e_{ik}\right] \le C$$

Applied to Delta Data

#	Cause of Hold (i)	H	N_i	α_i	$p_i = \frac{89 + N - N_i}{89 + N}$	$1/\lambda_i$ (min.)
1	Vehicle	41	11	0.432	0.915	3082.4
2	Weather	27	12	0.284	0.907	1024.3
3	Range	17	10	0.179	0.922	443.8
4	Payload	10	7	0.105	0.946	3704.4
	Totals	95	40	1.000		

Note that $\sum_{i=1}^{5} \alpha_i \left(\frac{1}{\lambda_i}\right) = 2090.9 \approx \frac{1}{\lambda} = 2014.9.$

Which is about a 1% difference.

Generating Ideas to Improve Launch-On-Time

ij	I_{ij}	s_{ij}	dp_{ij}	c_{ij} (dollars)
11	Better Vehicle Training Programs	80%	5%	0.13×10^6
12	More Vehicle Redundancy	80%	3%	1.1×10^6
21	Better Weather Prediction Equip.	60%	3%	0.15×10^6
22	Better Weather Checking Equip.	80%	5%	1.2×10^6
31	Better Range Training Programs	80%	5%	0.27×10^6
32	More Range Redundancy	90%	5%	1.8×10^6
33	Better Range Maintenance	75%	7%	0.5×10^6

ik	K_{ik}	t_{ik}	λ_{ik}	e_{ik} (dollars)
11	Add Vehicle AI Diagnostics	95%	10%	2.3×10^6
12	Redesign Vehicle for Modularity	95%	10%	3.1×10^6
13	Keep Vehicle Stock Parts on Hand	90%	7%	0.56×10^6
14	Better Vehicle Training Programs	80%	5%	0.14×10^6
31	Add Range AI Diagnostics	95%	10%	2.4×10^6
32	Better Range Training Programs	80%	5%	0.12×10^6
33	Keep Range Equip. Stock on Hand	90%	5%	0.53×10^6

Results of Running Model

n	ij	I_{ij}	A_n	"Improvement" /Cost	Rank
1	11	Better Vehicle Training Programs	0.044	.337	1
2	12	More Vehicle Redundancy	0.026	.024	11
3	21	Better Weather Prediction Equip.	0.020	.287	3
4	22	Better Weather Checking Equip.	0.044	.0403	8
5	31	Better Range Training Programs	0.043	.209	4
6	32	More Range Redundancy	0.048	.0109	13
7	33	Better Range Maintenance	0.057	.088	5

n	ik	K_{ik}	A_n	"Improvement" /Cost	Rank
8	11	Add Vehicle AI Diagnostics	0.026	.0115	12
9	12	Redesign Vehicle for Modularity	0.026	.009	14
10	13	Keep Vehicle Stock on Hand	0.018	.031	10
11	14	Better Vehicle Training Programs	0.011	.079	7
12	31	Add Range AI Diagnostics	0.095	.0397	9
13	32	Better Range Training Programs	0.040	.334	2
14	33	Keep Range Stock on Hand	0.045	.085	6

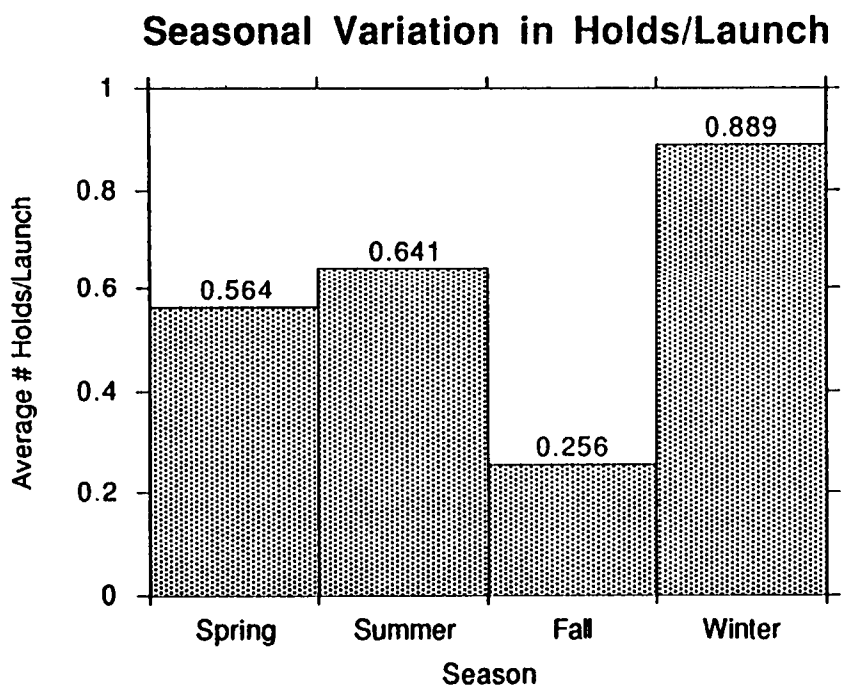
Conclusions & Future Work

- Understand Launch-On-Time Probability
- Have a realistic Method of Optimizing Launch-On-Time Improvement, when constrained by Cost, Weight, and/or Size
- Look into breaking down Causes into sub-causes
- Investigate alternative theoretical methods for obtaining the model
- Apply method to Airline "Leave-On-Time" problem

Seasonal & Time Variations to L-O-T Probability

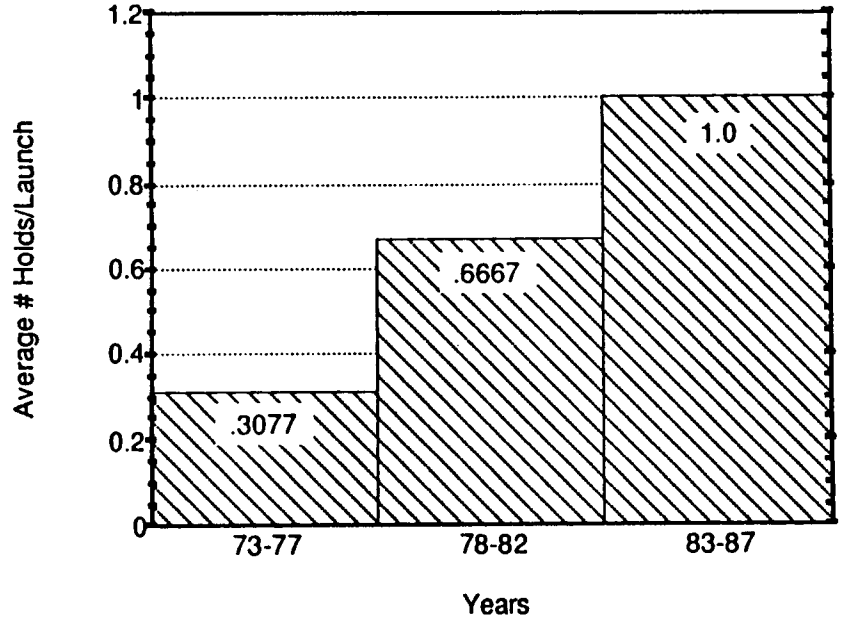
- Explore the Seasonal Effect on the Average # of Holds/Launch
- Explore "learning curve" effect on the Average # of Holds/Launch

Seasonal Variations



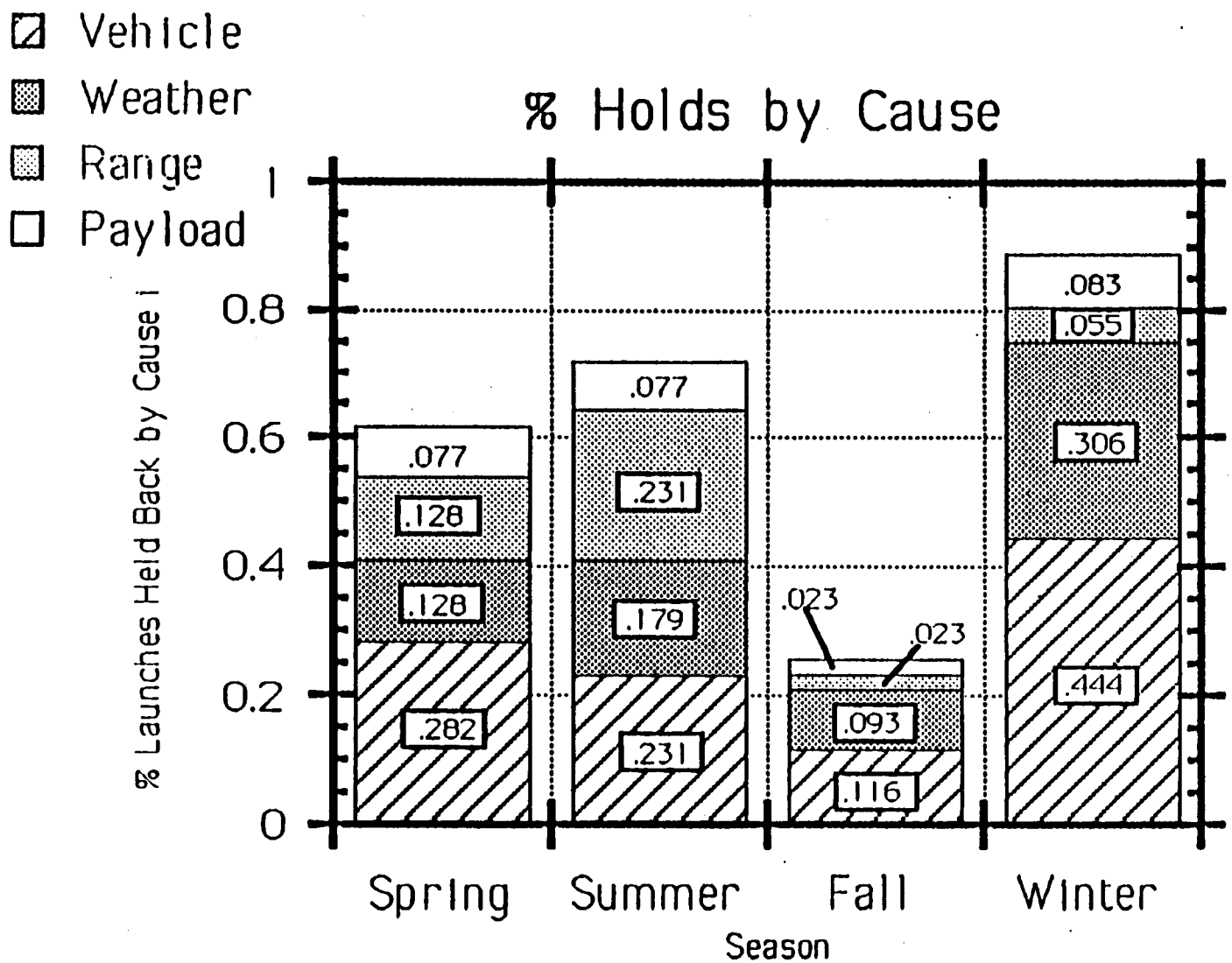
Average Number of Holds per Launch for the FourSeasons for 157 Launches (89 Delta, 38 Atlas/Centaur, and 30 Shuttle)

Variations in Holds/Launch with Time

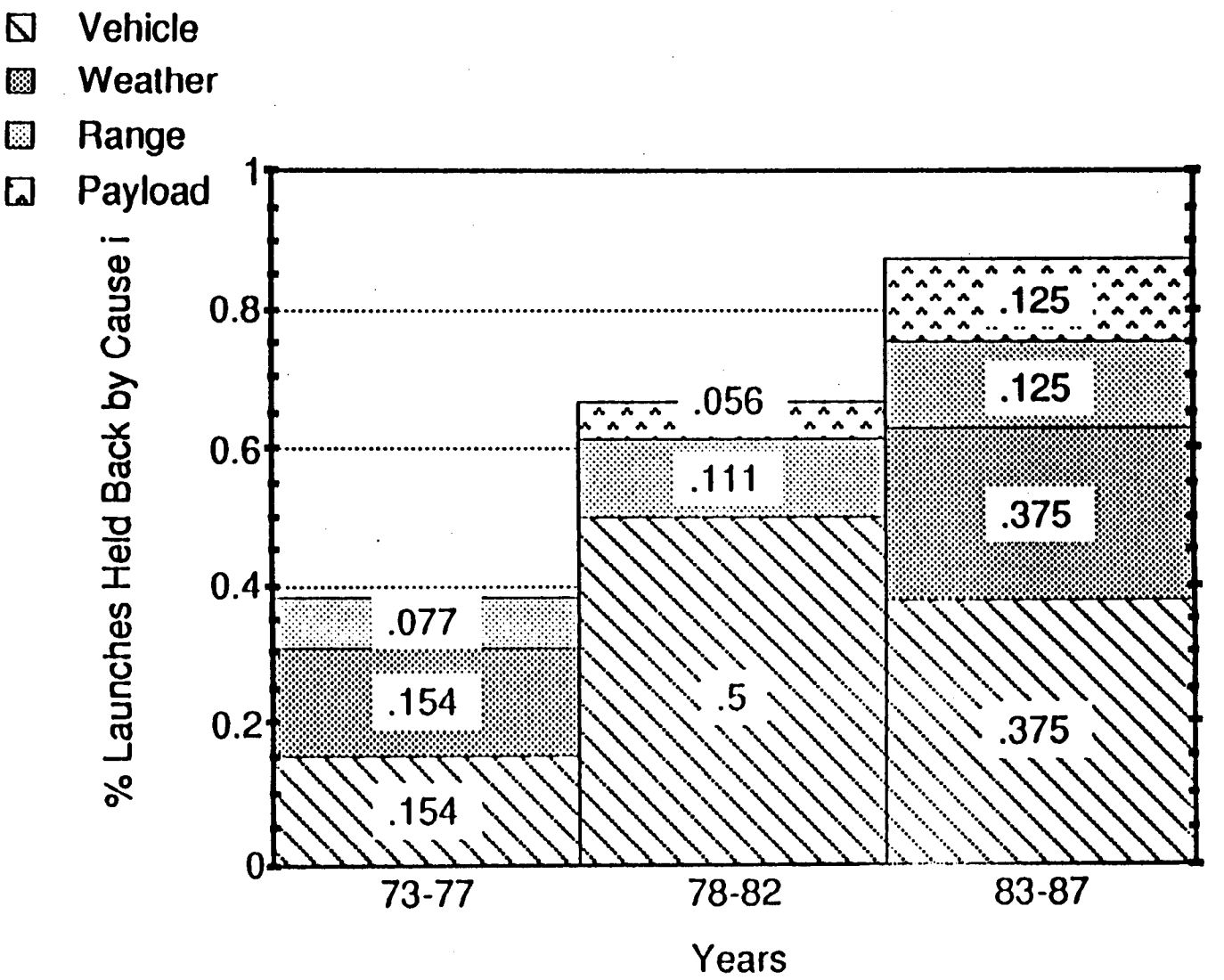


Average Number of Holds per Launch for Atlas/Centaur from 1973 - 1987.

Seasonal Breakdown



Time Period Breakdown



Conclusions

- The seasonal variation in $\overline{X}$ is real
- Important to the commercial aspect of Launch-On-Time
- Range holds high in Summer - competition for equipment
- Do Commercial Launch insurance rates reflect reality?
- Launch holds not following "Learning Curve" expectation - Possibly more interference, and aging range equipment
- Effect on Space Construction:

  - Plan assembly flights to avoid Winter/Summer (Use on-orbit warehousing?)
  - Must inprove Launch-On-Time to give smooth construction operation

Future Work

- Look for other effects on Launch-On-Time
- Get More Data to distinguish counter-flow effects

  When is the best time to launch range-wise
  When is the best time to launch weather-wise
  When is the best time to launch vehicle-wise

- Tie in effects with Launch Vehicle Simulation Model to identify true launch bottlenecks

N94- 70991

The Application of Depot Transfer/Rendezvous in Space Based Cyclic Orbit Missions

Randall E. Coffey
Ball Aerospace Systems and
Center for Space Construction

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Mission planning for future national space programs will seek means to abate the high dollar cost of mass delivery. To meet the fiscal objectives of these programs requires the development of improved transportation logistics, both in the primary Earth-to-low Earth orbit (LEO), and secondary orbit-to-orbit space transportation segments for delivery of construction materials, scientific payloads, and personnel. The deployment of space-based orbit transfer vehicles (OTV's), and development of innovative orbit transfer methodologies that reduce secondary cyclic mission support mass requirements (e.g. propellants) is a crucial step in meeting program budgetary goals.

The research performed in this thesis has developed an improved efficiency cyclic orbit transfer method, based on non-traditional optimization criteria, through the use of intermediate propellant depot orbits and rendezvous transfers. The technique was optimized for a reference cyclic transfer between LEO and Geostationary Earth Orbit (GEO) in the presence of realistic mission affects including: 1) non-planar transfers, 2) perturbed (non-Keplerian) orbit motions, and 3) mission transfer risk mitigation techniques. A semianalytic model was developed to optimize the depot orbit selection and sizing for LEO/GEO cyclic missions for three NASA reference OTV mission payload profiles.

The results demonstrated significant reductions in cyclic mission propellant requirements, when compared to current NASA aerobrake OTV missions, for durations of up to one week in GEO. The magnitude of the propellant mass savings was found to depend on GEO on-orbit durations, mission risk strategies, and payload profiles, with maximum propellant savings amounting to ~11 metric tons/mission. A first-order cost benefit analysis showed a recurring dollar savings from the use of the depot transfer/rendezvous method ranging from 5 to 83 million dollars per mission.

The increase in transfer efficiency is gained in a trade with longer mission durations, ~1 day extra transit time, and greater total transfer energies. The optimized depot method showed a preference for a low number of depots orbits, and uncovered a point of diminishing mission benefits indicating an insensitivity to depot orbit sizing parameters.

THE APPLICATION OF DEPOT TRANSFER/RENDEZVOUS IN SPACE-BASED CYCLIC ORBIT MISSIONS

Randall Coffey

OUTLINE

Introduction
- future national space programs/missions
- mission support transportation logistics

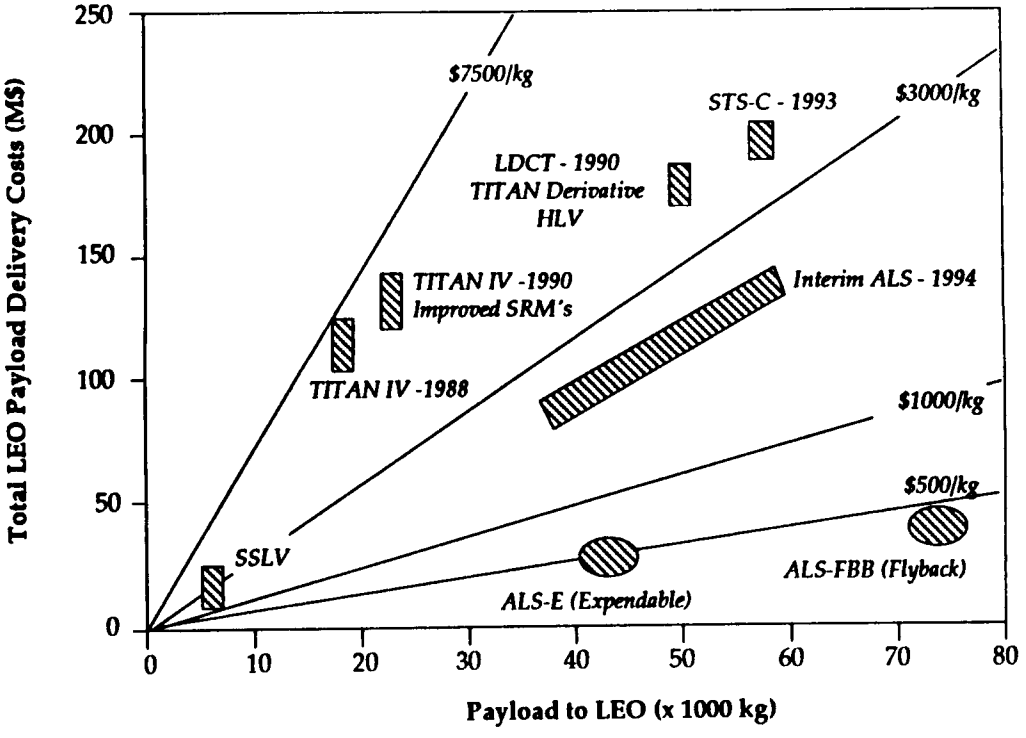
Cyclic near-Earth secondary (orbit-to-orbit) payload transfer
- traditional logistics optimization: bi-Hohmann (aerobraked OTV) transfer
- non-traditional logistics optimization: depot transfer/rendezvous

Depot transfer analytic tools & methods
- first-order perturbation theory
- ascent transfer with depot placement
- descent depot intercept targeting
- coupled propellant equations

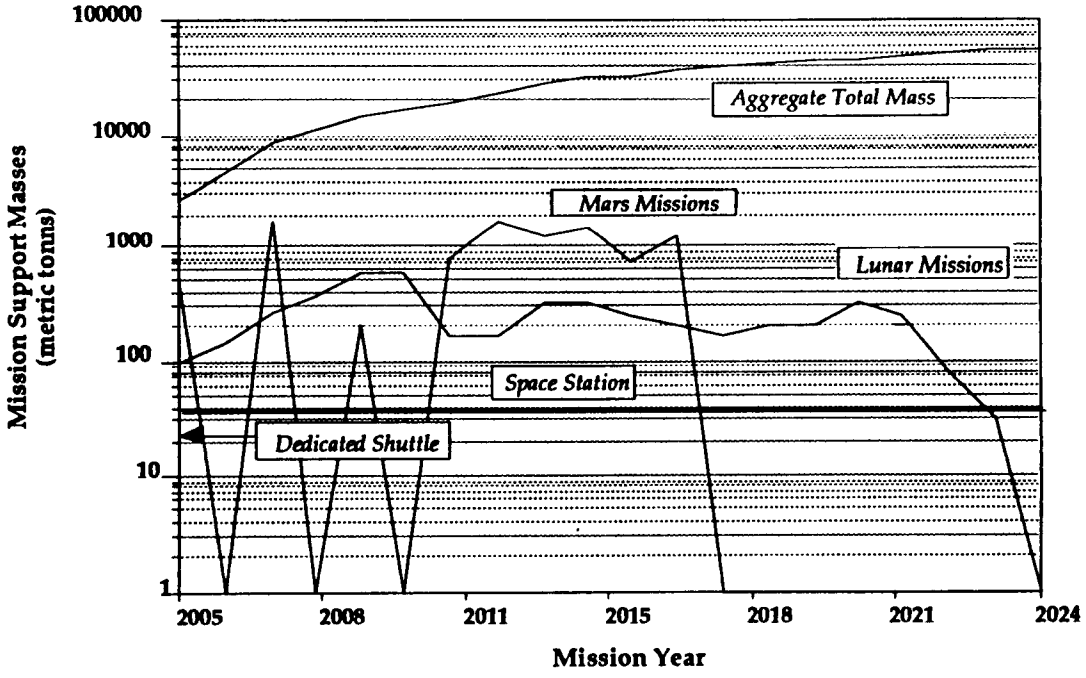
Depot transfer analysis results
- assumptions
- comparitive figures-of-merit

Conclusions/Contributions

CURRENT, NEAR, & NEXT GENERATION EARTH-TO-LEO LAUNCH COSTS AND CAPABILITIES

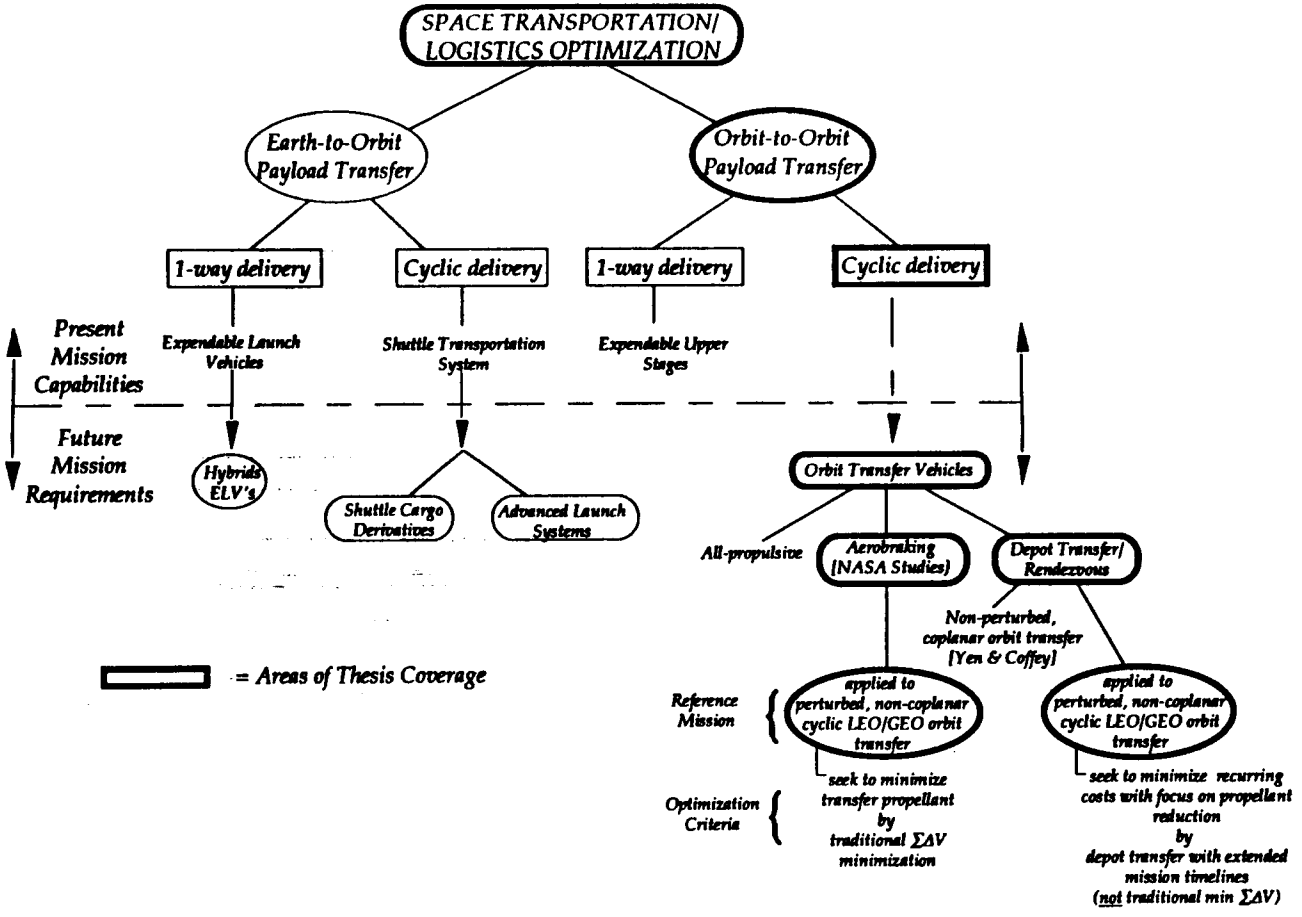


NATIONAL SPACE PROGRAM PROJECTED SUPPORT MASS REQUIREMENTS



* Adapted from NASA Office of Exploration Studies Technical Memo 4750, October, 1988.

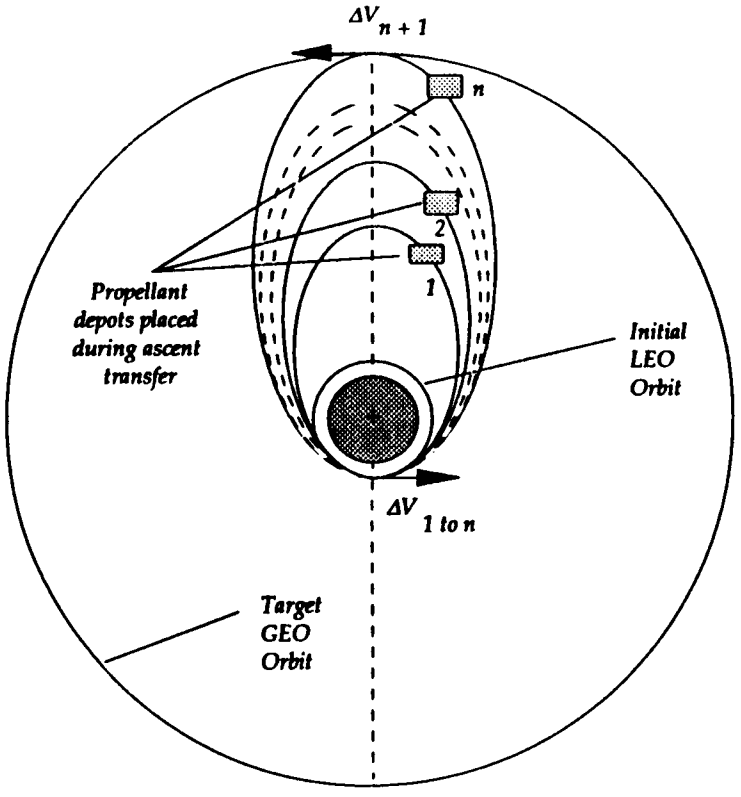
THESIS APPROACH TO CYCLIC TRANSFER OPTIMIZATION



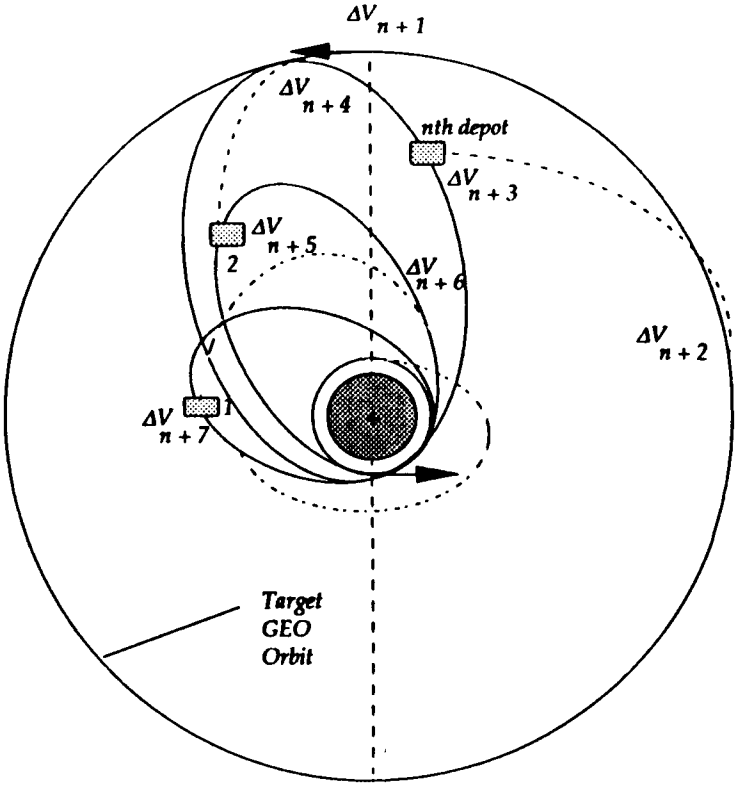
DEPOT TRANSFER ANALYSES

- Previous studies {Yen & Coffey} of depot transfer techniques have indicated ~39% propellant savings over a four burn minimum energy transfer, but have *idealized* the cyclic orbit transfer problem by assuming:
  - co-planar orbit to orbit transfers
  - unperturbed (Keplerian) orbit motion
- The thesis investigation of depot transfer/rendezvous cyclic mission optimization was performed in consideration of "*realistic mission effects*" including:
  - non-planar intermediate and terminal orbit-to-orbit transfers
  - perturbed orbit motions
  - mission transfer risk mitigation techniques
- A NASA reference LEO/GEO cyclic mission was used to compare depot transfer/rendezvous methods with current "optimized" aerobraked OTV mission designs and payloads.

CYCLIC TRANSFER WITH DEPOT PLACEMENT AND DESCENT RENDEZVOUS



Ascent with depot placement



Descent with depot rendezvous

SECONDARY TRANSFER OPTIMIZATION NON-TRADITIONAL THESIS APPROACH

- Future mission operations will require the total propellant to perform the cyclic transfer to be included as part of the initial LEO ascent mass, increasing the OTV mass and lowering propulsive efficiency.

- Even with the use of minimum energy transfers (i.e. Hohmann), cyclic propellant requirements are <u>not</u> determined by the mission $\Sigma\Delta V$, but by the applicaton of *large* ΔV's to *large* ascent/descent mission masses.

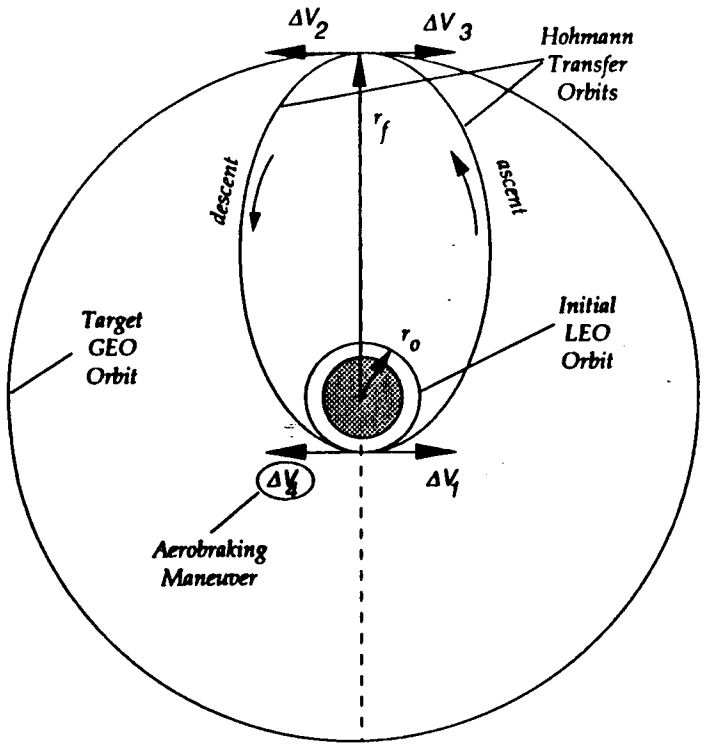
- Propulsion efficiency in the cyclic transfer can be increased by separating mass in the form of <u>propellant depots</u> during a multi-staged ascent, thus allowing the application of *smaller* ΔV's to *smaller* masses (i.e. in a segmented ascent).

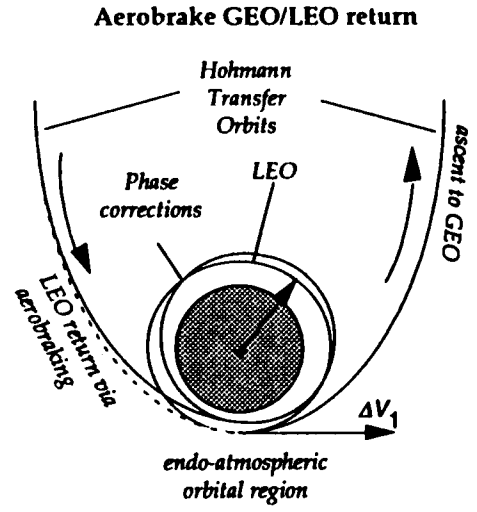
- Depots contain calculable amounts of propellant to accomplish the descent transfers of the cyclic mission via return transfer <u>depot rendezvous and refueling maneuvers.</u>

- The main trade-offs with improved depot transfer efficiencies are *longer* mission durations and *more* total mission ΔV.

- Both of these depot mission attributes are contrary to traditional logistics optimization criteria, but offer mission propellant savings comparable to, and in some instances, *better than aerobraking*.

TRADITIONAL LOGISTICS OPTIMIZATION FOCUS IS ON MINIMIZING $\sum \Delta V$





- Aerobraking OTV's may reduce the cyclic propellant requirements by ~50%, but require extended technology development, and high-risk mission operations.

FIRST-ORDER EPHEMERIS CALIBRATION

- Ephemeris estimation errors have a potential affect on cyclic mission energetics and transfer propellant requirements, but high accuracy output (i.e. low estimation error) demands increased modeling complexity and CPU time.
- Errors from the use of a simplified first-order theory assessed in a comparison with numerical integration of equations of motion (Cowell's method).
- Cowell integration included both lunar and solar perturbations, and assumed a 4x0 Earth gravity field consistent with first-order theory assumptions.
- Errors measured as the residual difference between analytic theory and numerical integration of orbit elements and position/velocity results for a range of potential orbits encountered in depot transfer missions, with:
  - eccentricities ranging from 0 to 0.72
  - inclinations ranging from 0 to 28.5 degrees
  - radii ranging from 6,878 to ~42,241 km
  - errors investigated over one full lunar cycle to allow for element lunar evictions

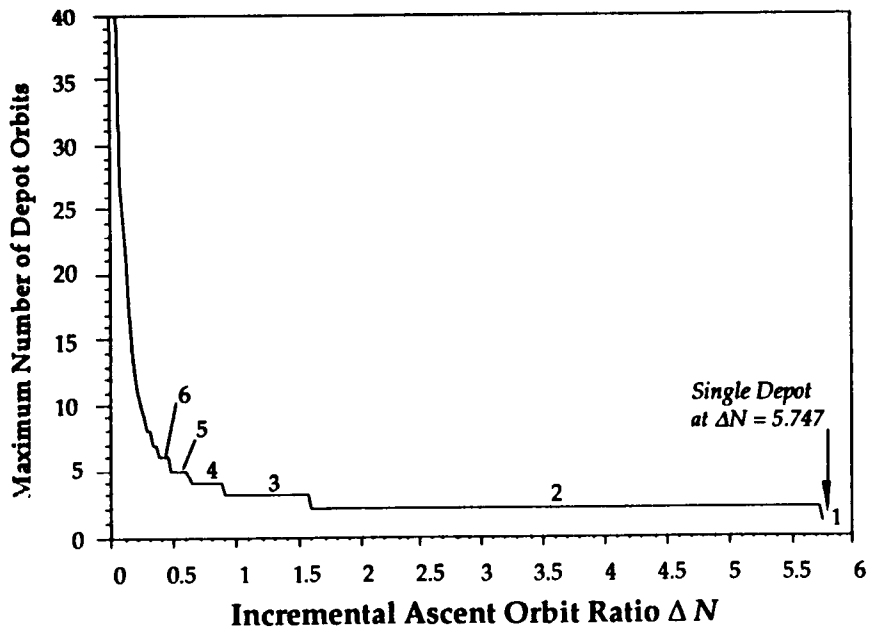
FIRST-ORDER EPHEMERIS GENERATOR

- Orbit motions and OTV/depot orbital positions predicted using a simplified first-order method adapted from Brouwer's theory.
  - consideration of Earth's potential only
  - *mean* elements (M, ω, Ω) propagated up through potential terms of (O) J_2^2
  - method includes both short and long periodic terms from J_3 to J_5
  - singularities avoided at zero inclination and zero eccentricity
- Osculating to mean or mean to osculating orbit element conversions performed exploiting linearized nature of first-order theory and successive approximation technique suggested by Aksnes and Uphoff.

ΔN AS AN ANALYSIS CONTROL PARAMETER

- The <u>incremental</u> ascent orbit ratio ΔN defines allowable orbit period increase between two adjacent orbits, and the *maximum* number of depots used in the cyclic transfer analysis.

Maximum number of depots:



ASCENT TRANSFER WITH DEPOT PLACEMENT

- Ascent depot orbit sizing is controlled with a non-dimensional parameter N, defining the period ratio of two adjacent orbits as:

$$Ni = \left[\frac{ai+1}{ai}\right]^{3/2}$$

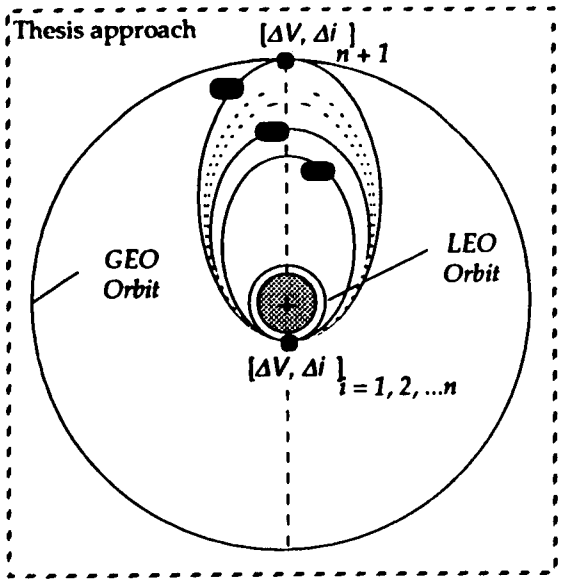
- A sequence of ascent transfers to reach GEO, each resulting in the placement of an orbiting propellant depot, is know as an *ascent suite* — as for example:

$$[\overset{n}{\underset{i=1}{N_i}}] = N_1 : N_2 : N_3 \cdots N_n = 1.5 : 2 : 1.5 \ldots 1.33,$$

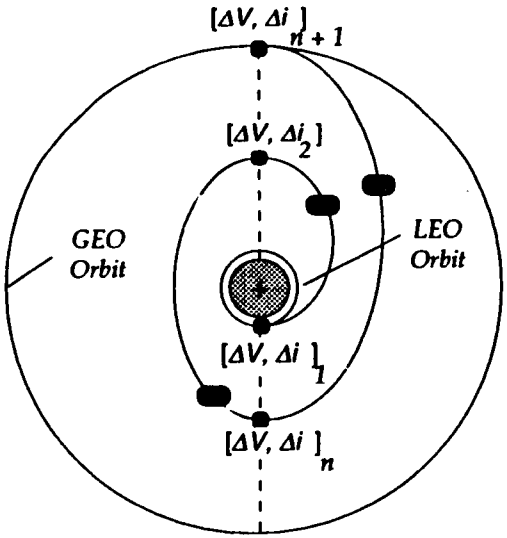
terminating in the nth orbit raising tangent to the GEO target altitude, and resulting in the placement of n propellant depots.

ASCENT TRANSFER PROFILE SELECTION

- Two nodal restrictive non-planar ascent transfer profiles allowing depot placement were examined:

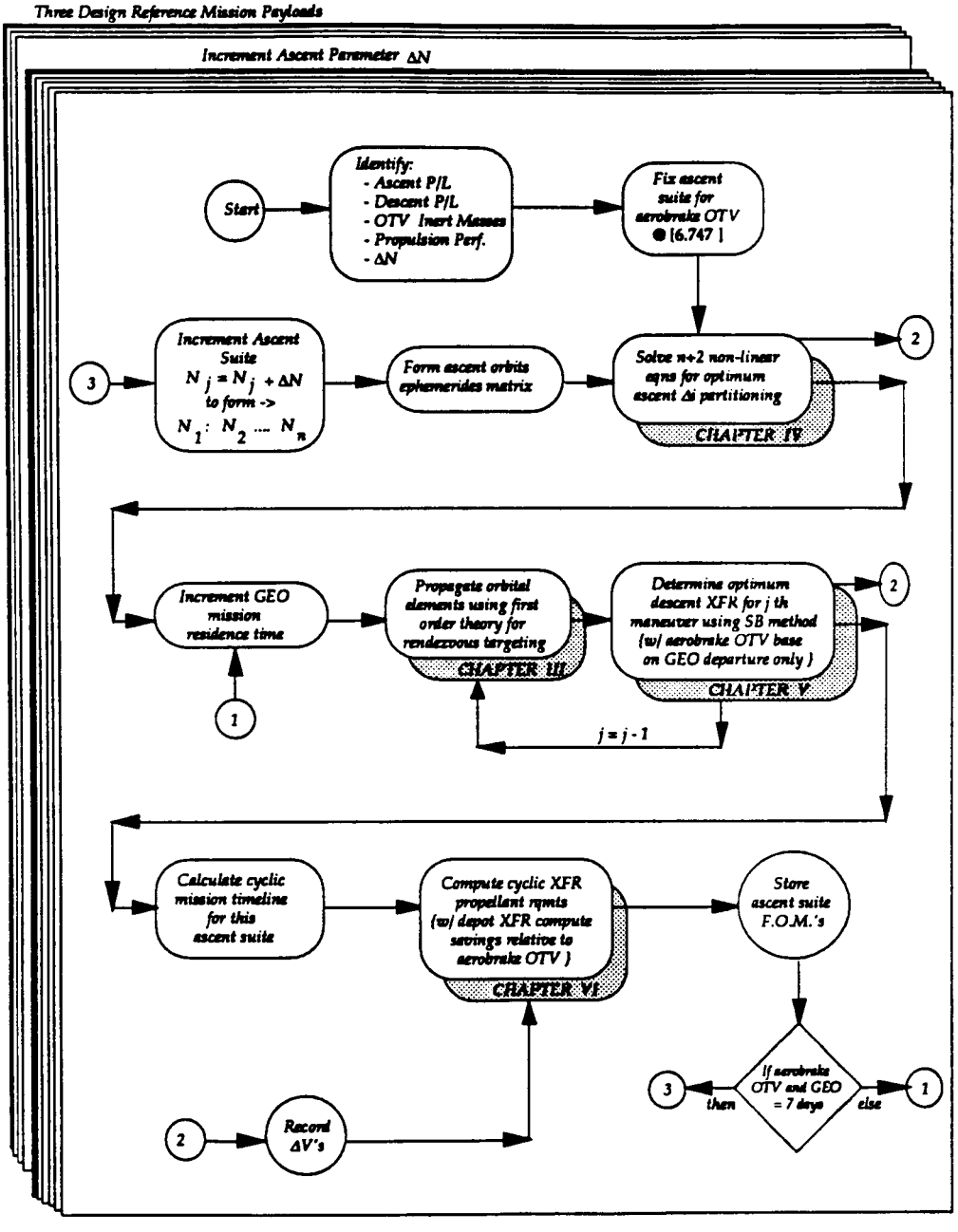


- *Longer* ascent times
- *Lower* ascent energies (always equivalent to minimum Hohmann ascent transfer energy ~ 4.16 km/sec)

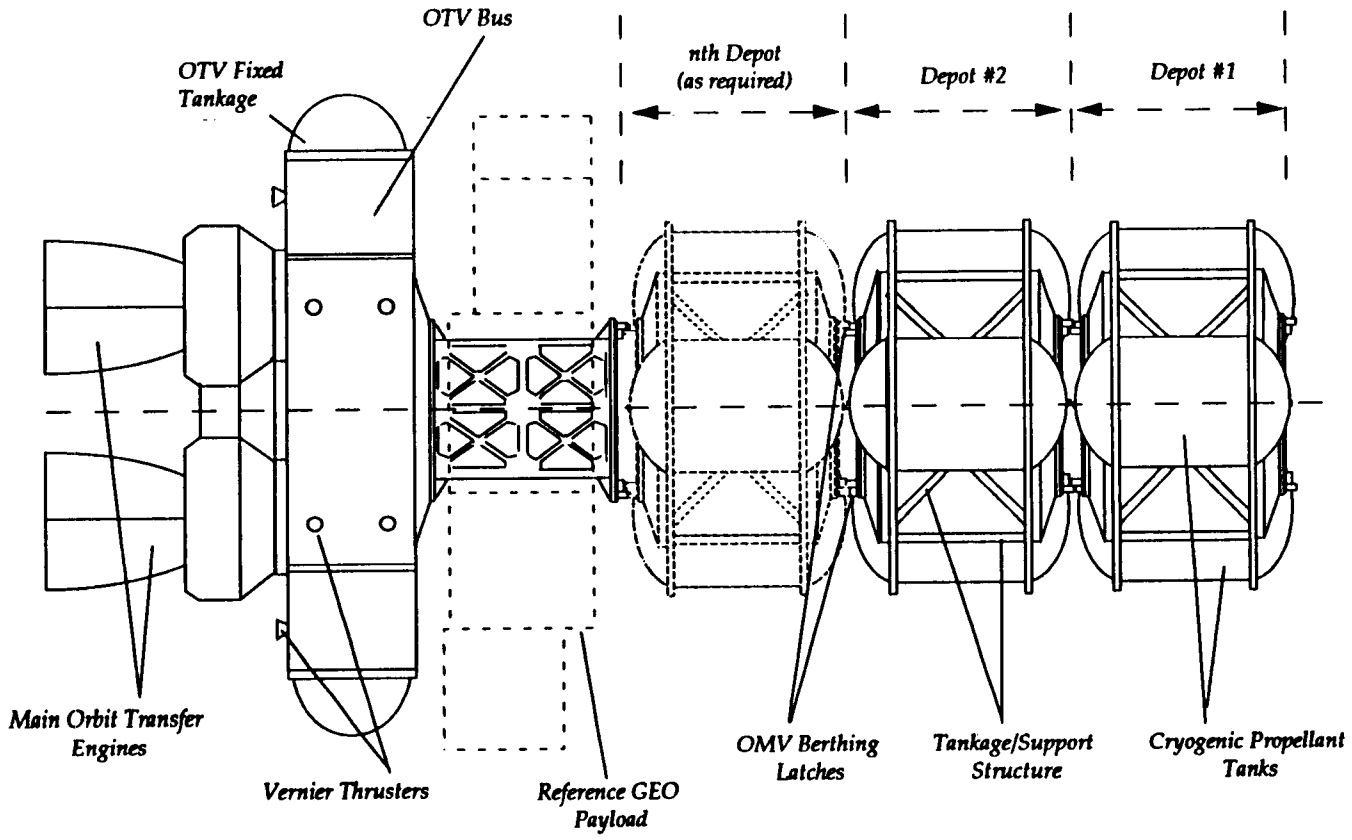


- *Shorter* ascent times
- *Higher* ascent energies

ANALYSIS MODEL LOGIC FLOW



DEPOT OTV CONCEPTUAL DESIGN



CONCLUSIONS

- Non-traditional approach to orbit transfer optimization (higher $\Sigma\Delta V$ and longer mission durations) can provide improved transportation logistics for a variety of future cyclic mission payload profiles.
- Optimum depot transfer techniques offer significant reductions in secondary transfer propellant masses (5 to 20%) over similar NASA aerobrake OTV cyclic missions.
- Cyclic mission logistics improvements are seen to depend on mission durations, OTV design improvements, and transfer risk strategies.
- Propellant reductions translate to millions of dollars saved in the Earth-to-LEO recurring delivery costs (from 5 to 83 million dollars/mission), and will depend on future Earth-to-LEO delivery costs.
- Using depot transfer methods, mission durations increase ~1 day in nominal descent transfer scenarios, and ~2 days in the event of a worst case descent operational delay.
- Propellant reductions shown to be insensitive to depot sizing resolutions.
- The theoretical maximum transfer efficiency with added intermediate depot orbits is outweighed by the increase in descent transfer/rendezvous energies.

CONTRIBUTIONS

- An alternative cyclic mission transfer method offering increased operational benefits (over current NASA cyclic OTV mission designs) derived from low-risk extensions of current and near-future space technologies and mission operations.

- Adapted and developed PC based tools and methods to analyze complex orbit transfer problems including:
  - simplified orbit propagation models
  - numerical solution to optimum intercept selection in restricted orbit transfer problem
  - development of analytic solution to *n*-optimal, non-planar ascent transfer energetics
  - analytic solution to highly coupled cyclic transfer propellant equations

- Established a proof-of-concept for advanced depot transfer techniques in the presence of realistic mission effects:
  - non-planar transfers
  - perturbed orbit motions
  - transfer risk mitigation techniques
  - realistic mission payload profiles

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COMBINING NEAR-TERM TECHNOLOGIES TO ACHIEVE A TWO-LAUNCH MANNED MARS MISSION

David A. Baker and Robert M. Zubrin
Martin Marietta Astronautics

This paper introduces a mission architecture called "Mars Direct" which brings together several technologies and existing hardware into a novel mission strategy to achieve a highly capable and affordable approach to the Mars and Lunar exploratory objective of the Space Exploration Initiative (SEI). Three innovations working in concert cut the initial mass by a factor of three, greatly expand out ability to explore Mars, and eliminate the need to assemble vehicles in Earth orbit. The first innovation, a hybrid Earth/Mars propellant production process works as follows. An Earth Return Vehicle (ERV), tanks loaded with liquid hydrogen, is sent to Mars. After landing, a 100 kWe nuclear reactor is deployed which powers a propellant processor that combines onboard hydrogen with Mars' atmospheric CO_2 to produce methane and water. The water is then electrolized to create oxygen and, in the process, liberates the hydrogen for further processing. Additional oxygen is gained directly by decomposition of Mars' CO_2 atmosphere. This provides an 18:1 mass leveraging factor for the return propellant. The second innovation, a hybrid crew transport/habitation method, uses the same habitat for transfer to Mars as well as for the 18 month stay on the surface. The crew return via the previously launched ERV in a modest, lightweight return capsule. This reduces mission mass for two reasons. One, it eliminates the unnecessary mass of two large habitats, one in orbit and one on the surface. And two, it eliminates the need for a trans-Earth injection stage. The third innovation is a launch vehicle optimized for Earth escape. The launch vehicle is a Shuttle Derived Vehicle (SDV) consisting of two solid rocket boosters, a modified external tank, four space shuttle main engines and a large cryogenic upper stage mounted atop the external tank. This vehicle can throw 40 tonnes (40,000 kg) onto a trans-Mars trajectory, which is about the same capability as Saturn-V. Using two such launches, a four person mission can be carried out every twenty-six months with minimal impact on shared Shuttle launch facilities at Kennedy Space Center (KSC). The same launch vehicle, habitat, and upper stage of the ERV can also be used to perform Lunar missions. It is concluded that the Mars Direct architecture offers a cost effective approach to accomplishing the Lunar and Mars goals of the Space Exploration Initiative.

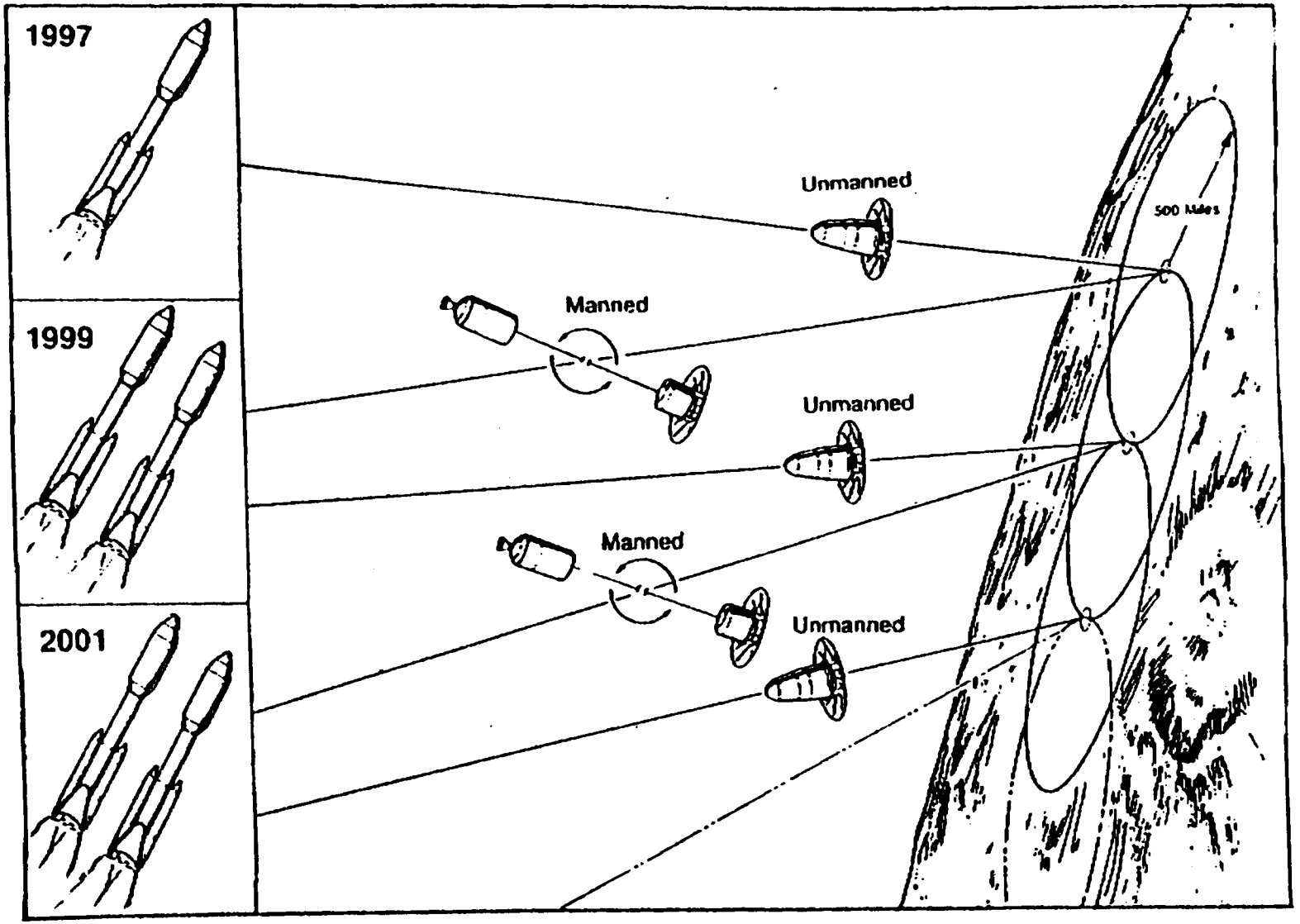
Mars Direct

David Baker and Robert Zubrin

MARTIN MARIETTA

Mars Direct Cover Page

Mars Direct Mission Sequence



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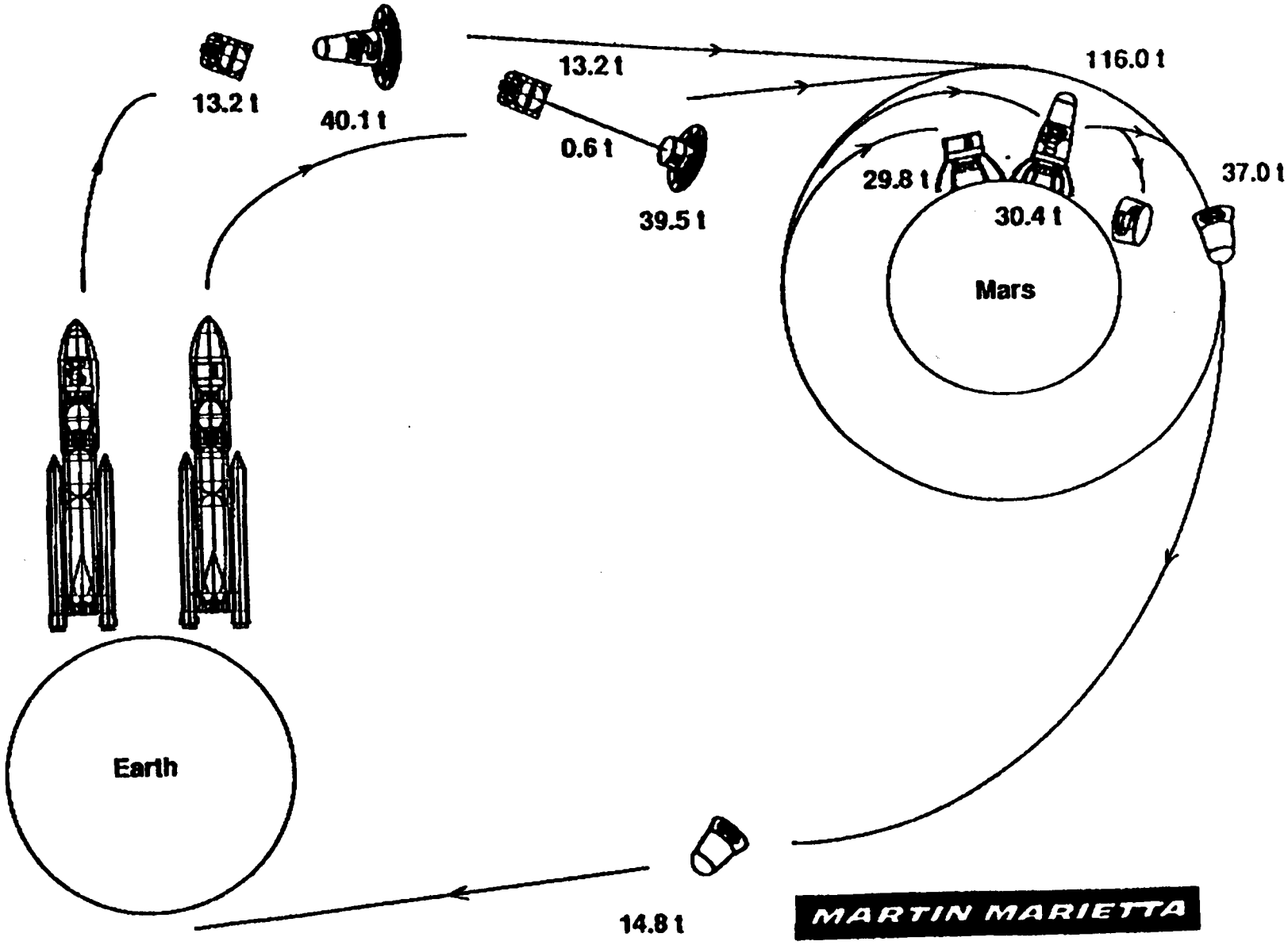
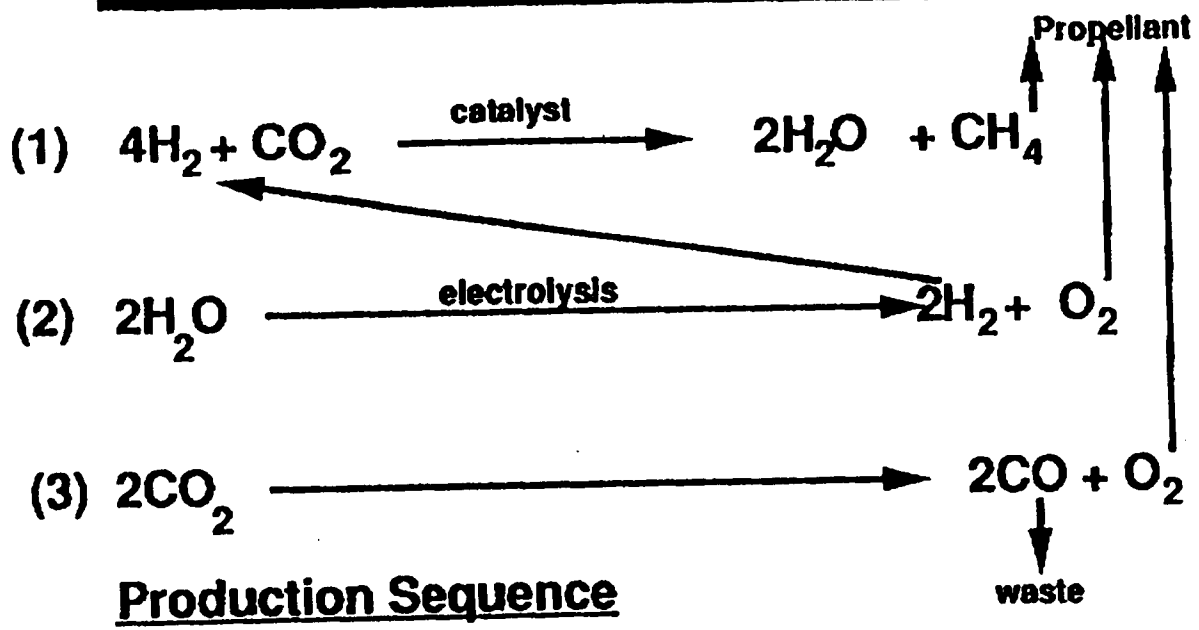
Mars Direct Mission Sequence

Mars Direct Mission Flow



Mars Direct Mission Flow

Methane/Oxygen Production Process



Production Sequence

- SP-100 Reactor is deployed 200 m away from ERV by robotic light truck.
- 5.8 tonne of H2 brought from Earth is reacted with CO2 to produce 37.7 tonne of CH4 and H2O via reaction (1).
- Reaction (2) is used iteratively with (1) to transform this to 23.2 tonnes of CH4 and 46.4 tonne of O2.
- Reaction (3) is used to produce 37.1 tonnes of additional O2.
- A total of 106.7 tonnes of CH4/O2 propellant has been produced, to be burnt at a mixture ratio of 3.6:1 (Isp=373 s).

MARTIN MARIETTA

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Reaction Rates

- Reaction (1) is exothermic. Limiting rate is energy cost of acquiring atmospheric CO_2 (80 kWe-hr/tonne). With 100 kWe reactor at full power, the required 31.9 tonne of CO_2 can be acquired in 25.5 hours. There is thus no long term storage requirement for LH_2 of the Martian surface.

- Reactions (2) and (3) are endothermic and energy intensive (5 MWe-hrs/tonne H_2O electrolysized, 3.8 MWe-hr/tonne O_2 produced from CO).

- With constant operation at full power, the 100 kWe reactor can drive reactions (2) and (3) to produce the required 83.5 tonnes of LOX in 155 days.

- Thus if we assume a 50% capacity factor for the reactor, the entire propellant acquisition process can be completed in 310 days.

MARTIN MARIETTA

Methane/Oxygen Production Strategy

- All H2 is brought from Earth → No dependance on Martian H2O
- All propellant is produced prior to manned launch → No "assumption" of production sucess is made.
- All propellant is produced in the immediate vicinity of an already landed Earth Return Vehicle. → No landing "within hose length" is needed.
- A fully fueled ground rover traveling with the manned vehicle allows for access to the ERV even if the manned vehicle misses the landing site by many miles.
- A second ERV/fuel factory following the manned vehicle out in convoy provides an additional fallback option should surface rendezvous fail.

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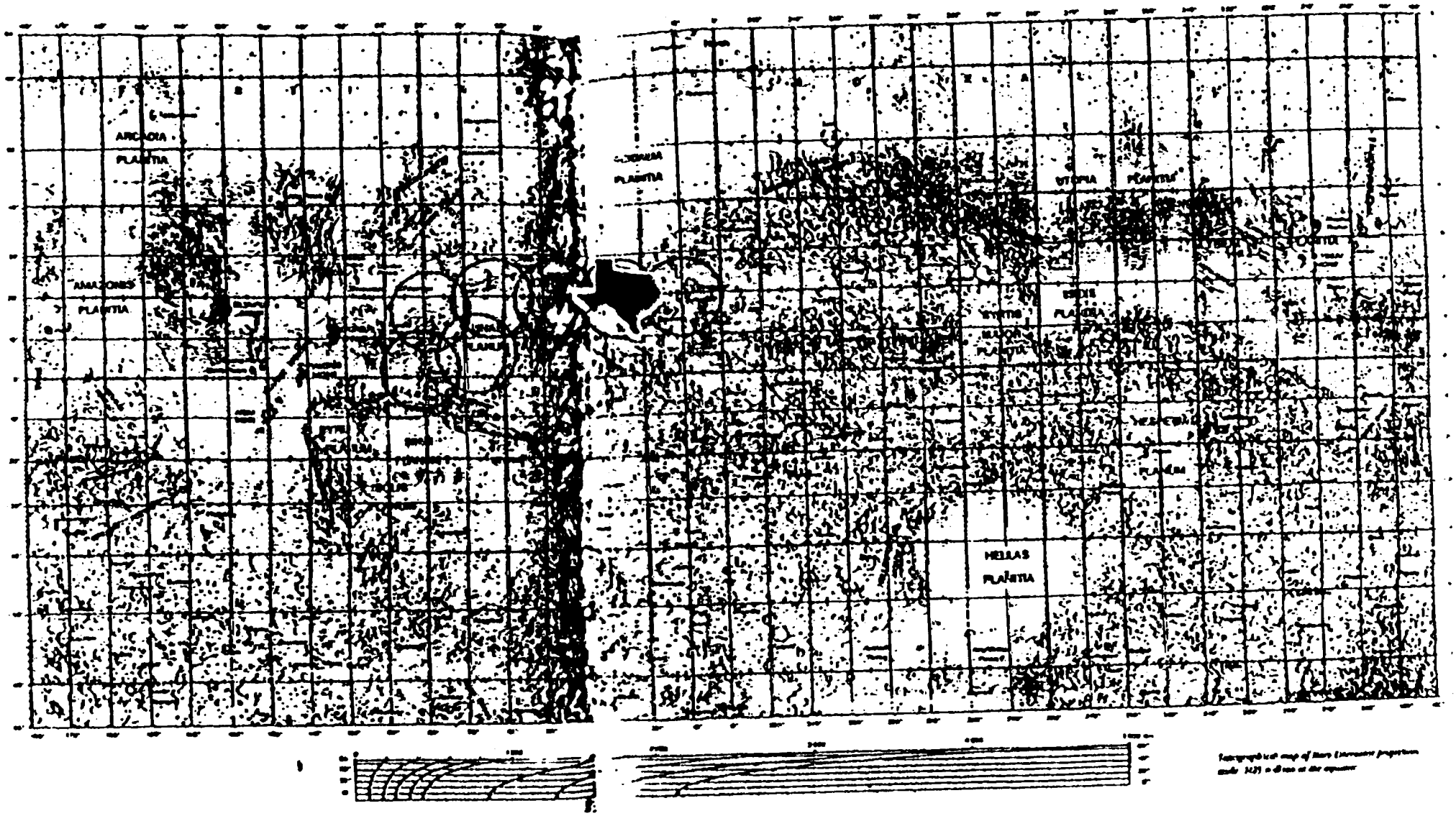
Advantages of Using Indigenous Methane/Oxygen

- Allows for direct return from Martian surface with much lower initial mass in LEO compared to a conventional mission.

- Allows for much greater surface mobility through the use of high powered CH4/LOX ground vehicles.
    - Long range: Sortie radii up to 300 miles are possible.
    - High speed allows more efficient use of sortie time and adds a safety factor in the event of an emergency.
- Provides a practical form of portable electric power source (>50 kWe)
    - Allows for mobile energy intensive surface science.
    - Drilling and excavation
    - Seismic exploration
    - High powered laser/spectrometer
- Drone recon aircraft and ballistic hopper sample collectors are enabled.
- Propellant production reactor later provides high power for base activities.

The use of indigenous propellants maximizes the "firepower" at the "business end" of the mission.

MARTIN MARIETTA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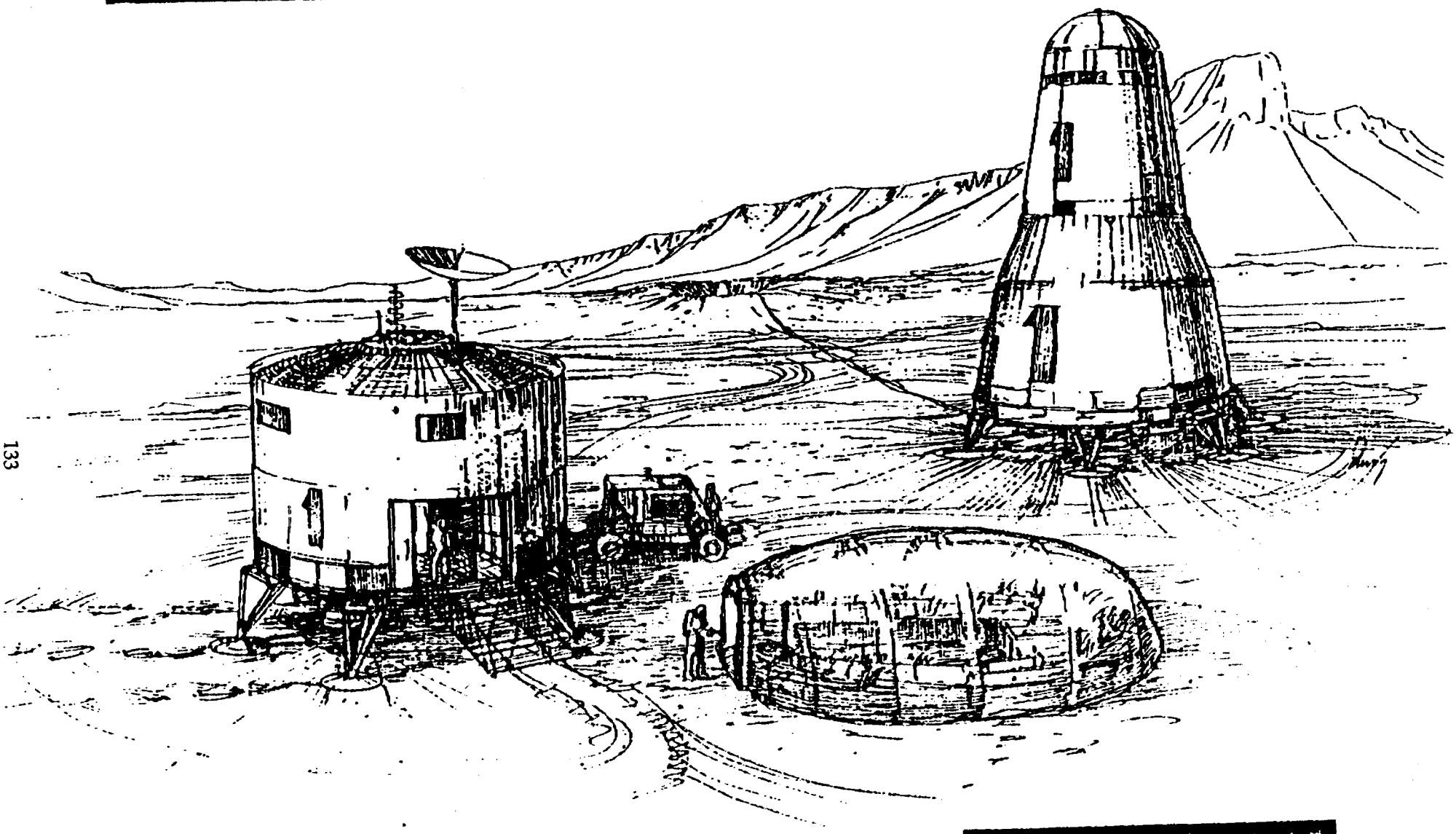
Mars Direct Surface Operations



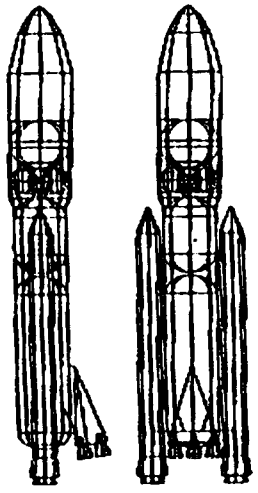
MARTIN MARIETTA

Mars Direct Surface Ops

OCT 03 '90 08:10AM

Lunar/Mars Direct Exploration Vehicles

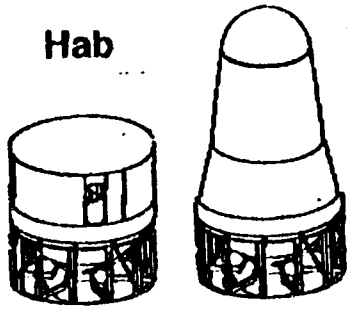
ETO Vehicle



Lunar Vehicles

Return Vehicle

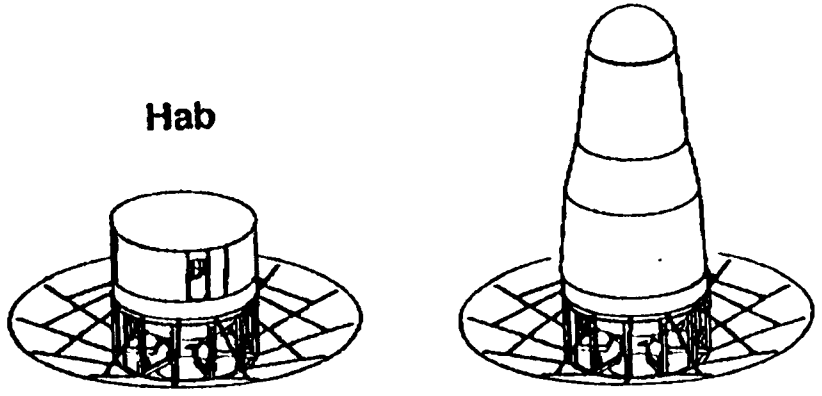
Hab



Mars Vehicles

Return Vehicle

Hab



- Common Systems Defined to Explore and Colonize the Moon and Mars
- IMLEO is the SAME for either Mars or Lunar Missions
- No LEO Assembly Required: Launch Direct to Moon or Mars
- ETO Vehicle is Inline Shuttle-C with Earth-Escape 2nd Stage on Top
  ETO Configuration Optimized not to LEO but to Earth Escape
- Mars Mission has Simple Tether Application to Achieve 3/8 g Gravity
- Mars Mission Combines Earth Hydrogen with Martian CO_2 to Create
  Methane and Oxygen (One kg of H_2 Creates 18 kg of Propellant)
- Surface Habitation and Crew Return Vehicles are Reusable
- No Orbiting Vehicles at Mars or Moon: All Elements go to Surface

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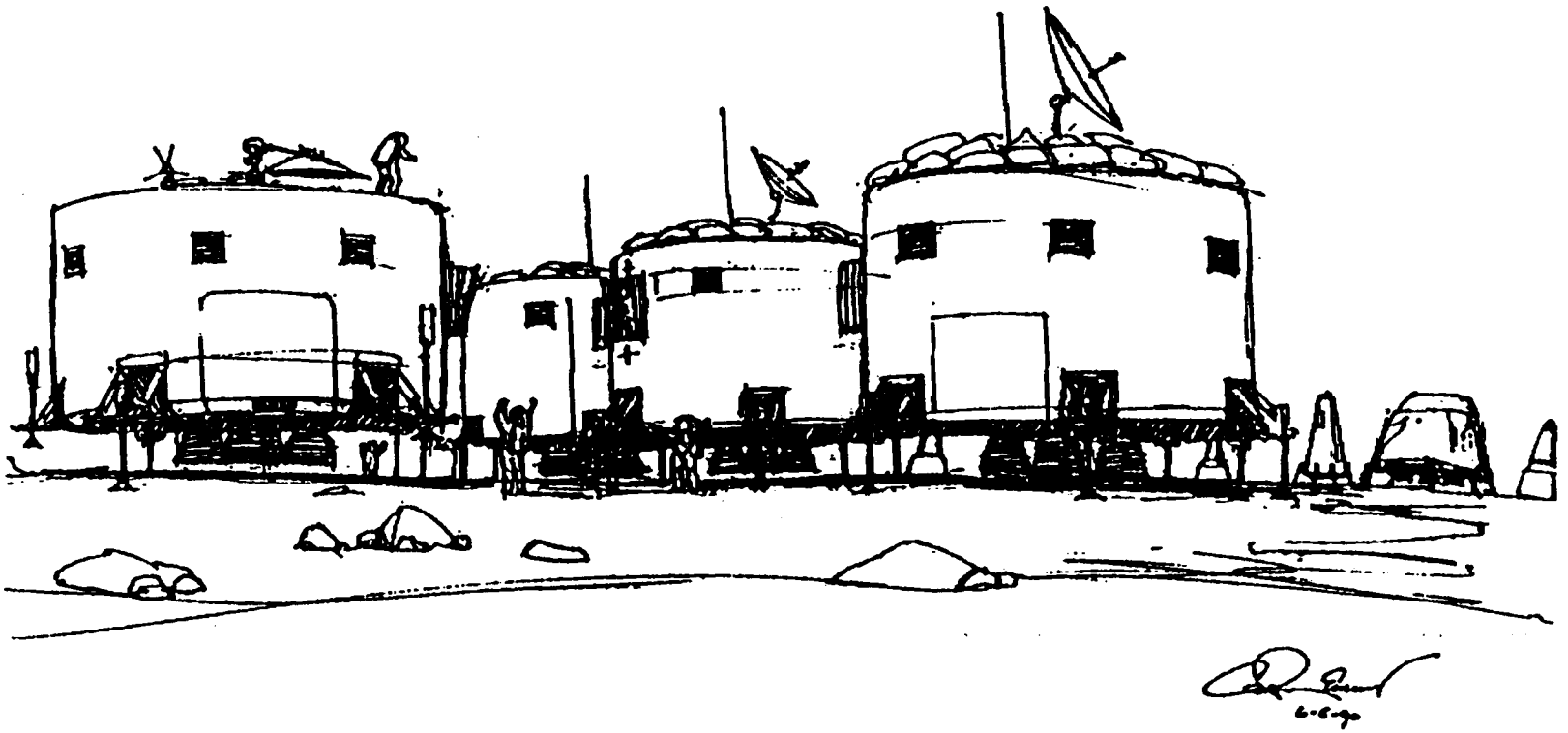
OCT 03 '90 08:13AM

Making The First Mars Settlement Using Mars Direct



MARTIN MARIETTA

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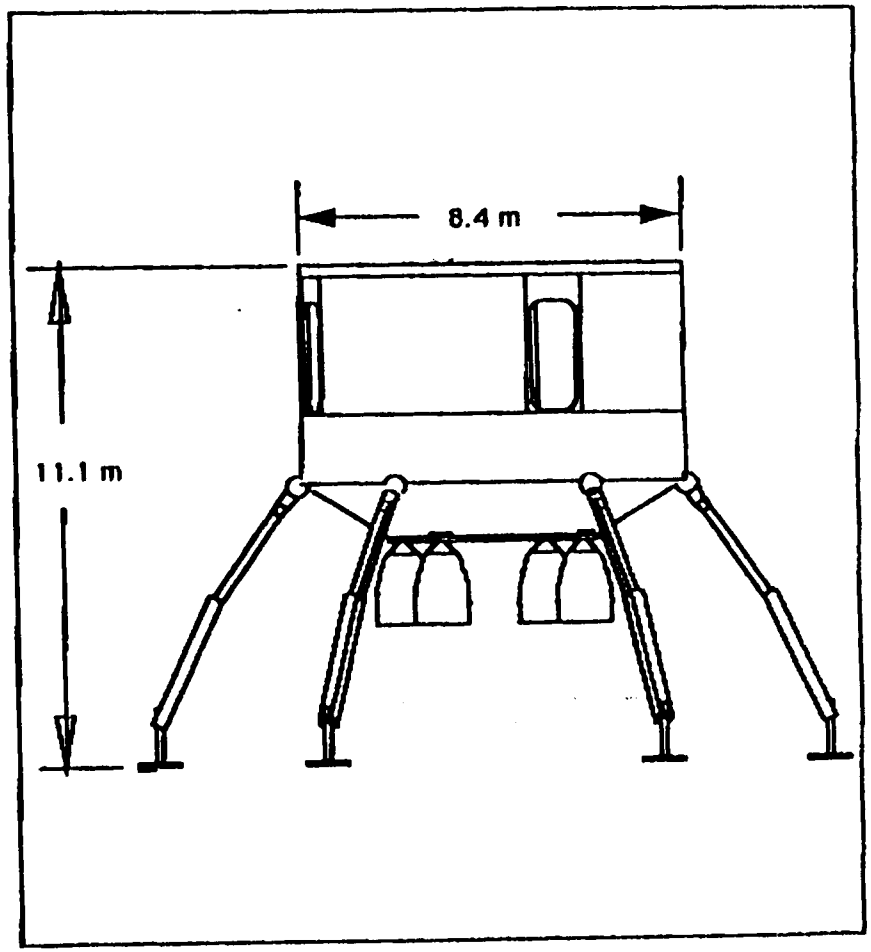
DB900615-7A

Habitation Mass Definition Sheet

Gross Mass (All Units in tonnes)	28.42
Main Structure (Weldalite)	6.72
Barrel Section Wall	1.97
Decks (3)	2.53
Central Airlock/Rad Shelter	1.82
4 Perimeter Airlock Doors	0.40
Interior Fittings	5.26
Walls	0.30
Furniture	0.45
Science Equipment	0.75
Exercise & Health	0.20
Plumbing & Lighting	0.50
Replacement Air (3 charges)	0.81
Solar Panel	0.25
Life Support System (Closed for Water and O2)	2.00
Consumables for Crew (Whole Food)	8.76
Crew	0.30
Personal Effects	0.30
Space Suits	0.30
Pressurized Rover	1.60
Deployed Surface Science	0.40
Contingency	4.17
Artificial Gravity Tether System	0.60



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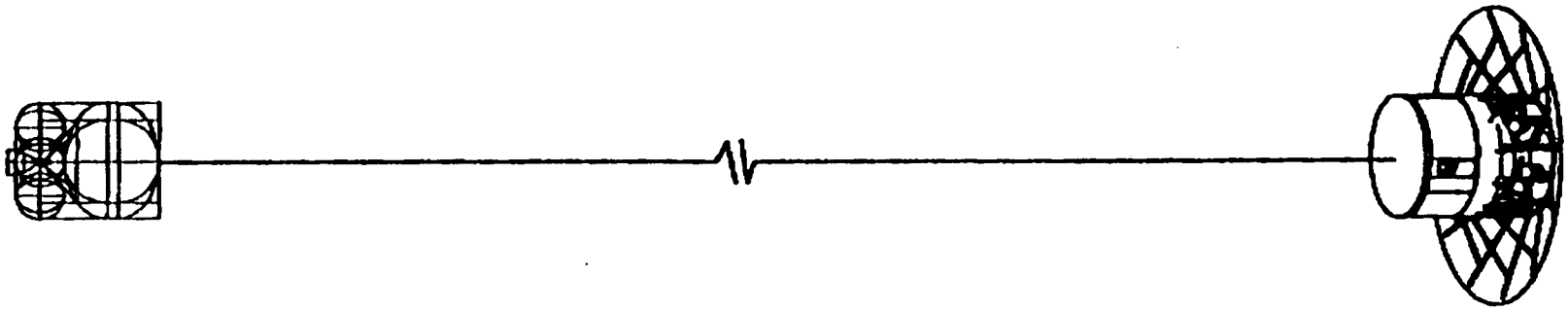
Mars Hab Vehicle Sheet

Mars Direct Tether Application for Artificial Gravity



- Mars Gravity Achieved with 1500 m Long Tether at Only One RPM
- One RPM also Reduces Wear on Despun Antennas, Solar Panels etc.
- Mission Continues if Tether Fails
- Spent TMIS is Counter-Balance (Residuals Provide Initial Spin-Up)
- No Despin Required: Tether (and TMIS) Simply Released Near Mars
- Total Tether System Mass is 600 kg based on Kevlar and 2 Safety Factor
- Zero-Burning of TMIS *Reduces* Tether System Mass

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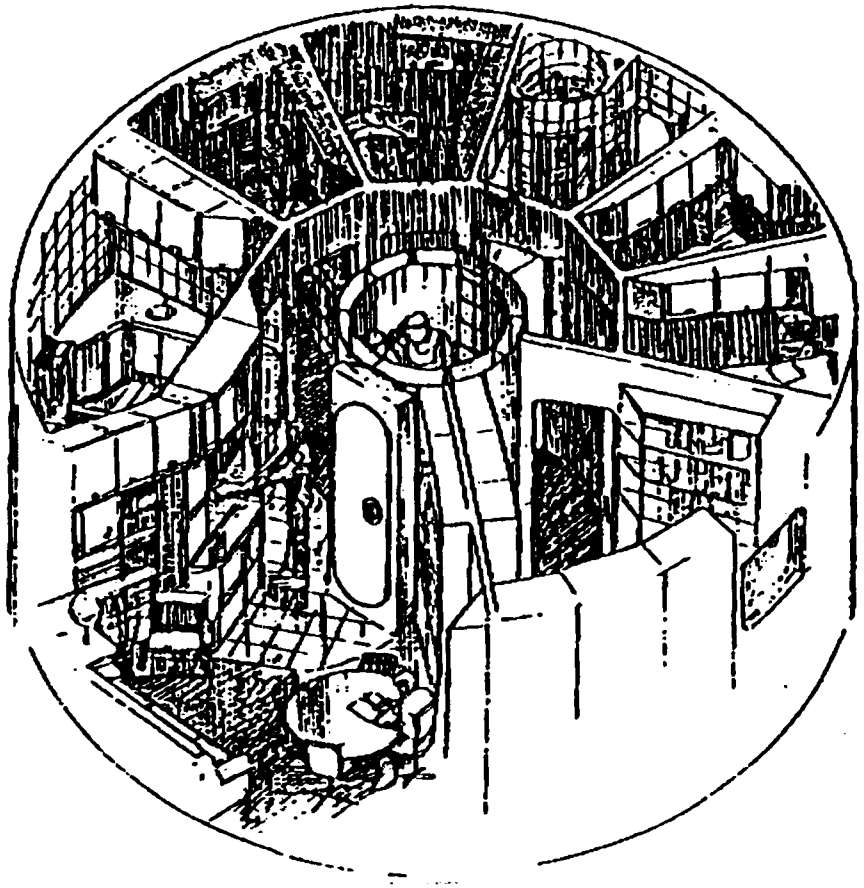
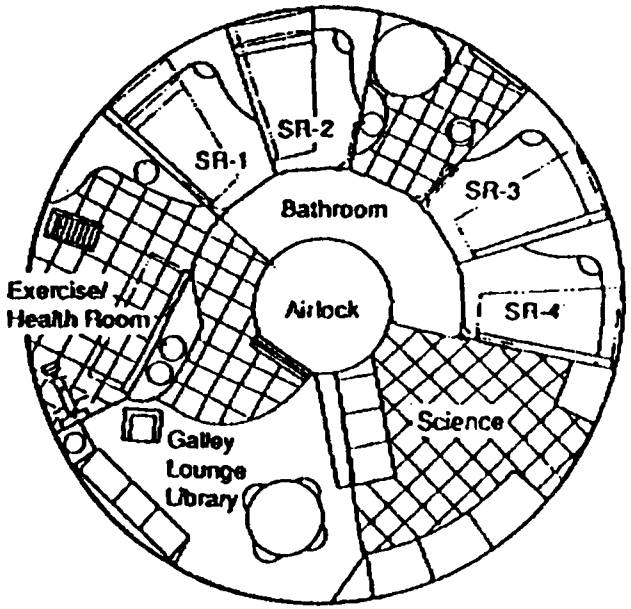
Mars Direct Transfer and Surface Habitation Layout





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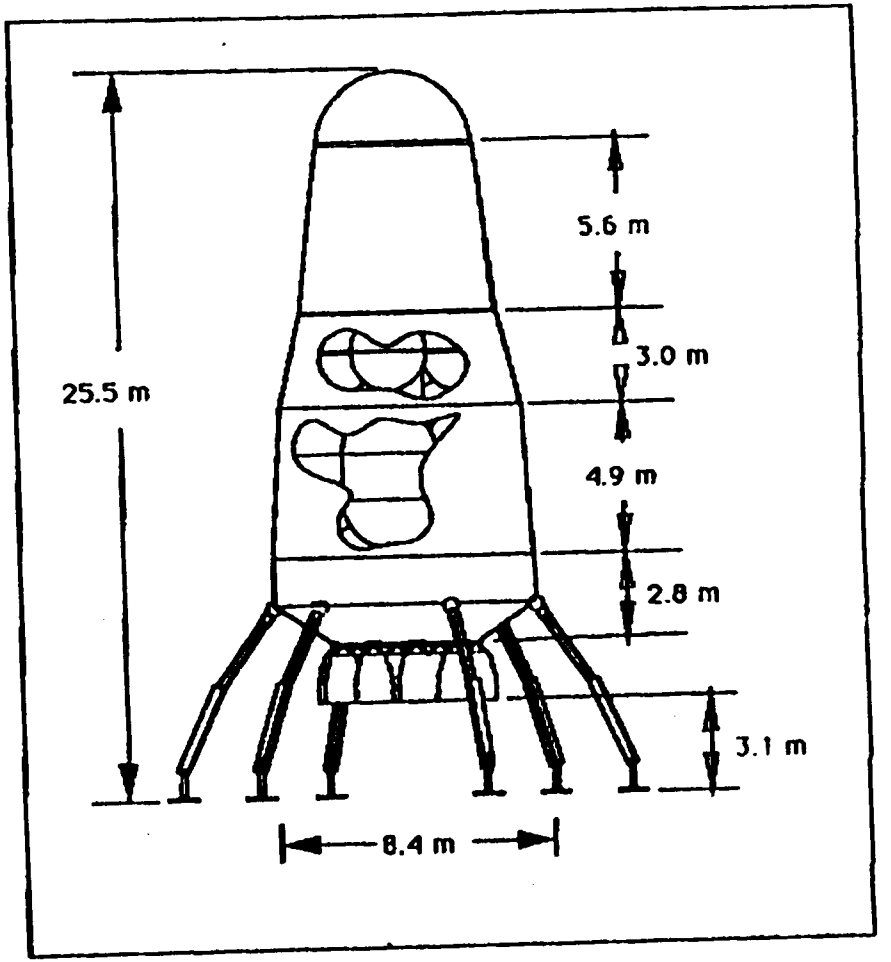
Mars Direct Transfer and Surface Hab

OCT 03 '90 08:13AM

Earth Return Vehicle Definition Sheet

Round Trip Payload	
Crew Cab (All Masses in tonnes)	7.10
RCS System	0.40
Biconic Brake (20%)	2.45
Stage-1 Dry (Expended Mars Suborbital)	6.33
Stage-2 Dry	1.77
Mars-Bound Only Payload	
Hydrogen for Propellant Prod.	5.81
SP-100 Reactor	4.50
Earth-Bound Only Payload	
Crew	0.30
Suits	0.30
Consumables	1.60
Soil Samples	0.10
Stage-1 Propulsion System	
Usable Propellant (From H2 & Atm)	70.16
Inert Mass	8.85
Total Engine Thrust (lbs)	191,784
Specific Impulse (sec)	373
Propellant Type	CH4/O2
Stage-2 Propulsion System	
Usable Propellant (From H2 & Atm)	22.17
Inert Mass	2.56
Total Engine Thrust (lbs)	20,382
Specific Impulse (sec)	373
Propellant Type	CH4/O2



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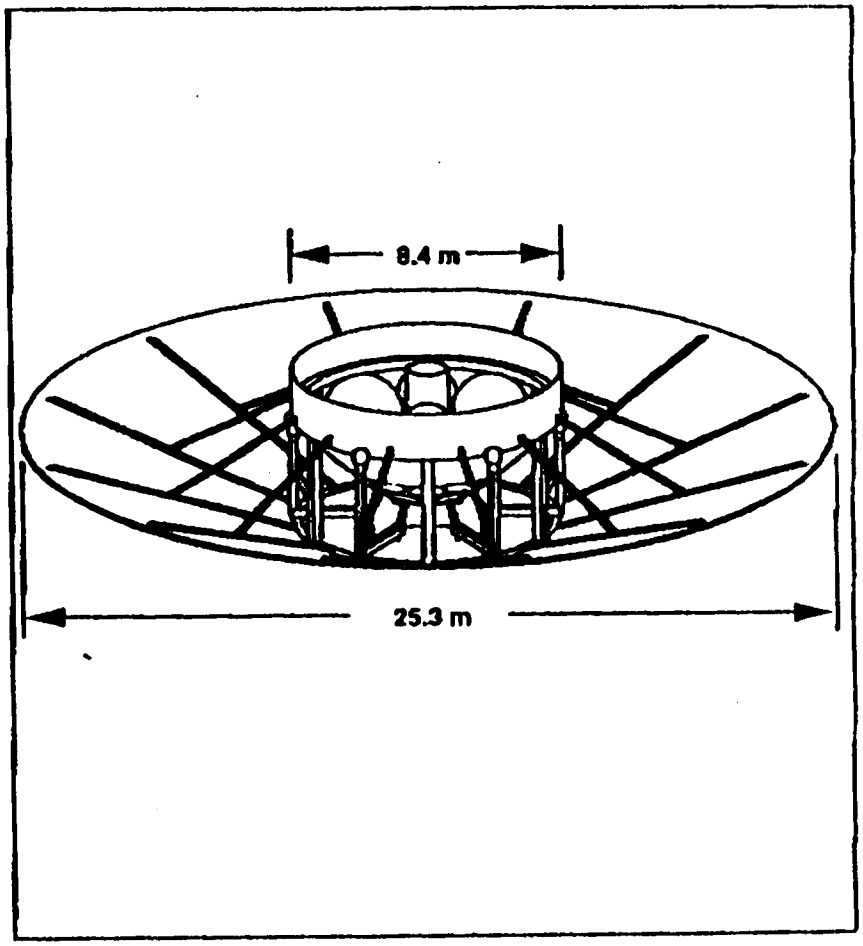
Earth Return Vehicle VDS

OCT 03 '90 08:14PM

Common Mars Aerobrake and Landing Stage

Gross Mass (All Masses in tonnes)	11.81
Mars Aerobrake (Flex-Fabric)	5.96
(Based on 15% of Gross @ Entry)	
(Diameter is 25 meters Deployed)	
Landing Propulsion Stage	5.85
Usable Propellant	3.85
Inert Mass	2.00
Tanks	0.15
Engine	0.67
Structure	0.23
Landing Legs	0.61
Avionics & Other Fixed Mass	0.20
Unusable Propellant	0.06
Reserve Propellant	0.08
Total Engine Thrust (lbs)	44,267
Specific Impulse (sec)	450
Propellant Type	H2/O2



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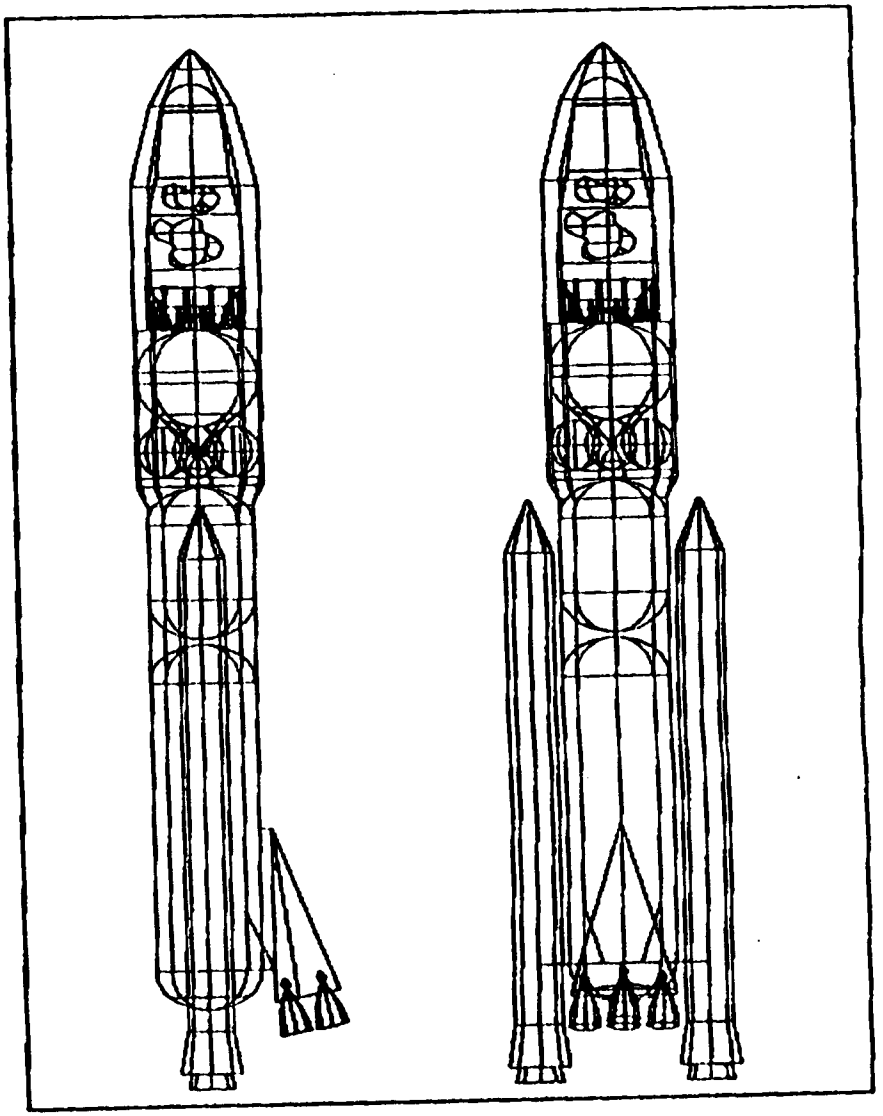
Common A/B & Lander VDS

OCT 03 '90 08:14AM

Shuttle Derived Vehicle with Upper Stage (SDV/US)

Trans-Mars Payload (All Weights in tonnes)	40.189
Height (m)	82.3
Stage-0	
2 Solid Rocket Boosters (SRB's)	
Stage-1	
External Tank (Including Residuals)	35.562
SSME Engine Pod (4 SSME's)	28.577
Usable Propellant in ET	723.492
Total SSME Thrust (kN, 104%)	8,706
Specific Impulse (sec)	453
Upper Stage (Ignited Sub-Orbital)	
Usable Propellant	158.760
Inert Mass	13.245
Tanks	5.679
Engine	2.268
Structure	3.241
Avionics & Other Mass	0.454
Unusable Propellant	1.603
Single Engine Thrust (kN)	1,113
Specific Impulse (sec)	450
Payload Fairing	20.412
Orbital Targetting	
Intermediate Park Orbit	185 km, Circular
Final C_3 Obtained	15 km^2/sec^2



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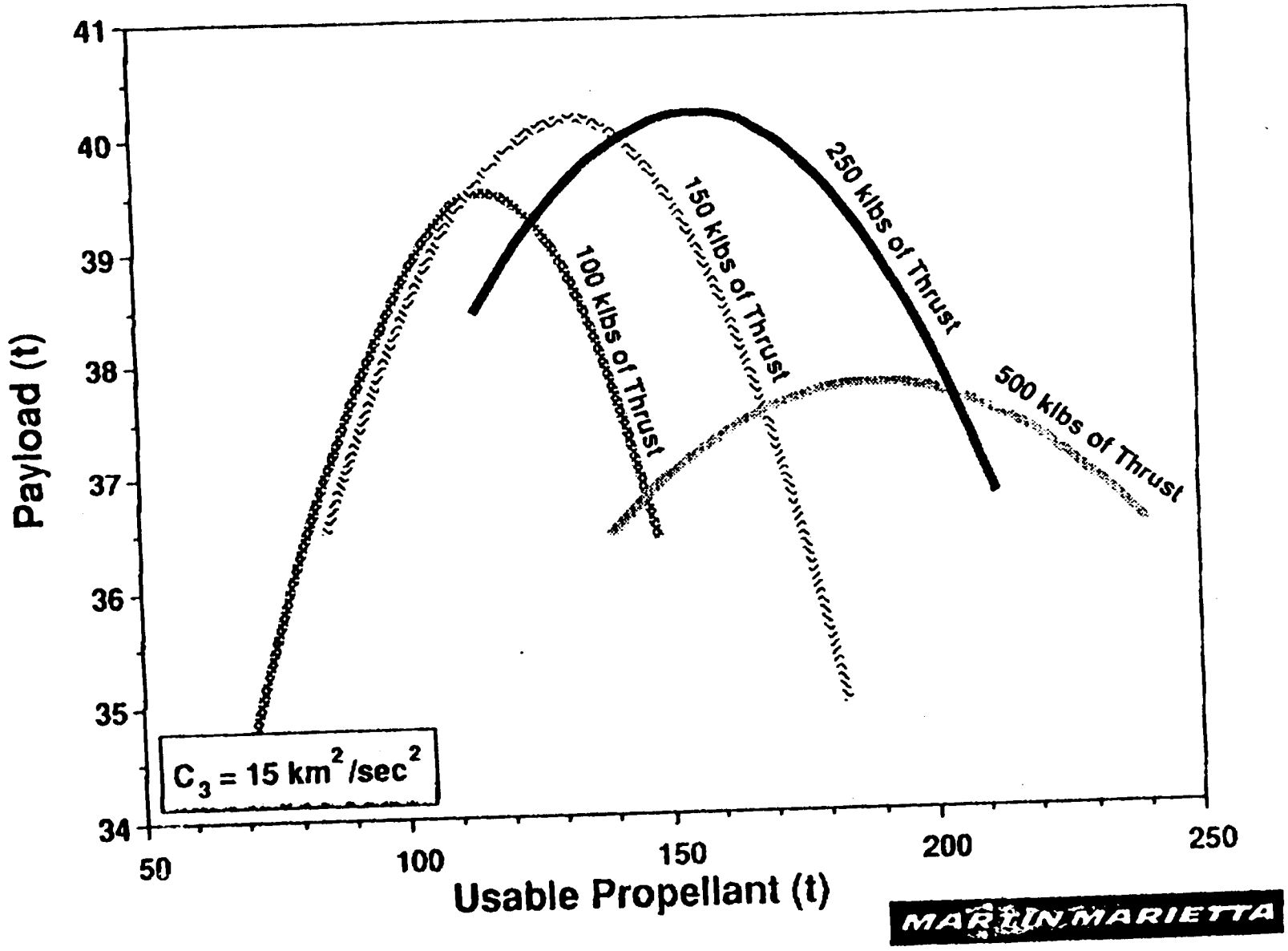
VDS-SDV/US

SDV/US Optimization for a Planetary Mission



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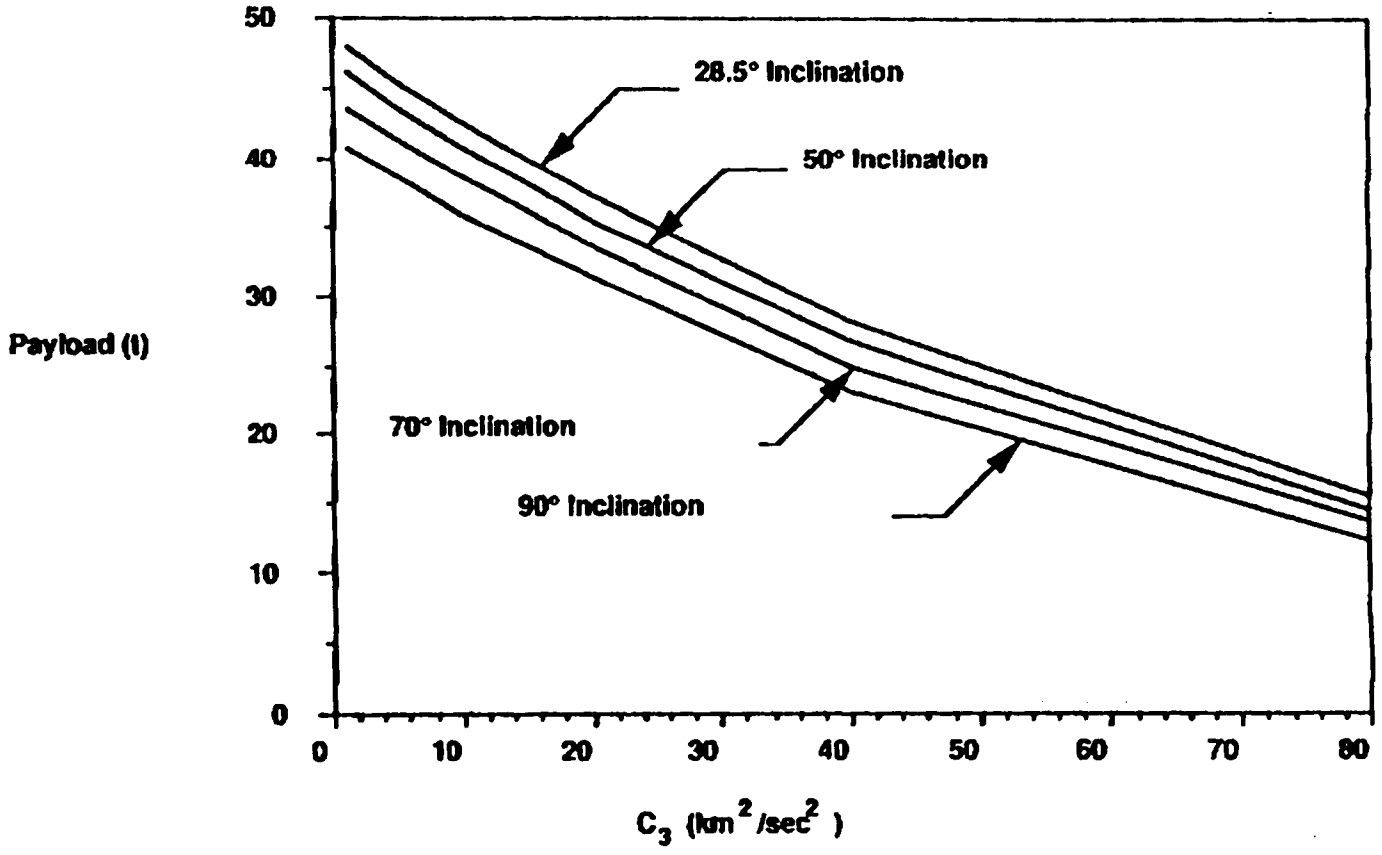
SDV/US Payload vs C_3 and Inclination



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SE900402-01B

SDV/US Performance to Trans-Mars and LEO

Performance for Actual Mars Opportunities

Center Day*	Month	Year	Inclination (deg)	C_3 (km^2/sec^2)	Flight Time (days)	Type	Payload (t)
1	December	1996	28.5	10	230	I	42.6
17	January	1999	35 to 28.5	10	190	I	42.2
17	March	2001	58 to 45	10	160	I	39.9
6	June	2003	28.5	10	190	I	42.6
8	August	2005	35	17.5	195	I	38.1
Baseline				15		I	39.9

* 2 Week Launch Window

Performance to 160 nm x 160 nm @ 28.5°

Launch Vehicle	Payload (t)
SDV/US (250 klbs thrust)	106.1
SDV/US (500 klbs thrust)	114.8
SDV/No Upper Stage	67.1

Downstream Capabilities to $C_3 = 15$

Launch Vehicle	Payload (t)
ASRB's (NTO-19)	43.5
ASE (481 sec, 250 klbs)	45.1
ASRB's and ASE	49.0

Launch Vehicle Uses Existing Pad, Does Not Greatly Impact Shuttle Operations (Average of One Launch Per Year)

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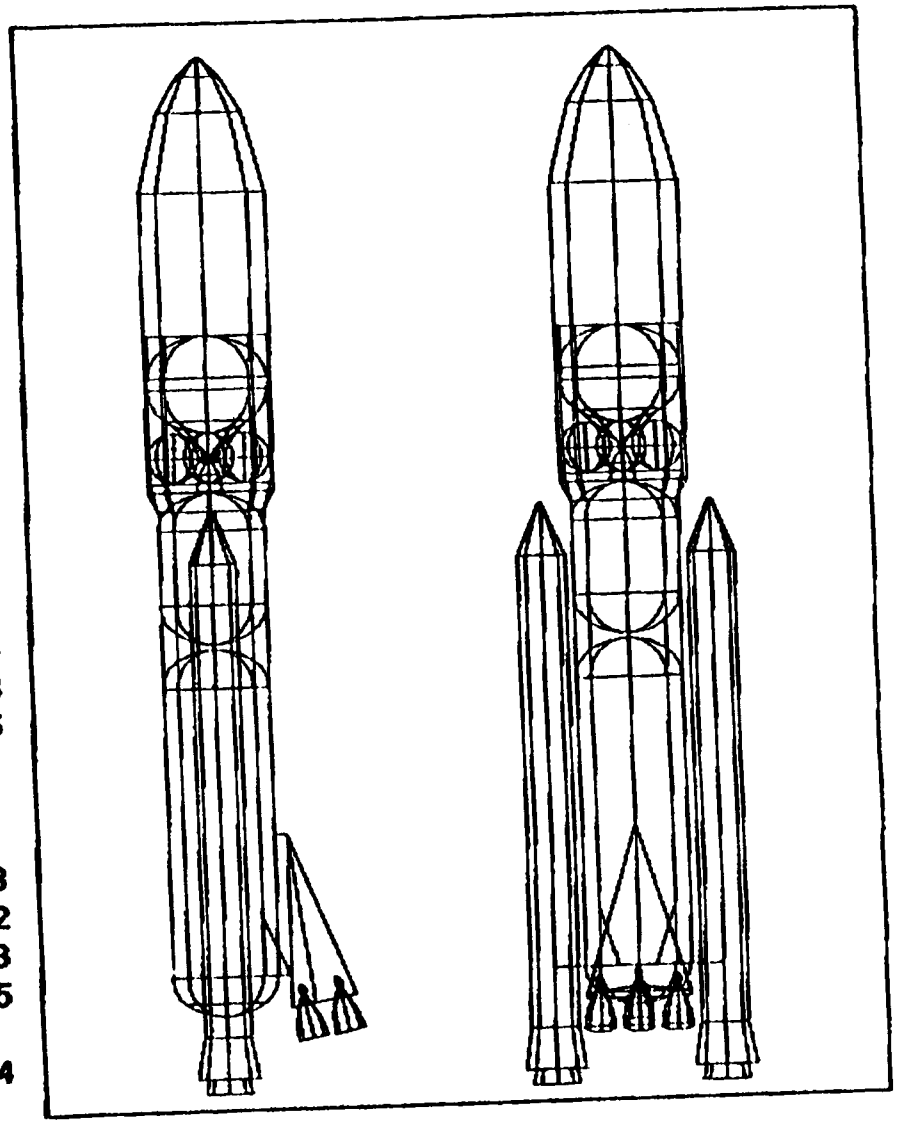
Ares Launch Vehicle Definition

Payload Capabilities (All Weights in tonnes)	
Trans-Mars ($C_3 = 15\ km^2/sec^2$)	47.2
Trans-Lunar (5 day transfer)	59.1
LEO (160 by 160 Nmi, 28.5 degrees)	121.2
Height (m)	82.3
Gross Mass (Without Payload)	2,194.6
Stage-0	
2 Advanced Solid Rocket Boosters	1,214.5
Stage-1	
External Tank (Including Residuals)	35.6
SSME Engine Pod (4 SSME's)	28.6
Usable Propellant in ET	723.5
Total SSME Thrust (kN, 104%)	8,706
Specific Impulse (sec)	453
Staging Relative Velocity (km/s) (LEO to Mars Range)	4.2 to 5.5
Stage-2 (Ignited Sub-Orbital)	
Usable Propellant	158.8
Inert Mass	13.2
Single Engine Thrust (kN)	1,113
Specific Impulse (sec)	465
Payload Fairing	20.4



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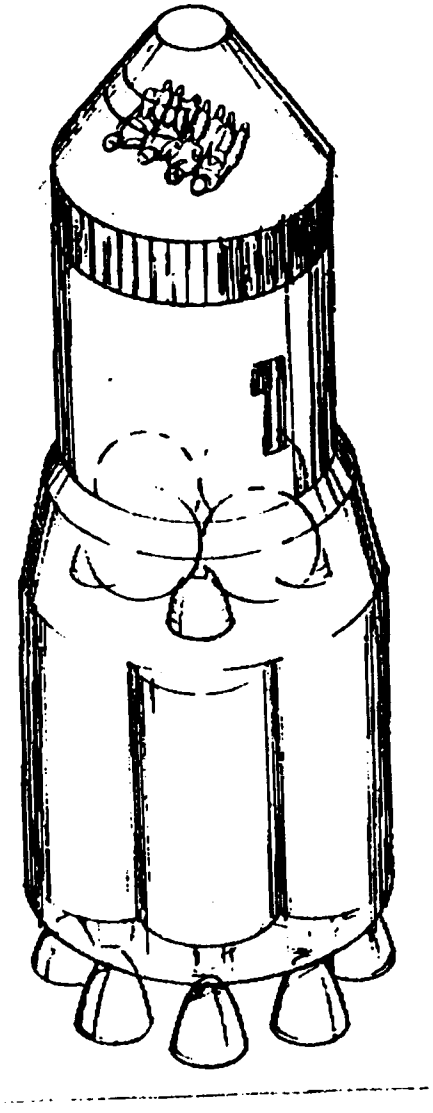
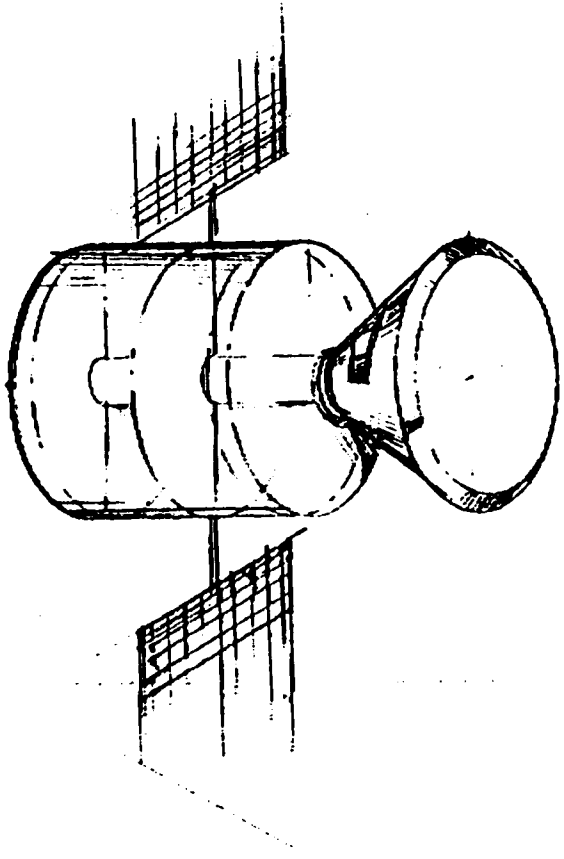
VDS-Ares

OCT 03 '90 08:16AM

ERV With Separate Reentry Vehicle and Transfer Cab





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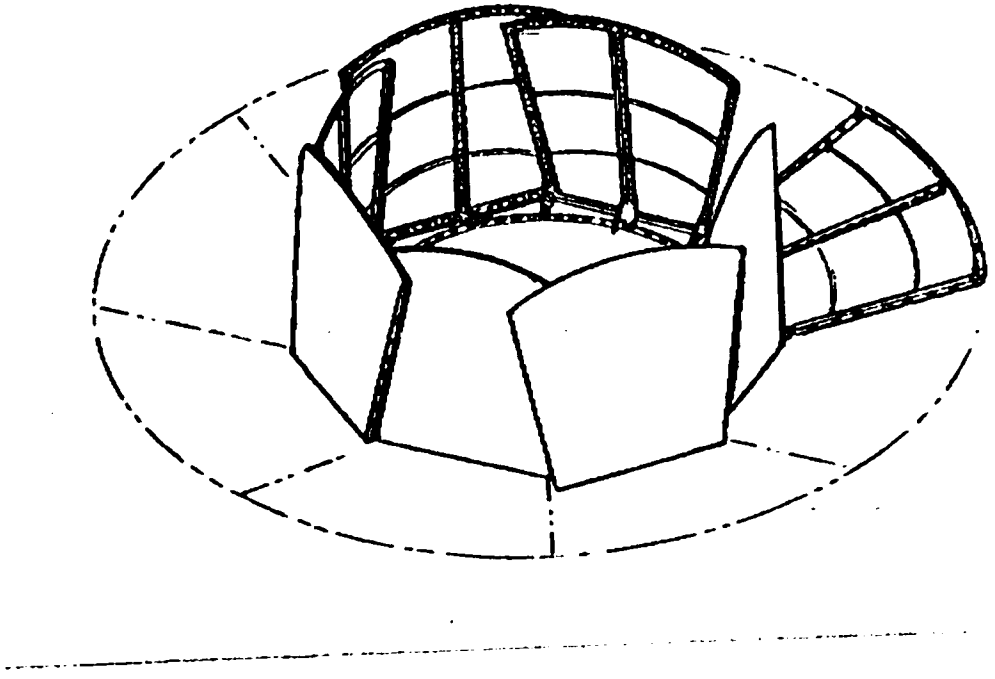
Separate ERV/Cab

OCT 03 '90 08:16AM

Mars Direct Alternative Rigid Panel Aerobrake



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Foldout Brake

Features of Mars Direct Mission

Two-Launch Mars Missions Are Possible With All Chemical Propulsion

No LEO Rendezvous or Assembly Required

Earth H_2 + Mars CO_2 Yields CH_4/O_2 Propellant and Avoids Prospecting or Solids Processing

Indigenous Propellant Reduces IMLEO and Greatly Increases Surface Mobility

Nobody is Left in Mars Orbit
- All Crew Available to Support Surface Science and Provide Backup for Each Other
- Reduces Radiation Dose
- Eliminates Park Orbit Constraints on Return Launch Windows
- Eliminates Elliptic Orbital Rendezvous
- Crew Spend 80% of the Mission in Mars Gravity, in One Habitat Module
  - (No Redundancy of MTV and Landed Habitat Modules)

Artifical Gravity Only on Mars-Bound Leg
- Crew Subjected to 180-200 Days of Zero-G Only During Earth Return
- Tether Mass not a Driver (600 kg)
- Spin rate of 1 RPM Ensures Minimal Rotational Side-Effects
- Tether Failure Not Mission Critical

Common Hab, Return and Launch Vehicles Enable Parallel Lunar and Mars Missions
- Lunar Missions Validate Mars Hardware Directly

LOR and H_2 Storage Issues Eliminated

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Features of Mars Direct Mission (Con't)

HLLV "Tuned" to Earth Escape Missions
- No Upper Stage Version Supports SSF Deployment
- Upper Stage Developed to Support SEI
- Down Stream Versions Incorporate:
  - ASRB's
  - SSME P/A Modules
  - High Performance Upper Stage Engines (480 Seconds, 250 klbs)

Launch Vehicle Uses Existing Pad, Does Not Greatly Impact Shuttle Operations
- (Average of One Launch Per Year)

Mars Direct Approach is Cost Effective
- Common and Fewer Hardware Elements
- No LEO Assembly
- Reduces Mars IMLEO by Factor of 3
- Reduces HLLV Flights
- More Mars Exploration Accomplished per Mission

If Mars Mission Figure of Merit is Based On: $\frac{\text{Man-Days on Mars Surface}}{\text{IMLEO}}$

Then:	Mars Direct is:	10 m•d/tonne	(4 crew, 600 days, 240 tonnes)
	Boeing Opposition is:	0.16 m•d/tonne	(4 crew, 30 days, 731 tonnes)

Enables Coherent, Unified and Cost Effective Lunar/Mars Program

MARTIN MARIETTA

OCT 03 '90 08:17AM

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Assessing the Feasibility of a Mars Cycling Transportation System

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P- 8

Michel E. Loucks

This paper examines the feasibility of a Mars cycling space vehicle in terms of Initial Mass to Low Earth Orbit (IMLEO) and rendezvous constraints. A minimum of two cycling spacecraft are used with the associated 'taxi' vehicles. Spacecraft designs are adapted from the 1988 NASA Office of Exploration "Exploration Studies Technical Report" and other reports. The cycler trajectories used are the 'Split-Cycler' or 'Escalator' trajectories documented by Hoffman et. al. of SAIC in 1989. The cycler concept is compared to the "Exploration Studies Technical Report" scenario and other concepts on the basis of IMLEO. The associated 'taxi' rendezvous logistics are assessed as are the sizing sensitivities of the 'taxi' vehicle with respect to the associated rendezvous launch windows.

This mission is compared to various other Manned Mars Mission concepts and the various construction issues are discussed. Also discussed are possible further topics of study for CSC with respect to this concept.

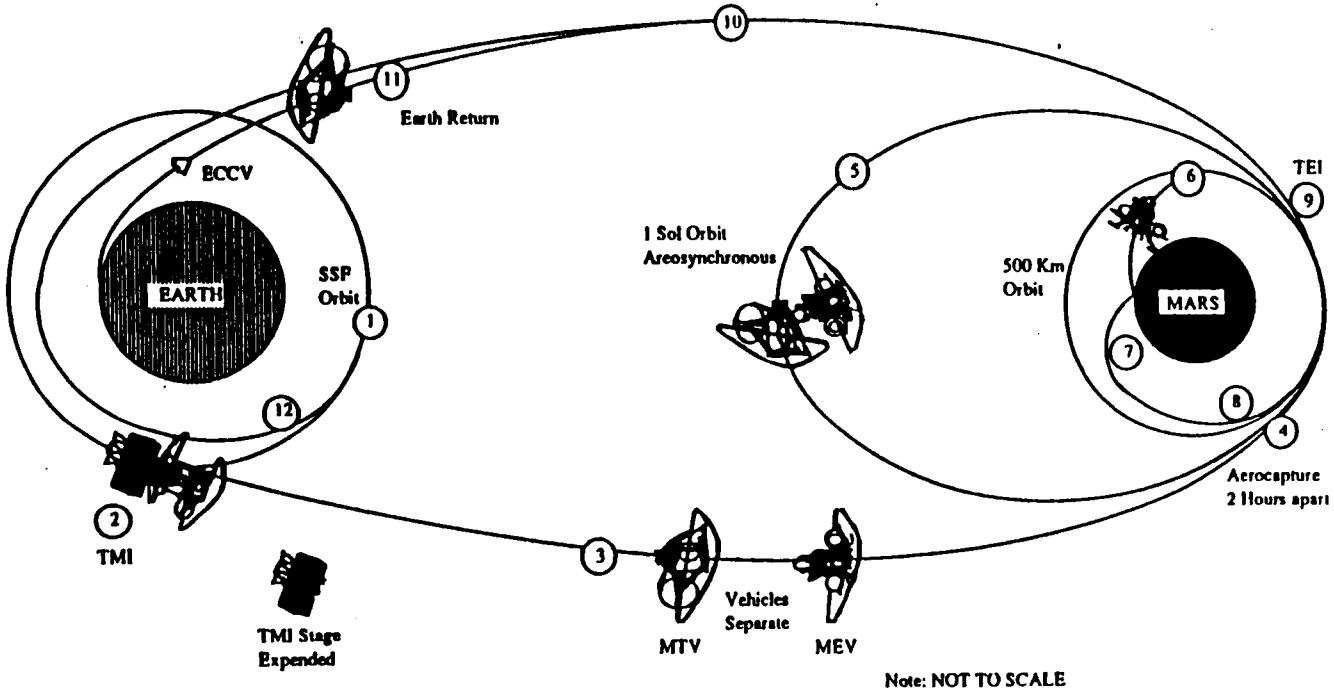
Center For Space Construction Systems Cluster

Assessing the Feasibility of a Mars Cycling Transportation System

Michel E. Loucks

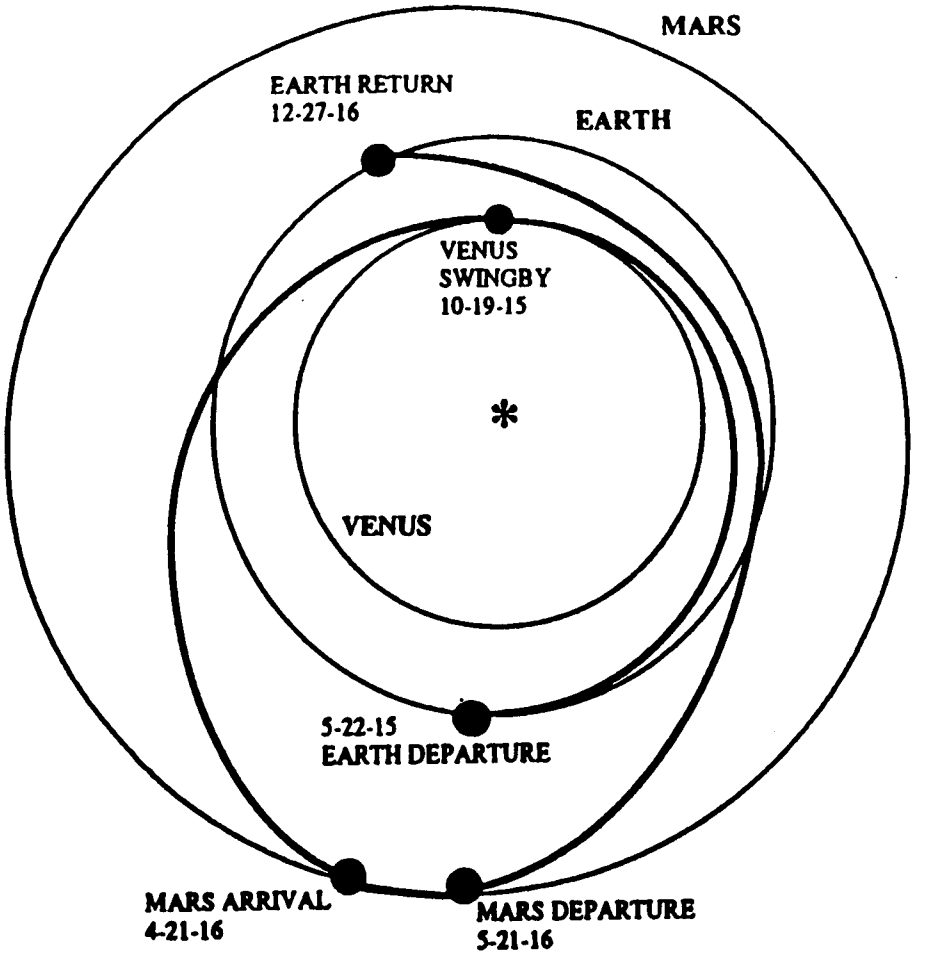
The Center for Space Construction
CSC A NASA Space Engineering Research Center at the University of Colorado
Systems Cluster

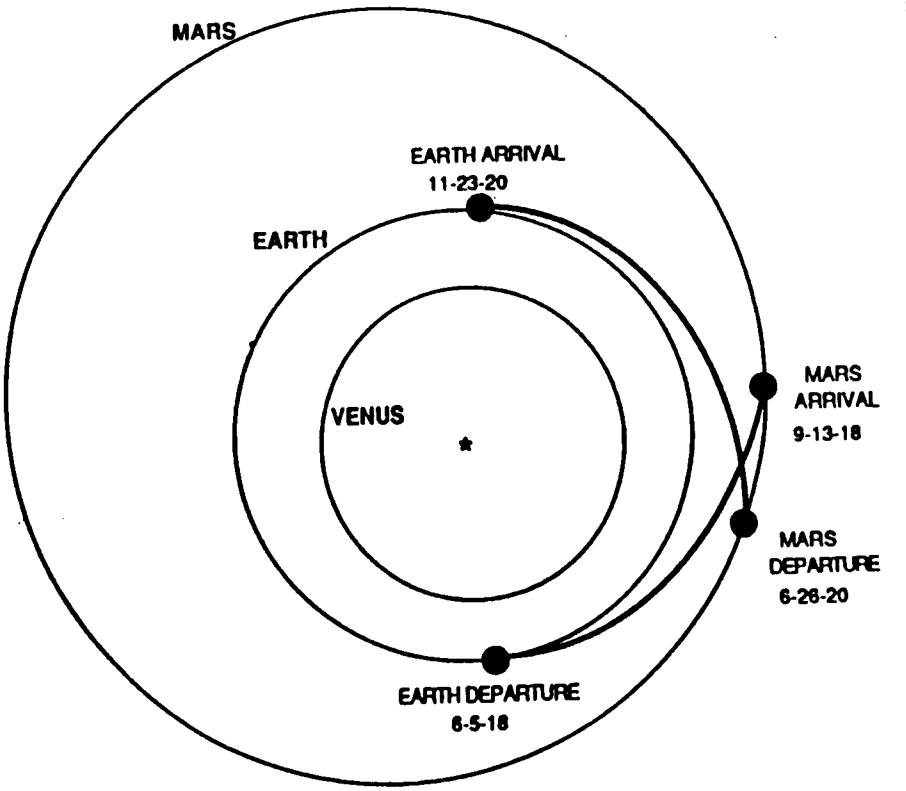
Conventional Manned Mars Mission



1 Separation from SSF	5 Mars Orbit Operations	9 Trans Earth Injection
2 Trans Mars Injection	6 Orbit to Landing	10 Trans Earth Coast
3 Trans Mars Coast	7 Ascent	11 Earth Return
4 Mars Orbit Insertion	8 Ascent Rendezvous	12 SSF Rendezvous

Conventional Manned Mars Mission Human Transportation Trajectory





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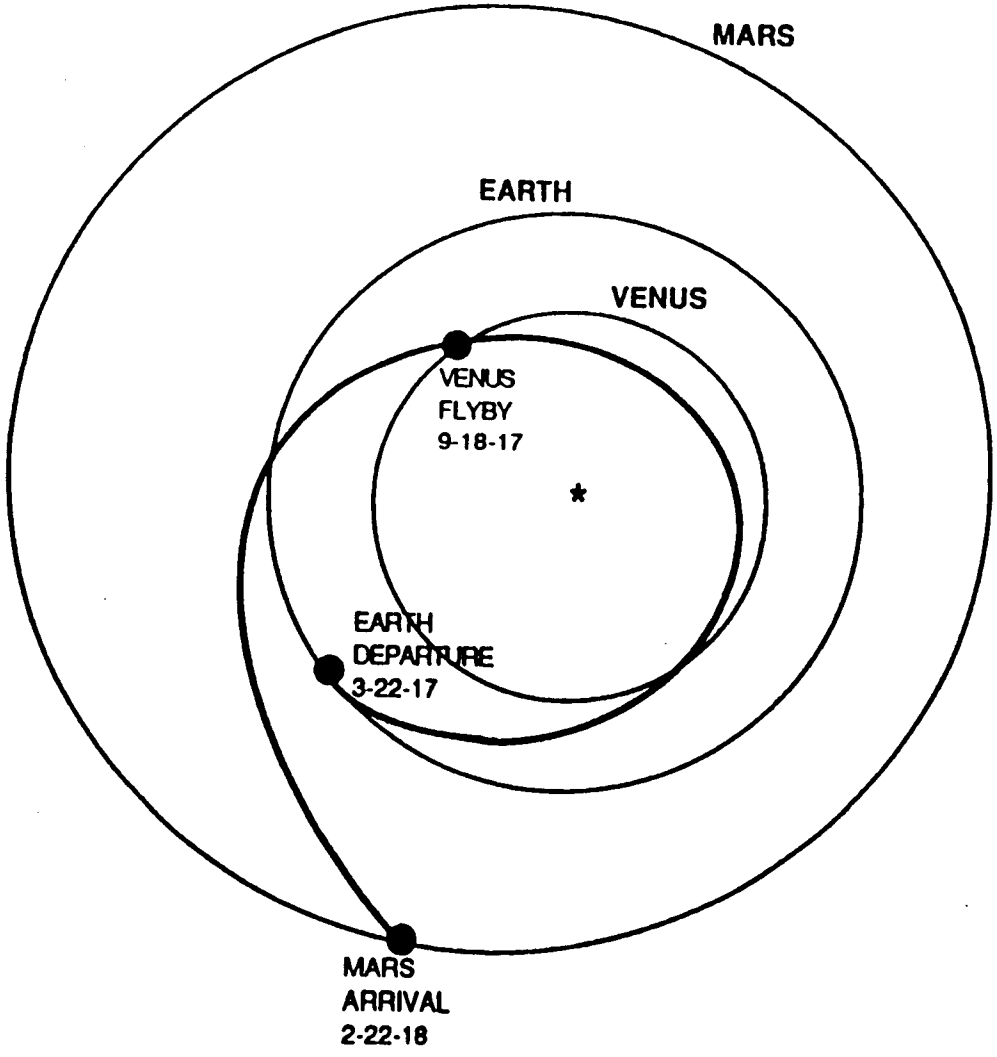
M. Loucks – 10/3/90 – 3

Conventional Manned Mars Mission Cargo Transportation Trajectory



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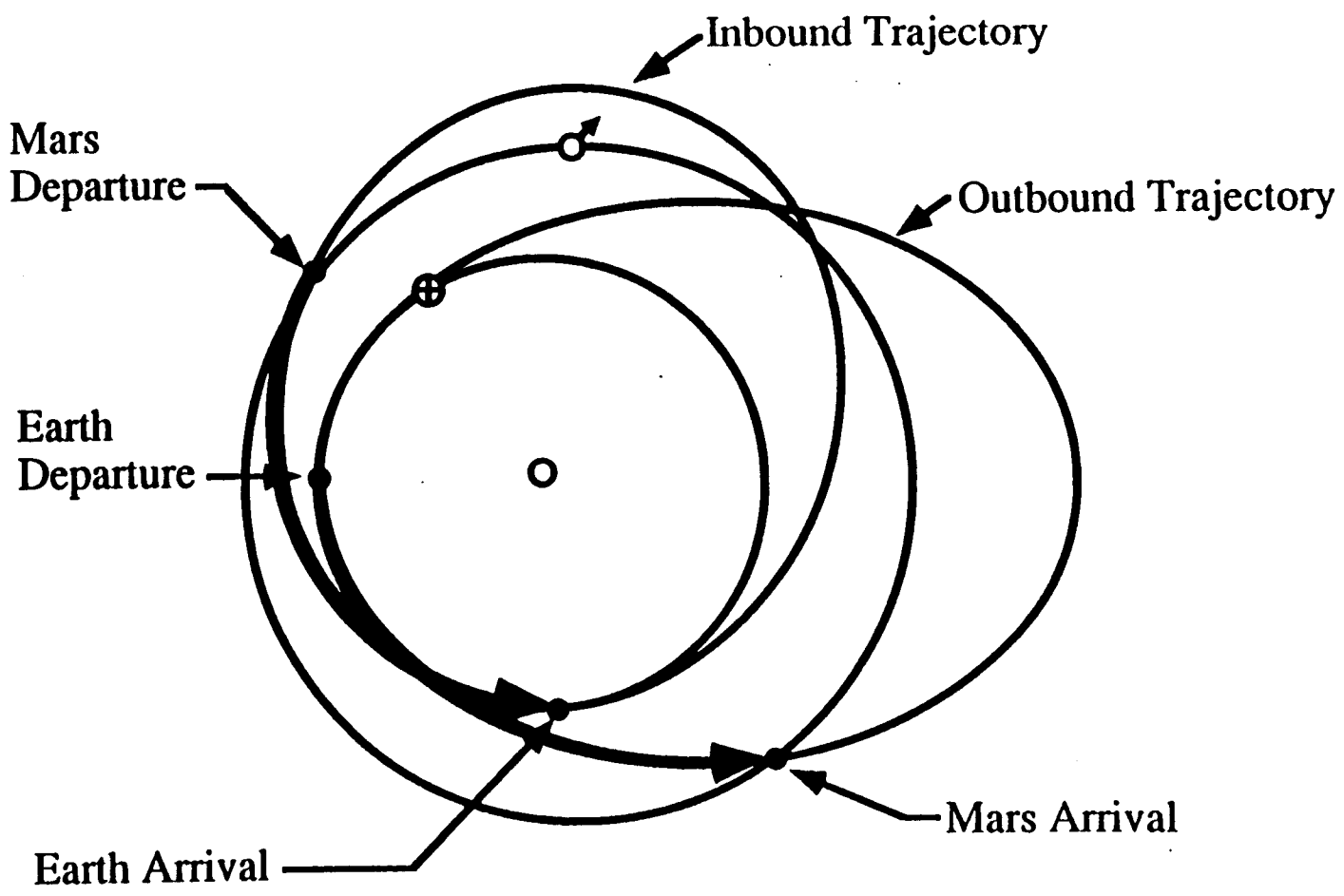
M. Loucks – 10/3/90 – 4

Split-Cycler Trajectories For Mars Human Transportation Mission



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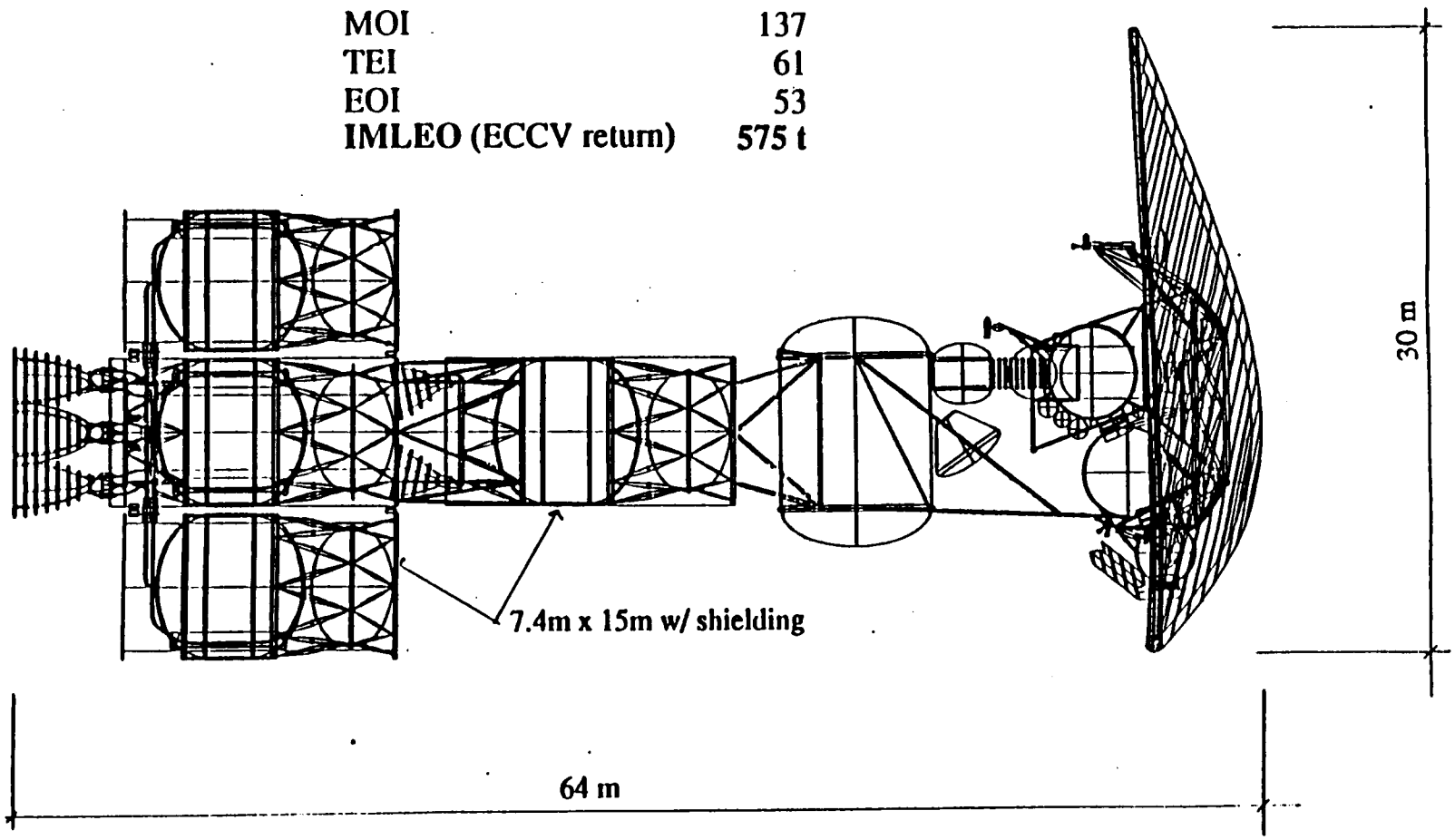
M. Loucks – 10/3/90 – 5

Conventional Manned Mars Mission Propulsive Transfer Vehicle (Manned)

TMI	137
MOI	137
TEI	61
EOI	53
IMLEO (ECCV return)	575 t



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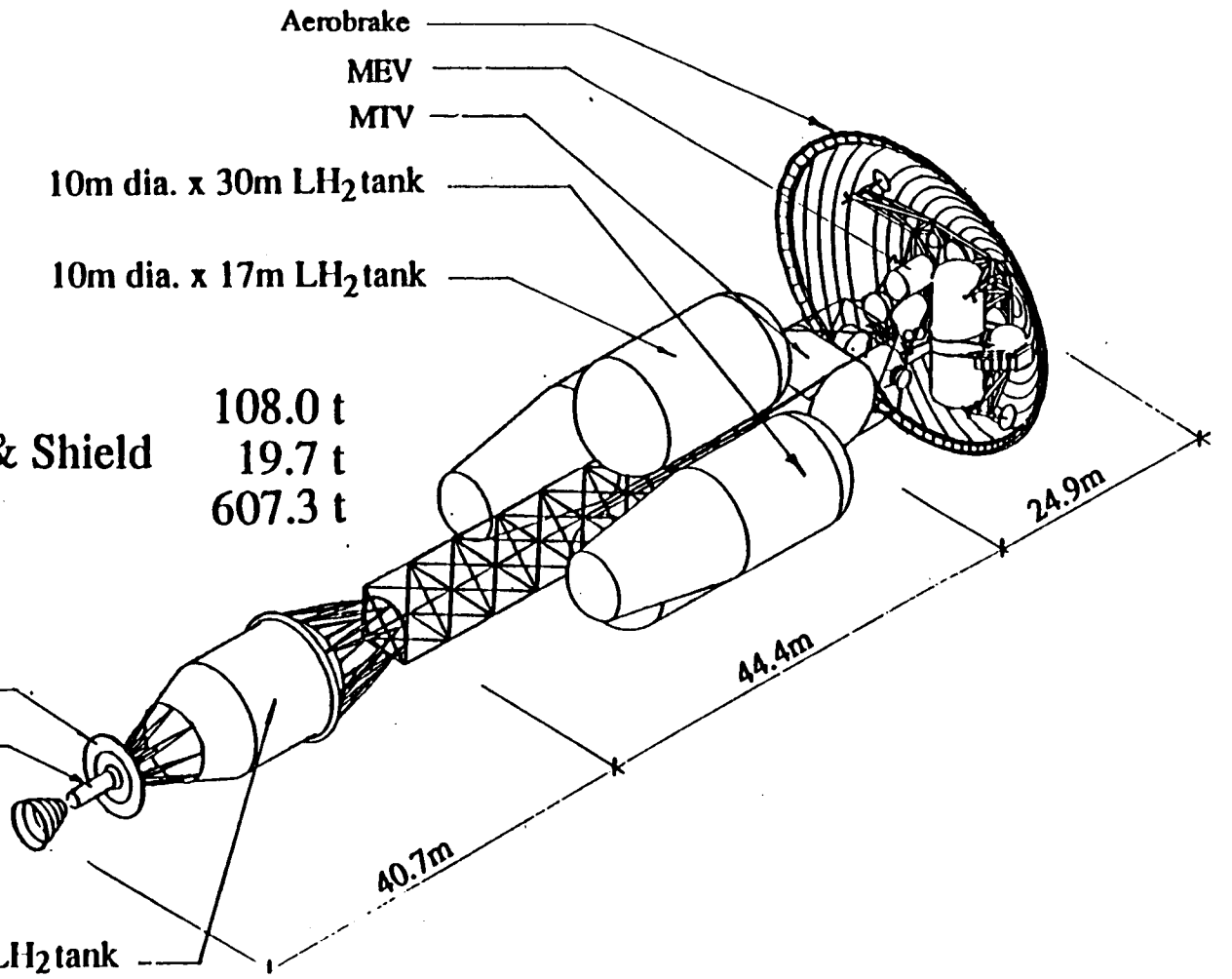
Conventional Manned Mars Mission Nuclear Thermal Transfer Vehicle (Manned)



MEV/MTV	108.0 t
Propulsion, Frame & Shield	19.7 t
Propellant & Tanks	607.3 t
IMLEO	735.0 t

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Systems Cluster

M. Loucks – 10/3/90 – 7

Session Four

THE CONSTRUCTION WORKFORCE

Elaine Hansen,
Chair

omit

Construction Operations

Elaine Hansen

The Operations Cluster of NASA's Engineering Research Center for Space Construction is addressing several key issues in Space Construction which will have a significant impact on the way we assemble, operate, service and evolve our future space systems.

Specific issues addressed are:

What are the appropriate roles for humans and machines in Space Construction?

Will the next generation of construction machines be decentralized?

What command, control and communications services are needed to support this decentralized workforce?

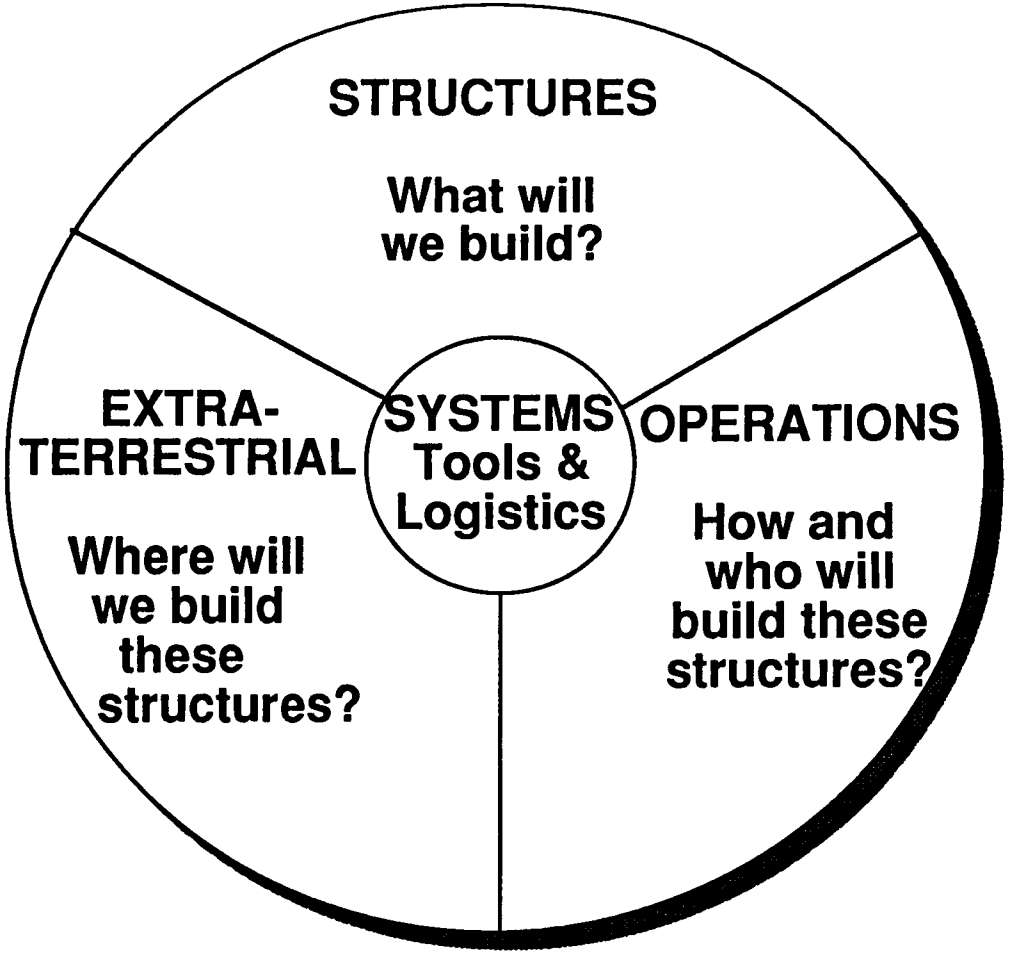
How can we improve the lot of humans working in space?

These issues and the tools, concepts and innovative approaches needed to address them will be covered in an afternoon of presentations and an evening of demonstrations and posters.

Construction Operations

— Introduction —

Center for Space Construction
— Clusters —



cSc The Center for Space Construction
A NASA Space Engineering Research Center at the University of Colorado
Operations Cluster

E. Hansen — 10/17/90 — 2

Construction Operations
— Research Domain —

- Many issues need to be addressed
- The CSC Ops group is addressing a subset of these which:
  - Match the interests and expertise of group members
  - Will make a significant impact on *how* we will work in space and *who* will make up this work force

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p. 6

CONSTRUCTOR SELECTION FOR SPACE CONSTRUCTION

Chris Grasso
Elaine Hansen
Brent Helleckson
Richard Johnson
Steve Jolly
Jane Pavlich

Introduction: Brent Helleckson
A space construction task is influenced by the requirements of the task itself, and by the system available to execute it. Given the difficulty in independently defining the task, and the fact that the types of constructors available range from humans to autonomous machines, the problem of matching the appropriate constructor to the task is daunting. To address the problem of constructor selection, the authors have developed a generic construction process model which identifies the requirements of given tasks. This model is used to define the construction system.

Task Breakdown: Jane Pavlich
In considering the creation of a construction system, breaking down the desired tasks uncovers the functions that the constructors must provide. Tasks are broken down into lower level tasks. Each consists four components necessary in completing that task: effecting, information gathering, analysis, and regulation. This breakdown leads to the description of a constructor system in terms of task timing requirements and cognition requirements.

Deriving the Construction System: Chris Grasso
In order to define a construction system which uses a mix of humans and robots, a rational analysis of tasks must be performed before deciding on a particular approach. Tasks are arranged in a tree, with task dependencies explicitly represented in the structure of that tree. By attaching physical, timing and cognitive needs to each node, the task breakdown can be used to drive the selection of effectors and control mechanisms. This in turn leads to a useful description of a mixed construction system. This description is then evaluated and improved iteratively.

Constructor Selection Models: Richard Johnson
Space construction projects, such as orbital assembly of a Mars transfer vehicle or building of a lunar base, can involve both human and machine constructors. Selection of a pool of constructors requires a model trading off constructor capabilities and requirements. Initial optimization work using a linear model illuminated several significant representational and data-gathering problems. This presentation discusses these problems and outlines future research tasks for improving selection models.

Center For Space Construction Operations Cluster

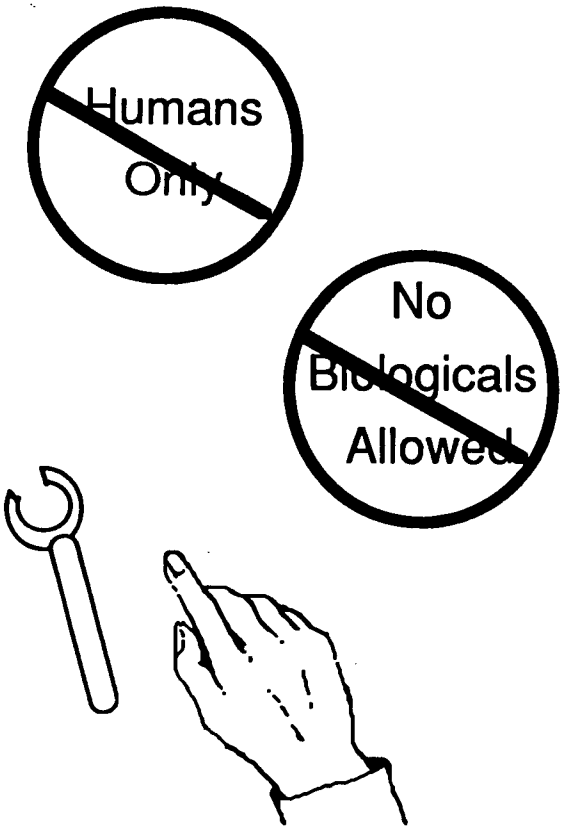
Constructor Selection Research

Chris Grasso, Elaine Hansen, Brent Helleckson, Richard Johnson, Steve Jolly, Jane Pavlich

Problem Statement

Assume:

- Construction in space cannot be done exclusively by humans
- Construction in space cannot be done exclusively by machine
- Construction in space will best be accomplished by a blend of humans and machines



By what process can the selection of a construction system, and the matchup of task and constructor be logically and rationally accomplished?

Previous Approach

Construction Goal

Task Description

Constructor Primitives

Constructor Methods

Task Requirements
- Physical Action
- Recognition
- Decision-making

Constructor Capabilities
- Physical Action
- Recognition
- Decision-making

Match-up of Candidate Systems

Optimization and Selection

Construction Operations
— Issues Addressed —

1. What are the appropriate roles for humans and machines (alone and in combination) as construction workers?

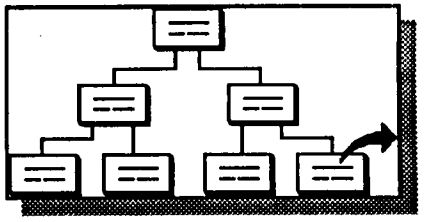
2. Will the next generation of construction machines be centralized or decentralized?

3. Can our command, control and communications services support a decentralized philosophy?

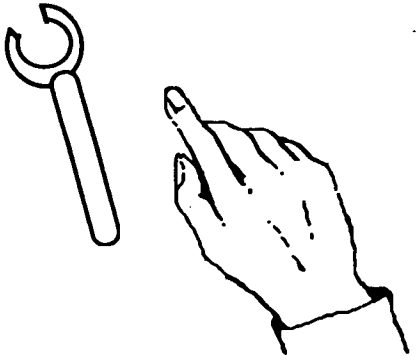
4. How can we improve the lot of humans working in space?

Presentations

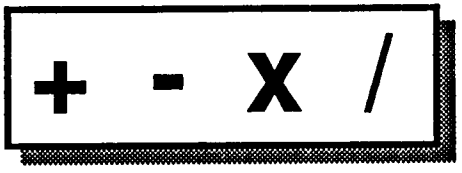
- Revised Task Breakdown Methodology
  - Jane Pavlich



- Construction System Derivation
  - Chris Grasso



- Mathematical Modelling of Selection
  - Richard Johnson



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Task Breakdown

by

Jane Pavlich

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J. Pavlich— 10/18/90— 1

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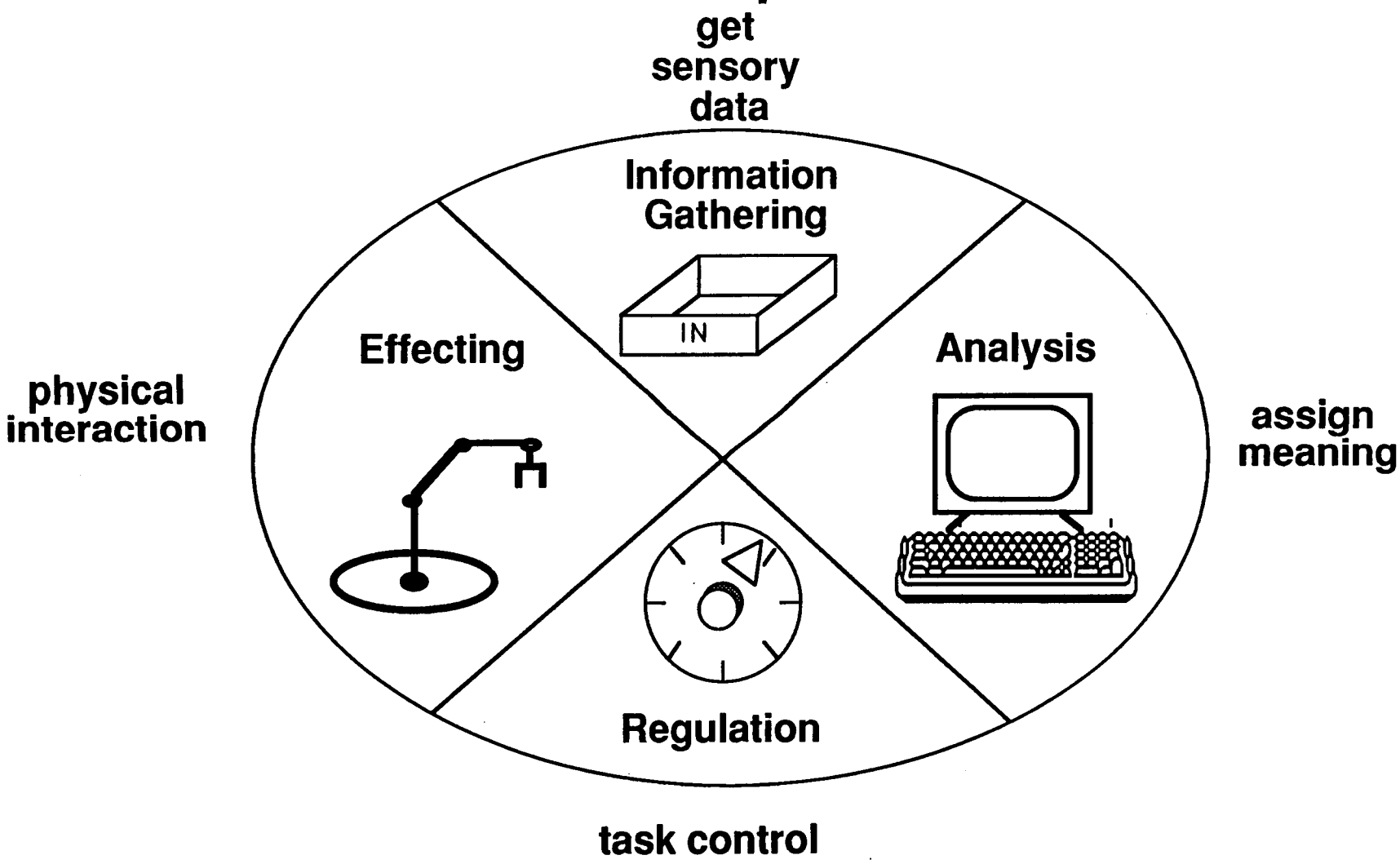
Task Components



Utilization of each component is task dependant

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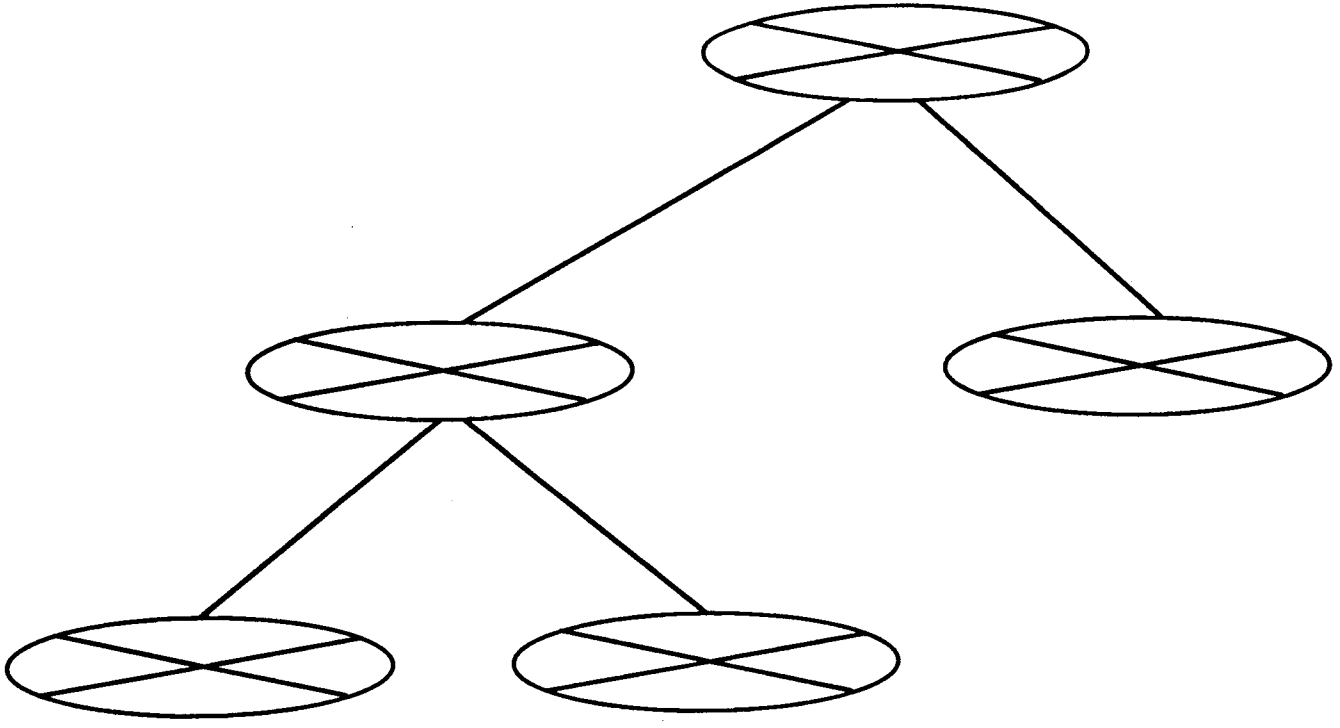
Task Breakdown



Each task contains the four components, regardless of level

Task Breakdown: an Example
Change a Tire

- get spare
  - transport spare
  - inspect

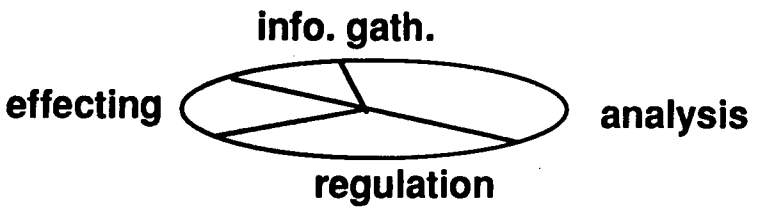
- remove vehicle weight from tire
  - support tire
  - remove bolts
    - loosen bolts
    - unthread bolts
  - get tire off mount

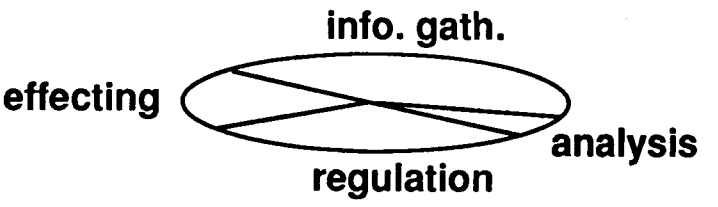
- emplace spare
  - align spare with mount
  - place spare in position
  - support spare
  - emplace bolts
    - thread bolts
    - tighten bolts

Conclusions

- Four components describe a task. They are:
  - effecting
  - information gathering
  - analysis
  - regulation

- Uncertainties effect the relative amount of information gathering and analysis that occurs





- Task timing requirements drive the "location in time" of cognition

Derivation of the Construction System

by

Chris Grasso

CSC Operations Cluster

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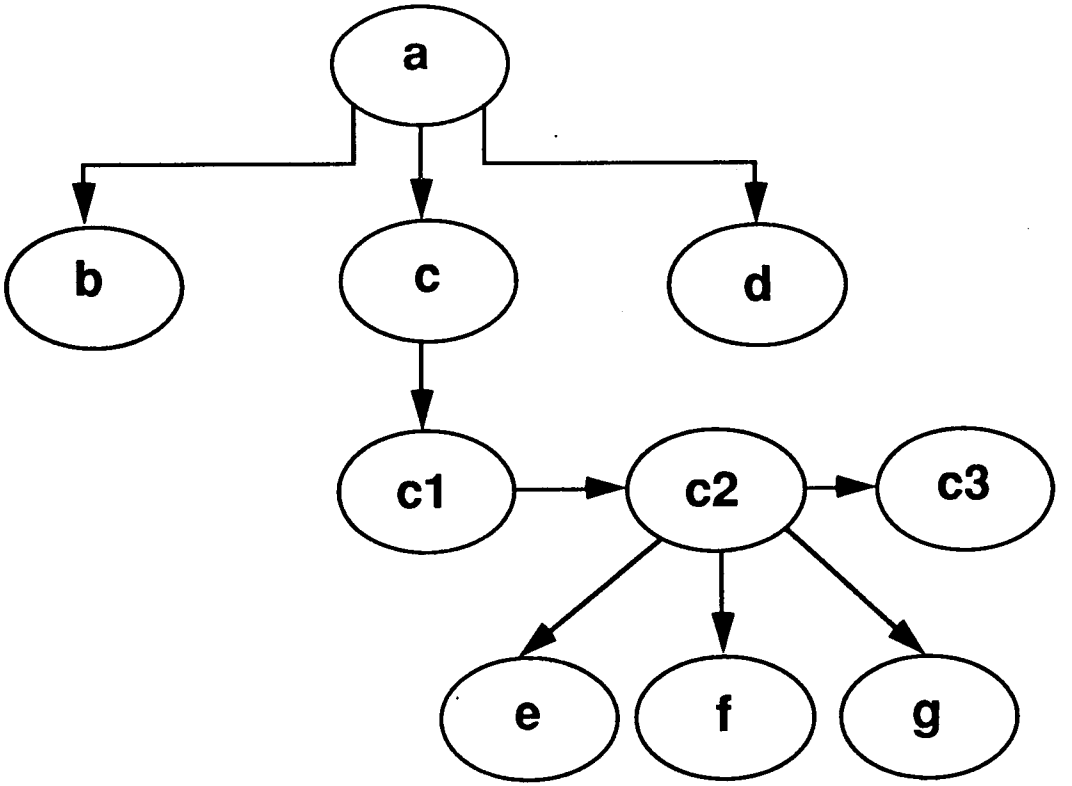
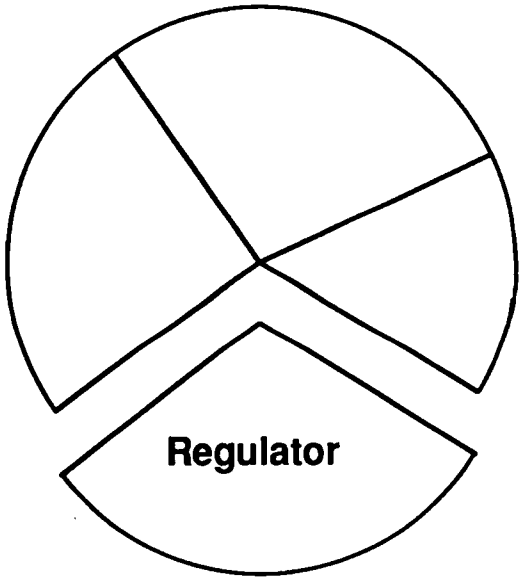
Tasks are broken down into subtasks
Dependencies are represented by sequential constructs



b, c, and d can occur in any order, or in parallel

c1, c2, and c3 must be completed in order for c to be complete

The Regulator



Responsible for controlling and coordinating the task

Takes knowledge compiled by the analyzer in order to respond to changing conditions

Task Regulator Activities

Regulator Activities

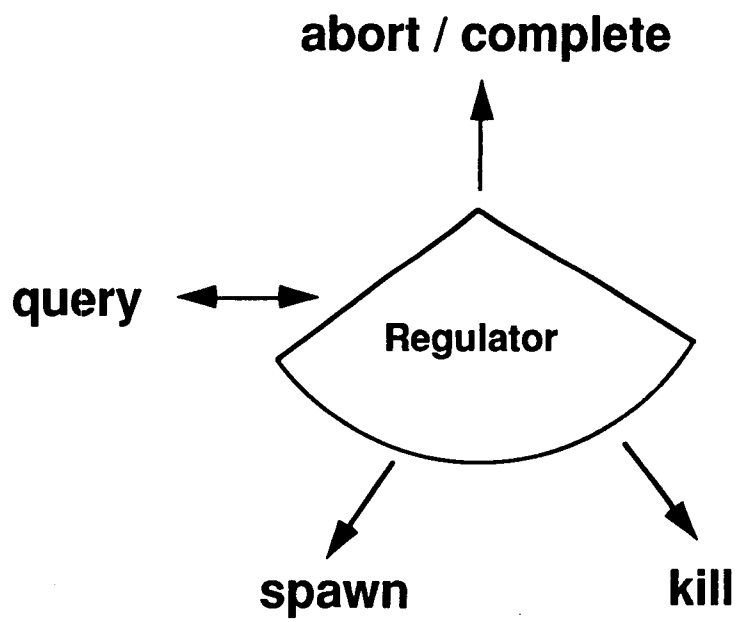
- none
- reflex
- reschedule
- reorder
- replan

Implementation

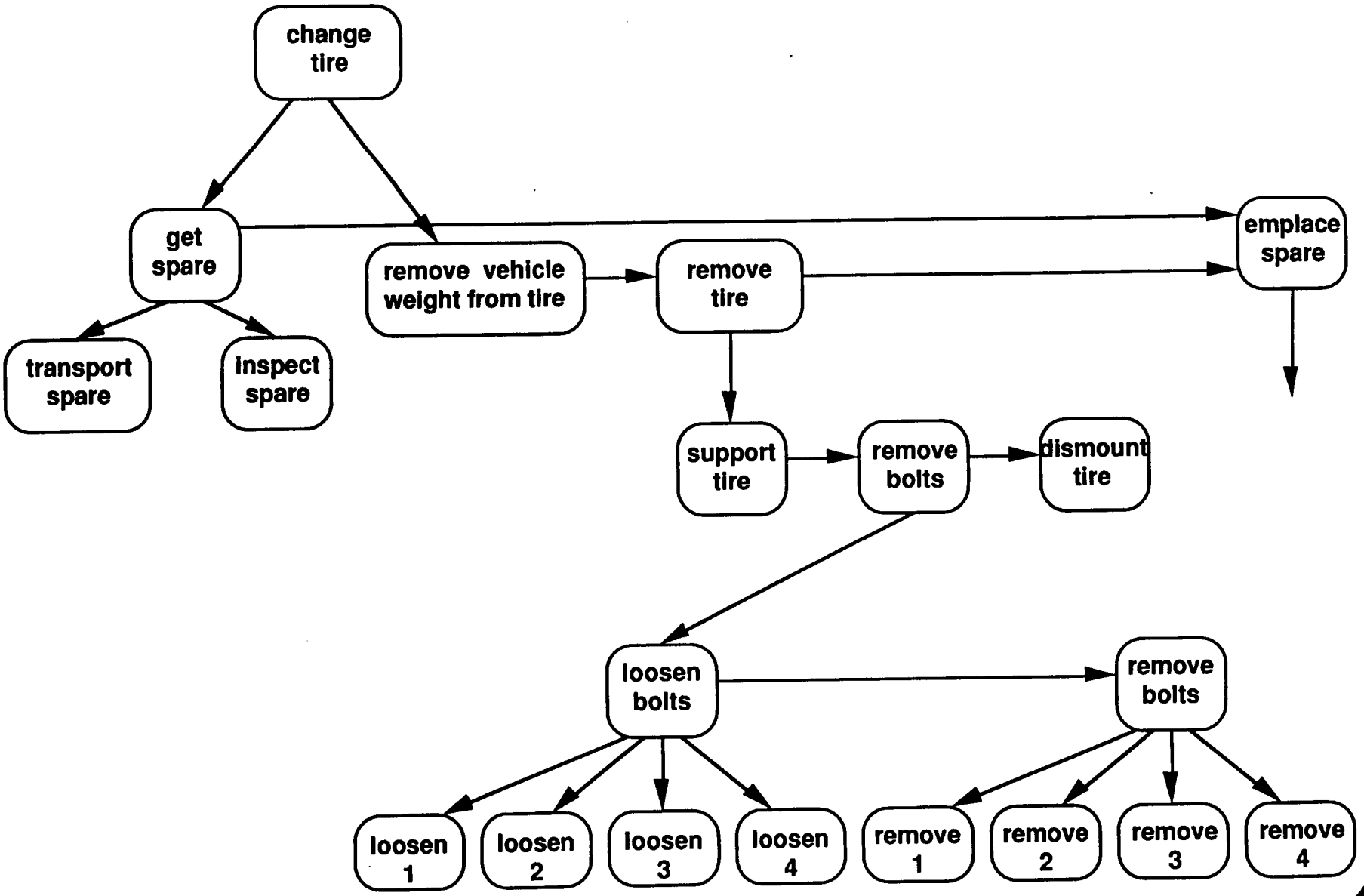
- none
- hardwired
- if-then
- rule based
- pattern matching
- judgement

Task Control Mechanisms Between Task Regulators

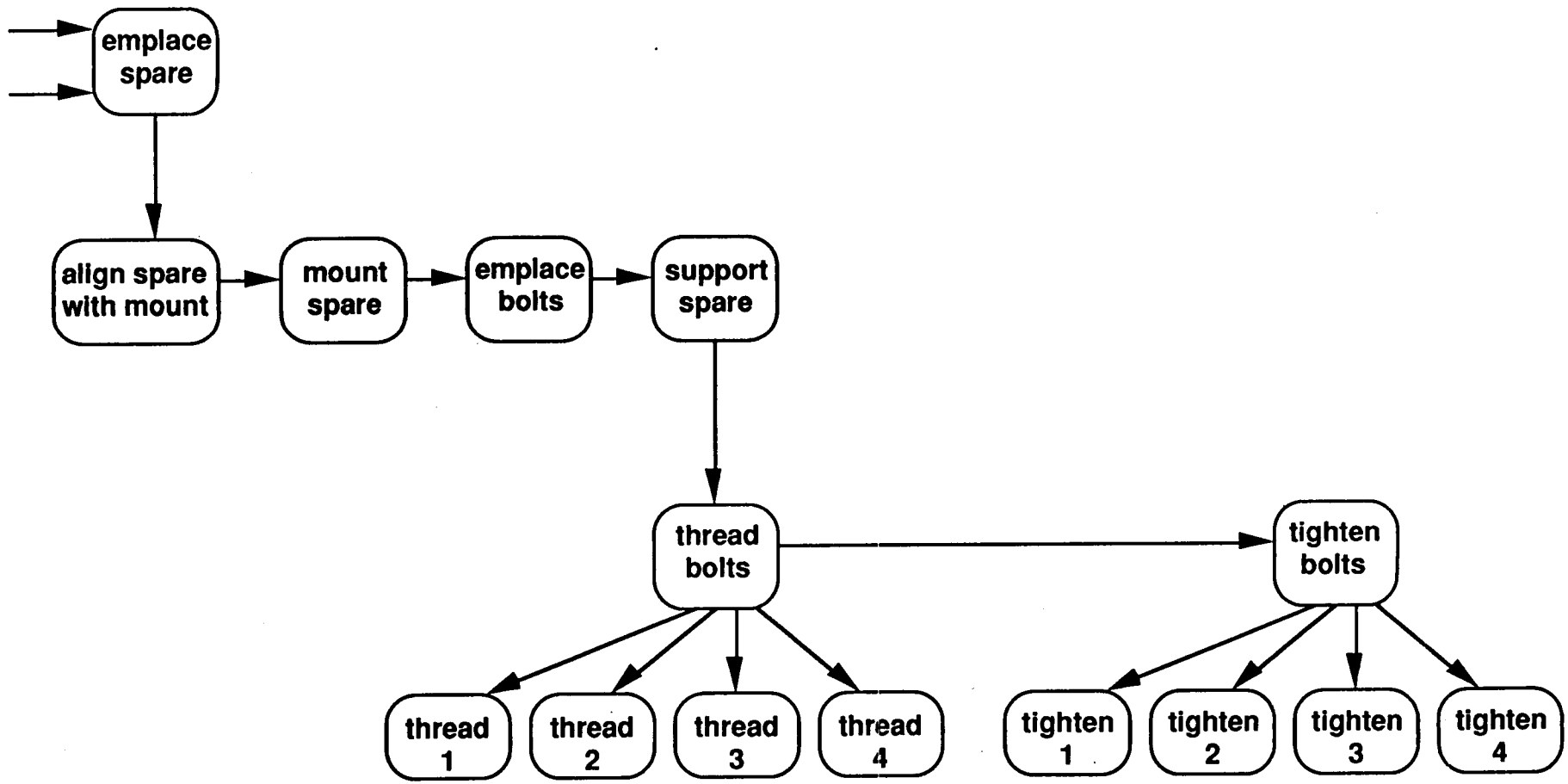
abort self
complete self
kill child
spawn child
query



Task Breakdown: an Example



Task Breakdown: an Example (cont)



Example Task Decision Matrix

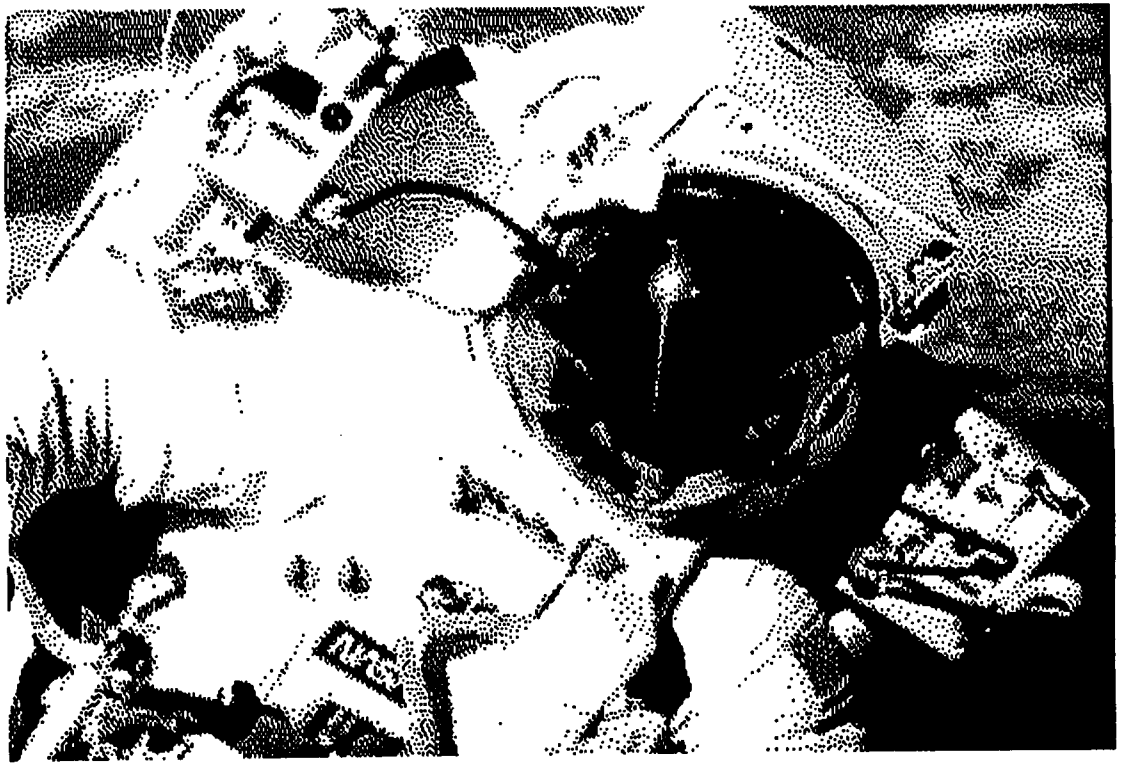
Weight	Size	Precision	Sensitivity of Object	Level of Information
Heavy	Large	Fine	Rugged	Complete
Moderate	Moderate	Moderate	Moderate	Incomplete
Light	Small	Coarse	Fragile	Absent

Conclusions

- It is possible to specify a mix of constructors logically, rather than by using a priori assumptions.
- All tasks can be described in terms of the four components.
- Tasks translate to construction system needs.
- There are a handful of discriminators:
  - task timing requirements
  - task dependencies
  - cognition requirements
  - physical requirements
- Individuals and groups can use these guidelines to make rational decisions
- Mathematical techniques may assist in the selection process

Constructor Selection Models

for Space Construction Missions



Richard J Johnson & George W Morgenthaler

1990 October 17-19 Center for Space Construction, A NASA Space Engineering Research Center at the University of Colorado RJJ

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System Design Outline

- Discover requirements that design must meet
- Produce **complete list** of design options that might meet requirements
- Filter out options that violate known physical laws
- Pick "best" of the remaining options that meet the requirements

"Best" is hard to define - usual construction trades include:

Cost

Schedule

Risk

Picking the Best Constructor Pool

- Many possible constructors
- Many possible combinations of those constructors
- Unlike on Earth, only a small number of the possibilities will actually be used

Combinatorial explosion

- Computation no substitute for design synthesis and intuition
- Enable more extensive exploration of alternatives

CSC is developing a series of Phase A design tools to help mission designers choose the "best" constructor pool

The Arsenal

Linear Programming (LP)

Integer Linear Programming (ILP)

Non-Linear Programming

Multiple Objective Optimization

Simulated Annealing

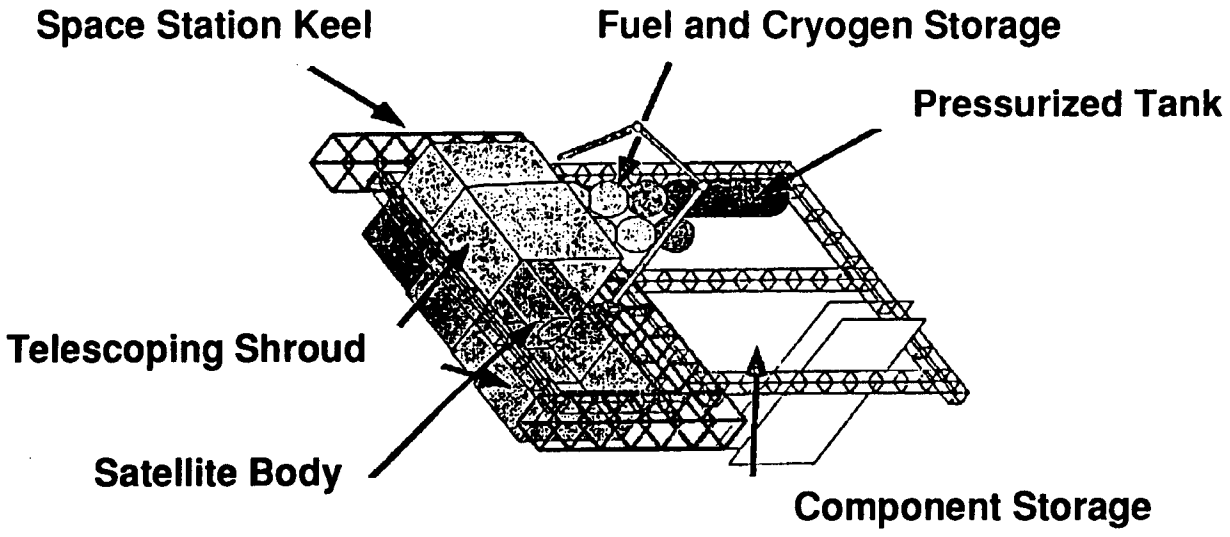
Neural Networks

Genetic Algorithms

Tabu Search

Prototype Model

Simple Task: Build a Satellite Servicing Bay



- The "best" constructor pool is the one with the lowest total cost
- Some performance and cost data is available for EVA crew members
- Performance and cost assumptions made for other constructors

Prototype Model Structure

Linear programming approach

Objective function (minimize cost):

$$\text{Minimize } \mathbb{C} = \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} C_i$$

Constraints:

Finish all the tasks

$$\sum_{i=1}^{m} X_{ij} P_{ij} >= \text{Total Work required to do task } T_j$$

Don't overwork the constructors

$$\sum_{j=1}^{n} X_{ij} <= \text{Time Available for constructor } W_i$$

Model Input

Constructor productivities – minutes/task unit

Constructor costs – $/minute

Prototype Results and Lessons

Results:

- EVA astronauts sole constructor used
- Other constructors unused due to lack of larger program context

Lessons:

- Need more and better data on constructor capabilities
- Linear model forces amortization – work-arounds exist
- Most useful definitions of "best" may require non-linear, iterative solution techniques
- Need multiple mission program context for reasonable technology development representation and technology risk analysis

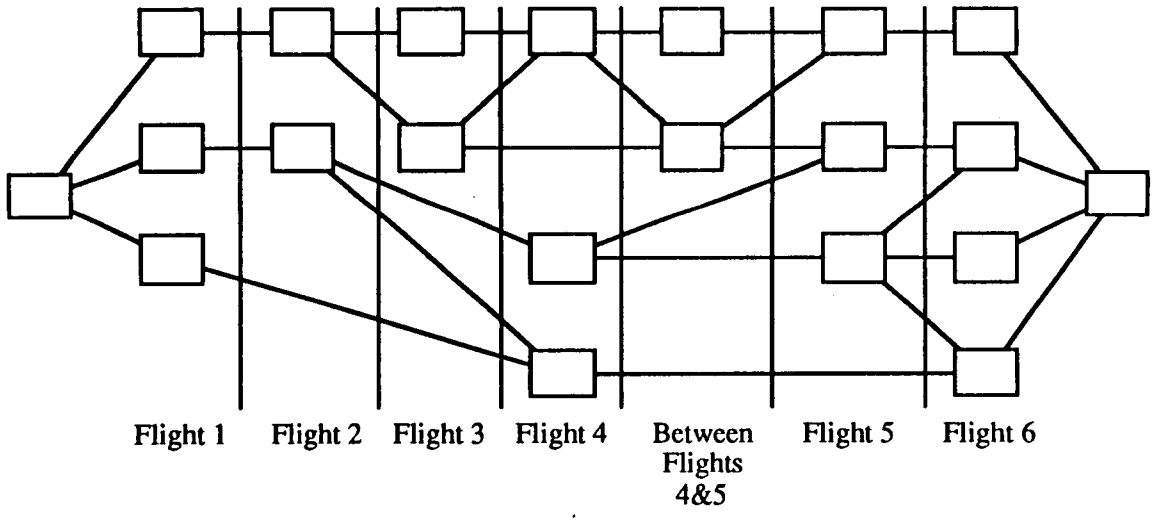
Continuing Work

- Introduce additional realistic constraints
- Build integer linear programming representation
- Add stochastic aspects and multiple objectives
- Explore more accurate representations and iterative solution methods (simulated annealing, genetic algorithms, neural nets, tabu search, ...)

Additional Realistic Constraints

- Support Services Constraints
- Workspace Volume Constraints
- Communication Constraints
- Equipment Availability Constraints
- Simultaneity and Logistic Re-supply Constraints
- Schedule Constraints
- Sequential Visit Missions

Simultaneity & Schedule

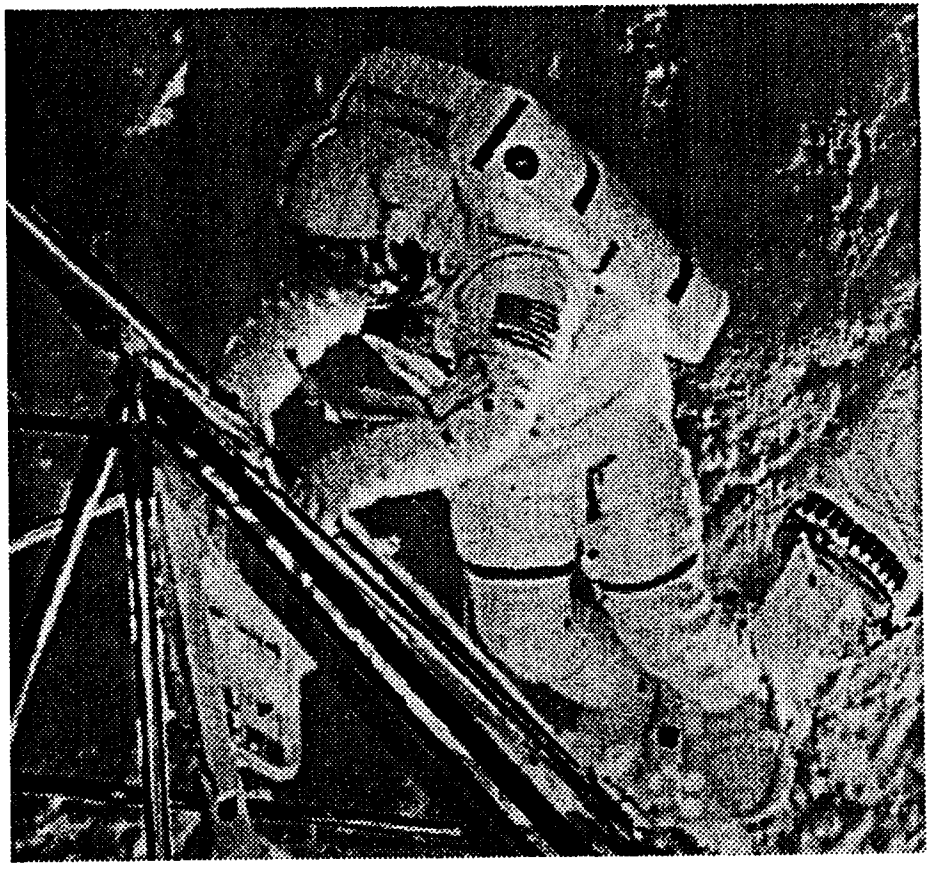


Search Methods

- Local Optimization
  - Only take those moves that lead to better (downhill) states
- Multiple-local-optimization
  - Simulated Annealing
    - Adds random element
    - Pick uphill moves with a slowly diminishing probability
  - Tabu Search
    - Adds memory
    - Pick best move that doesn't undo a recent move

Finale

- A rational basis for trades between multiple candidate constructor pools is being developed by operations group
- Programming and search methods can help designers synthesize a more defensible product
- At a minimum, such methods can point to the most significant trades and trends



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Session Five

TROTERS: A NEW CONCEPT FOR WORKERS

Renjeng Su,
Chair

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TROTERS (TINY ROBOTIC OPERATION TEAM EXPERIMENT) A NEW CONCEPT OF SPACE ROBOTS

Renjeng Su

In view of the future need of automation and robotics in space and the existing approaches to the problem, we propose a new concept of robots for space construction. The new concept is based on the basic idea of decentralization. Decentralization occurs, on the one hand, in using teams of many coorperative robots for construction tasks. Reduncy and modular design are explored to achieve high reliability for team robotic operations. Reliability requirement on individual robots is greatly reduced. Another area of decentralization is manifested by the proposed control hierarchy which eventually includes humans in the loop. The control strategy is constrained by various time delays and calls for different levels of abstraction of the task dynamics. Such technology is needed for remote control of robots in an uncertain environment. Concerns of human safety around robots are thus relaxed. This presentation also introduces the required technologies behind the new robotic concept. Three of these supporting technologies are discussed with more details in the following presentations.

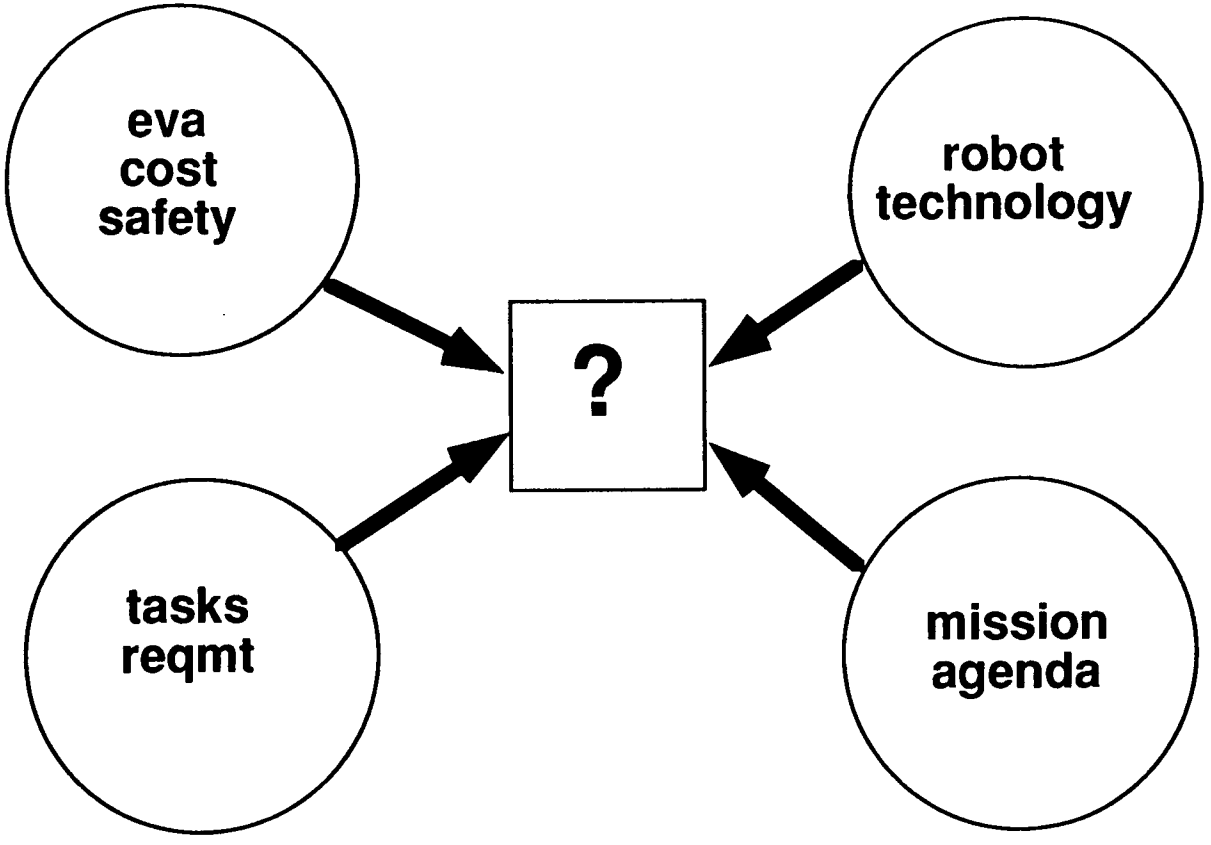
TROTER
(Tiny Robotic Operation Team Experiment)
A NEW CONCEPT OF SPACE ROBOTS

Ren Su

Outline:

1. Introduction to the new concept of space robotics (Su)
2. Decentralized approach to remote control of multiple robots (Stephen)
3. Modeling and control of discrete event dynamical systems (Hunter)
4. Fuzzy logic for symbolic modeling and control (Wang)

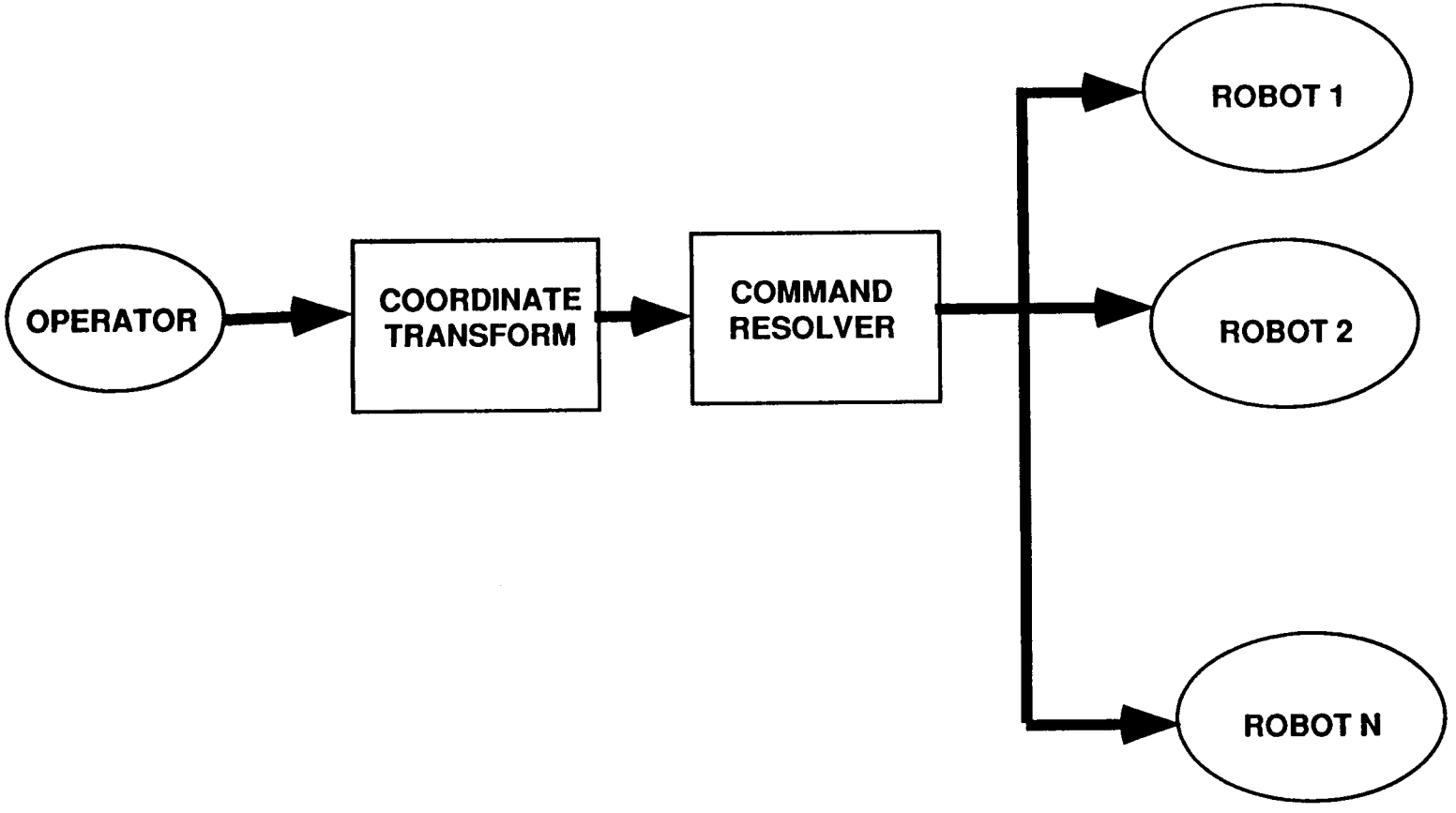
CONSTRAINTS FOR SELECTING ROBOTIC CONSTRUCTORS



CHARACTERISTICS OF EXISTING APPROACH TO SPACE ROBOTICS

- EXTENSION OF MANUFACTURING ROBOTIC TECHNOLOGY
- CENTRALIZED CONTROL
- VERY HIGH RELIABILITY REQUIREMENT
- EXPENSIVE ONE-OF-THE-KIND DESIGN
- VERY HIGH HUMAN SAFETY REQUIREMENT

A CENTRALIZED APPROACH TO COORDINATION CONTROL



A NEW CONCEPT OF ROBOTIC CONSTRUCTORS

TROTERS
(TINY ROBOTIC OPERATION TEAM EXPERIMENT)

1. A TEAM OF MANY SMALL MOBILE ROBOTS
2. REMOTE CONTROLLED
3. MODULAR CONTROL SOFTWARE, LINKABLE IN RUN TIME
4. HIERARCHICAL CONTROL WITH HUMAN IN THE OUTER LOOP

CHARACTERISTICS OF TROTERS

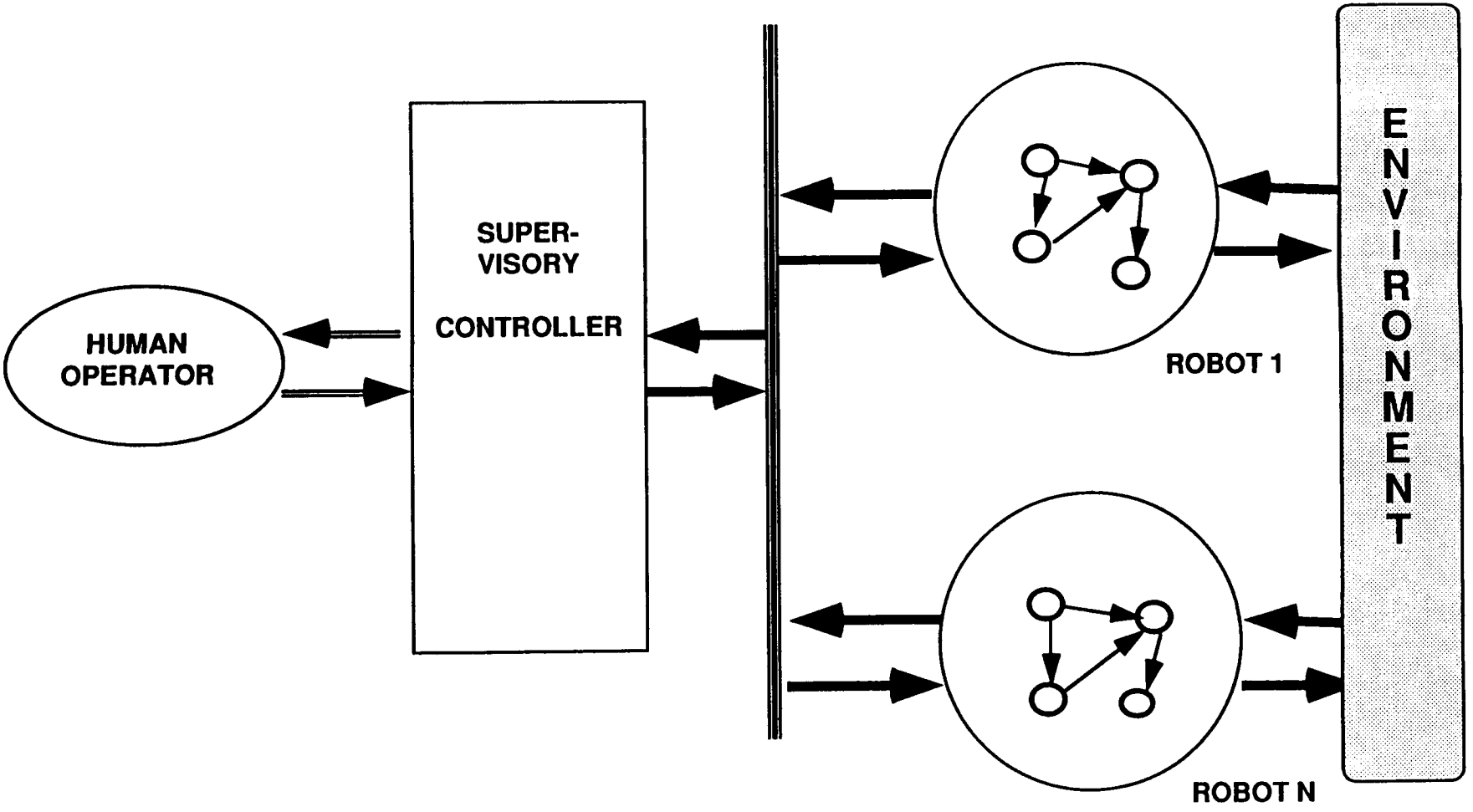
1. LOW-COST ROBOTS BASED ON EXISTING TECHNOLOGY
2. FLEXIBLE RECONFIGURATION FOR VARIOUS TASKS
3. HIGH TEAM RELIABILITY, LOW REQUIREMENT FOR INDIVIDUAL RELIABILITY
4. POTENTIAL AUTOMATIC MAINTENANCE
5. DECENTRALIZED CONTROL: COORDINATION AND SUPERVISORY CONTROL
6. RELAXED HUMAN SAFETY REQUIREMENT

REQUIRED CONTROL TECHNOLOGY FOR TROTERS

1. COORDINATION CONTROL OF MULTIPLE ROBOTS WITH VARIABLE CONFIGURATION
2. CONTROL HIERARCHY OF VARIOUS CLOSED-LOOP BANDWIDTHS
3. SYMBOLIC SUPERVISORY CONTROL
4. SYMBOLIC MODELING OF DYNAMICAL SYSTEMS
5. DATA COMPRESSION FOR REMOTE DECISION MAKING

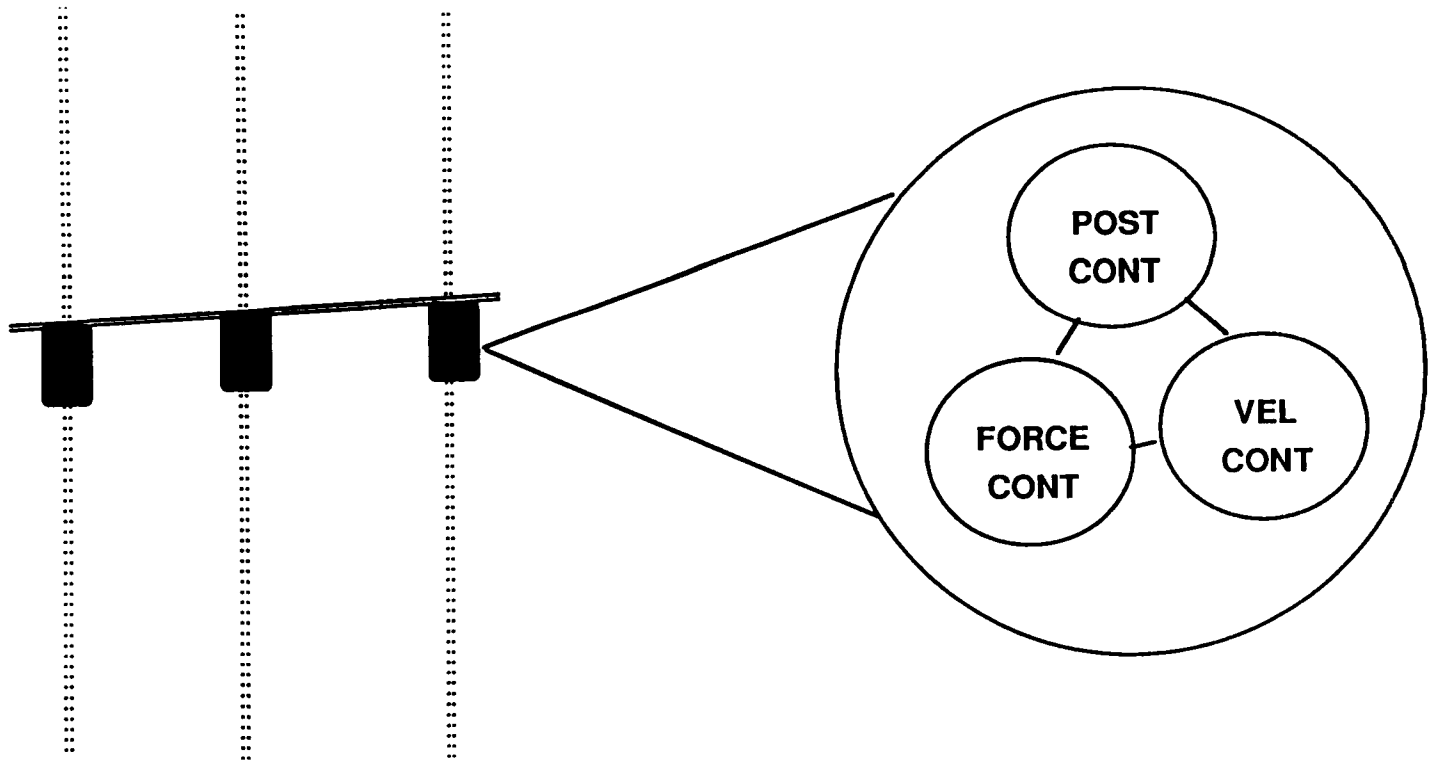
DECENTRALIZED CONTROL FOR REMOTE CONTROL OF MULTIPLE ROBOTS

(Chris Stephen)



MODEL TRAIN SYSTEM FOR TROTER EXPERIMENT

(OPS group)



SYMBOLIC SUPERVISORY CONTROL

(Dan Hunter)

PROBLEMS:

1. HOW TO MODEL DYNAMICAL SYSTEMS AS DISCRETE EVENT DYNAMICAL SYSTEMS (DEDS)?
2. HOW TO CONTROL DEDS?

APPROACHES:

1. DEDS MODELING USING TEMPORAL LOGIC AND FINITE STATE MACHINES
2. CONTROL SYNTHESIS PROBLEM FORMULATED AS
   (a) SCHEDULING PROBLEM
   (b) SUPERVISOR DEDS SYNTHESIS PROBLEM

SYMBOLIC MODELING USING FUZZY LOGIC

(Leo Wang)

PROBLEMS:

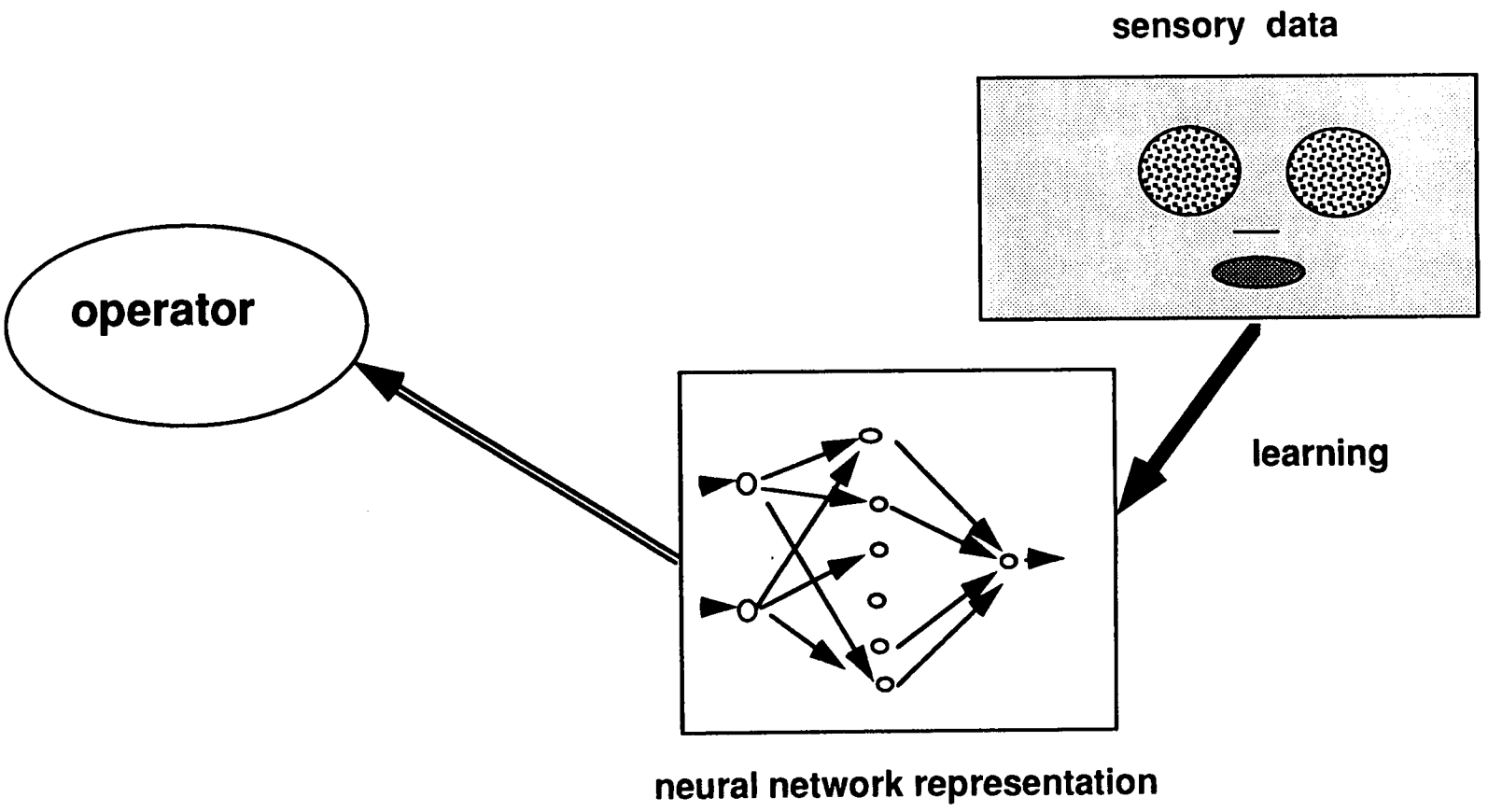
1. HOW TO DESCRIBE NUMERICAL DYNAMIC SYSTEMS BY SYMBOLIC TERMS?
2. HOW TO DEVELOP RULE BASE CONTROL LOGIC?

APPROACHES:

1. USING FUZZY LOGIC TO TRANSFORM NUMERICAL DATA INTO SYMBOLIC DATA
2. USING ADAPTIVE TECHNIQUES TO DERIVE RULES FROM HUMAN OPERATORS AND/OR DIRECT INPUT-OUTPUT DATA

DATA COMPRESSION TECHNIQUES

(Noureddine Kermiche)



REMARKS

1. TROTERS PROVIDE A NEW ALTERNATIVE TO SPACE AUTOMATION AND ROBOTICS
2. RESEARCH INTO THIS NEW APPROACH IS IN ITS INFANCY
3. CONSTRUCTION OF TROTERS CAN BE DONE MUCH MORE RAPIDLY AND AT MUCH LOWER COST
4. HIGH RELIABILITY, EFFICIENT MAINTENANCE AND REPAIR
5. EMPHASIS ON SOFTWARE RATHER THAN HARDWARE SYSTEMS, EXPANDABLE SYSTEMS
6. MAJOR DEVELOPMENT NEEDED TO TEST THE CONCEPT

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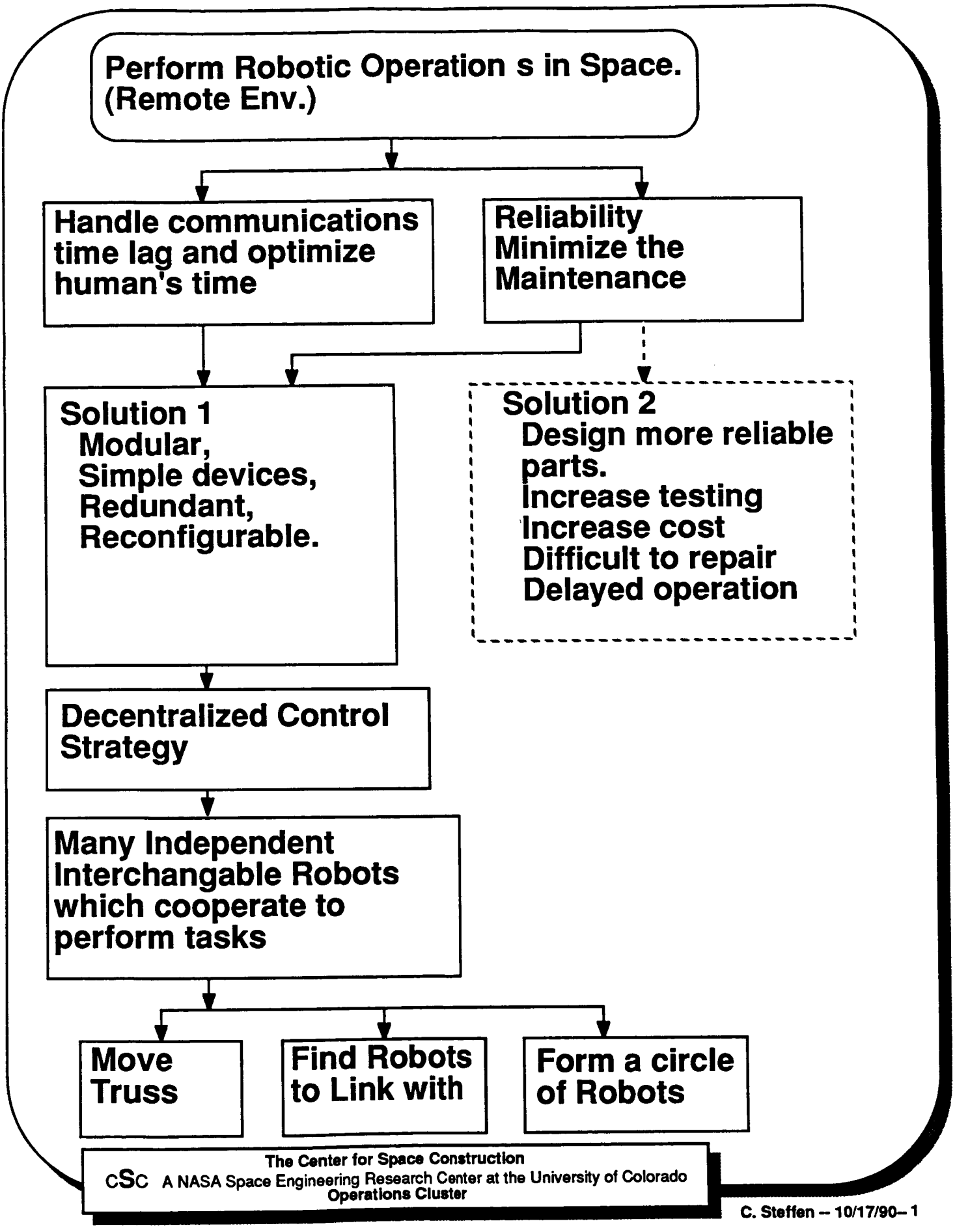
DECENTRALIZED CONTROL

Chris Steffen

The first part of the talk will consist of an overview of the time-delay problem and the reliability problem which arise in trying to perform robotic construction operations at a remote space location. The effects of the time-delay upon the control system design will be itemized. A high level overview of a decentralized method of control which is expected to perform better than the centralized approach in solving the time-delay problem will then be proposed. The lower level, decentralized, autonomous, Troter Move-Bar algorithm will then be presented. (Troters are coordinated independent robots.) The solution to the reliability problem is connected to adding redundancy to the system. One method of adding redundancy will be presented.


Perform Robotic Operation s in Space. (Remote Env.)
Handle communications time lag and optimize human's time
Reliability Minimize the Maintenance
Solution 1
Modular,
Simple devices,
Redundant,
Reconfigurable.
Solution 2
Design more reliable parts.
Increase testing
Increase cost
Difficult to repair
Delayed operation
Decentralized Control Strategy
Many Independent Interchangable Robots which cooperate to perform tasks
Move Truss
Find Robots to Link with
Form a circle of Robots
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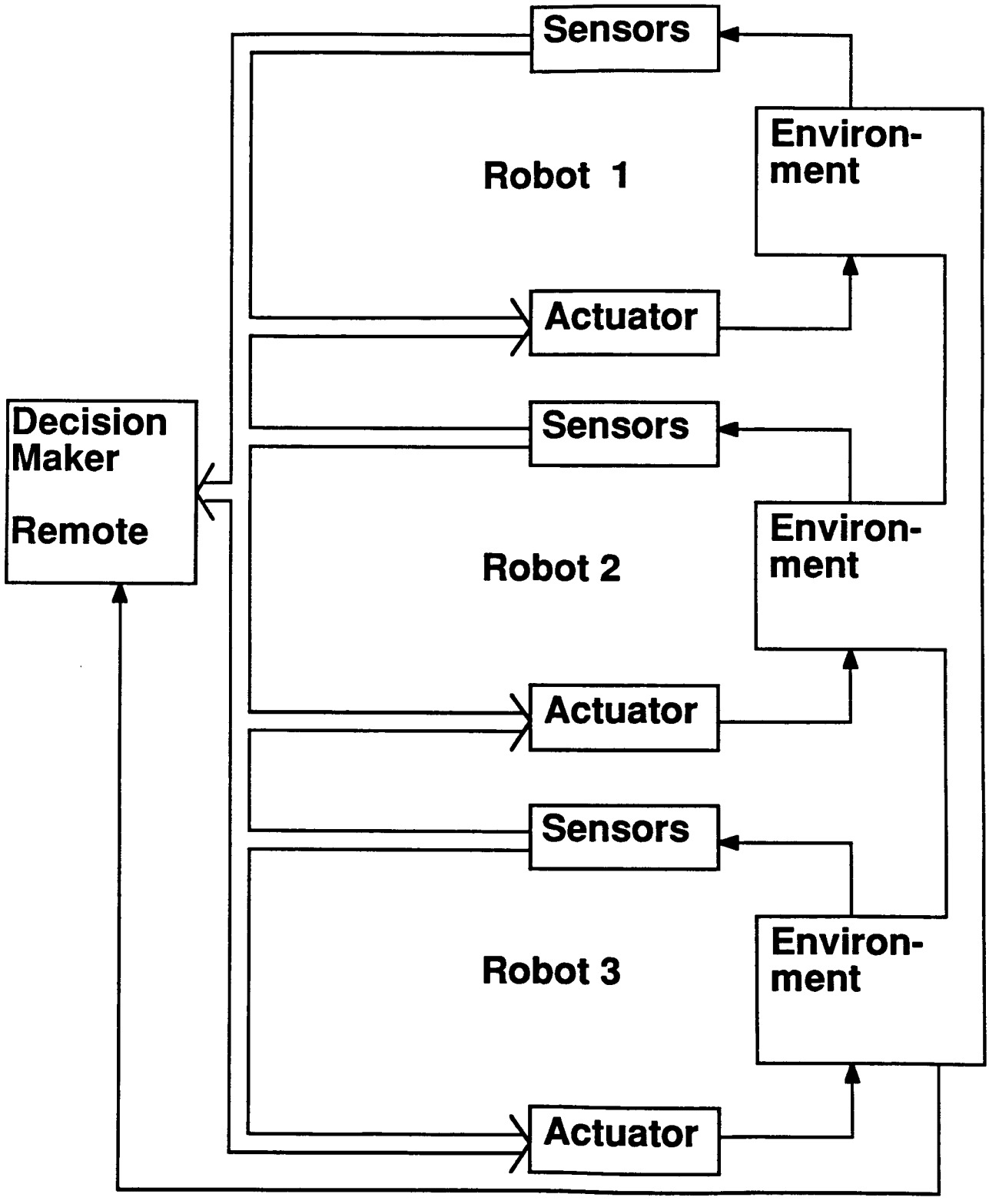
Centralized Control System



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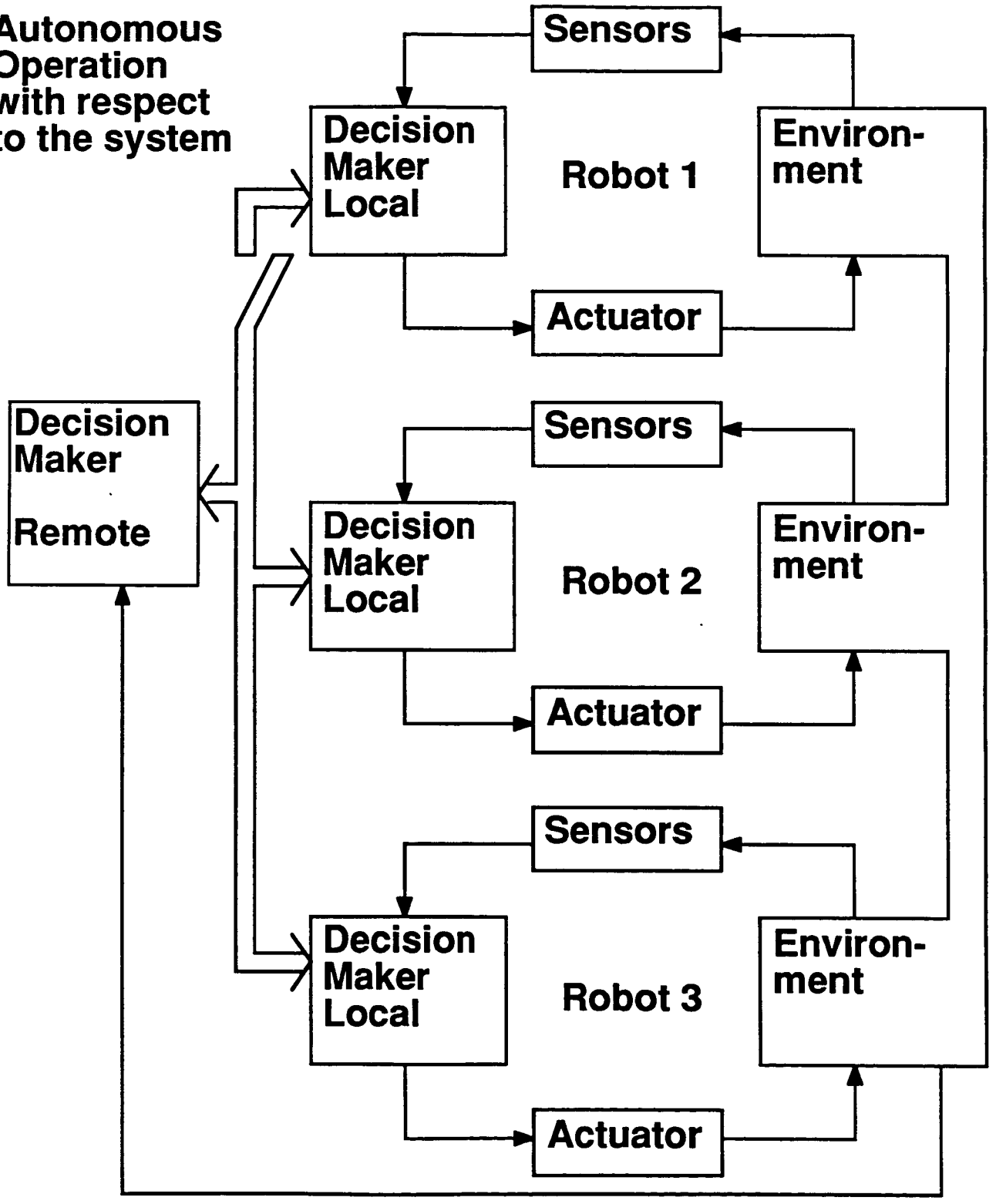
Decentralized Control System

Autonomous Operation with respect to the system



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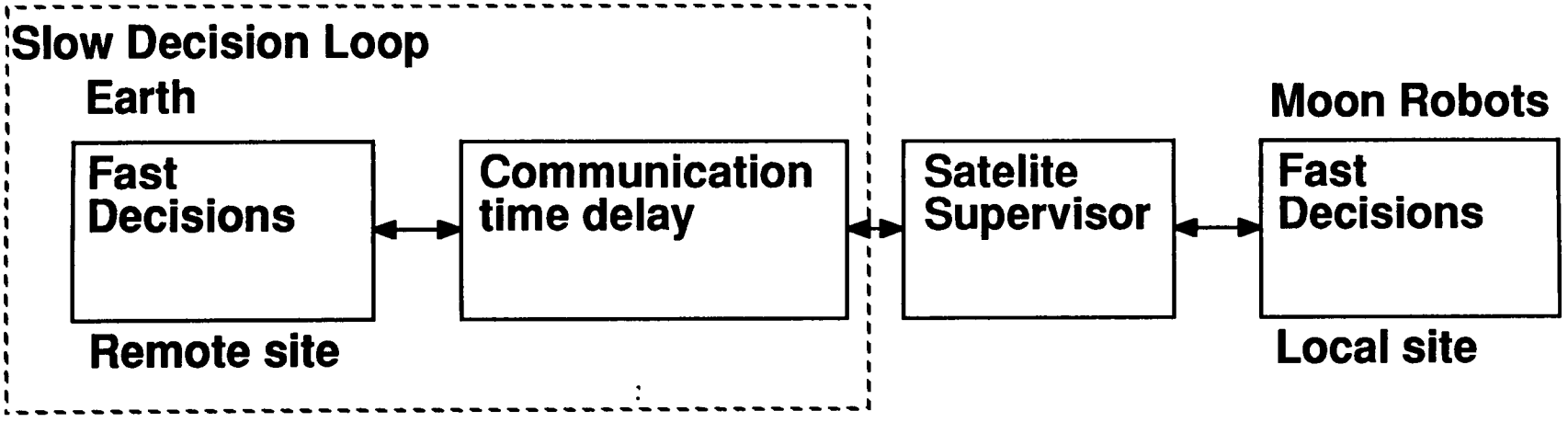
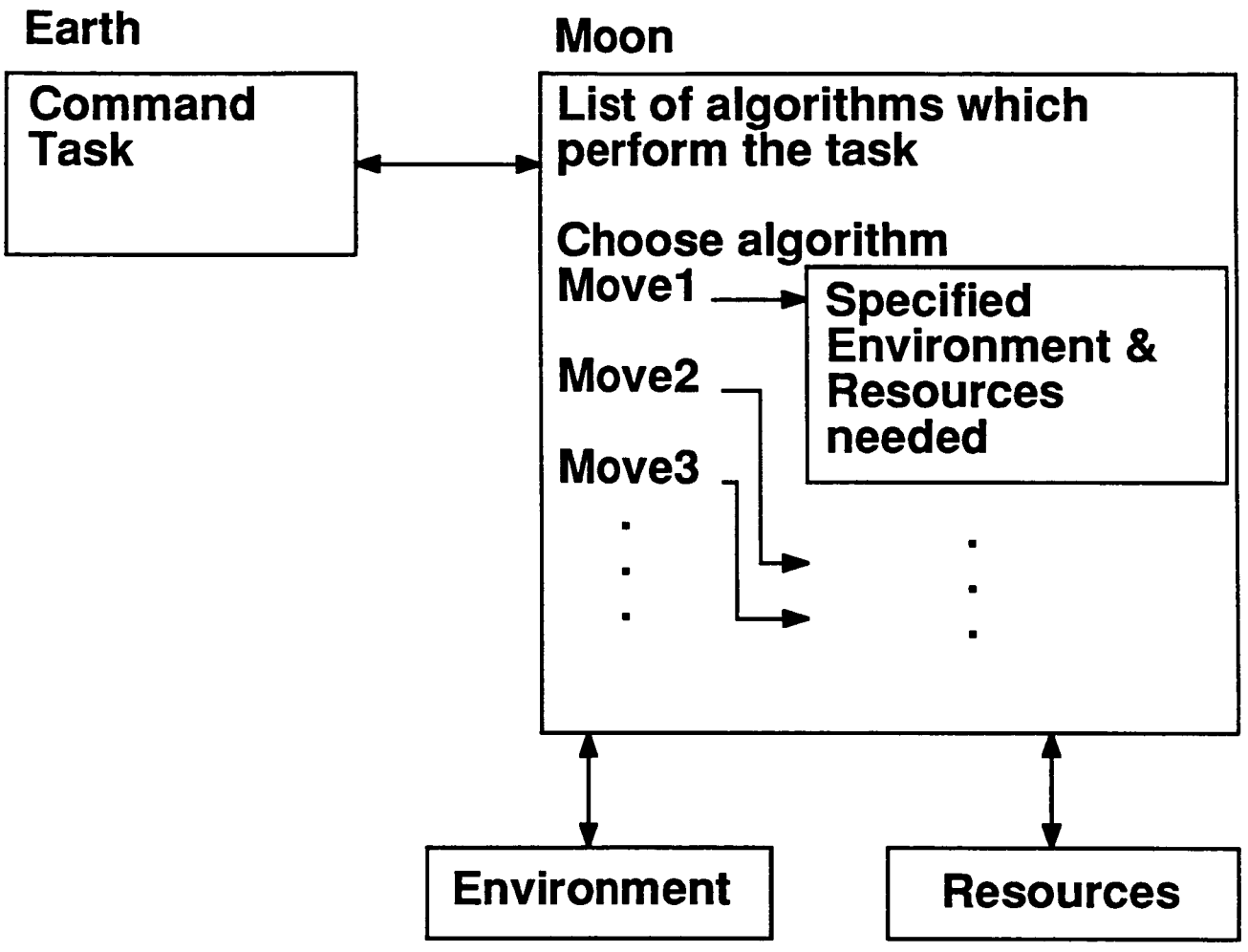
Time Lag Problem



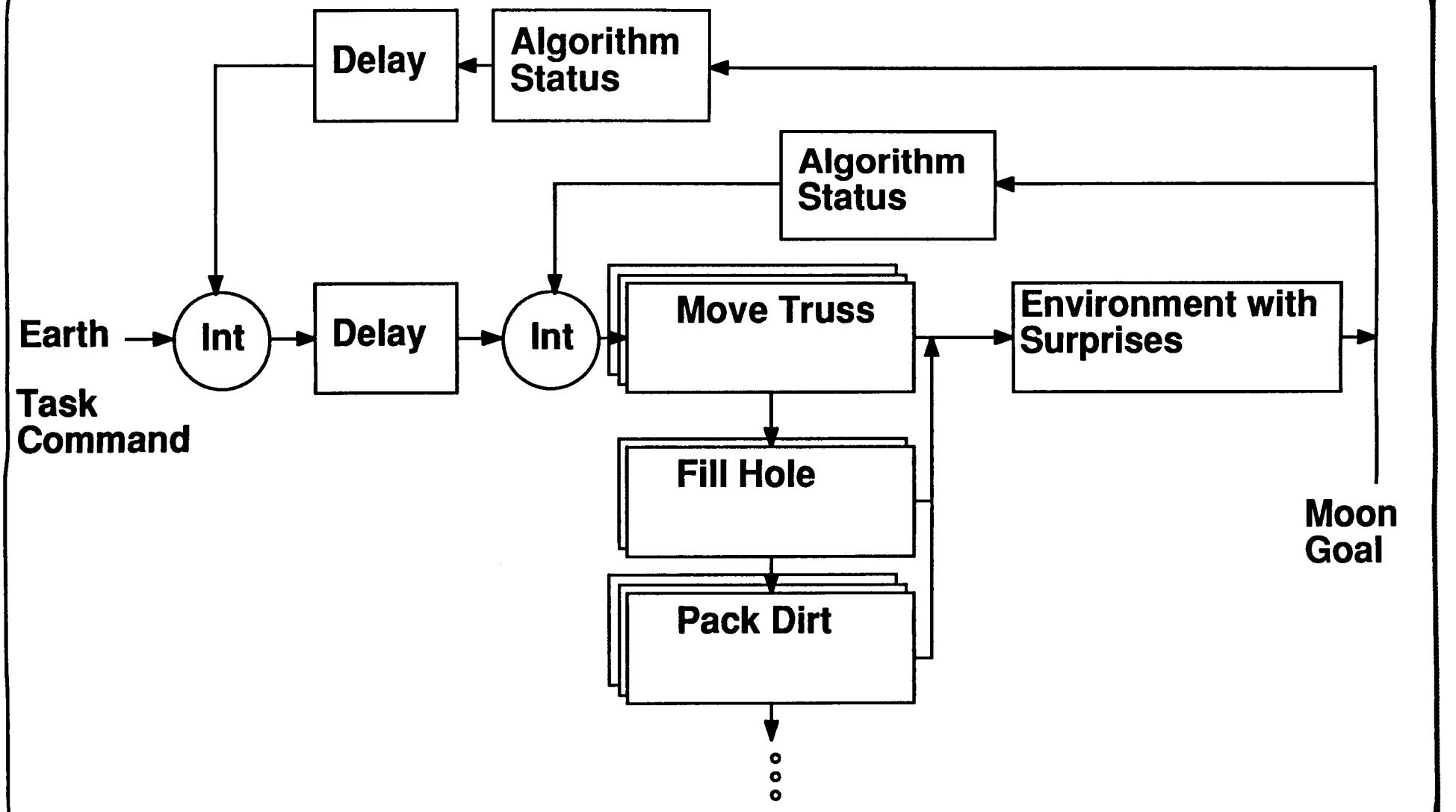
- Basic Centralized Control Assumption
  - Centralized Decision Maker is faster than the reaction time of the Moon Robots.

- Case for Decentralized Control
  - An Earth based Decision Maker cannot make decisions at a rate which is faster than the reaction time of the Moon based robots due to the communications time-lag.

Solution to the Time-lag Problem



Control System Structure



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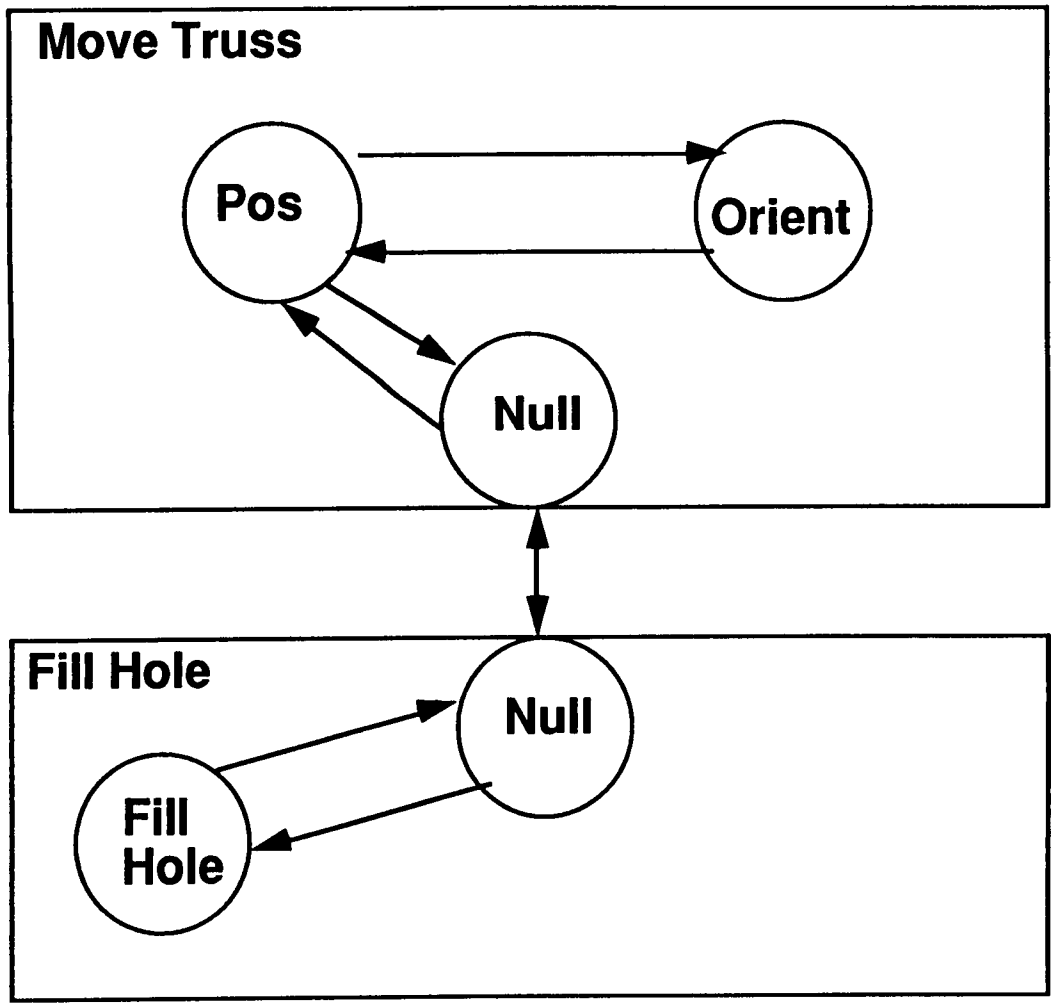
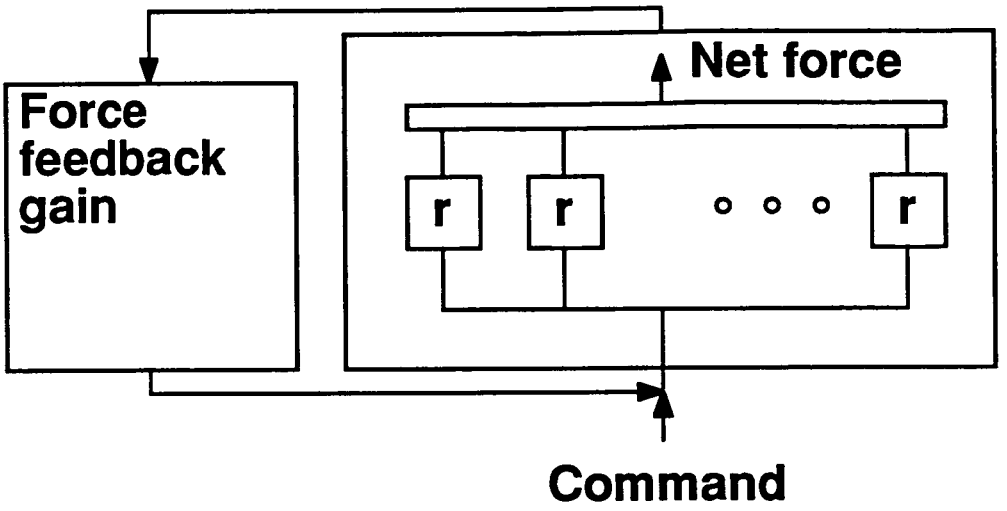
Task Decomposition in Terms of Finite State Machines



Reliability

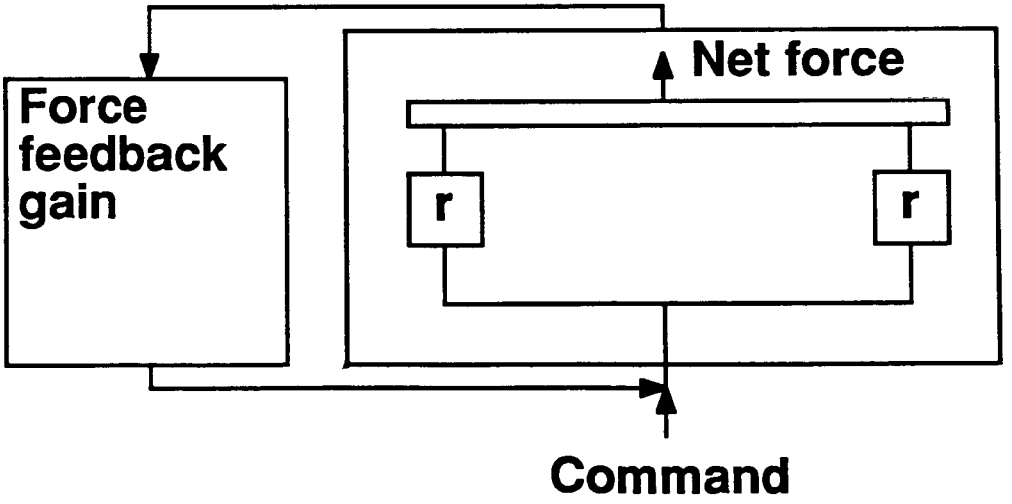
More Reliable

Multiple Robot Approach

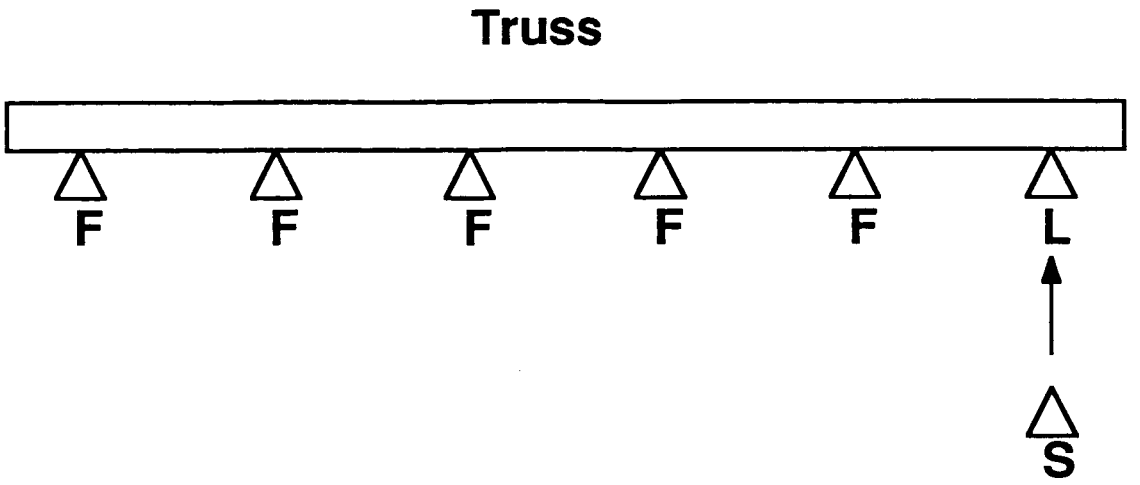


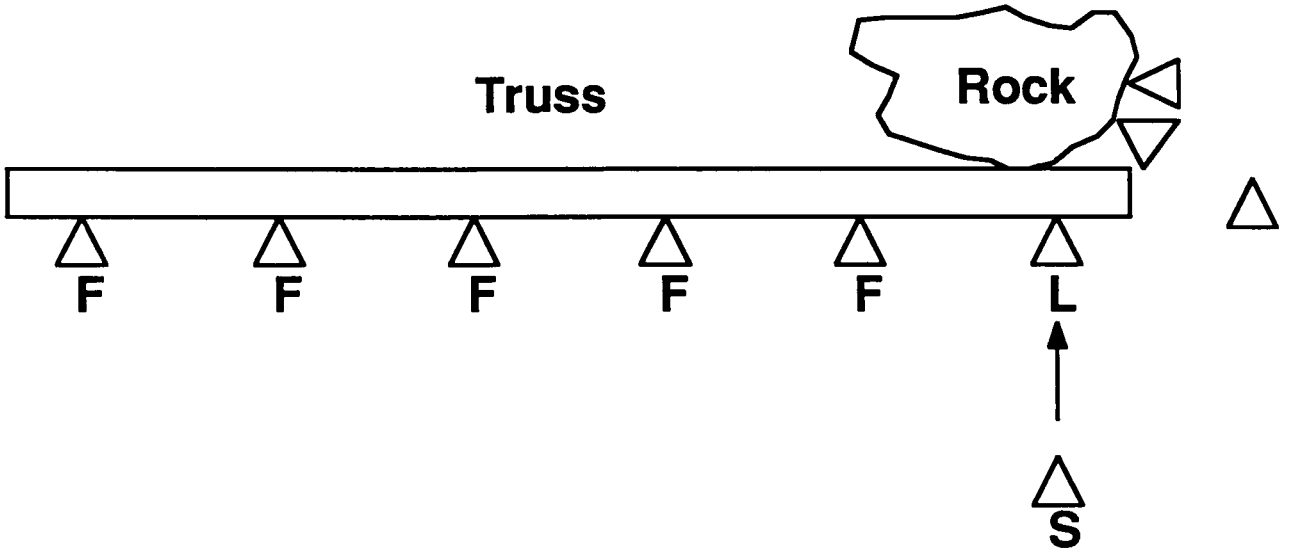
Less Reliable

Two Robot Approach



Example - Move Truss





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MODELLING MACHINE ENSEMBLES WITH DISCRETE EVENT DYNAMICAL SYSTEM THEORY

Dan Hunter

Discrete Event Dynamical System (DEDS) theory can be utilized as a control strategy for future complex machine ensembles that will be required for in-space construction. The control strategy involves orchestrating a set of interactive submachines to perform a set of tasks for a given set of constraints such as minimum time, minimum energy or maximum machine utilization. Machine ensembles can be hierarchically modelled as a global model that combines the operations of the individual submachines. These submachines are represented in the global model as local models.

Local models, from the perspective of DEDS theory, are described by a set of system and transition states, an event alphabet that portrays actions that takes a submachine from one state to another, an initial system state, a partial function that maps the current state and event alphabet to the next state, and the time required for the event to occur. Each submachine in the machine ensemble is represented by an unique local model.

The global model combines the local models such that the local models can operate in parallel under the additional logistic and physical constraints due to submachine interactions. The global model is constructed from the states, events, event functions, and timing requirements of the local models. Supervisory control can be implemented in the global model by various methods such as task scheduling (open-loop control) or implementing a feedback DEDS controller (closed-loop control).

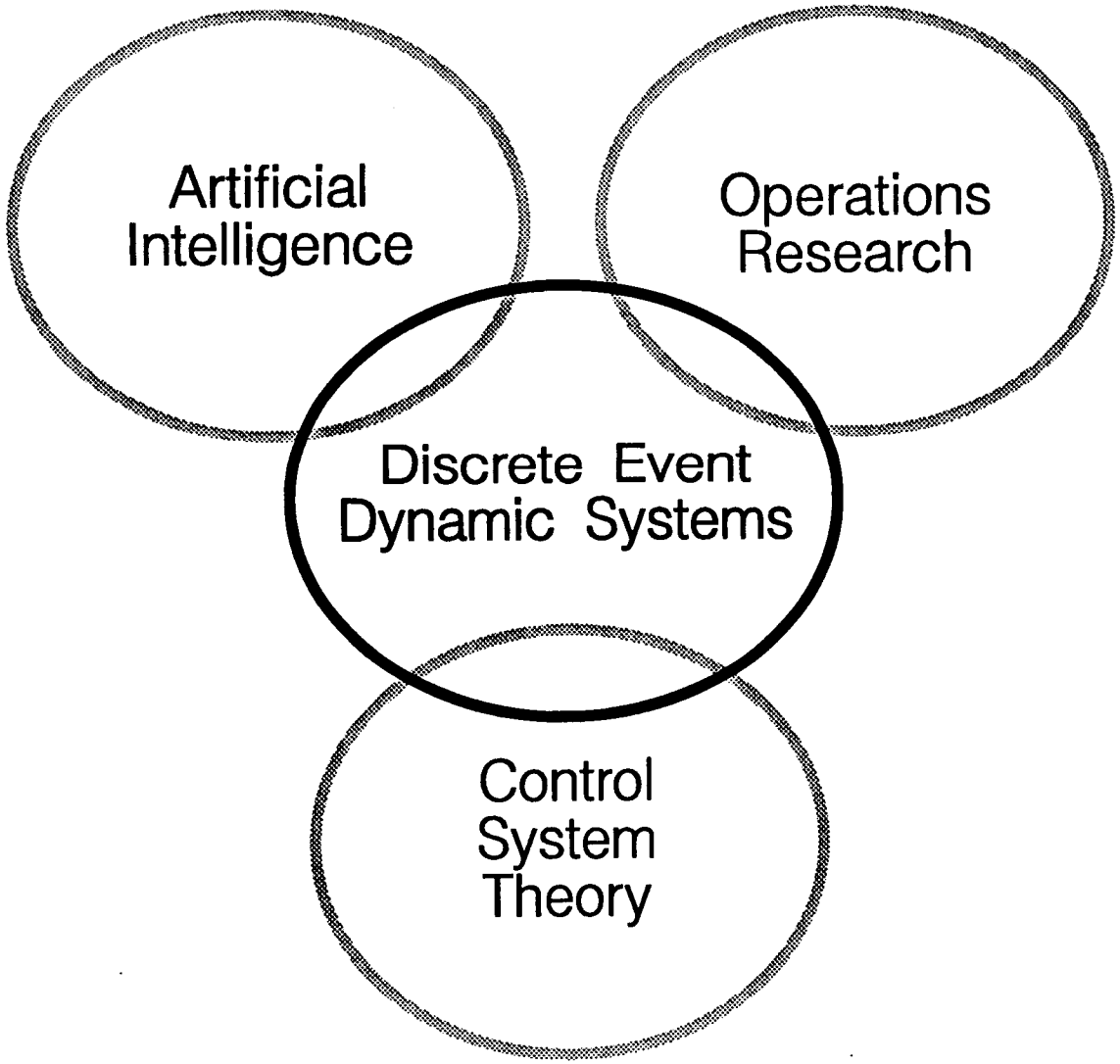
Modelling Machine Ensembles with Discrete Event Dynamic System Theory

Dan Hunter

Discrete Event Dynamic Systems (DEDSs)

* Data Compression Technique
* Used to describe man-made dynamic systems which cannot be satisfactorily described by ordinary or partial differential equations
* Suitable for supervisory teleoperations (narrow communication bandwidth, symbolic commands)
* The system's "states" change only at discrete instants of time
* The evolution of the system depends on the occurence and timing of various discrete events
* No widely accepted formalism

Relation of DEDS to Other Technical Fields



Discrete Event Dynamic Models (DEDMs)

* Formalism based on Extended State Machine Theory of Wonham

* Objective: To model DEDSs in a simple framework suitable for analysis

Approach:

- Break complex machines into an ensemble of simple submachines

- Model the simple submachines as local DEDMs

- Combine the local models into a global model that correctly models the complex machine

Local Models

$G = (Q, \Sigma, qo, \delta)$

where Q = set of states

Σ = event alphabet

q_o = initial state

δ = mapping: $Q \times \Sigma \rightarrow Q \cup \phi$ (ϕ = invalid state)

with null event ε: $\varepsilon \in \Sigma$, $\delta(q_i,\varepsilon) = q_i$

Note: $\delta(\sigma_i,q_i) = q_{i+1}$ can be extended to a string $\sigma = \sigma_1\sigma_2...\sigma_n$.
That is, if $\delta(\delta(q_{i-1},\sigma_{i-1}),\sigma_i) = q_{i+1}$ for $i=1,2,...,n$, then

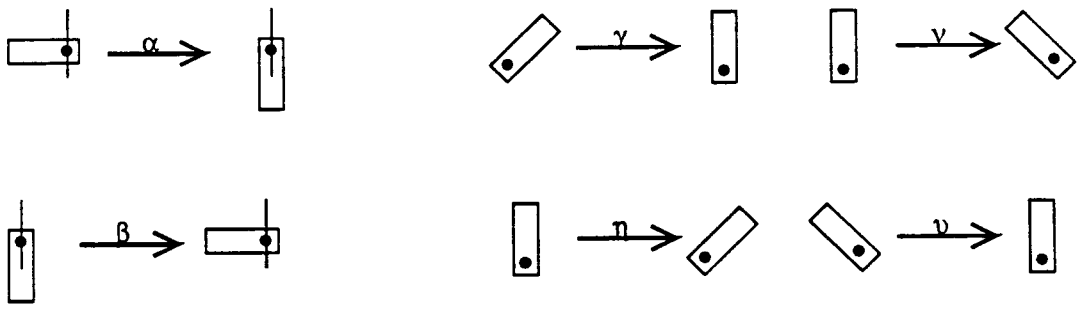
$$\delta(\sigma,q_1) = q_{n+1}$$

Local Models for a 2-Link Leg

Machine 1 (Lower leg) | Machine 2 (Upper leg)

States

Events



Notation

$Q1 = \{a,b\}$

$\Sigma 1 = \{\alpha,\beta\}$

$\delta(a,\alpha) = b$

$\delta(b,\beta) = a$

$\delta(a,\beta) = \phi$

$\delta(b,\alpha) = \phi$

$Q2 = \{j,k,l\}$

$\Sigma 2 = \{\gamma,\varphi,\eta,\nu,\upsilon,\varpi\}$

$\delta(j,\gamma) = k \quad \delta(k,\nu) = l$

$\delta(k,\eta) = j \quad \delta(l,\upsilon) = k$

All (event,state) pairs not mentioned lead to invalid states ϕ

Global Models

* Vector combination of Local Models

$$\underline{Q} = Q^1 \times Q^2 \times \ldots \times Q^n$$

$$\underline{\Sigma} = \Sigma^1 \times \Sigma^2 \times \ldots \times \Sigma^n$$

$$\underline{q_0} = [q_0^1, q_0^2, \ldots, q_0^n]^T$$

$$\underline{\delta} = \underline{Q} \times \underline{\Sigma} \rightarrow \underline{Q} \cup \underline{\phi} \qquad (\underline{\phi} = \text{invalid state vector})$$

* Difficulty: Determining invalid global states (conflicts) due to machine interaction conflicts. Approaches include:

  - Discovering physical conflicts using a Block World concept

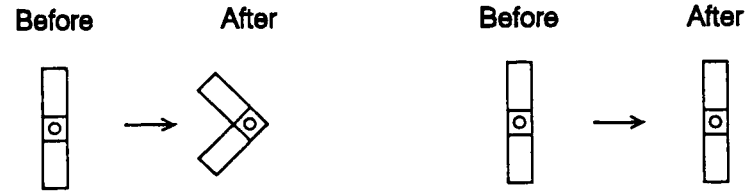
  - Discovering Machine/Environment conflicts using a Rule Based System based on known facts

Global Model for a 2-Legged Machine (Contains 4 Local Models)

Notation	Left Foot	Right Foot

$\delta(q1,\sigma1) = q2$

$$\begin{array}{l} \text{Left} \\ \text{Right} \end{array} \left\{ \begin{array}{c} \begin{bmatrix} b \\ k \end{bmatrix} \begin{bmatrix} \beta \\ \nu \end{bmatrix} \\ \begin{bmatrix} b \\ k \end{bmatrix} \begin{bmatrix} \varepsilon \\ \varepsilon \end{bmatrix} \end{array} \right. \quad \begin{bmatrix} a \\ l \\ b \\ k \end{bmatrix}$$



$\delta(q2,\sigma2) = q3$

$$\begin{array}{l} \text{Left} \\ \text{Right} \end{array} \left\{ \begin{array}{c} \begin{bmatrix} a \\ l \end{bmatrix} \begin{bmatrix} \alpha \\ \varepsilon \end{bmatrix} \\ \begin{bmatrix} b \\ k \end{bmatrix} \begin{bmatrix} \varepsilon \\ \varepsilon \end{bmatrix} \end{array} \right. \quad \begin{bmatrix} b \\ l \\ b \\ k \end{bmatrix}$$

$\delta(q3,\sigma3) = q4$

$$\begin{array}{l} \text{Left} \\ \text{Right} \end{array} \left\{ \begin{array}{c} \begin{bmatrix} b \\ l \end{bmatrix} \begin{bmatrix} \varepsilon \\ \varepsilon \end{bmatrix} \\ \begin{bmatrix} b \\ k \end{bmatrix} \begin{bmatrix} \varepsilon \\ \eta \end{bmatrix} \end{array} \right. \quad \begin{bmatrix} b \\ l \\ b \\ j \end{bmatrix}$$

$\delta(q4,\sigma4) = q5$

$$\begin{array}{l} \text{Left} \\ \text{Right} \end{array} \left\{ \begin{array}{c} \begin{bmatrix} b \\ l \end{bmatrix} \begin{bmatrix} \varepsilon \\ \upsilon \end{bmatrix} \\ \begin{bmatrix} b \\ j \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \end{bmatrix} \end{array} \right. \quad \begin{bmatrix} b \\ k \\ a \\ k \end{bmatrix}$$

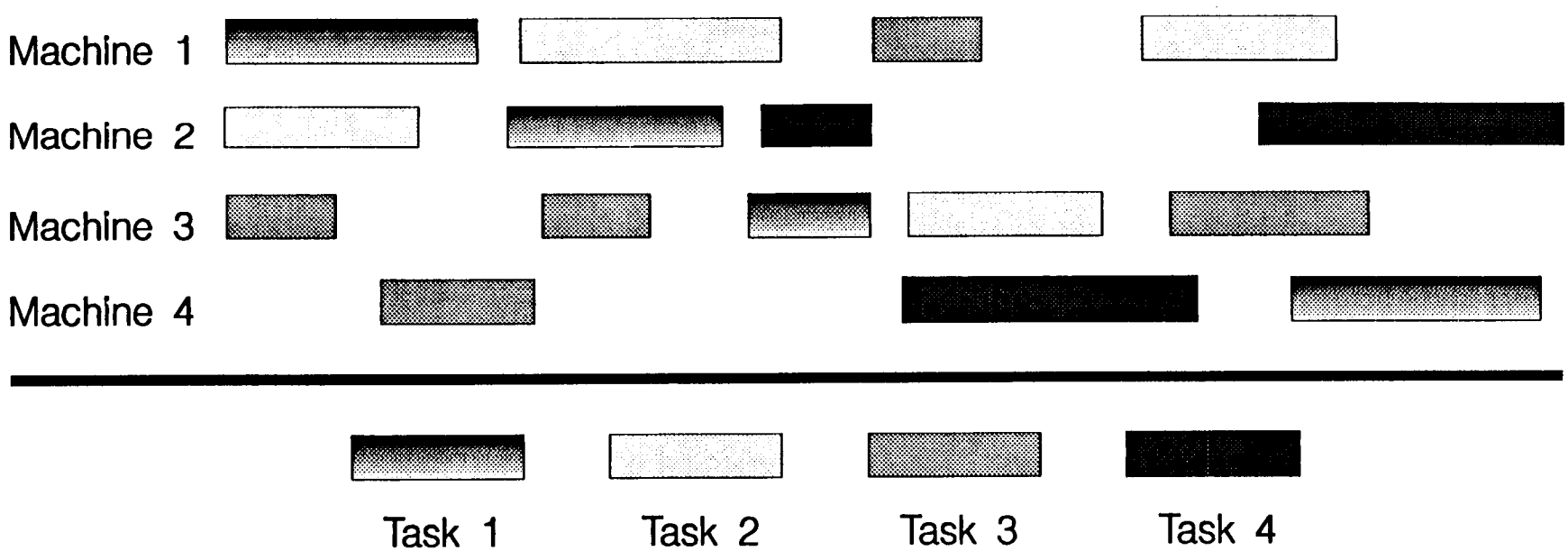
$\delta(q5,\sigma5) = q6$

$$\begin{array}{l} \text{Left} \\ \text{Right} \end{array} \left\{ \begin{array}{c} \begin{bmatrix} b \\ k \end{bmatrix} \begin{bmatrix} \varepsilon \\ \varepsilon \end{bmatrix} \\ \begin{bmatrix} a \\ k \end{bmatrix} \begin{bmatrix} \alpha \\ \varepsilon \end{bmatrix} \end{array} \right. \quad \begin{bmatrix} b \\ k \\ b \\ k \end{bmatrix}$$

Walking Sequence: $\delta(q1,\sigma) = q6 = q1$ where $\sigma = \sigma1\sigma2\sigma3\sigma4\sigma5$

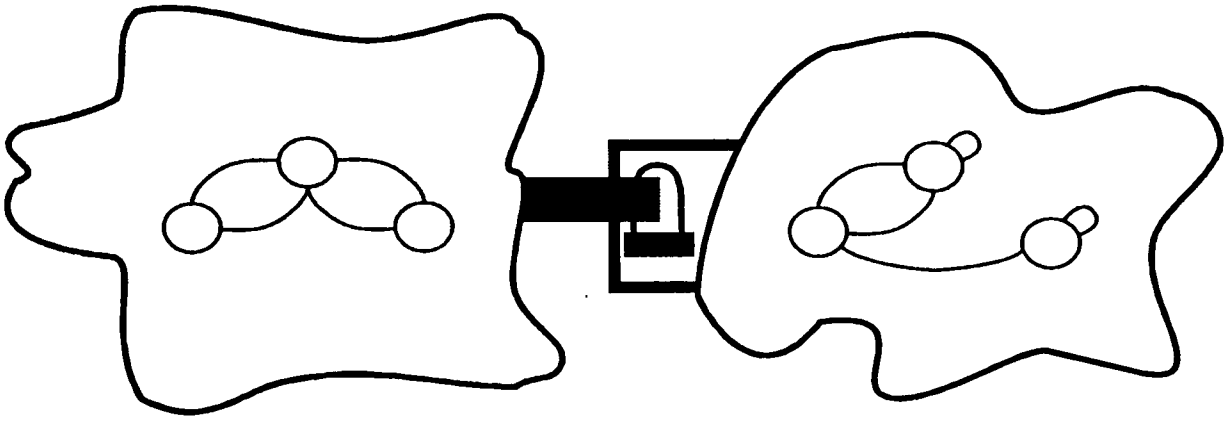
DEDS Control Strategy #1: Task Scheduling

* Operations Research Approach
  - Open Loop
  - Signal conditioning
* Scheduling is based upon the DEDS global model



DEDS Control Strategy #2: Feedback DEDS Controller

* Control System Theory Approach
    - Closed Loop
    - Structure modification
        - Controllability & Reachability
* Lock the Global Model and Controller thru event synchronization to synthesize a new DEDS model that has the desired structure



Controller Global DEDM

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FUZZY LOGIC CONTROLLER (FLC)

Leo Wang†

The purpose of using FLC originally is to replace human operators in some control task. The presentation gives brief introduction of fuzzy logic controller and the related concepts in fuzzy sets.

Fuzzy modelling is a process of system identification by using a model of fuzzy structure. Representation capability of fuzzy modelling in nonlinear function approximation is shown by mathematical analysis. General conclusions and results of simulation example will be given.

Finally, configuration of a fuzzy adaptive controller and the adaptive control algorithms will be presented, accompanied with simulation results of example in which a nonlinear plant is controlled by the proposed fuzzy adaptive controller to do the model-following.

† Department of Electrical Engineering, University of Colorado

SYMBOLIC MODELLING & CONTROL USING FUZZY LOGIC

(Leo Wang)

PROBLEMS :

1. HOW TO DESCRIBE NUMERICAL DYNAMIC SYSTEMS BY SYMBOLIC TERMS ?

2. HOW TO DEVELOP RULE-BASED CONTROL LOGIC ?

APPROACHES :

1. USING FUZZY LOGIC TO TRANSFORM NUMERICAL DATA INTO SYMBOLIC DATA

2. USING ADAPTIVE TECHNIQUES TO DERIVE RULES FROM HUMAN OPERATORS AND/OR DIRECT INPUT -OUTPUT DATA

FUZZY LOGIC
WHAT, WHY & HOW

Fuzzy set A set whose members have graded memberships.

Fuzzy logic logic system which represents a class of objects by the membership grading in the reference fuzzy sets.

Why fuzzy logic -> Approximate reasoning

Bring reasoning mechanism closer to human thinking

Fuzzy Modelling

IF $x(k)$ is *small* and $\dot{x}(k)$ is *negative medium*
THEN $x(k+1)$ is *negative small*

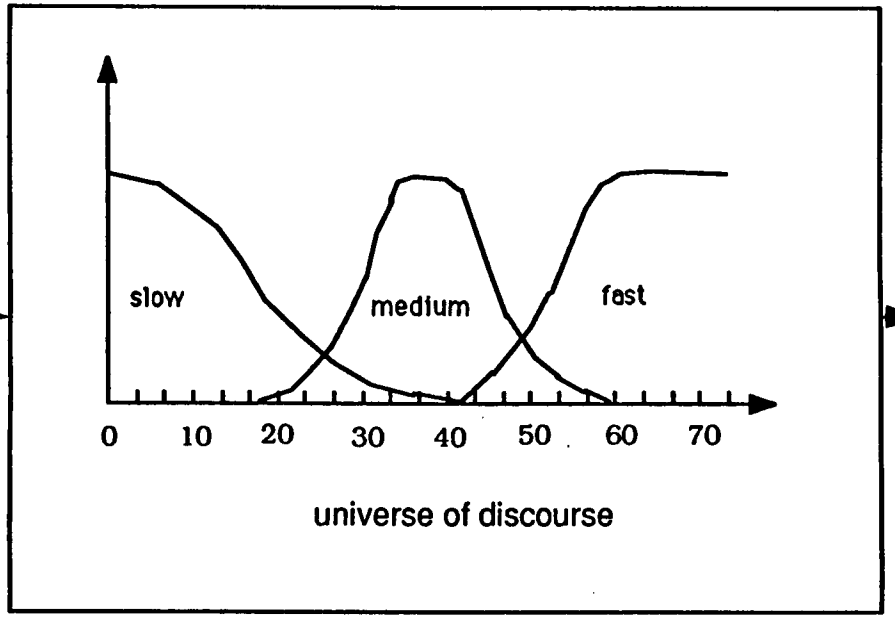
Fuzzy Logic Controller

IF $e(k)$ is *negative small* and $\dot{e}(k)$ is *near zero*
THEN $u(k+1)$ is *positive small*

ASSIGNMEMT OF MEMBERSHIP FUNCTIONS

speed of vehicle

v = 30 mph



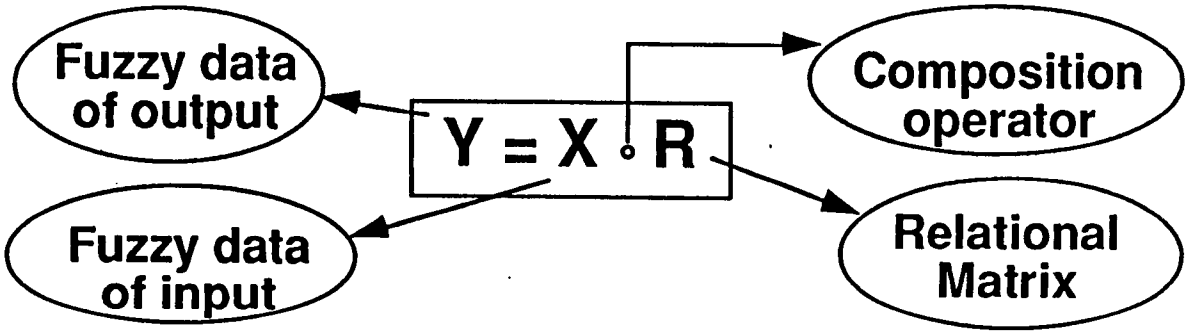
Symbolic data

[0.1,0.8,0]

FUZZIFICATION

IF v is slow THEN u is large increment

FUZZY MODELLING BY RELATIONAL EQUATION



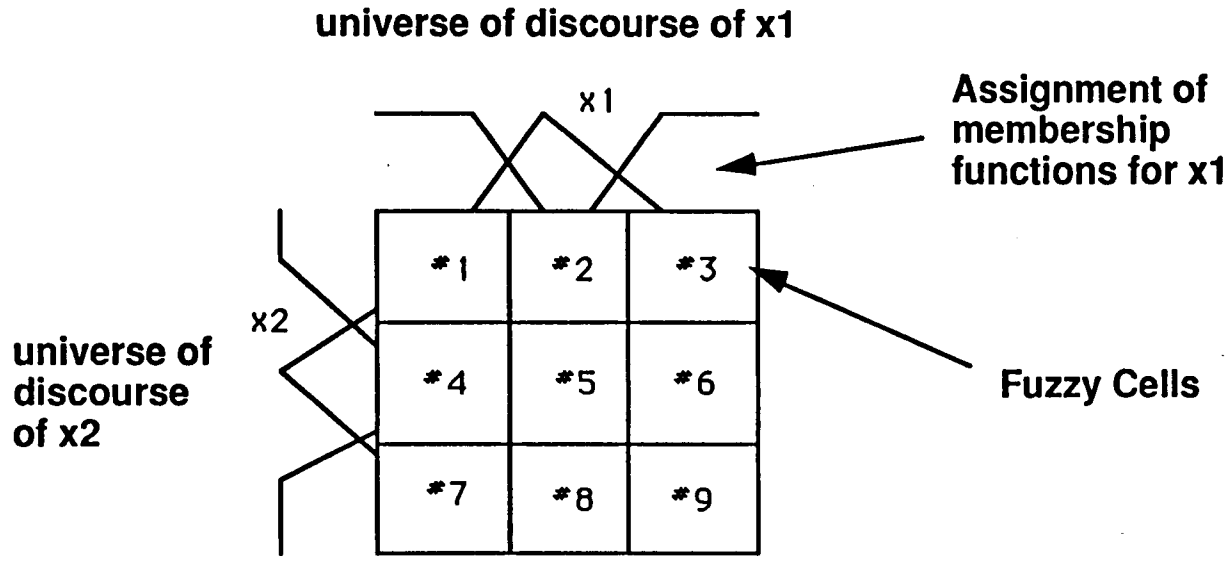
IF x is A1 THEN y is B1
IF x is A2 THEN y is B2

$$R = \begin{bmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{bmatrix}$$

$$R = \begin{bmatrix} 0.9 & 0.1 \\ 0.3 & 0.6 \end{bmatrix}$$

IF x is A1 THEN y is B1 with certainty 0.9
IF x is A1 THEN y is B2 with certainty 0.1
IF x is A2 THEN y is B1 with certainty 0.3
IF x is A2 THEN y is B2 with certainty 0.6

FUZZY MODELLING BY RULES OF INTERNAL FUNCTIONS



membership functions representing specific linguistic variables

Rules

If (x_1 is A_1^i) and ... and (x_k is A_k^i)
Then $y^i = f^i(x_1, x_2, \ldots, x_k)$

internal functions of premise variables

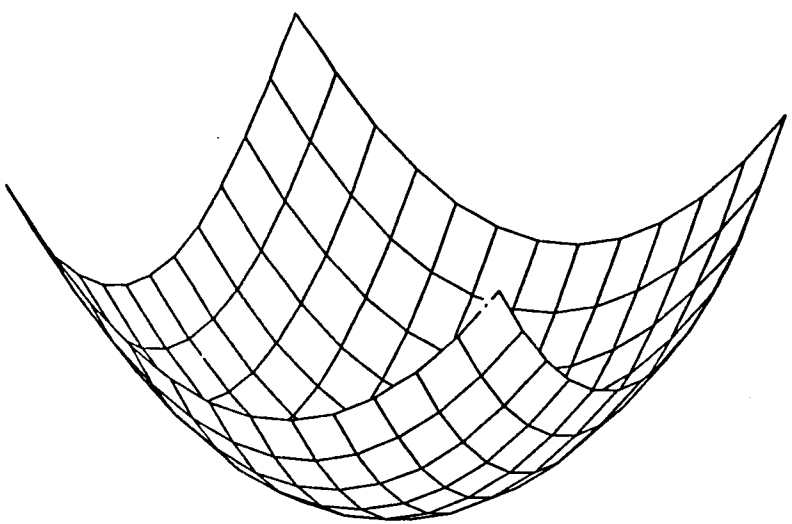
Final output

$$y = \frac{\sum_{i=1}^{n} (A_1^i(x_1) \wedge \ldots \wedge A_k^i(x_k))\, f^i(x_1, \ldots, x_k)}{\sum_{i=1}^{n} (A_1^i(x_1) \wedge \ldots \wedge A_k^i(x_k))}$$

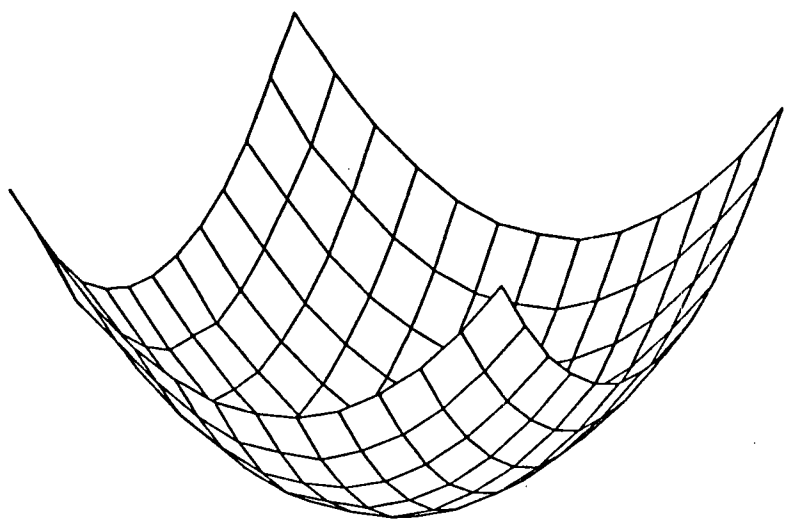
EXAMPLE OF FUZZY MODELLING

$$f(x1, x2) = x1^2 + x2^2$$

True function values

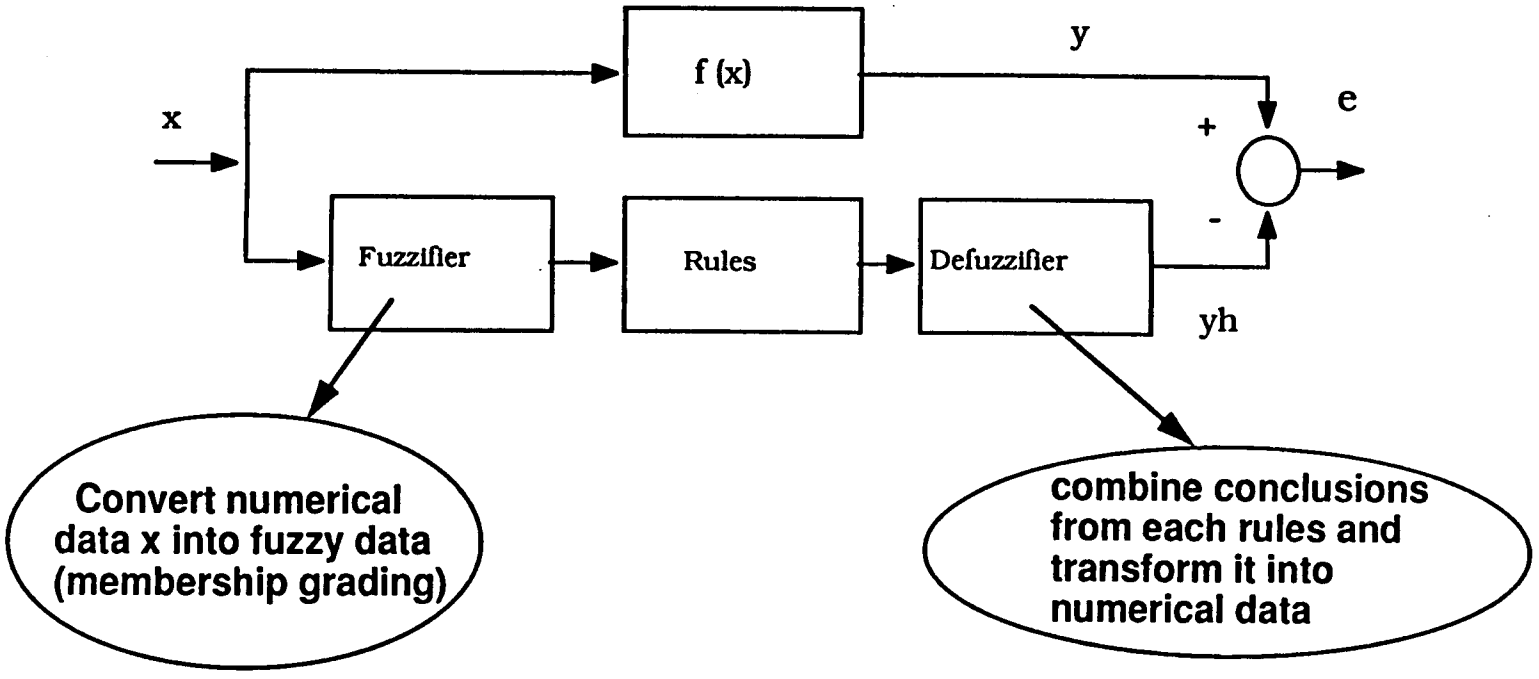


Estimated function values from fuzzy model



FUZZY MODELLING

Process of modelling the behaviors of system by fuzzy relations



RULE-BASED CONTROLLER
&
FUZZY LOGIC CONTROLLER

Rule-based Controller (RBC)

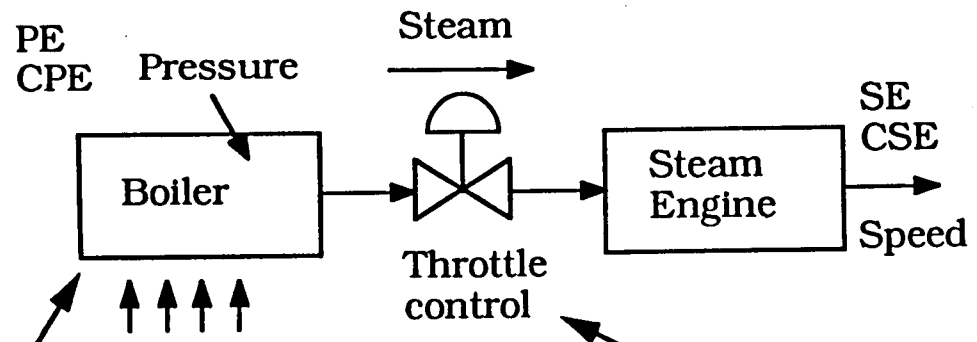
Controller who uses sets of rules to make control decisions. The rules have the form

IF conditions THEN actions

Fuzzy Logic Controller (FLC)

A RBC whose conditions and actions in rules are defined in fuzzy sets.

EXAMPLE
ENGINE SPEED CONTROL BY FLC



IF SE=NB, CSE=not(NB or NM)
THEN TC=PB

IF PE=NB, CPE=not(NB or NM)
THEN HC=PB

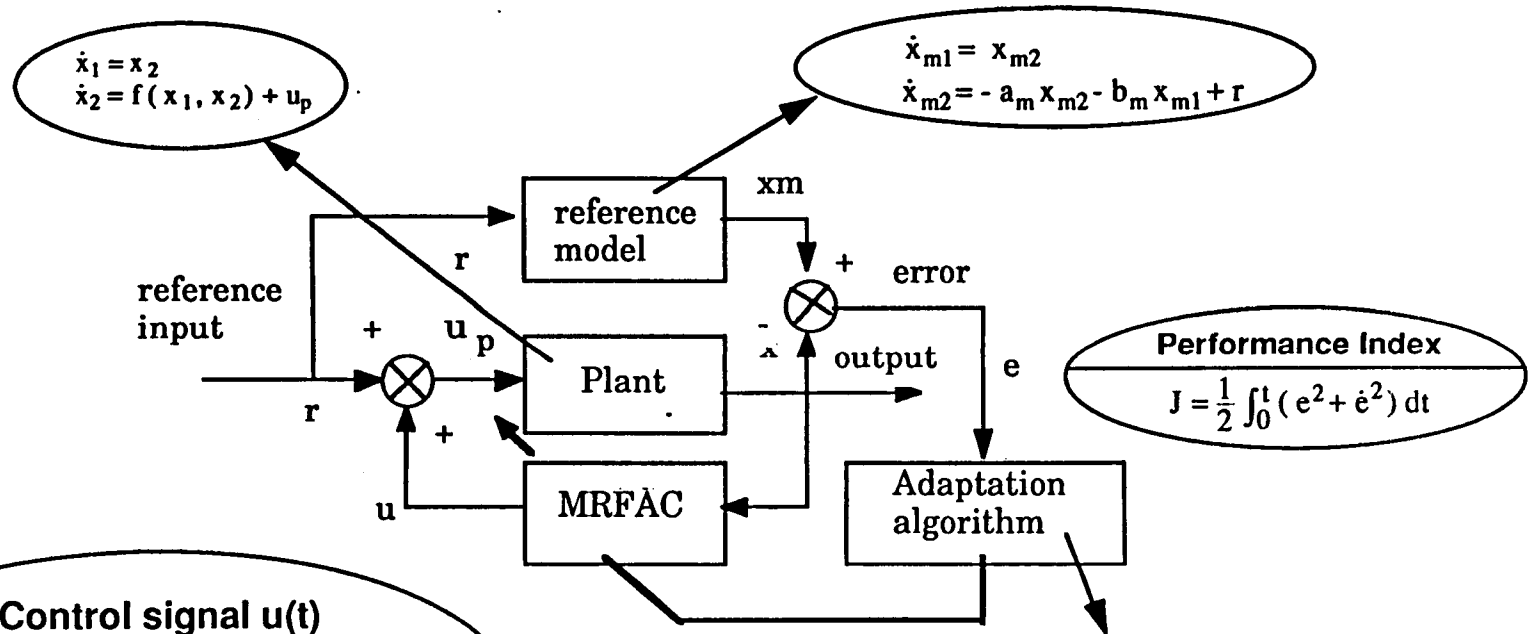
IF PE=NS, CPE=(PS or NZ)
THEN HC=PM

N=negative,P=positive,NZ=near zero
B=Big, M=Medium,S=Small

PE=pressure error, CPE=change of PE
SE=speed error, CSE=change of SE

Sample rules acquired from experienced operators

MODEL-REFERENCE FUZZY ADAPTIVE CONTROLLER



Performance Index

$$J = \frac{1}{2}\int_0^t (e^2 + \dot{e}^2)\,dt$$

Control signal u(t)

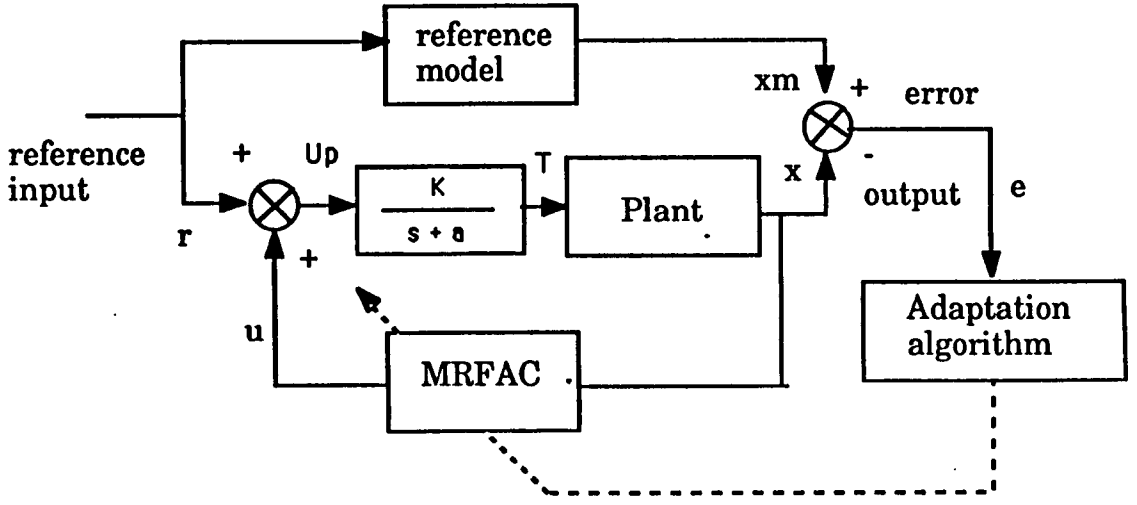
$$u = \frac{\sum_{s=1}^{n}\left[(A_1^s(x_1) \wedge A_2^s(x_2))(p_0^s + p_1^s x_1 + p_2^s x_2)\right]}{\sum_{s=1}^{n} A_1^s(x_1) \wedge A_2^s(x_2)}$$

Laws of parameters adaptation

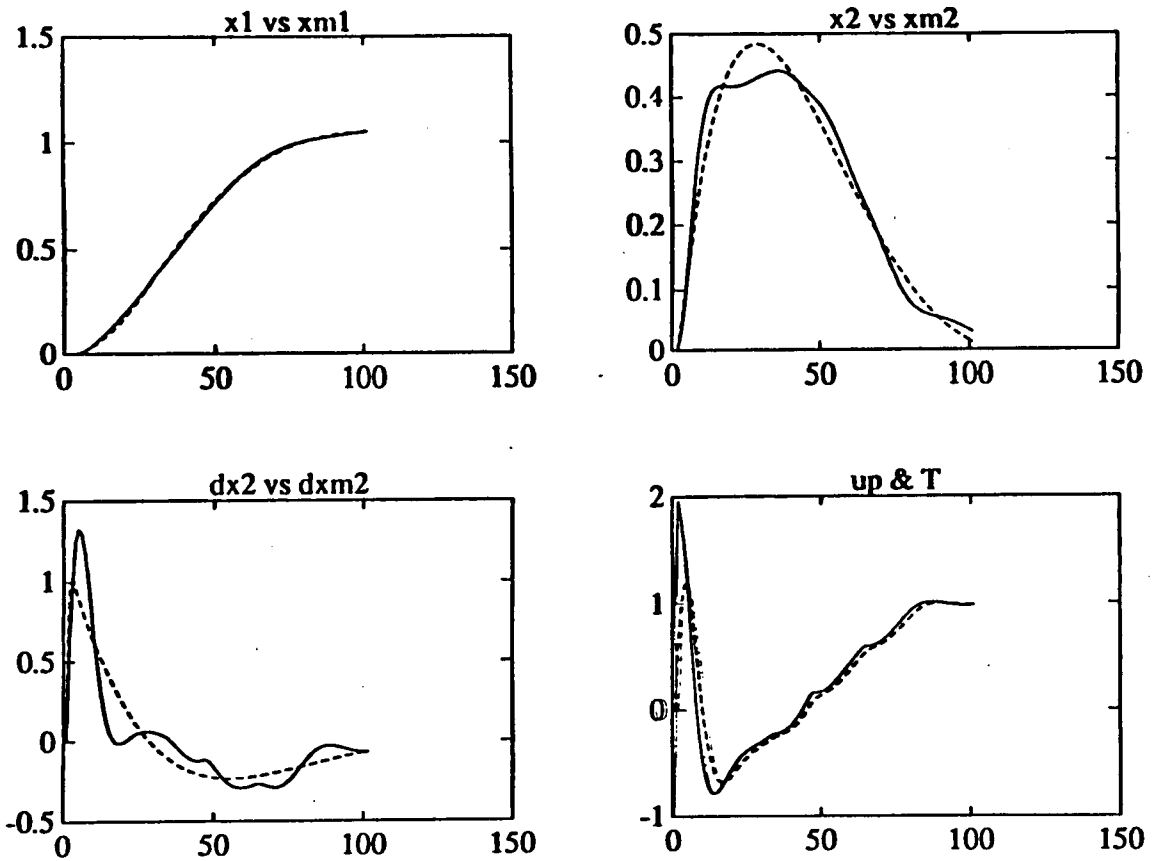
$$p^i_{n,new} = p^i_{n,old} - \alpha_n \frac{\partial J}{\partial p^i_n}$$

$$\frac{\partial J}{\partial p^i_0} = -e \int\int \frac{(A_1^i(x_1) \wedge A_2^i(x_2))}{\sum_{s=1}^{n}(A_1^s(x_1) \wedge A_2^s(x_2))}\,dt_1 dt_2 - \dot{e}\int \frac{(A_1^i(x_1) \wedge A_2^i(x_2))}{\sum_{s=1}^{n}(A_1^s(x_1) \wedge A_2^s(x_2))}\,dt_1$$

EXAMPLE OF MODEL-REFERENCE FAC



SIMULATION RESULT OF EXAMPLE



Session Six

C^3 CONSTRUCTION ENVIRONMENT

Randal Davis,
Chair

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RESEARCH INTO COMMAND, CONTROL AND COMMUNICATIONS IN SPACE CONSTRUCTION

Randal Davis

Coordinating and controlling large numbers of autonomous or semi-autonomous robot elements in a space construction activity will present problems that are very different from most command and control problems we encounter in the space business. As part of our research into the feasibility of robot constructors in space, the CSC Operations Group is examining a variety of command, control and communications (C^3) issues. Two major questions being asked are: can we apply C^3 techniques and technologies already developed for use in space; and are there suitable terrestrial solutions for extraterrestrial C^3 problems? This presentation provides an overview of the control architectures, command strategies and communications technologies that we are examining and describes plans for simulations and demonstrations of our concepts.

Research on Command, Control and Communications in Space Construction

- Key Technical Areas Addressed
- Focusing Our Expertise on the Design of Robot Constructors
- Activities During the Past Year

Key Technical Areas Addressed

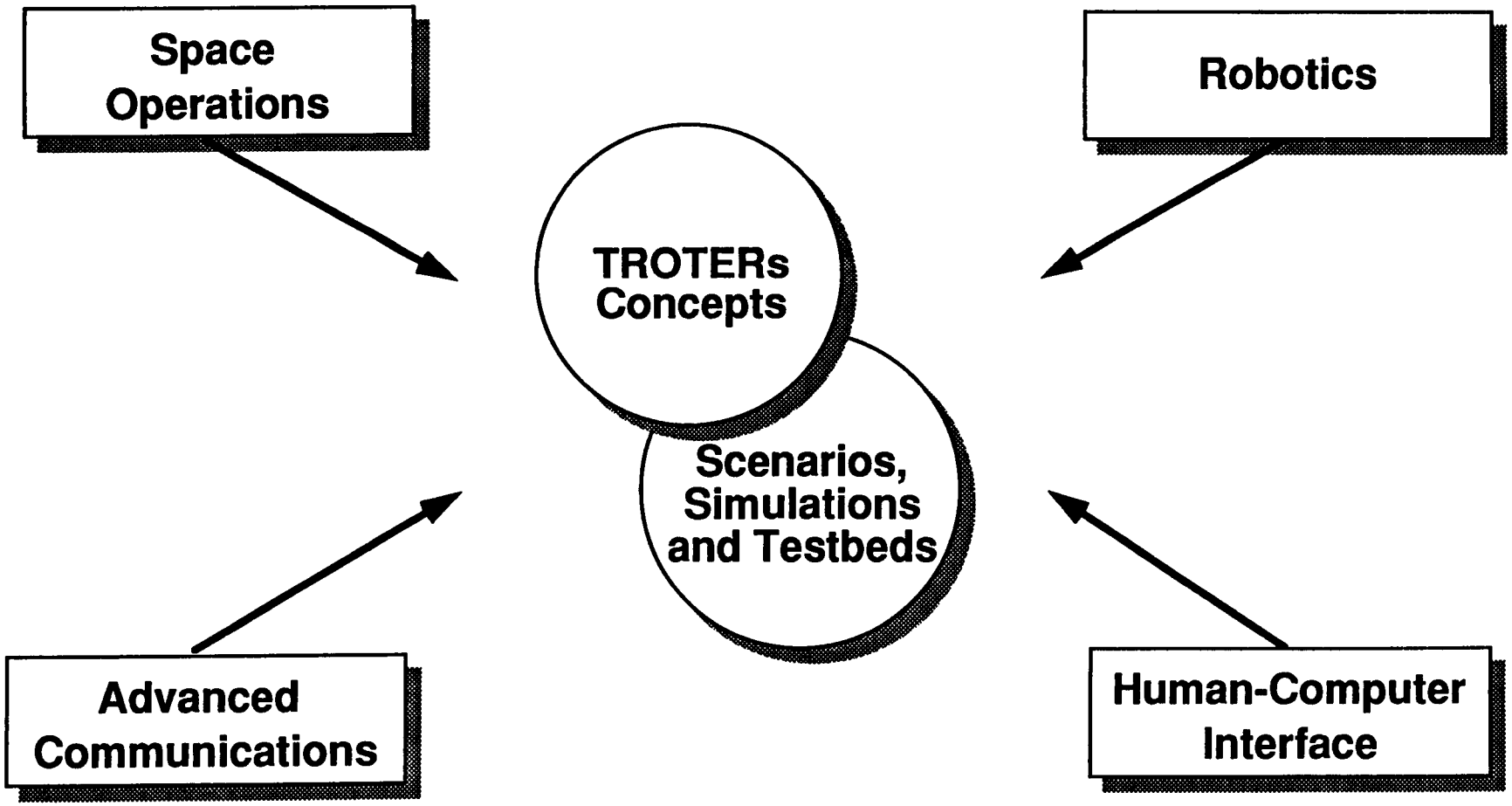
Communications

- Space-to-Earth Communications During Construction
- Communications Between Robots and Humans
- Wireless Communications Between Robot Workers
- Communications Between the Components of a Robot

Command and Control

- Multi-tiered Control
- Definition of Tasks for Execution By Robots
- Human Supervision of the Robot Ensemble
- Coordination Between Cooperating Robots
- Teleoperations Techniques

Focusing Our Expertise on the Design of Robot Constructors



Activities During the Past Year (1)

- TROTERs Concept Development
  - Key requirements of TROTERs defined and research issues identified
  - Simple operations tasks demonstrated through simulations and testbed
  - Scenarios developed for more advanced capabilities

- Human-Computer Interface
  - Developed a control system for the Scorbot robot using CU's OASIS teleoperations software and GSFC's TAE+ user interface package
  - Adapted the NoPumpG direct manipulation human-computer interface for use by CSC
    - Has been used in a TROTERs task demonstration

- Teleoperations Techniques
  - Tested MIDI keyboard in Martin Marietta's controller evaluation system

Activities During the Past Year (2)

- Communications
  - Examined application of the Manufacturing Message System (MMS) Protocol to automated devices within space construction projects
    - Applying technology originally developed by our associate CTA for the Space Station Freedom Program
    - Planned for incorporation into our testbed
  - Examining packet radio for communicating between robots

- Command and Control Techniques
  - Working on how to specify tasks for robot constructors and how to expedite the production and verification of task plans
    - Evaluating Space Station User Interface Language as a means for specifying activities to be performed
  - Participating in AIAA Command and Control Working Group
    - With CSC associates CTA, GSFC, JPL, JSC and McDonnell Douglas

Activities During the Past Year (3)

- Simulations and Testbeds
  - Evaluation of robot simulator software packages completed
    - CimStation package from Silma selected, procured and integrated into our testbed
  - Using CimStation models of Flight Telerobotics Servicer from Martin Marietta for research into Space Station assembly
  - Added CimStation to remote control test of LaRC dual-arm robot
    - Demonstrating that simulation has a useful role in monitoring construction operations
  - Developed object-oriented simulation of TROTERS
  - Produced train demonstration of TROTERS concepts
  - Added vision system to Scorbot robot for research into vision-guided manipulation

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MODELLING ROBOT CONSTRUCTION SYSTEMS

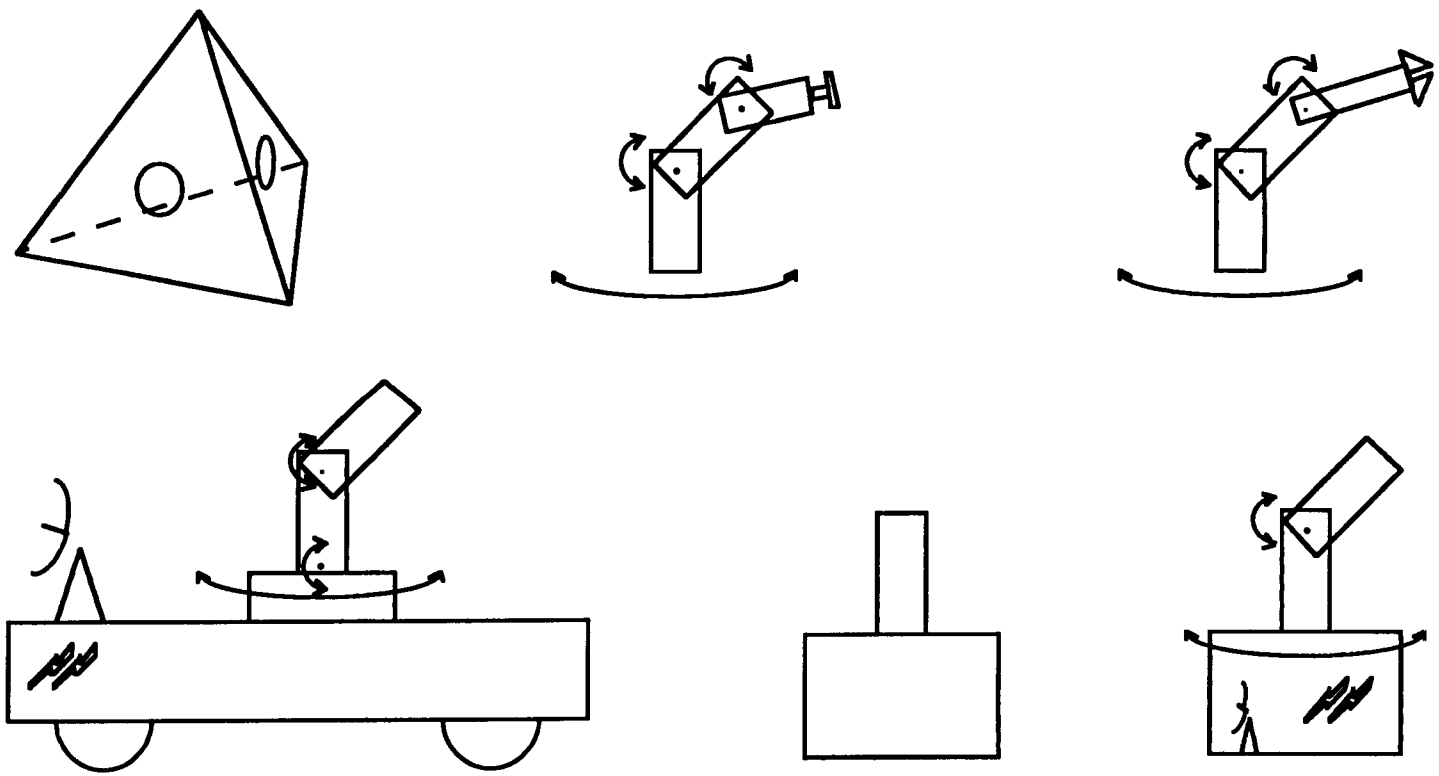
Chris Grasso

TROTERs are small, inexpensive robots that can work together to accomplish sophisticated construction tasks. To understand the issues involved in designing and operating a team of TROTERs, the robots and their components are being modeled. This presentation introduces a TROTER system that features standardized component behavior. An object-oriented model implemented in the Smalltalk programming language is described and the advantages of the object-oriented approach for simulating robot and component interactions are discussed. The presentation includes preliminary results and a discussion of outstanding issues.

Modelling Robot Construction Systems

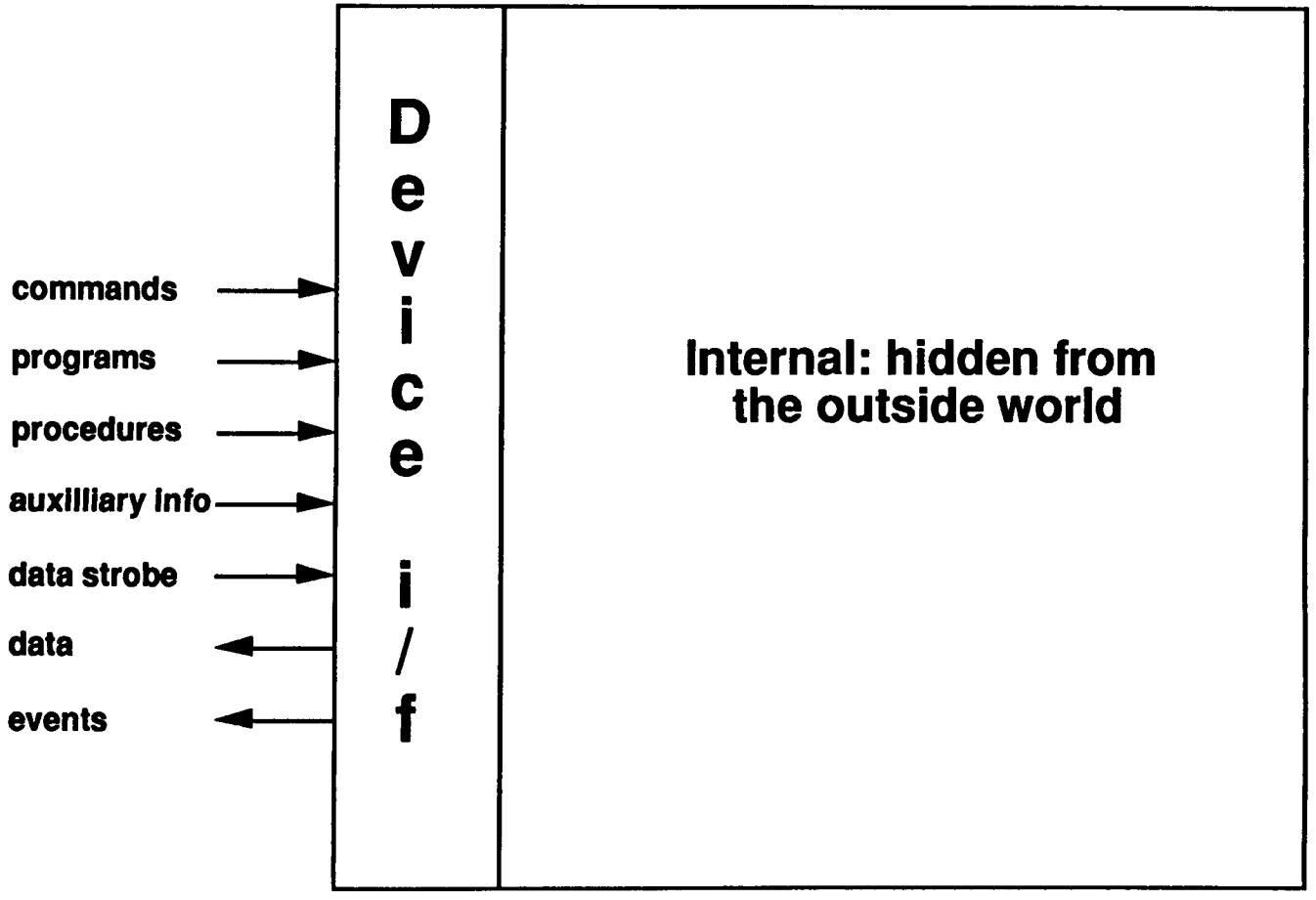
- TROTERs — Team of small, inexpensive robots
- Explore mechanisms for coordinating an ensemble of TROTERs
- Simulate to discover problems and issues to address

Strawman Set of Modular Components



This set of components is used to explore modularity and component interaction. It is not intended as the final form of the TROTER system.

Standard Component Block Diagram



All TROTER components look like this to each other and the outside world.

Object-Oriented Approach

Step 1

Define Classes of Objects

Hierarchical definition of capabilities

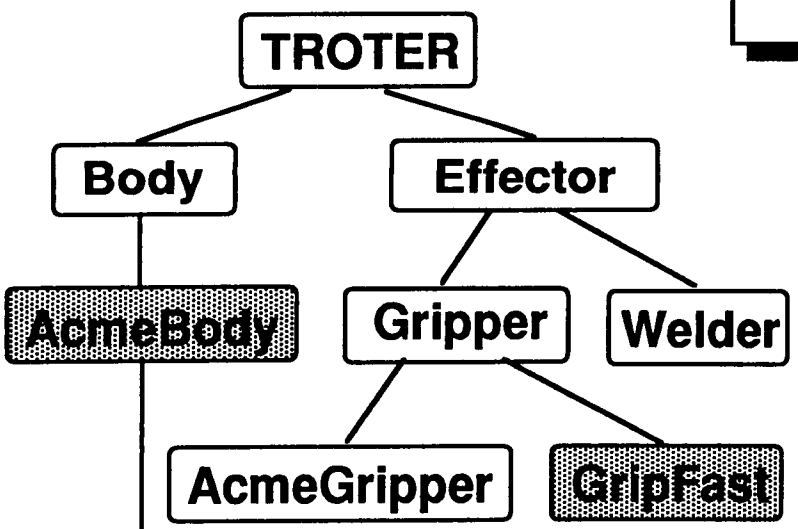
Step 2

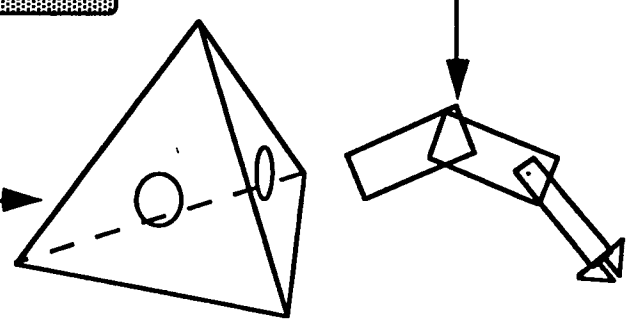
Create Objects From Classes

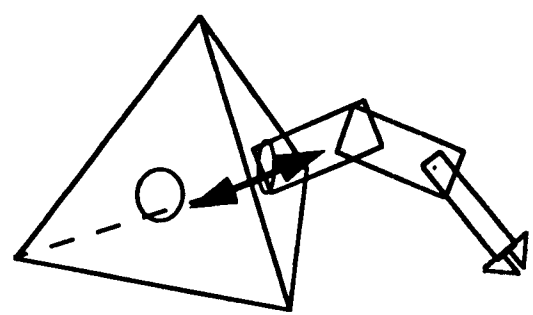
Step 3

Assemble Objects Into a System

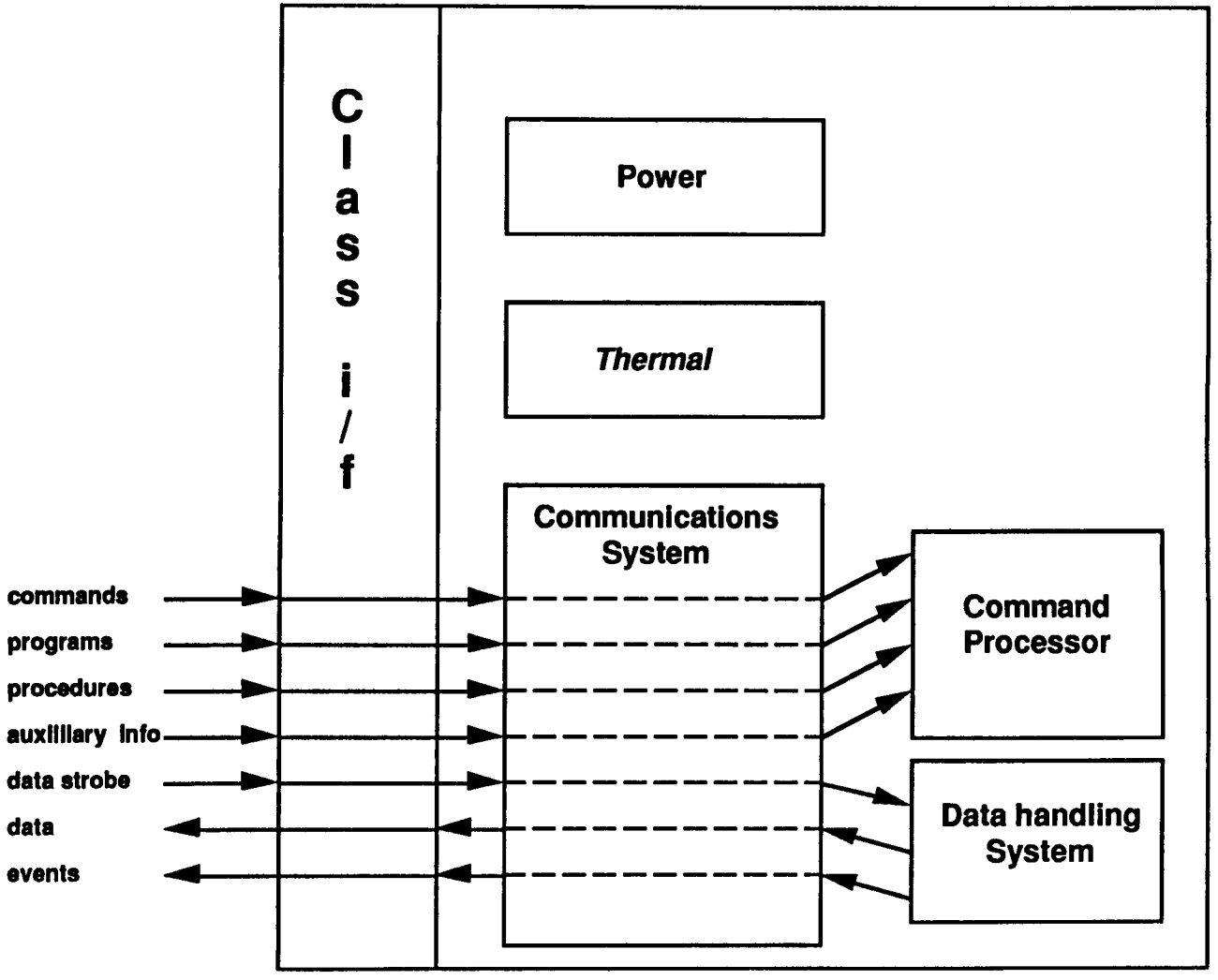
Objects communicate by passing messages







Body Block Diagram



Simulation Technique

- Define and implement TROTER classes
- Determine feasible TROTER systems
- Objects send messages to other objects
- Each object is fairly simple, but the interactions are complex
- Update behavior over time
- Allow domination of one object by another attached object (e.g. a Body controls a Transporter, a Transporter moves a Body)

Issues Discovered and Future Direction

- Message switching must be performed when one object dominates another
- Resource allocation is more difficult to model than expected
- Behavior is much more easily modeled in an object-oriented fashion than in a functional fashion
- Incremental improvements to the TROTERs is simple
- An element to be manipulated can be modeled in the same fashion, and can control a team of TROTERs in order to cause itself to be assembled into a structure

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P-11

THE HUMAN OPERATOR INTERFACE

Clayton Lewis

Controlling a team of cooperating robots poses challenges for human operators, as well as for the robotic systems themselves. The operator must be able to monitor the progress of many simultaneous operations, and intervene to modify the activities of single robots or groups of robots. We use scenarios to present some approaches to this problem.

Human Operator Interface for Robot Teams

- Controlling a team of cooperating robots will be challenging
- For large numbers of robots we will want one operator to control many
- We can explore the issues in a scenario
  - scenario must describe task and robot characteristics

Road Scenario Family

- Task: create dust-free "road" for lunar base
- Robots:
  - ~100 to work in parallel
  - subsumption architecture
  - autonomous avoidance behavior
  - autonomous surface treatment for neighborhood of current location
  - autonomous motion transverse to road
  - autonomous motion in file along road

Task Strategy

- Robots assemble along side of road
- Work across width of road
- Move in file along road to untreated section

Role of Human Operator

- Rate of work will vary with surface details
- Rate and direction of motion will be noisy
- Surface features may require other treatment
- Robots may fail

Video Overlay Approach

- Give robots ability to transmit status to operator
- Give (at least some) robots ability to transmit video of their vicinity
- Provide video overview of entire work area
- Visually mark robots so individuals can be identified
- Software identifies robot images in work area video
  - overlays selectable fields on robots images
- Operator can select individual robot or group on video screen

Robot Trouble Scenario

- Robot signals internal problem
- Image of robot is highlighted in video of work area
- Operator can readily select neighboring robots
  - can direct neighbors to remove patient and redeploy

Big Rock Scenario

- A rock needing special treatment is encountered
- (Prescreening of road course could avoid this)
- Robots at rock signal problem
- They are highlighted on video of work area
- Operator can request video from robots near rock
- Operator can locate rock and recruit other tools
- Operator can select blocked robots and direct them to redeploy

Fast Work Scenario

- Robots working on one section of road complete their sweep early
- Operator can easily observe this
- Operator can override group movement for these robots

Advantages of Video Overlay

- Operator has global view of robots and work
- Operator does not have to process input and status from all robots
- Much of needed status is in overview
- Operator can directly select robots concerned in a problem
  - either individually or as a group
  - selection directs input and output
- Exploits autonomy while retaining control

Virtual Guideposts

- Subsumption architecture permits cheap robots
  - limited vision and navigation
- Guideposts could be used to coordinate motion of such robots
- Video overlay interface could allow operator to place virtual posts
  - would override real posts within subsumption architecture

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Session Seven

HUMAN FACTORS IN SPACE CONSTRUCTION

Frank Barnes,
Chair

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Human Factors in Space Construction
Session Chair: Frank Barnes

In this session we will examine a number of aspects of the problems for humans who are operating for extended periods in space. We are concerned with the ability of humans to both survive and work effectively. The first two talks, by Cindy Bingham and Paul Carter, describe some proposed experiments to examine the use of time-varying magnetic fields as a possible way of reducing the loss of the effectiveness of the immune system with extended periods of weightlessness. The third talk by Steve Thilenius will be divided into two parts. The first part will examine the use of neural networks as an interface between humans and robots. The second will describe the implementation of a new algorithm for time-slot interchange in silicon, which grows like $\log n$ rather than $n \log n$ in terms of the number of switches required to implement it. This approach should be a major asset in the use of time-division multiplexing to control a large number of robots over a single communications channel. The fourth talk by George Morgenthaler will deal with the problems of contamination in a closed environment which is to be inhabited for extended periods of time. The final talk by Frank Barnes and Stein Sture will look at the use of acoustic resonances and electrical discharges for moving regolith.

HUMAN FACTORS IN SPACE CONSTRUCTION
OCTOBER 9, 1990
SESSION CHAIR: FRANK BARNES

1. INTRODUCTION

A. Effect of Space Environment on Human Performance – Cindy Bingham, Paul Carter

1. Background on Reduction of Bone Strength
2. Decrease in Viability of the Immune System

B. The Interface between Humans and Robots – Steve Thilenius

1. Multiplexing of Data for Communications to Multiple Robots; Time Slot Interchange Algorithm
2. Use of Neural Nets in Command and Control

C. Control of the Environment for Long-Term Habitation – George Morgenthaler

D. Use of Acoustic Resonances and Electrical Discharges for Moving Regolith – Frank Barnes, Stein Sture

2. POSSIBLE EFFECTS OF ELECTRIC FIELDS OR TIME-VARYING MAGNETIC FIELDS ON THE IMMUNE SYSTEM

A. Effects on Bone Growth

B. Postulate Effects of Bone-Generated E Fields on Bone Marrow

1. Growth of Stem Cells → T Cells

C. Experiments to Check This

D. Benefits for Treatment of Osteoporosis and Old-Age Patients

comt

PROBLEMS IN THE HUMAN-ROBOT INTERFACE

I. Command and Control Vocabulary

1. Nature of Human Command Vocabulary
   A. Example: "Go Get the Beam"

2. Present Robot Vocabulary
   A. Differential Equations + Coordinate-Oriented
      Example: x to y

3. Are Neural Nets a Good Way to Solve These Interface Problems?

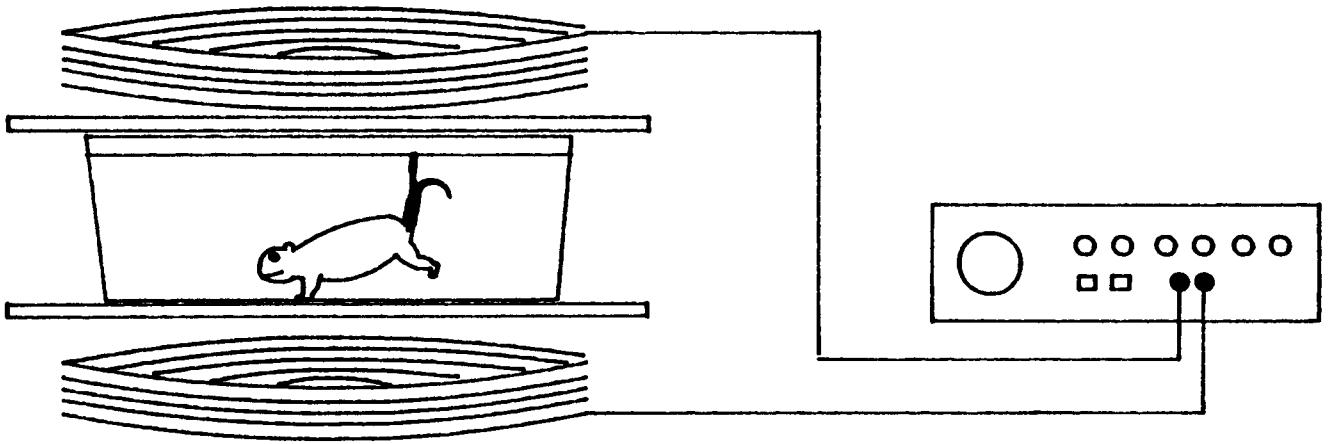
II. Communication Channel Limitations

1. If we have many robots to command, or many different sensors providing data, we need an efficient multiplex-demultiplex system

2. The Implementation of the Ramanan-Jordan-Sauer Time-Slot Interchange Algorithm in Si

Whole Body Pulsed Magnetic Fields and Osteoporosis

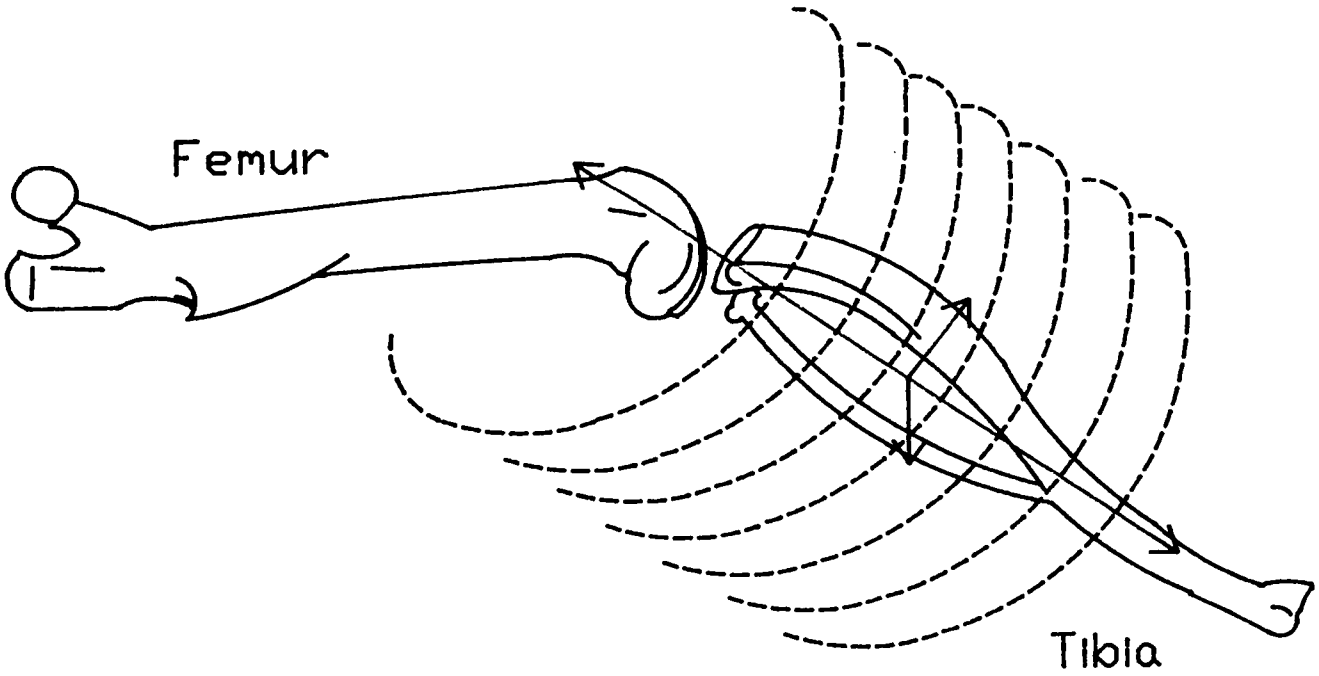
BioServe Space Technologies

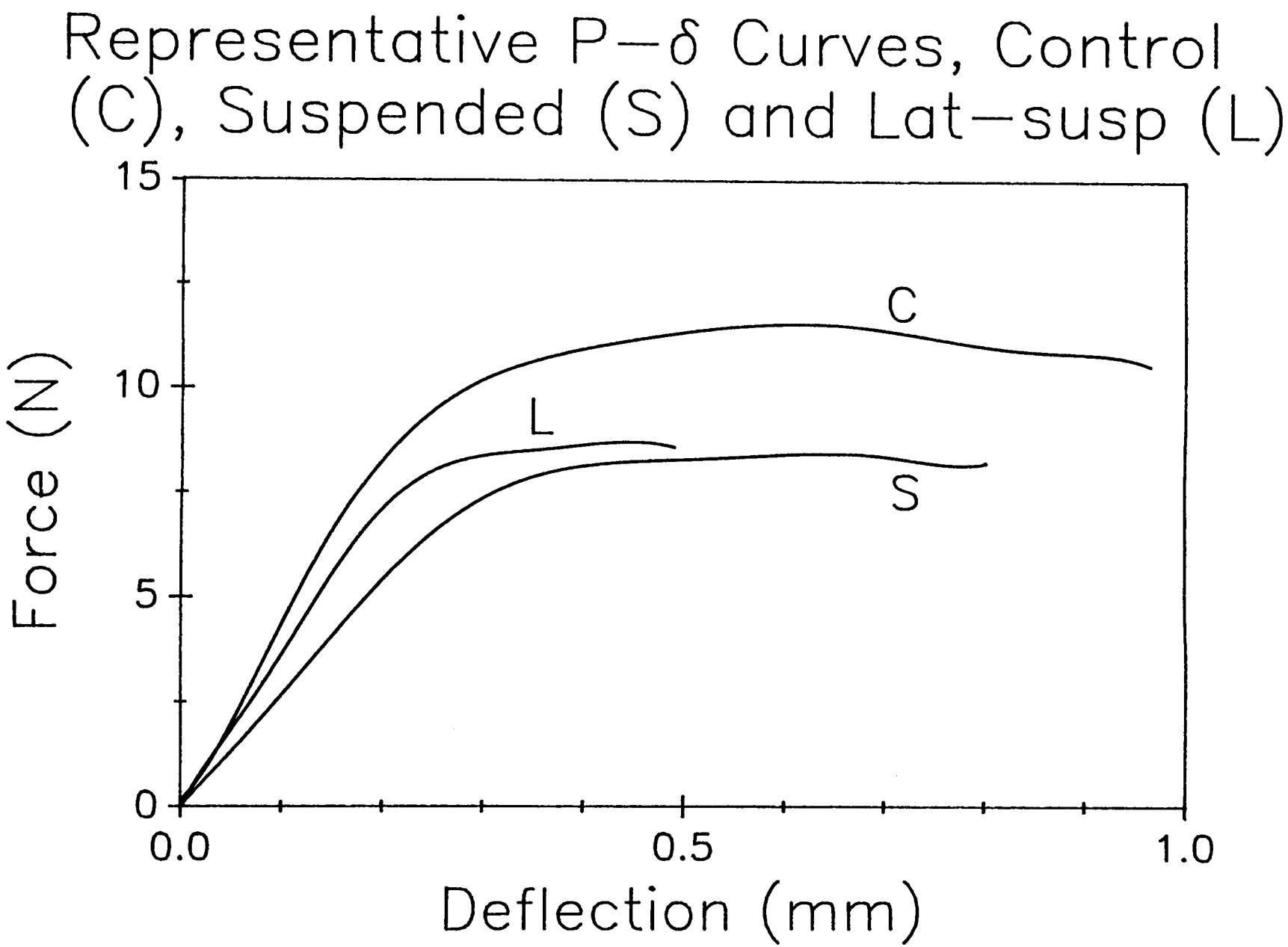


SJ Simske, MW Luttges and H Wachtel, 1988-1990

Localized Fields:

Lateral Orientation




Representative P−δ Curves, Control (C), Suspended (S) and Lat−susp (L)
Force (N)
15
10
5
0
0.0
0.5
1.0
Deflection (mm)
C
L
S

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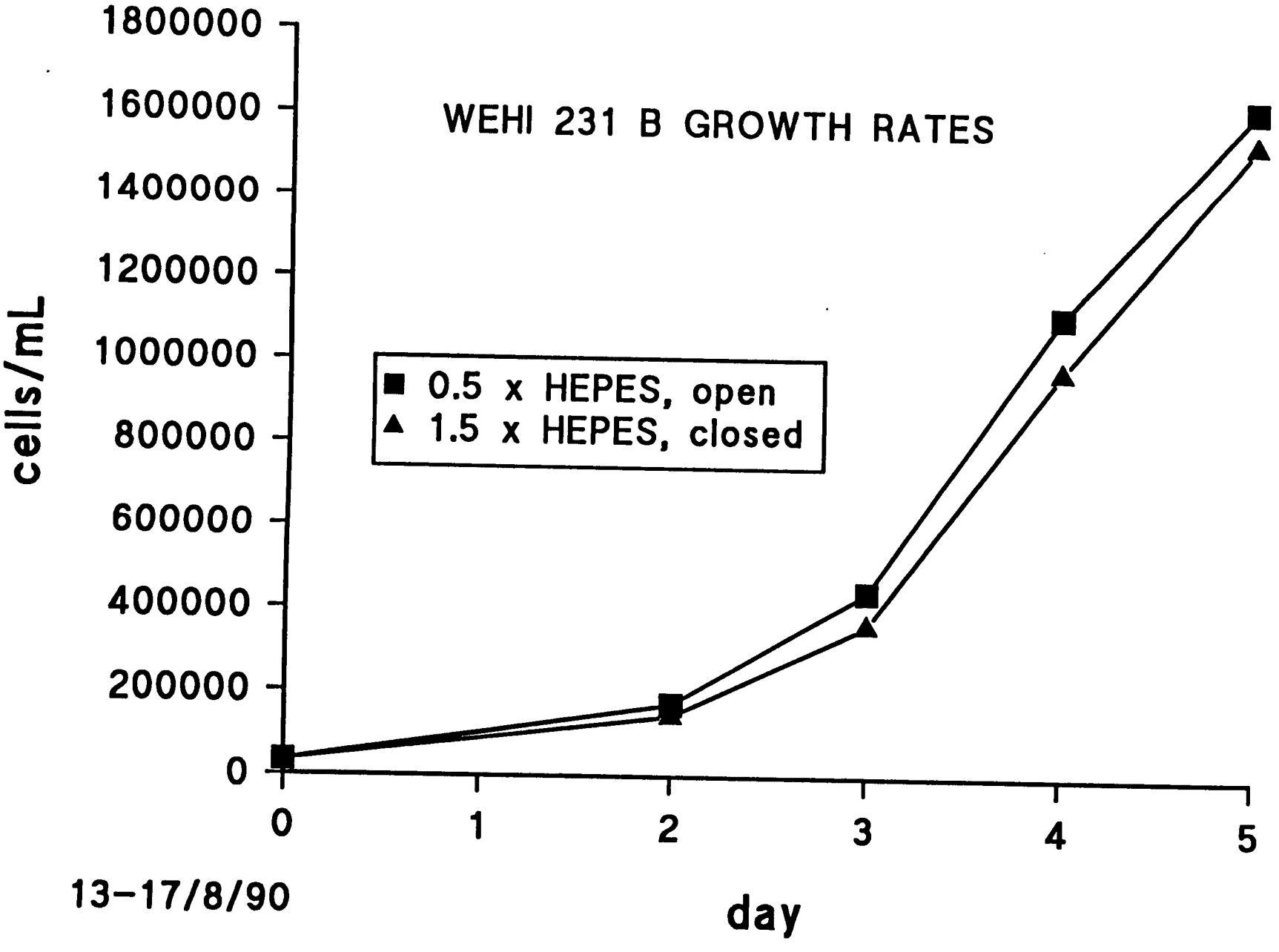
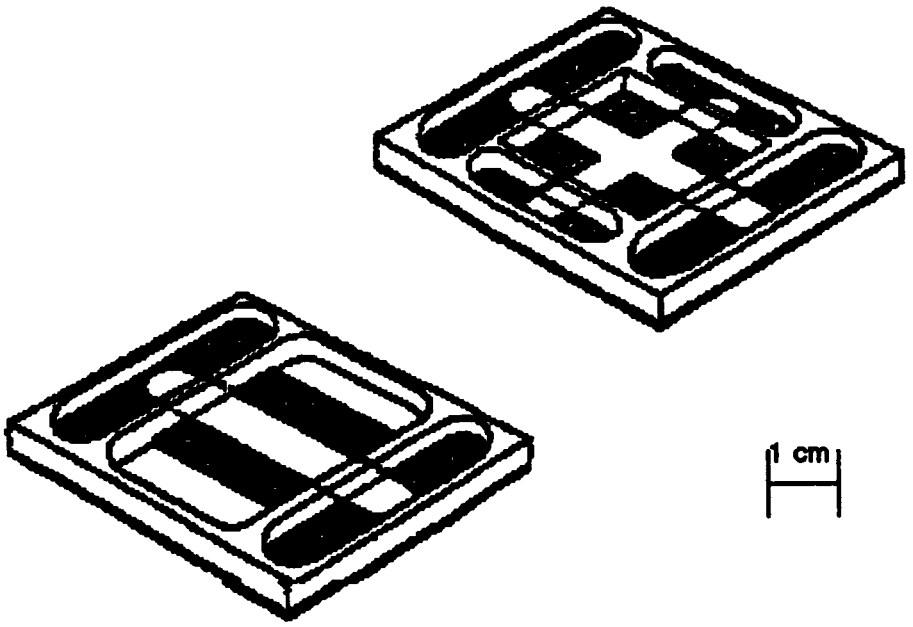
REDUCTION OF BONE STRENGTH

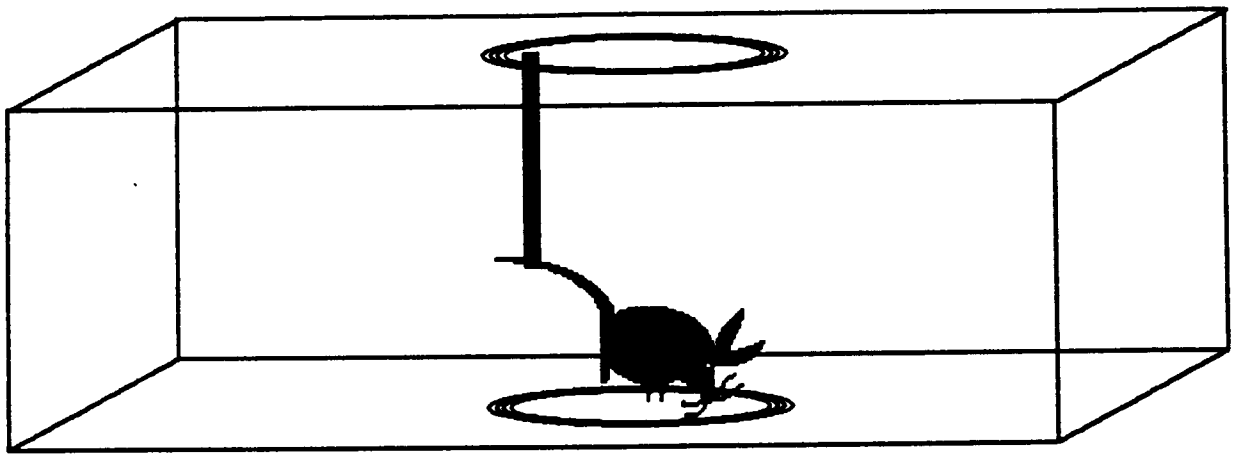
Cindy Bingham


WEHI 231 B GROWTH RATES
cells/mL
1800000
1600000
1400000
1200000
1000000
800000
600000
400000
200000
0
0.5 x HEPES, open
1.5 x HEPES, closed
0
1
2
3
4
5
day

13-17/8/90



Experimental Chambers used to apply the electric field to the cell cultures.



Mouse suspended by rotating cuff in electromagnetic field.

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P. 2

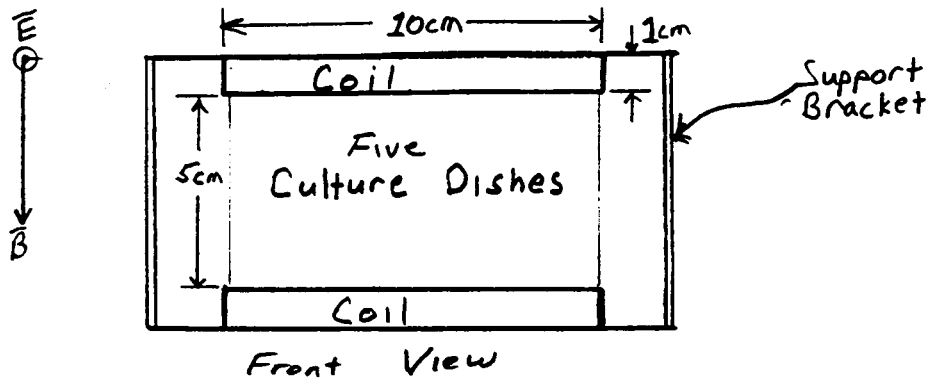
HYPO-GRAVITY AND IMMUNE SYSTEM EFFECTS

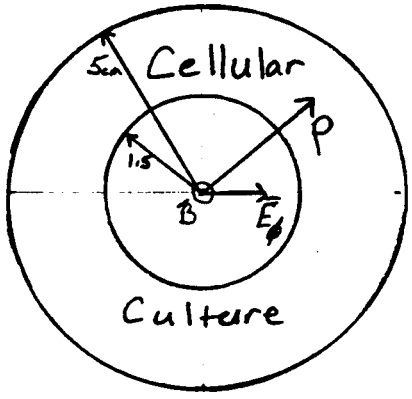
Paul D. Carter
Dr. Frank Barnes

Recent studies on the effects of hypo-gravity on astronauts have shown depressed response of the immune system component cells (e.g. T-lymphocytes activity) and associated bone-mass loss due to de-mineralization. The widespread use of various electrical stimulation techniques in fracture repair and bone growth make use of the inherent piezoelectric and streaming potentials in Ca^{2++} depositation. We have designed in-vitro and in-vivo experiments to determine if these potentials, absent or greatly reduced in space, could be artificially enhanced to advantageously effect the bone marrow and, consequently, immune system cells. The bone marrow plays an extremely important role in the development and maturation of all blood cells and, specifically, T- and B-lymphocytes. It is our belief that simulated E-fields will enhance this development when 'ambient' physiological fields are absent during spaceflight or extended bedrest.

Our investigation has begun with a look at the component immune system cells and their growth patterns in vitro. We are developing two exposure chambers to determine field effects. The first chamber will induce E-fields by current densities produced from an agar-bridge electrode arrangement. The cells will be immersed in a nutrient agar and isolated from the electrodes by an agar bridge to prevent electrolytic contamination. The second chamber will induce current densities by mutual induction from a magnetic field produced by a solenoid coil. Cells will be isolated in a small radial area to reduce (1/r) effects and for accurate field calculations. We anticipate inducing currents in the nano- and microampere range as indicated by our calculations of physiological fields.

Helmholtz Coil Exposure Apparatus





$$\oint_\ell \bar{E}\, d\bar{\ell} = \oint_S -\frac{d}{dt}\bar{B}\, d\bar{s}$$

$$E_\phi = -\pi f B_0 \rho \cos(2\pi f t)$$

$$\bar{J} = \sigma \bar{E}$$

With: $1\,nA/cm^2 < J < 50\,\mu A/cm^2$

$DC < f < 50\,kHz$

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P-4

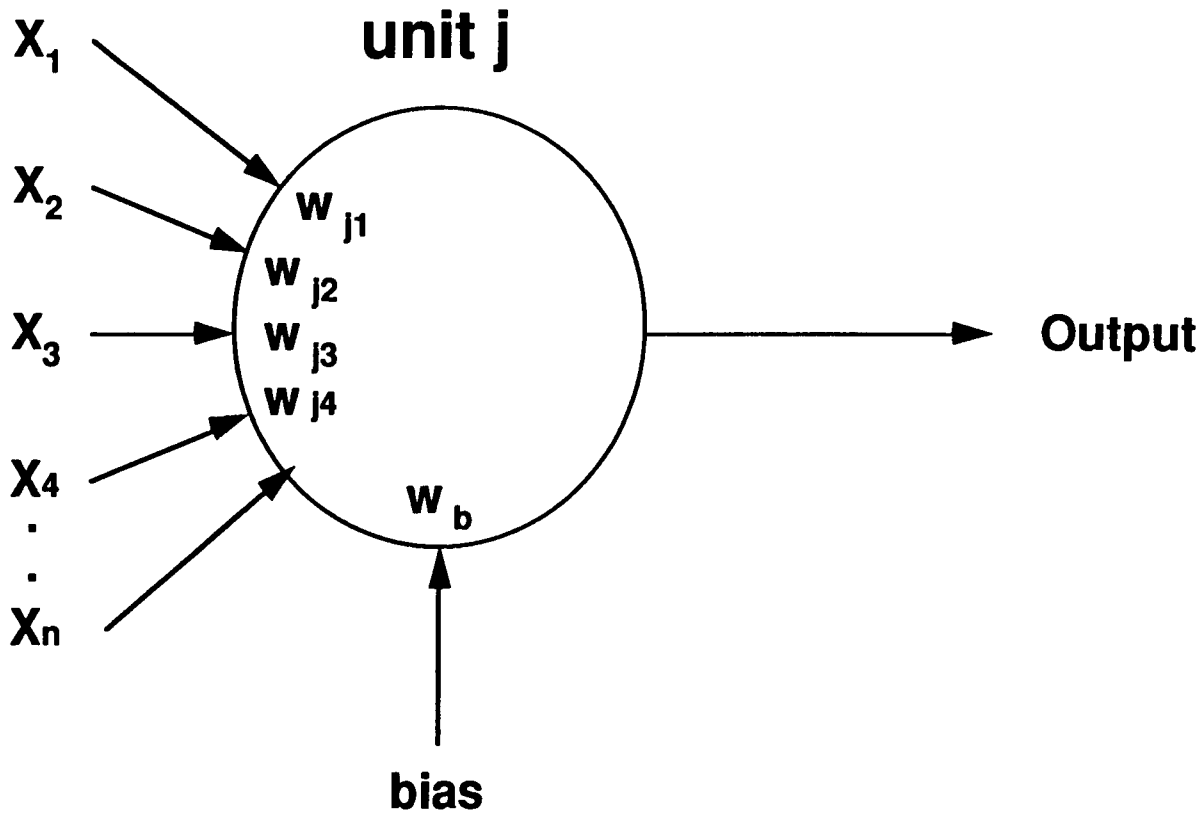
APPLICATION OF NEURAL NETWORKS IN SPACE CONSTRUCTION

Stephen C. Thilenius
Frank Barnes

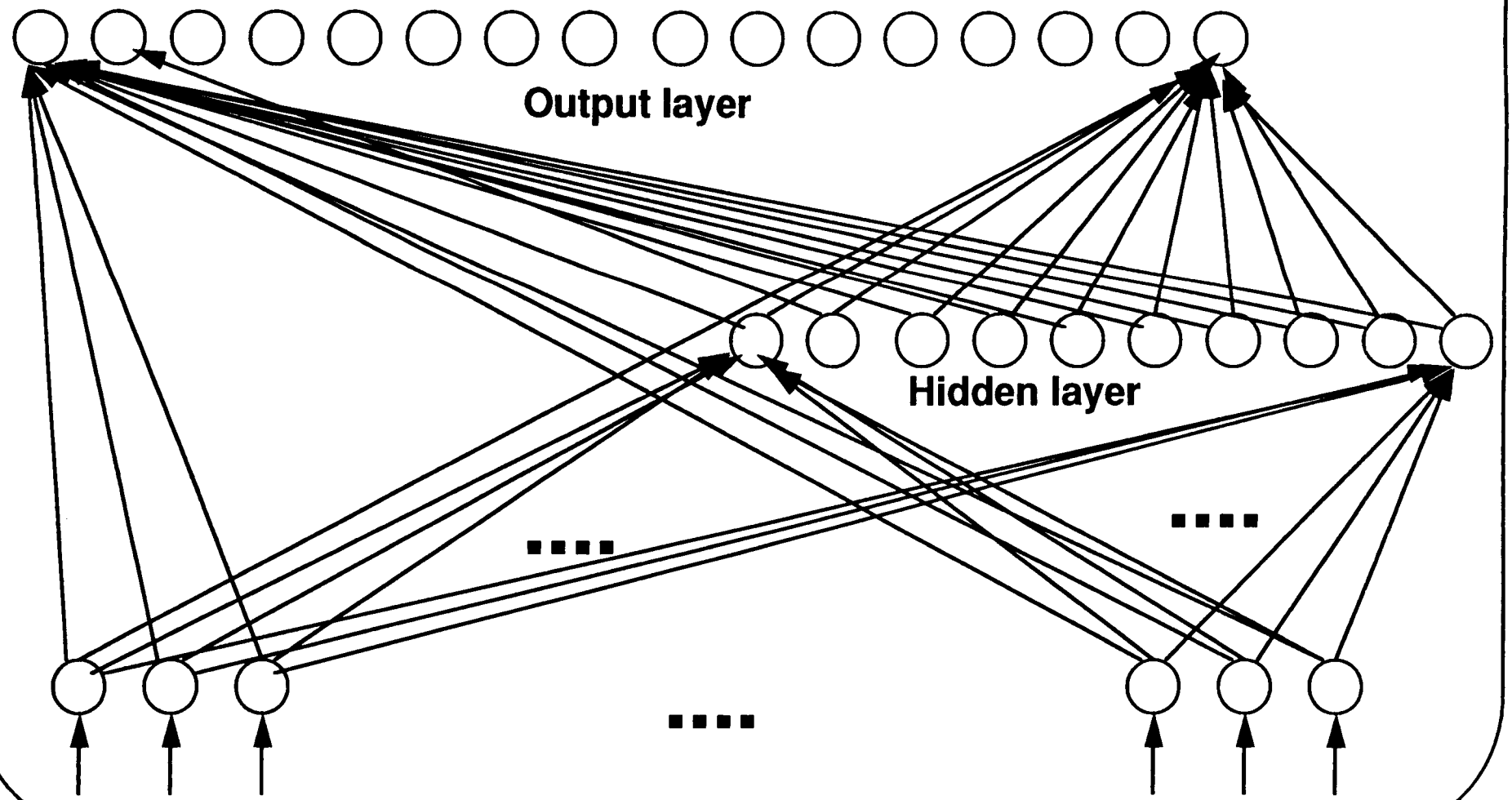
When trying to decide what task should be done by robots and what tasks should be done by humans with respect to space construction, there has been one decisive barrier which ultimately divides the tasks: can a computer do the job? Von Neumann type computers have great difficulty with problems that the human brain seems to do instantaneously and with little effort. Some of these problems are pattern recognition, speech recognition, content addressable memories, and command interpretation. In an attempt to simulate these talents of the human brain, much research has currently been done into the operation and construction of artificial neural networks.

The efficiency of the interface between man and machine, robots in particular, can therefor be greatly improved with the use of neural networks. For example, wouldn't it be easier to command a robot to "fetch an object" rather then having to remotely control the entire operation with remote control?

Neural Networks

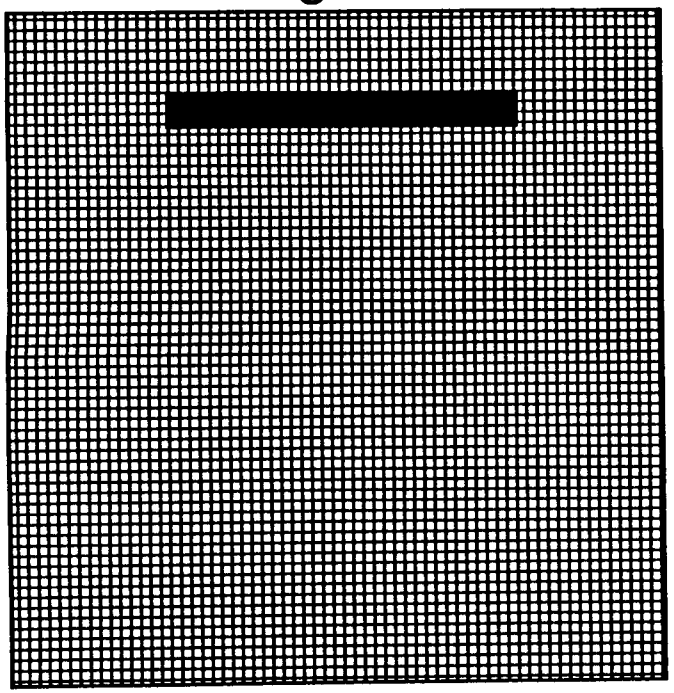


3 Layer Architecture



Training Data

32X32 Digitized Grid



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MULTIPLEXING OF DATA FOR COMMUNICATIONS TO MULTIPLE ROBOTS

TIME SLOT INTERCHANGE ALGORITHM

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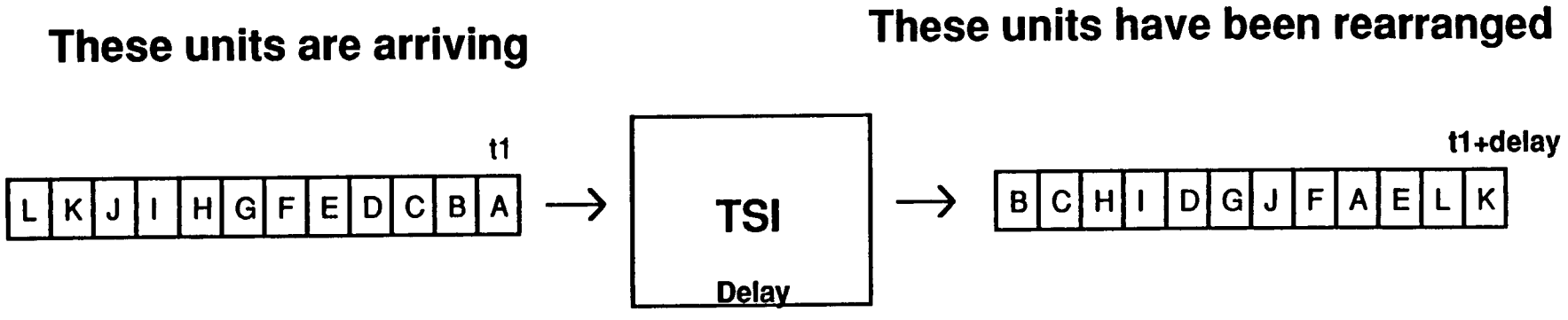
Steve Thilenius

Time Slot Interchanging

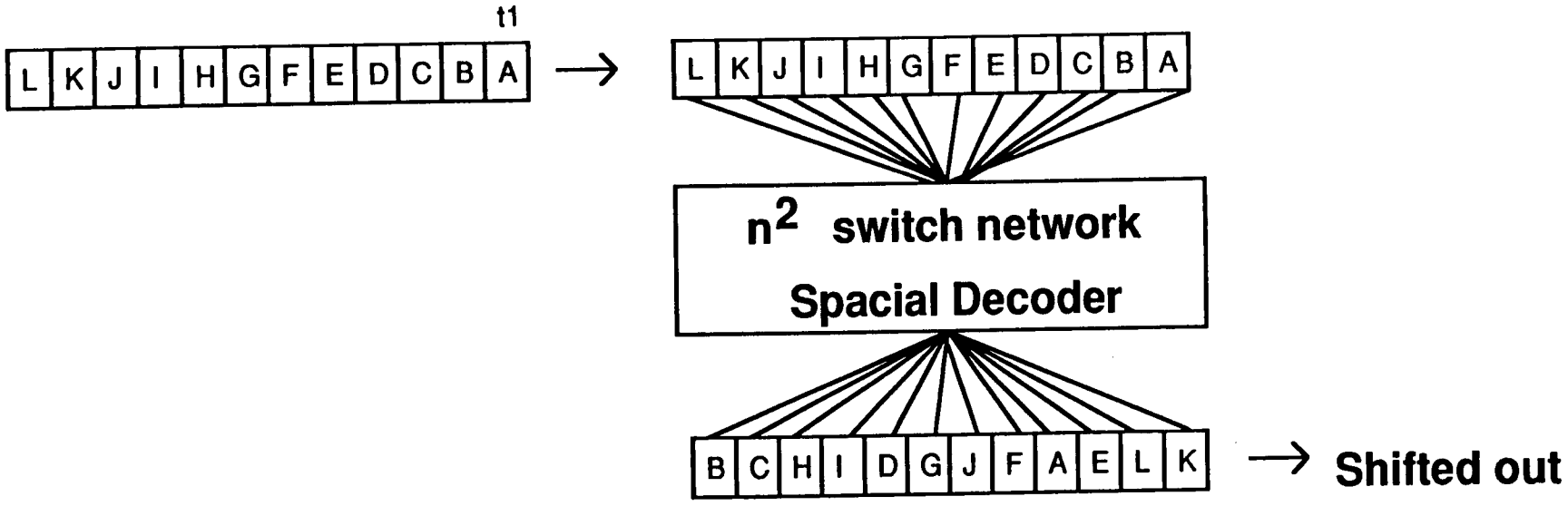
The purpose of a time slot interchanger is to rearrange incoming units in time. For example:



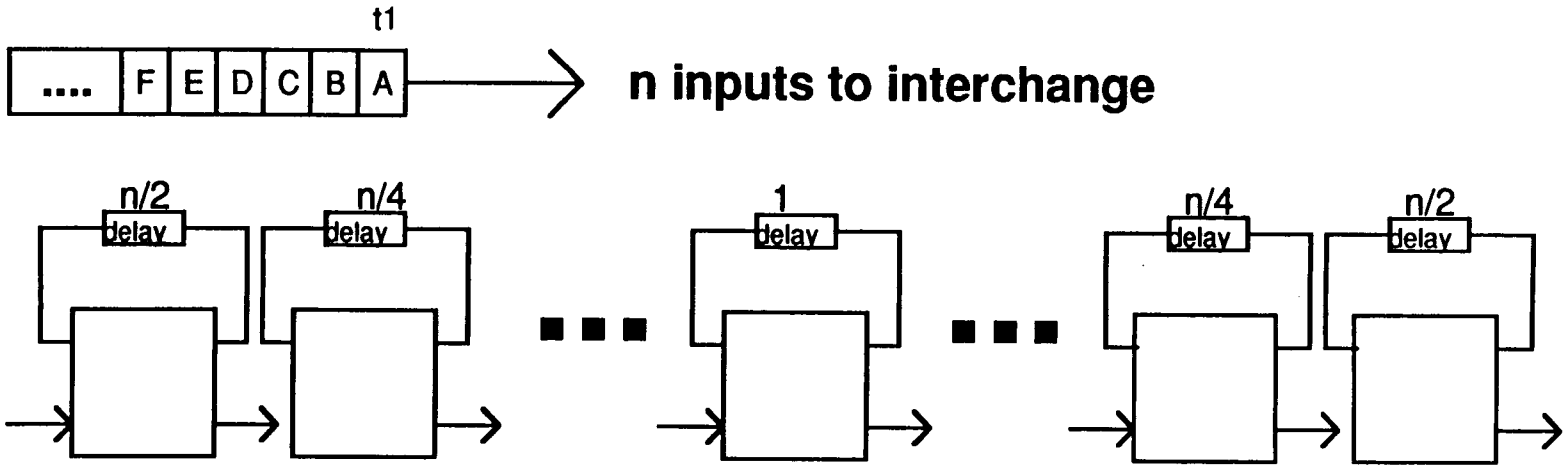
The Old Way

- **Bennice networks**

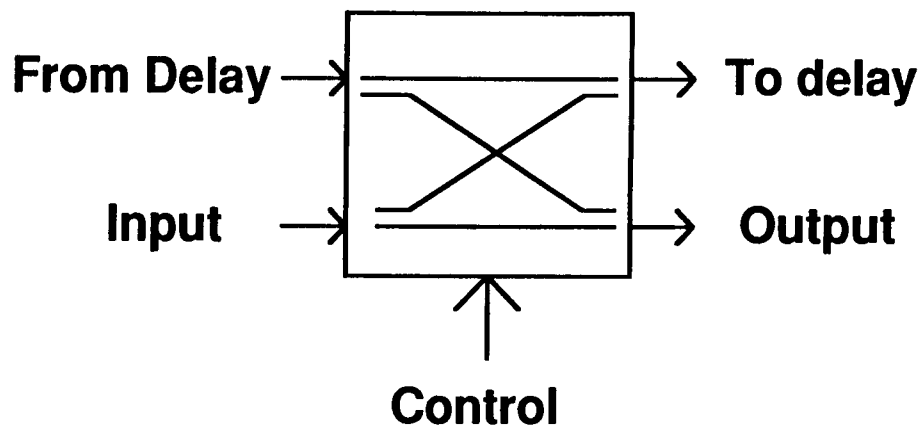
  The traditional way to solve this problem is by shifting the incoming information into a registrer and then do spacial decoding.



The New Way



The Control signal determines whether or not the block will switch the inputs or not.



Amount of Hardware

old way: n^2 switches and 2n delay elements (the shift registers)

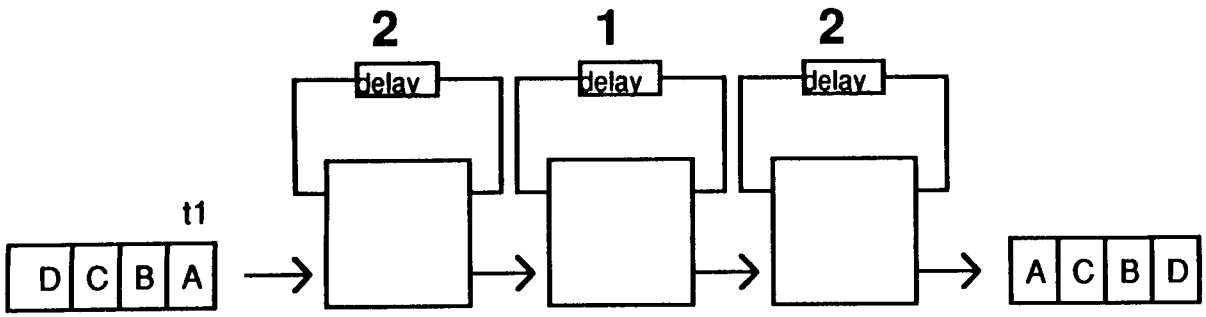
ex. if n=128 we need 16384 switches and 256 memory elements

new way: 2*log (n)-1 switches and 2*n-1 memory elements

ex. if n=100 we need 13 switches and 255 memory elements

How it Works

Lets look at an example of n=4



How it Works

t	input	C1	d1	d2	C2	d1	C3	d1	d2	output
1	A	1	A	-	-	-	-	-	-	-
2	B	1	B	A	-	-	-	-	-	-
3	C	1	C	B	1	A	-	-	-	-
4	D	0	B	C	0	A	1	D	-	-
5	-	1	-	B	1	C	1	A	D	-
6	-	-	-	-	1	B	1	C	A	D
7	-	-	-	-	-	-	0	A	C	B
8	-	-	-	-	-	-	1	-	A	C
9	-	-	-	-	-	-	1	-	-	A

C=1 switchs

C=0 doesn/t switch

The Algorithm

let:
A=00
B=01
C=10
D=11

In the Algorithm we go backwards

from BCAD to ABCD

input	C1	input	C2	input	C2	output
11	1	11	1	00	1	00=A
01	1	00	0	11	1	01=B
10	1	10	1	10	1	10=C
00	0	01	1	01	0	11=D

look at last bit

look at first bit

set first 3 to switched position
Then look at 00. Look and see if
10 is in the same half. If it is switch it.

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SPACE HABITAT CONTAMINATION MODEL

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George W. Morgenthaler

President Bush in his July 20, 1989 speech at the Air and Space Museum in Washington, D.C. celebrating the 20th Anniversary of the Apollo Lunar Landing, set the future course for the United States National Space Program. He said that the United States was going "back to the Moon. Back to the future. And this time, back to stay. And then, a journey into tomorrow, a journey to another planet. A manned mission to Mars." (Ref. 1)

When one considers the missions that are involved in this Space Exploration Initiative (SEI), a continuous Lunar Base at which astronauts will perform scientific experiments as well as being the center for Lunar resource exploitation, a human visit to the surface of Mars, and, later, the development of a Mars base, one recognizes that we have entered a new realm of space exploration activity. During the SEI era, human beings who are involved in such missions will be away from Earth for extended periods of time, even for years. For example, the classical Hohmann transfer round trip mission to Mars would involve a flight of 31 months, including the stay time in the vicinity of Mars. Of course, other Mars trips such as the Venus Fly-By mission (22 months) and the Mars Sprint mission (15 months) pose much less taxing problems, but still problems which put human space presence in a domain where human survival has not yet been tested and thoroughly understood. Humans have never before been placed into an isolated, low-gravity, hermetically sealed, contaminant-prone environment for periods well in excess of one year and then been expected to function normally upon return to Earth.

This presentation develops a systems model to help analyze the space habitat containment growth problem and to indicate the thresholds of astronaut risk, astronaut operational impairment, and methods of risk mitigation. The model inputs have been discussed with toxicology experts at the University of Colorado Health Services Center and the University of Rochester.

SPACE HABITAT CONTAMINATION MODEL

George W. Morgenthaler

A Joint research effort between
the University of Rochester Toxicology Center
and the University of Colorado,
of importance to Space Construction.

Figure 1

CENTER FOR SPACE ENVIRONMENTAL HEALTH (CSEH)

FOCUS: Systems Approach to Human Health Risks Due to Environments of Long Duration Space Missions

PROPOSED RESEARCH:

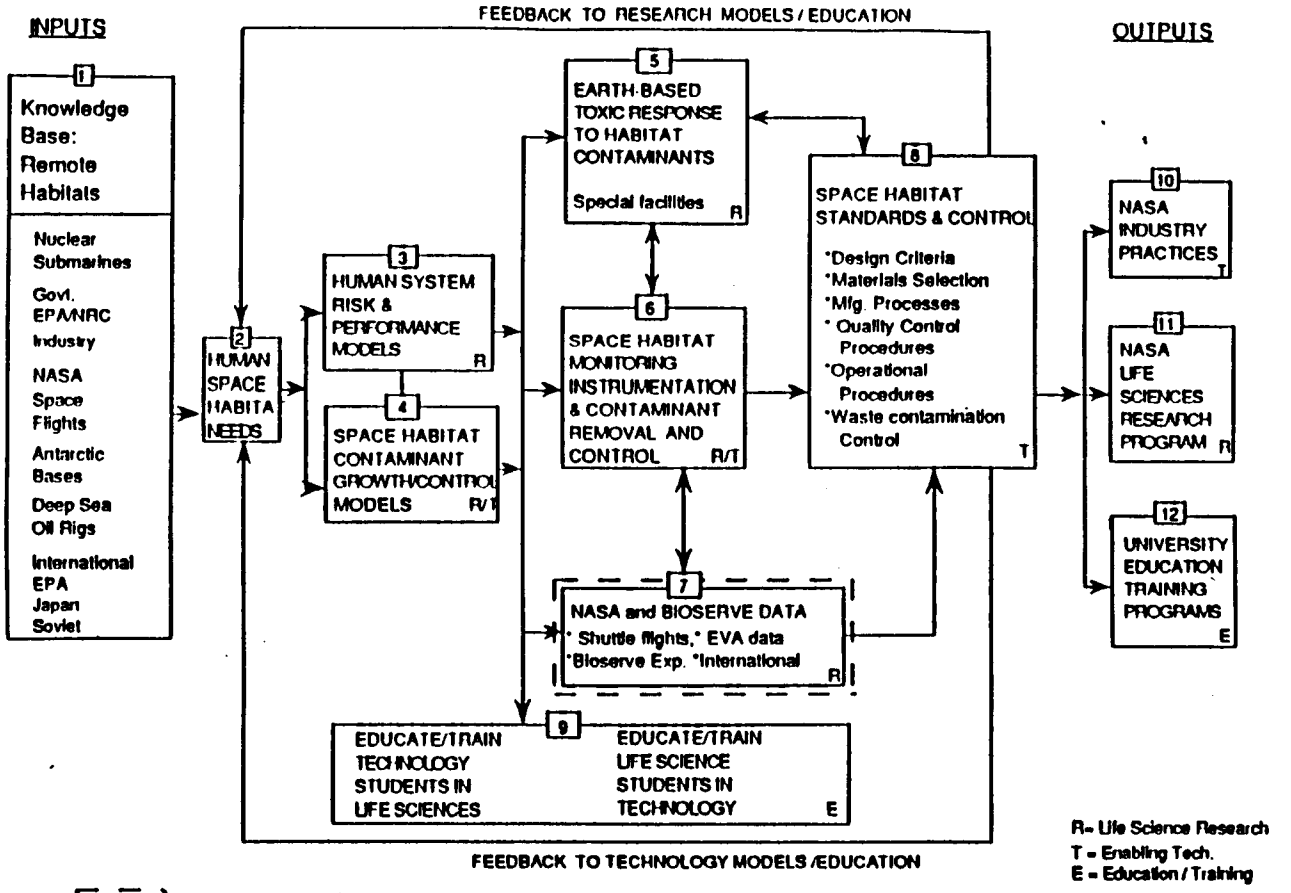
1. Database on humans in remote and constrained habitats.
2. Develop baseline mission models of space habitat human needs. (Space Stations, Lunar Bases, Interplanetary S/C, Mars Bases)
3. Model space habitat contaminant growth: atmosphere, water and wastes.
4. Develop human risk and performance models.
5. Perform clinical research and Earth tests to calibrate/validate human risk and performance models.
6. Develop space habitat standards, controls and monitoring systems.
7. Recommend space habitat monitoring and contaminant removal technologies.

Education and Training: interdisciplinary studies, new courses, enriched degrees.

Outreach and Knowledge Transfer: extramural educational workshops, seminars, short courses with Industry, NASA, and university involvement.

Figure 2

Figure 2. SPACE HABITAT ENVIRONMENTAL HEALTH AND ENABLING TECHNOLOGY PROJECTS



Abbreviations frequently used in this proposal

CIRES:	Cooperative Institute for Reseach in Environmental Sciences
CSAT:	Center for Space and Advanced Technology
EHSC-UR:	Environmental Health Sciences Center at the University of Rochester
EHSC-UC:	Environmental Health Sciences Center at the University of Rochester
JSC:	Johnson Space Center
MMC:	Martin Marietta Corporation
UR:	University of Rochester
UC:	University of Colorado

Figure 3

1998 - 2035 SPACE MISSIONS ANALYSES (BASE-LINE MISSIONS)

Mission Type	Mission Duration at Gravity State	Number of Astronauts	EVA/ MMU Activity	Life Support System	On-board Environmental Health Substance Threats	Monitoring Systems	Contamination Mitigation Measures
Space Stations	0.00 g 30 years	5-20		Space Station Freedom Derivative	Ammonia, Hydrazine, etc.	Atmospheric, Water, Waste } SSF	
Lunar Bases	0.16 g 25 years	5-10		Space Station Freedom Derivative		?	
Inter-planetary Spaceflight	0.00 g 15-31 months	10		Controlled Ecology Life Support System (CELSS)		?	
Mars Bases	0.38 g 1-10 Years	10-15		Next Generation Bio-regenerative LSS		?	

Figure 4

SYSTEM MODEL AND ENVIRONMENTAL HEALTH DATA BASE: CSEH RESEARCH DRIVERS

(For each Mission Type: Space station, Interplanetary S/C, Lunar/Mars Bases)

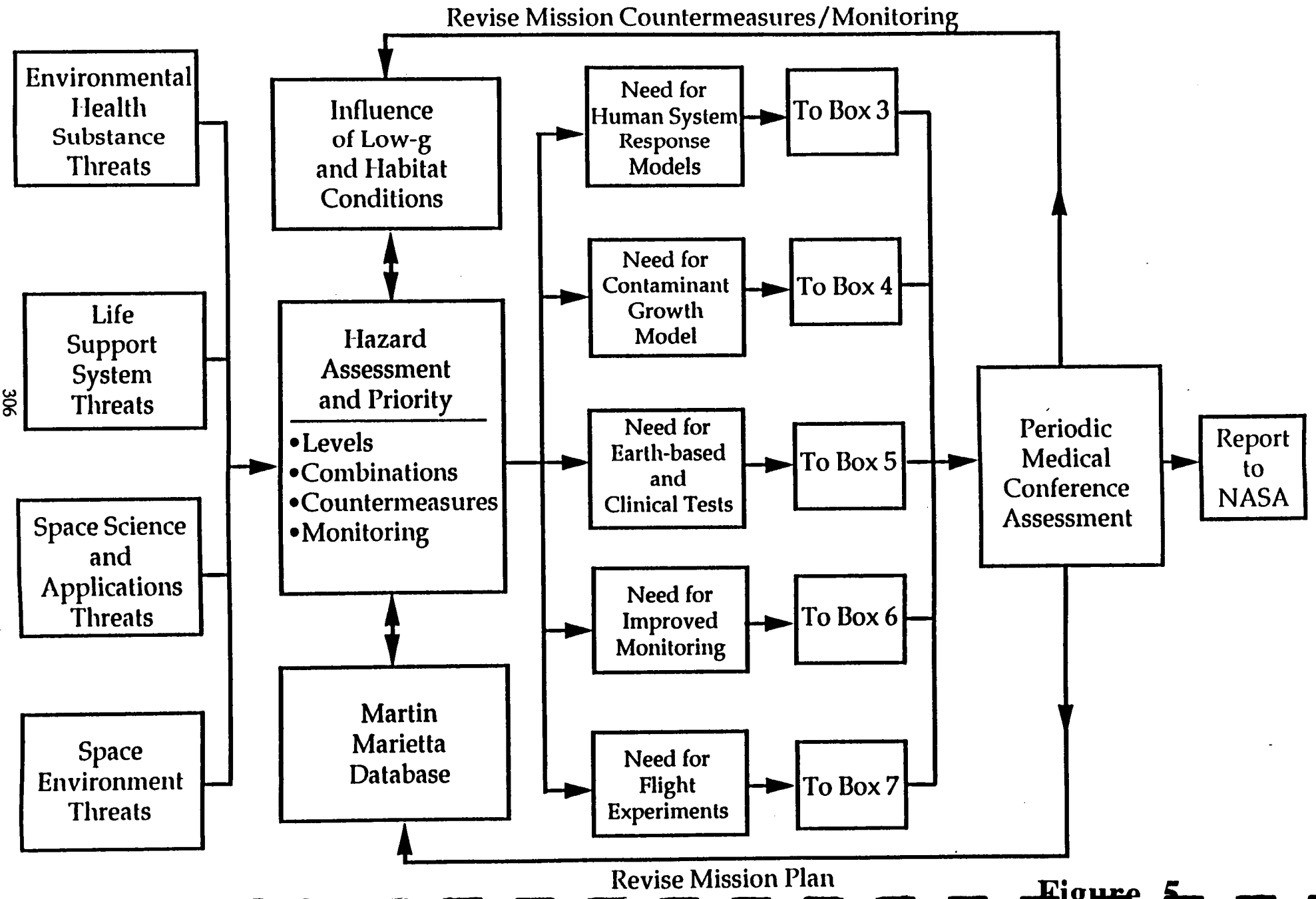


Figure 5

ENVIRONMENTAL HEALTH ISSUES IDENTIFICATION
(Often context specific)

EXAMPLE: Lunar Base Scenario - LO_2 and In-situ Materials (Los Alamos Lab)

- Microwave technology to drive out interstitial hydrogen from regolith. Hazardous outgassing? (H_2S, etc.)
- "Subterrene" (Molybdenum- tipped, SP100-powered melting probe) for making crater-wall caves. Hazardous outgassing?
- Applications of sulfur for Lunar construction - Sulfur cementicious products. Hazardous outgassing?
- Lunar dust - abrasive, spicule-like, ultra-fine, adhering. Hazardous to humans and equipment?
- Advanced real-time, continuous monitoring equipment: optical, multi-spectral analyses; asymmetric molecules/polarization; "Zeeman interferometry" (parts per billion).
- Low-g effects.

Figure 6

HUMAN SPACE HABITAT CONTAMINANT THREATS (Box 2) TIMELINE

Space Stations O-g	Space Station Freedom Contaminants	Science Experiment Contaminants	Commercial Space Process Contaminants	Advanced Space Station (with s/c Assembly Hanger)	Advanced LSS test contaminants
Interplan-etary space craft O-g	Review of baseline Space-Craft Contaminants	On-Orbit Assembly Operations	EVA and Manned Maneuvering Units	Refueling and Re-supply	Plant food growth and Waste Disposal
Lunar Bases 1/6-g	Review of Baseline Design Concept Contaminants	Rover and Base Construction Activity Contaminants	Scientific Base Contaminants	Lunar Exploration Process Contaminants	Propellant and Cargo Handling Contaminants
Mars Bases .38g	Review of Baseline Design Concept Contaminants	Pre-cursor (soil sample return) determination of contaminants	Rover and Base Construction Activity Contaminants	Scientific Base Contaminants	Propellant and Cargo Handling Contaminants
	Year 1	Year 2	Year 3	Year 4	Year 5

Figure 7

Rate of change of moles or molecules	=	inlet or entering rate of species into control volume	−	outlet or exit of species from control volume	+	rate of chemical reaction or generation of species inside control volume

Figure 9. Sample Contamination Model Word Equation

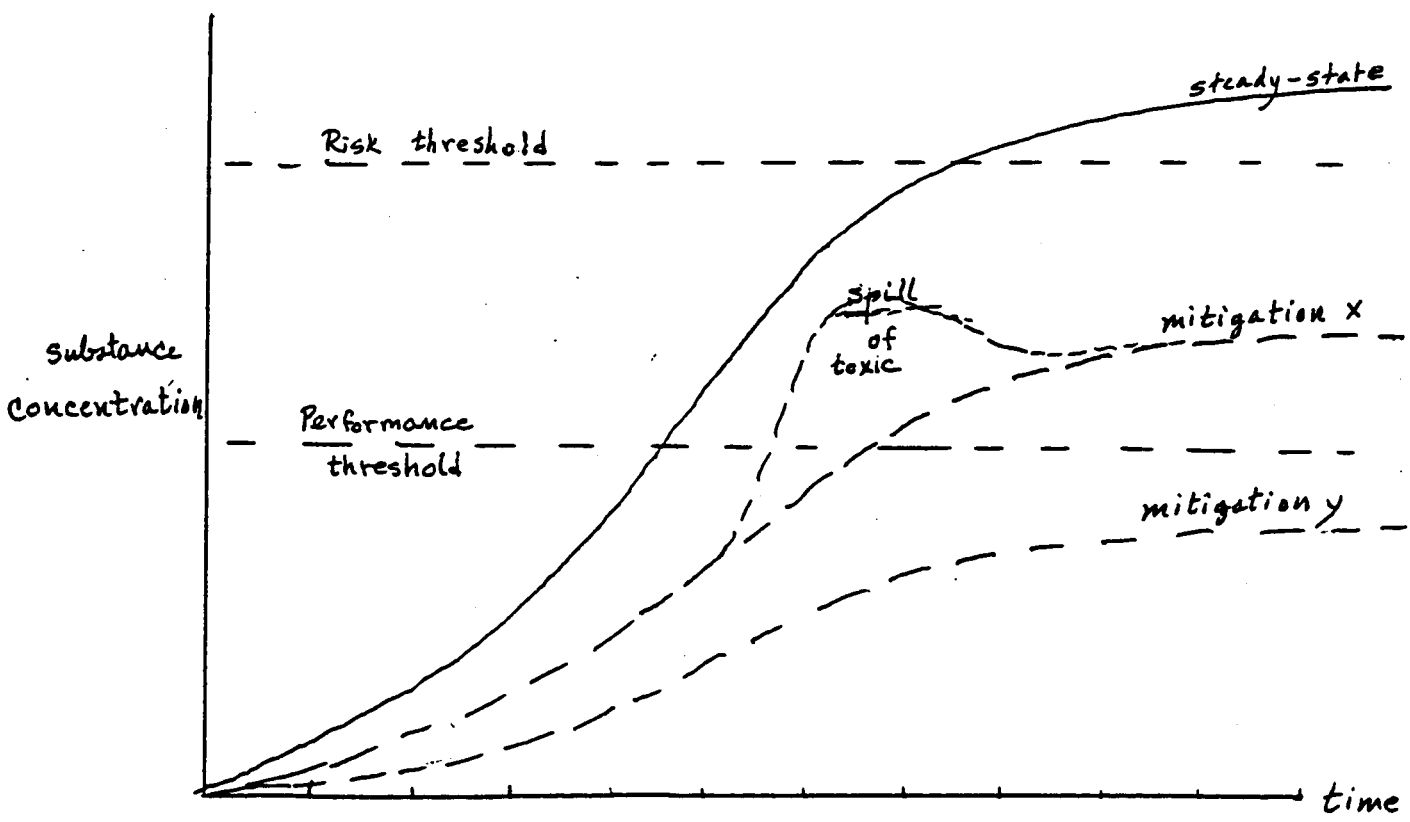


Figure 8. Toxic Thresholds, Spill Transients, and Mitigations

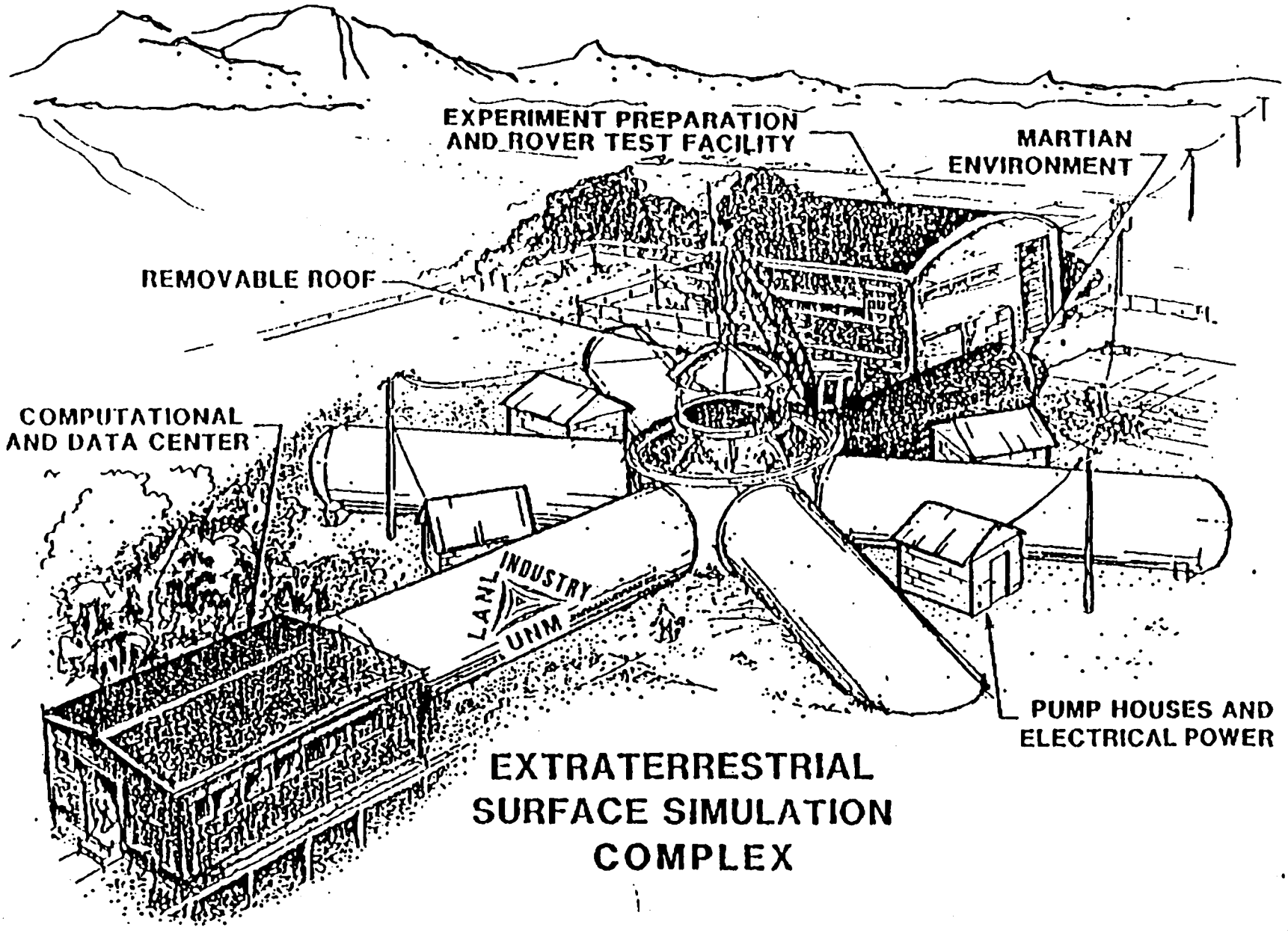


Figure 9 Shown is one of several possible CETEC layouts. (From a New Mexico Engineering Research Institute/Los Alamos National Laboratory Drawing)

Can Man Survive in Space ?

- Man has adapted to the environment on Earth
- Magnetic and atmospheric shields protect man on Earth
- Excess radiation can lead to illness, death, cancer and genetic defects
- Man on Earth is exposed to approximately 0.1 Rem/year of ionizing radiation

McDonnell Douglas
Space Systems Company

Solar Cycle Dependance

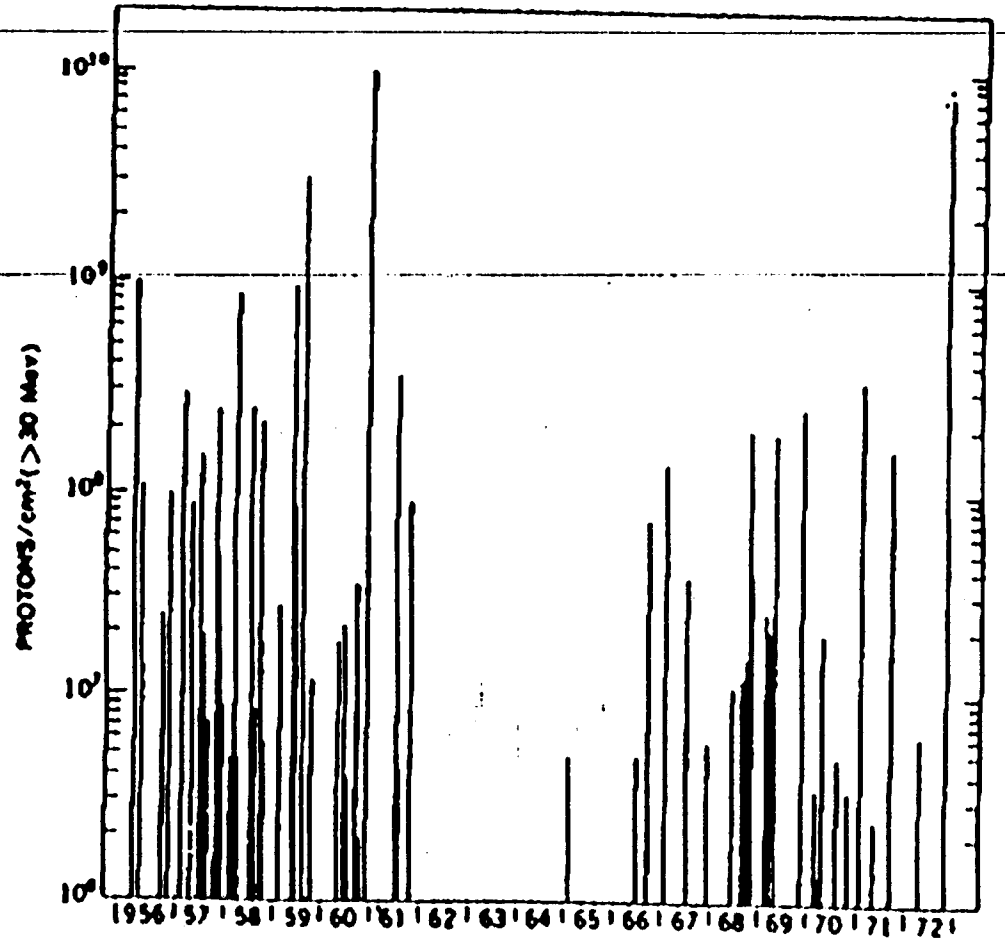


Fig. 4.1 – Event-integrated proton fluxes above 30 MeV for the major solar events of the 19th and 20th solar cycles (King, 1974).

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Some Radiation Dose Values

Earth Background Levels - 0.1 Rem/year

Chest X-ray - 0.05 Rem

Radiation Limits	general population	0.5 rem/year	
	radiation worker	5.0 rem/year	250 rem Career
	Astronaut	50.0 rem/year	300 rem career

Galactic Cosmic Ray dose (free space) 40 - 100 rem/year ????

Center of Inner Radiation Belt 1000 Rem/hour
~1000 Km altitude.

Large Solar Flare >100 Rem/hour

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Figure 10

Omit

USE OF ACOUSTIC RESONANCES AND ELECTRICAL DISCHARGES FOR MOVING REGOLITH

Frank Barnes
Stein Sture

omit
70
P.318

Session Eight

STRUCTURES, DYNAMICS, CONTROL AND ASSEMBLY OF LARGE FLEXIBLE SPACE STRUCTURES

Martin M. Mikulas, Jr.,
Chair

STRUCTURES, DYNAMICS, CONTROL, AND ASSEMBLY

(OF LARGE FLEXIBLE SPACE STRUCTURES)

MARTIN M. MIKULAS, JR.

CENTER FOR SPACE CONSTRUCTION
ANNUAL SYMPOSIUM

University of Colorado
Boulder, Colorado

October 17,18, &19, 1990

STRUCTURES, DYNAMICS, CONTROL, AND ASSEMBLY

(AGENDA)

8:00 - 8:30	Martin M. Mikulas	Overview & Structural Considerations Associated With In-Space and Lunar Construction
8:30 - 9:15	Charbel Farhat	Large Scale Structural Dynamic Analysis & Verification
	- Greg Thorwald	On The Maneuvering of a Flexible Space Crane
	- Brian Reisenauer	Feedback Control of Space Crane During Repositioning
9:15 - 9:45	---------- BREAK ----------	
9:45 - 10:30	Mark Balas	Control of Flexible Structures
	- Roger Davidson	CSI Compensation With Adaptive Residual Mode Filters
10:30 - 11:00	Howard Snyder	Low-Gravity Fluid Mechanics
11:00 - 11:15	James Wade	Construction Interruptibility Studies

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OVERVIEW AND STRUCTURAL CONSIDERATIONS ASSOCIATED WITH IN-SPACE AND LUNAR CONSTRUCTION

Martin M. Mikulas, Jr.

In the absence of gravitational pull, the major design condition for large space structures is that of a transient dynamic load rather than the traditional static load associated with earth based structures. Because of the reduced loading in space, structures can be designed significantly lighter than their counterparts on earth. For example, the Space Shuttle remote manipulator arm is capable of positioning a 60,000 lb payload, yet weighs less than 1000 lbs. The significant reduction in weight of large space structures is commonly accompanied by a very low natural structural frequency that causes an unprecedented level of complexity for mission applications which require a high level of positioning and control accuracy. This problem is exacerbated by the large analytical models required for accuracy and by the interactive dynamic behavior caused by other disciplines such as fluids and thermal effects. Although Lunar-base structures must be designed for a gravitational load (one-sixth of earth's), the launch penalties for lunar structures are such that there is a large motivation to keep structural weight to a minimum. Thus, structural flexibility remains a concern. A major challenge identified in future space missions is that of construction. Construction studies of the Space Station Freedom have shown that proper construction aids are necessary to keep EVA man-hours to an acceptable level. Preliminary construction studies of various Lunar-base concepts indicate that construction equipment will again be an enabling factor.

This talk presents an overview of the research being conducted on structures and assembly aspects of large flexible in-space and Lunar-base structures in the Center for Space Construction. A short review is presented on results of past studies of construction of in-space structures with an emphasis on the Space Station Freedom. Finally, a presentation is given of recent studies being conducted to identify construction approaches and automated equipment for a lunar base.

OVER-VIEW

STRUCTURES, DYNAMICS, CONTROL, AND ASSEMBLY

(OBJECTIVE)

To Develop Technology For The Structural Evaluation Of Alternative In-Space And Lunar-Base Construction Concepts Including:

CONCEPTS - Identification and development of new structural concepts and construction aids

DYNAMICS - Interactive effects on dynamic performance of various enviornment and self generated disturbances

CONTROLS - Development of stable control algorithms, and design of effective combination of hierarchial and adaptive controls

FLUIDS - Development of validated analytical methods for low-g fluid/structure interaction

CONSTRUCTION - Development and evaluation of the effect of construction approaches, including interruptions, on structural design

STRUCTURES, DYNAMICS, CONTROLS, AND ASSEMBLY

(Major Focus Problems)

	Concepts	Dynamics	Controls	Fluids	Constructions Methods
S.S.Freedom		Past	Past	Current	Current
ISAAC Facility		Current	Current	Future	Future
Lunar Base Construction	Current	Future	Future	Future	Current
Mars Transfer Vehicle	Future	Future	Future	Future	Future
?					

STRUCTURES, DYNAMICS, CONTROLS, AND ASSEMBLY

(Major Experimental Interactions)

	Concepts	Dynamics	Controls	Fluids	Constructions Methods
TRW			Current		
Martin Co			Current		
USAF Academy			Future		
Mini Mast			Past		
MIT MODE				Future	
EASE/ACCESS					Past
CSI		Current	Current		
LaRC Space Crane		Current	Current	Future	Future
U. Co. Lunar Crane	Current	Future	Future	Future	Future
U. Co. T.B. Truss	Current	Future	Future	Future	

STRUCTURES, DYNAMICS, CONTROL, AND ASSEMBLY

(Near Term Goals ~ 1 Yr)

CONCEPTS	- Identify and analyze concepts for a Lunar based crane for automated construction
DYNAMICS	- Demonstration of large flexible body slewing codes as analytical testbed
CONTROLS	- Quantify benefits of distributed/adaptive control approach over conventional approaches for large angle excursions and automated construction
FLUIDS	- Establish guidelines for criticality of interdisciplinary interactions such as thermal/dynamic and low-g fluid/structural dynamics
CONSTRUCTION	- Analyze the problem of interruptions during assembly in space and identify optimal feasible approaches
ALL	- IDENTIFY AND DEVELOP INTERDISCIPLINARY TESTBEDS

STRUCTURES, DYNAMICS, CONTROL, AND ASSEMBLY

(Intermediate Goals ~ 2 Yrs)

CONCEPTS - Select promising concept for lunar based crane and quantify significant structural parameters

DYNAMICS - Application of large scale finite element analysis to the nonlinear dynamic response of a highly flexible space crane

CONTROLS - Develop high-order simulation of actively controlled structures; Test candidate controllers on laboratory structure experiment

FLUIDS - Develop models of fluid management processes considered enabling and use in trade-off studies to determine optimal system

CONSTRUCTION - Incorporate interruptibility with DYCAM for construction analysis

ALL - CONSTRUCT AND OPERATE INTERDISCIPLINARY STRUCTURAL TESTBEDS

IN- SPACE CONSTRUCTION

POTENTIAL ON-ORBIT CONSTRUCTION APPROACHES

1 - COMPLETELY DEPLOYABLE SPACECRAFT

2 - MODULAR SPACECRAFT

3 - COMPLETELY ERECTABLE SPACECRAFT

4 - HYBRID SPACECRAFT

- Large Integrated Components
- Pressure Vessels
- Modules
- Erectable And/Or Deployable Trusses

PRIMARY DESIGN DRIVERS FOR LARGE SPACE STRUCTURES

MAJOR COST FACTORS	MAIN ELEMENTS
DESIGN DEVELOPMENT AND FLIGHT QUALIFICATION	STRUCTURAL PREDICTABILITY SUBCOMPONENT GROUND TESTS RELIABITY OF CONSTRUCTION
FABRICATION	COMMONALITY PART COUNT
LAUNCH	LOW WEIGHT COMPACT STOWAGE
ON-ORBIT CONSTRUCTION	CONSTRUCTION TIME RELIABILITY & MAINTENANCE COMMONALITY CONSTRUCTION FACILITY

CURRENT SPACE STATION IS BASIS FOR AN INTEGRATED CONSTRUCTION SYSTEM

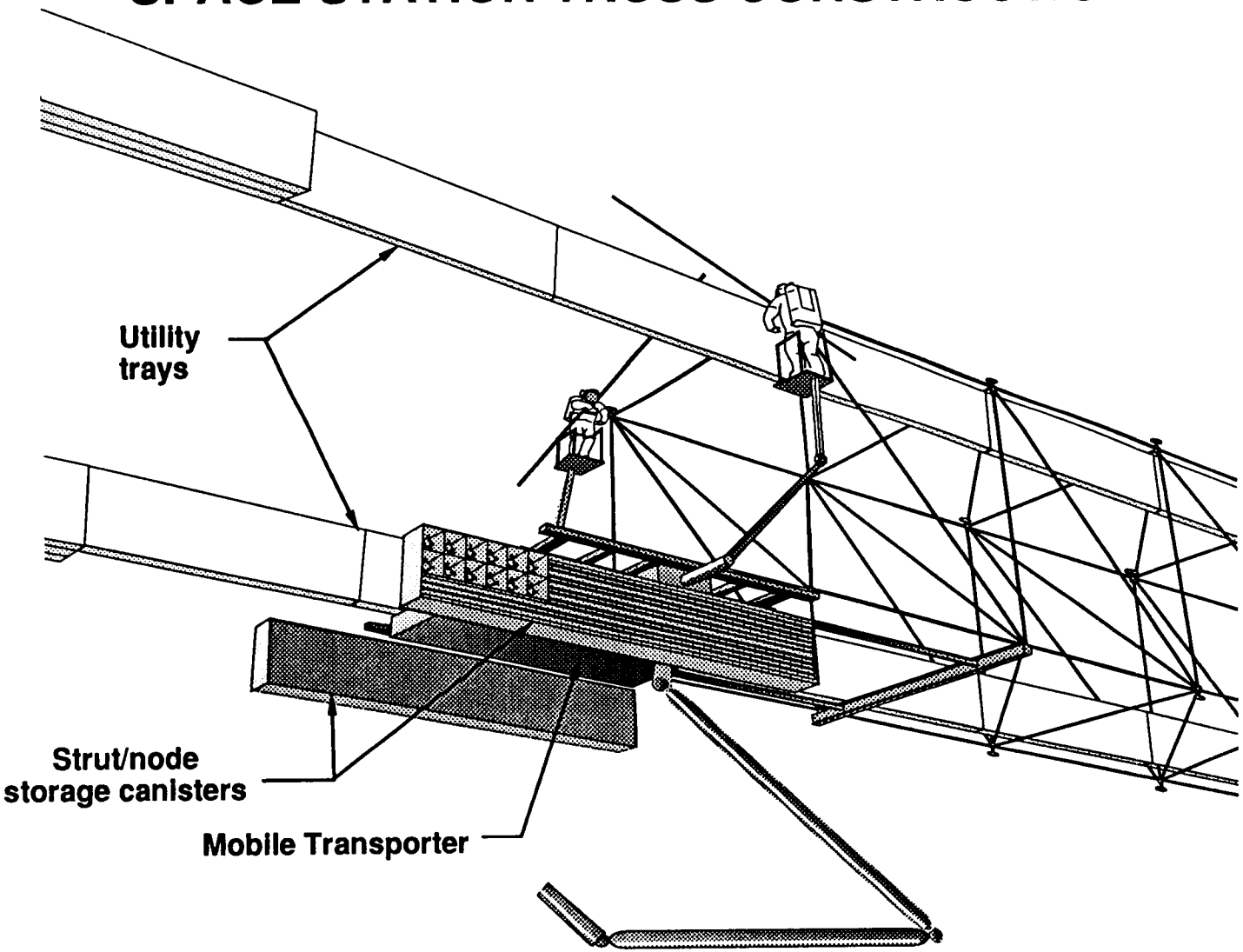
o 5 METER ERECTABLE SPACE STATION

- Expandable To Meet Construction Needs
  (Truss Is Construction Scaffolding)
- Stiff Truss To Minimize Disturbances
- Truss Can Be Used To Build Protective Shelters
- Truss Is Roadbed For Transporter

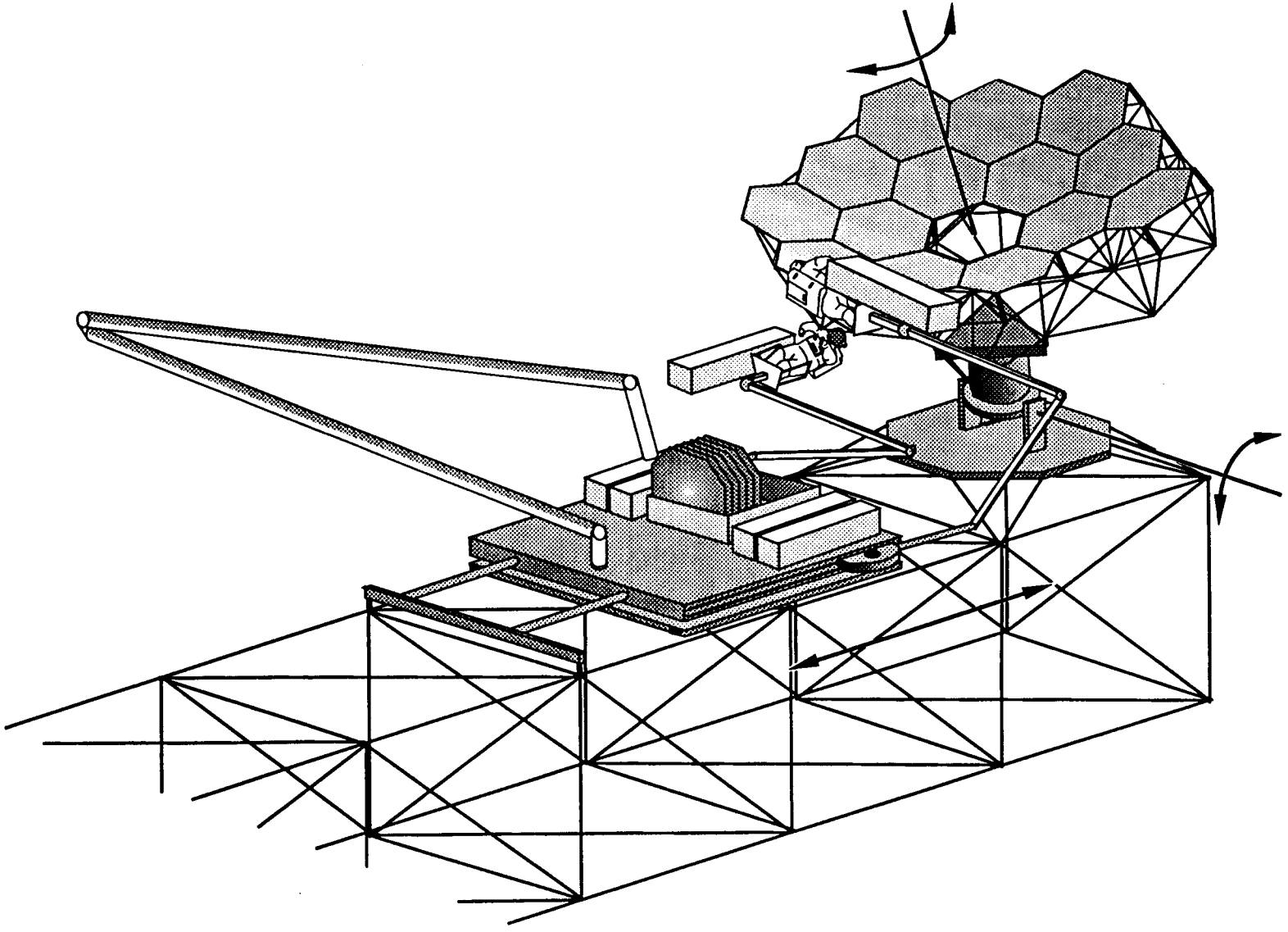
o MOBILE TRANSPORTER

- Used In Constructing The Station
- Used For Station Maintenance And Repair
- Provides Controlled Transport And Positioning Of Payloads
- Shuttle "Free-Flying" Not Required
- Basic Construction Aid For Other Spacecraft
- Enabling Capability For Automated Construction Operations

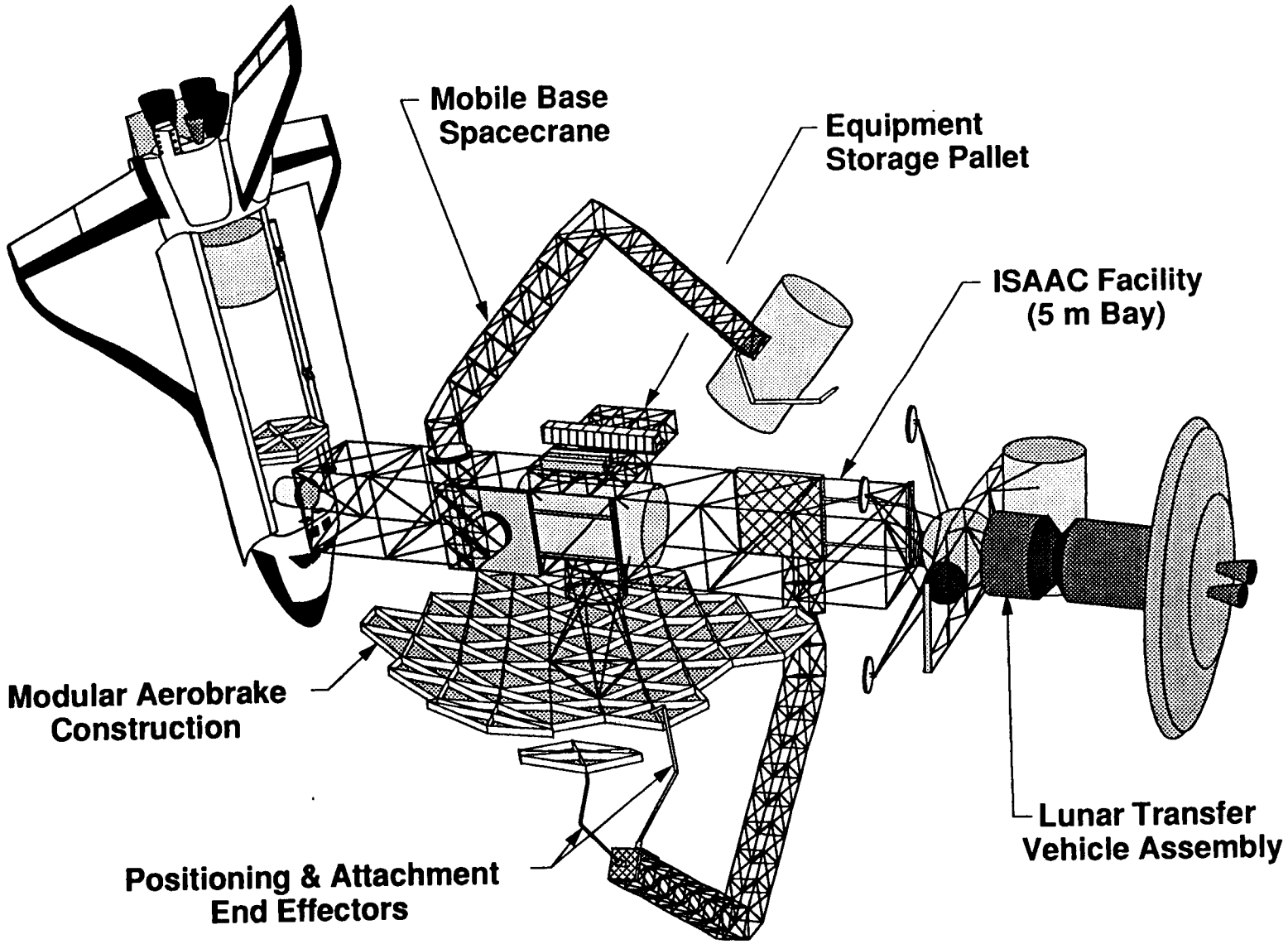
MOBILE TRANSPORTER CONFIGURED FOR SPACE STATION TRUSS CONSTRUCTION



CONSTRUCTION OF PRECISION REFLECTOR USING MOBILE TRANSPORTER



IN-SPACE ASSEMBLY AND CONSTRUCTION FACILITY CONCEPT



LESSONS LEARNED TO DATE ON IN-SPACE CONSTRUCTION

DEPLOYABLE SPACECRAFT

- Numerous "simple" mechanical failures
- Difficult to build redundancy into mechanical systems
- Concept must be well demonstrated before it will be used

SPACE STATION FREEDOM

- Truss construction is small portion of assembly time
- Utilities,system installation, and maintenance are major time sinks
- Manipulator arm flexibility and control, drive construction time
- Automated construction needs significant development

ACCESS/SPACE STATION/PATHFINDER

- Proper construction aid (equipment) is heart of construction process

LUNAR-BASE CONSTRUCTION

LUNAR SURFACE CONSTRUCTION ISSUES

O <u>SIZE AND MASS OF CONSTRUCTION ELEMENTS</u>

- Similar to deployable/erectable/modular issue for orbital construction
- Where should construction take place? - Earth?, Earth-orbit?, Lunar surface?
- Highly emotional area with no shortage of opinions

O <u>ROLE OF HUMANS IN CONSTRUCTION</u>

- Basic assumption is that human role is primarily supervisory

O <u>TYPE AND SIZE OF CONSTRUCTION TOOLS</u>

- Major drivers
  - Size of surface base
  - Mass of construction elements
  - Reliabilty and maintenance under adverse conditions (vaccumn, abrasion,etc.)
  - Construction time

LUNAR SURFACE CONSTRUCTION NEEDS

O <u>CONSTRUCTION STRUCTURAL ELEMENTS (MODULES)</u>

- Establish construction requirements
- Develop various structural concepts
- Develop design and analysis capability for structural elements
- Quantify characteristics of structural concepts

O <u>ROLE OF HUMANS IN CONSTRUCTION</u>

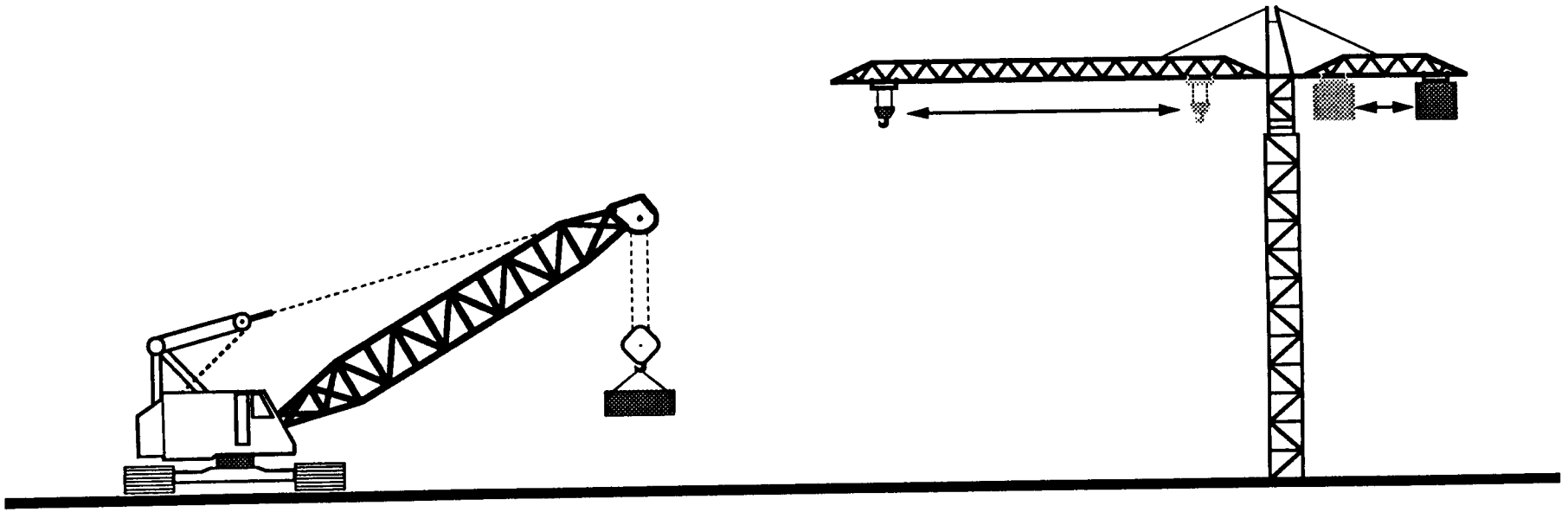
- Develop and simulate realistic construction scenarios
- Conduct construction tests

O <u>CONSTRUCTION TOOLS</u>

- Establish construction requirements
- → Develop construction tool concepts
- Develop design and analysis capability for construction tools including:
  - Dynamics and strength
  - Active control
  - Fluid motion

O DEVELOP FULLY AUTOMATED CONSTRUCTION SCENARIOS AND CAPABILITY

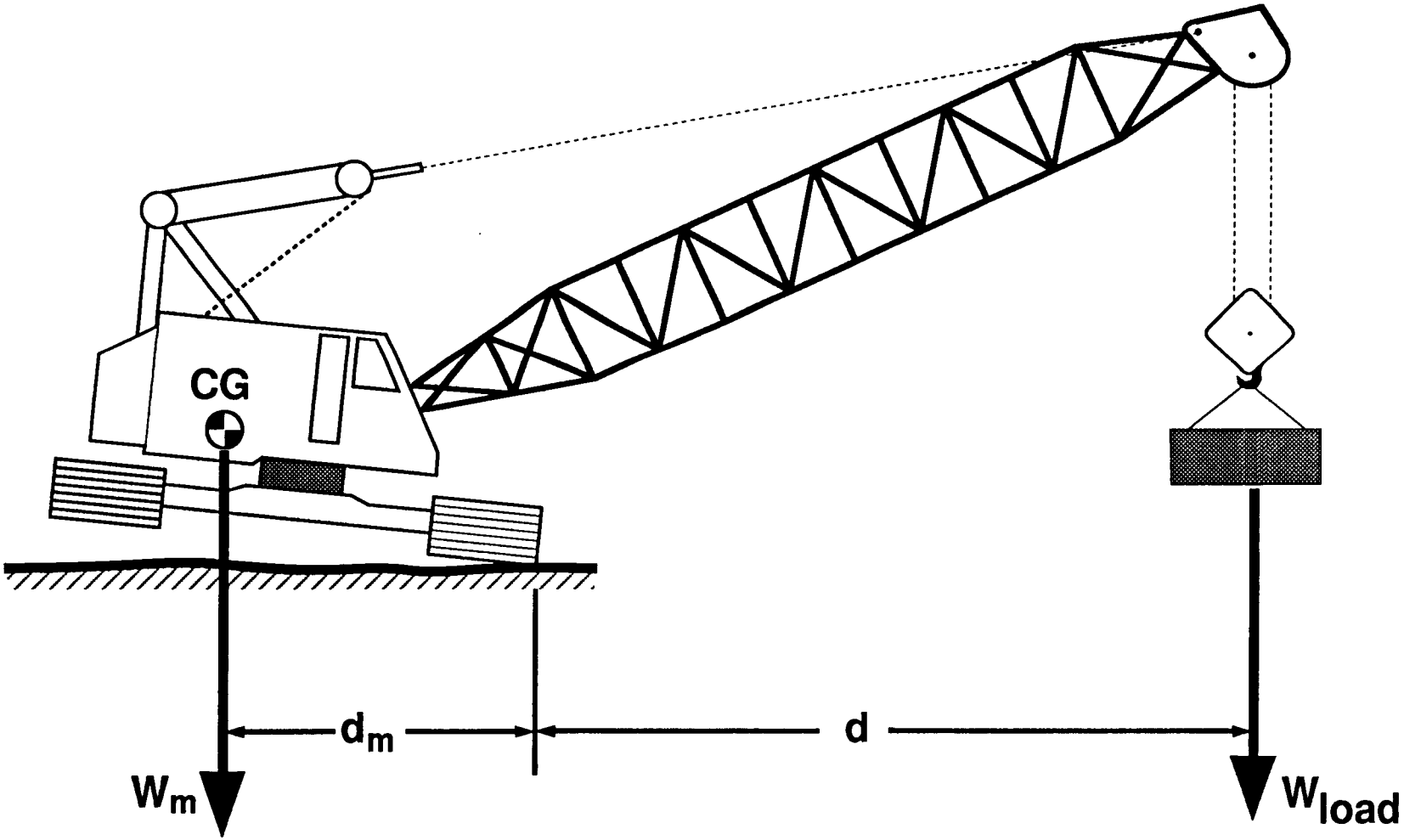
MAJOR CLASSES OF CRANES CONSIDERED



MOBILE

STATIONARY TOWER

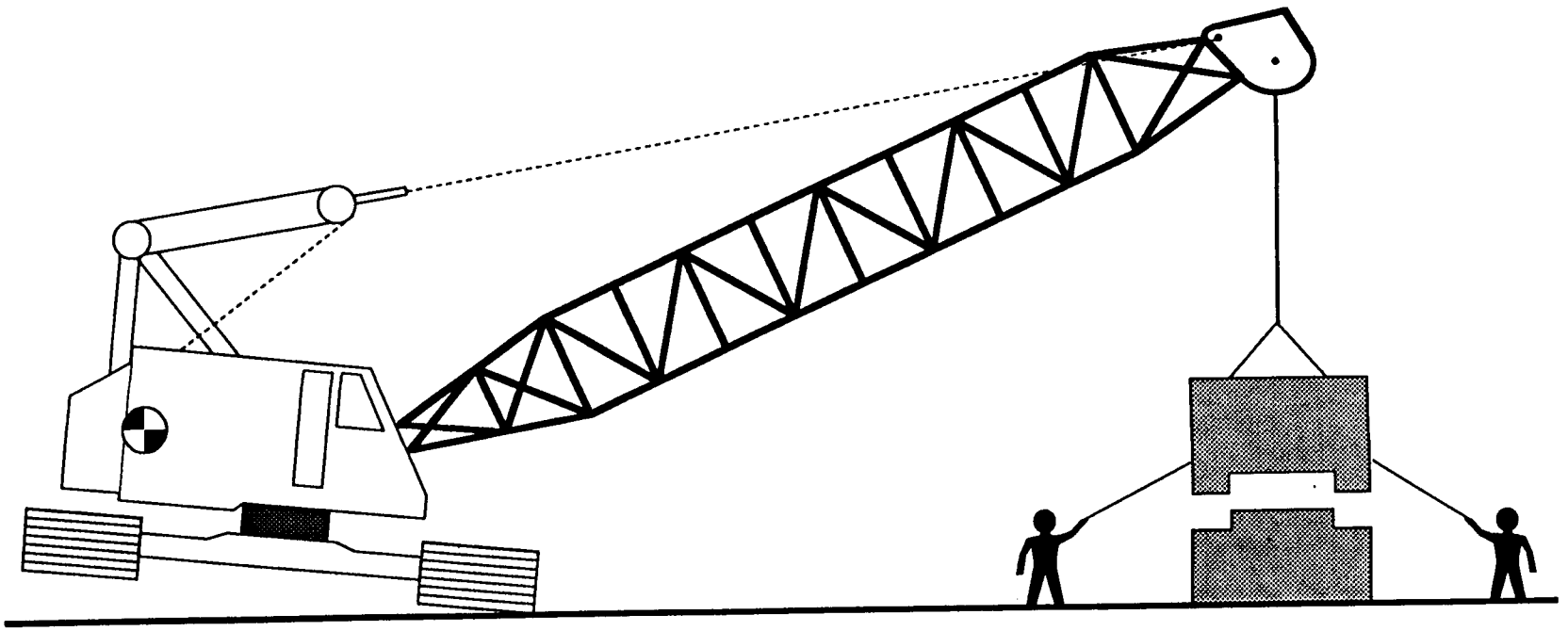
MOBILE CRANE MAJOR DESIGN CONSIDERATION IS MASS REQUIRED TO OFFSET OVERTURNING MOMENT



$$W_m \times d_m = W_{load} \times d$$

$$W_m = \frac{80}{20} \cdot 60{,}000 = 240{,}000 \text{ Lbs}$$

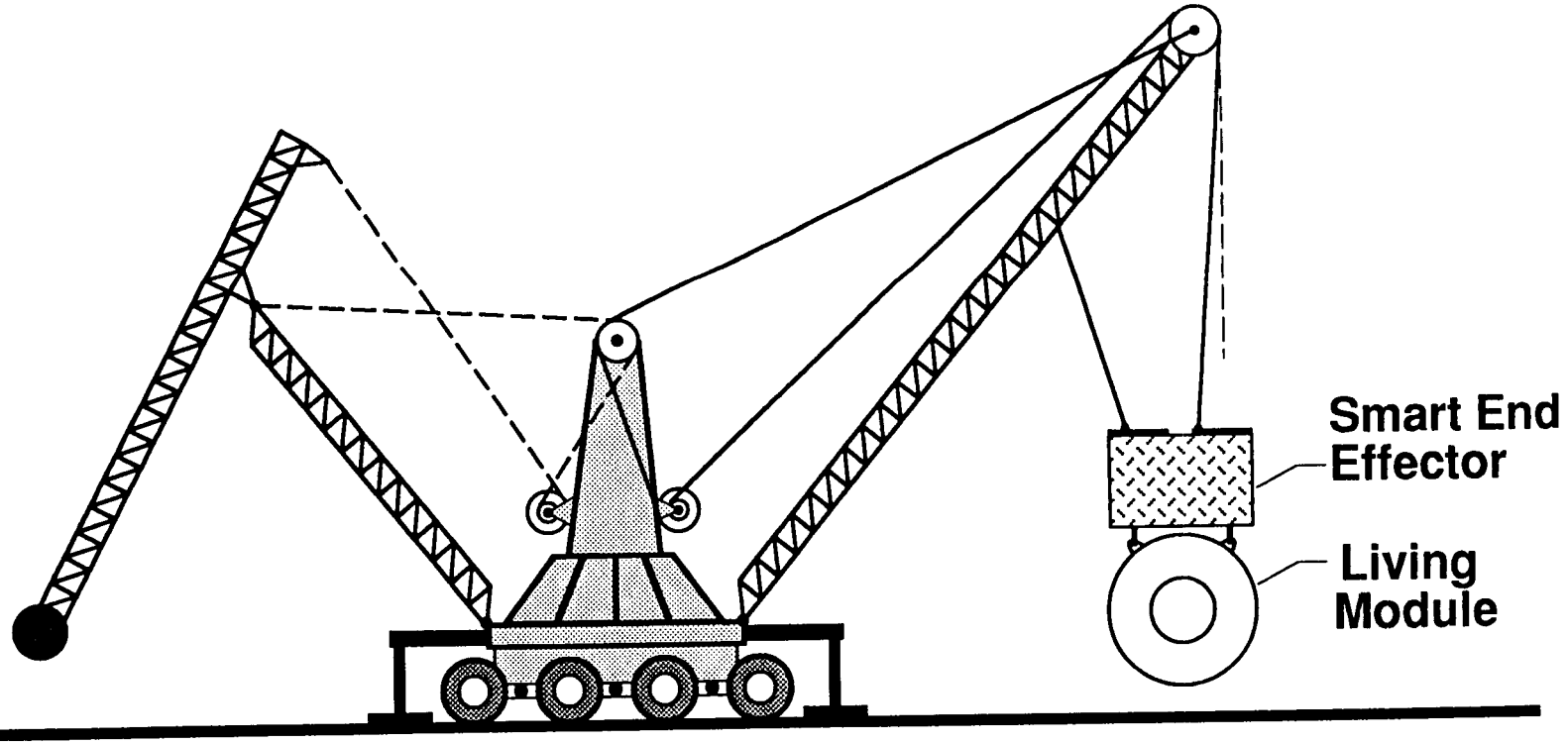
TYPICAL MOBILE CRANE HAS TWO MAJOR SHORTCOMINGS FOR LUNAR BASE APPLICATION



1) Very large mass required to resist tipping

2) Human guidance required for accurate positioning

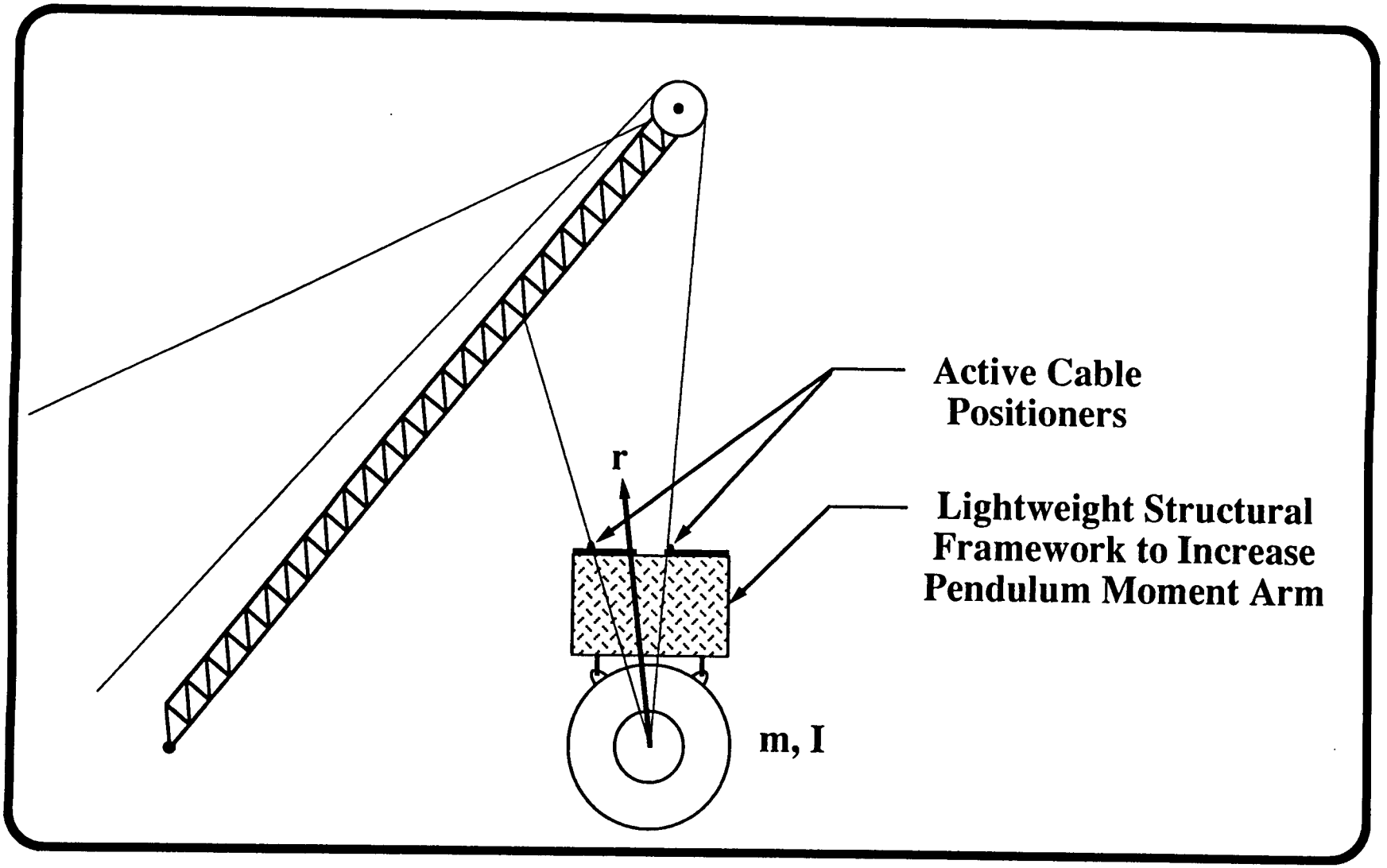
COUNTER-BALANCED ACTIVELY-CONTROLLED LUNAR CRANE INCORPORATES TWO NEW FEATURES FOR IMPROVED PERFORFORMANCE



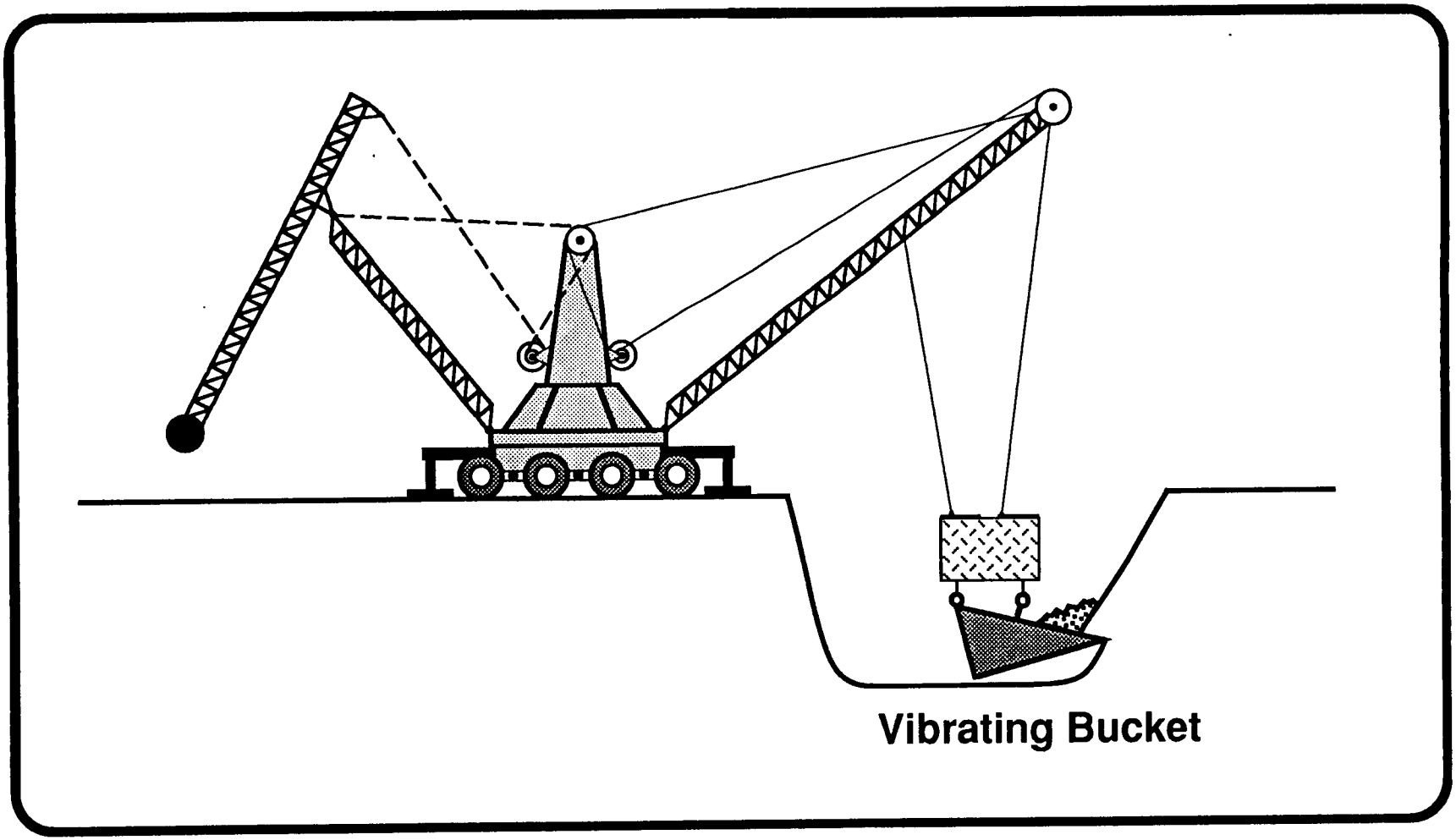
1) Active Counter Weight to Reduce Overturning Moment

2) Multiple Payload Suspension Cables to Provide Stable Precision Positioning

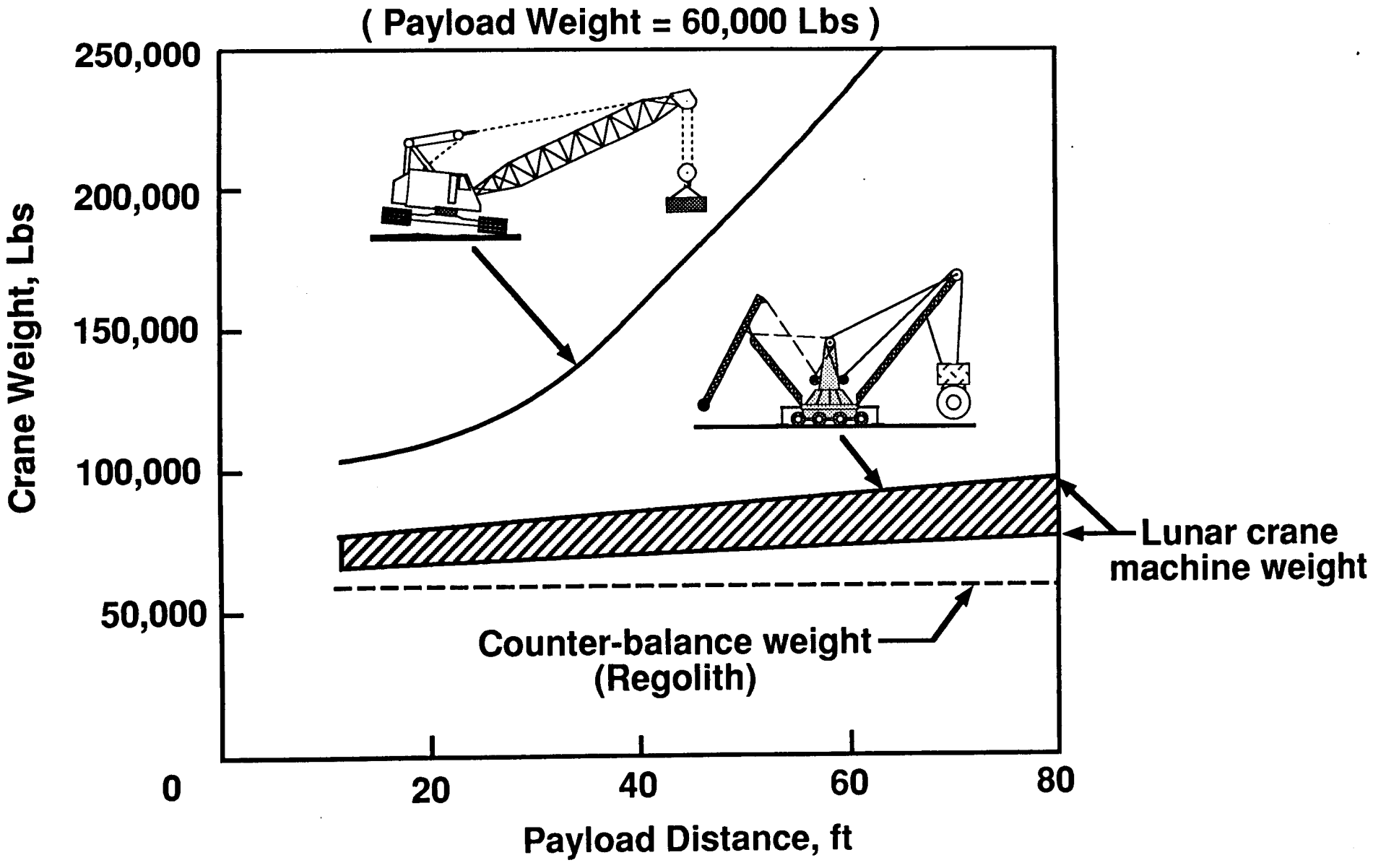
LUNAR CRANE PENDULUM MECHANICS



LUNAR CRANE CAN PROVIDE EXCAVATING CAPABILITY USING A VIBRATING EXCAVATOR



COUNTER-BALANCED LUNAR BASE MOBILE CRANE WILL WEIGH ORDER-OF-MAGNITUDE LESS THAN EARTH BASED TYPE MOBILE CRANE



CURRENT NEAR TERM LUNAR BASE AUTOMATED CONSTRUCTION TASKS

IDENTIFY CONSTRUCTION REQUIREMENTS

- Lunar-Base Size & Operations
- Robotics & EVA
- Structural concepts (erectable, deployable, modular, inflatable, etc.)

ESTABLISH CHARACTERISTICS OF EARTH BASED EQUIPMENT

- Weight (mobile gear, turret, boom, cables, etc.)
- Performance parameters (payload, operation distance, speed, precision)

DEVELOP LUNAR BASE AUTOMATED CONSTRUCTION DEVICE

- Explore several concepts
- Quantify weight and stiffness
- Conduct dynamic simulation
- Develop and apply control algorythm
- Design testbed

UPDATING FINITE ELEMENT STRUCTURAL MODELS USING A FEW SENSORS

Charbel Farhat
Francois Hemez

A rational procedure for large scale structural dynamic linear analysis-test correlation is introduced. Unlike most published work in this area, this procedure requires that only a few degrees of freedom of the structure be measured -- that is, only a few sensors are needed to carry out the dynamic tests. Because the procedure is iterative, a formal mathematical proof of convergence is given and its efficiency is illustrated with simple structural examples. A prototype code is currently being developed to tackle real-life large-scale structures.

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ON THE MANEUVERING OF A FLEXIBLE SPACE CRANE

Mark Balas
Charbel Farhat
Brian Reisenauer
Greg Thorwald

The design of an articulated space crane under NASA's "Pathfinder" program continues to push forward. However, the large size and extreme flexibility of the crane entail major difficulties in precision positioning. To illustrate this and to gain more insight into its structural dynamic behavior, we have built three-dimensional rigid, flexible, homogenized and non-homogenized finite element models (FEM) of the articulated space crane and simulated its three-dimensional maneuvering. We have also begun to develop control strategies for the flexible system using first a simplified finite element model. The model captures much of the system's low frequency characteristics. From the FEM, a reduced-order model (ROM) based controller is designed based on a specific configuration of the crane. The ROM controller rotates the fixed shape crane about the alpha joint and uses three torque wheels at the tip to actuate its control law. Our analysis of the closed-loop system shows the de-stabilizing effect of control interaction with unmodeled system dynamics (Controller-Structure-Interaction). Making use of a parallel bank of residual-mode filters (RMF), we are able to compensate for C.S.I. and restore system stability and performance. The implementation of the discrete-time control law on the simplified multi-body model is completed using the SAMCEF code.

ON THE MANEUVERING OF A FLEXIBLE SPACE CRANE

MARK BALAS, CHARBEL FARHAT, BRIAN REISENAUER AND GREG THORWALD

Department of Aerospace Engineering Sciences
and Center for Space Structures and Controls
University of Colorado at Boulder
Boulder, CO 80309-0429

GOALS

1. Specific Structure: Space Crane

2. Challenging Issues:
   - Flexible structure
   - Low frequency modes
   - Crane maneuvering
   - Vibration supression

3. Focus on Numerical Simulation Tools:
   - Multibody dynamic simulation
   - Control computation module
   - Preprocessor to input structure and maneuvers
   - Postprocessor to view results usefully

DEVELOPMENT OF CRANE MODEL

1. 2D Rigid and Flexible—easiest

2. 3D Rigid—must now handle rotation matrix correctly
   3D Flexible—need accurate beam model

3. 3D Truss—emulate full structure

4. Actuators—model the control mechanisms

USE OF EXISTING SOFTWARE

1. Rigid body and flexible beam elements

2. Kinematic joint elements

3. Useful, but may be a black box approach

4. May not allow for addition of specialized elements

5. May not allow for addition of computational modules; i.e. control.

MANEUVERING / CONTROL

1. Inverse Kinematics; joint angles as a function of tip position.

2. Open-loop torque command as a realistic control method?
   (one d.o.f. example)

3. Closed-loop control is an alternative.
   Offers simultaneous maneuvering and vibration control.

ONE D.O.F. EXAMPLE

1. Given velocity, $u'(t)$, for $0 < t < T$
2. Determine acceleration and position by differentiation and integration.
3. Use the equation of motion to compute the applied force.

$$f(t) = mu''(t) + cu'(t) + ku(t)$$

4. The dynamic response using the computed force will return the given specified data.

5. This method, however, would be impractical for a many d.o.f. coupled structure; an alternative is needed.

DYNAMIC BEHAVIOR COMPARISON

1. Similar Rigid and Flexible Structures, 3-Link chain

2. Same applied torque to each structure

3. Observe dissimilar tip motion
   (animation of results)

4. For a maneuvering flexible structure, closed-loop control is needed.

OBSERVATIONS

1. Need to add more complicated joint elements; such as the alpha joint, and hinge actuators.

2. Simulation software should allow for the modular addition of closed-loop control.

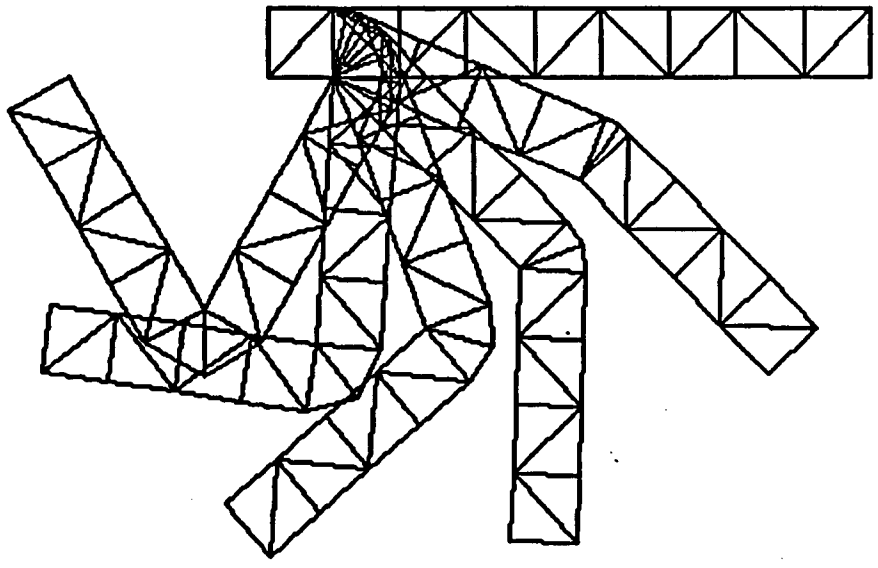
3. Develop an interface to allow for easy entry of specified maneuver data.

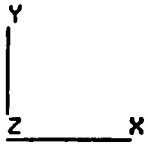
FUTURE DEVELOPMENTS

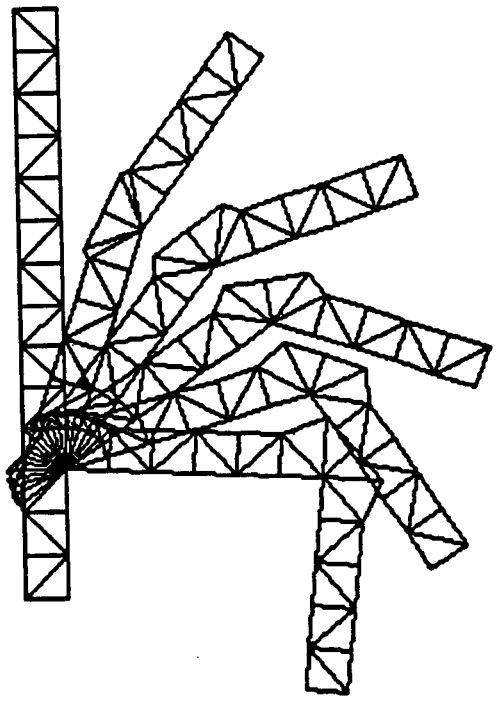
1. Further determine the requirements and benefits of a 3-D truss model.

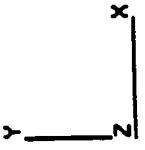
2. Study the effects on the dynamics and maneuvering control for a crane attached to a free-flying base.

2-D truss kinematic response

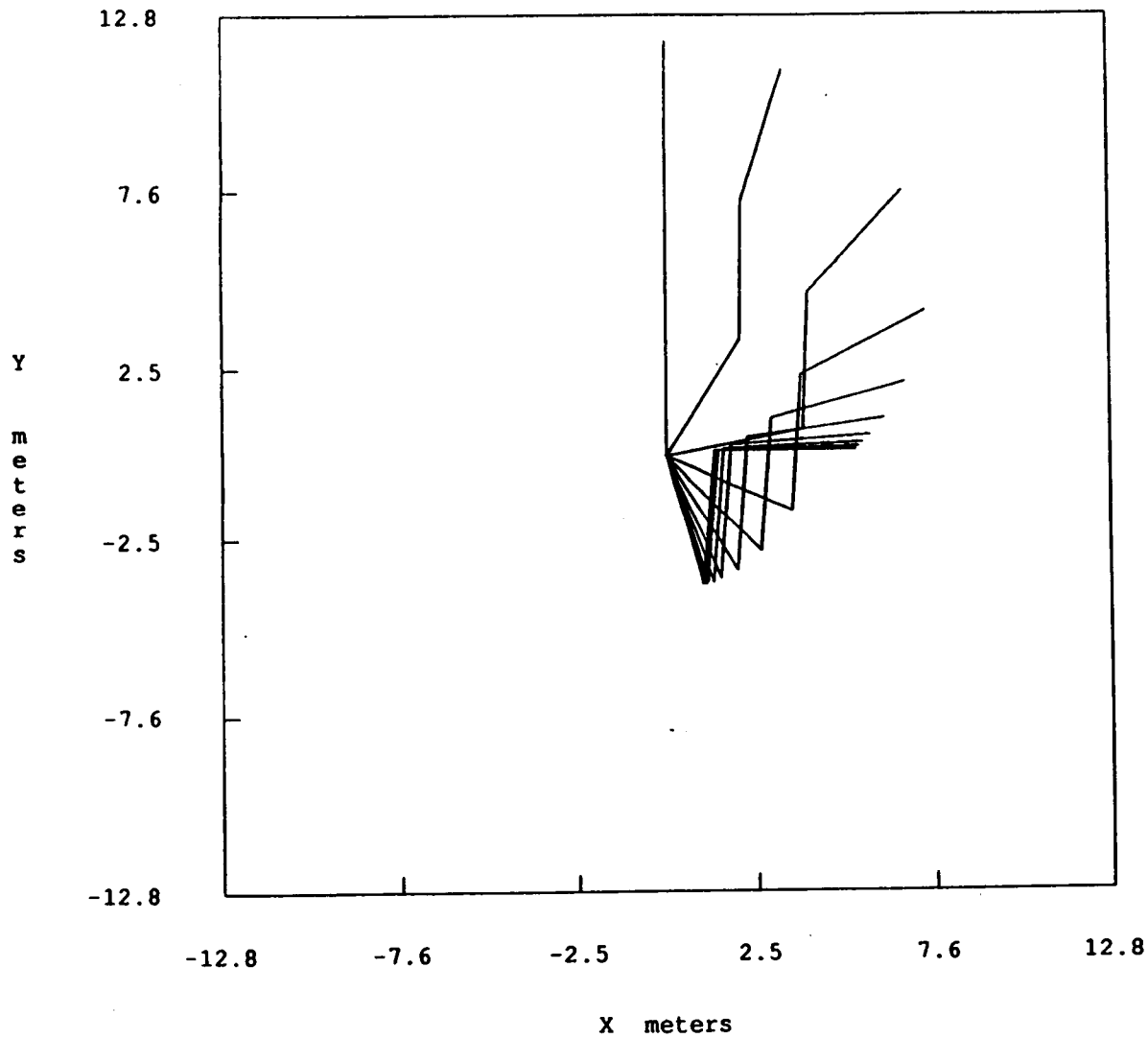




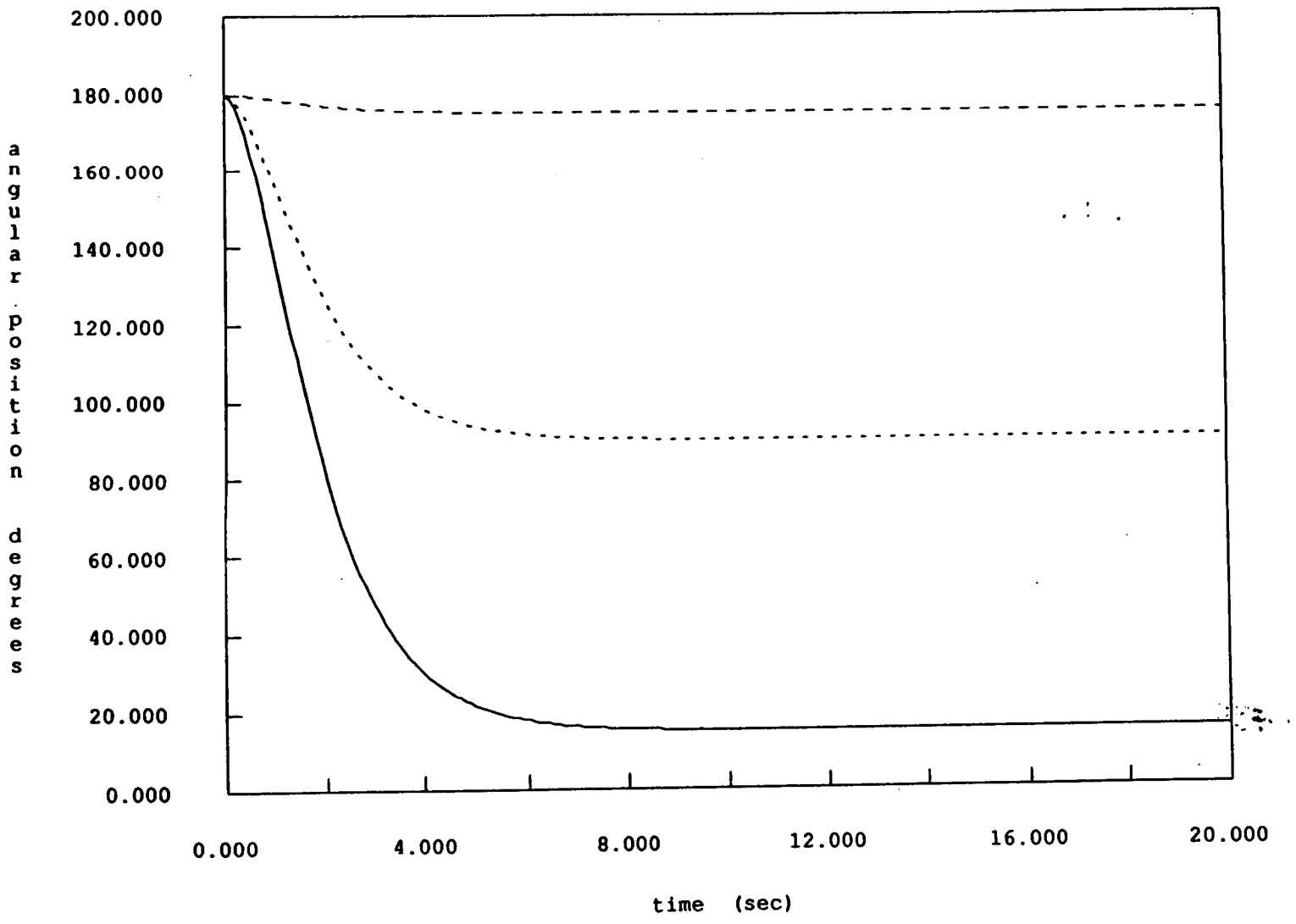



X
Y
Z

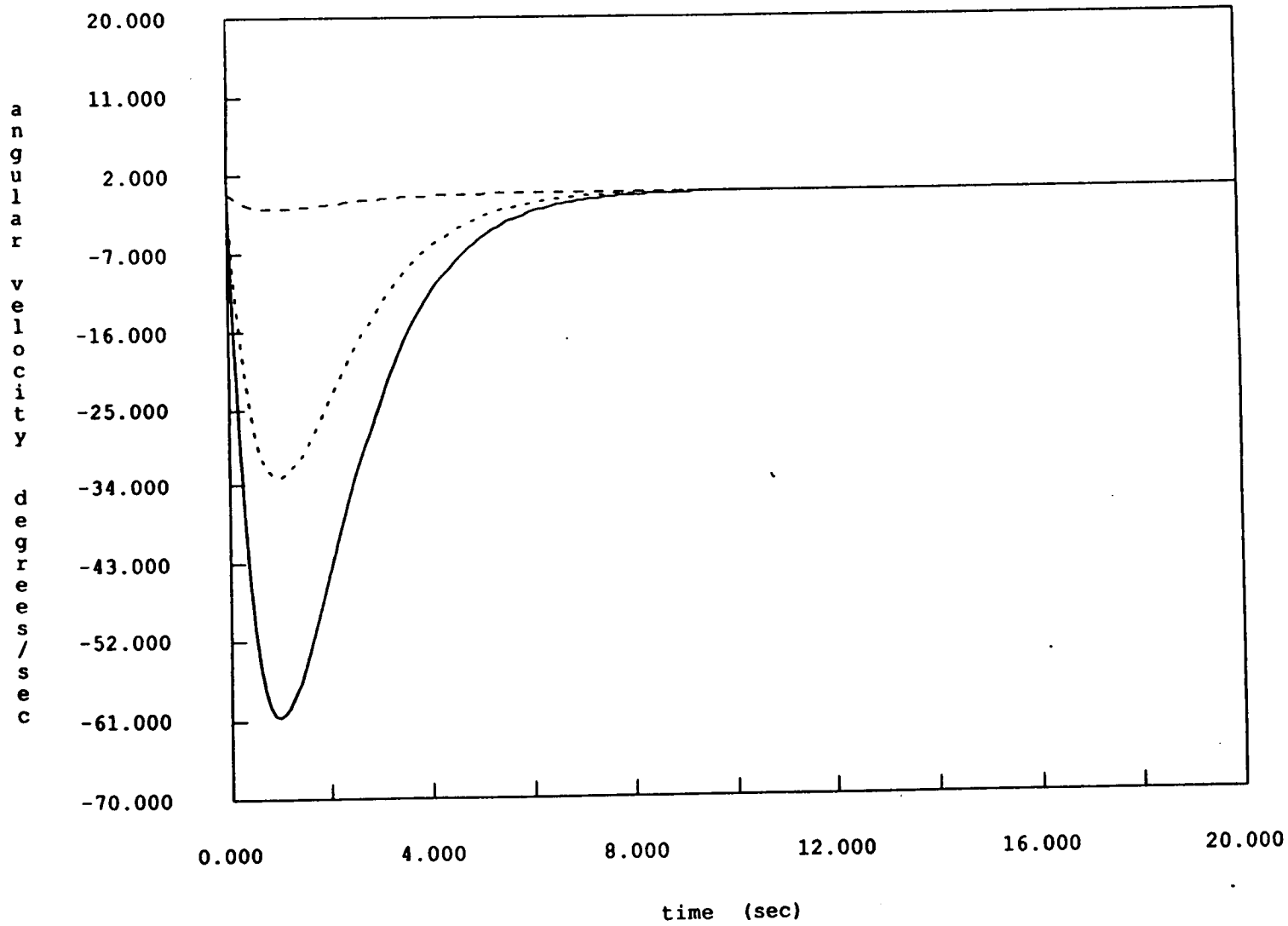
Arm Motion



multi-body pendulum; angular position vs time



multi-body pendulum; angular velocity vs time



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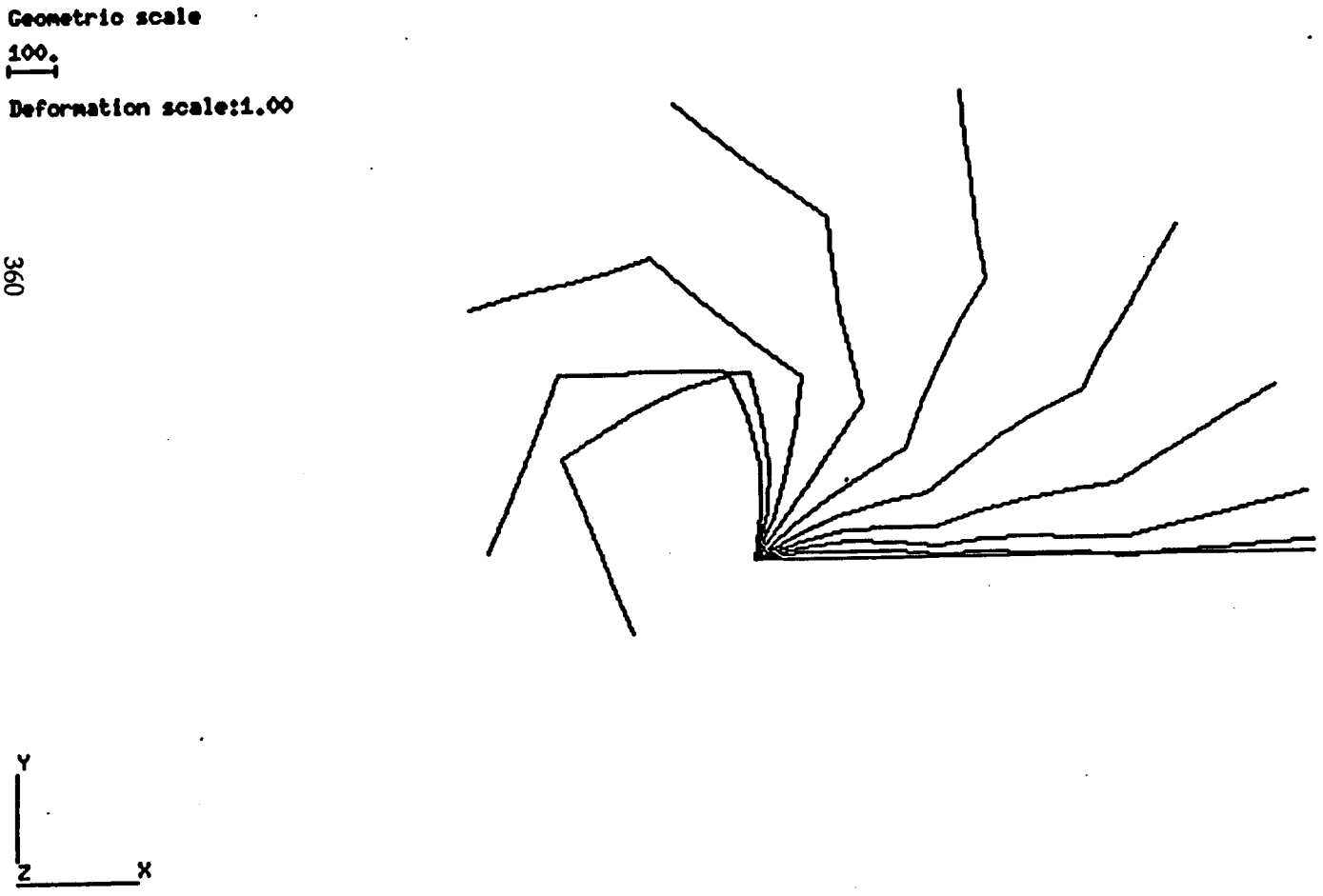
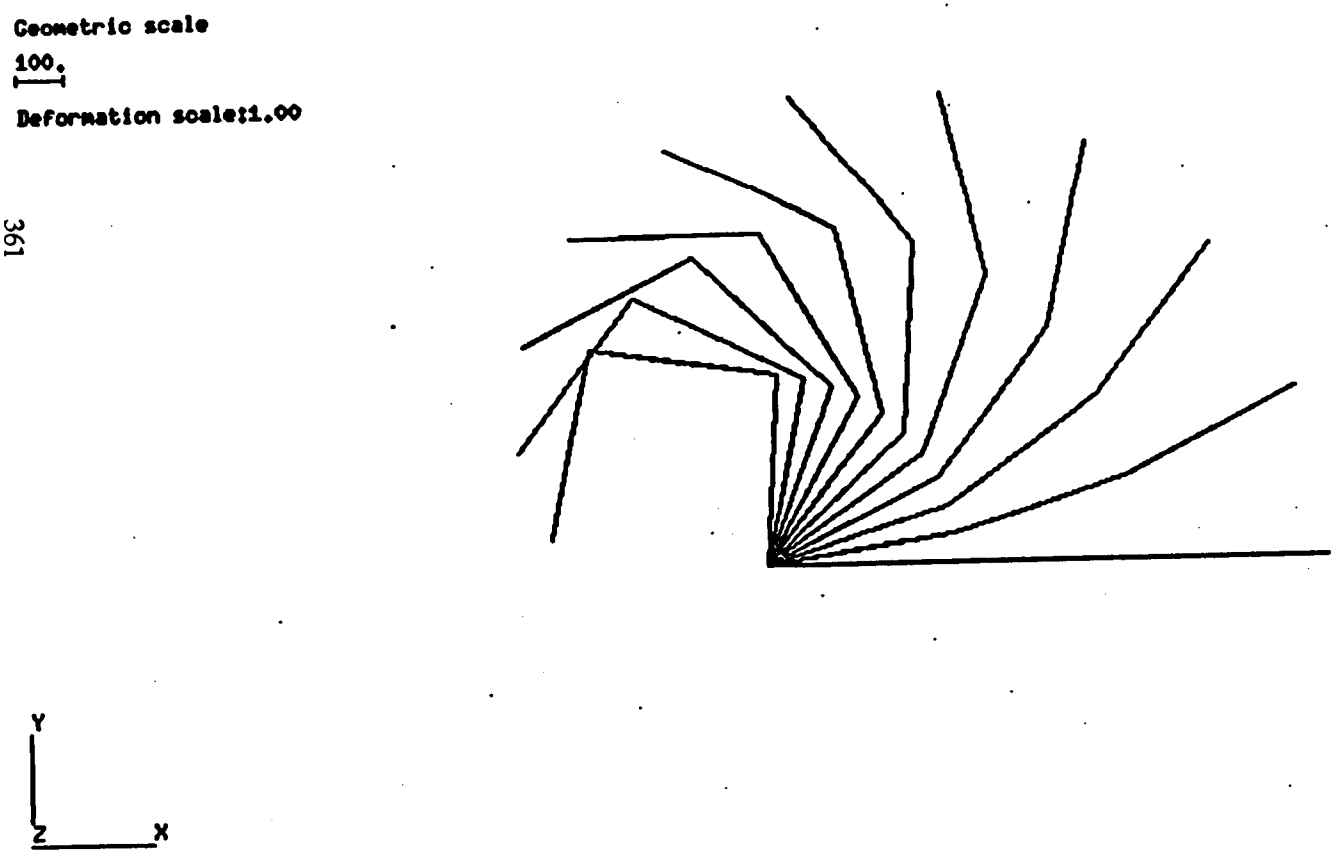
2-D flexible model response



2-D rigid model response



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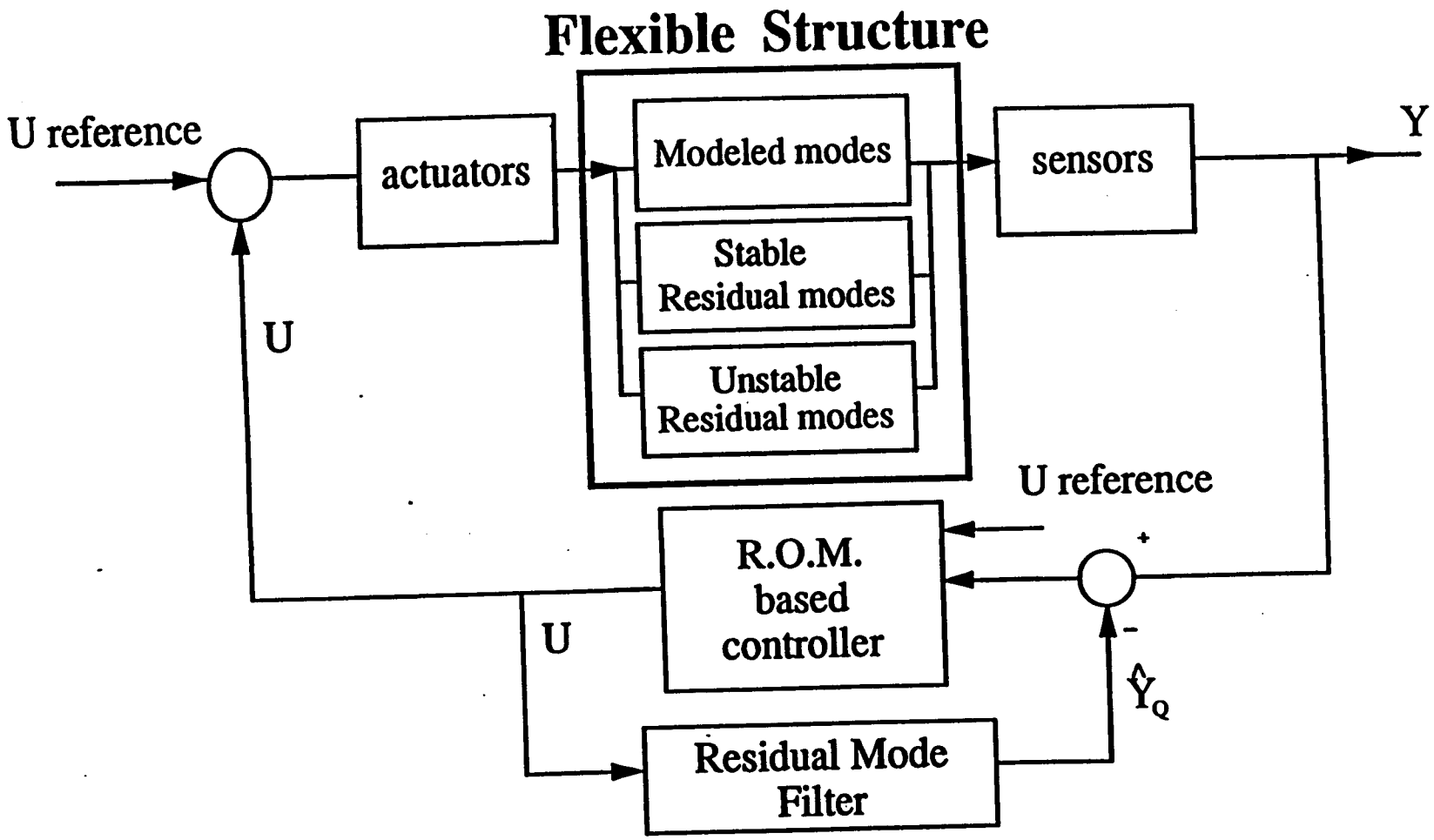
ROM/RMF CONTROL OF THE ARTICULATED-TRUSS SPACE CRANE

Brian T. Reisenauer

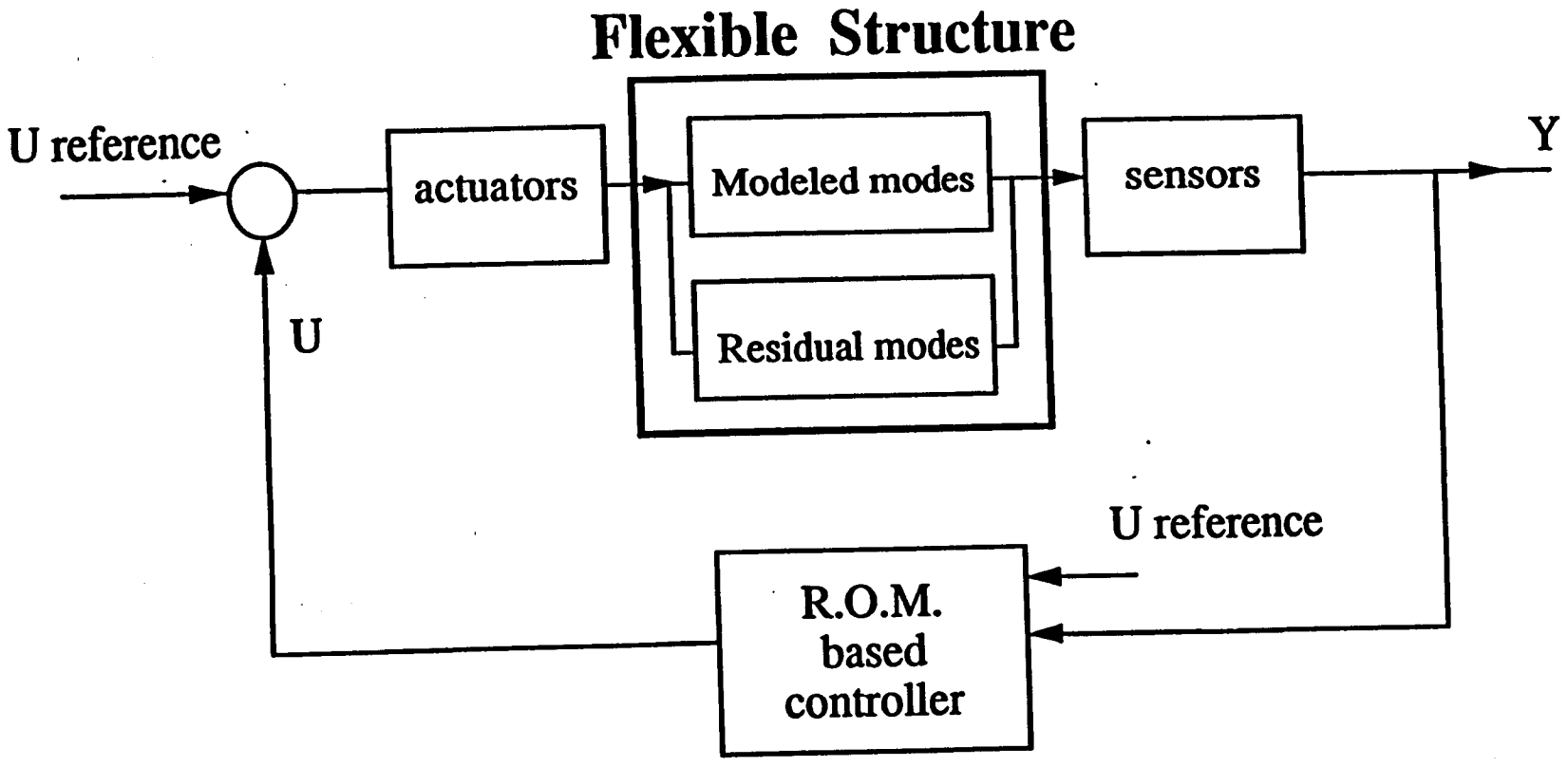
The design of an articulated space crane under NASA's "Pathfinder" program continues to push forward. However, the large size and extreme flexibility of the crane entail major difficulties in precision positioning. We have begun to develop control strategies for the flexible system using a simplified finite element model. The model captures much of the system's low frequency characteristics. From the FEM, a reduced-order model (ROM) based controller is designed based on a specific configuration of the crane. The ROM controller rotates the fixed shape crane about the alpha joint and uses three torque wheels at the tip to actuate its control law. Our analysis of the closed-loop system shows the de-stabilizing effect of control interaction with unmodeled system dynamics (Controller-Structure Interaction). Making use of a parallel bank of residual-mode filters (RMF), we are able to compensate for C.S.I. and restore system stability and performance. Finally, the implementation of the discrete-time control law on the simplified multi-body model is completed using SAMCEF.

ROM/RMF Control of Large Flexible Structures



- Develop R.M.F. as a bank of parallel second-order filters; one filter for each unstable residual mode.
- R.M.F. interrupts the control loop around all unstable residual modes; R.O.M control input is screened.
- R.M.F. compensates for C.S.I., insuring system stability.

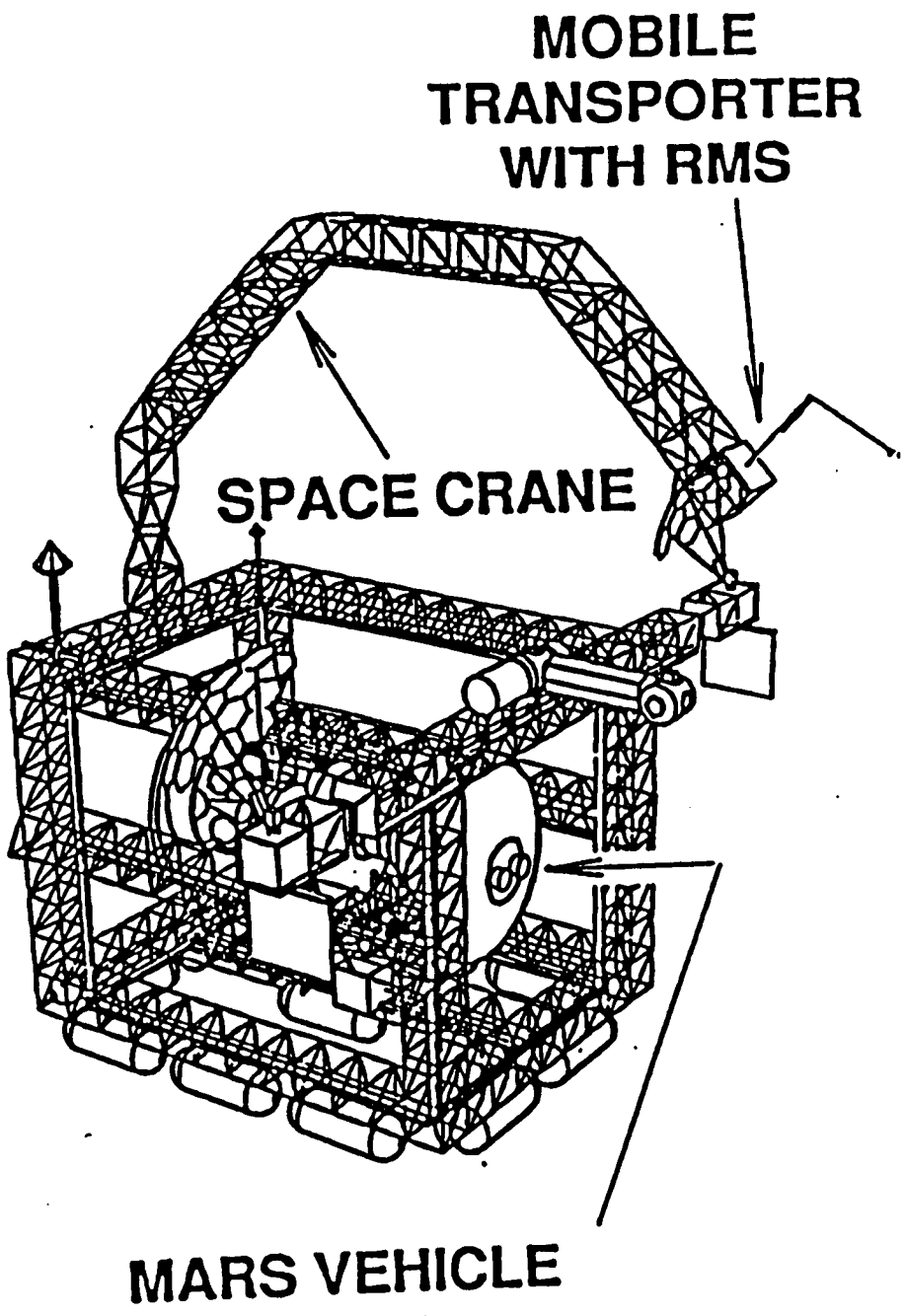
ROM-based Control of Large Flexible Structures

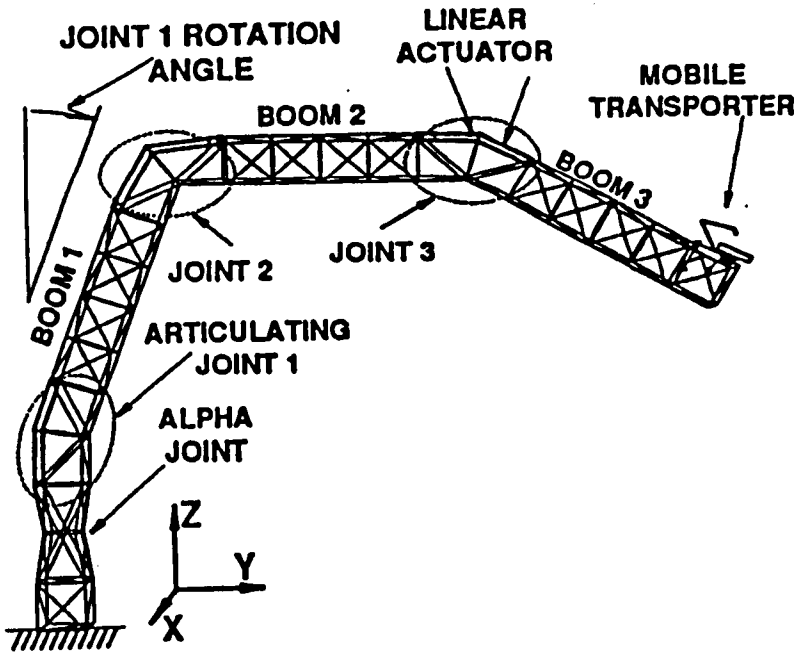


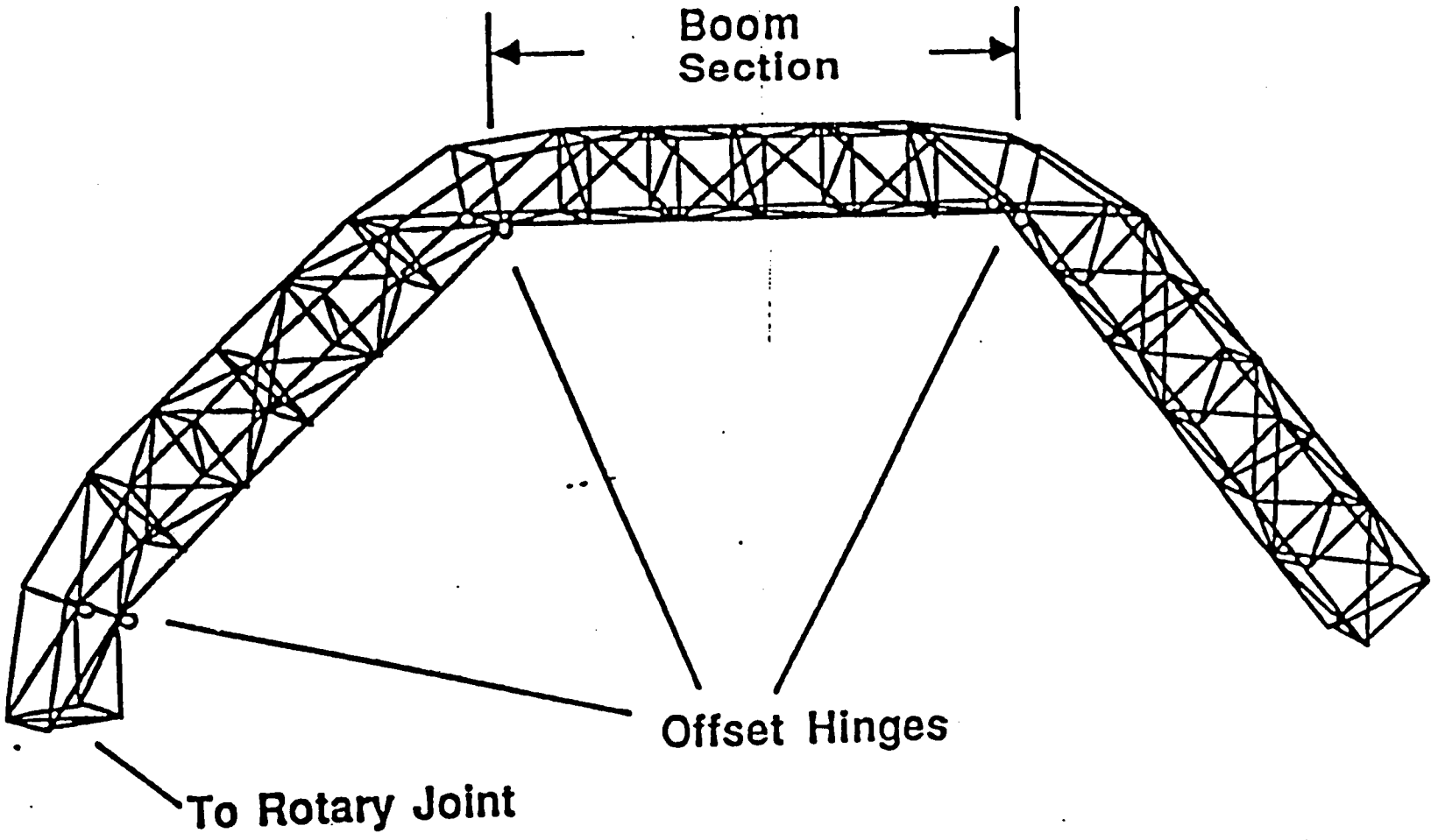
- Develop a R.O.M. controller, designed for performance.
- Dimension of the controller << dimension of the structure.

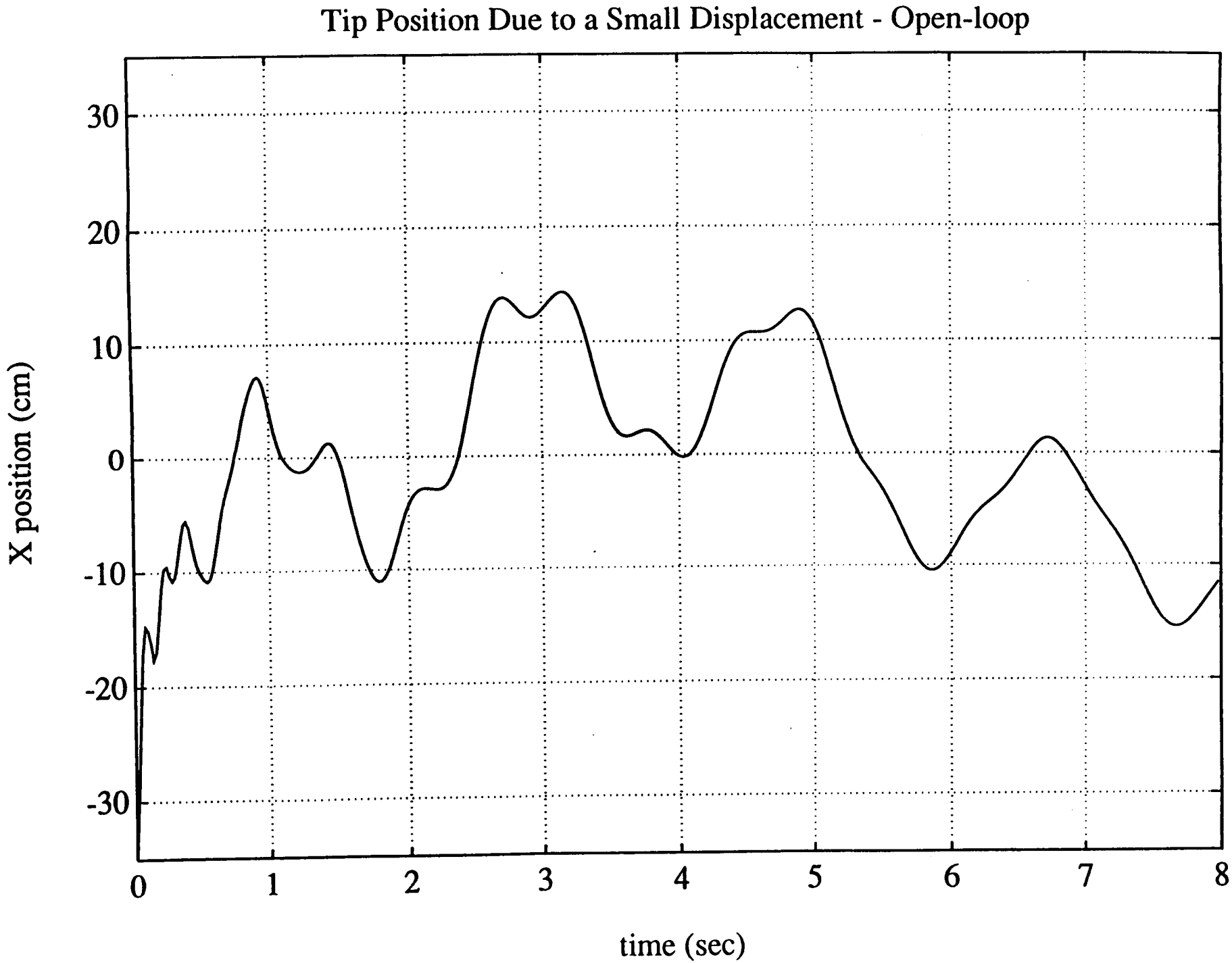
BUT

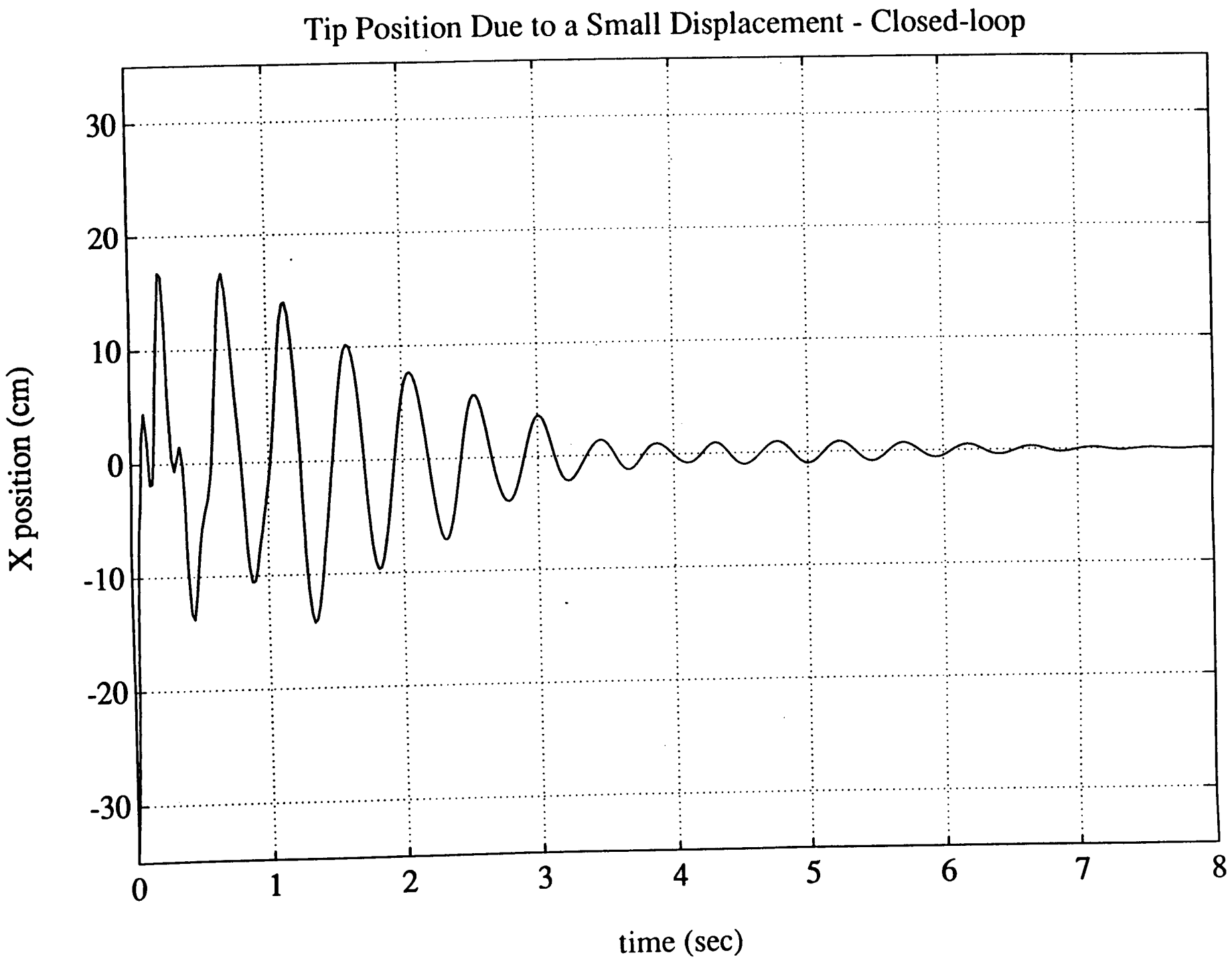
- Energy is pumped into all modes by the R.O.M. controller.
- Some residual modes may be driven unstable; this is known as Controller / Structure Interaction (C.S.I.)

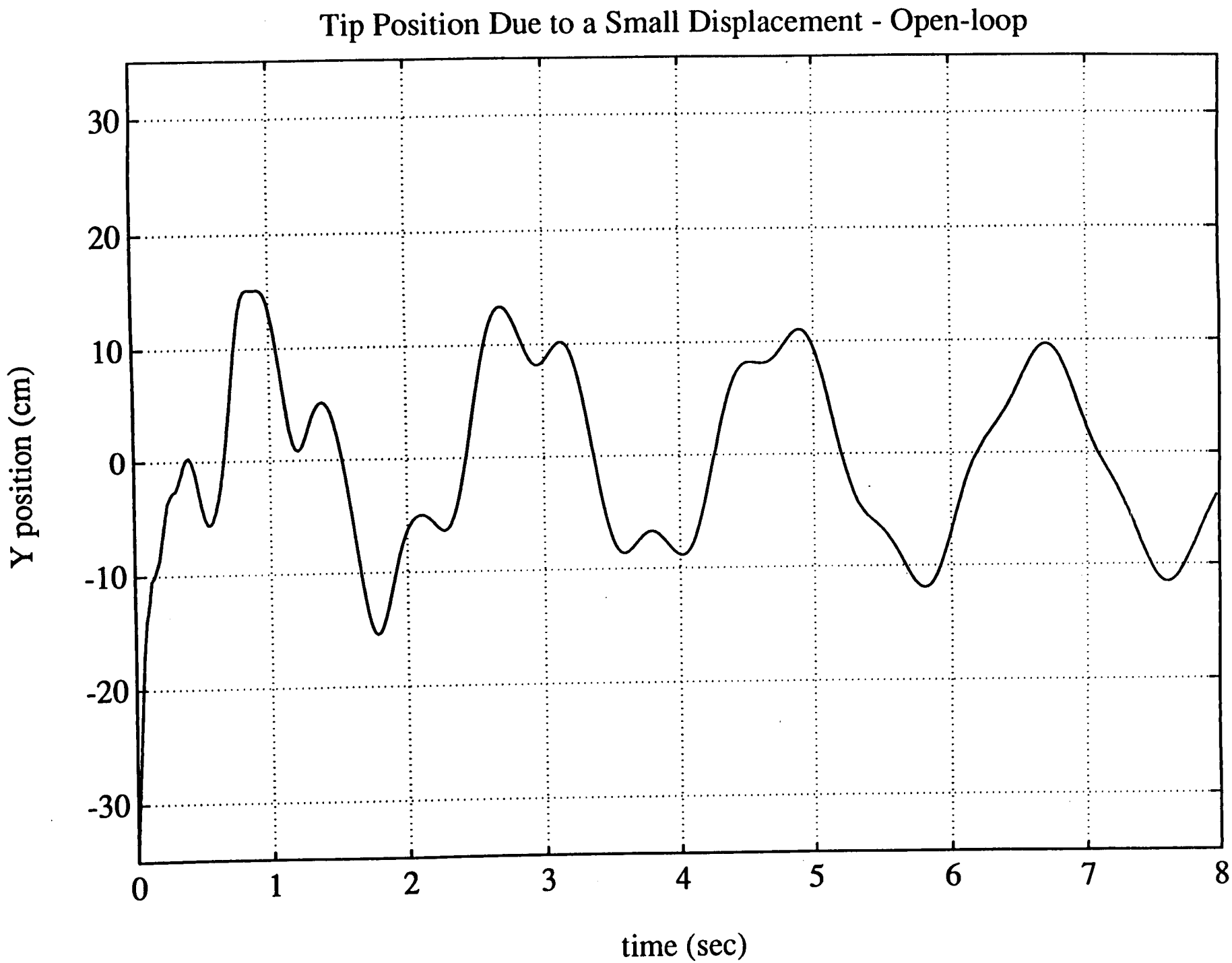

MOBILE
TRANSPORTER
WITH RMS
SPACE CRANE
MARS VEHICLE

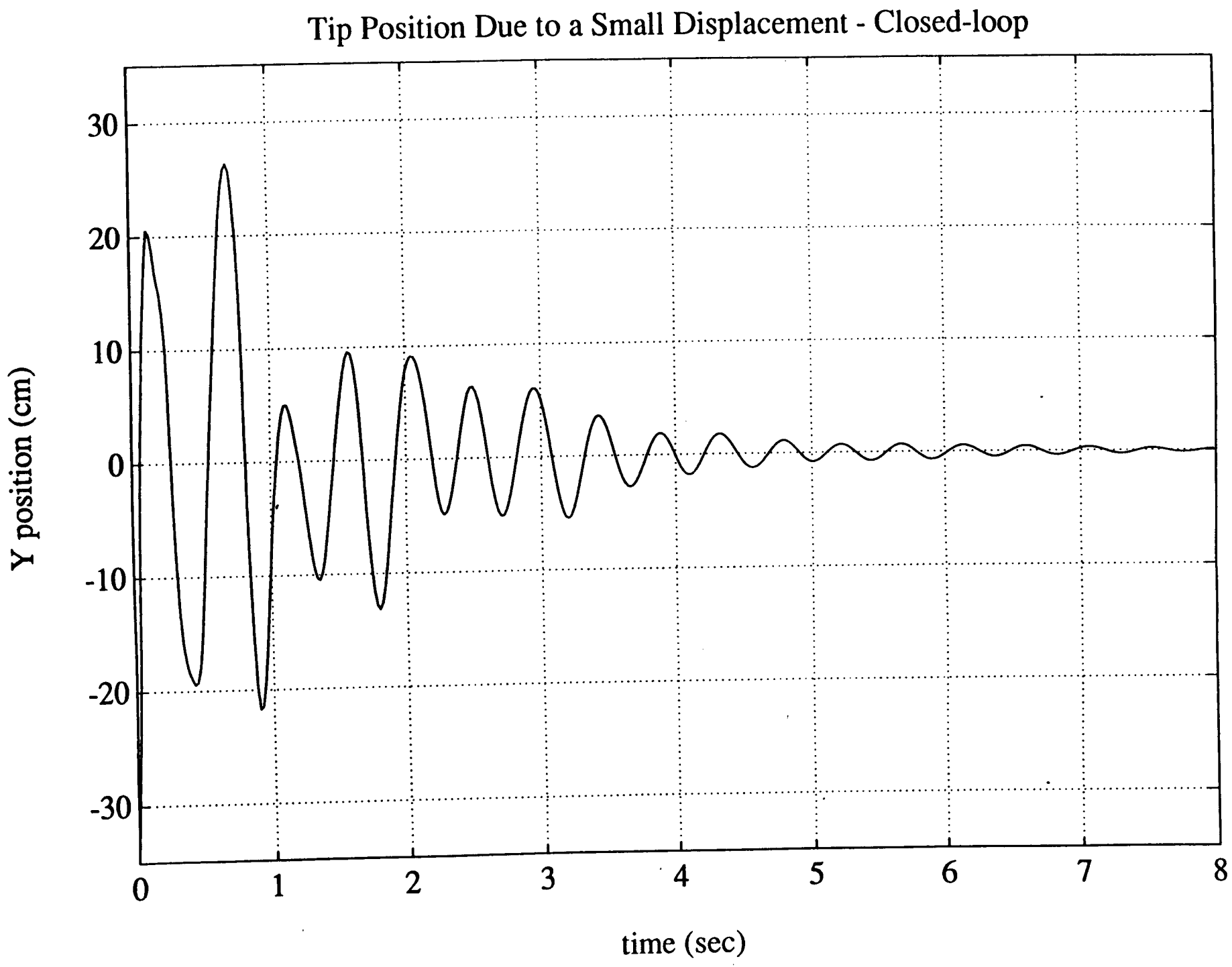

JOINT 1 ROTATION
ANGLE
LINEAR
ACTUATOR
MOBILE
TRANSPORTER
BOOM 2
BOOM 3
BOOM 1
JOINT 2
JOINT 3
ARTICULATING
JOINT 1
ALPHA
JOINT
Z
Y
X

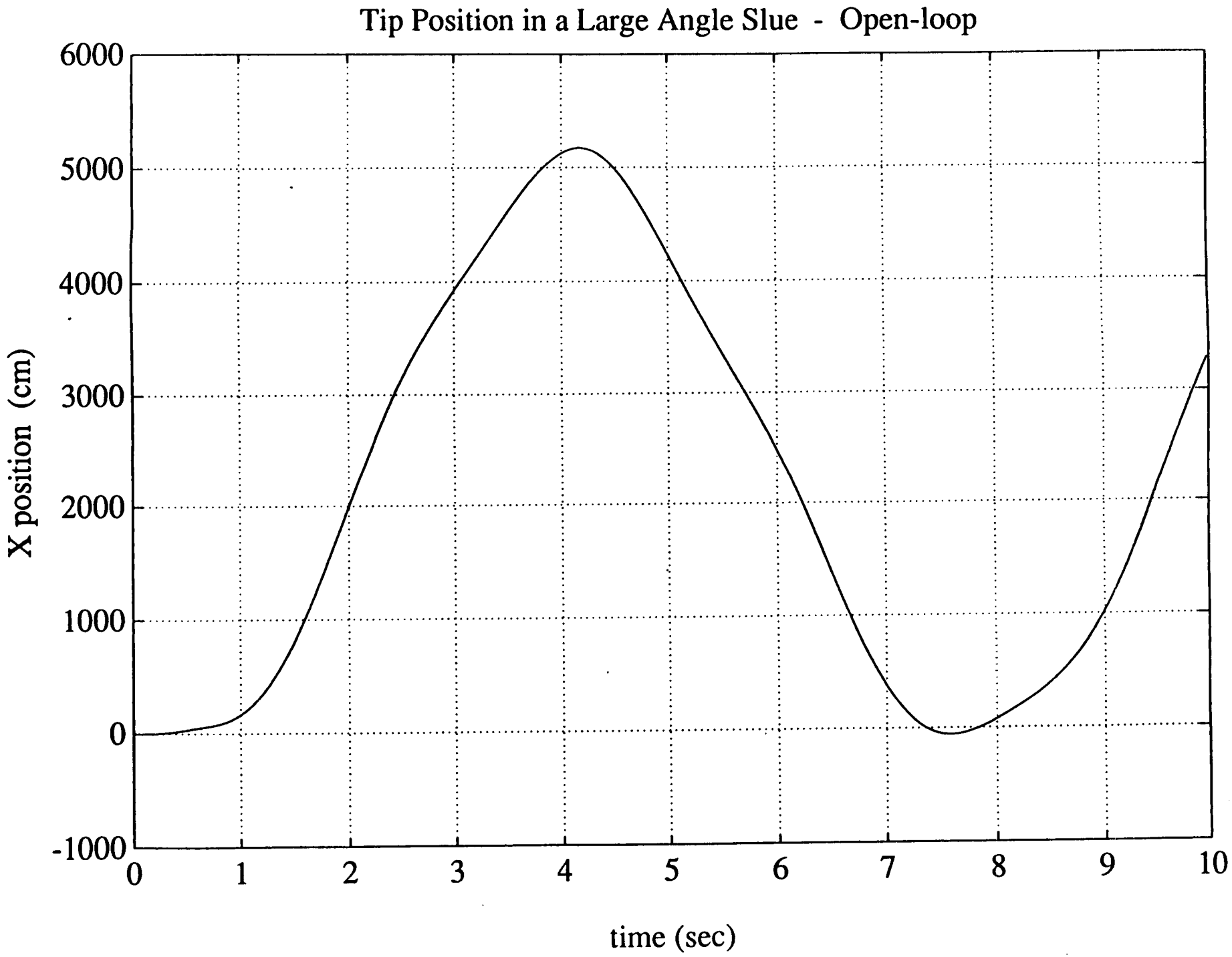

Boom
Section
Offset Hinges
To Rotary Joint

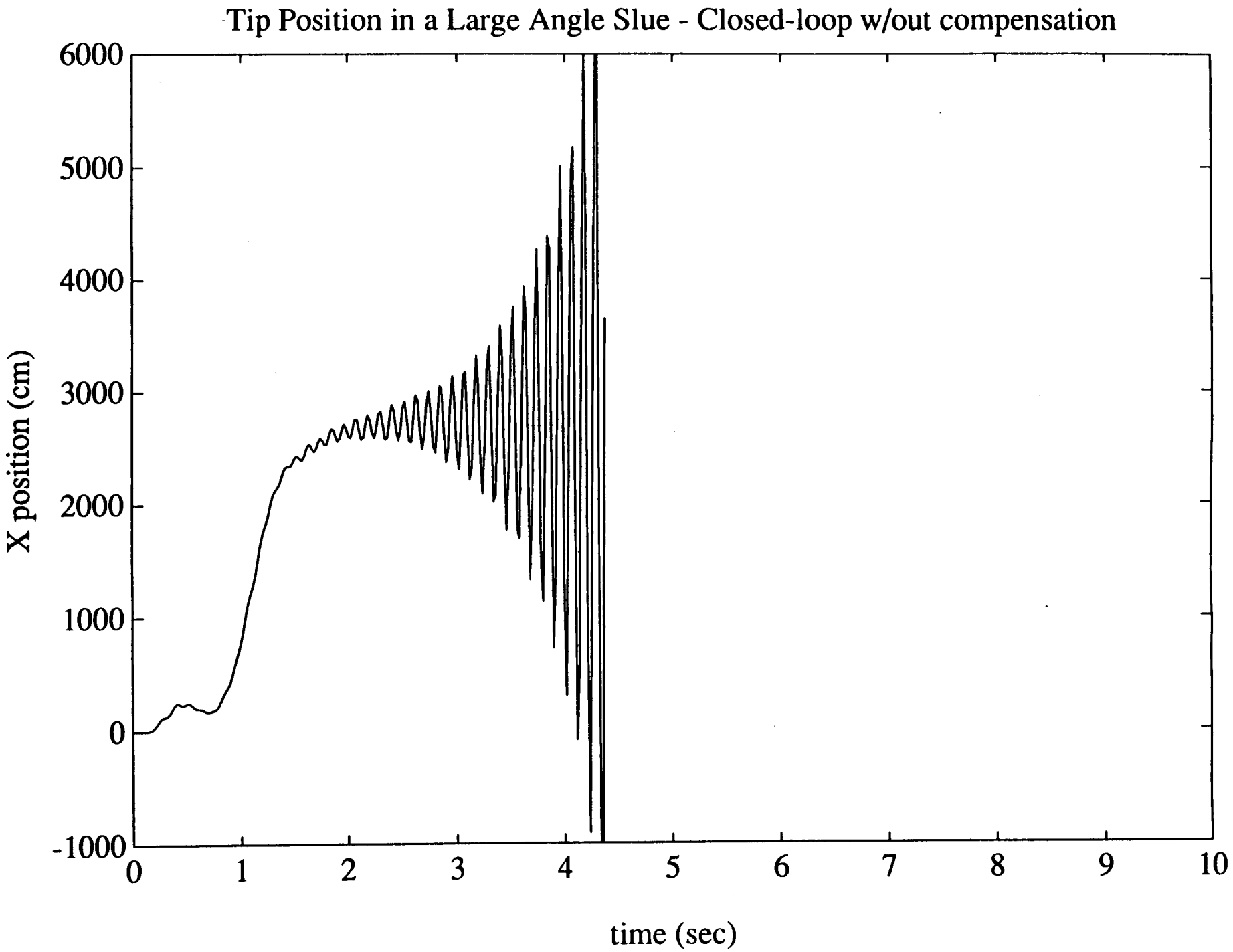

Tip Position Due to a Small Displacement - Open-loop
X position (cm)
30
20
10
0
-10
-20
-30
0
1
2
3
4
5
6
7
8
time (sec)

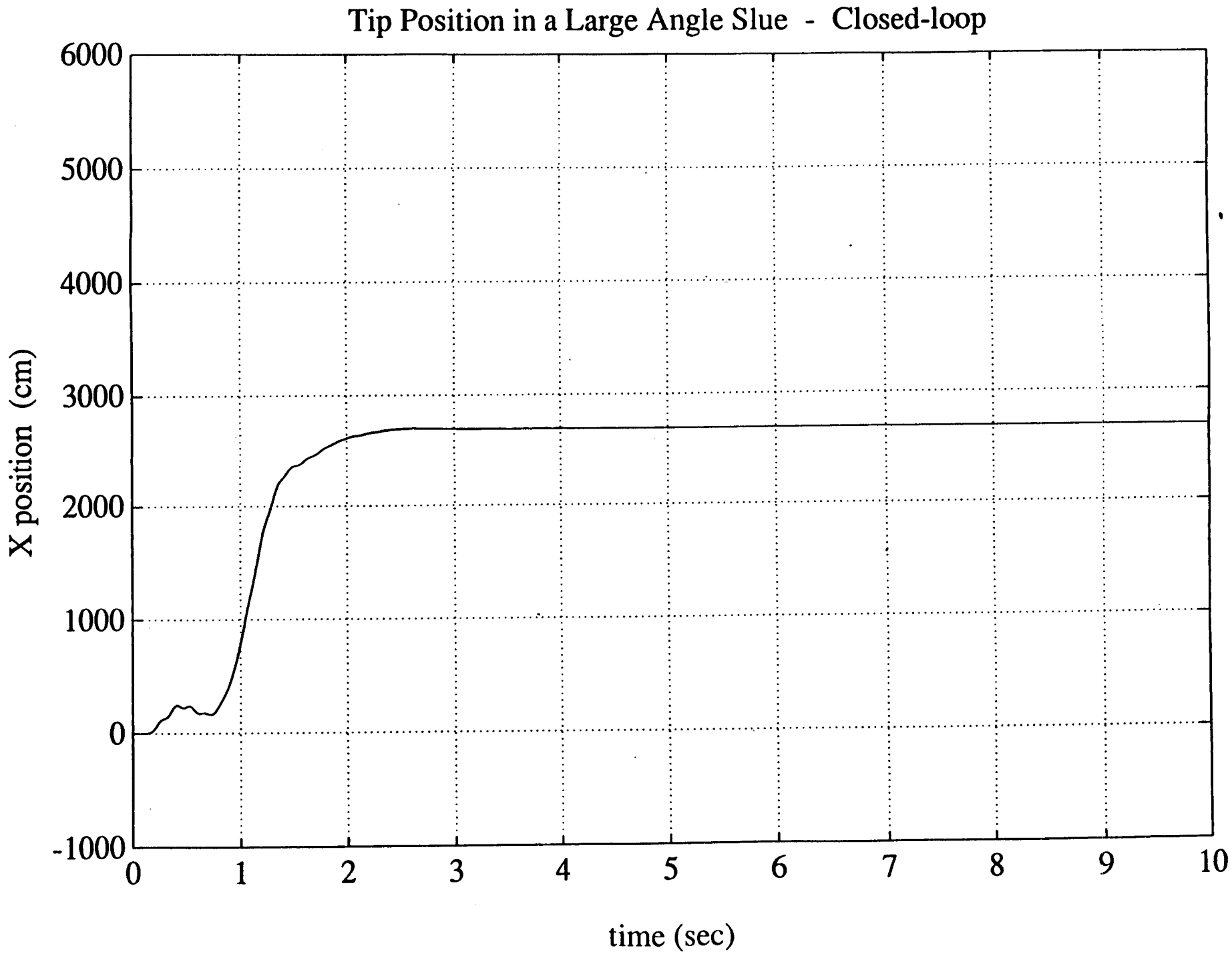

Tip Position Due to a Small Displacement - Closed-loop
X position (cm)
30
20
10
0
-10
-20
-30
0
1
2
3
4
5
6
7
8
time (sec)


Tip Position Due to a Small Displacement - Open-loop
Y position (cm)
30
20
10
0
-10
-20
-30
0
1
2
3
4
5
6
7
8
time (sec)


Tip Position Due to a Small Displacement - Closed-loop
Y position (cm)
30
20
10
0
-10
-20
-30
0
1
2
3
4
5
6
7
8
time (sec)


Tip Position in a Large Angle Slue - Open-loop
6000
5000
4000
3000
2000
1000
0
-1000
X position (cm)
0
1
2
3
4
5
6
7
8
9
10
time (sec)


Tip Position in a Large Angle Slue - Closed-loop w/out compensation
6000
5000
4000
3000
2000
1000
0
-1000
X position (cm)
0
1
2
3
4
5
6
7
8
9
10
time (sec)


Tip Position in a Large Angle Slue - Closed-loop
6000
5000
4000
3000
2000
1000
0
-1000
X position (cm)
0
1
2
3
4
5
6
7
8
9
10
time (sec)

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CONTROLLER-STRUCTURE INTERACTION COMPENSATION USING ADAPTIVE RESIDUAL MODE FILTERS

p. 1

Roger A. Davidson
Mark J. Balas

It is not feasible to construct controllers for large space structures or large scale systems (LSS's) which are of the same order as the structures. The complexity of the dynamics of these systems is such that full knowledge of its behavior cannot be processed by today's controller design methods. The controller for system performance of such a system is therefore based on a much smaller reduced-order model (ROM). Unfortunately, the interaction between the LSS and the ROM-based controller can produce instabilities in the closed-loop system due to the unmodeled dynamics of the LSS.

Residual mode filters (RMF's) allow the systematic removal of these instabilities in a matter which does not require a redesign of the controller. In addition RMF's have a strong theoretical basis. As simple first- or second-order filters, the RMF CSI compensation technique is at once modular, simple and highly effective. RMF compensation requires knowledge of the dynamics of the system modes which resulted in the previous closed-loop instabilities (the residual modes), but this information is sometimes known imperfectly.

An adaptive, self-tuning RMF design, which compensates for uncertainty in the frequency of the residual mode, has been simulated using continuous-time and discrete-time models of a flexible robot manipulator. Work has also been completed on the discrete-time experimental implementation on the Martin Marietta flexible robot manipulator experiment. This paper will present the results of that work on adaptive, self-tuning RMF's, and will clearly show the advantages of this adaptive compensation technique for controller-structure interaction (CSI) instabilities in actively-controlled LSS's.

on
to
P412

Flexible Structures Control

Mark J. Balas

Graduate Students:

→ Roger Davidson
Ali Gooyabadi
Ralph Quan
→ Brian Reisenauer
Philip Good

Brian Reisenauer - Flexible Manipulator Experiments

Roger Davidson - Adaptive RMF

Shin-Ching Liang - Direct Adaptive Control via Hypustability

Jose Galvez - Adaptive Control Using Projection Estimators

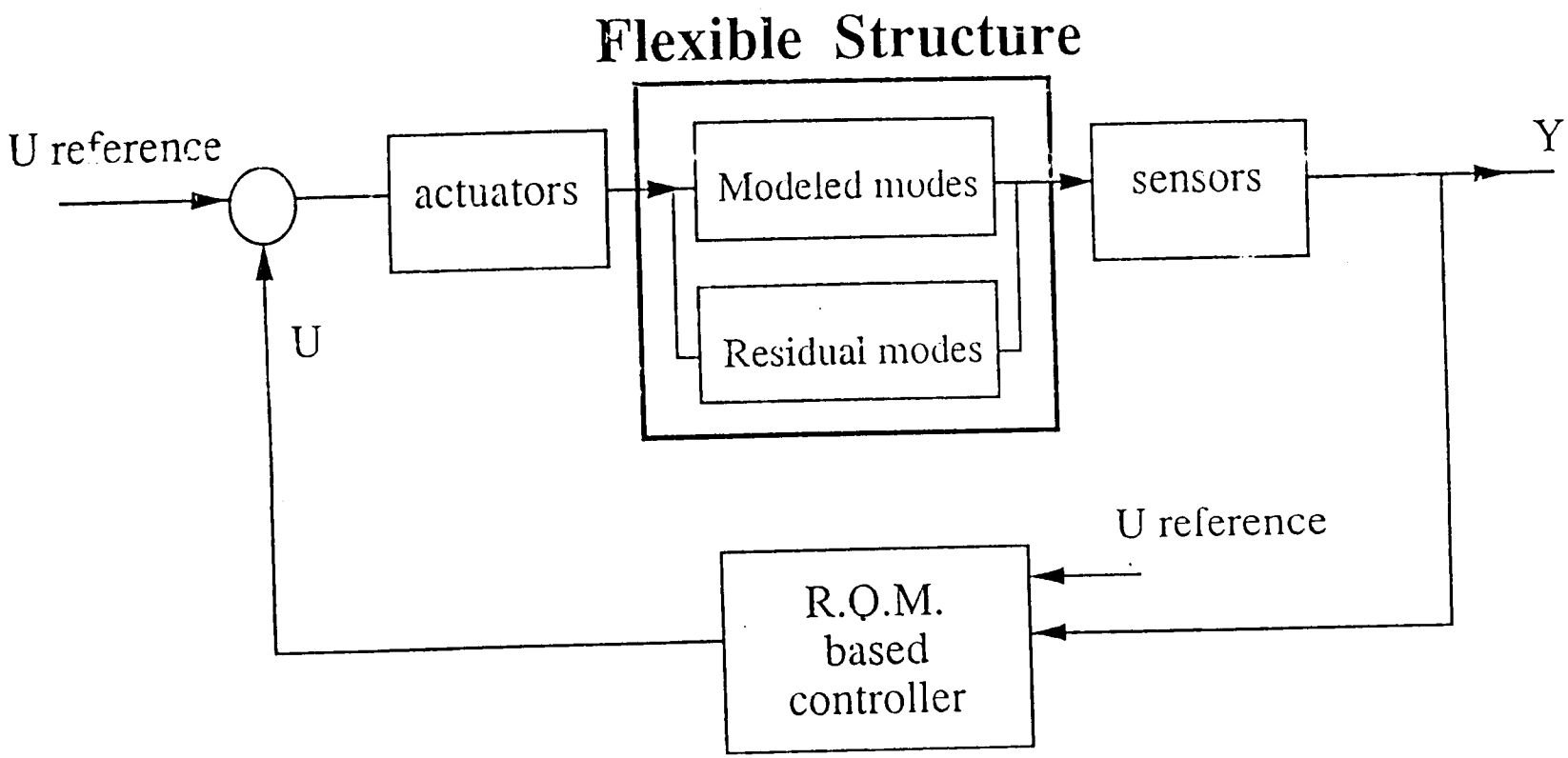
Ralph Quan - High Order Simulation of Controlled LSS using Finite Element Models

Ali Gooyabadi - Hybrid Actuation Problems for LSS

Jim Mohl - A New Flexible Structures Experiment Control

Phil Good - On-Line Parameter Estimation for Adaptively Controlled LSS vs Direct Adaptive LSS Control (Dynamic Test Article)

Figure 1 : ROM-based Control of Large Flexible Structures



- Develop a R.O.M. controller, designed for performance.
- Dimension of the controller << dimension of the structure.

BUT

- Energy is pumped into all modes by the R.O.M. controller.
- Some residual modes may be driven unstable; this is known as Controller / Structure Interaction (C.S.I.)

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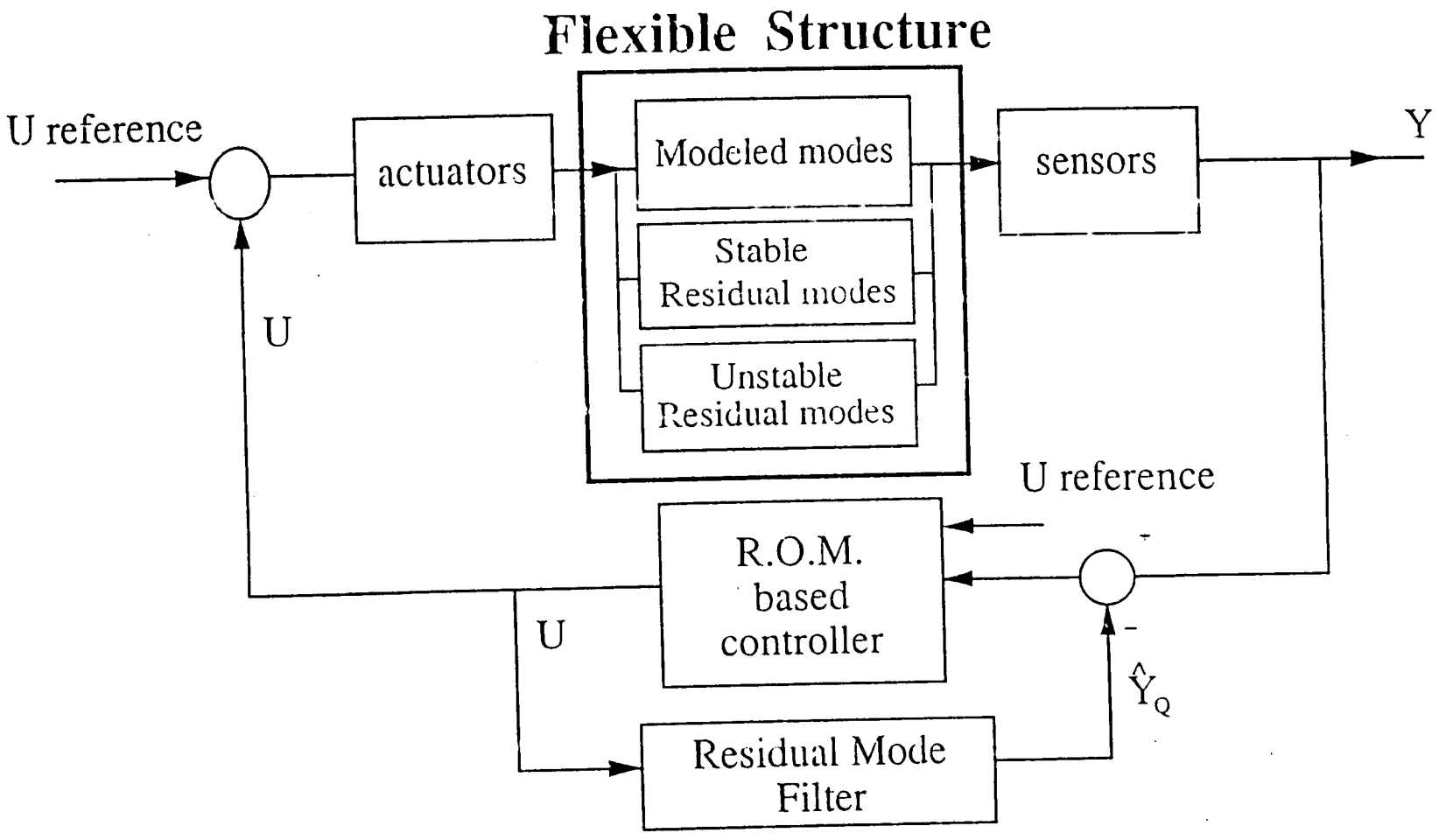
Figure 2 : ROM/RMF Control of Large Flexible Structures



- Develop R.M.F. as a bank of parallel second-order filters; one filter for each unstable residual mode.
- R.M.F. interrupts the control loop around all unstable residual modes; R.O.M control input is screened.
- R.M.F. compensates for C.S.I. , insuring system stability.

Figure 3 : Flexible Robot Manipulator at Martin Marietta

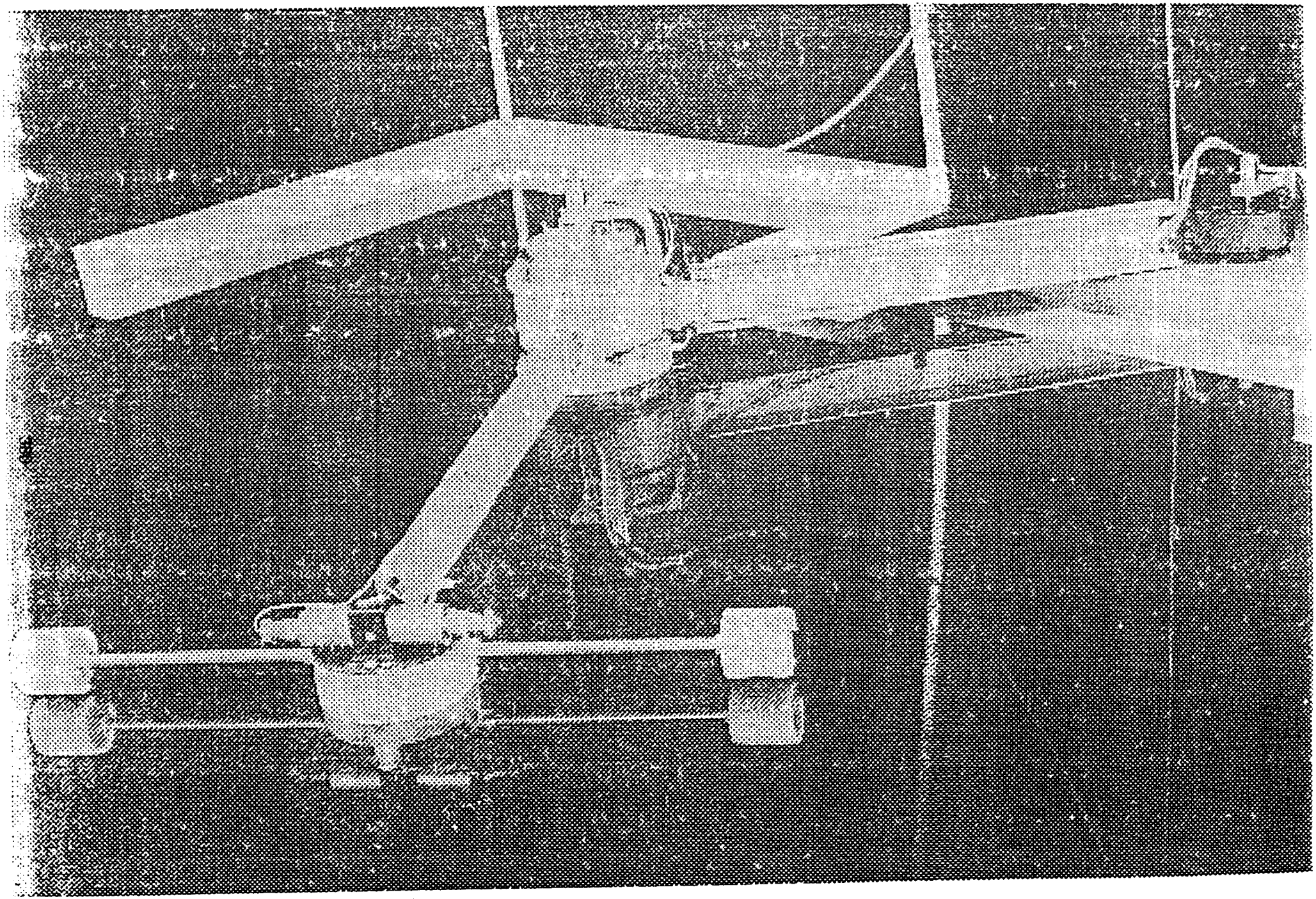


Figure 5 : Open-loop Eigenvalues

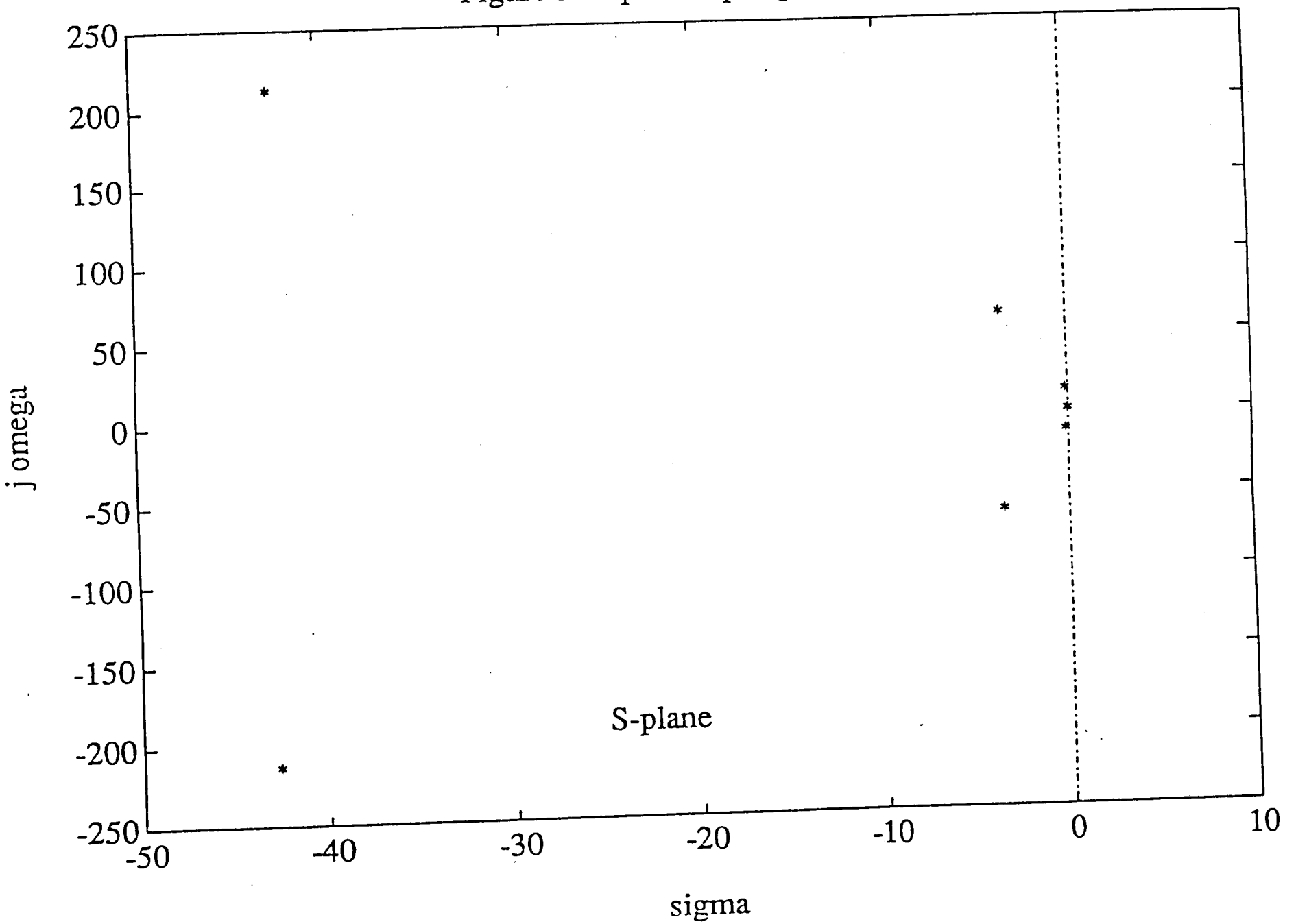


Figure 4 : Closed-loop Eigenvalues Without CSI Compensation

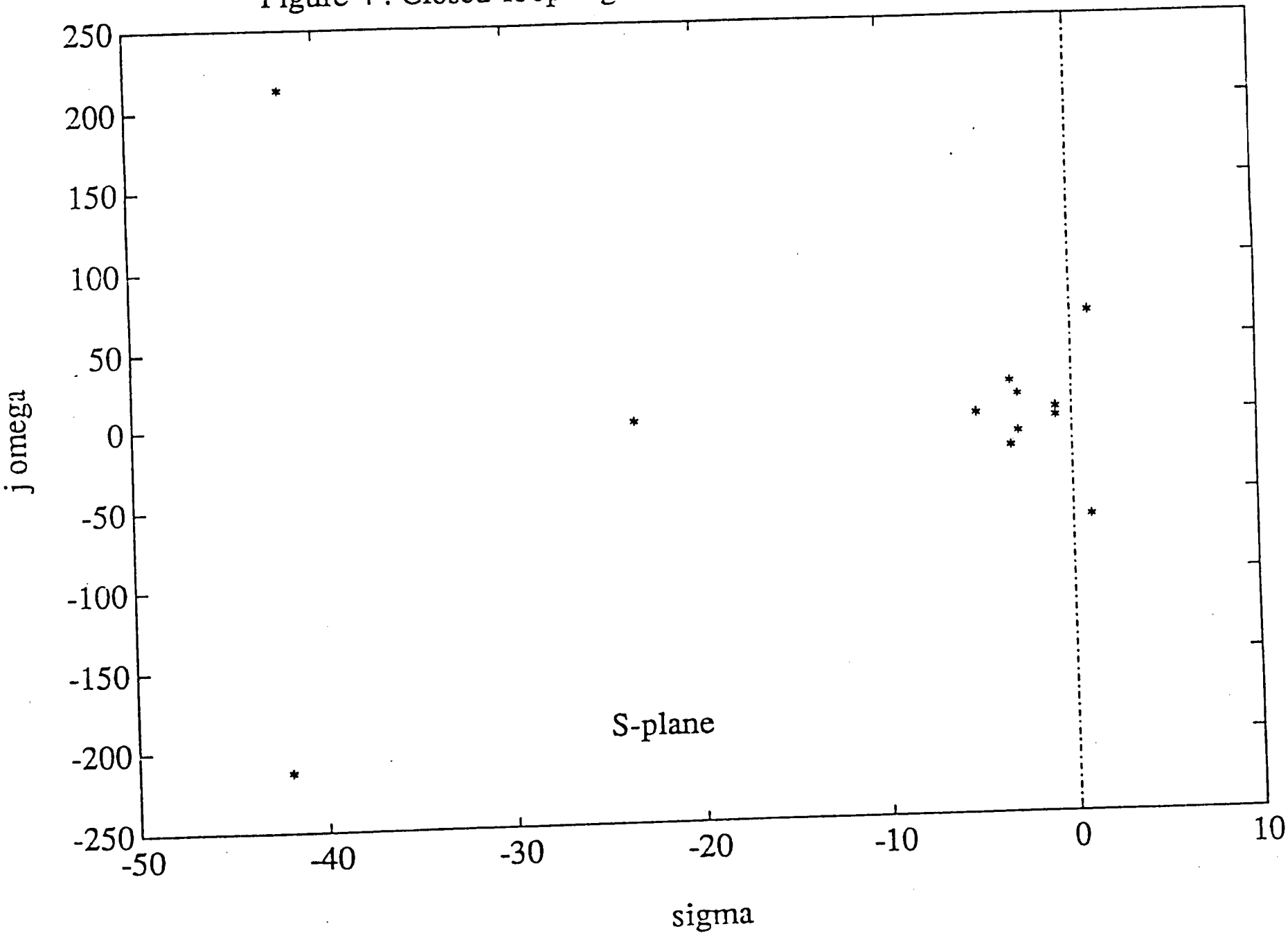


Figure 6 : Closed-loop Eigenvalues With CSI Compensation

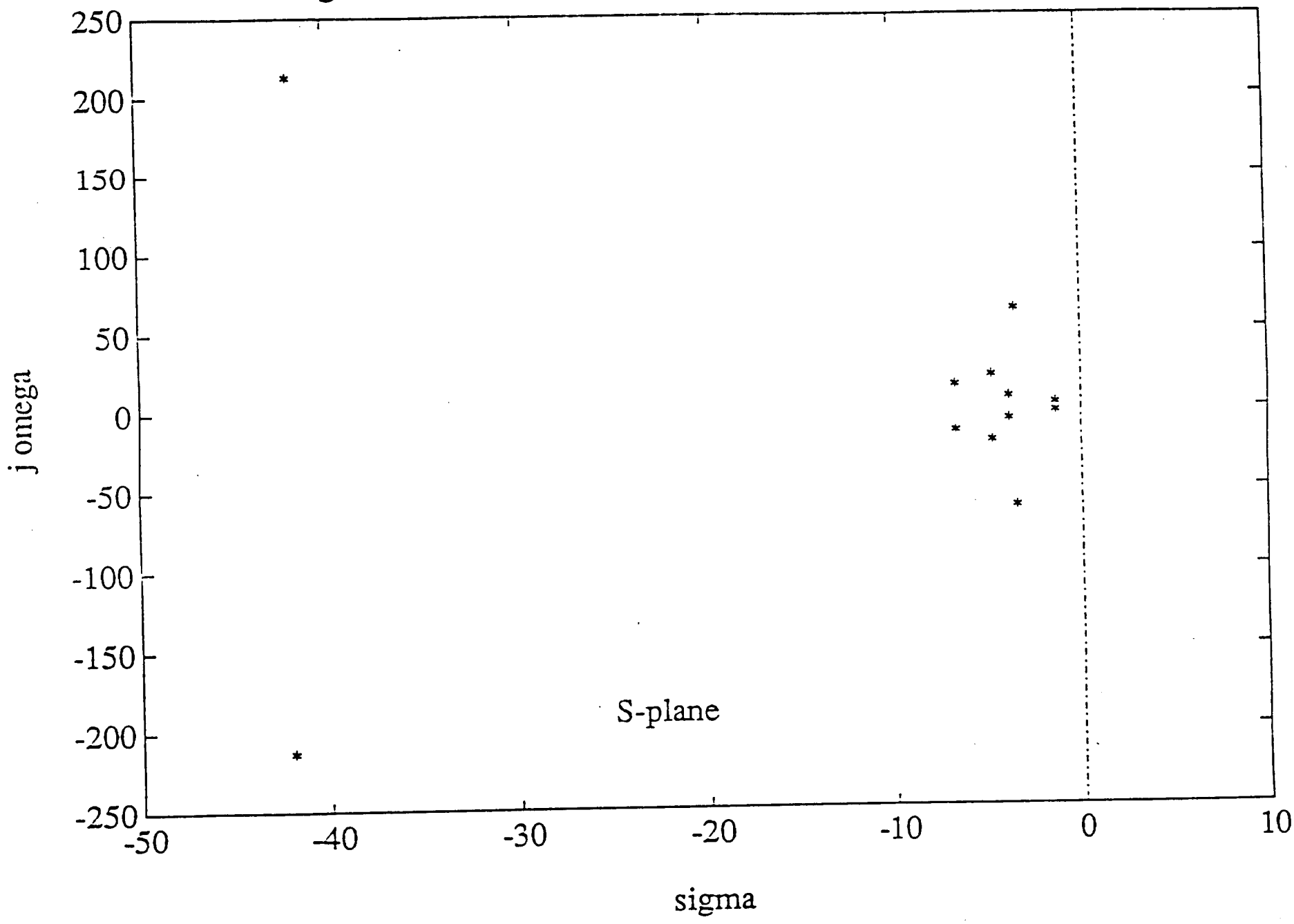


Figure 7 : Hub Position Without CSI Compensation

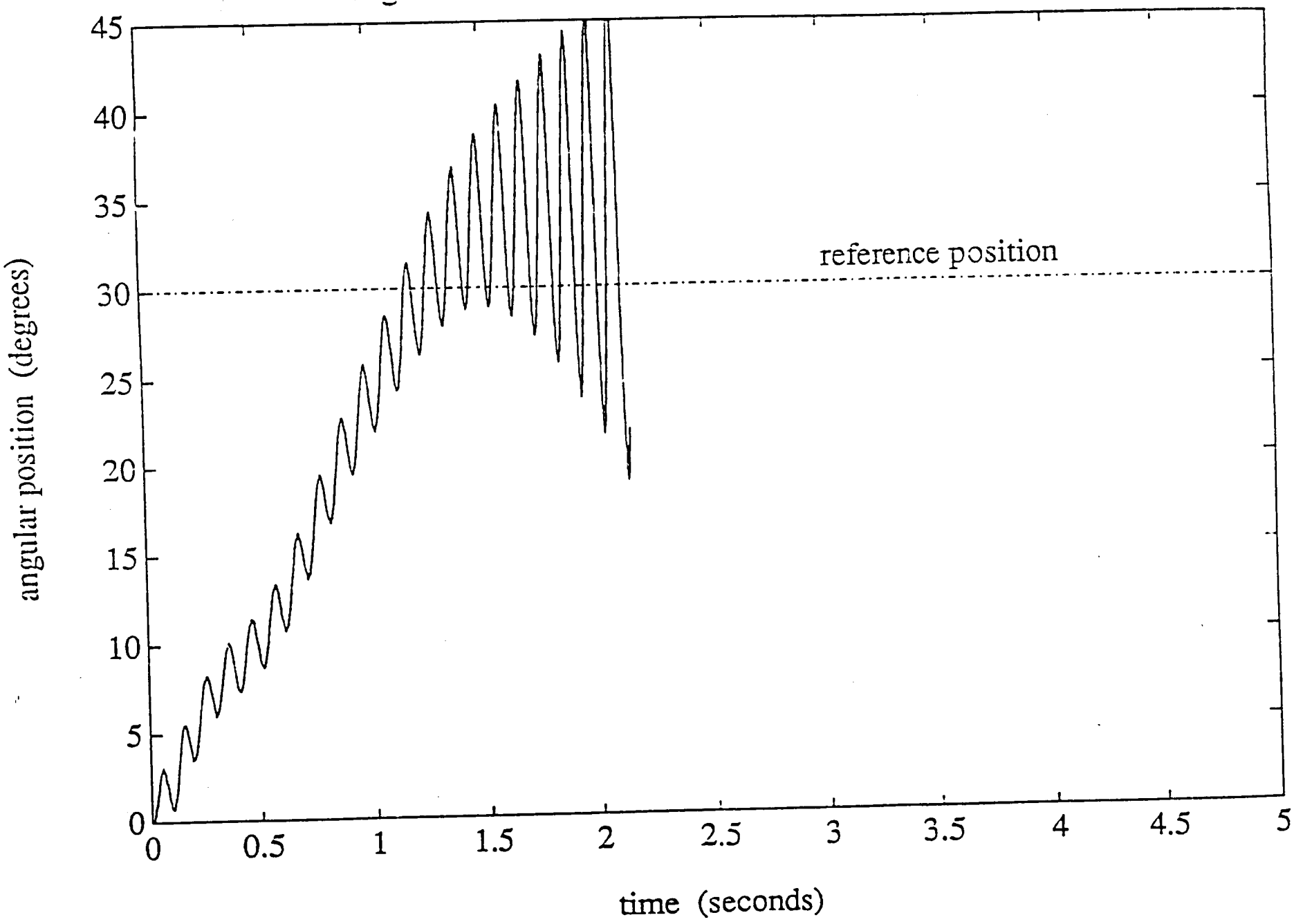


Figure 10 : Hub Position With CSI Compensation

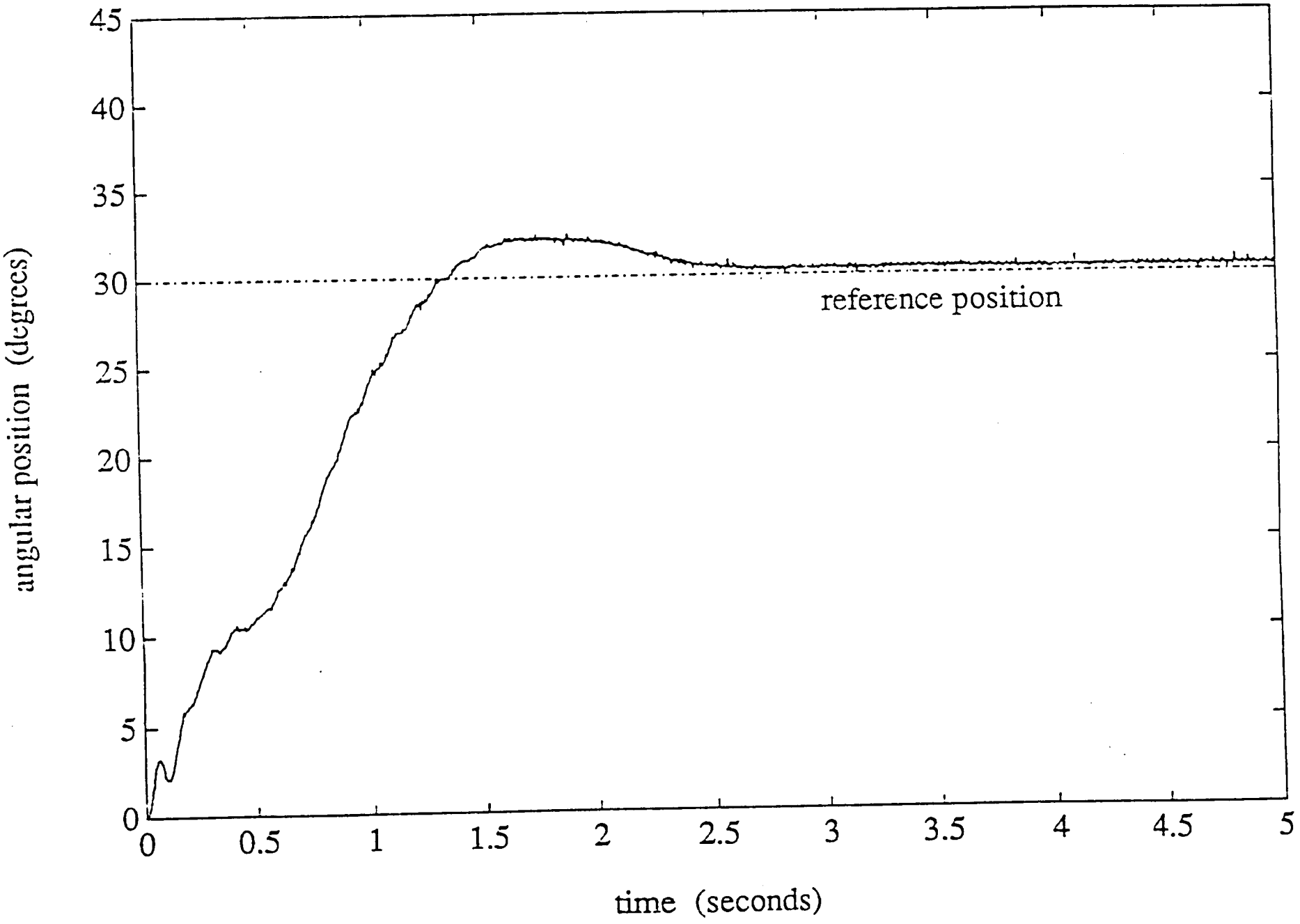


Figure 9 : Control Command Without CSI Compensation

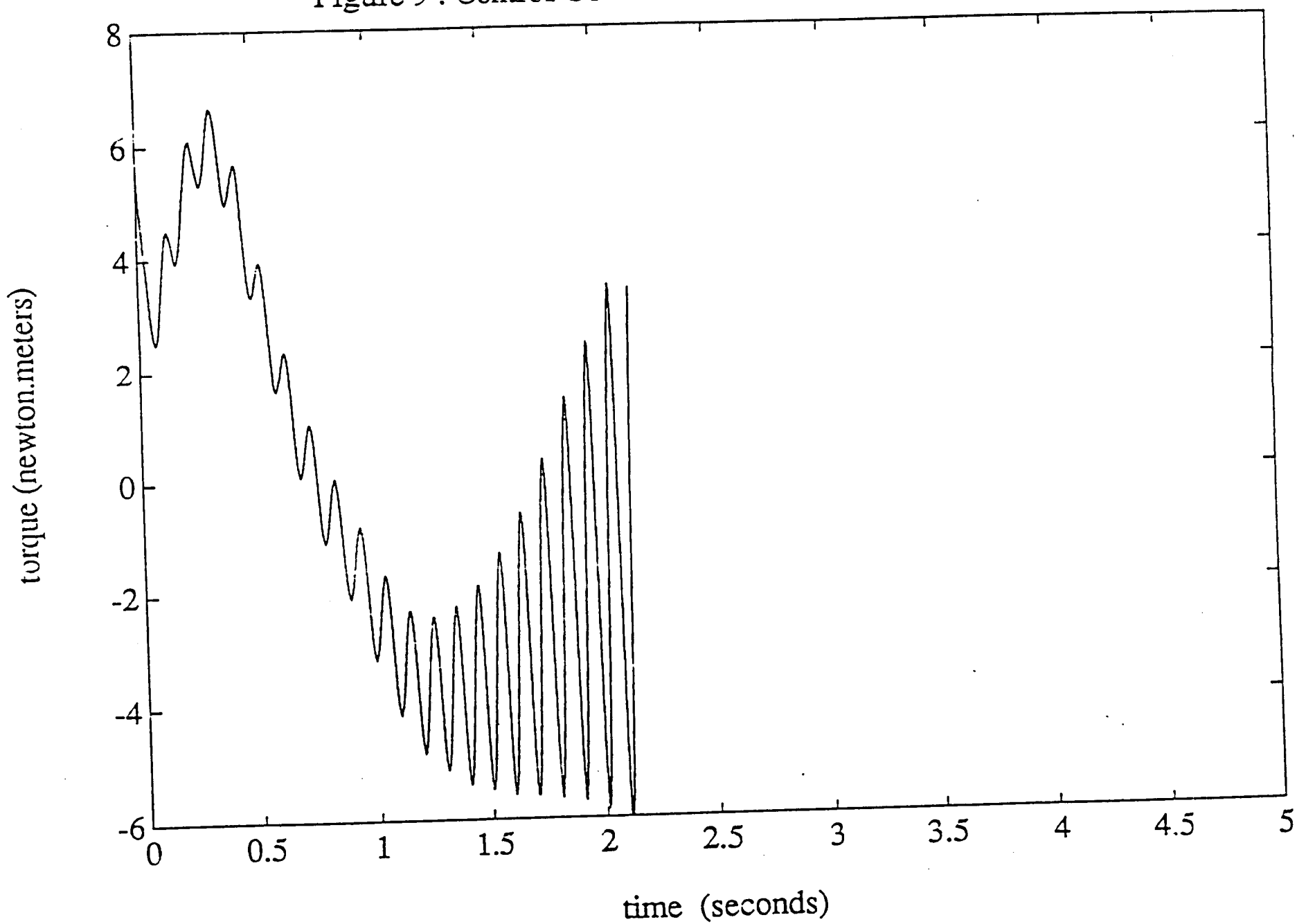
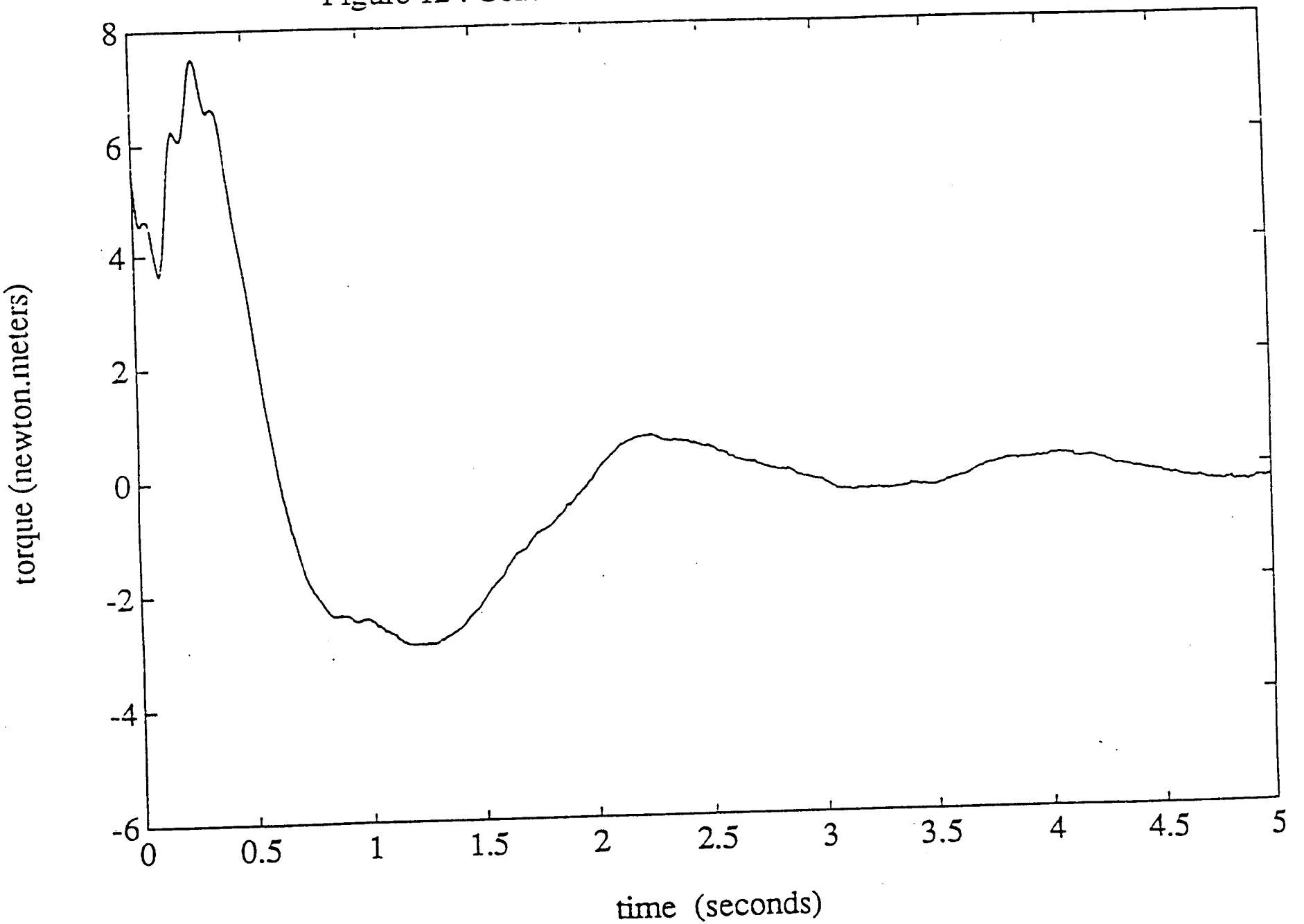
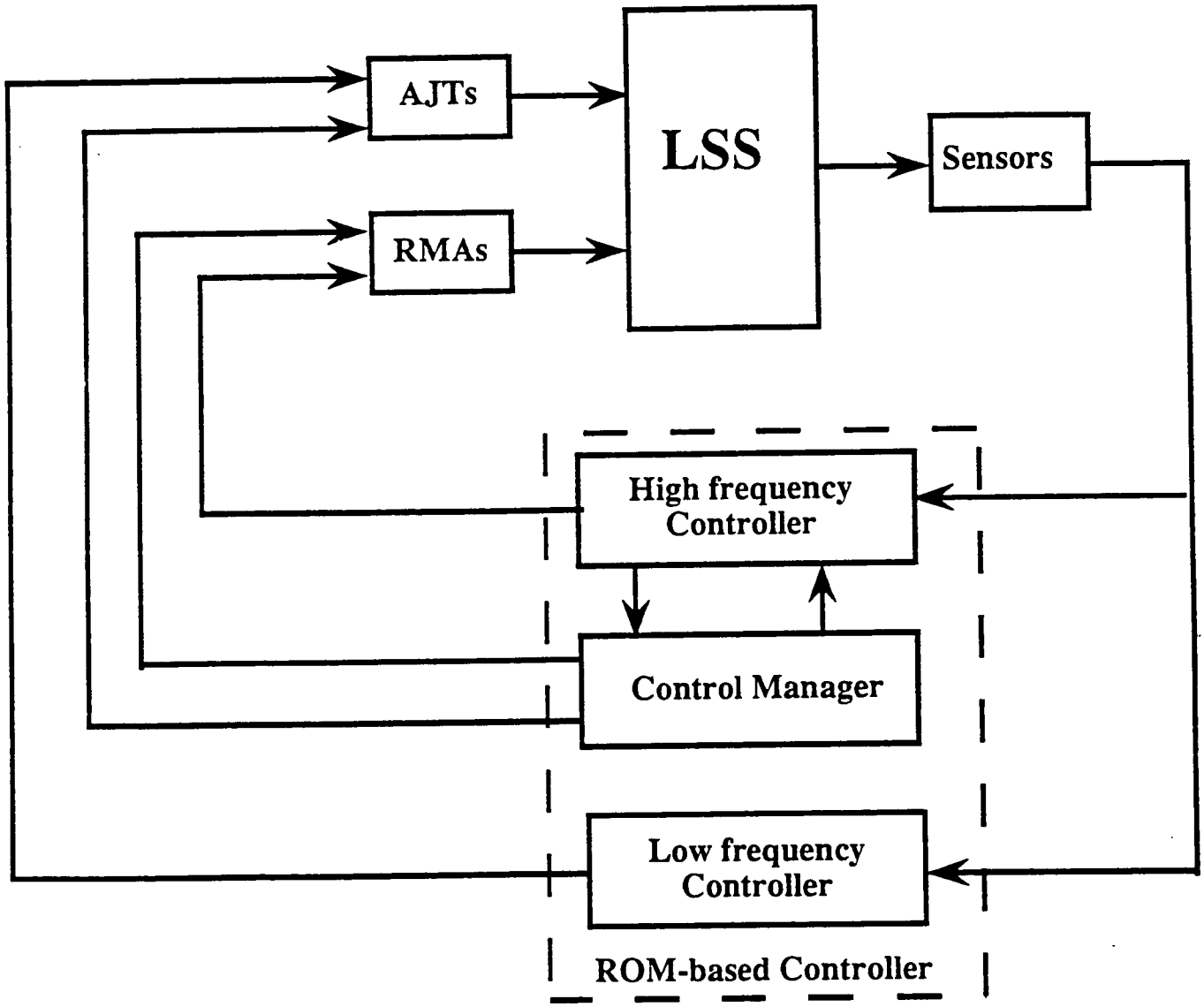
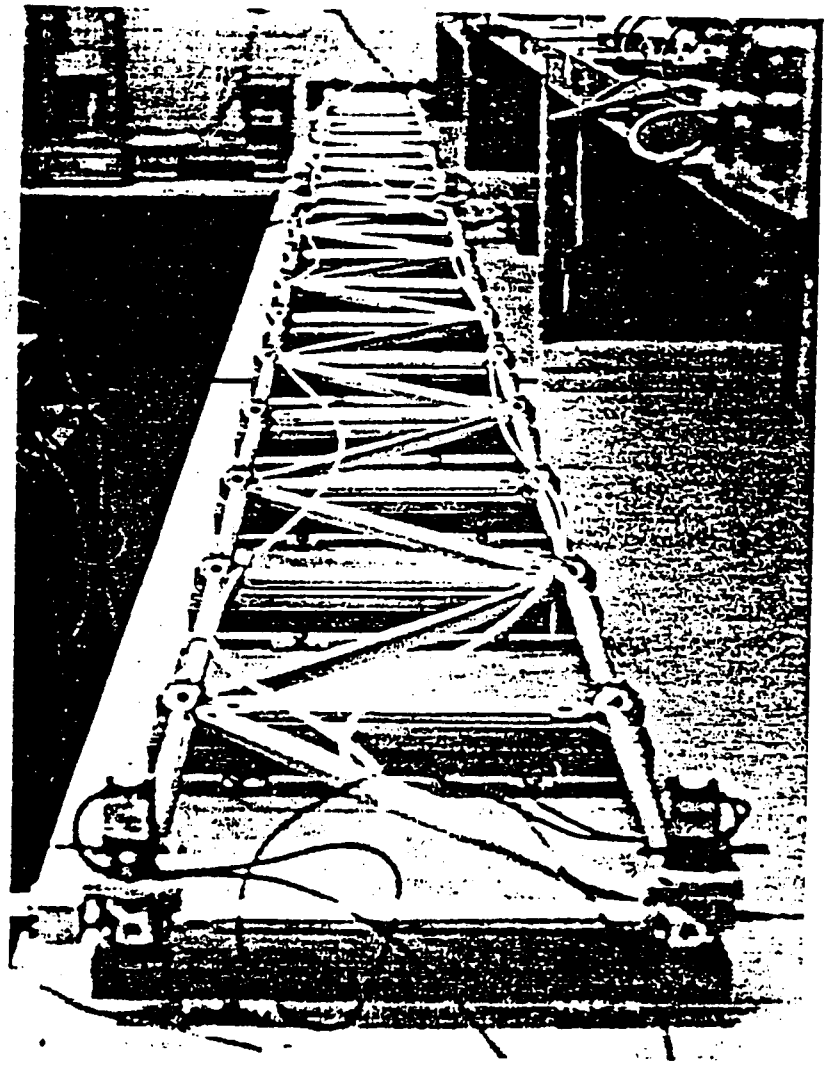


Figure 12 : Control Command With CSI Compensation



Hybrid Actuation(HA)





The planar truss view from tip toward root.

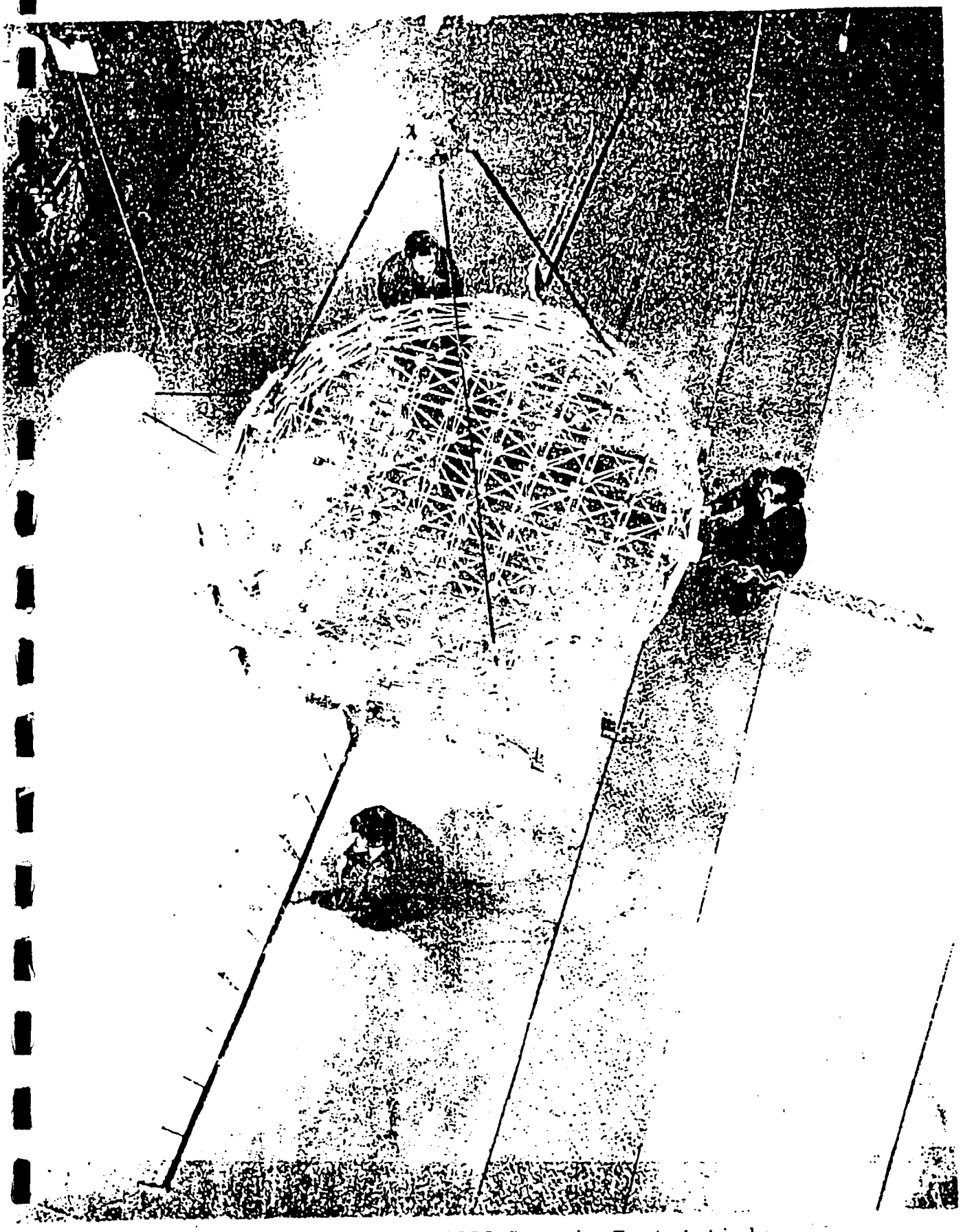


Figure 2-1: PACOSS Dynamic Test Article

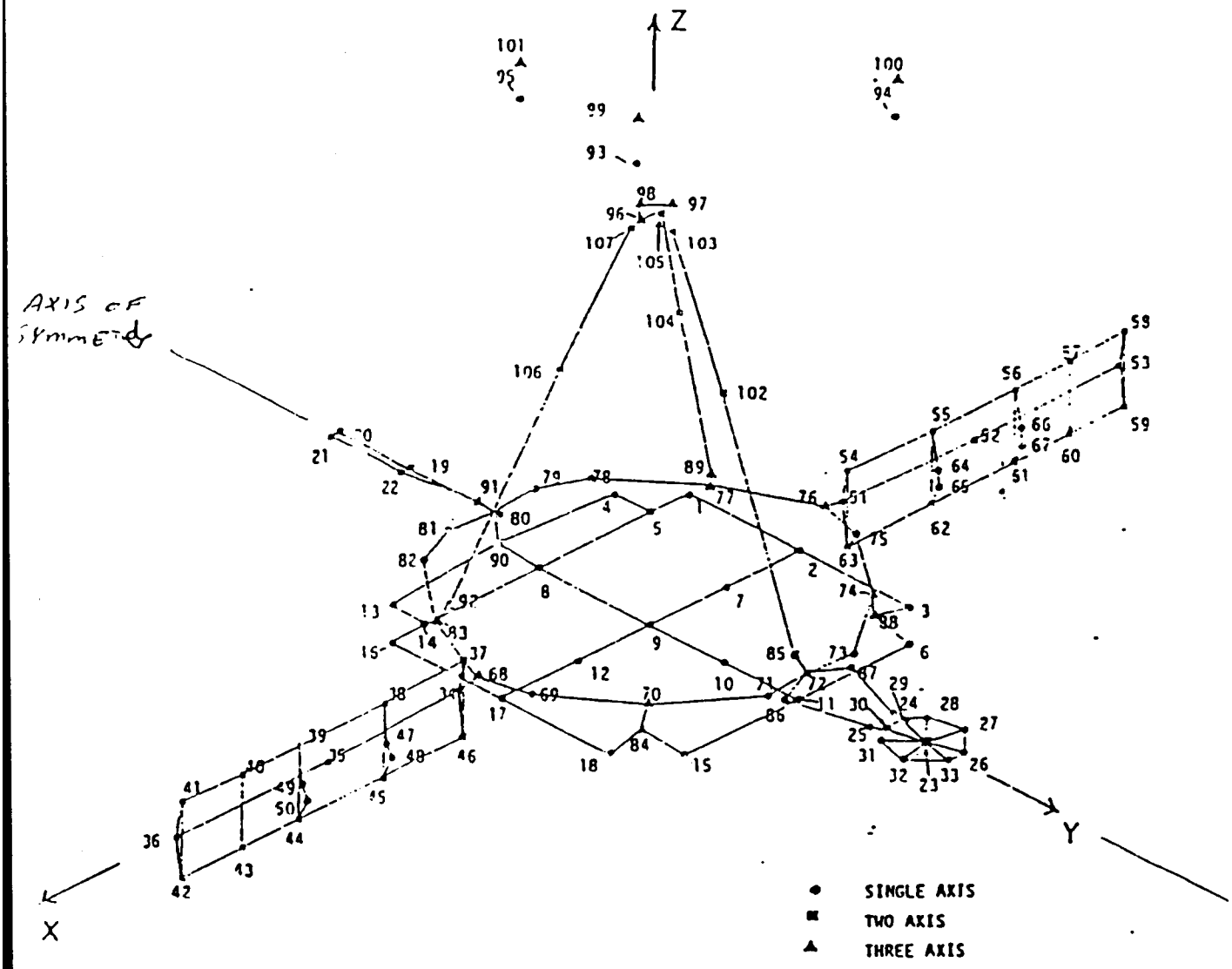
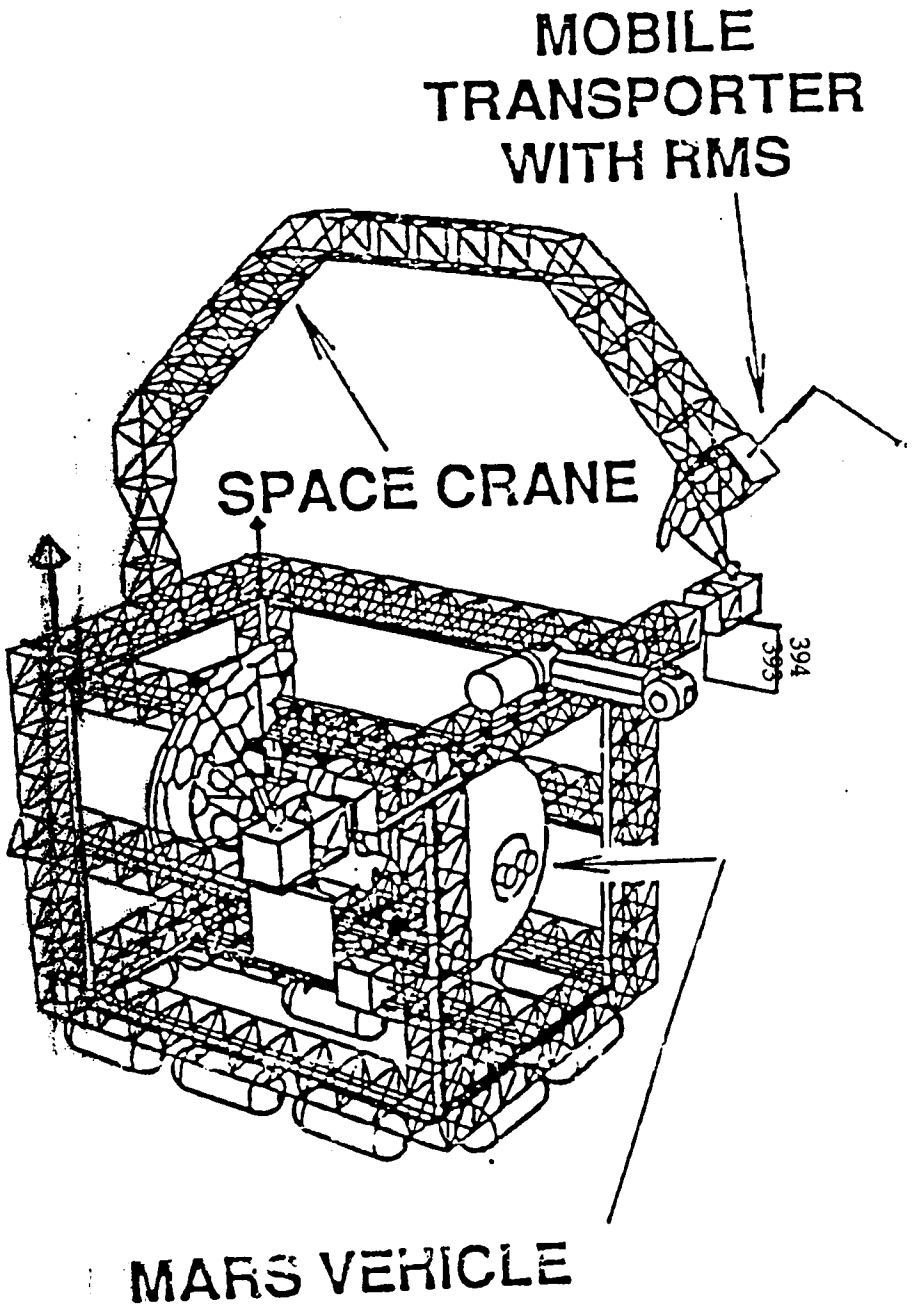
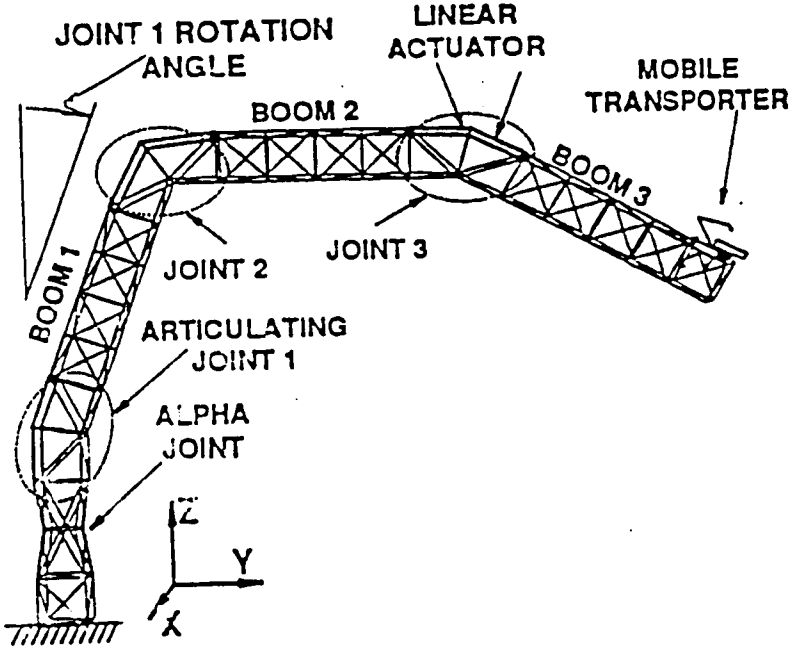


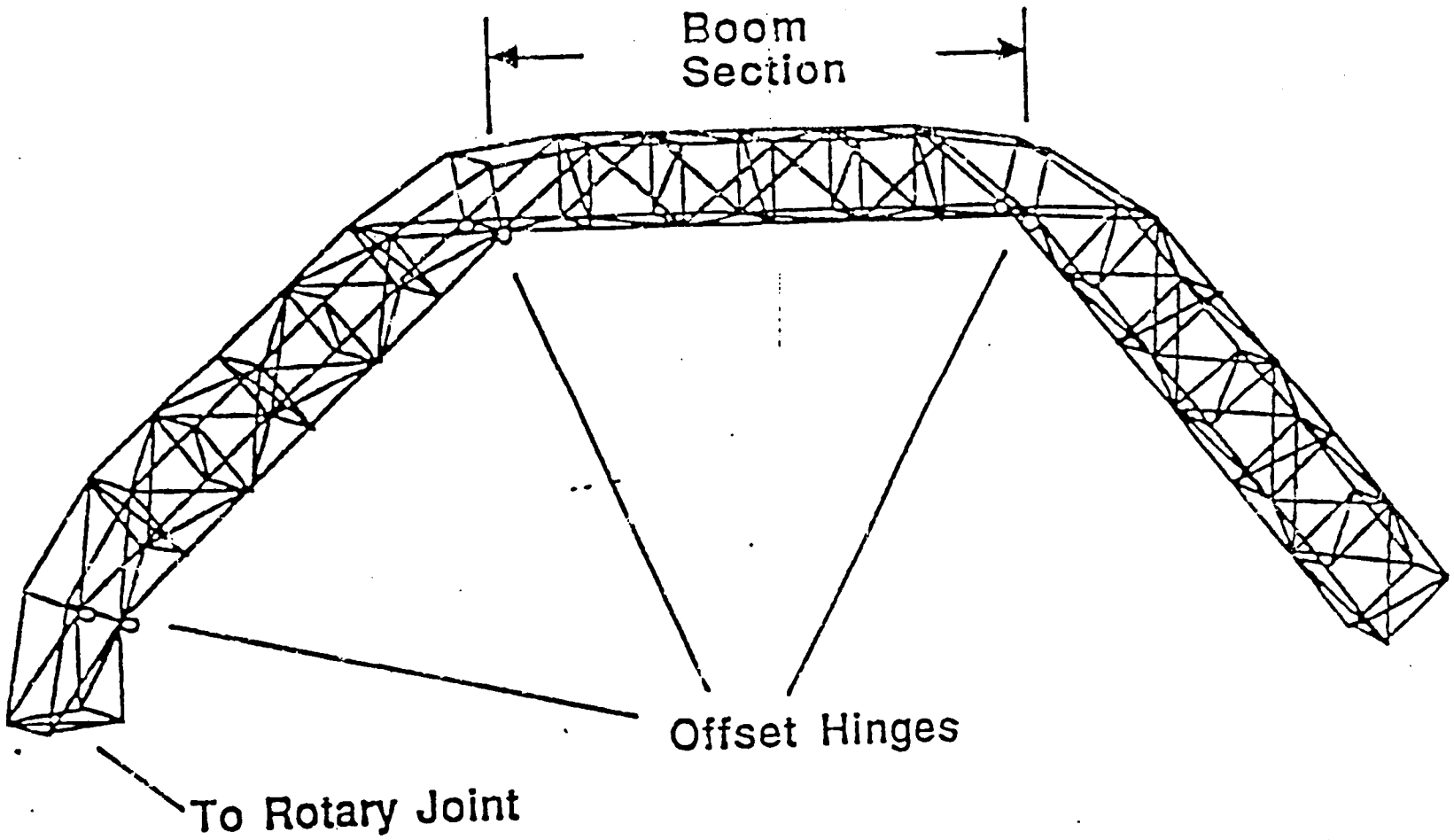
Figure 5-1 DTA Measurement Points

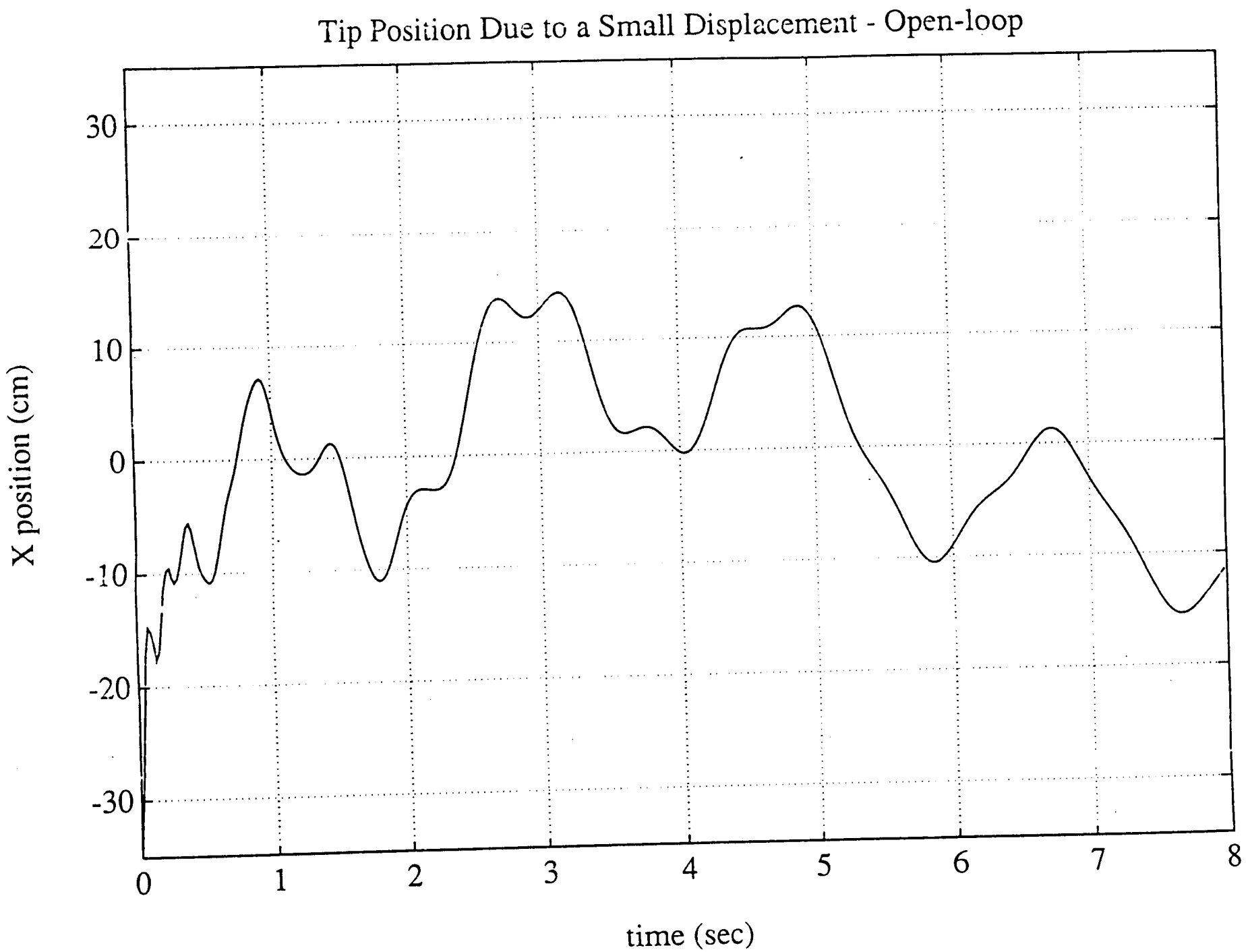
```
>> ttt = [[1:39]' fp phic(9:10,:)' zp]
```

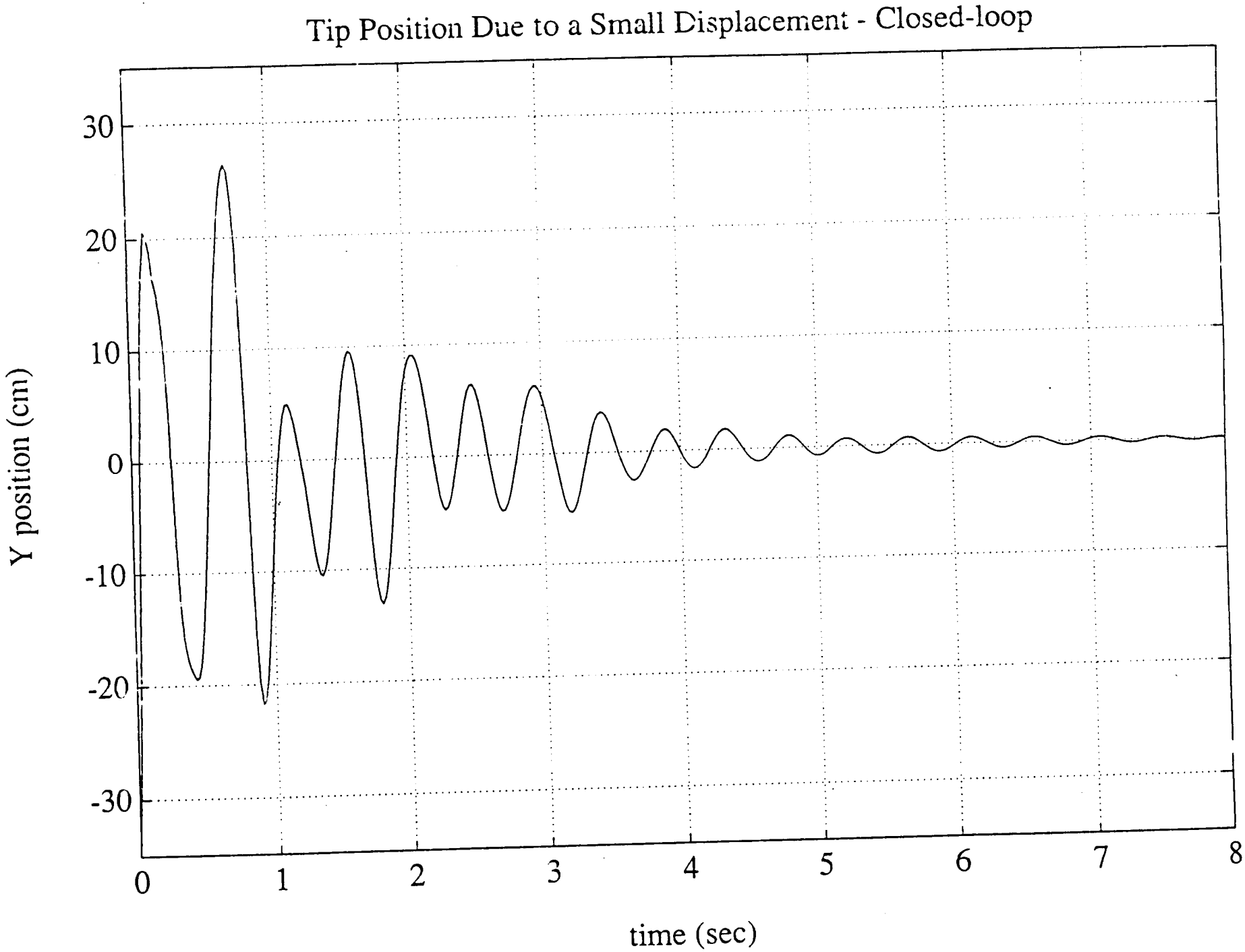
#	freq (Hz)	phic(9,:)	phic(10,:)	zeta
1.0000	0.1228	0.0000	-0.0118	0.1000
2.0000	0.1542	0.0000	-1.4099	0.1000
3.0000	0.1687	1.3907	0.0000	0.1000
4.0000	0.2593	0.0946	0.0000	0.0100
5.0000	0.2904	0.0001	-0.7327	0.0100
6.0000	0.2913	0.7285	0.0001	0.0100
7.0000	0.7436	0.2575	-0.0001	0.5000
8.0000	0.7437	0.0001	0.2622	0.5000
9.0000	1.0343	0.0000	-0.1410	0.0564
10.0000	1.0593	0.0133	0.0000	0.0573
11.0000	1.4912	0.0749	0.0000	0.5000
12.0000	1.4950	0.0000	0.0267	0.5000
13.0000	1.4962	0.0000	0.0010	0.5000
14.0000	1.4967	-0.0059	0.0000	0.5000
15.0000	1.4969	0.0000	0.0000	0.5000
16.0000	1.5087	0.2058	0.0000	0.5000
17.0000	1.5178	0.0000	0.2304	0.5000
18.0000	1.5305	0.0000	0.1676	0.5000
19.0000	2.6586	0.0000	0.5967	0.0279
20.0000	3.1263	0.0000	-0.0480	0.0702
21.0000	3.1672	-0.0675	0.0000	0.0568
22.0000	3.4671	0.2091	-0.0001	0.0424
23.0000	3.5103	0.9583	-0.0001	0.0862
24.0000	3.6981	0.0009	0.5568	0.0478
25.0000	3.8003	0.1668	-0.0022	0.1004
26.0000	4.4321	0.0000	0.2551	0.0595
27.0000	4.4453	0.0000	-0.1288	0.0351
28.0000	4.4441	0.0303	0.0000	0.0294
29.0000	4.8649	0.0000	0.7690	0.1212
30.0000	5.0475	0.0120	-0.0002	0.0679
31.0000	5.8408	-0.0008	0.0170	0.0228
32.0000	5.8414	-0.0642	-0.0002	0.0236
33.0000	5.9976	-0.0212	0.0003	0.0330
34.0000	6.4077	0.7102	0.0000	0.0992
35.0000	7.7656	-0.0013	-0.0306	0.0604
36.0000	9.4088	1.3004	0.0009	0.0713
37.0000	9.5817	0.0016	-0.8053	0.0717
38.0000	10.0891	0.0000	0.0228	0.0145
39.0000	10.9898	-0.0211	0.0000	0.0145

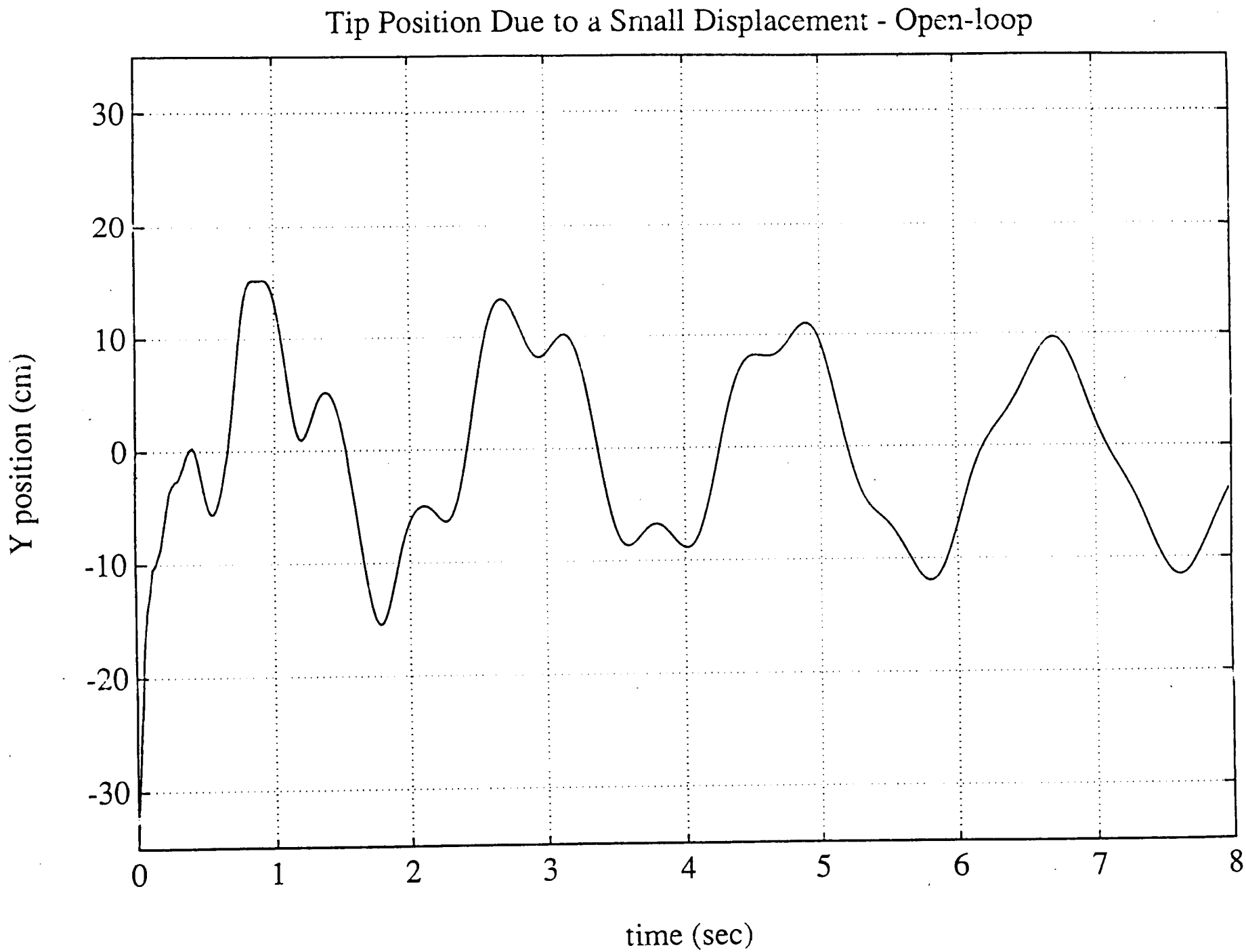

MOBILE
TRANSPORTER
WITH RMS
SPACE CRANE
MARS VEHICLE

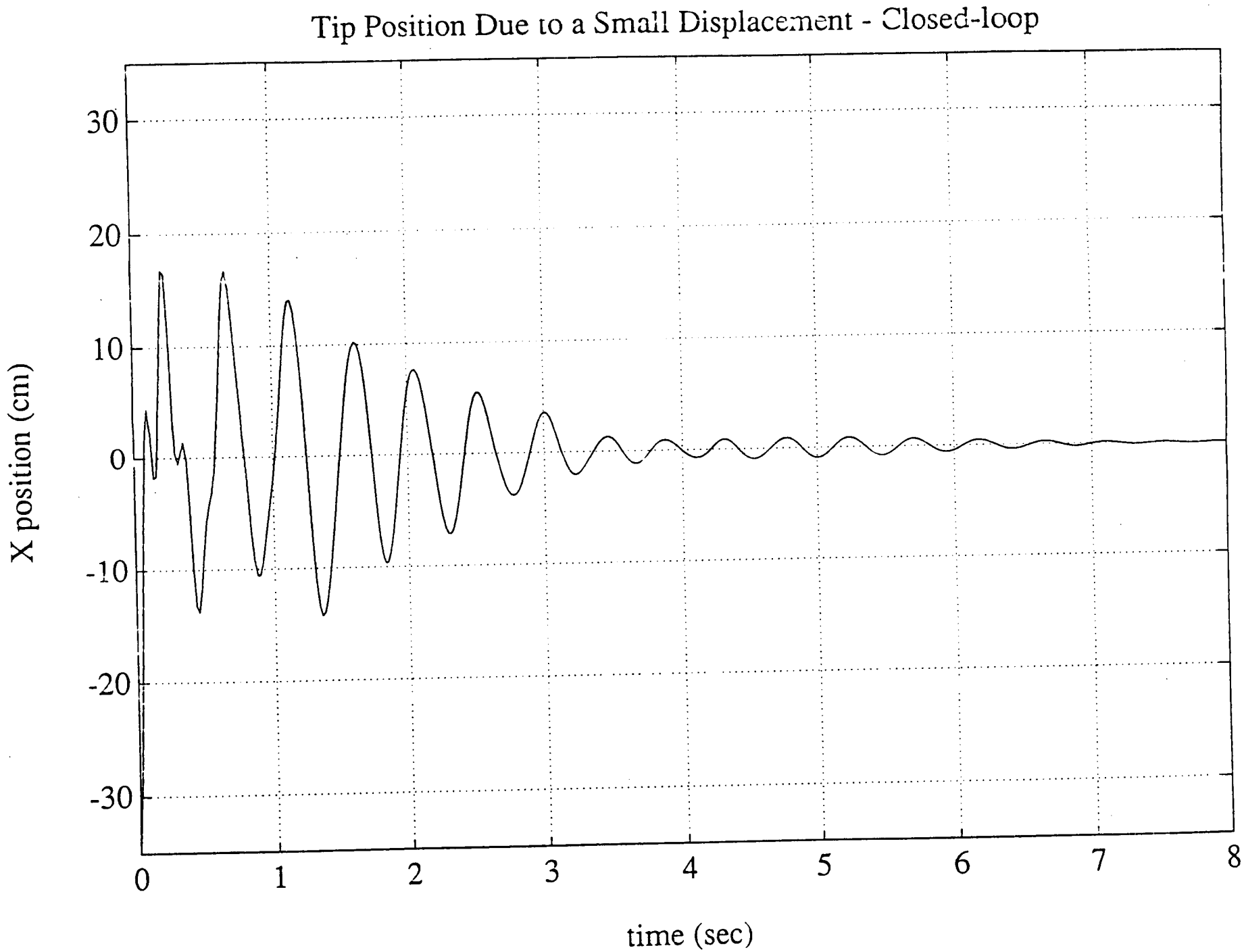

JOINT 1 ROTATION
ANGLE
LINEAR
ACTUATOR
MOBILE
TRANSPORTER
BOOM 2
BOOM 3
BOOM 1
JOINT 2
JOINT 3
ARTICULATING
JOINT 1
ALPHA
JOINT
Z
Y
X

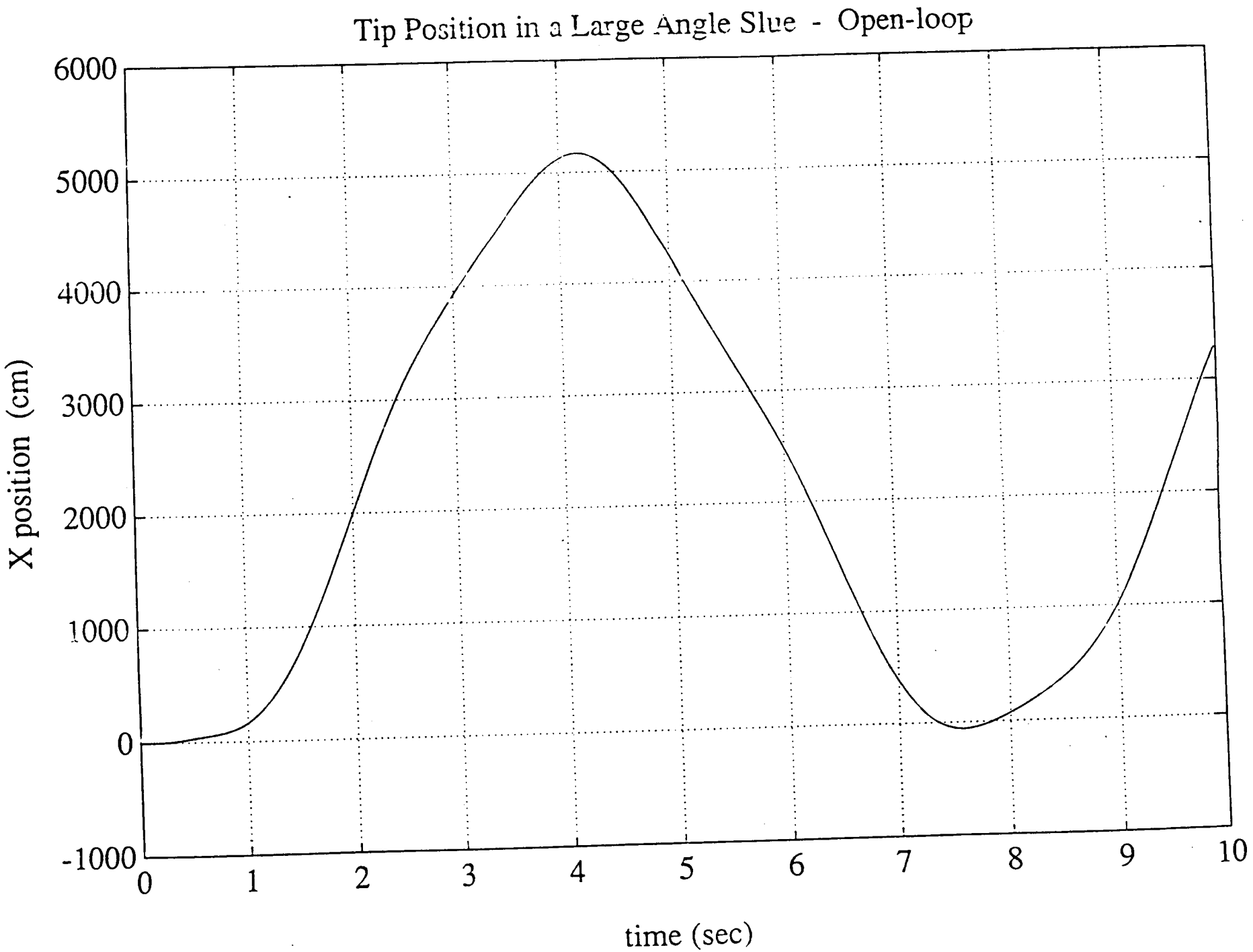

Boom
Section
Offset Hinges
To Rotary Joint

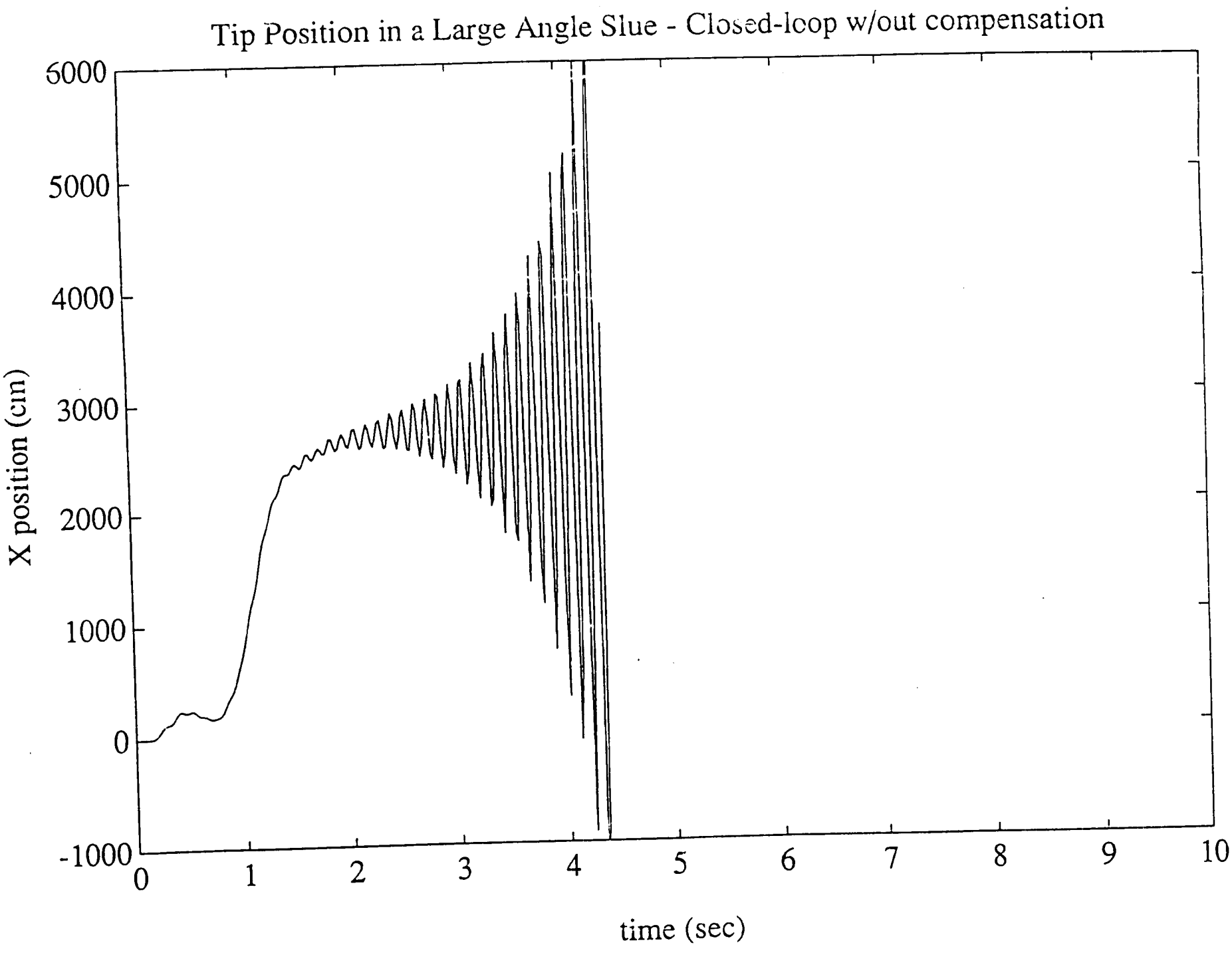

Tip Position Due to a Small Displacement - Open-loop
X position (cm)
30
20
10
0
-10
-20
-30
0
1
2
3
4
5
6
7
8
time (sec)

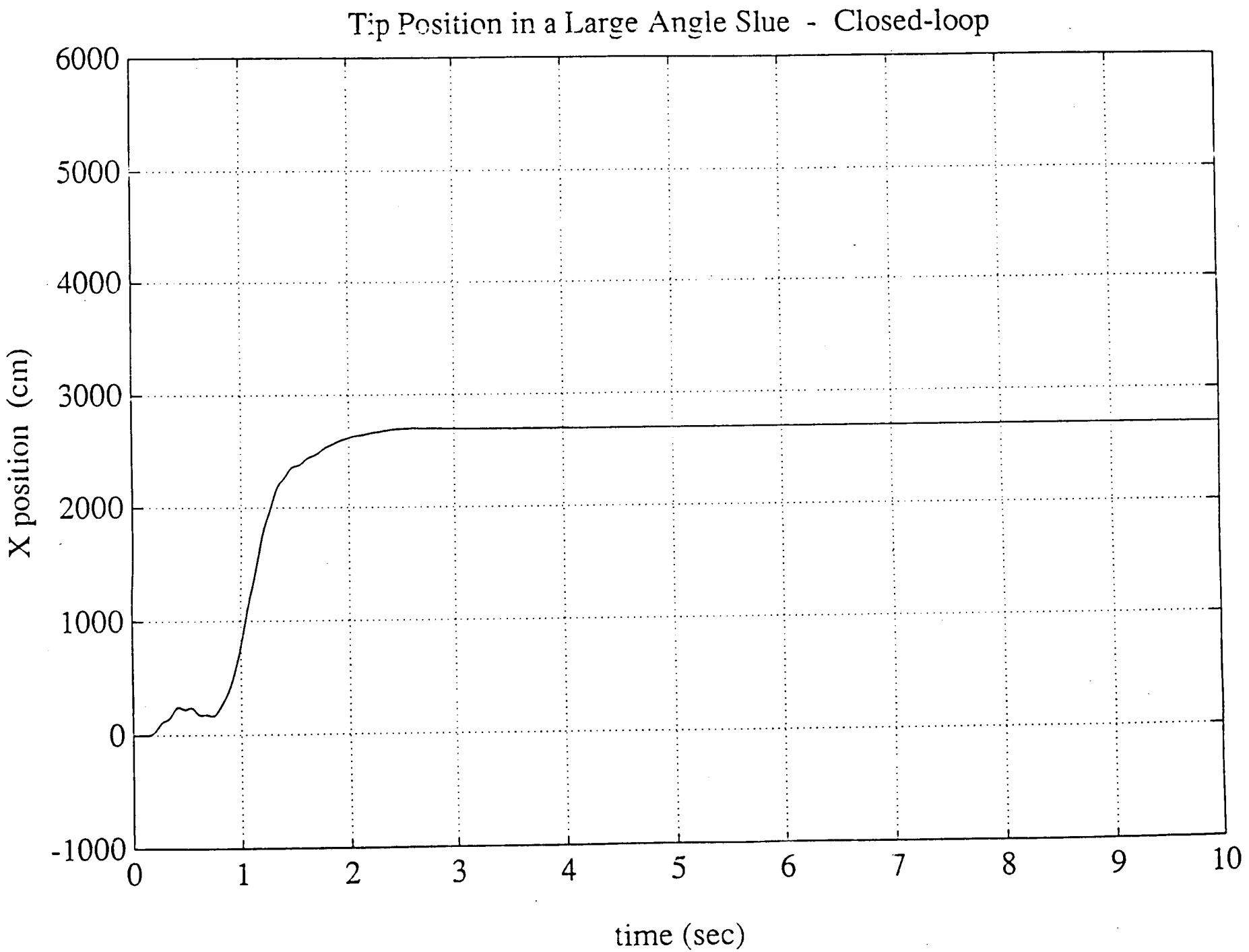

Tip Position Due to a Small Displacement - Closed-loop
Y position (cm)
30
20
10
0
-10
-20
-30
0
1
2
3
4
5
6
7
8
time (sec)


Tip Position Due to a Small Displacement - Open-loop
Y position (cm)
30
20
10
0
-10
-20
-30
0
1
2
3
4
5
6
7
8
time (sec)


Tip Position Due to a Small Displacement - Closed-loop
X position (cm)
30
20
10
0
-10
-20
-30
0
1
2
3
4
5
6
7
8
time (sec)


Tip Position in a Large Angle Slue - Open-loop
6000
5000
4000
3000
2000
1000
0
-1000
X position (cm)
0
1
2
3
4
5
6
7
8
9
10
time (sec)


Tip Position in a Large Angle Slue - Closed-loop w/out compensation
X position (cm)
6000
5000
4000
3000
2000
1000
0
-1000
0
1
2
3
4
5
6
7
8
9
10
time (sec)


Tip Position in a Large Angle Slue - Closed-loop
6000
5000
4000
3000
2000
1000
0
-1000
X position (cm)
0
1
2
3
4
5
6
7
8
9
10
time (sec)

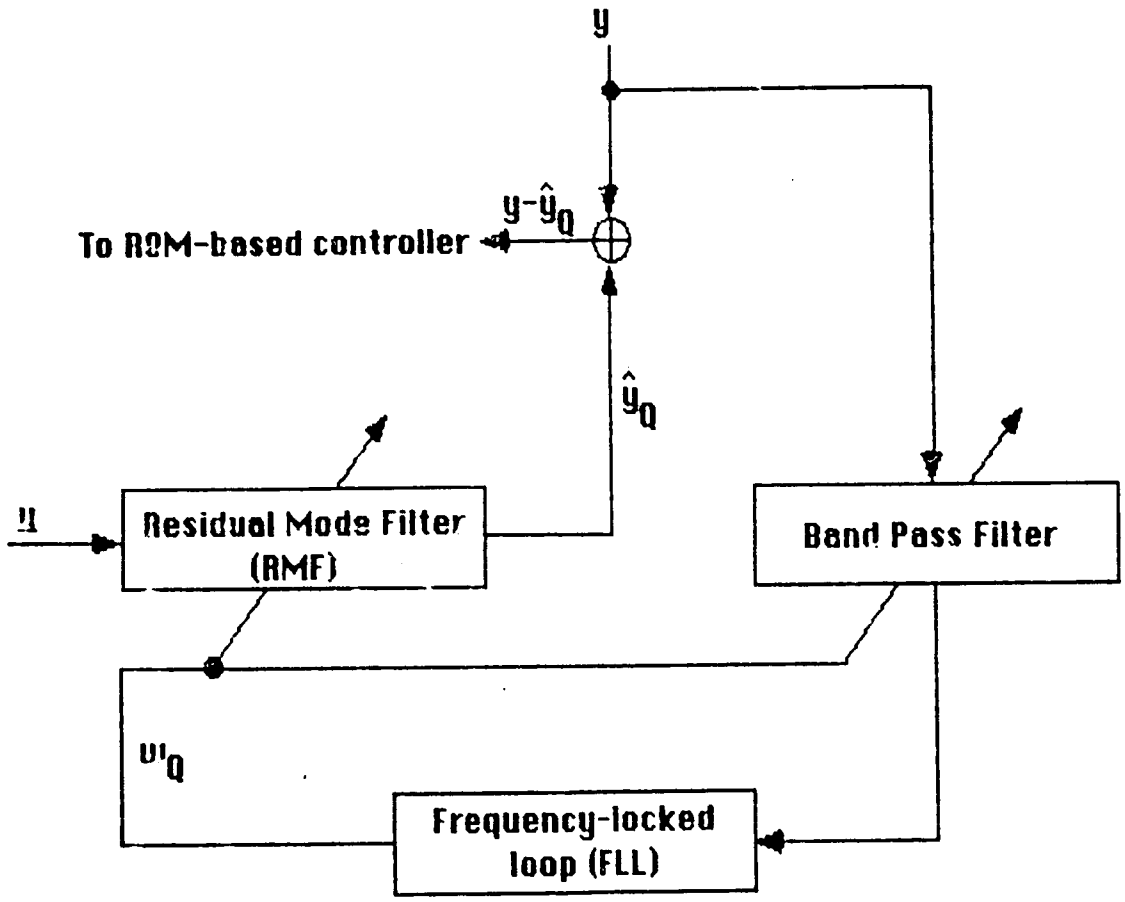


Figure 4. The adaptive, self-tuning RMF.

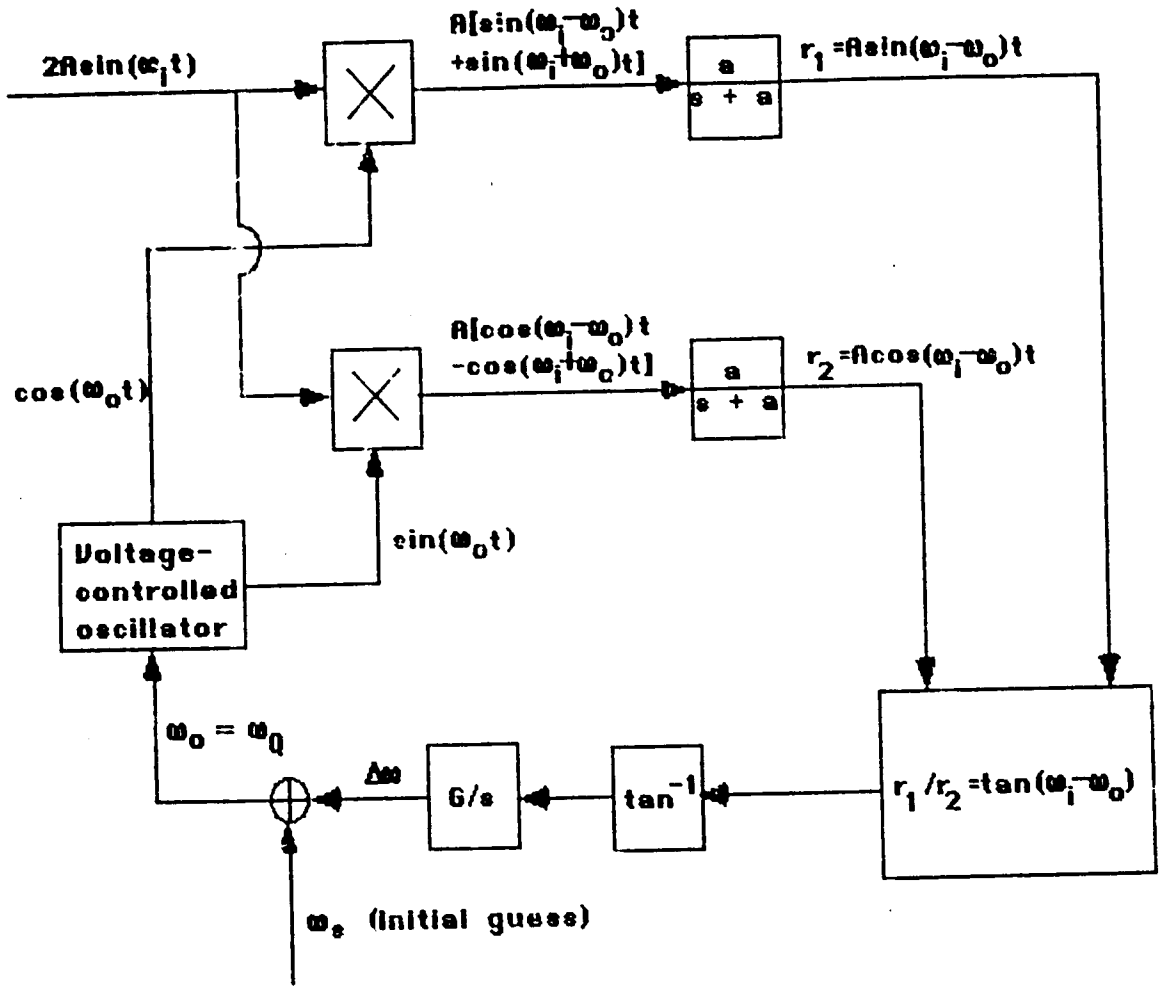


Figure 5. The FLL design which was used in this research

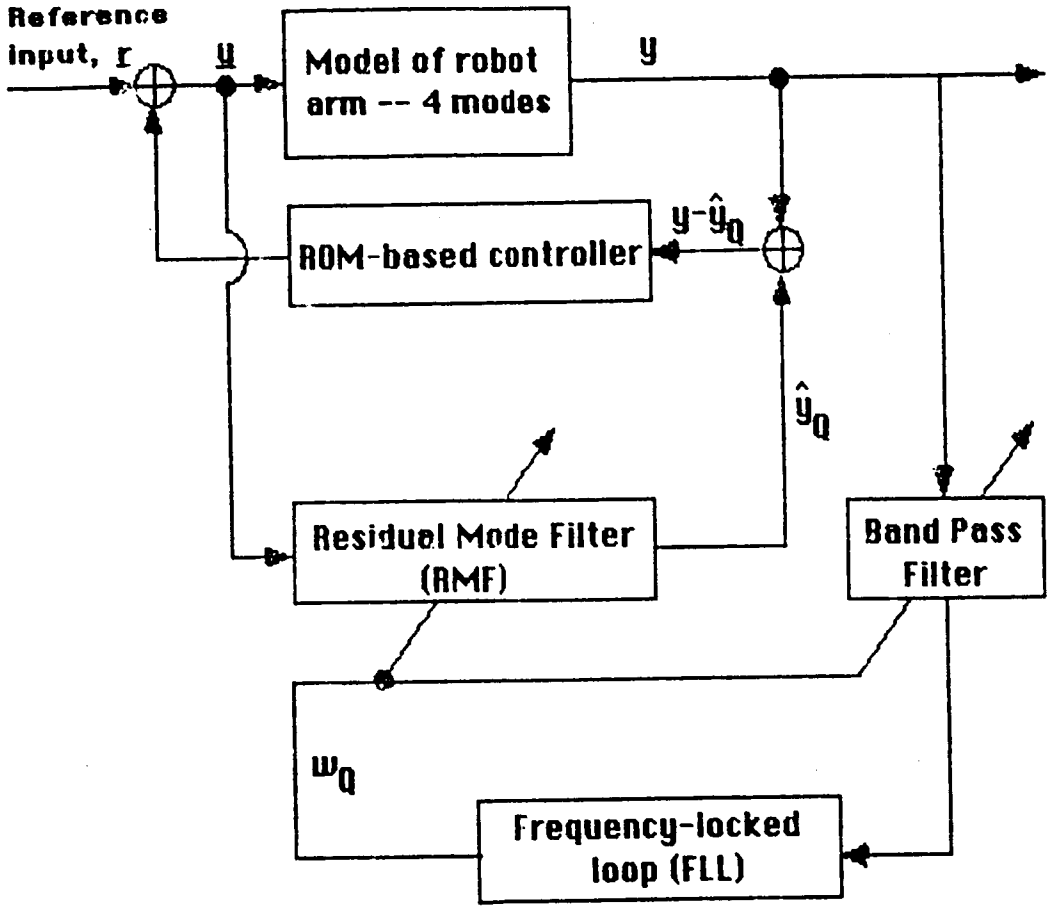
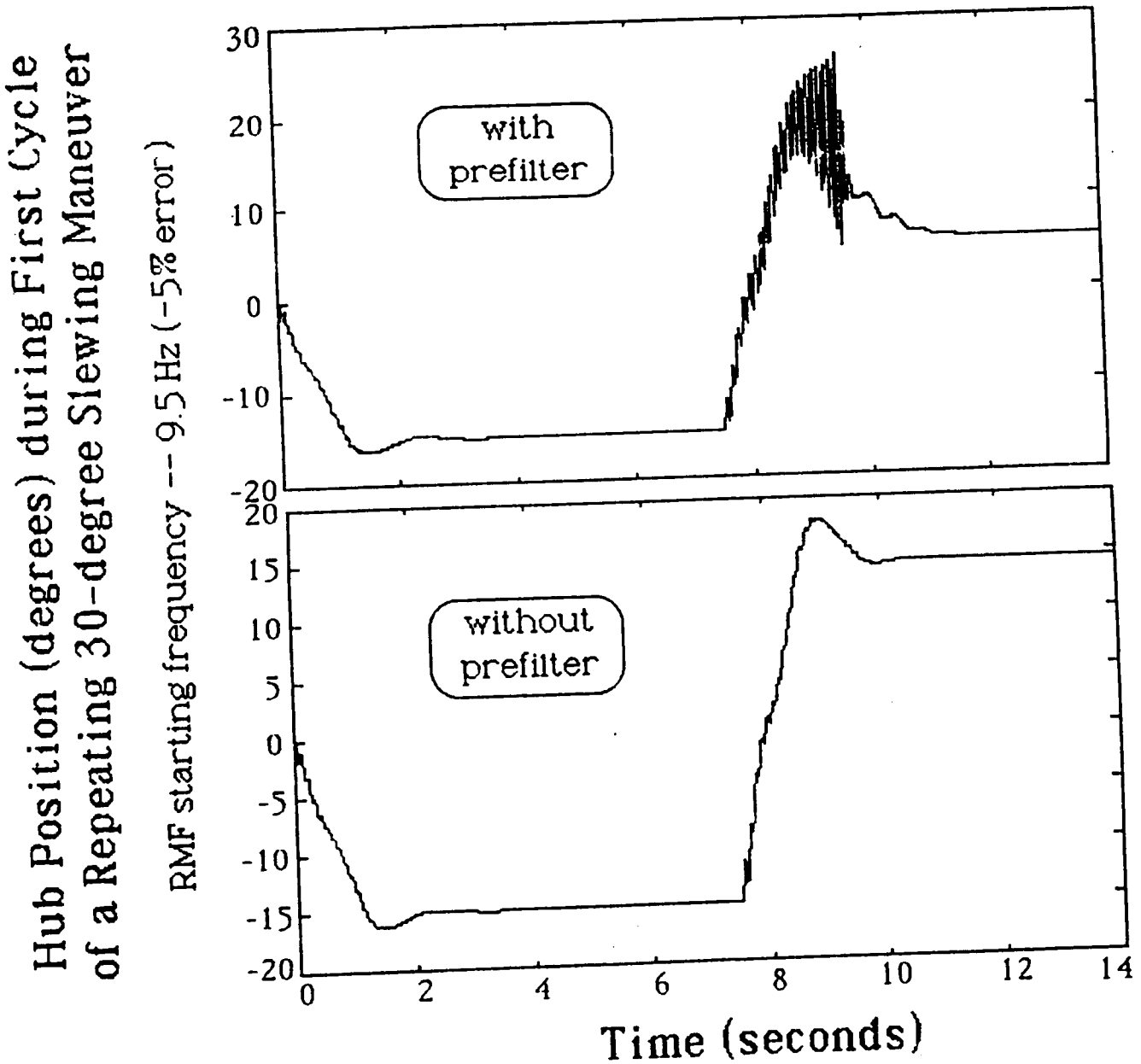


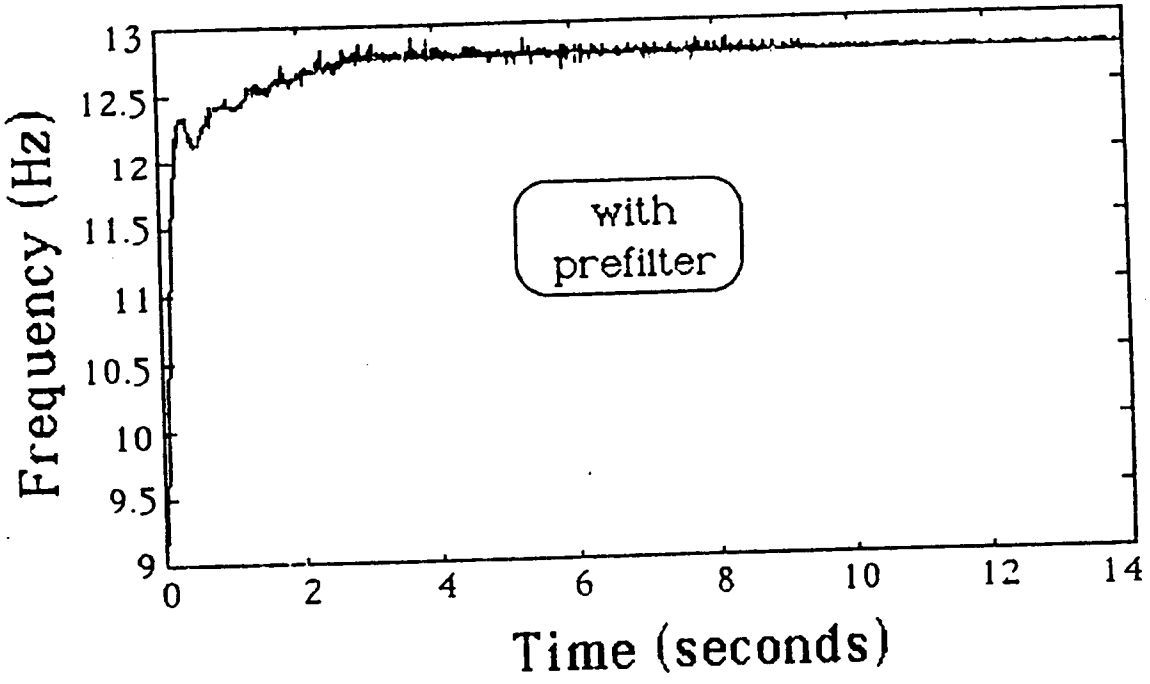
Figure 6. Block diagram of closed-loop system with adaptive RMF.

Effect of the tunable bandpass prefilter on performance of CSI compensation with the adaptive RMF



Adaptive RMF Frequency during First Cycle of a Repeating 30-degree Slewing Maneuver

RMF starting frequency -- 9.5 Hz (-5% error)



Adaptive RMF Frequency during First Cycle of a Repeating 30-degree Slewing Maneuver

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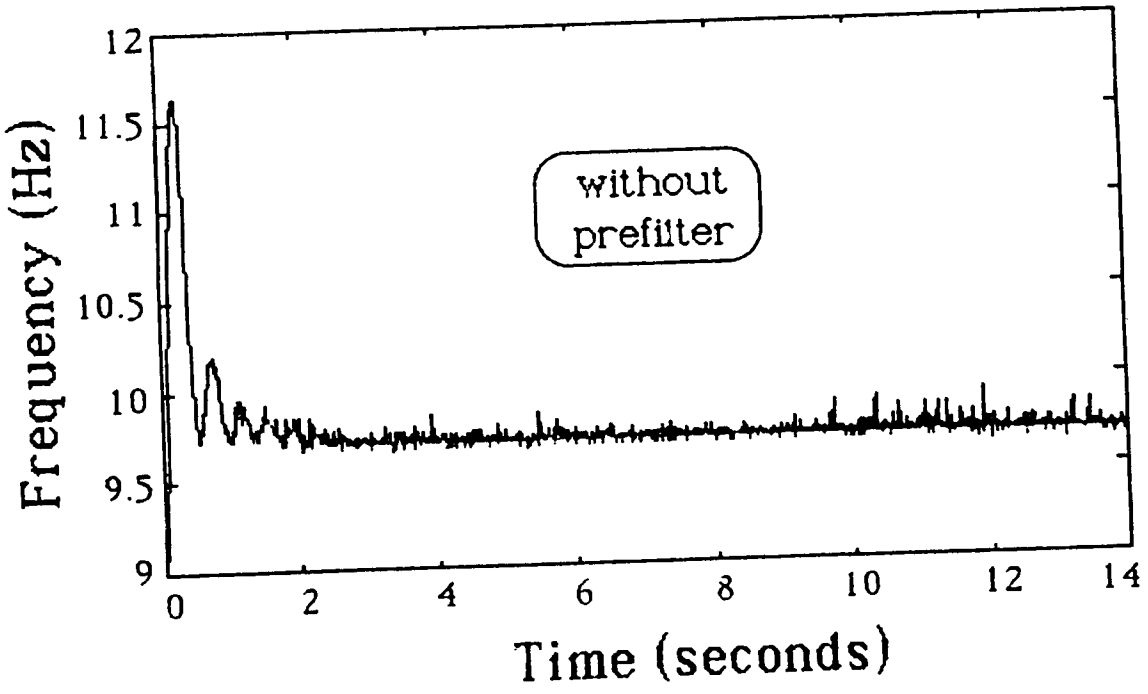
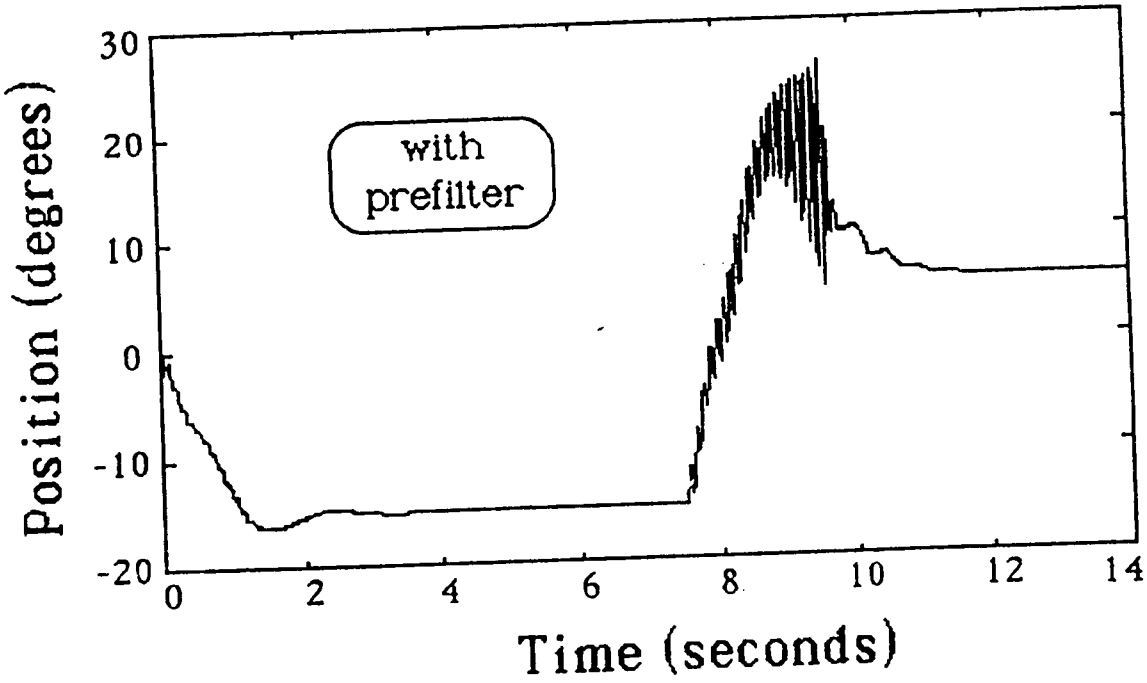


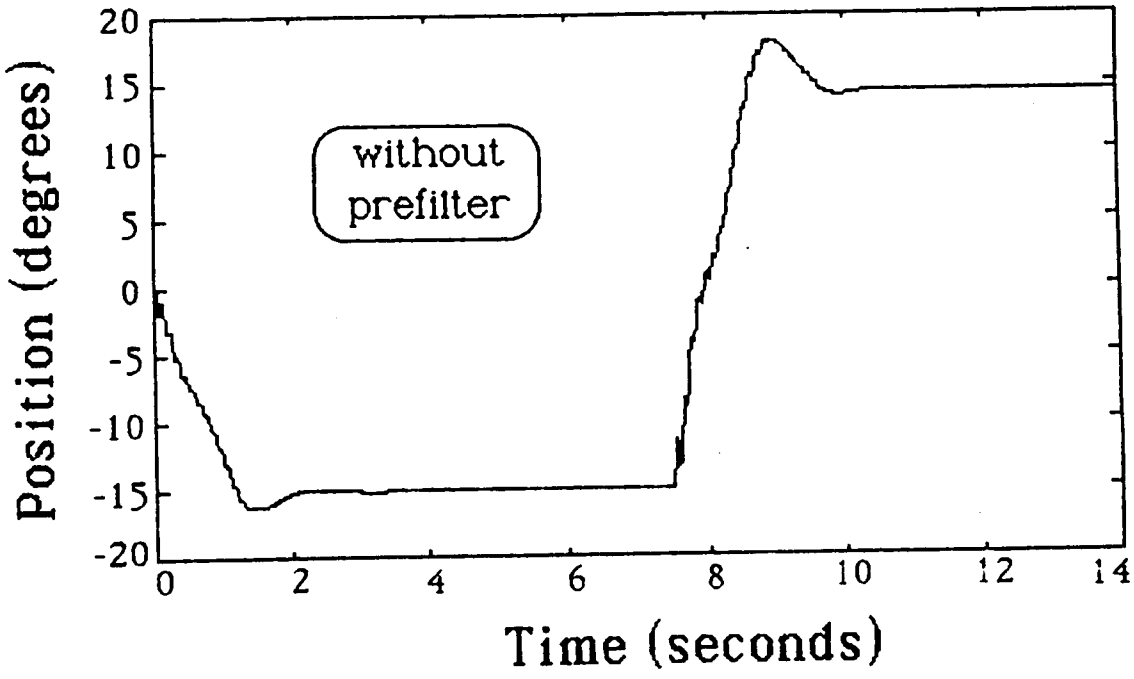
Hub Position during First Cycle of a Repeating 30-degree Slewing Maneuver

RMF starting frequency -- 9.5 Hz (-5% error)



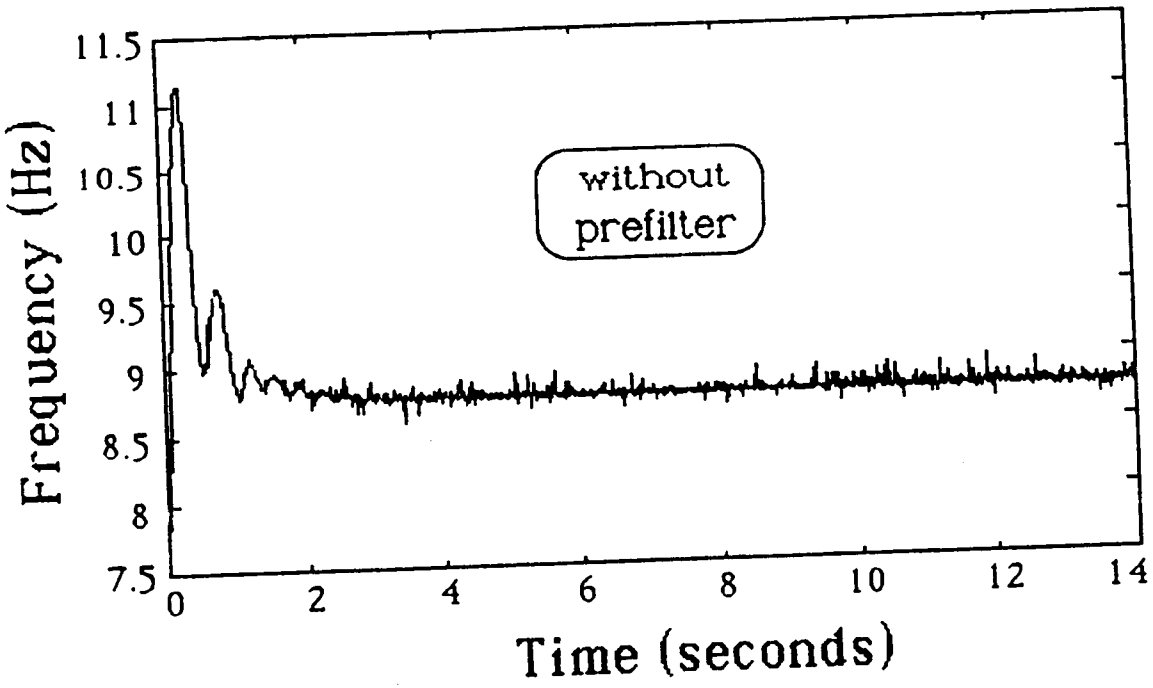
Hub Position during First Cycle of a Repeating 30-degree Slewing Maneuver

RMF starting frequency -- 9.5 Hz (-5% error)



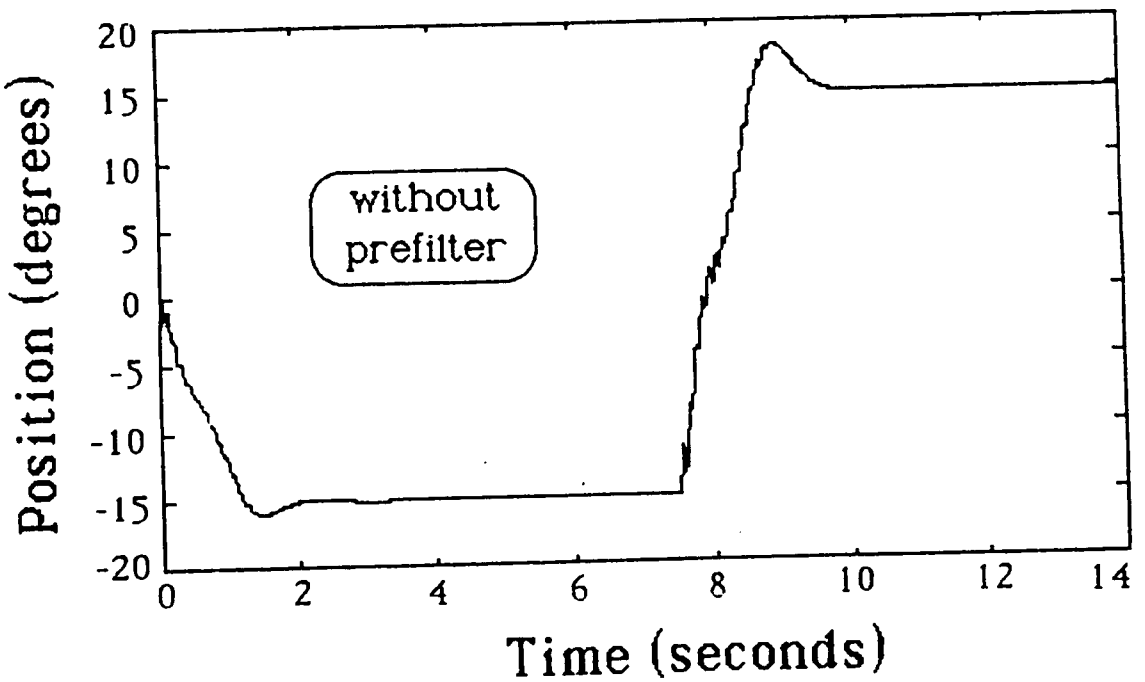
Adaptive RMF Frequency during First Cycle of a Repeating 30-degree Slewing Maneuver

RMF starting frequency -- 8.5 Hz (-15% error)



Hub Position during First Cycle of a Repeating 30-degree Slewing Maneuver

RMF starting frequency -- 8.5 Hz (-15% error)



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FLUID MANAGEMENT IN THE OPTIMIZATION OF SPACE CONSTRUCTION

Howard Snyder

Fluid management impacts strongly on the optimization of space construction. Large quantities of liquids are needed for propellants and life support. The mass of propellant liquids is comparable to that required for the structures. There may be a strong dynamic interaction between the stored liquids and the space structure unless the design minimizes the interaction. The constraints of cost and time require optimization of the supply/resupply strategy. The proper selection and design of the fluid management methods for: slosh control; stratification control; acquisition; transfer; gauging; venting; dumping; contamination control; selection of tank configuration and size; the storage state and the control system can improve the entire system performance substantially. Our effort consists of building mathematical/computer models of the various fluid management methods and testing them against the available experimental data. The results of the models are used as inputs to the system operations studies. During the past year, the emphasis has been on modeling: the transfer of cryogens; sloshing and the storage configuration. The work has been intermeshed with ongoing NASA design and development studies to leverage the funds provided by the Center.

FLUID MANAGEMENT

in

SPACE CONSTRUCTION

Prof. HOWARD SNYDER

FLUIDS MANAGEMENT

IMPACT ON CONSTRUCTION OPTIMIZATION

- NEED FOR LARGE QUANTITIES OF LIQUIDS

  PROPELLANTS
  LIFE SUPPORT

- SAVE WEIGHT BY STORING AT SATURATION

- MASS COMPARABLE TO THAT OF STRUCTURE

- USED FOR VARIOUS MISSIONS

  SPACE STRUCTURES
  MARS INTERPLANETARY MANNED
  UNTETHERED FREE FLYER
  EXTERNAL TANKS

MAJOR IMPACTS

- O DYNAMICS

  SLOSHING

  SHIFT IN C.M. DUE TO CONSUMPTION

  IMPULSE DURING TRANSFER AND VENT

  DOCKING FOR RESUPPLY

  EXCITES STRUCTURAL VIBRATIONS

- O SUPPLY/RESUPPLY

  FREQUENCY AND AMOUNT OF RESUPPLY

  TIME LINES

  IMPACTS TOTAL COST AND TIMEI

- O NEED FOR HUMAN, ROBOTIC, AUTOMATIC INTERACTION FOR SYSTEM OPERATION

  SELECT OPTIMAL MIX

OPTIMIZATION

- O PURPOSE

  REDUCE DYNAMIC INTERACTION

  OPTIMIZE RESUPPLY CYCLE

  OPTIMIZE CONTROL OF FLUID SYSTEM

- O CHOICES

  SELECTION OF MANAGEMENT METHOD FOR:

  SLOSH CONTROL
  STRATIFICATION CONTROL
  ACQUISITION OF LIQUID
  TRANSFER
  GAUGING
  VENTING AND DUMPING
  CONTAMINATION CONTROL

  SELECTION OF STORAGE SYSTEMS

  TANK CONFIGURATION AND SIZE
  STORAGE STATE

  SELECTION OF SYSTEM CONTROL METHODS

  APPORTION RESPONSIBILITY TO:
  AUTOMATIC, ROBOTIC, HUMAN

FUNCTIONS OF

FLUID MANAGEMENT SYSTEM

- TRANSPORTATION FROM EARTH TO BASE
- TRANSPORTATION FROM BASE TO SATELLITES
- STORAGE
- DISTRIBUTION AND CONTROL AT BASE
- HABITABILITY BY ASTRONAUTS
- DISPOSAL AND CONTAMINATION CONTROL

FUNCTIONAL UNITS of

FLUID MANAGEMENT SYSTEM

- O STORAGE CONTAINER
- * O THERMAL AND STRATIFICATION CONTROL
- * O VENTING AND DUMPING
- * O GAUGING
- * O SLOSHING AND DYNAMIC INTERACTION
- * O ACQUISITION OF LIQUID
- * O PUMPING
- * O TRANSFER
- O DISPERSING
- O SEPERATION OF SOLIDS
- O WASTE FLUID TREATMENT

* AN IDENTIFIED ENABLING TECHNOLOGY AND KNOWLEDGE OF PROCESS INADEQUATE

TASKS

- MODEL PROCESSES IDENTIFIED AS ENABLING TECHNOLOGY FOR SPACE CONSTRUCTION

- COMPARE MODEL RESULTS WITH EXPERIMENTAL DATA AS IT BECOMES AVAILABLE

- MESH FLUIDS MODELS WITH STRUCTURES MODELS

  INPUT FLUID SYSTEM PARAMETERS INTO STURCTURES MODELS

  SERVE AS EXPERT ON FLUIDS AND CRYOGENICS FOR SYSTEM OPTIMIZATION TEAM

FLUIDS MANAGEMENT SUBCLUSTER

- HOWARD SNYDER
  - PROFESSOR AEROSPACE ENGINEERING
  - CONSULTANT BALL AEROSPACE SYSTEMS
- ALLAN MORD
  - SYSTEMS MANAGER BALL AEROSPACE
  - ADJOINT PROFESSOR AEROSPACE ENG
- GARY MILLS
  - GRADUATE STUDENT AEROSPACE ENG
  - SENIOR ENGINEER BALL AEROSPACE
- DAVID NEWELL
  - GRADUATE STUDENT AEROSPACE ENG
  - STUDENT ENGINEER BALL AEROSPACE
- DAVID PINTER
  - UNDERGRADUATE STUDENT AEROSPACE

USE OF NASA STUDY CONTRACTS AND IR&D AT BALL AEROSPACE SYSTEMS TO LEVERAGE CENTER FUNDS

CENTER WORK EXTENDS BEYOND WHAT IS REQUIRED IN NASA CONTRACTS

PROJECTS – PROGRESS

LAST YEAR FLUID QUANTITY GAUGING

- O DEVELOPED EXPERIMENTAL APPARATUS, THEORY OF OPERATION AND DATA REDUCTION ALGORITHM
- O MET NASA SPECIFICATION FOR TEST USING WATER ON EARTH
- O BASELINED FOR SSF AND TEST WITH CRYOGENS ON COLDSAT

THIS YEAR COOPERATIVE OSCILLATION OF BUBBLES

HIGH PRESSURE MODEL

TRANSFER MODEL

OPTIMIZATION OF LUNAR STORAGE OF CRYOGENS

COOPERATIVE OSCILLATIONS OF BUBBLES

A NEW TYPE OF SLOSHING
CAUSES CENTER OF MASS TO MOVE
INTERACTION WITH STRUCTURAL OSCILLATIONS

- DISCOVERED LAST YEAR
  REPORTED ON THERORY AND EXPERIMENTAL VERIFICATION LAST YEAR

- EXTENDED THEORY TO COVER CASE OF THREE OR MORE BUBBLES OF COMPARABLE SIZE

- PUBLISHED RESULTS

- NEEDS EXPERIMENTAL WORK ON SATURATED LIQUID

HIGH PRESSURE GAS MODEL

- ALTERNATE METHOD OF STORING GASES IN SPACE
- TECHNOLOGY ALREADY DEVELOPED FOR ASTRONAUT EVA BOTTLES – UP TO 600 ATMOSPHERES
- EXPECT LARGE TEMPERATURE RANGE IN EXTERNAL STORAGE
- NEED THEORY OF GAS MIXTURES AT HIGH PRESSURE FOR LARGE TEMPERATURE RANGE
- FRACTIONIZATION CONDENSATION FOR FIXED VOLUME
- DEVELOPED MODEL WITH COMPOSITION AND THREE CRITICAL PARAMETERS FOR EACH GAS AS INPUTS – GAS VERY NON-IDEAL
- CALCULATES ANY THERMODYNAMIC PROPERTY OF FLUID MIXTURE BEFORE OR AFTER CONDENSATION AND CONDITIONS FOR CONDENSATION

TRANSFER MODEL

- O COMPUTER MODEL OF TRANSFER OF CRYOGEN IN A LONG TUBE
- O DEVELOPED AT BALL AEROSPACE OVER PAST FOUR YEARS
- O VERY VERSITILE – BENDS, CONSTRICTIONS, HEAT SOURCES, VALVES, ETC
- O APPLIED TO A SIMPLE PIPE
  LARGE THERMODYNAMIC PROPERTY VARIATIONS FROM END TO END
- O USED TO OPTIMIZE DESIGN OF TRANSFER SYSTEM
- O RESULTS OF MANY RUNS UNDER LARGE RANGE OF CONDITIONS SHOWS FOUR REGIMES OF FLOW
- O FOUND SINGLE DIMENSIONLESS PARAMETER WHICH DETERMINES FLOW REGIME AND SCALES TEMPERATURE AND PRESSURE PROFILES

OPTIMIZATION OF LUNAR STORAGE OF CRYOGENS

- SPECIFICATIONS DEVELOPED BY INTERATION WITH SYSTEMS CLUSTER
- LECTURE BY GRADUATE STUDENTS MILLS AND NEWELL FRIDAY MORNING

PROJECTS – PROGRESS

IN PREPERATION

- O DYNAMICS AND CONFIGURATION OF BUBBLES IN A STORAGE TANK IN LOW–G

FUTURE

- O OSCILLATIONS OF A SINGLE BUBBLE IN LOW–G
- O SWIRL AS A MANAGEMENT METHOD
- O THERMAL GRADIENT INDUCED MIGRATION OF BUBBLES
- O ACOUSTIC COALESCENSE OF BUBBLES
- O SIMULATION OF LOW–G PIPE FLOW USING VERTICAL TUBES

TRANSFER IN SIMPLE PIPES

- RAN BALL AEROSPACE MODEL FOR LARGE RANGE OF CONDITIONS

- FOUND FOUR FLOW REGIMES

  1. THERMAL BOUNDARY LAYER PRESSURE NEARLY LINEAR

  2. TEMPERATURE AND PRESSURE NEARLY LINEAR

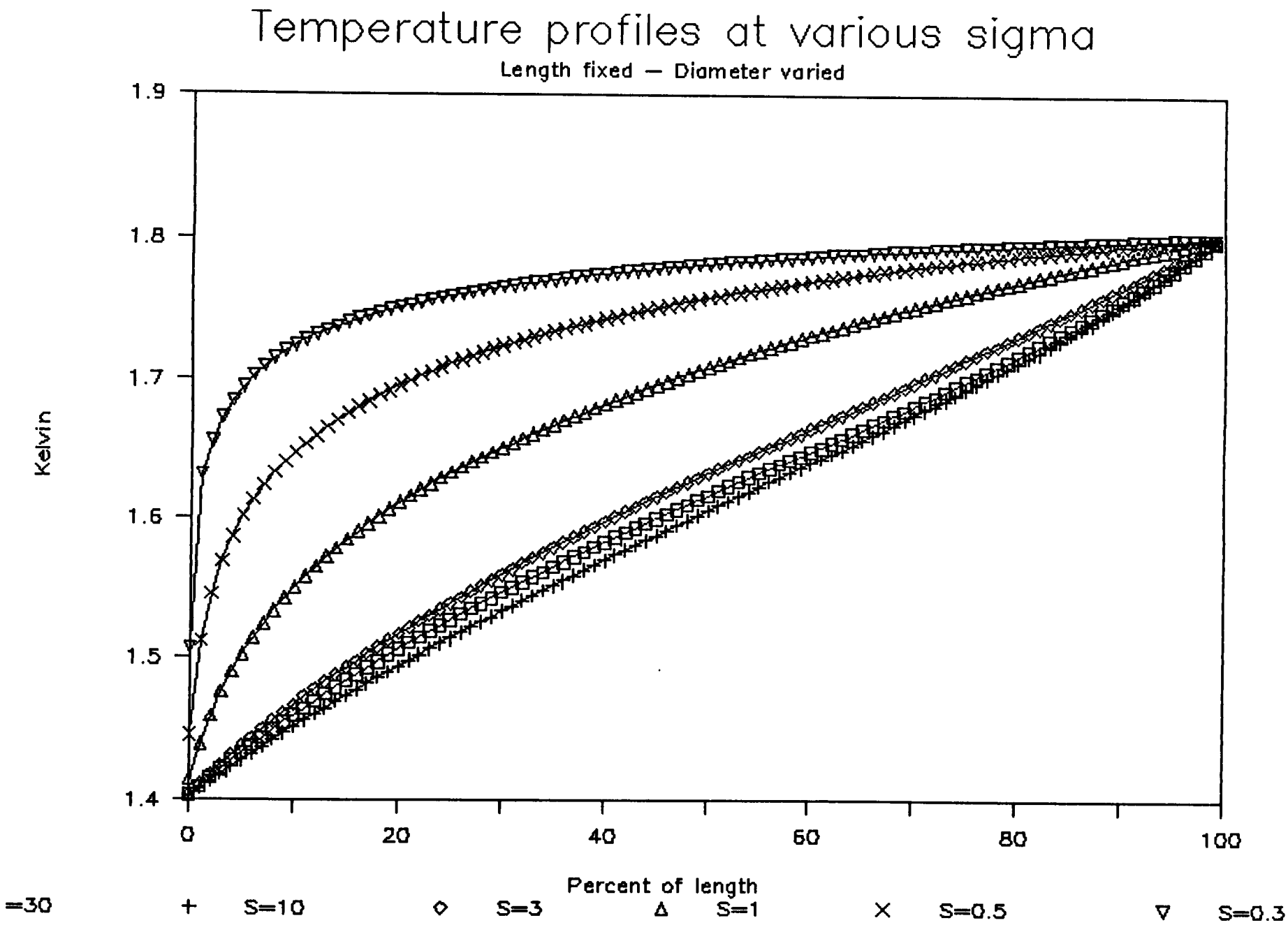
  3. PRESSURE MAXIMUM TEMPERATURE NEARLY LINEAR

  4. PRESSURE AND TEMPERATURE MAXIMUM

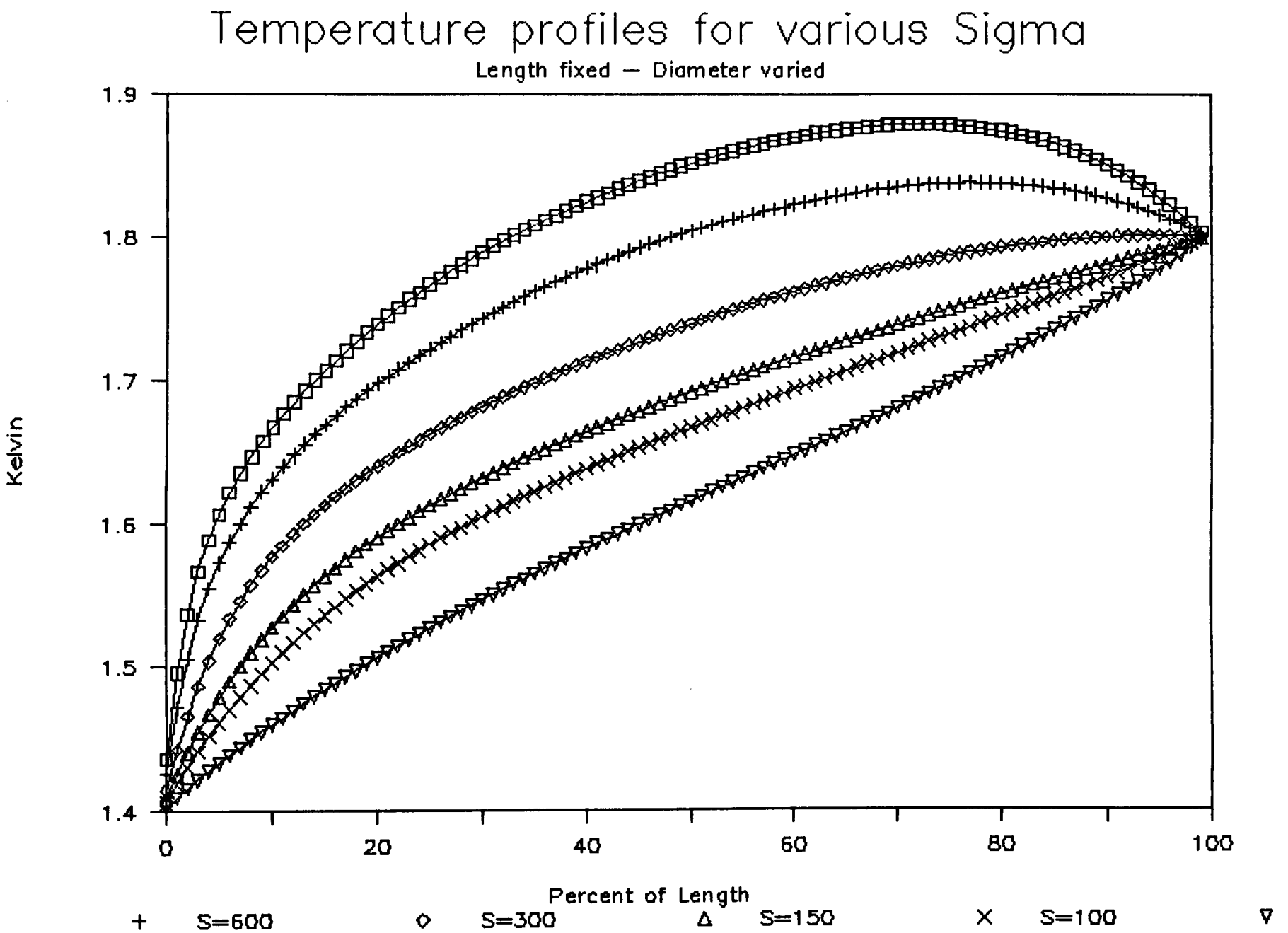
- FOUND SINGLE DIMENSIONLESS PARAMETER THAT DETERMINES REGIME AND SCALES TEMPERATURE AND PRESSURE PROFILES

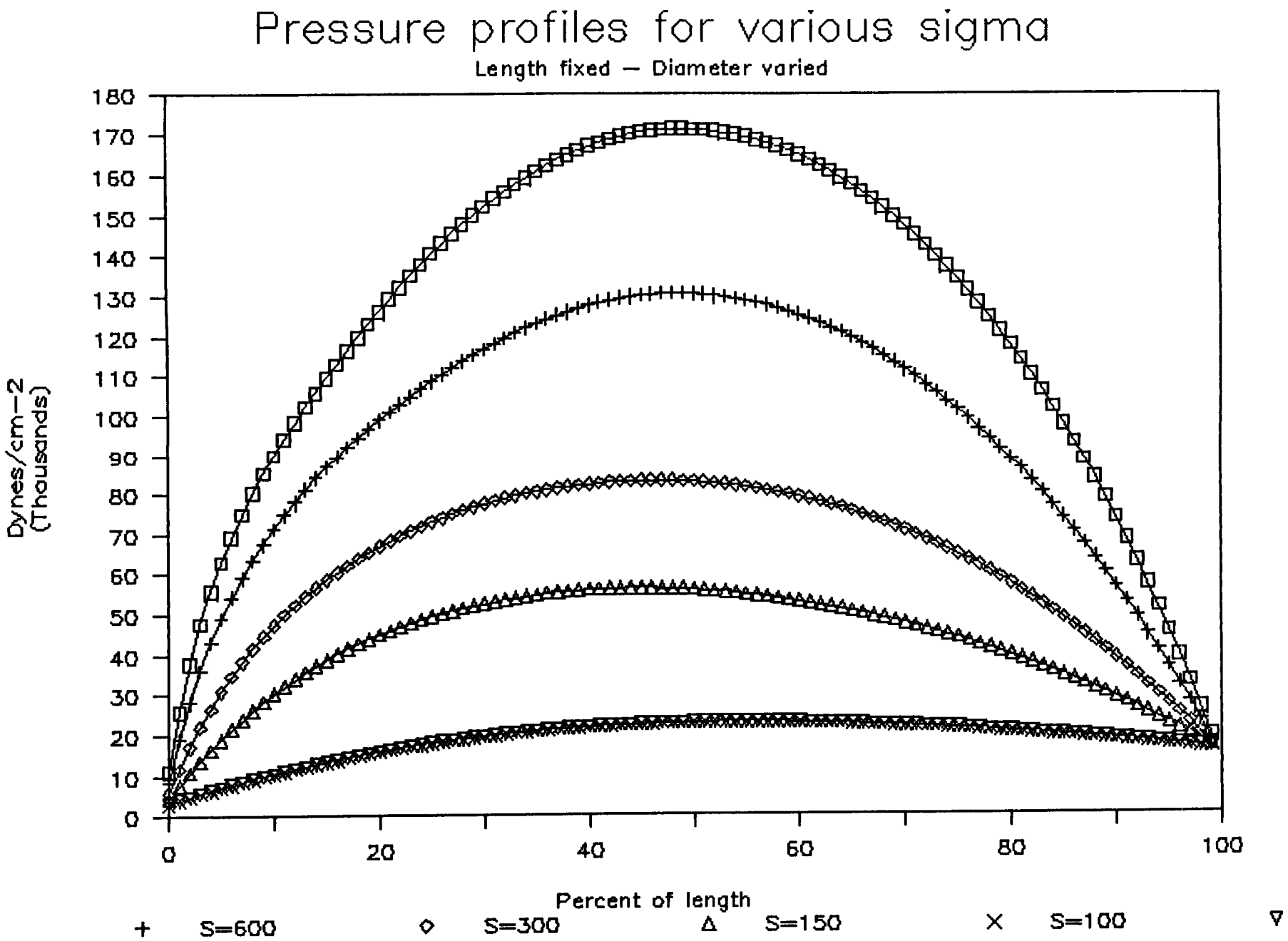
- IMPORTANCE

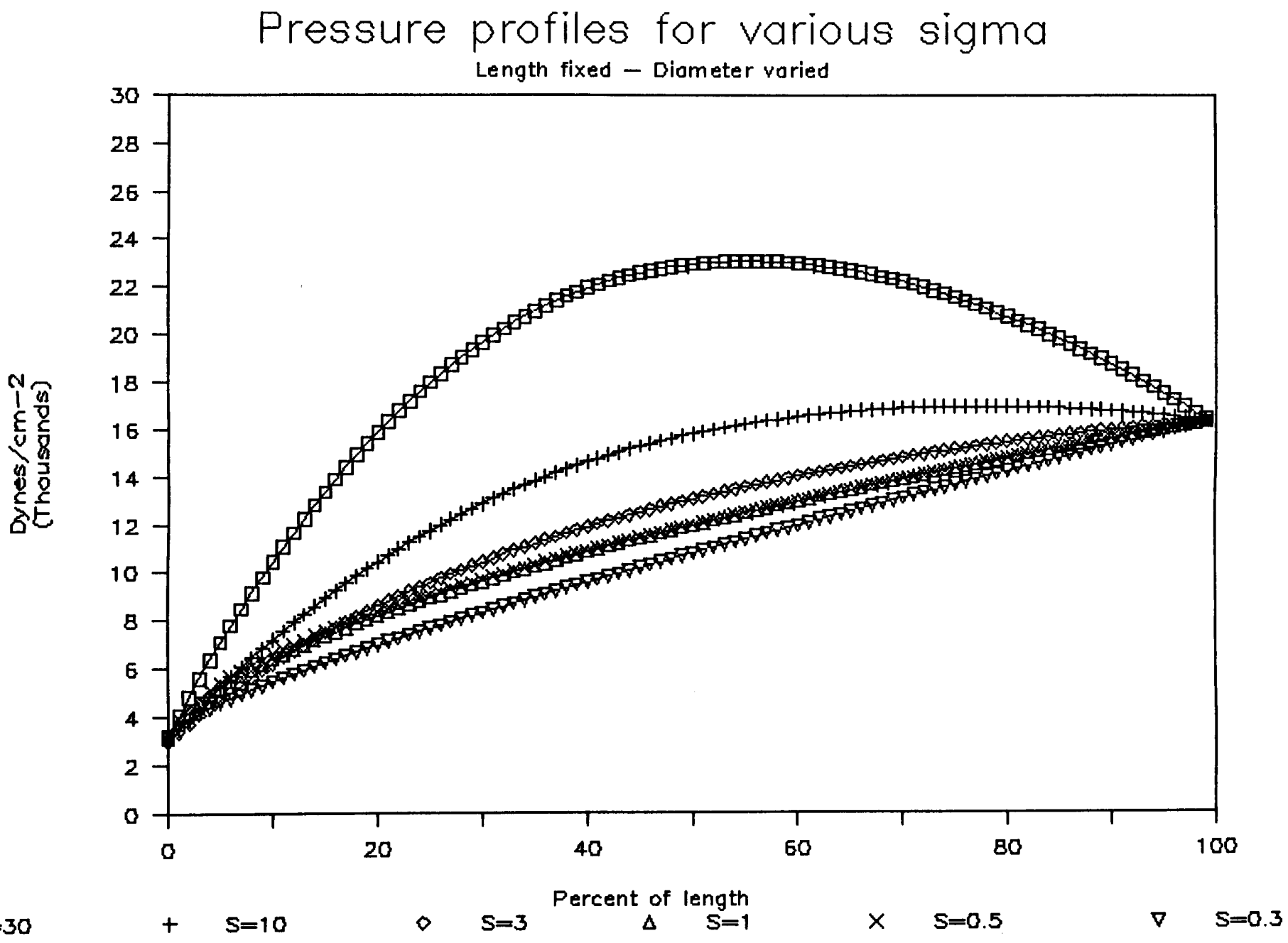
  BOILING AND TWO-PHASE FLOW IN LOW-G
  OPTIMIZE MASS TRANSPORT
  SHOWS HOW TO MAKE TRADE-OFF

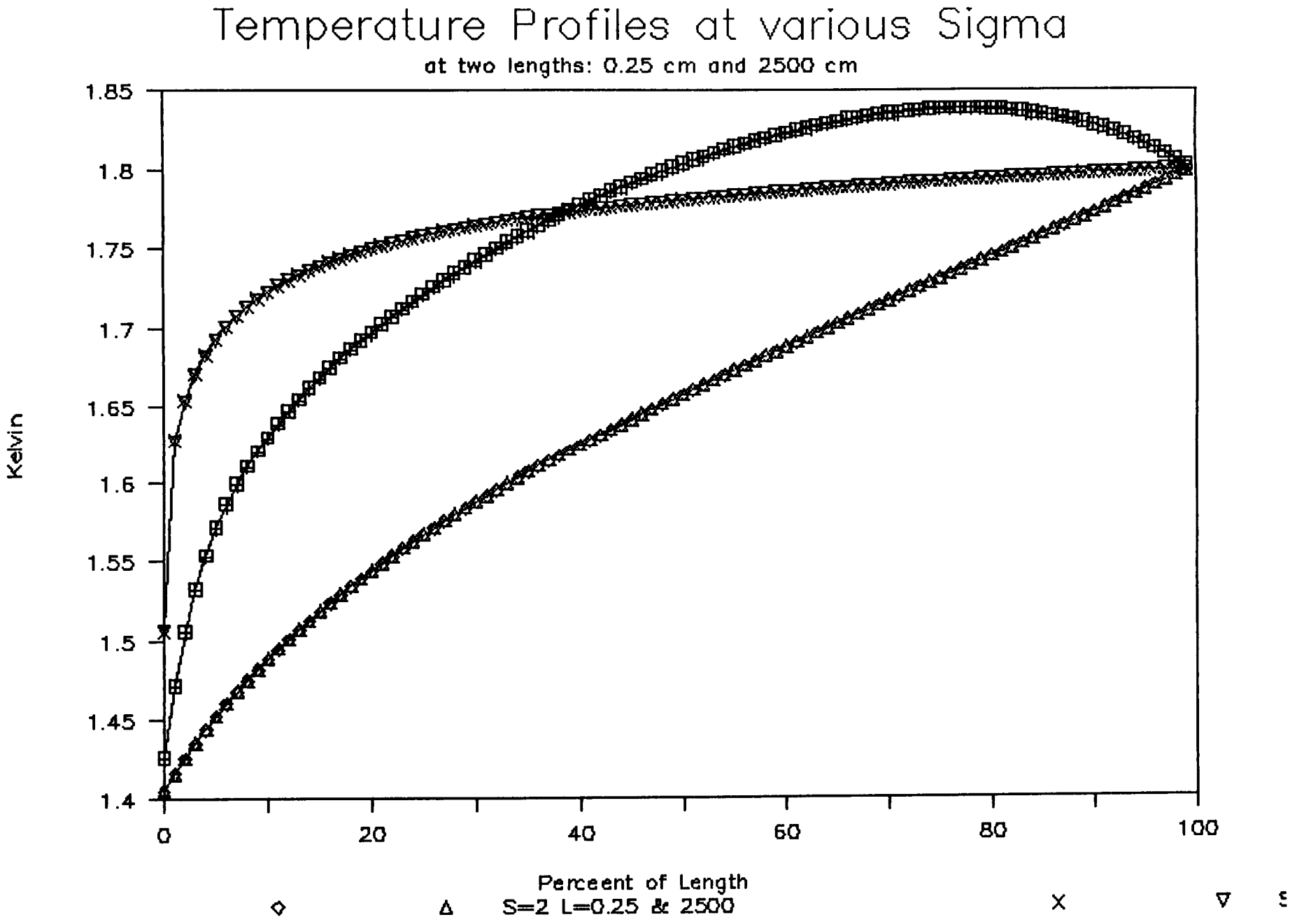

Temperature profiles at various sigma
Length fixed — Diameter varied
Kelvin
1.9
1.8
1.7
1.6
1.5
1.4
0
20
40
60
80
100
Percent of length
+ S=10
◇ S=3
Δ S=1
× S=0.5
∇ S=0.3

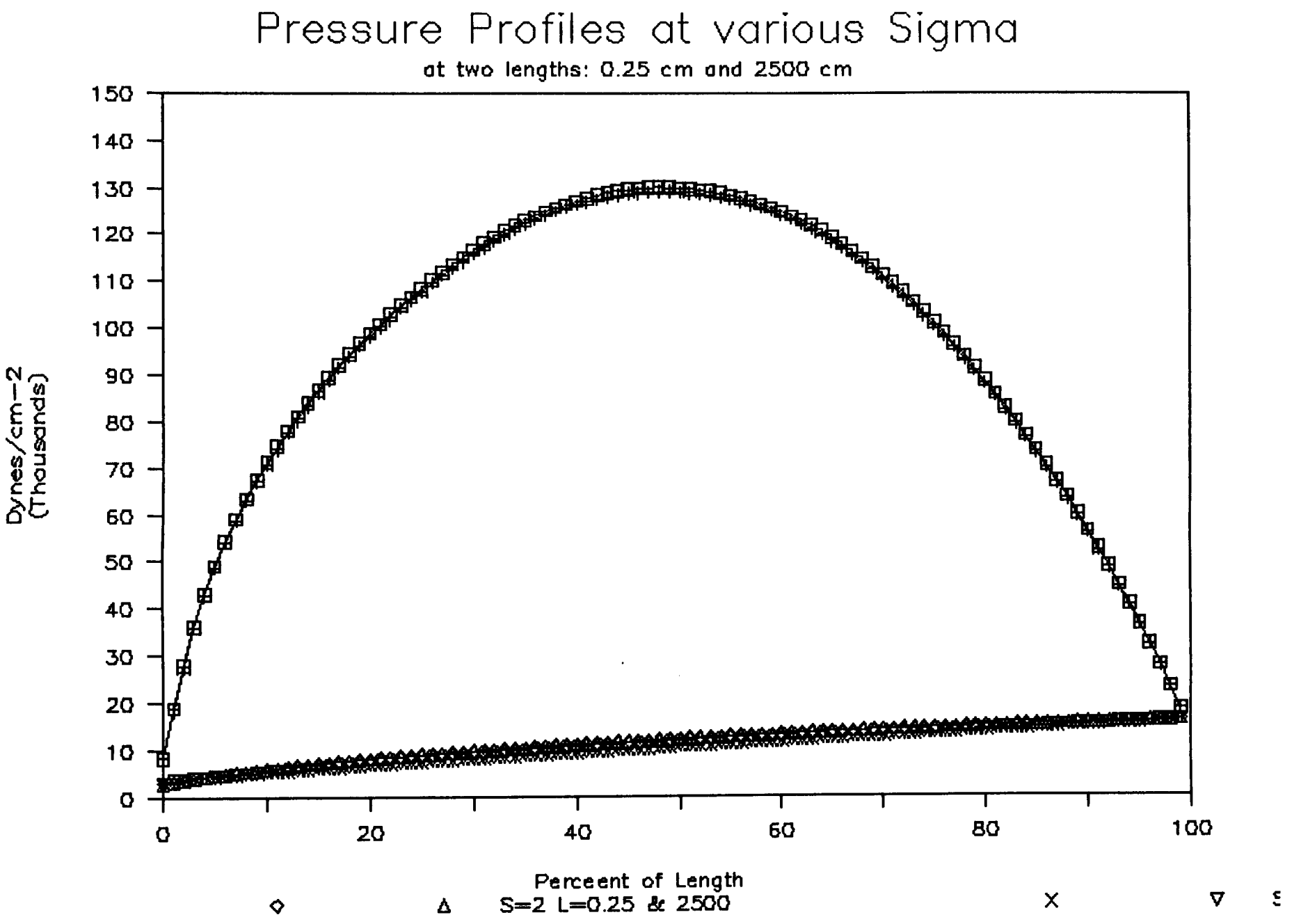
=30


Temperature profiles for various Sigma
Length fixed — Diameter varied
Kelvin
1.9
1.8
1.7
1.6
1.5
1.4
0
20
40
60
80
100
Percent of Length
+ S=600
◇ S=300
Δ S=150
× S=100
∇


Pressure profiles for various sigma
Length fixed — Diameter varied
Dynes/cm-2
(Thousands)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
Percent of length
+ S=600
◇ S=300
Δ S=150
× S=100
∇


Pressure profiles for various sigma
Length fixed — Diameter varied
Dynes/cm-2
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
20
40
60
80
100
Percent of length
=30
+ S=10
◇ S=3
Δ S=1
× S=0.5
∇ S=0.3


Temperature Profiles at various Sigma
at two lengths: 0.25 cm and 2500 cm
Kelvin
1.85
1.8
1.75
1.7
1.65
1.6
1.55
1.5
1.45
1.4
0
20
40
60
80
100
Percent of Length
S=2 L=0.25 & 2500


Pressure Profiles at various Sigma
at two lengths: 0.25 cm and 2500 cm
Dynes/cm-2
(Thousands)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
Percent of Length
S=2 L=0.25 & 2500

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SPACE ASSEMBLY INTERRUPTABILITY WITH APPLICATIONS TO SPACE STATION FREEDOM*

James W. Wade

The task of assembling large structures in space creates the possibility of construction interruptions. The unscheduled interruption of the assembly process may require abandoning the Station and returning to Earth. This interruption may be due to: crew illness/injury, Shuttle Orbiter mechanical failure, Orbiter or Station pressure loss, space debris damage etc. If not handled properly, these interruptions may jeopardize crew safety, Orbiter operations and the recoverability of the structure being assembled. The problem of space assembly interruptability was first addressed in January 1989 by astronaut Vance Brand (NASA-JSC) to Dr. George Morgenthaler at the University of Colorado - Boulder, at which time an Interruptability Team was organized at the University to study the problem of Space Station Freedom assembly interruptability.

The approach which is being undertaken at the University of Colorado is to create a methodology capable of analyzing generic structures. This is being accomplished by developing a software tool, DYCAM, to plan assembly sequences, and will be used in conjunction with INTERPRO, the INTERrupatbility PROgram, to analyze the Space Station Freedom assembly interruptability problem. Using an automated networking approach with some human interaction, the most favorable near-term safing† options will be calculated in the event of an interruption. PERT network techniques are employed to analyze which of these near-term improvements provide the optimal long-term response, as far as impact on the time and cost of the overall project are concerned.

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* Prepared for the University of Colorado, Center for Space Construction (CSC) 1990 Symposium, Boulder, CO.

† Safing options or tasks are defined as those activities which are performed after an interruption in order to stabilize the configuration.

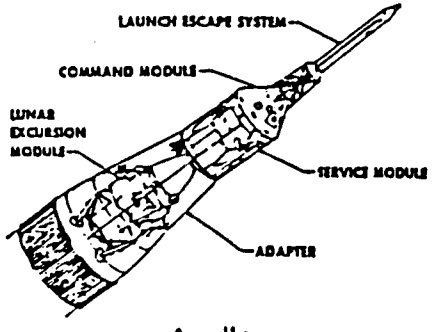
SPACE-BASED ASSEMBLY INTERRUPTABILITY

WITH APPLICATIONS TO SPACE STATION FREEDOM

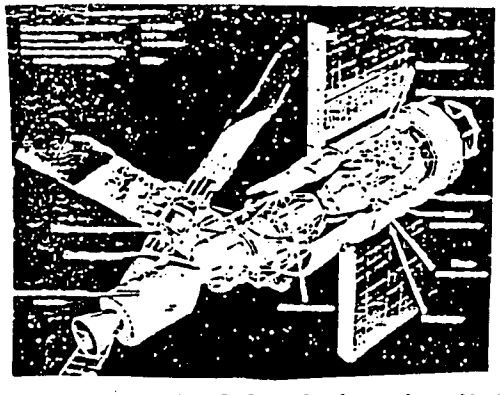
James W. Wade
University of Colorado-Boulder
Center for Space Construction
Systems Cluster
CSC 1990 Symposium

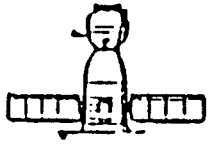
PREVIOUS/PRESENT SPACE ASSEMBLY METHODS

- Apollo, Skylab, Salyut, Soyuz: Completely ground assembled and tested.
- Final size determined by launch vehicle capability

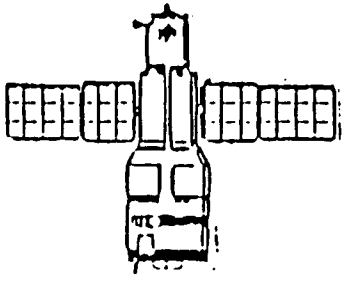


Apollo



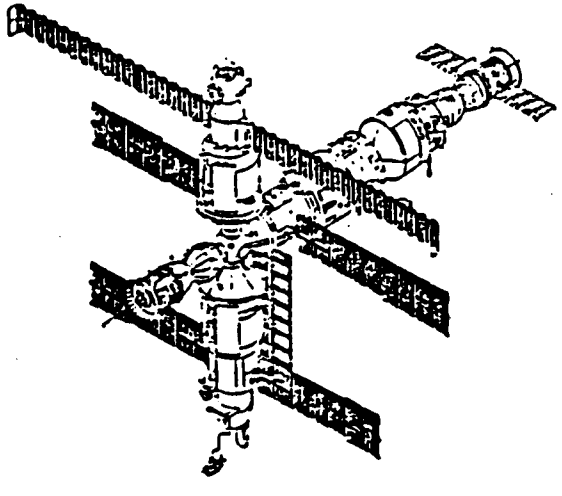


Soyuz



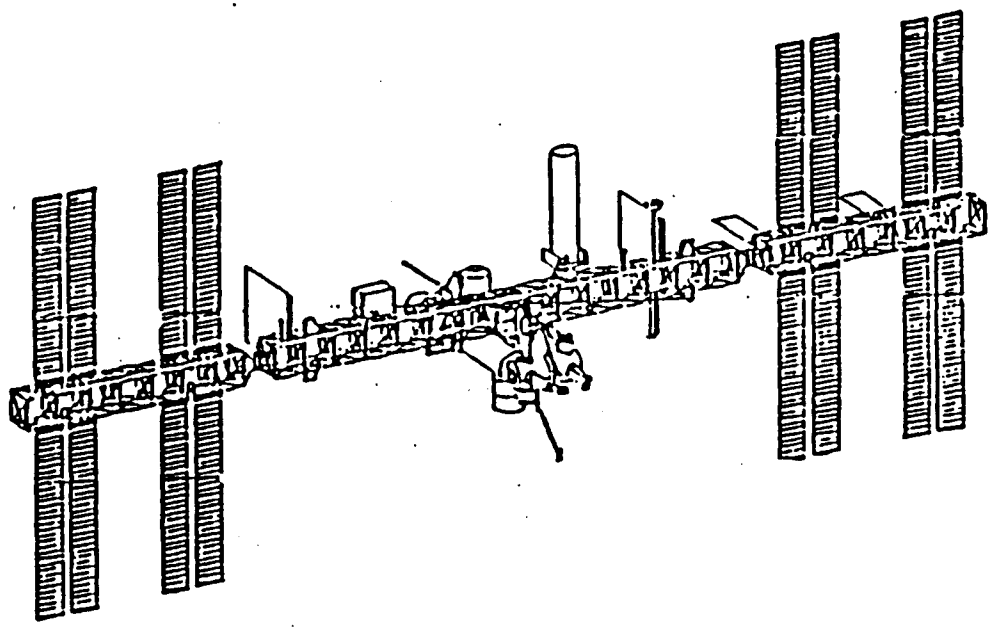
Salyut

- Mir (present Soviet station): Modular build-up
- Higher cost due to system duplication



FUTURE ASSEMBLY

- Space Station Freedom will require 29 Space Shuttle flights to assemble.
- First vehicle ever to be assembled & components integrated on-orbit.
- During assembly, the orbiter and/or station may be unstable (due to orbiter c.g., station orbit lifetime, etc.). An interruption at such a time may cause loss of orbiter and/or station.

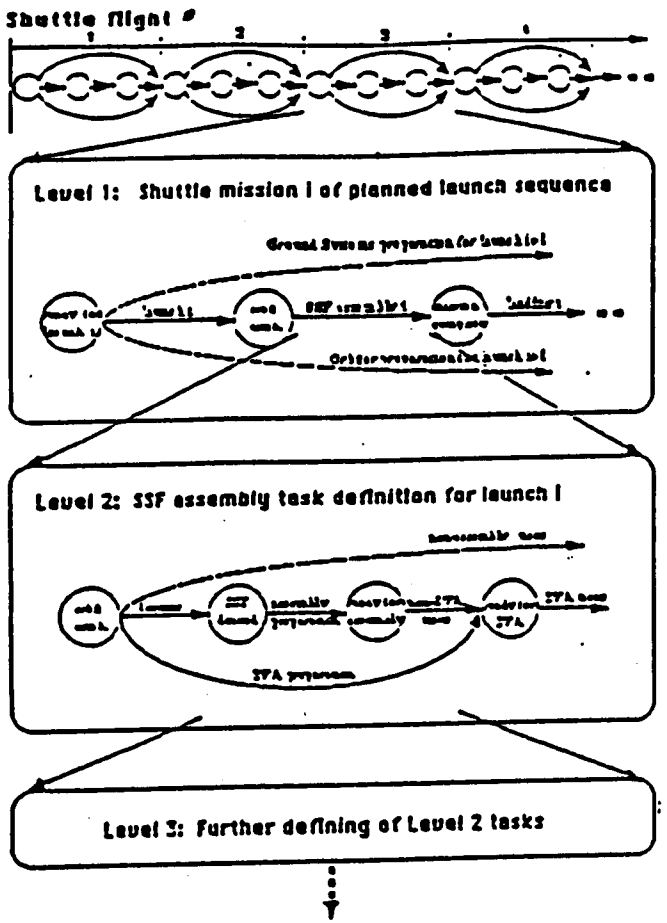


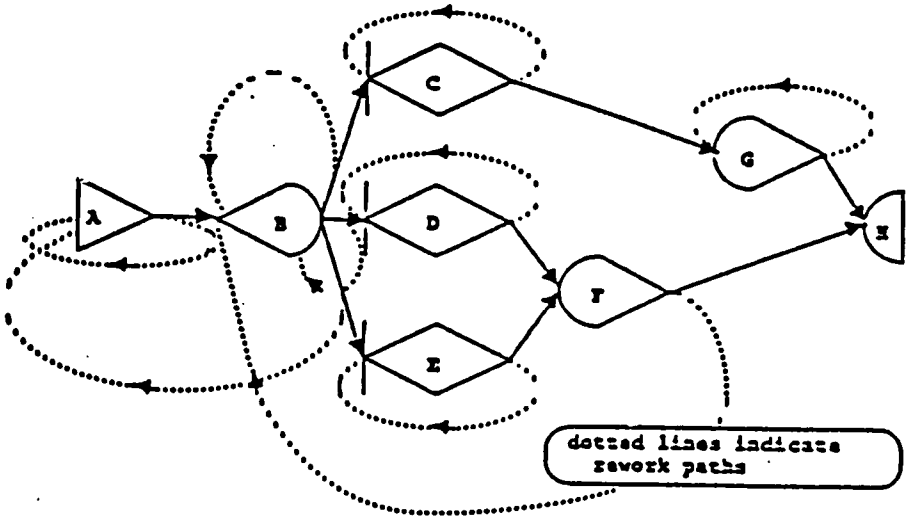
PREVIOUS RESEARCH

- Began with Dr. George Morgenthaler & Roger Davidson (graduate student) when astronaut Vance Brand addressed the SSF interruptability problem to them.

- PIRET-Program Interruptability and Risk Evaluation Technique.
  - Founded by Morgenthaler and Davidson
  - Overall process of assembly (launch, orbiter processing, assembly, etc.)
  - Top-down approach
  - Critical areas in assembly process identified on an overall basis (such as extra Orbiter Processing Facilities needed)
  - Estimate made on impact of an interruption on overall time and cost
  - Required rework paths to be pre-defined
  - No "real time" response to astronauts or controllers available

PIRET LEVELS AND NETWORK





INTERRUPTABILITY THEORY
THREE PHASE APPROACH

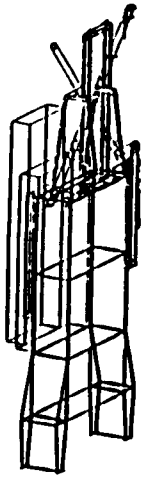
- Began with in Fall 1989, with graduate student James Wade
- Primarily concerned with on-orbit stability
- Break assembly sequence in Assembly Junctions (AJs) at the component level
- Three phases of research:

<u>Phase 1</u>: Identify the state stabilities at each AJ.
Assemble or disassemble to nearest AJ.
Students: Chan, Hwang, Sato, Wade
Completed May 1990

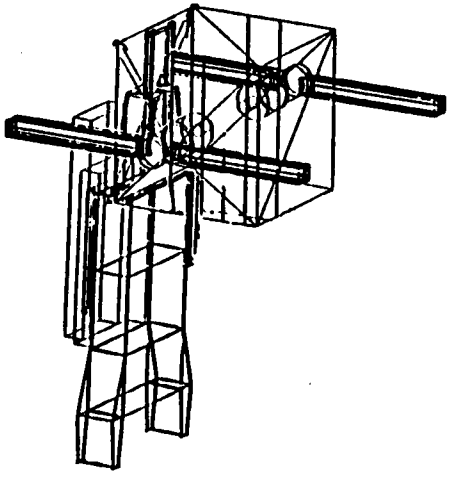
<u>Phase 2</u>: Using Contingency Theory ideas, generate feasible, alternate tasks which may stabilize each AJ.
Options include: Temporary placement (Store on-orbit)
Throw-away (Capture later)
Hybrid of Phase 1 & 2 methods
Students: Canku, Hwang, Sato, Wade
Majority completed August, 1990

<u>Phase 3</u>: Identify the optimal option with respect to the impact on the overall project time and cost.
Students: Hwang, Robertson, Sato, Wade
Research in Progress

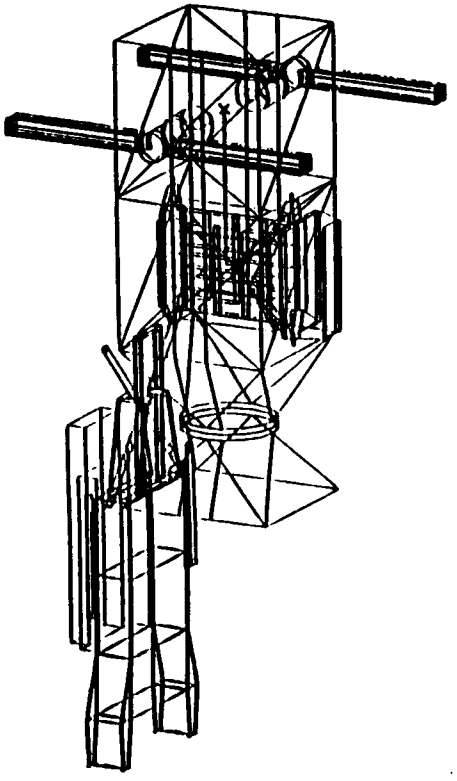
POSSIBLE ASSEMBLY JUNCTIONS FOR SSF FLIGHT 1



A.J. #1
AWP CONSTRUCTION



A.J. #2
BUILD BAY #1



A.J. FINAL FOR FLT 1
ADD ALPHA JOINT

AJ STABILITY

FLIGHT # 2

AJ	TASK	COMPONENT	CG STAB	MARG	AT STAB	KD	EVA TIME
0	INITIAL CG OF ORBITER		1	16.89	1	20.00	0.00
1	REMOVE ORB	TRUSS BOX	1	14.77	1	20.00	5.00
2	REMOVE ORB	UTILITY SPOOL	1	47.93	1	15.18	10.00
3	INDEX	AWP	1	47.93	1	15.18	10.00
4	INDEX	TRUSS BOX	1	47.93	1	15.18	0.00
5	INDEX	FTS	1	47.93	0	999.00	0.00
6	REMOVE FROM	TRUSS BOX	1	47.93	0	999.00	5.00
7	BUILD	SB8-FULL-BAY	1	47.93	1	16.04	12.00
8	REMOVE FROM	UTILITY SPOOL	1	47.93	1	16.04	1.00
9	BUILD	SB8-LOWER-TRAY	1	47.93	1	19.74	2.00
10	REMOVE ORB	SU-RCS-TNK-FARM	1	28.73	1	11.74	15.00
11	REMOVE ORB	SU RCS PALLET	1	27.73	1	9.75	30.00
12	REMOVE FROM	UTILITY SPOOL	1	27.73	1	9.75	1.00
13	BUILD	SB8-UPPER-TRAY	1	27.73	1	20.00	2.00
14	REMOVE ORB	SL-RCS-TNK-FARM	0	-6.56	1	9.96	15.00
15	REMOVE ORB	SL-RCS-TRAY	0	-8.76	1	19.97	15.00
16	REMOVE ORB	SL RCS PALLET	0	-10.78	1	11.44	15.00
17	REMOVE ORB	STBD-RCS-EXT	0	-12.86	1	6.34	15.00
18	INDEX	AWP	0	-12.86	1	6.34	10.00
19	INDEX	TRUSS BOX	0	-12.86	1	6.34	0.00
20	INDEX	FTS	0	-12.86	1	10.26	0.00
21	REMOVE FROM	TRUSS BOX	0	-12.86	1	10.26	5.00
22	BUILD	SB7-HALF-BAY	0	-12.86	1	17.53	12.00
23	REMOVE FROM	UTILITY SPOOL	0	-12.86	1	17.53	1.00
24	BUILD	SB7-LOWER-TRAY	0	-12.86	1	19.17	2.00
25	REMOVE FROM	UTILITY SPOOL	0	-12.86	1	19.17	1.00
26	BUILD	SB7-UPPER-TRAY	0	-12.86	0	999.00	2.00
27	INDEX	AWP	0	-12.86	0	999.00	5.00
28	INDEX	TRUSS BOX	0	-12.86	0	999.00	0.00
29	INDEX	FTS	0	-12.86	0	999.00	0.00
30	REMOVE FROM	TRUSS BOX	0	-12.86	0	999.00	5.00
31	BUILD	SB6-HALF-BAY	0	-12.86	0	999.00	12.00

PHASE 1 & 2 INTERRUPTABILITY RESPONSE

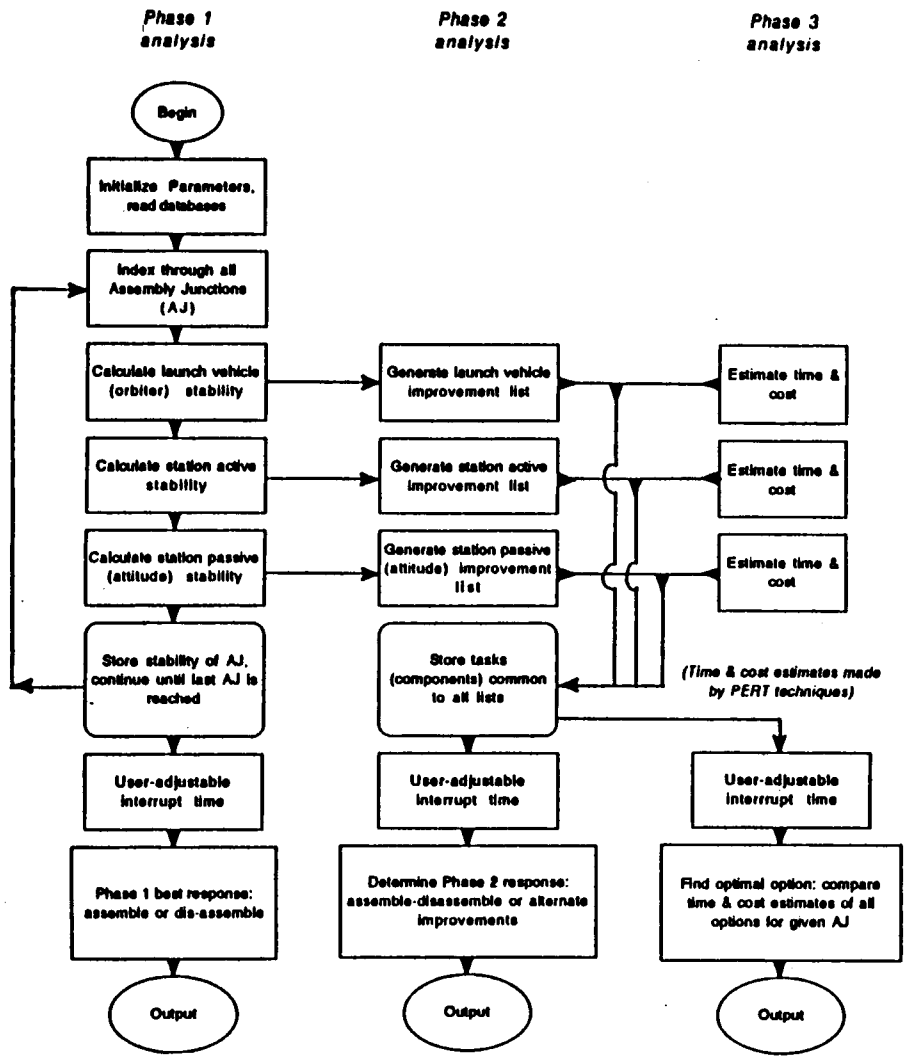
```
*****************************************************************
INTERUPT TIME: 50.00  CONTINGENCY TIME: 25.00  ALLOWED FIX TIME: 25.00
FLIGHT #   2 AJ #   6
   ORIGINAL ASSEMBLY JUNCTION STABILITY
            ORBITER STABILITY            1     CGMARGIN (INCHES)   47.93
            STATION ATTITUDE STABILITY   0     KD (N-m-s)         999.00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
*** PHASE 1 ANALYSIS ***
    OPTION 1
 TASK      COMPONENT          REQ. TIME (MIN.)
 BUILD        SB8-FULL-BAY        12.00
 REMOVE FROM  UTILITY SPOOL        1.00
 BUILD        SB8-LOWER-TRAY       2.00

NEW ASSEMBLY JUNCTION STABILTY:
            ORBITER STABILITY            1     CGMARGIN (INCHES)   47.93
            STATION ATTITUDE STABILITY   1     KD (N-m-s)          19.74
-----------------------------------------------------------------
*** PHASE 2 ANALYSIS ***
    OPTION  2
 PASSIVE ATTITUDE CONTROL
                                   NEW ON-STATION LOCATION (X,Y,Z)
 REMOVE ORB   SU-RCS-TNK-FARM        (   -5.12,    32.75,     0.00)
 TOTAL TIME REQUIRED =    15.00

NEW ASSEMBLY JUNCTION STABILTY:
            ORBITER STABILITY            1     CGMARGIN (INCHES)   28.73
            STATION ATTITUDE STABILITY   1     KD (N-m-s)          14.73

            NON-EXISTENT SYSTEMS:
                                   POWER
                                   THERMAL CONTROL
                                   COMMUNICATION
                                   AVIONICS
                                   REBOOST
                                   ATTITUDE CONTROL
  COMPONENT    IMPACT ON COMPONENTS DUE TO LACK OF POWER
 NO COMPONENTS RELYING ON THIS SYSTEM

  COMPONENT    IMPACT ON COMPONENTS DUE TO LACK OF THERMAL CONTROL
 NO COMPONENTS RELYING ON THIS SYSTEM

  COMPONENT    IMPACT ON COMPONENTS DUE TO LACK OF COMMUNICATION
 NO COMPONENTS RELYING ON THIS SYSTEM

  COMPONENT    IMPACT ON COMPONENTS DUE TO LACK OF AVIONICS
STBD-SA1-SI-IE UNABLE TO CORRECTLY POINT SOLAR ARRAYS

  COMPONENT    IMPACT ON COMPONENTS DUE TO LACK OF REBOOST
 NO COMPONENTS RELYING ON THIS SYSTEM

  COMPONENT    IMPACT ON COMPONENTS DUE TO LACK OF ATTITUDE CONTROL
 NO COMPONENTS RELYING ON THIS SYSTEM
```

PHASE 2 IMPROVEMENTS TO FIRST 7 SSF FLIGHTS

Flight	# Unstable AJs	Fixable AJs - Phase 1 Approach Interrupt Time (Minutes) 50	%	100	%	Fixable AJs - Phase 2 Approach Interrupt Time (Minutes) 50	%	100	%
1	11*	6	55%	10	91%	8	73	10	91
2	31	10	32	28	90	10	32	31	100
3	0	-	-	-	-	-	-	-	-
4	3	0	0	1	33	0	0	2	67
5	1	1	100	1	100	1	100	1	100
6	25*	3	12	21	84	24	96	24	96
7	0	-	-	-	-	-	-	-	-
Totals	71	20	28%	61	86%	43	61%	68	96%

* These flights have an initially unstable conditions, which can only be corrected by payload packaging.

THREE PHASE INTERRUPTABILITY APPROACH FLOW CHART



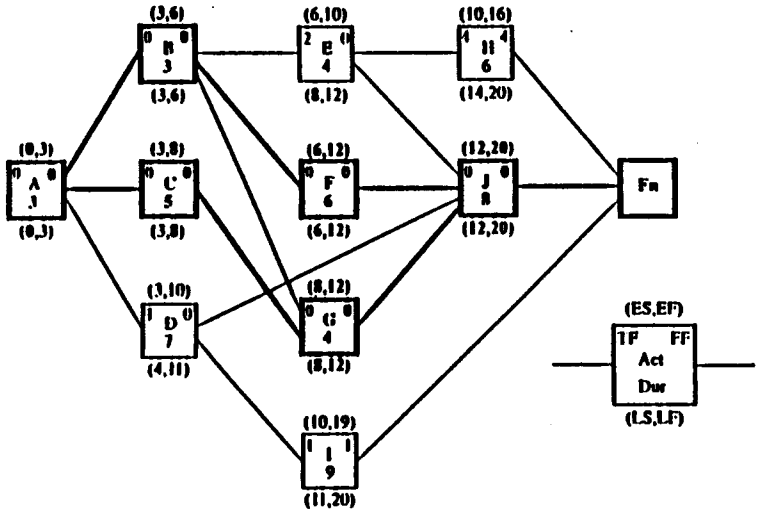
PRESENT RESEARCH

- Three areas of research
  1) Expand station states:
     - Orbit lifetime
     - Power
     - Thermal

  2) Expand feasible options (finish up Phase 2):
     - Throw-away options
     - Hybrid options

  3) Assess feasible options:
     - Determine time-cost impact of each option on overall project using PERT network analysis techniques
       i. Impact of extra launches (repackage shuttle to compensate for interruption).
       ii. Component cost and manufacture time
       iii. EVA time and cost for component relocation
     - Represent PERT network in matrix manner
     - Determine optimal options
       i. Probability of on-time & on-cost completion.
       ii. Display time-cost efficiency curve.

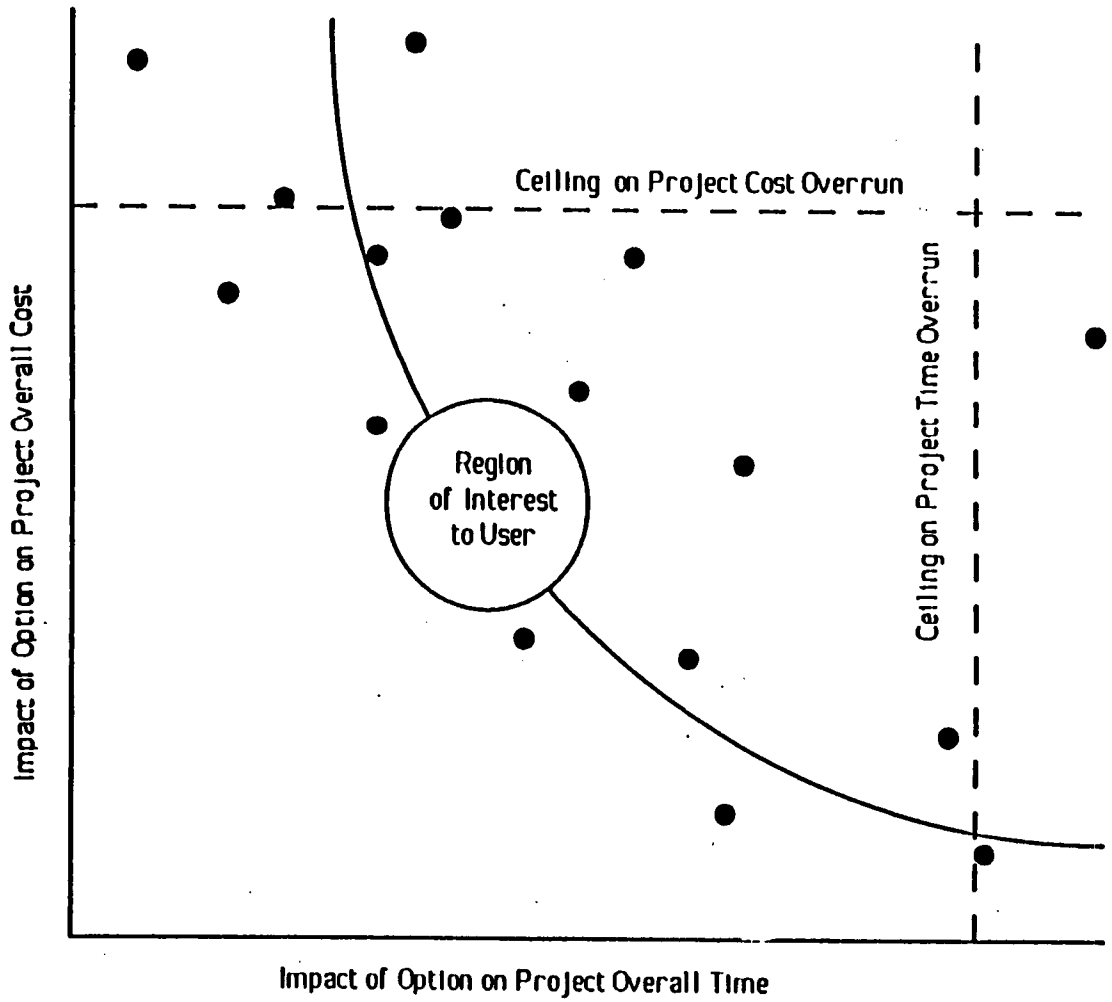
GRAPHIC AND MATRIX PERT REPRESENTATION



Act	A	B	C	D	E	F	G	I	H	J	Fn	EF	Act
Dur	3	3	5	7	4	6	4	9	6	8	0		
ES	0	3	3	3	6	6	8	10	10	12	20		
	0/0	0/0	0/0	0/1								3	A
		0/0			0/0	0/0	2/2					6	B
			0/0				0/0					8	C
				0/1				0/1		2/2		10	D
					0/2				0/4	2/2		10	E
						0/0				0/0		12	F
							0/0			0/0		12	G
								1/1			1/1	19	I
									4/4		4/4	16	H
										0/0	0/0	20	J
											0/0	20	Fn

TF/H

TIME-COST EFFICIENCY CURVE



DATA NEEDED

- State performance requirements (orbit lifetime, power surplus, etc.)
- Time and cost data for SSF components (minimal, nominal, peak)

CONCLUSION

- Space-assembly interruptability will be a definite problem in the near future.

- Previous research laid a firm foundation for present research

- Status of the three phase approach:
  Phase 1 - complete
  Phase 2 - ~ 75% complete
  Phase 3 - currently being studied

- Interruptability model will be ready for (scrubbed) Space Station Freedom analysis.

- Three phase approach will allow real-time information to be attained while still identifying the optimal, overall option.

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to
P. 470

Session Nine

TEST AND VERIFICATION

Subhendu K. Datta,
Chair

S3-38
165810

SPACE STRUCTURES: TEST AND VERIFICATION

Subhendu K. Datta

Objectives:
The goal of the work reported here is to develop an ultrasonic sensor capability to monitor structural integrity via acoustic emission signature and ultrasonic guided and scattered wave fields. Structural elements considered are: composite tubes, plates, and welded and mechanical joints.

Current Research:
In this session we report on dynamic model studies of guided pulse propagation in composite plates and tubes. One of the analysis methods is a wave propagation based stiffness method in which the displacement variation through the thickness is approximated by polynomial interpolation functions. This has the flexibility that arbitrary ply lay-ups and fiber orientation varying from lamina to lamina can be analyzed. The guided Rayleigh-Lamb modes thus determined are then used to study pulse propagation in a composite tube and scattering by welded joints and other defects in plate structures. It is shown that transmitted and reflected wave amplitudes depend critically on the weld properties, size, nature of defects, and material properties of the structure. The second analysis method uses the Green's displacement tensor of the plate structure to study the response of the plate to impact (or acoustic emission). The analysis applies to composite (anisotropic) or homogeneous isotropic plates. Theoretical predictions are compared with experiments on a glass plate using PVDF sensors and ball impact. Model studies are reported also on the wave field measured by an array sensor in a composite plate with a delamination defect.

Associates(C.U.)

Supported by CSC:

Dr. Robert L. Bratton (Ph.D., August 1990), Research Associate

Mr. Thomas Kohl, Ph.D. student (Expected graduation, Summer 1992)

Mr. Chris Dahlquist, M.S. student (Expected graduation, August 1991)

Mr. Ted Cobb, Undergraduate Assistant (Expected graduation, May 1991)

Mr. John Dorighi, Undergraduate Assistant (Expected graduation, May 1991)

Mr. Mike O'Shea, Undergraduate Assistant (Expected graduation, May 1991)

Supported by other grants:

Mr. Te-Hua Ju, Ph.D. candidate (Expected graduation, December 1991)

Mr. Shaw-Wen Liu, Ph.D. candidate (Expected graduation, May 1991)

External Collaborators:

Mr. W. Prosser, NASA LaRC

Dr. E. Madaras, NASA LaRC

Dr. D. Nichols, USAF Academy

Center for Space Construction

Second Annual Symposium
October 12-19, 1990

Session: Test and Verification

- Overview
- Modeling Studies of Ultrasonic Evaluation of Welded Joints and Delamination Defects (*Subhendu Datta*)
- Ultrasonic Evaluation of Cracks (*Robert Bratton*[1])
- Pulse Propagation in Composite Tubes (*Thomas Kohl*[2])

- Experimental and Theoretical Study of Rayleigh-Lamb Wave Propagation (*Wayne Rogers*)
- Acoustic Emission in Space Station Truss Tubes (*John Dorighi*[3])

---

[1]Research Associate, Ph.D. (August 1990)

[2]Research Assistant

[3]M.E. Undergraduate

Center for Space Construction

Space Structures: Test and Verification

Accomplishments

- Analysis techniques for investigation of pulse propagation in jointed plates and in composite tubes
  (*SKD; students: Y. Al-Nassar*[1], *T. Kohl*)

- Investigation of ultrasonic characterization of defects in composite and welded plates
  (*SKD; students: T.-H. Ju*[2], *Y. Al-Nassar; Research Associate: R. Bratton*)

- Experimental study of embedded sensors(PVDF) and applications
  (*WPR; students: M. O'Shea*[3]*; Associate D. Nichols*[4])

- Experimental and theoretical study of Rayleigh-Lamb Waves in plates
  (*WPR,SKD; student: T. H. Ju*)

- Acoustic emission in space station truss tubes
  (*WPR;student: J. Dorighi; Associates W. Prosser*[5]*, E.Madaras*[5])

---

[1] Ph.D., May 1990

[2] Research Assistant

[3] ME Undergraduate

[4] USAF Academy

[5] NASA-LaRC

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Space Structures: Test and Verification

Use of Array Sensors for Ultrasonic Evaluation of Delamination

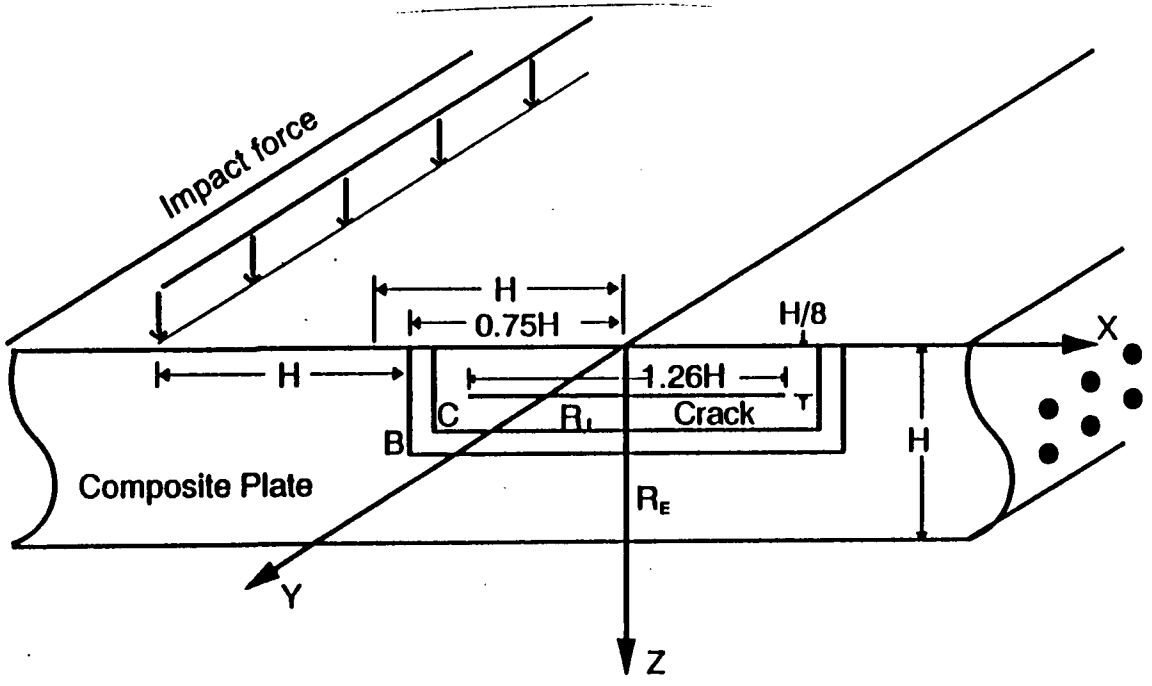
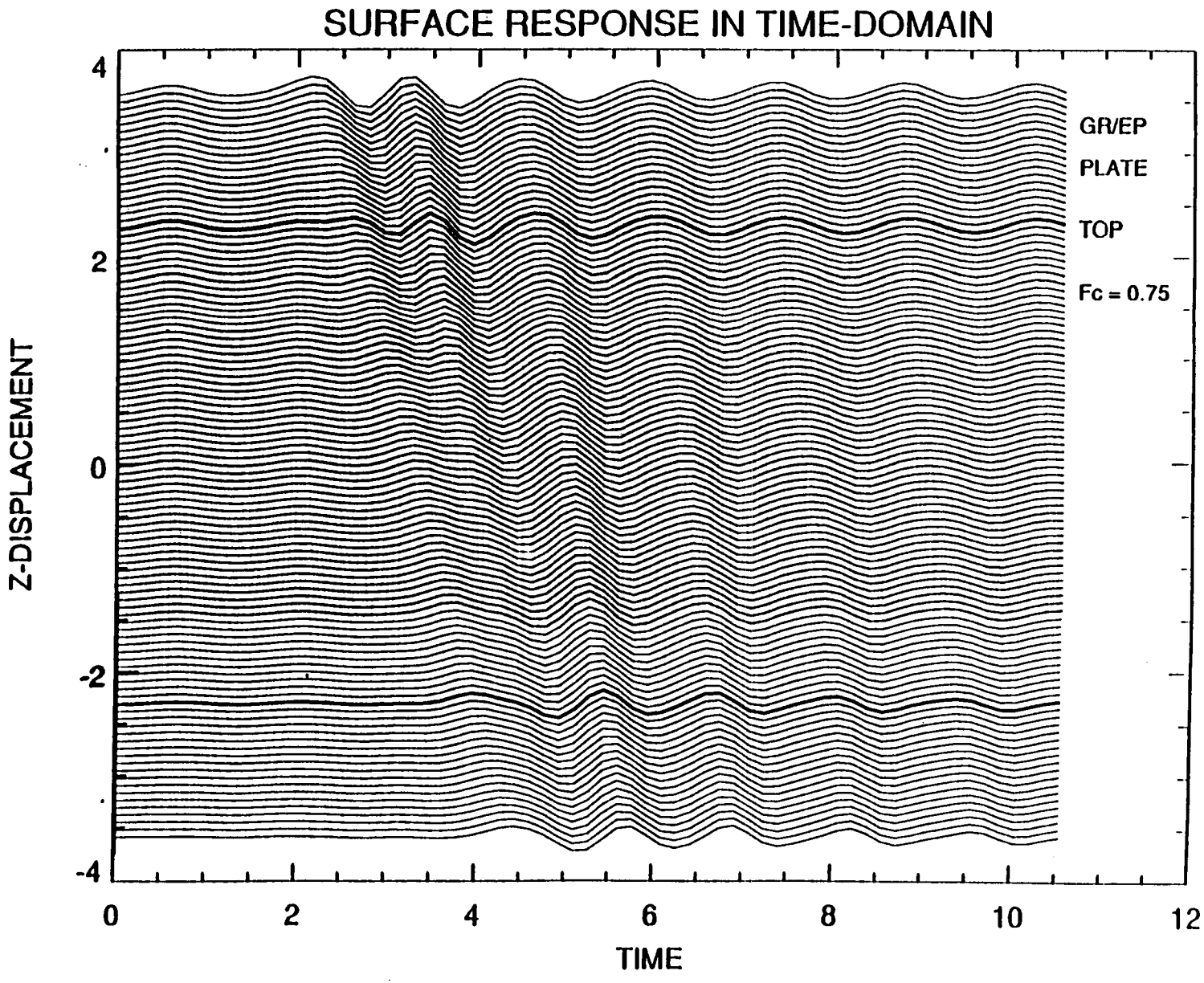
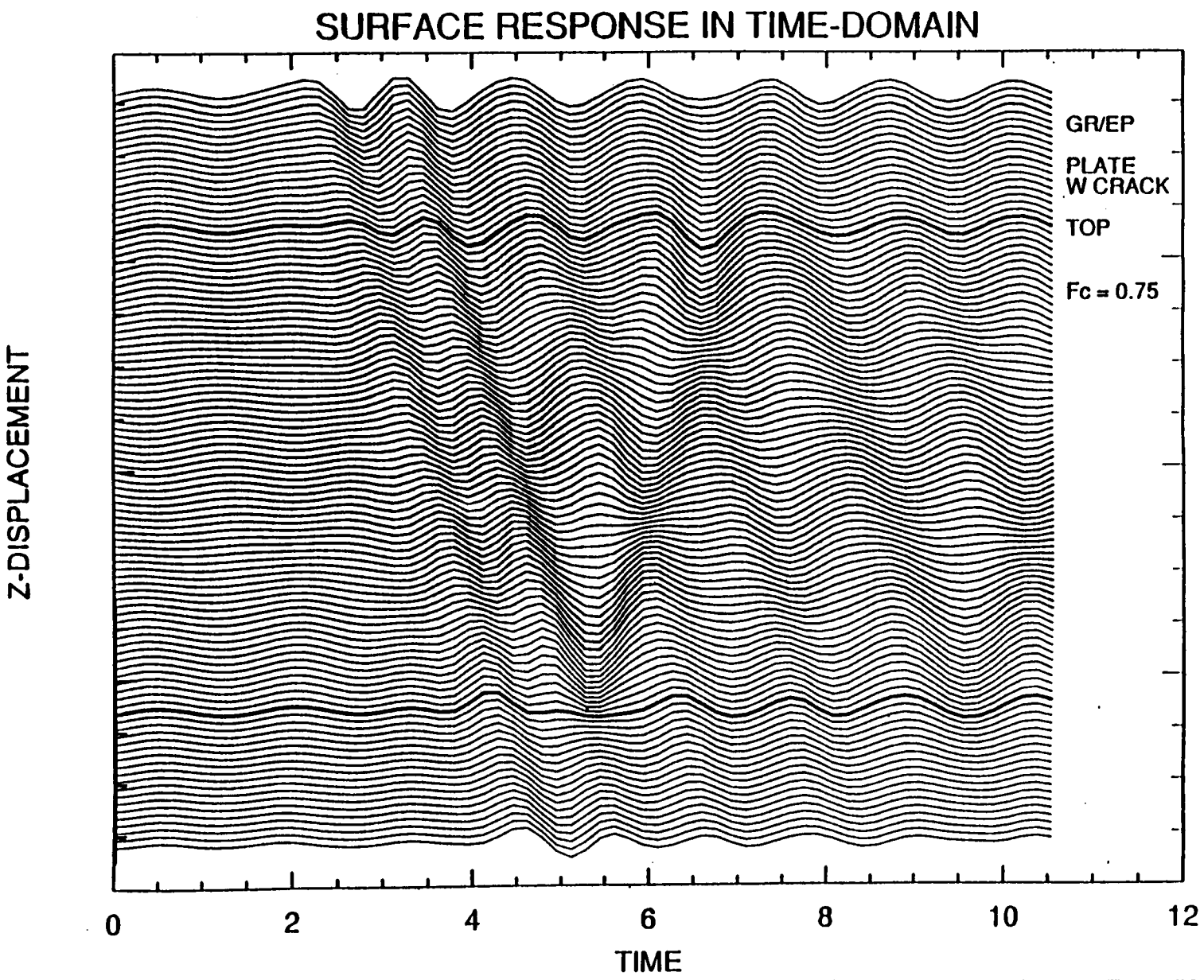
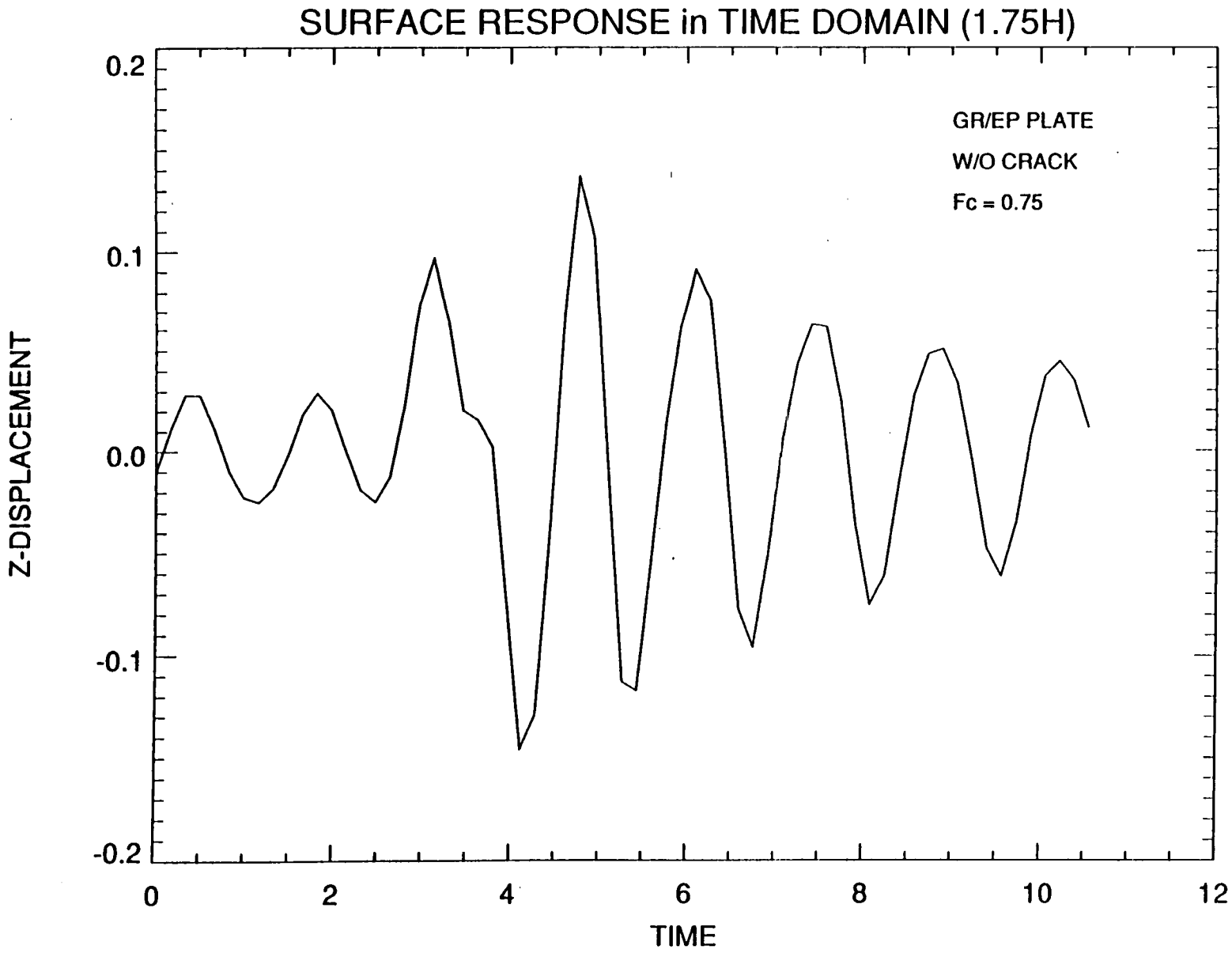
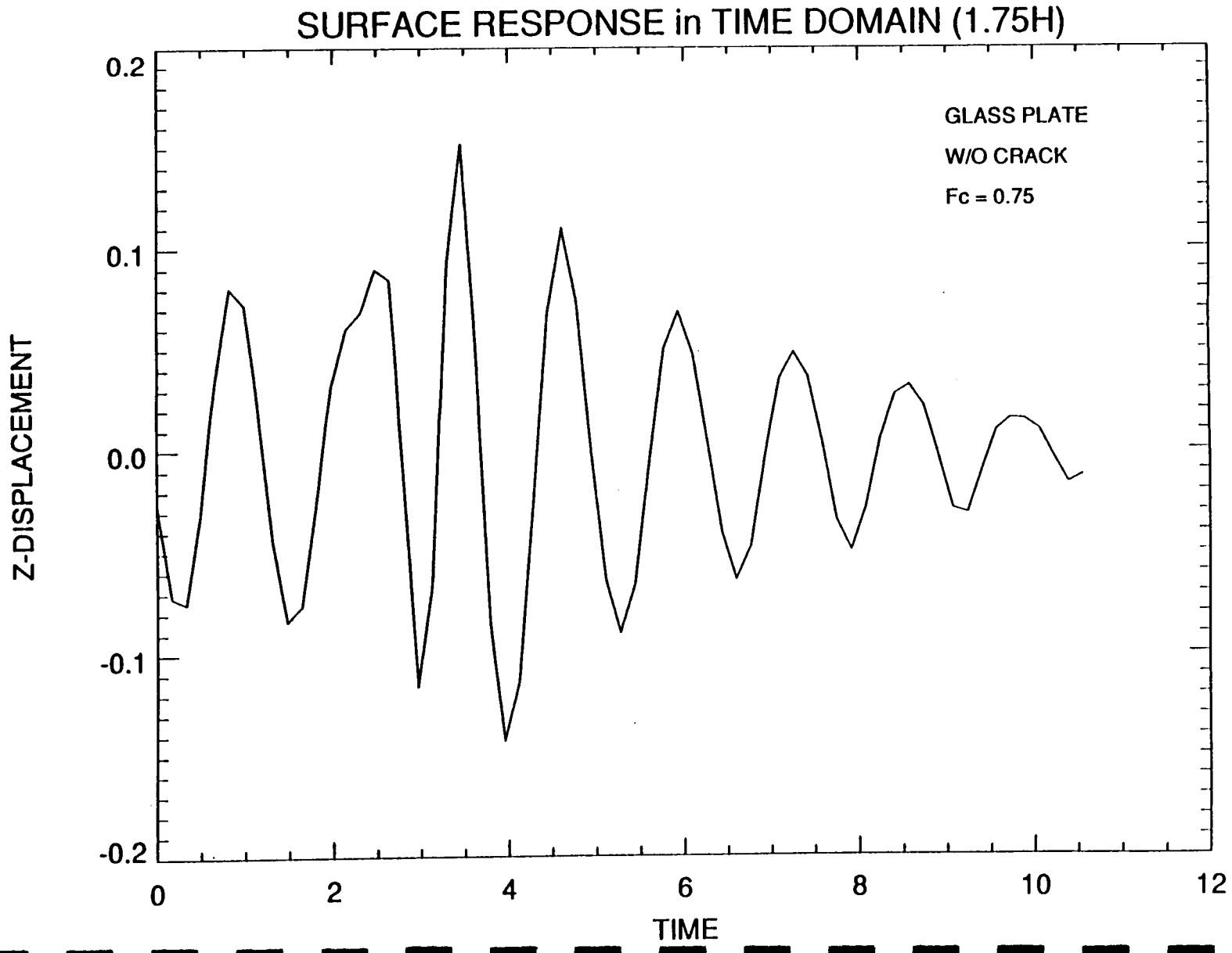


Fig. 1 Ultrasonic NDE of Delamination in Gr/Epoxy Plate


SURFACE RESPONSE IN TIME-DOMAIN
Z-DISPLACEMENT
4
2
0
-2
-4
0
2
4
6
8
10
12
TIME
GR/EP
PLATE
TOP
Fc = 0.75


SURFACE RESPONSE IN TIME-DOMAIN
GR/EP
PLATE
W CRACK
TOP
Fc = 0.75
Z-DISPLACEMENT
0
2
4
6
8
10
12
TIME


SURFACE RESPONSE in TIME DOMAIN (1.75H)
GR/EP PLATE
W/O CRACK
Fc = 0.75
Z-DISPLACEMENT
0.2
0.1
0.0
-0.1
-0.2
0
2
4
6
8
10
12
TIME


SURFACE RESPONSE in TIME DOMAIN (1.75H)
GLASS PLATE
W/O CRACK
Fc = 0.75
Z-DISPLACEMENT
0.2
0.1
0.0
-0.1
-0.2
0
2
4
6
8
10
12
TIME

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Space Structures: Test and Verification

Ultrasonic Evaluation of Welded Plates

$$U^I = \sum_{j=1}^{J} A_j(\omega_j) \sum_{n=1}^{N_j} U_n e^{ik_n x}.$$

$$U^R = \sum_{j=1}^{J} A_j(\omega_j) \sum_{m=1}^{N_j} \sum_{n=1}^{N_j} R_{mn}(\omega_j) U_n e^{ik_n x}$$

$$U^T = \sum_{j=1}^{J} A_j(\omega_j) \sum_{m=1}^{N_j} \sum_{n=1}^{N_j} T_{mn}(\omega_j) U_n e^{ik_n x}$$

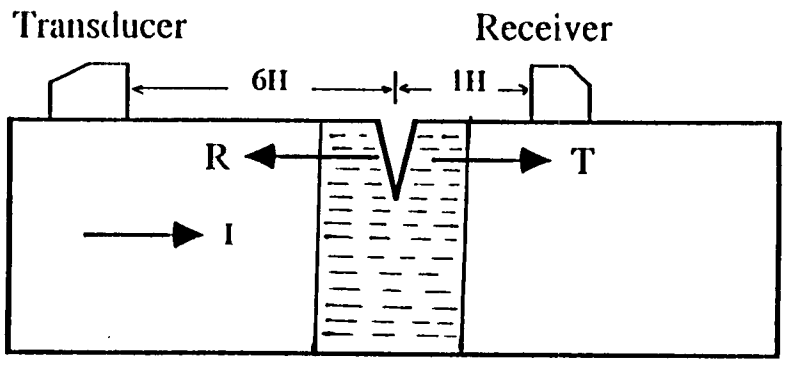
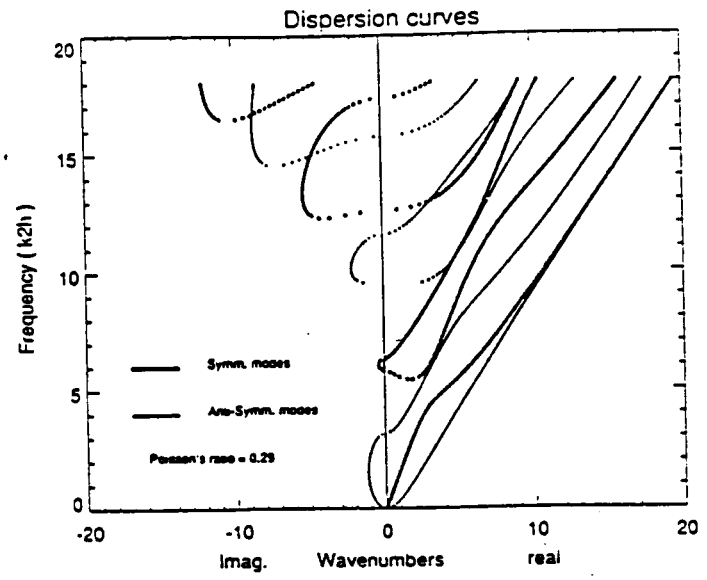
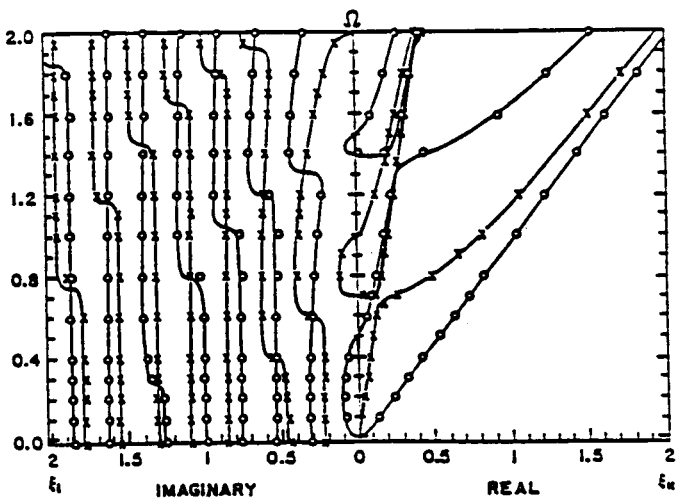
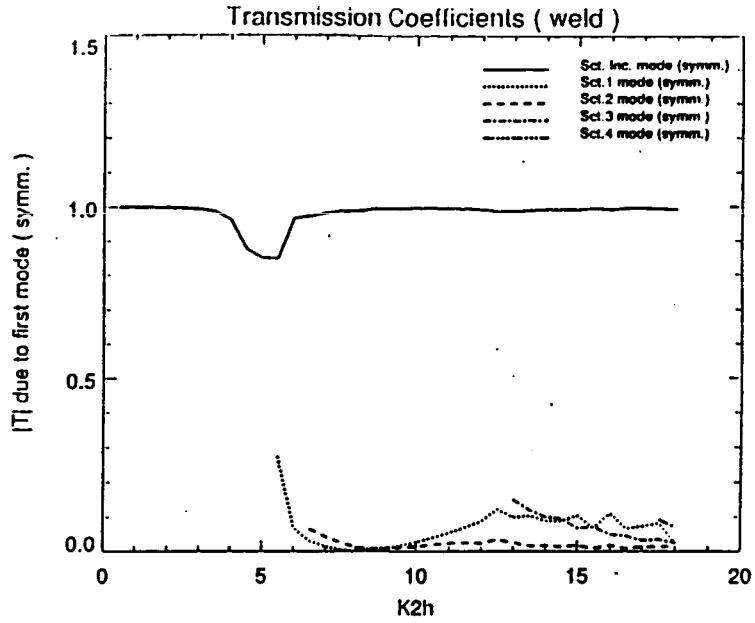
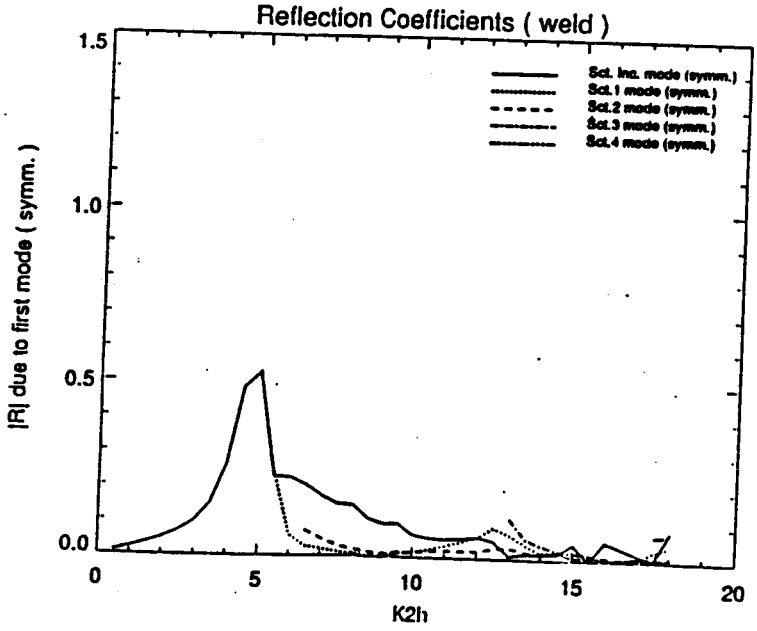


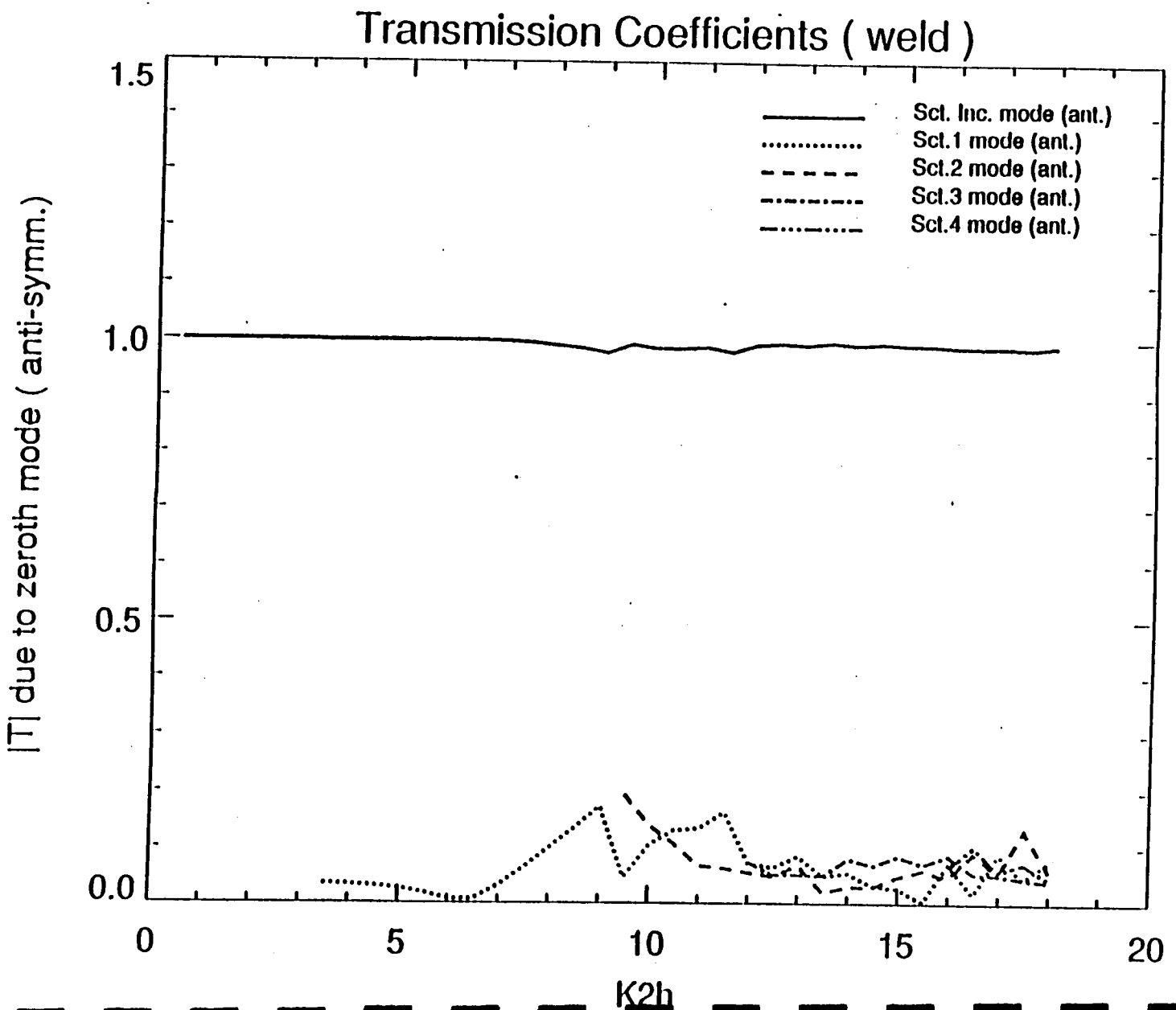
Fig. 6 Geometery and Test Simulation

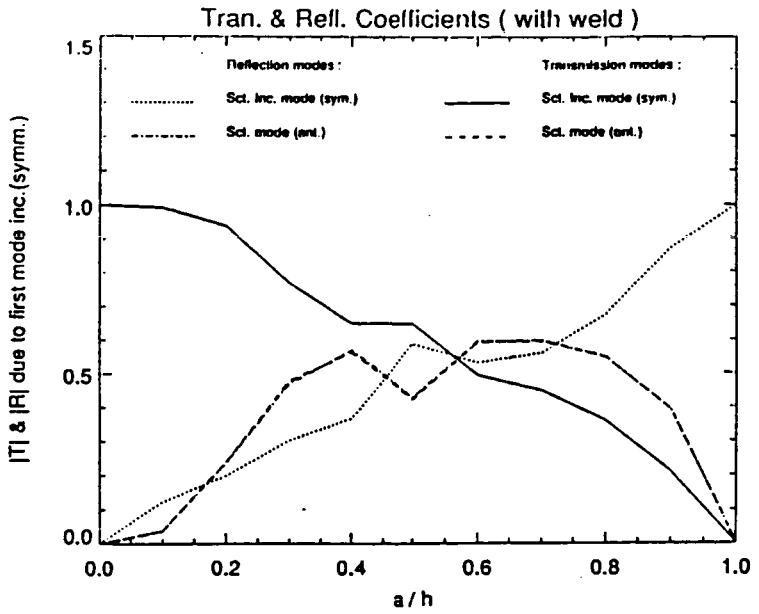

Dispersion curves
Frequency (k2h)
Symm. modes
Anti-Symm. modes
Poisson's ratio = 0.29
Imag.
Wavenumbers
real

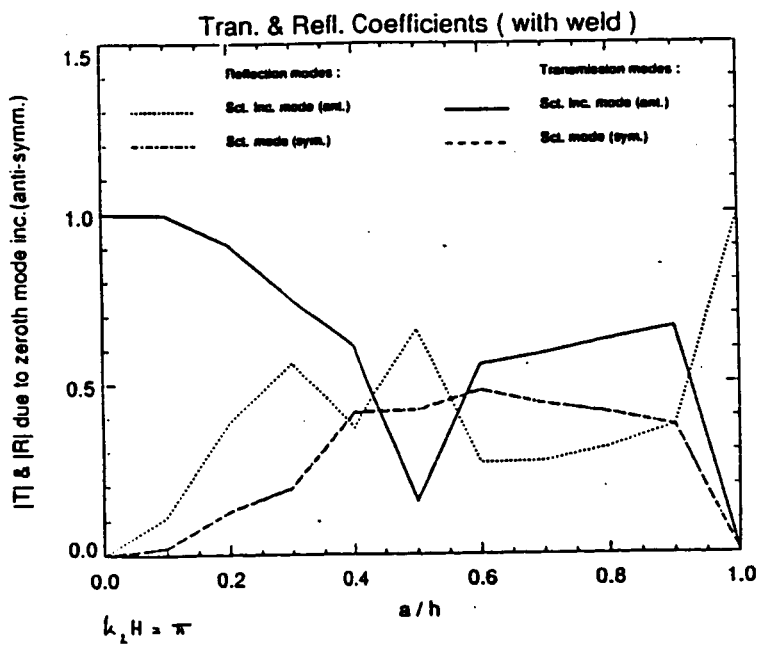

Ω
IMAGINARY
REAL


Transmission Coefficients (weld)
Sct. Inc. mode (symm.)
Sct.1 mode (symm.)
Sct.2 mode (symm.)
Sct.3 mode (symm.)
Sct.4 mode (symm.)
|T| due to first mode (symm.)
1.5
1.0
0.5
0.0
0
5
10
15
20
K2h


Reflection Coefficients (weld)
Sct. Inc. mode (symm.)
Sct.1 mode (symm.)
Sct.2 mode (symm.)
Sct.3 mode (symm.)
Sct.4 mode (symm.)
|R| due to first mode (symm.)
1.5
1.0
0.5
0.0
0
5
10
15
20
K2h


Transmission Coefficients (weld)
Sct. Inc. mode (ant.)
Sct.1 mode (ant.)
Sct.2 mode (ant.)
Sct.3 mode (ant.)
Sct.4 mode (ant.)
|T| due to zeroth mode (anti-symm.)
1.5
1.0
0.5
0.0
0
5
10
15
20
K2h


Tran. & Refl. Coefficients (with weld)
Reflection modes :
Sct. Inc. mode (sym.)
Sct. mode (ant.)
Transmission modes :
Sct. Inc. mode (sym.)
Sct. mode (ant.)
|T| & |R| due to first mode inc.(symm.)
a / h
0.0
0.5
1.0
1.5
0.0
0.2
0.4
0.6
0.8
1.0


Tran. & Refl. Coefficients (with weld)
Reflection modes :
Sct. Inc. mode (ant.)
Sct. mode (sym.)
Transmission modes :
Sct. Inc. mode (ant.)
Sct. mode (sym.)
|T| & |R| due to zeroth mode inc.(anti-symm.)
a / h
0.0
0.5
1.0
1.5
0.0
0.2
0.4
0.6
0.8
1.0
$k_z H = \pi$

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Space Structures: Test and Verification

Plans

- Investigation of ultrasonic scattering by delaminations and matrix cracks in laminated plates and tubes.
- Thermal/Dynamic response of composite laminates.
- Pulse propagation in laminated composite tubes including joint dynamics and extensions to truss assembly.

Center for Space Construction

Space Structures: Test and Verification

Plans

- Develop sensor array systems for material characterization.
- Ultrasonic testing and acoustic emission in composites.
- Evaluation of damage caused by environmental effects and impact.
- Characterization of joints.

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p. 6

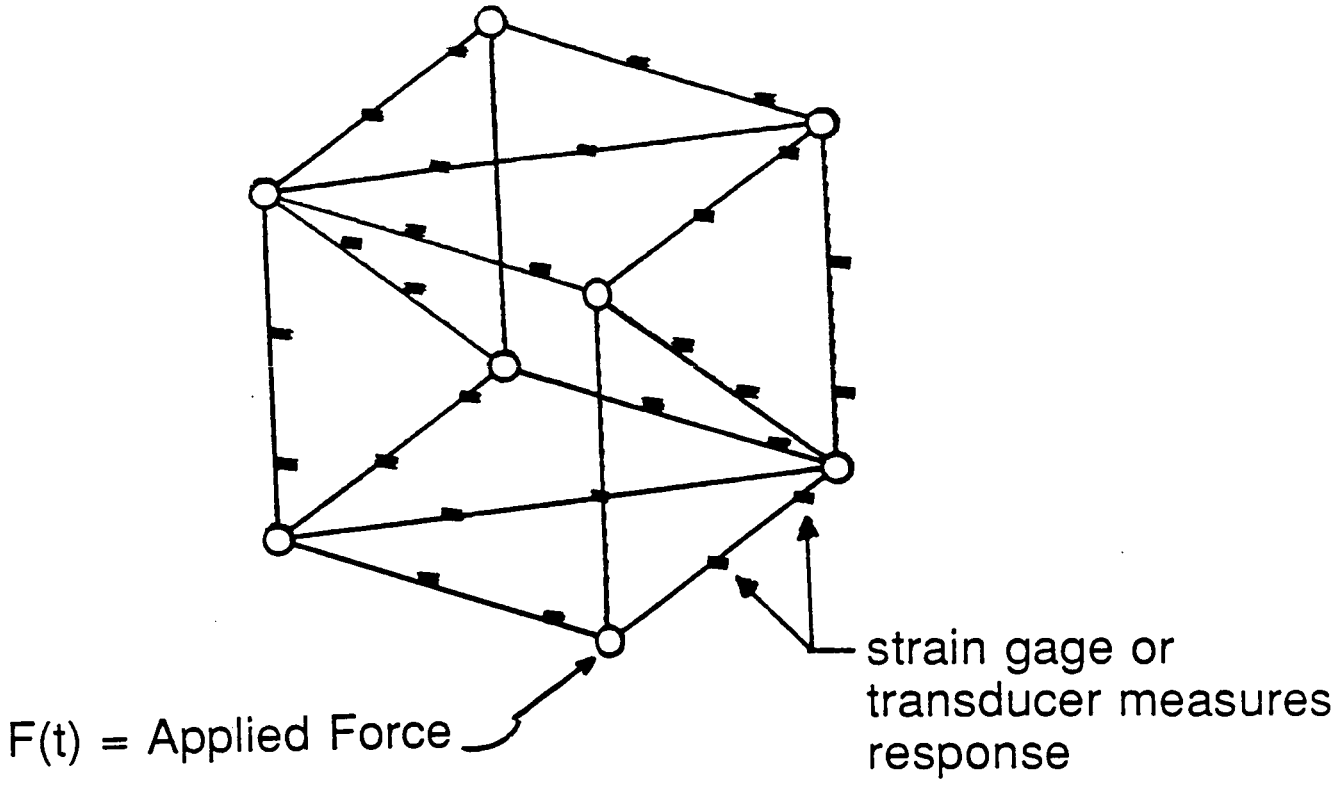
N94-71015

PULSE PROPAGATION IN COMPOSITE TUBES FOR ULTRASONIC EVALUATION

Thomas W. Kohl
Subhendu K. Datta
Arvind Shah†

Recent revelations about potential EVA times predicted for inspection of large space structures make it clear that any reductions of this time by methods of inspection which may be efficiently implemented remotely are extremely desirable. The work undertaken is the study of detailed 3-D dynamics of the components of the truss assembly (truss tubes and joints) in order to be able to implement an ultrasonic inspection system which may be remotely operated to detect potential problems in the truss assembly such as material degradation or delamination in the truss tubes. Application may also be made to problems of impact response of the truss structure. We report here on the modeling of dynamics of finite composite tubes with dimensions consistent with those of space station tubes. Numerical modeling reported here may be applied to tubes with uniaxial or angle-ply laminae and arbitrary ply lay-ups. For specified time varying tube end conditions, the complete 3-D dynamic response at any position within the tube may be determined including any number of reflections. The response is determined first in the frequency domain using a wave propagation based finite element method and the time response is then obtained using a fast Fourier transform. As an application of the method to the problem of material degradation, we consider the alteration in the axial strain time response to changes in material properties as might occur with distributed matrix cracking. The subsequent change in the response can be seen in both the magnitudes and times of arrival of the elastic waves. In order to demonstrate the 3-D capability of the numerical method, results showing the extent of circumferential/longitudinal motion coupling for different numbers of lamina in "specially orthotropic" tubes are presented. Decreased coupling for increasing numbers of plies is shown. The capability of capturing this coupling is being investigated as a potential tool for characterizing delamination. The work presented here will be supplemented with modeling of truss joints, integration of the joint and tube models, defect characterization and experimental verification of the modeling procedures.

† Department of Civil Engineering, University of Manitoba



OBJECTIVE

♦ Decrease EVA time for inspection of large space structure truss assembly components including truss tubes and joints by implementing remote inspection methods.

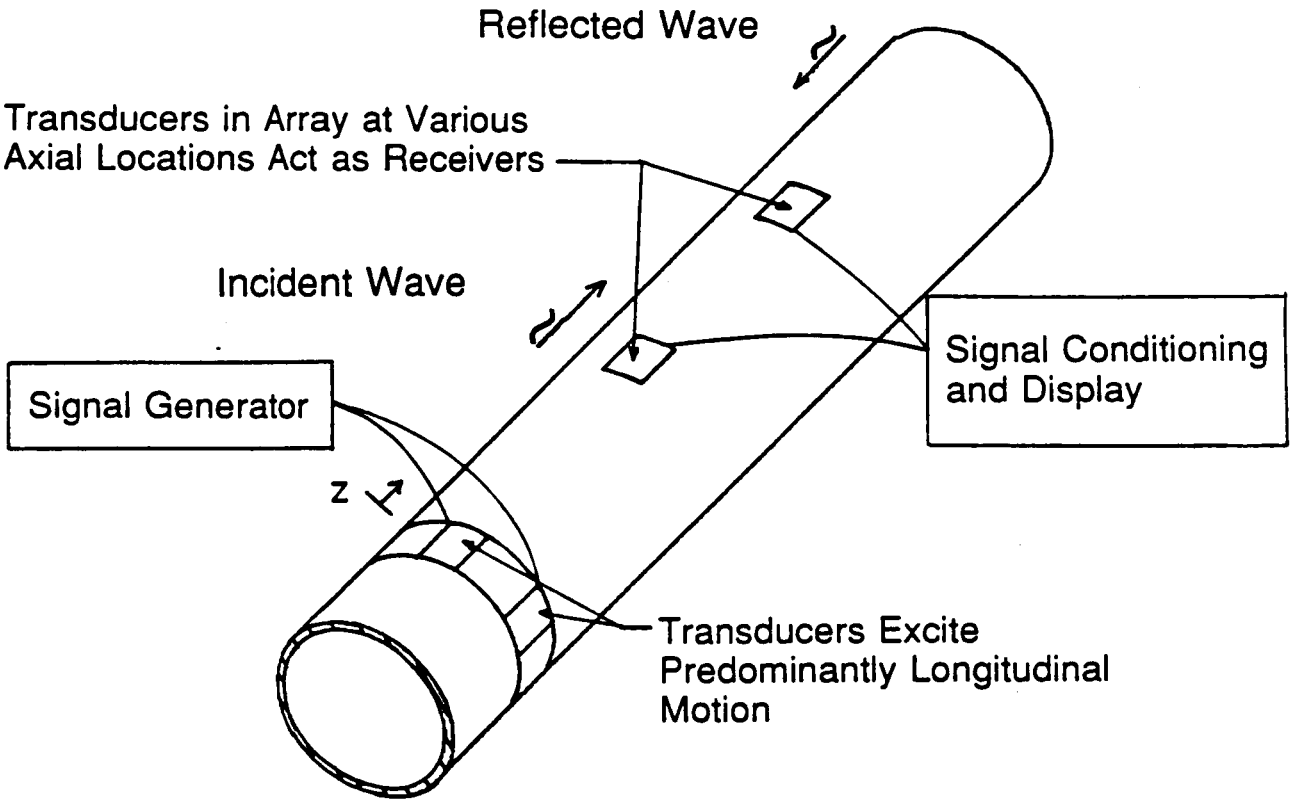
METHOD

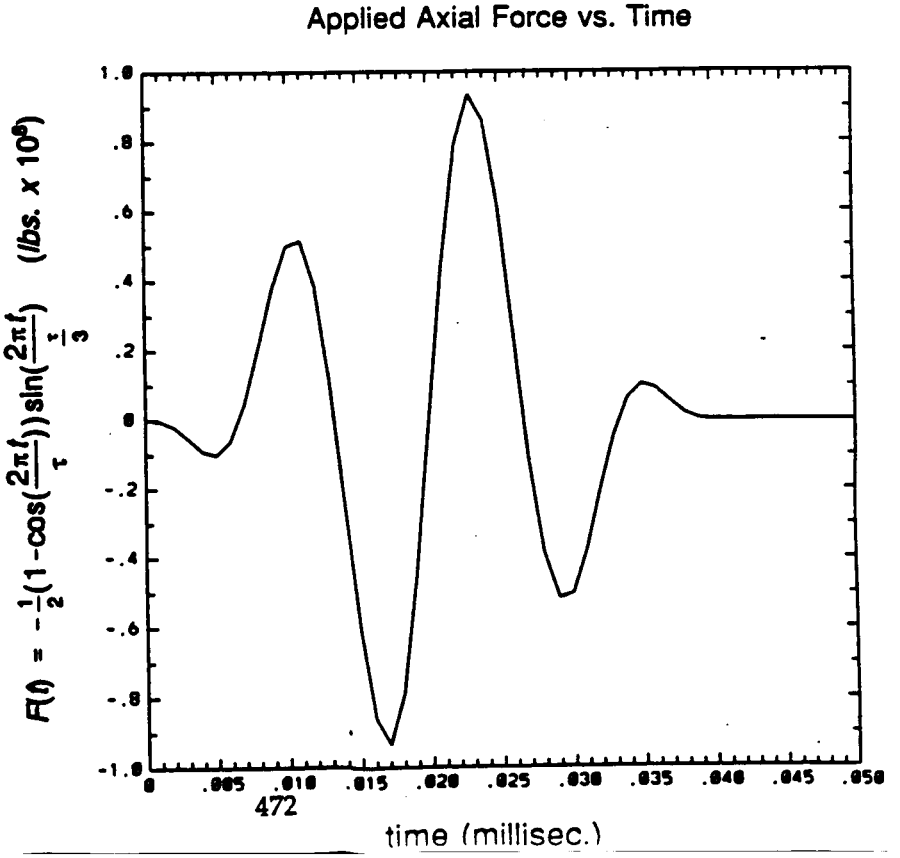
♦ Apply a controllable excitation at some location in the truss assembly.

♦ Measure the dynamic response at several locations.

♦ Characterize defects in the structure from the measured response.

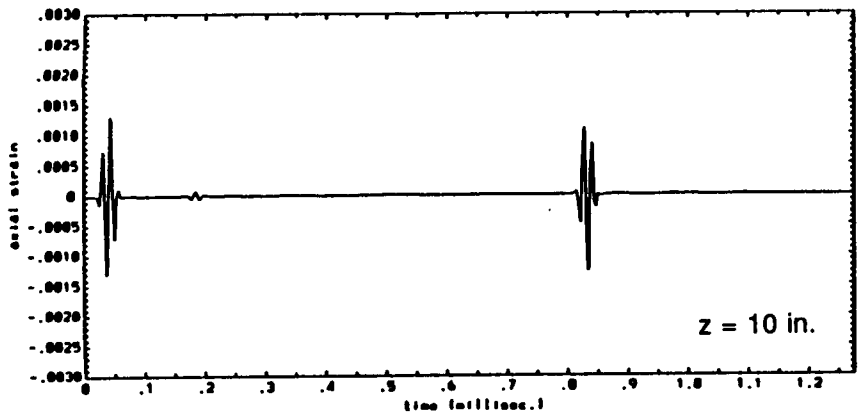
An Experimental Apparatus

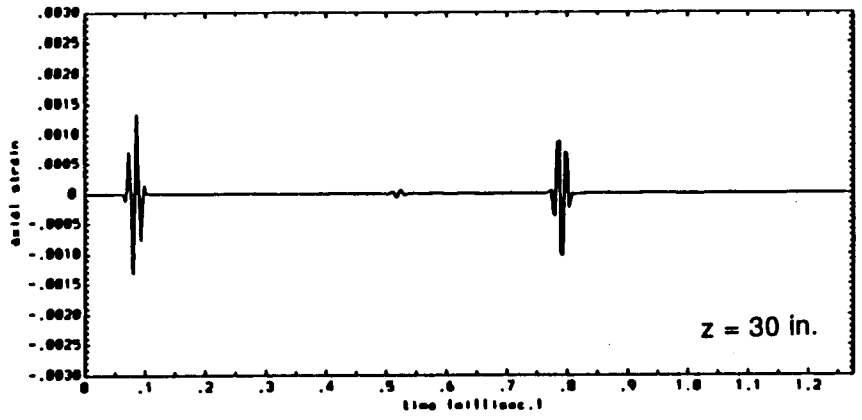


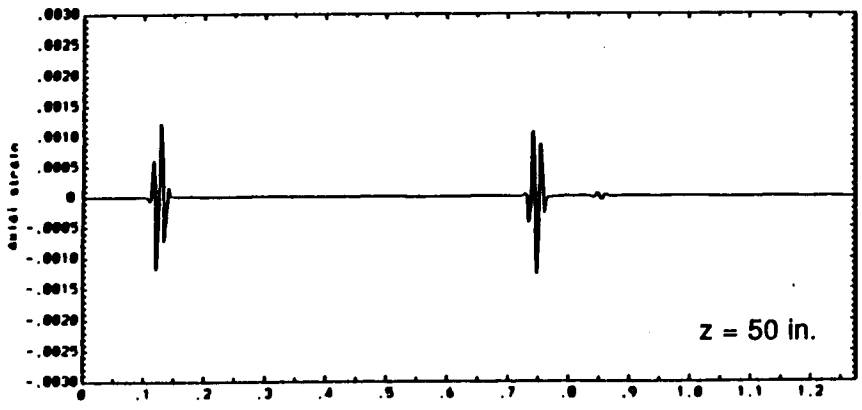


Effect of Distributed Damage on Wave Speed and Amplitude

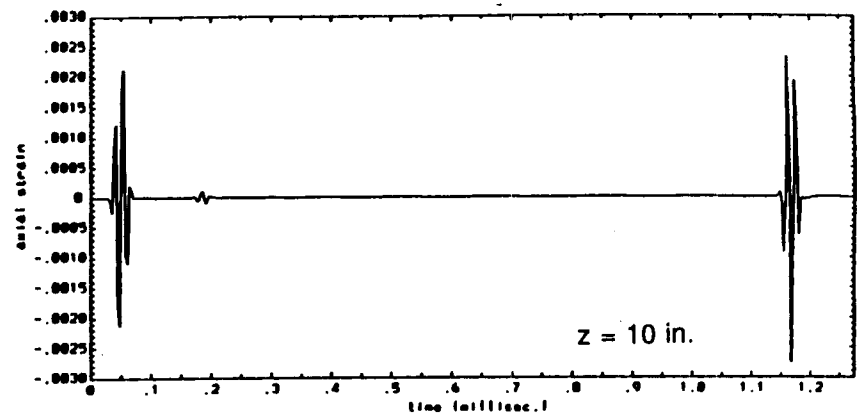
$[15,-15]_s^2$ Tube Time Responses (E_L=40 Mpsi)

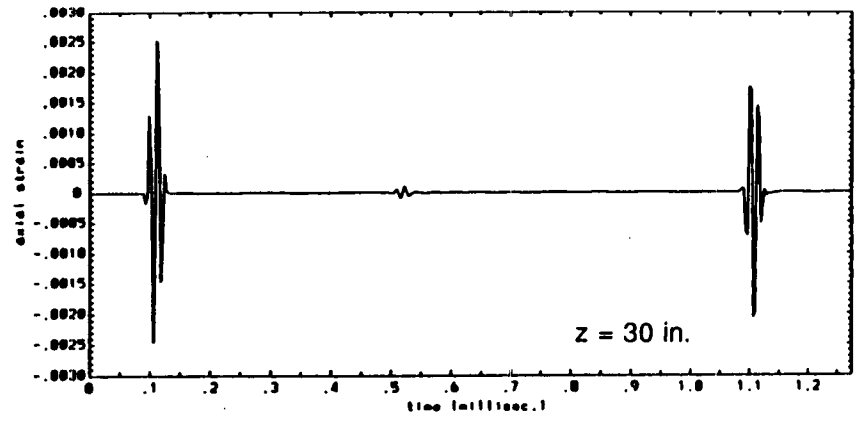


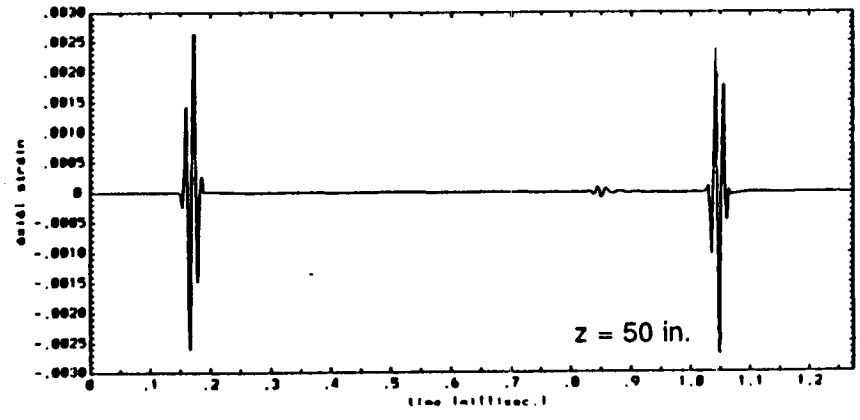




$[15,-15]_s^2$ Tube Time Responses with Distributed Damage (E_L=20 Mpsi)

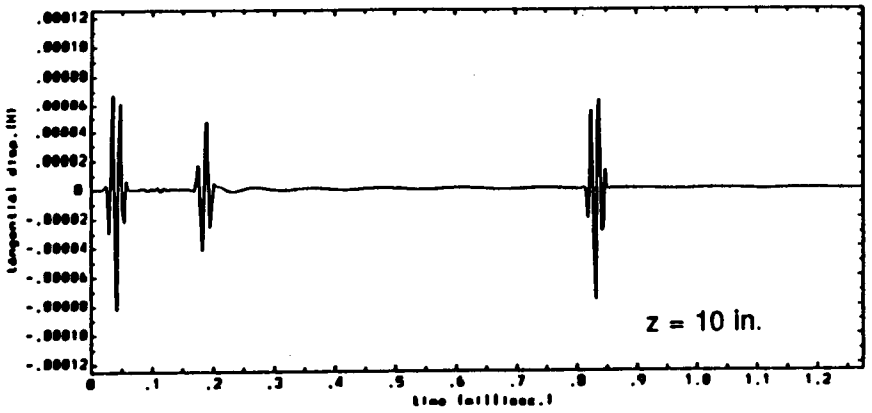


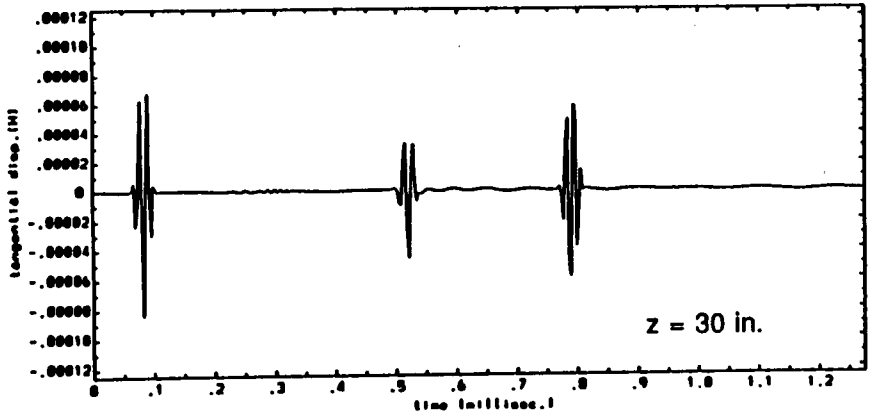


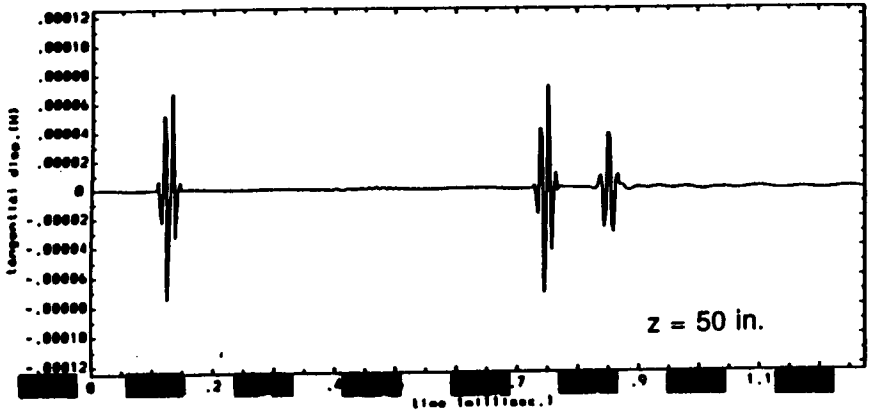


Effect of Ply Lay-up on Tangential/Longitudinal Motion Coupling

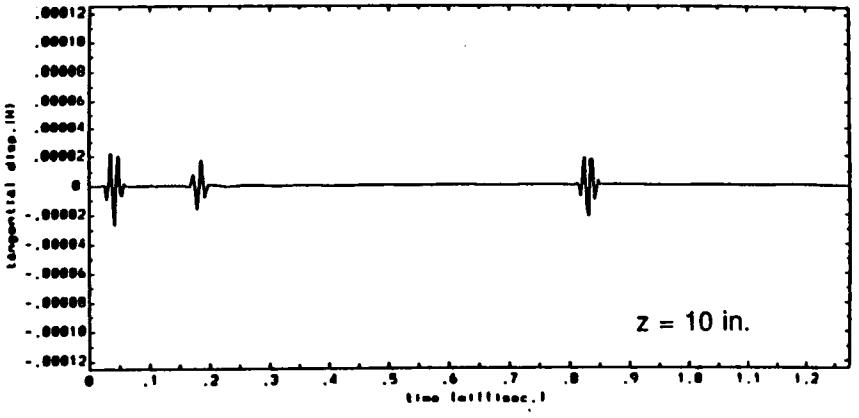
$[15,-15]_s^2$ Tube Time Responses

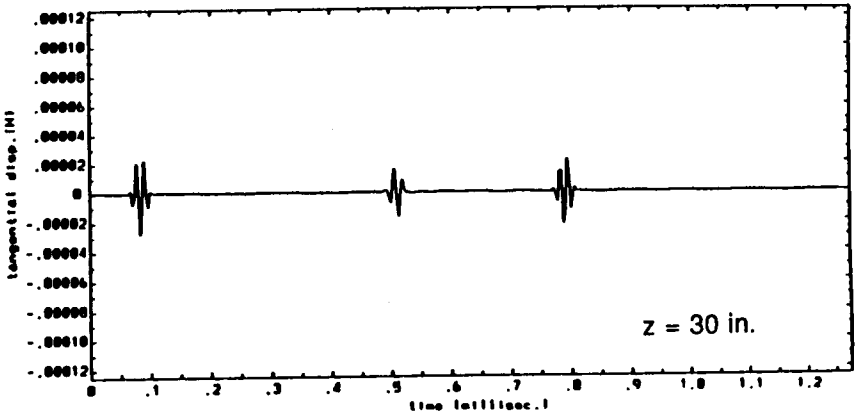


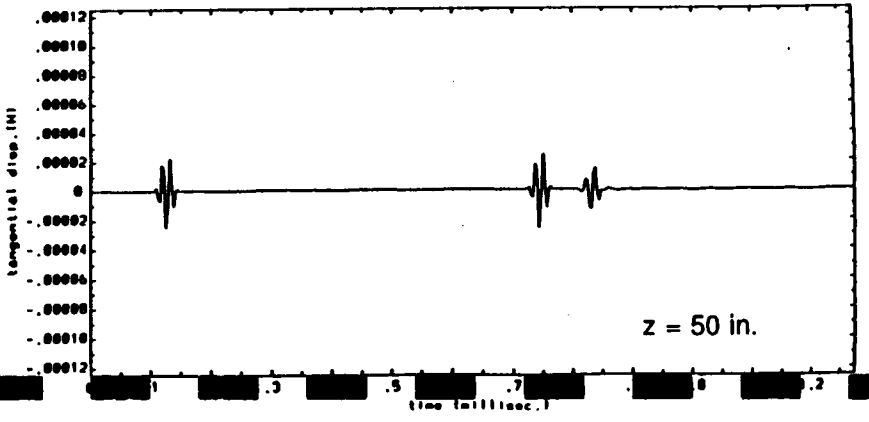




$[15,-15]_s^6$ Tube Time Responses







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FUTURE RESEARCH

- Detailed analysis of 3-D dynamics of space station joints.

- Integration of tube and joint models.

- Experimental verification of dynamic models of undamaged tube and joint specimens.

- Evaluation of significant defects in truss tubes and joints through dynamic modeling.

- Experimental verification of defect characterization models.

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SCATTERING OF LAMB WAVES BY CRACKS IN A COMPOSITE GRAPHITE FIBER-REINFORCED EPOXY PLATE

Robert Bratton
Subhendu Datta
Arvind Shah†

Recent investigations of space construction techniques have explored the use of composite materials in the construction of space stations and platforms. These composites offer superior strength to weight ratio and are thermally stable. For example, a composite material being considered is laminates of graphite fibers in an epoxy matrix. The overall effective elastic constants of such a medium can be calculated from fiber and matrix properties by using an effective modulus theory as shown in Datta, et. al.[1] The investigation of propagation and scattering of elastic waves in composite materials is necessary in order to develop an ability to characterize cracks and predict the reliability of composite structures. The objective of this investigation is the characterization of a surface breaking crack by ultrasonic techniques. In particular, the use of Lamb waves for this purpose is studied here. The Lamb waves travel through the plate, encountering a crack, and scatter. Of interest is the modeling of the scattered wave in terms of the Lamb wave modes. The direct problem of propagation and scattering of Lamb waves by a surface breaking crack has been analyzed. This would permit an experimentalist to characterize the crack by comparing the measured response to the analytical model. The plate is assumed to be infinite in the x and y directions with a constant thickness in the z direction. The top and bottom surfaces are traction free. Solving the governing wave equations and using the stress-free boundary conditions results in the dispersion equation. This equation yields the guided modes in the homogeneous plate. The theoretical model is a hybrid method that combines analytical and finite elements techniques to describe the scattered displacements. A finite region containing the defects is discretized by finite elements. Outside the local region, the far field solution is expressed as a Fourier summation of the guided modes obtained from the dispersion equation. Continuity of tractions and displacements at the boundaries of the two regions provides the necessary equations to determine the expansion coefficients and the nodal displacements. In the hybrid method used here these defects can be of arbitrary shapes as well as inclusions of different materials.

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† University of Civil Engineering, University of Manitoba

[1] S.K. Datta, H.M. Ledbetter, and R. Kriz, Int. J. Solids Struct. **20**, 429 (1984).

Scattering of Lamb Waves by Cracks in a Composite Graphite Fiber-Reinforced Epoxy Plate

- Recent investigations of space construction techniques have explored the use of composite materials in the construction of space stations and platforms.
- These composites offer superior strength to weight ratio and are thermally stable.
- The investigation of propagation and scattering of elastic waves in composite materials is necessary in order to develop an ability to characterize cracks and predict the reliability of composite structures.

Material Constants

- These composite materials can be characterized as transversely isotropic having five distinct elastic constants.
- The overall elastic constants can be predicted using an effective modulus theory.

Description of Defects

- Typical defects are:

  Debonding causing delaminations

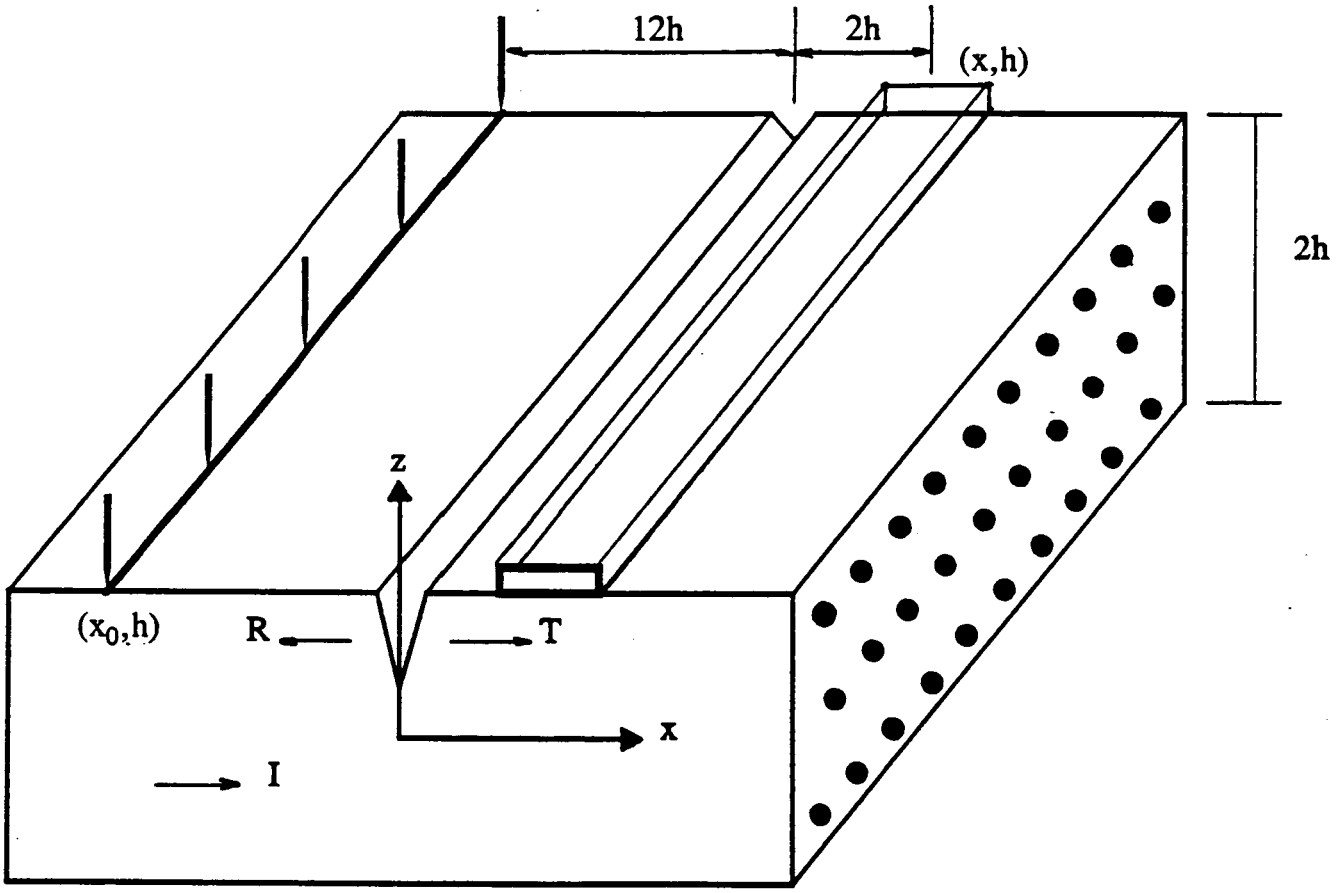
  Pull away of reinforcing particles or fibers from the matrix

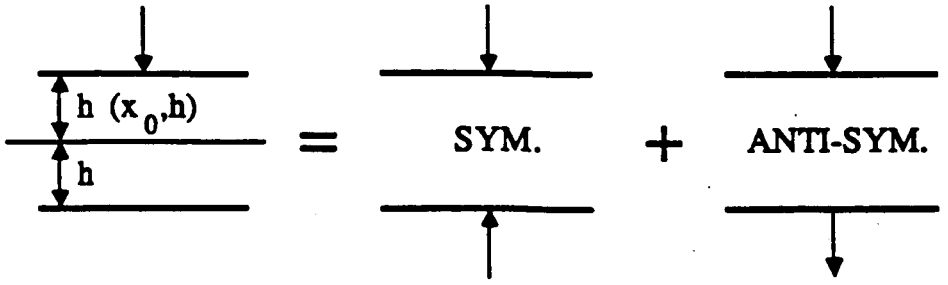
  Matrix cracks

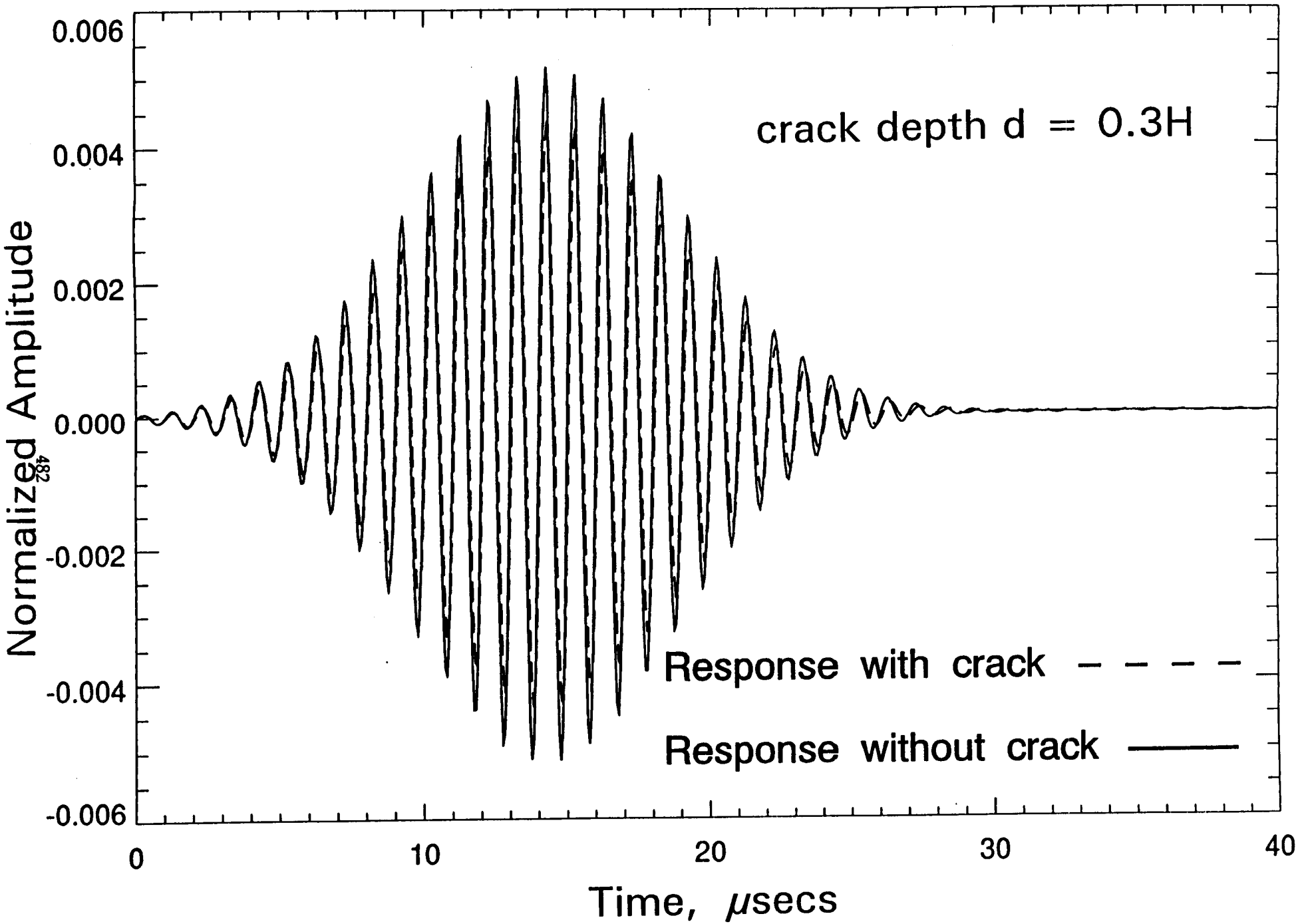
Goal

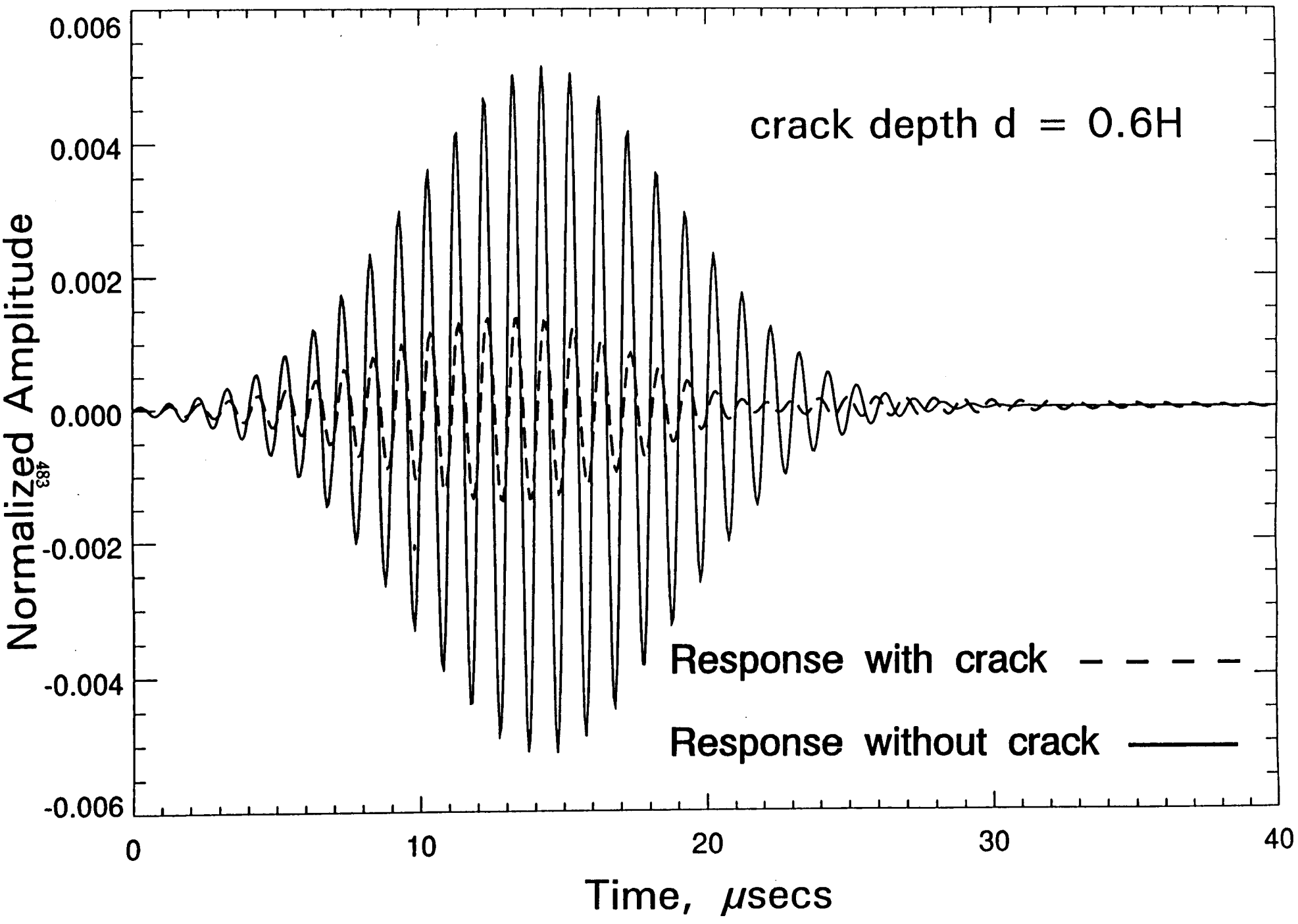
The object of this investigation is the characterization of a crack by ultrasonic techniques

- Use a transducer to send elastic waves into the plate
- The waves travel encountering the crack and scattered
- The scattered wave reaching the surface of the plate is measured by the receiver
- A theoretical model will be shown which models the measured scattered field
- Thus characterization would be possible by comparing the theoretical model with the experiments


12h
2h
(x,h)
2h
z
(x0,h)
R
T
x
I


h (x0,h)
h
=
SYM.
+
ANTI-SYM.


crack depth d = 0.3H
Response with crack
Response without crack
Normalized Amplitude
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
0
10
20
30
40
Time, μsecs


crack depth d = 0.6H
Response with crack
Response without crack
Normalized Amplitude
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
0
10
20
30
40
Time, μsecs

Research Efforts

- Develop models for the propagation of elastic waves in transversely isotropic plates; determine the Lamb modes.
- Incorporate this modal information into the construction of a model for scattering of elastic waves by a crack in a plate.

Conclusions

- Demonstration of a hybrid numerical model which provides the time response of an anisotropic plate containing a crack being excited by a single Lamb mode.
- This hybrid model provides analysis to assist the experimentalist in interpreting the measured time response.

Future Work

- Extend the capabilities of the hybrid method to the analysis of the time response from array sensors.
- Investigate the time response due to a source using plate or beam continuum models of large lattice space structures.
- Investigate the time response due to a source using discrete truss structure models.

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EXPERIMENTAL AND THEORETICAL STUDY OF RAYLEIGH-LAMB WAVE PROPAGATION

W.P. Rogers
S.K. Datta
T.H. Ju†

Many space structures, such as the Space Station Freedom, contain critical thin-walled components. The structural integrity of thin-walled plates and shells can be monitored effectively using acoustic emission and ultrasonic testing in the Rayleigh-Lamb wave fequency range. A new PVDF piezoelectric sensor has been developed that is well suited to remote, inservice nondestructive evaluation of space structures.

In the present study the new sensor was used to investigate Rayleigh-Lamb wave propagation in a plate. The experimental apparatus consisted of a glass plate (2.3m x 25.4mm x 5.6 mm) with PVDF sensors (3 mm diam.) mounted at various positions along its length. A steel ball impact served as a simulated acoustic emission source, producing surface waves, shear waves and longitudinal waves with dominant frequencies between 1 kHz and 200 kHz.

The experimental time domain wave-forms were compared with theoretical predictions of the wave propagation in the plate. The model uses an analytical solution for the Green's function and the measured response at a single position to predict response at any other position in the plate. Close agreement was found between the experimental and theoretical results.

† Department of Mechanical Engineering

Experimental and Theoretical Study of Rayleigh-Lamb Wave Propagation

Wayne Rogers, S.K. Datta

Center for Space Construction
University of Colorado at Boulder

T.H. Ju

Department of Mechanical Engineering
University of Colorado at Boulder

Motivation

- Assure reliability of materials in space structures while in service.
- Detect and characterize damage or degradation of material properties.
- Methods must be: quantitative, automated, remote, light weight, rugged, ...
- Quantitative relationship between measurements, damage events, material properties, and continued reliability in service.

Traditional NDE methods

- Visual inspection, dye penetrant inspection, X-ray, eddy current, ...

- Ultrasonic testing: probe interior using pulse-echo, measure global and local elastic properties, detect and characterize localized damage.

- Acoustic emission: detect damage events as they occur, use signals to locate and identify source, measure elastic properties using *natural* noise.

Smart Materials

- Sensors integral to the structure, act as a *Nervous system*. Example - optical fiber strain sensors.

- Measure strain, vibration, acoustic emission, ..., which are sensitive, quantitative parameters reflecting material state.

- Use these measurements to detect and quantify localized or distributed damage and global degradation of material properties.

PVDF piezoelectric polymeric film transducers

- Hz - MHz band-width, 120 dB sensitivity.

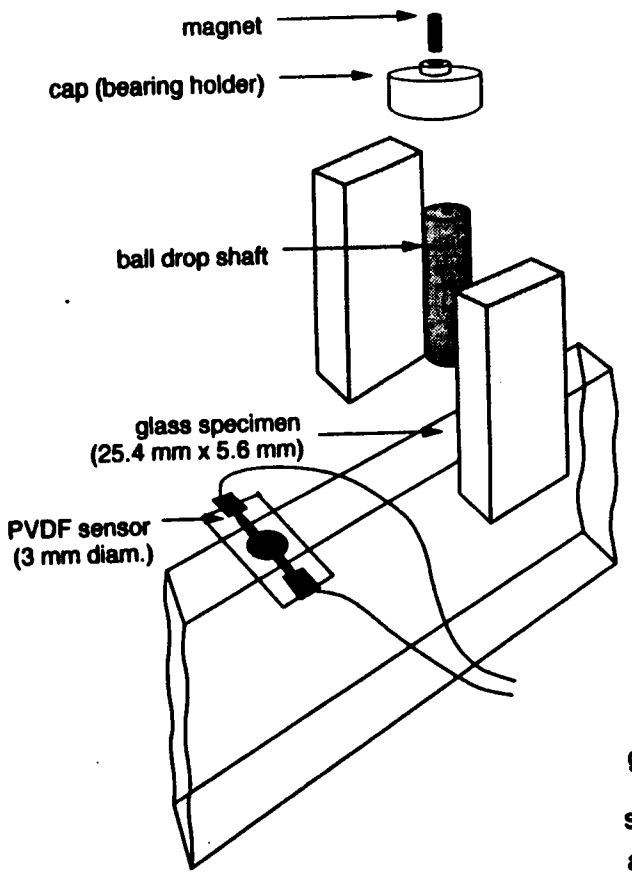
- Light, small, flexible, easily fabricated, well suited to transducer arrays, commercially available, inexpensive.

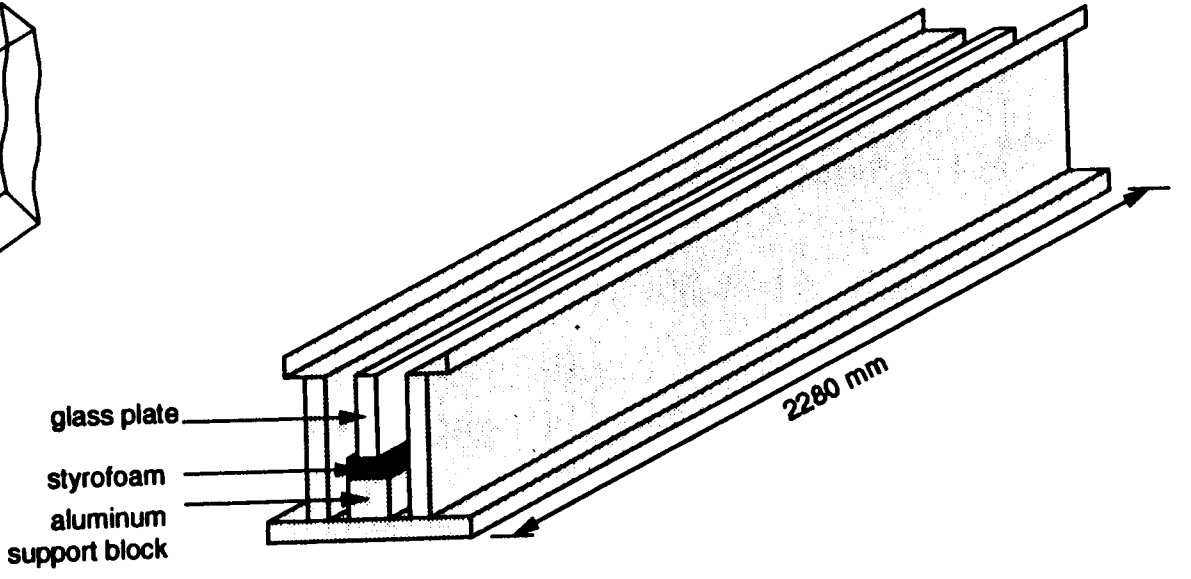
Objectives

- Demonstrate PVDF sensor using apparatus with well defined acoustic emission source and boundary conditions. Characterize band-width and sensitivity with acoustic emission signal.

- Compare experimental results with model of Rayleigh-Lamb wave propagation.

Ball drop experimental apparatus





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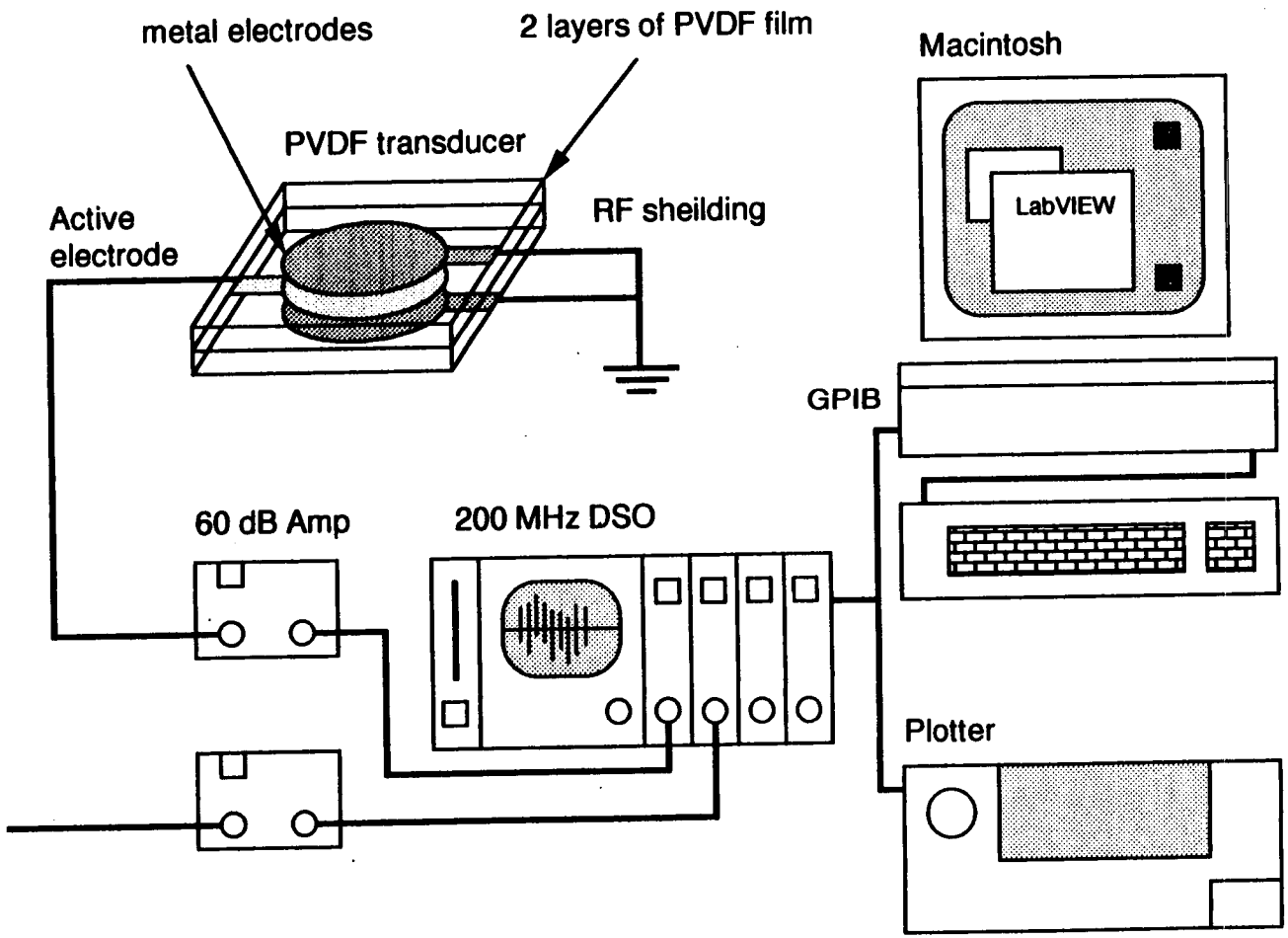
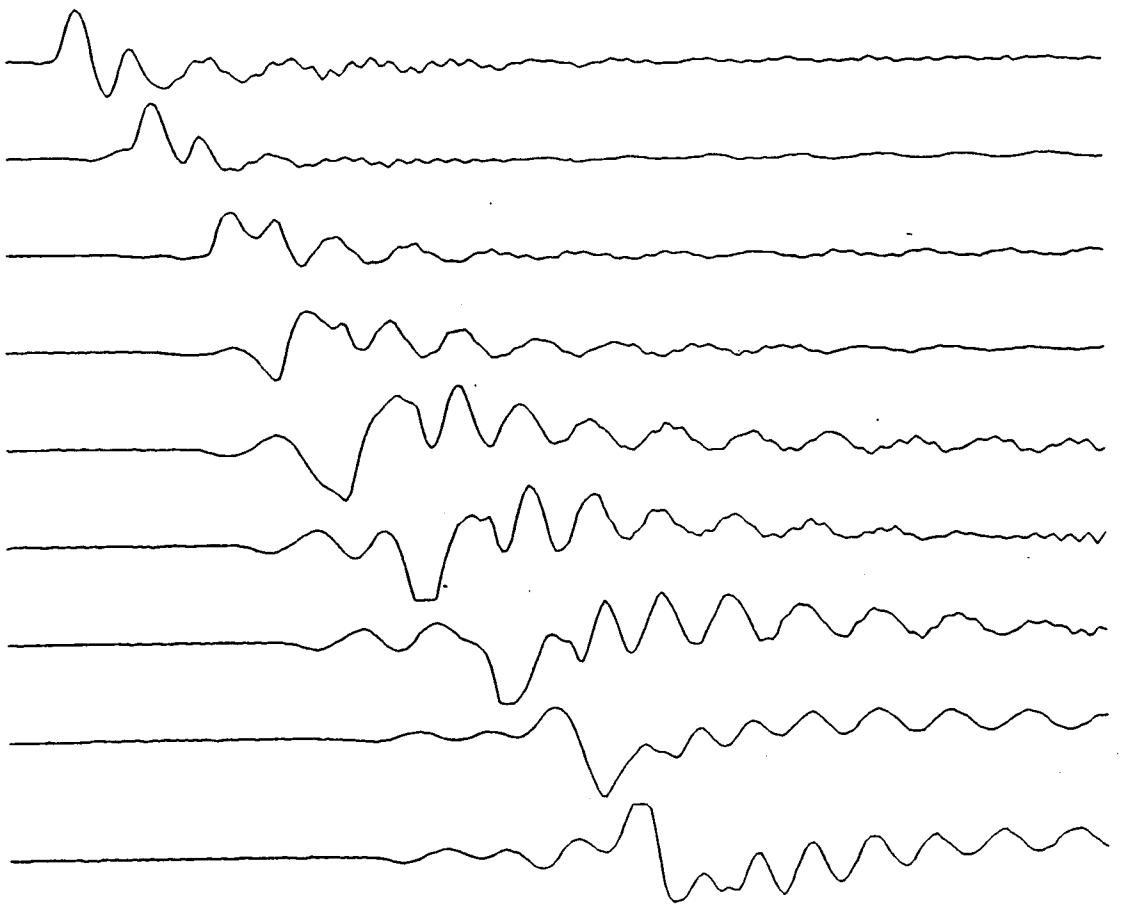
Electronics for PVDF sensor and acoustic emission acquisition



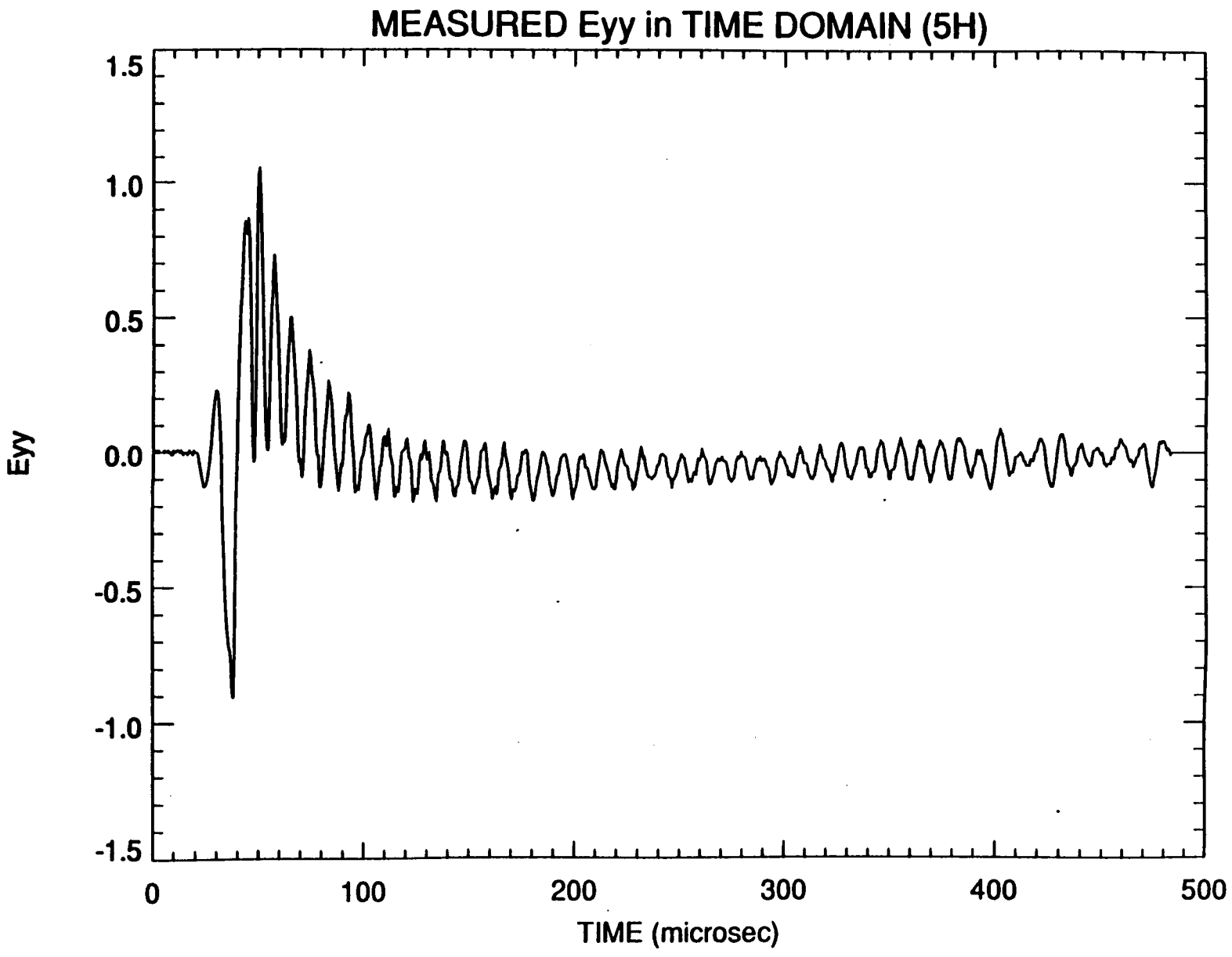
Wave-forms with sensor located various distanced from the source



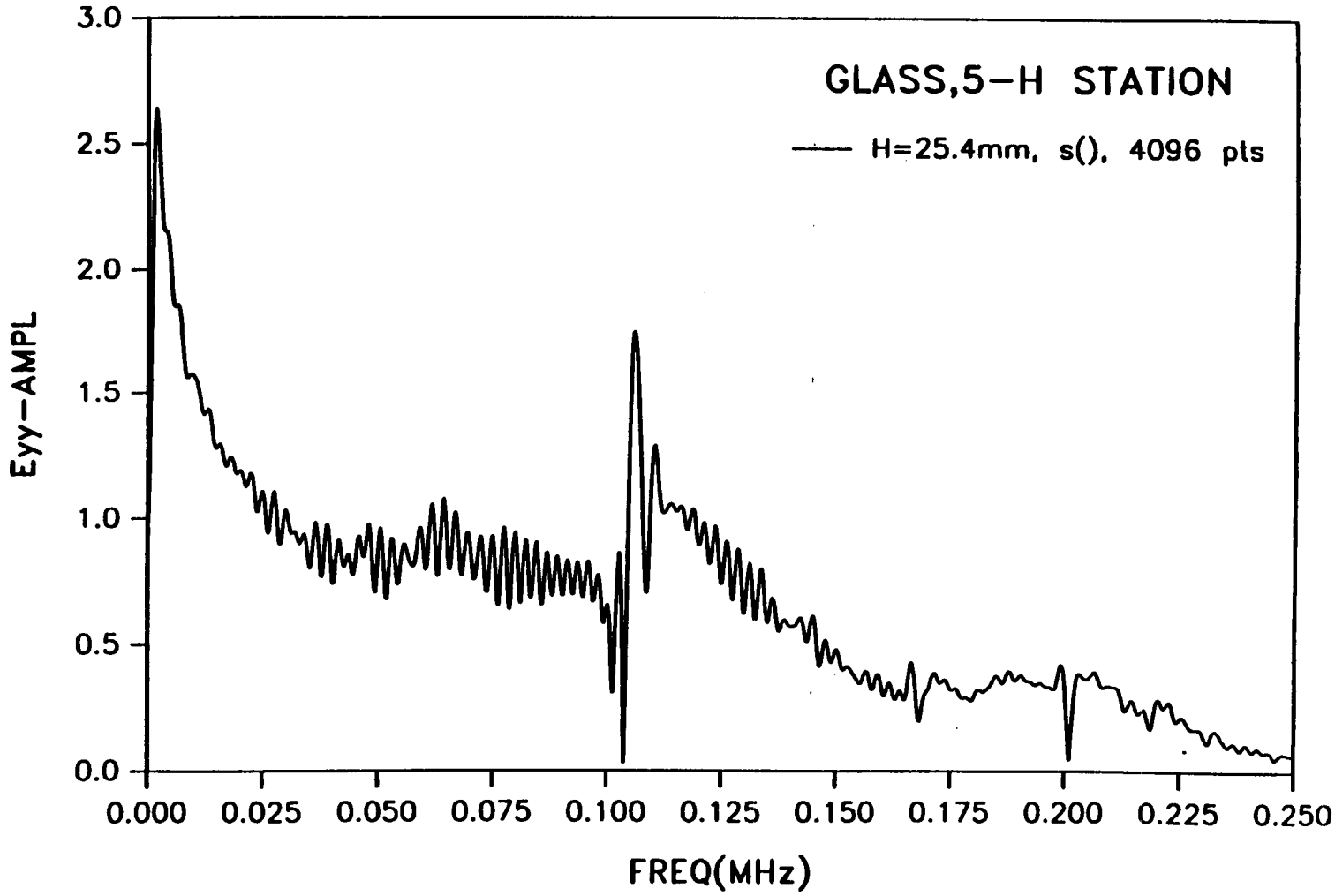
Model of wave propagation

- Plate can be treated as two dimensional plane stress in the far field.

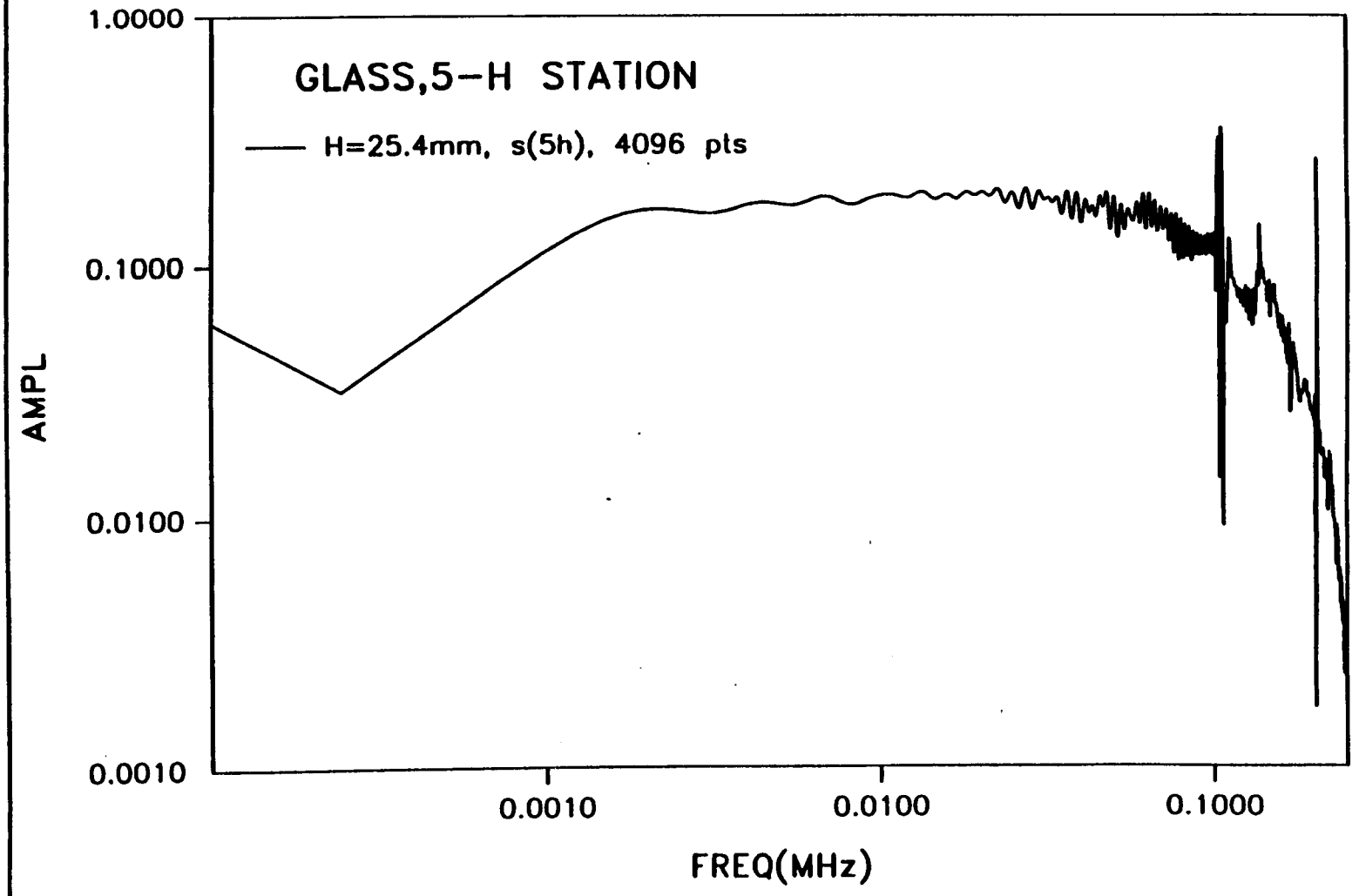
- Measurement in the time domain is transformed to frequency domain. This frequency spectrum at a particular position together with the analytical solution for the Green's function are used to extract the source function. The source function is used to calculate the response in the frequency domain at any other position. By inverse FFT the time domain response is obtained.


MEASURED Eyy in TIME DOMAIN (5H)
Eyy
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0
100
200
300
400
500
TIME (microsec)

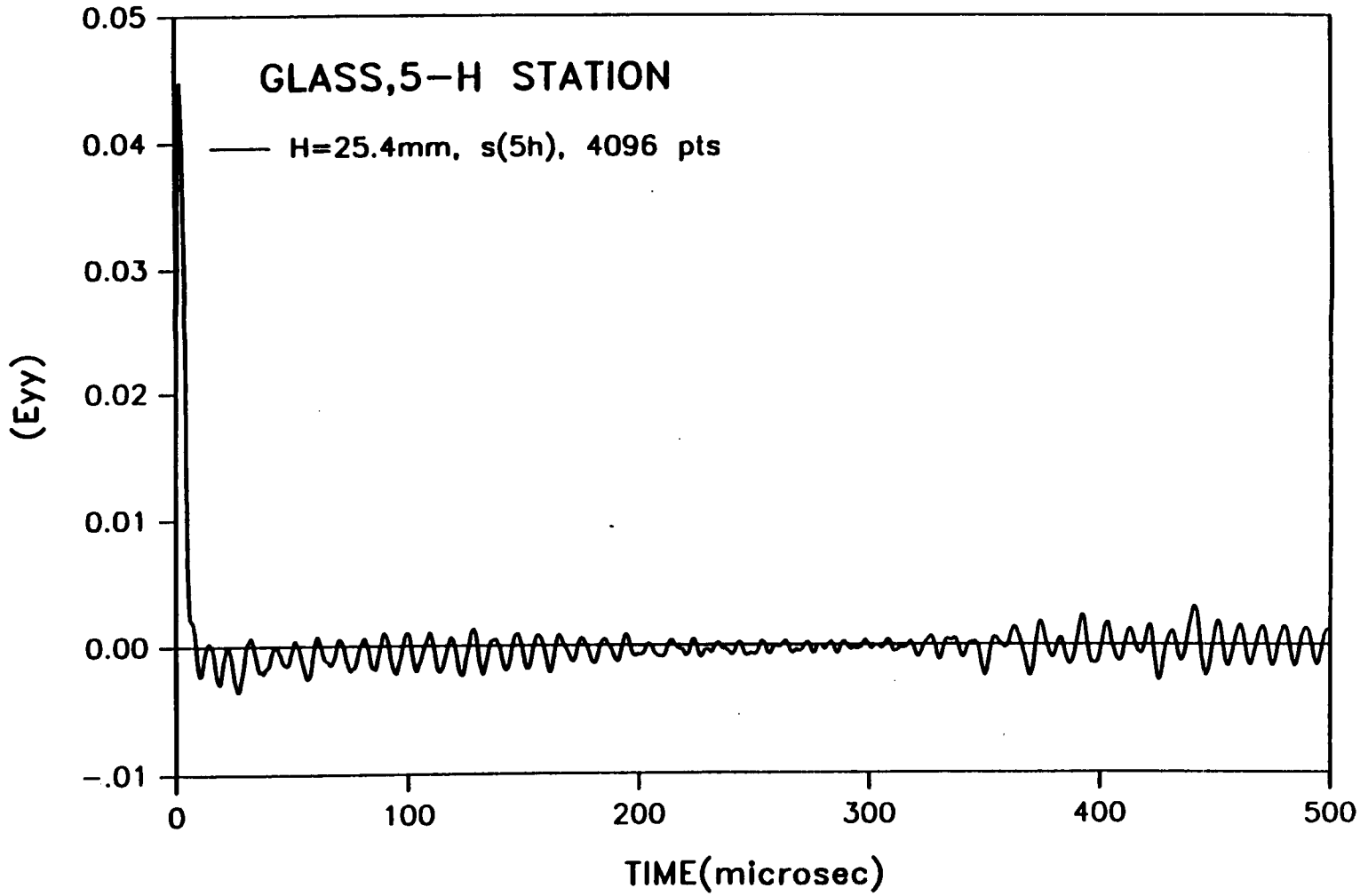
MEASURED Eyy in FREQ DOMAIN



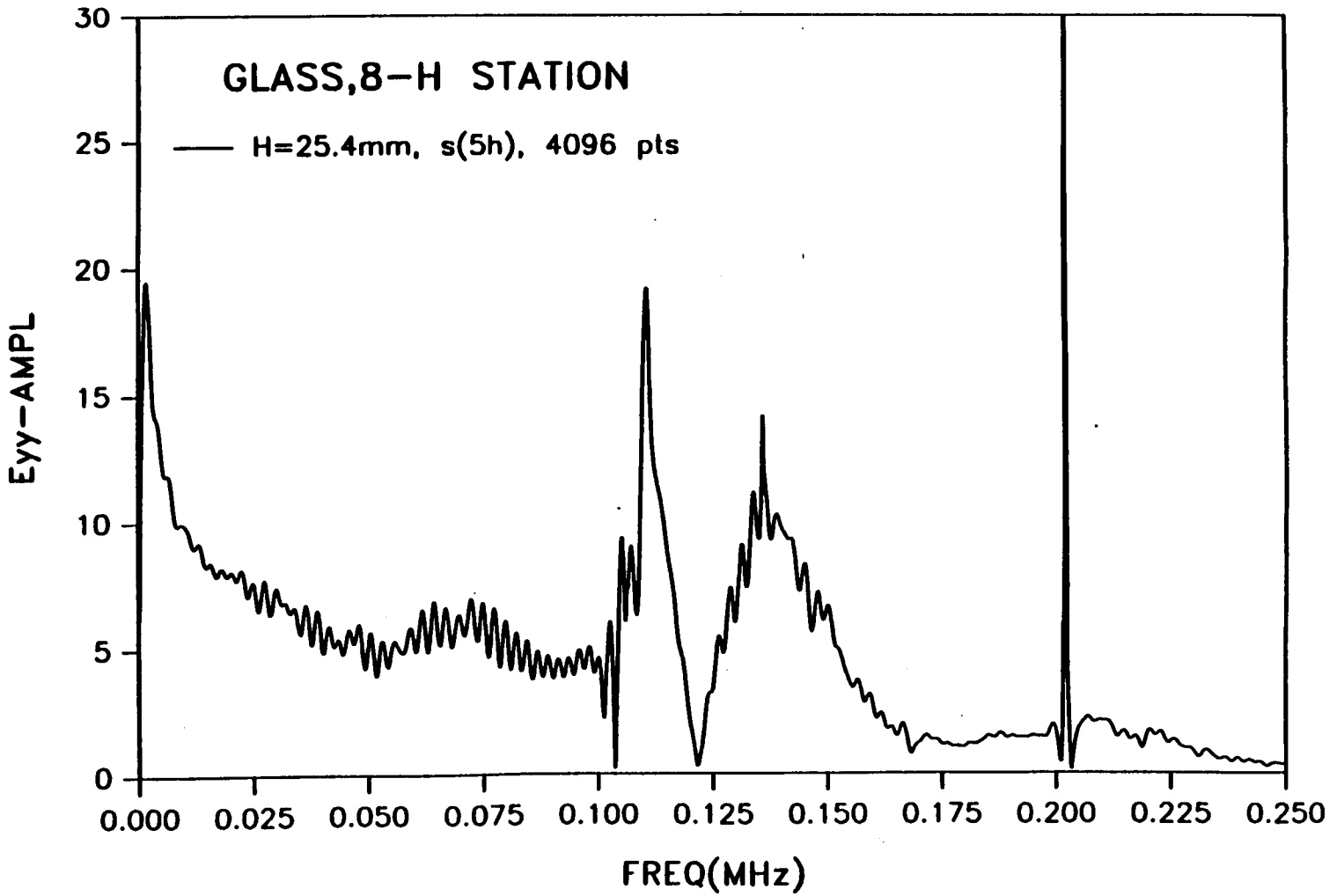
SOURCE EXTRACTED in FREQ DOMAIN

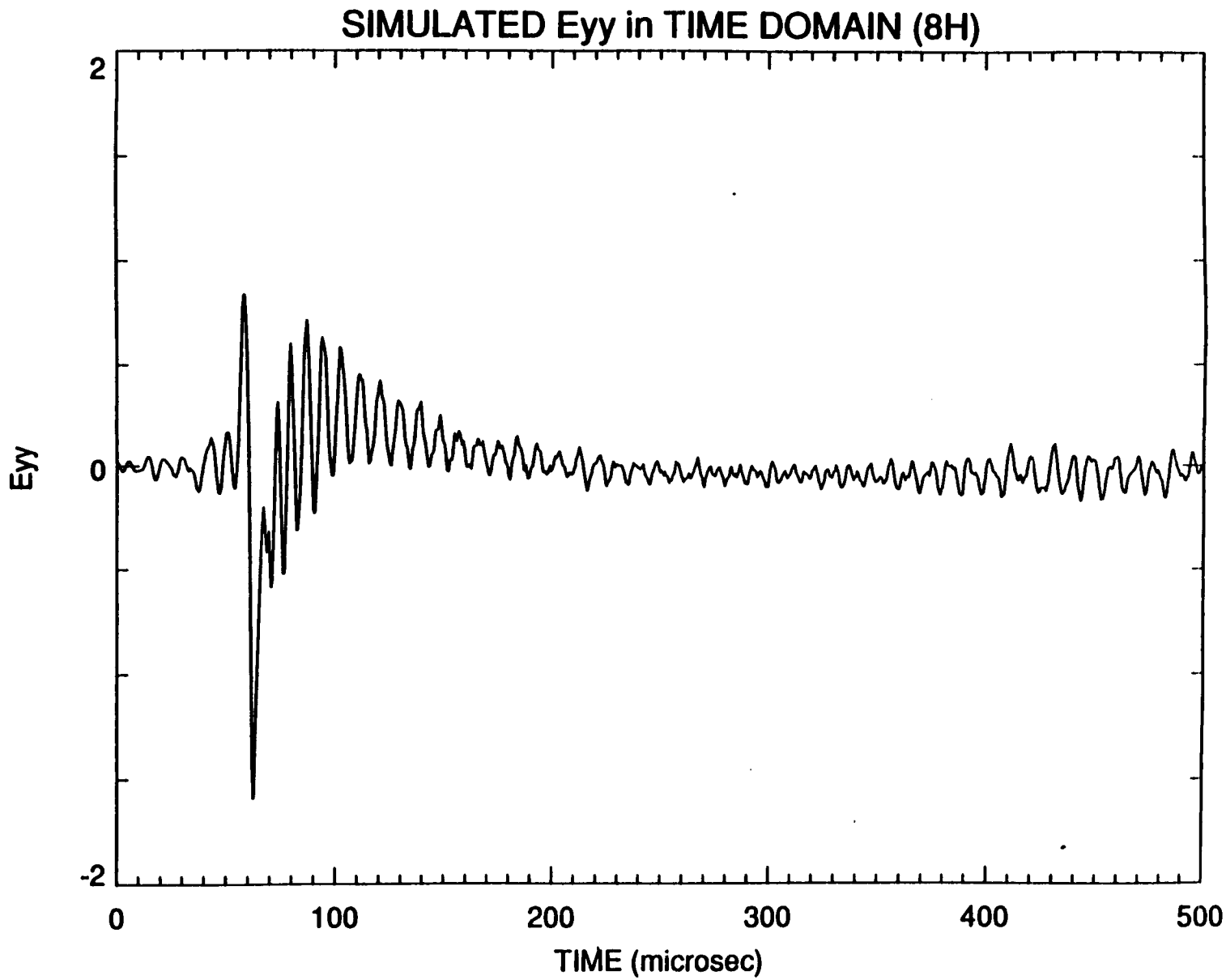


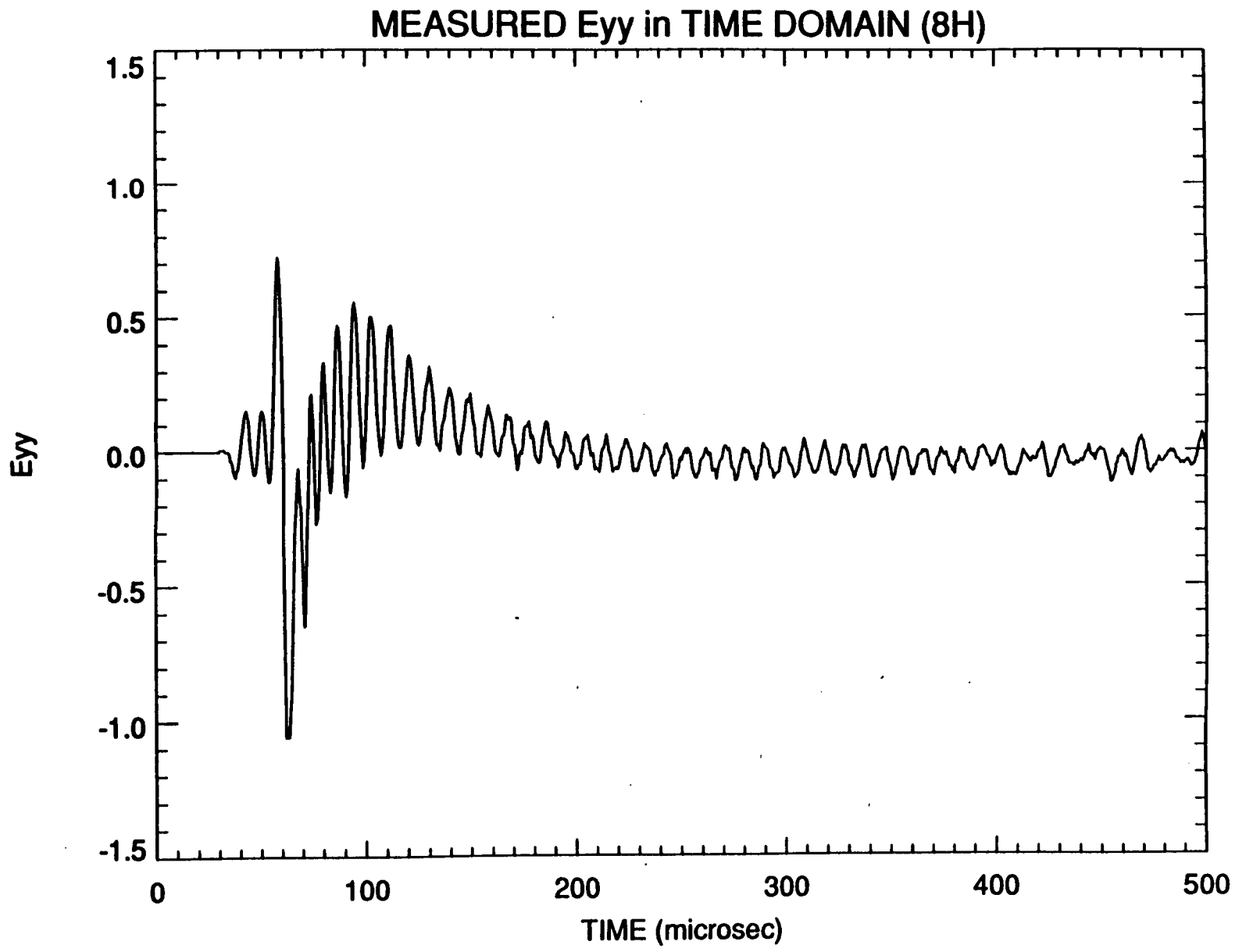
SOURCE EXTRACTED in TIME DOMAIN

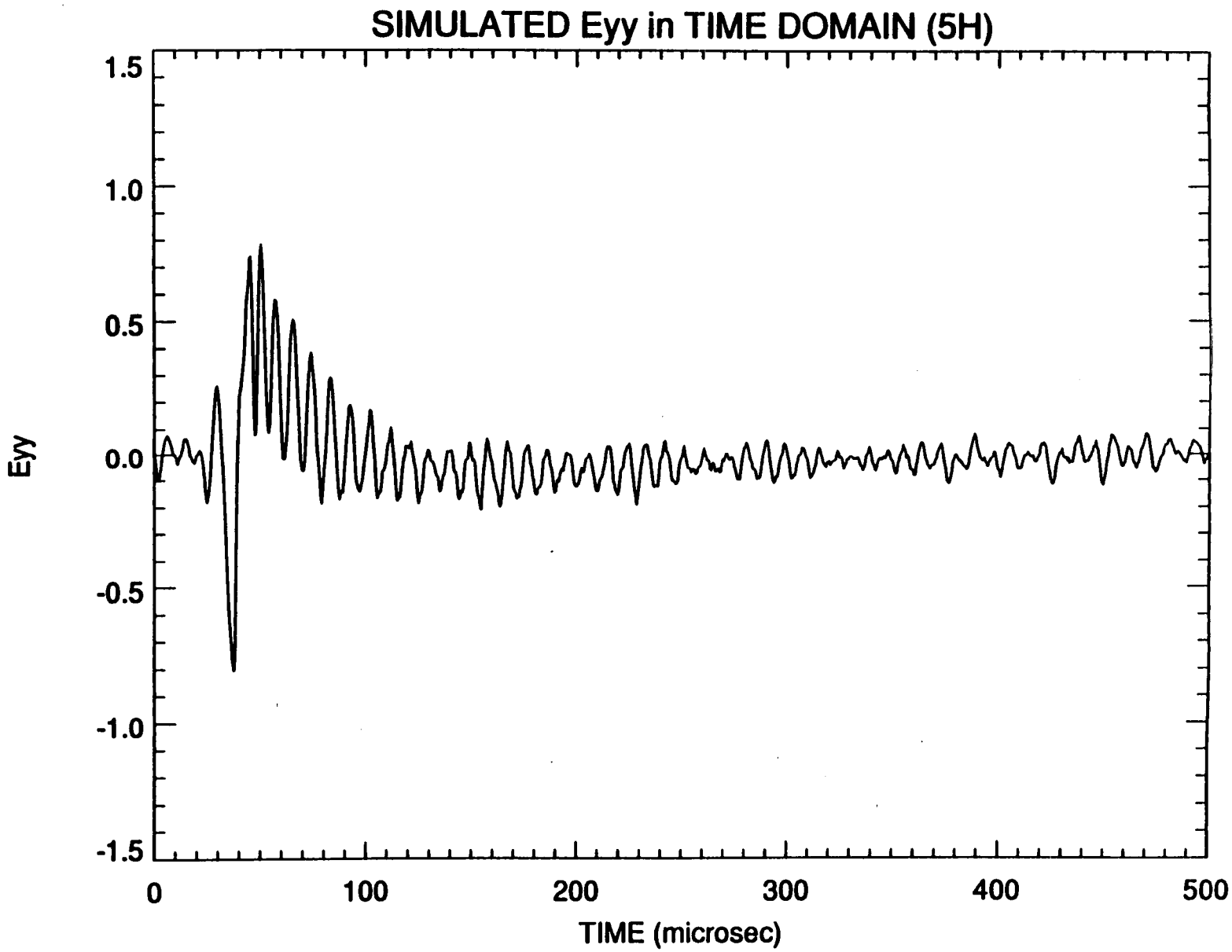


SIMULATED Eyy in FREQ DOMAIN




SIMULATED Eyy in TIME DOMAIN (8H)
Eyy
2
0
-2
0
100
200
300
400
500
TIME (microsec)


MEASURED Eyy in TIME DOMAIN (8H)
Eyy
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0
100
200
300
400
500
TIME (microsec)


SIMULATED Eyy in TIME DOMAIN (5H)
Eyy
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0
100
200
300
400
500
TIME (microsec)

Conclusions

- PVDF transducer is a broad-band sensitive sensor for acoustic emission detection.

- Model of wave propagation in a plate accurately predicts the wave-forms observed experimentally.

Future work

- Acoustic emission in graphite/epoxy composites in bending. Correlation between acoustic emission and damage events such as matrix cracking and fiber breakage. Reliability predictions.

- Arrays of PVDF sensors. Source location and identification.

- Measurement of Rayleigh-Lamb wave phase velocities in graphite/epoxy plates and tubes.

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ACOUSTIC EMISSION IN SPACE STATION TRUSS TUBE

John Dorighi
Wayne Rogers
Bill Prosser†
Eric Madaras†

Wavespeeds were measured in a 2" diameter graphite/epoxy composite tube with a layup of [+/-10,+/-30,+/-10]s. An acoustic emission source was simulated by a lead pencil break which excited flexural and extensional waveforms. Arrival times for both waveforms were measured at 0, 45 and 90 degrees relative to the tube axis. In order to calculate wavespeeds, the arrival times were measured for at least seven different distances from the source for each orientation. These wavespeeds were compared with analytical results predicted by classical plate theory. Measured extensional wavespeeds showed a close correspondence with analytical values. However, the measured flexural wavespeeds did not match those predicted by classical plate theory.

† Nondestructive Measurement Science Branch, NASA Langley Research Center

Acoustic Emission in Space Station Truss Tube

John Dorighi, Wayne Rogers

Center for Space Construction

University of Colorado at Boulder

Bill Prosser, Eric Madaras

Nondestructive Measurement Science Branch

NASA / Langley Research Center

Outline

I. tube characteristics

A) determination of layup

II. wavespeed measurements

A) classical plate theory

B) experimental apparatus

C) experimental procedure

D) results

III. conclusions

overview:

1) Gr/Ep tubes chosen for SSF truss structure

2) Need on orbit NDE methods

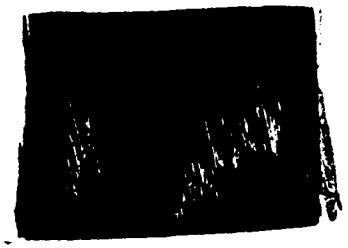
objective:

1) Measure wavespeeds in Gr/Ep tubes

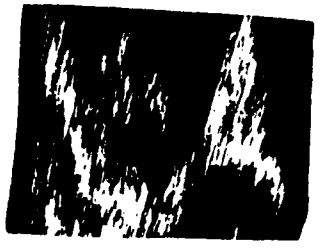
2) Compare with Classical Plate Theory

AS4/976 COMPOSITE TUBE LAYUP

LAYER 12 (+10)
(outer)



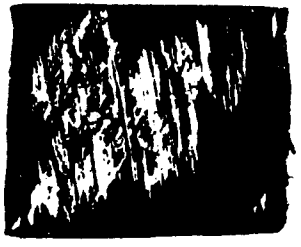
LAYER 11 (-10)



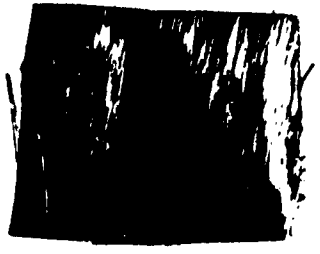
LAYER 10 (+30)

LAYER 9 (-30)

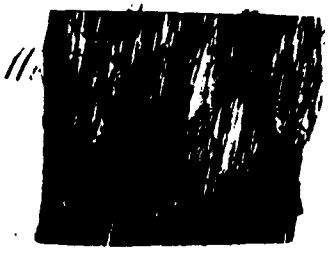
LAYER 8 (+10)



LAYER 7 (-10)



LAYER 6 (-10)

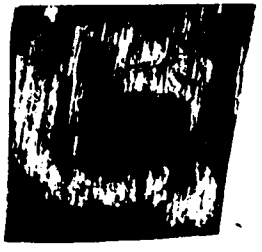


LAYER 5 (+10)

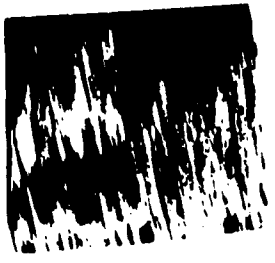
LAYER 4 (-30)

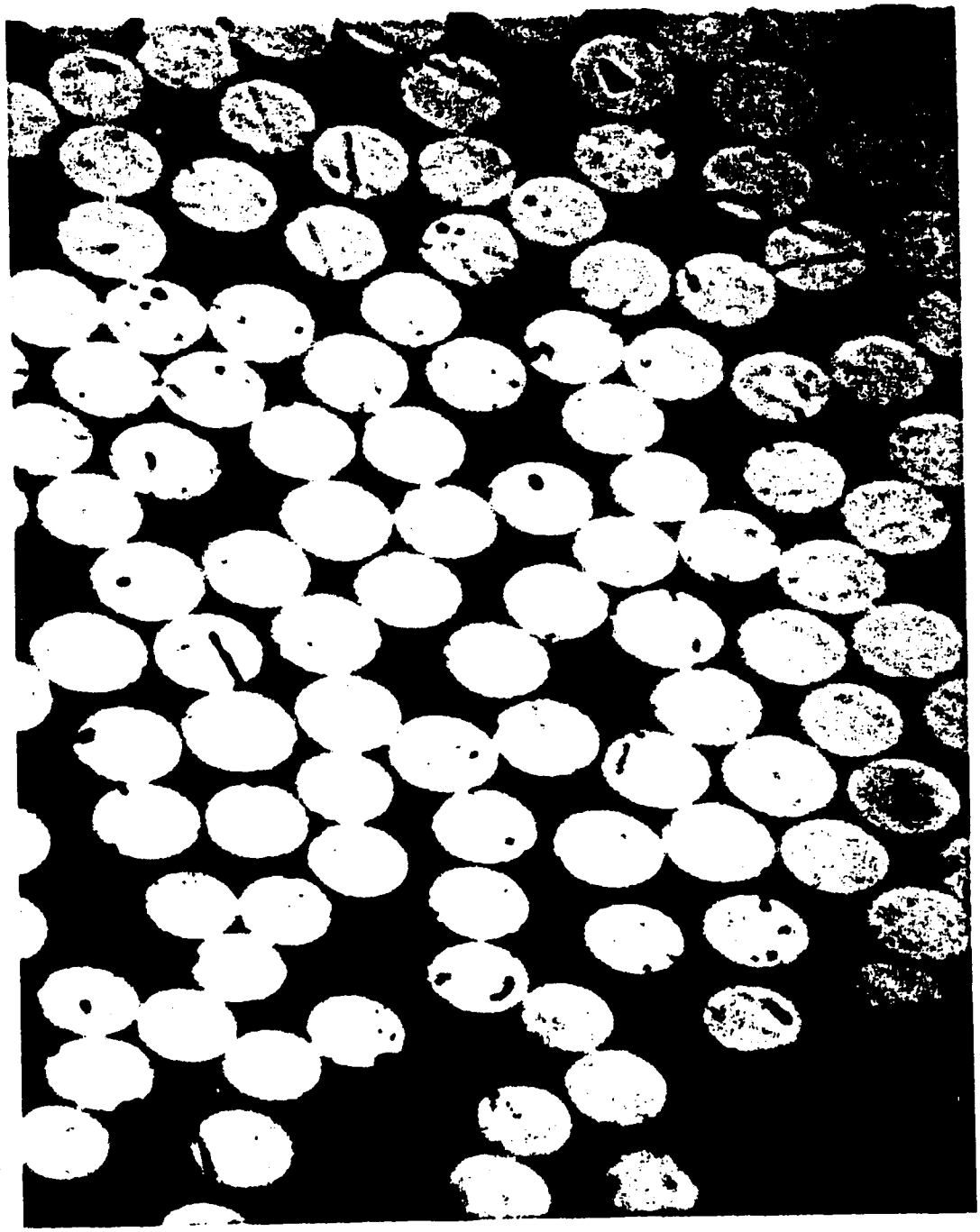
LAYER 3 (+30)

LAYER 2 (-10)



LAYER 1 (+10)
(inner)





Laminated Plate Stiffness Equations

In-Plane Stiffness

$$\frac{A_{ij}}{h} = \sum_{k=1}^{n} \overline{C_{ij}^{(k)}} \left(h_k - h_{k-1}\right)$$

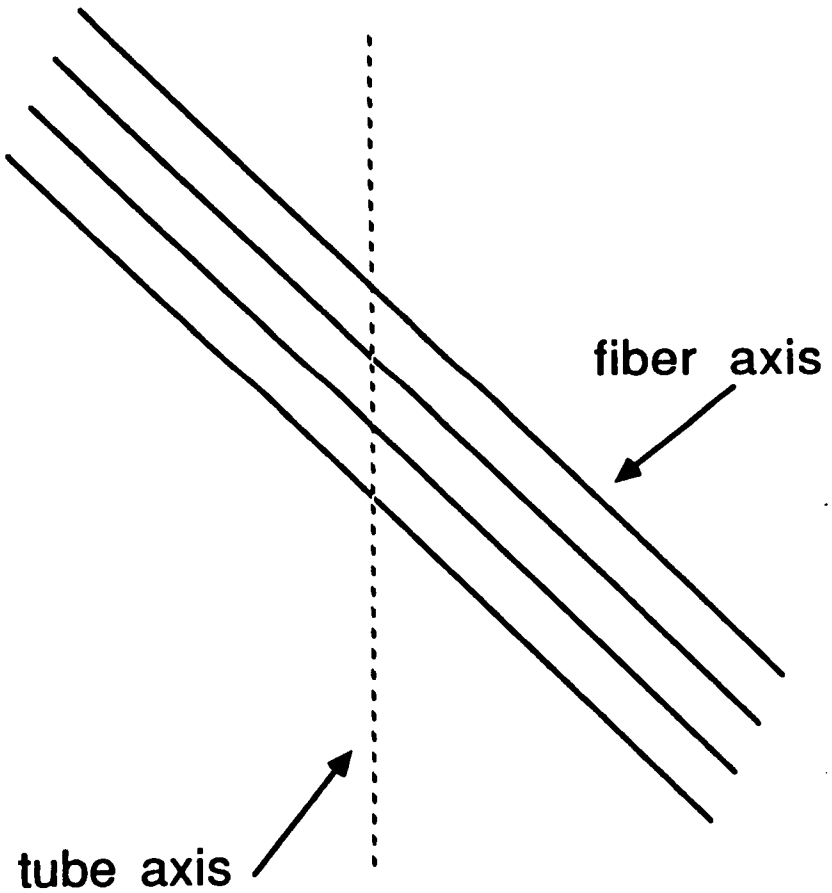
Flexural Stiffness

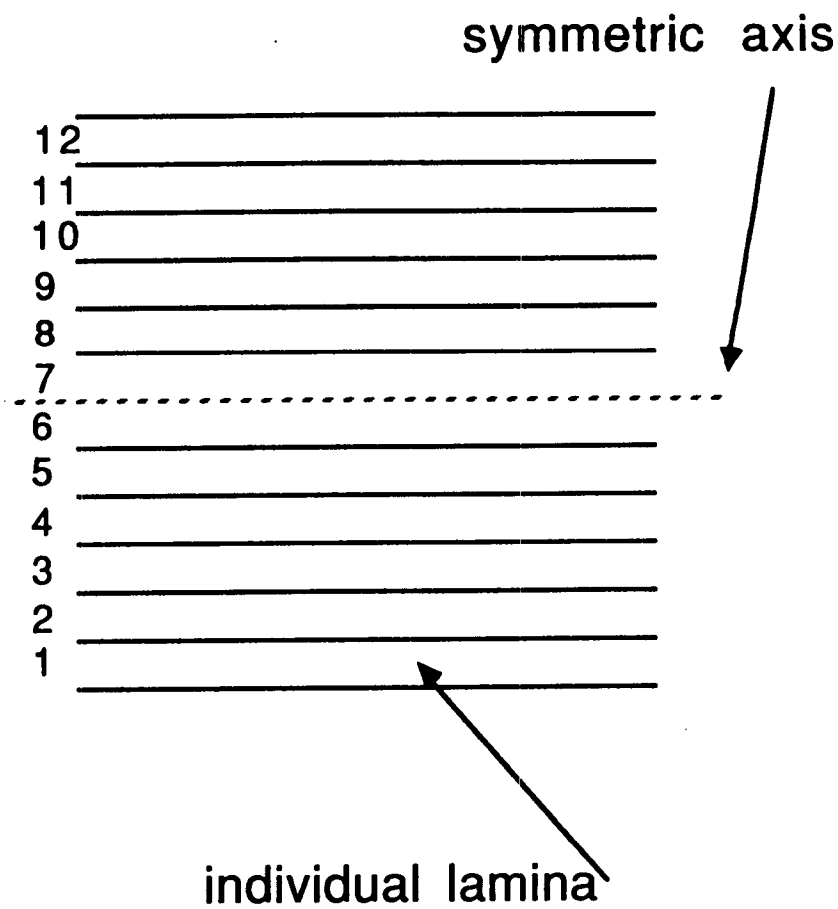
$$\frac{D_{ij}}{h} = \frac{1}{3} \sum_{k=1}^{n} \overline{C_{ij}^{(k)}} \left(h_k^3 - h_{k-1}^3\right)$$

$\overline{C_{ij}^{(k)}}$ - lamina stiffness referenced to the tube axis

h_k - distance of each lamina from the neutral axis

Laminated Plate Stiffness Equations (cont.)





Wavespeed Equations from Classical Plate Theory

Extensional (in-plane)

$$C_e = \sqrt{\frac{A_{11}}{\rho h}}$$

A11/h - laminate in-plane stiffness

ρ - density of medium

Flexural (out-of-plane)

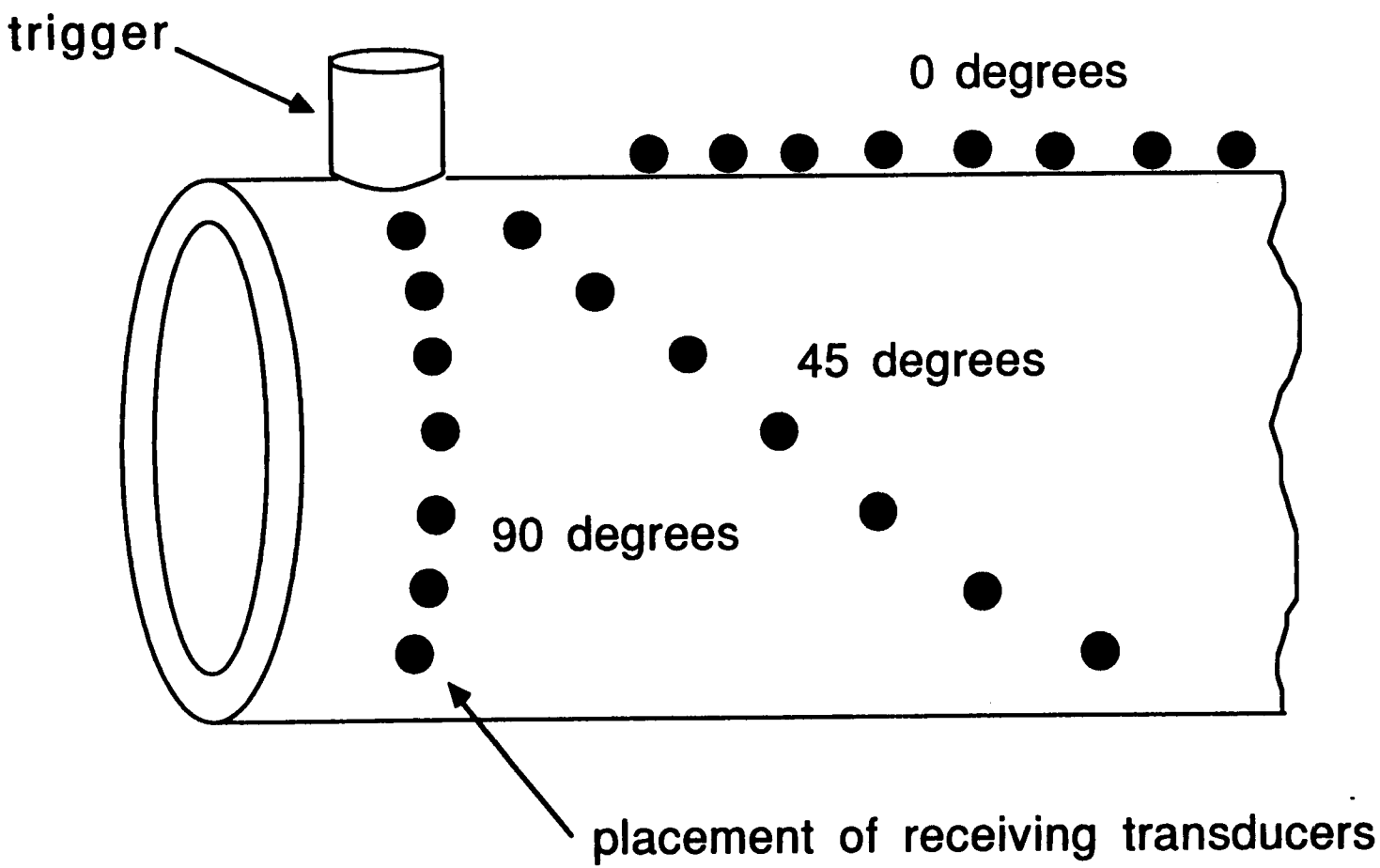
$$C_f = \sqrt[4]{\frac{D_{11}}{\rho h}}\sqrt{\omega}$$

D11/h - laminate flexural stiffness

ρ - density of medium

ω - angular frequency

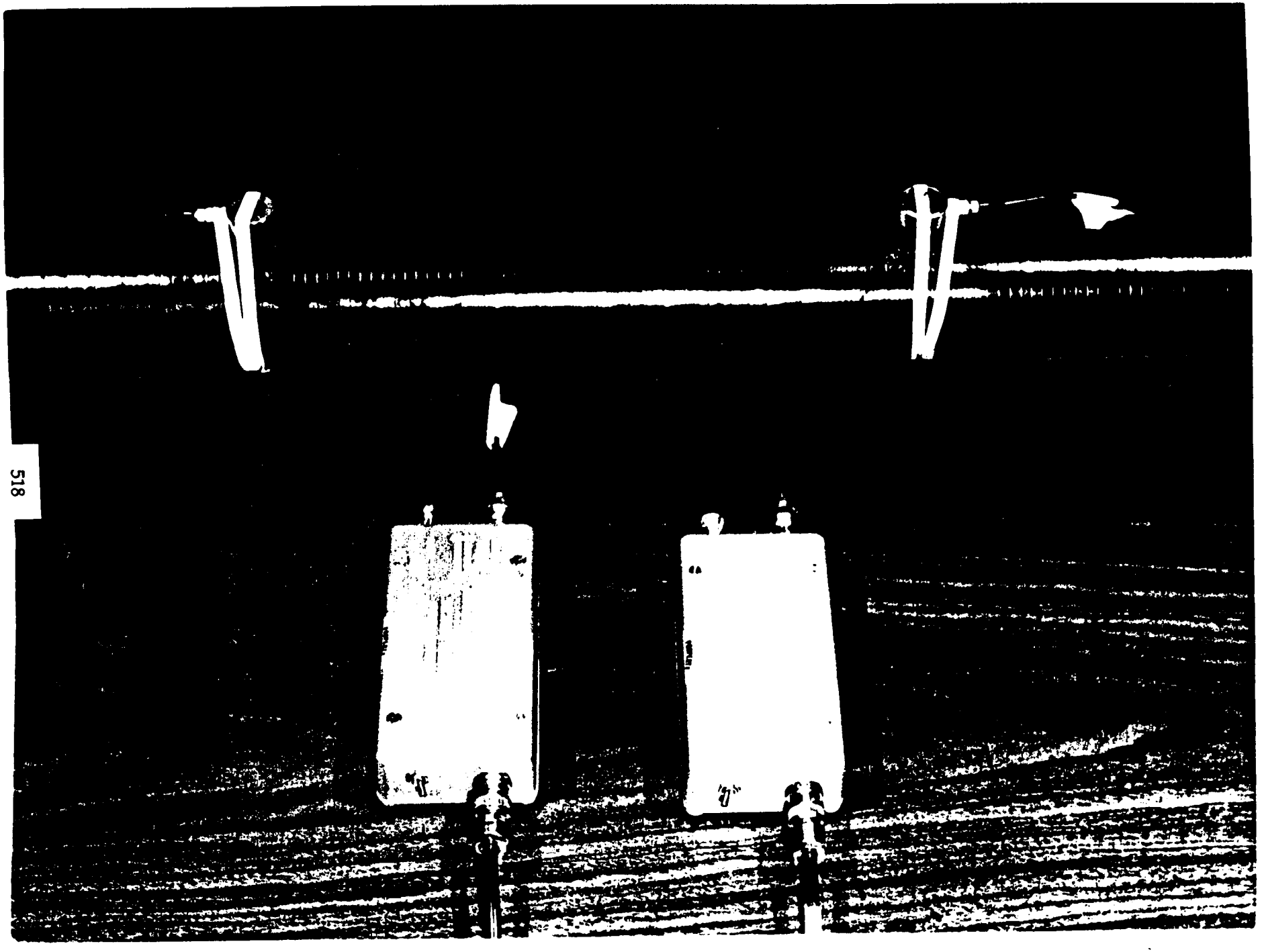
Transducer Placement for Wavespeed Measurements



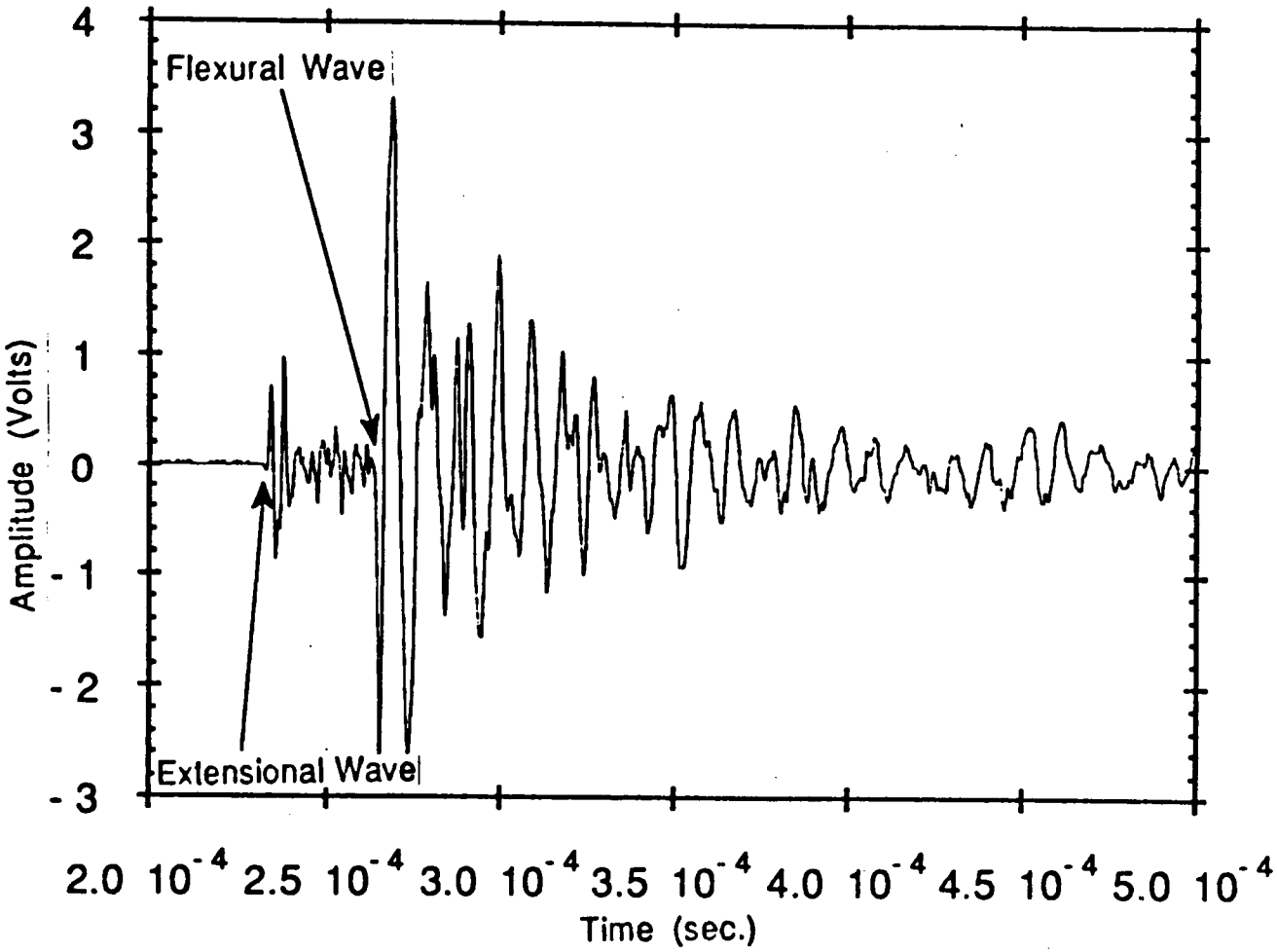
NASA

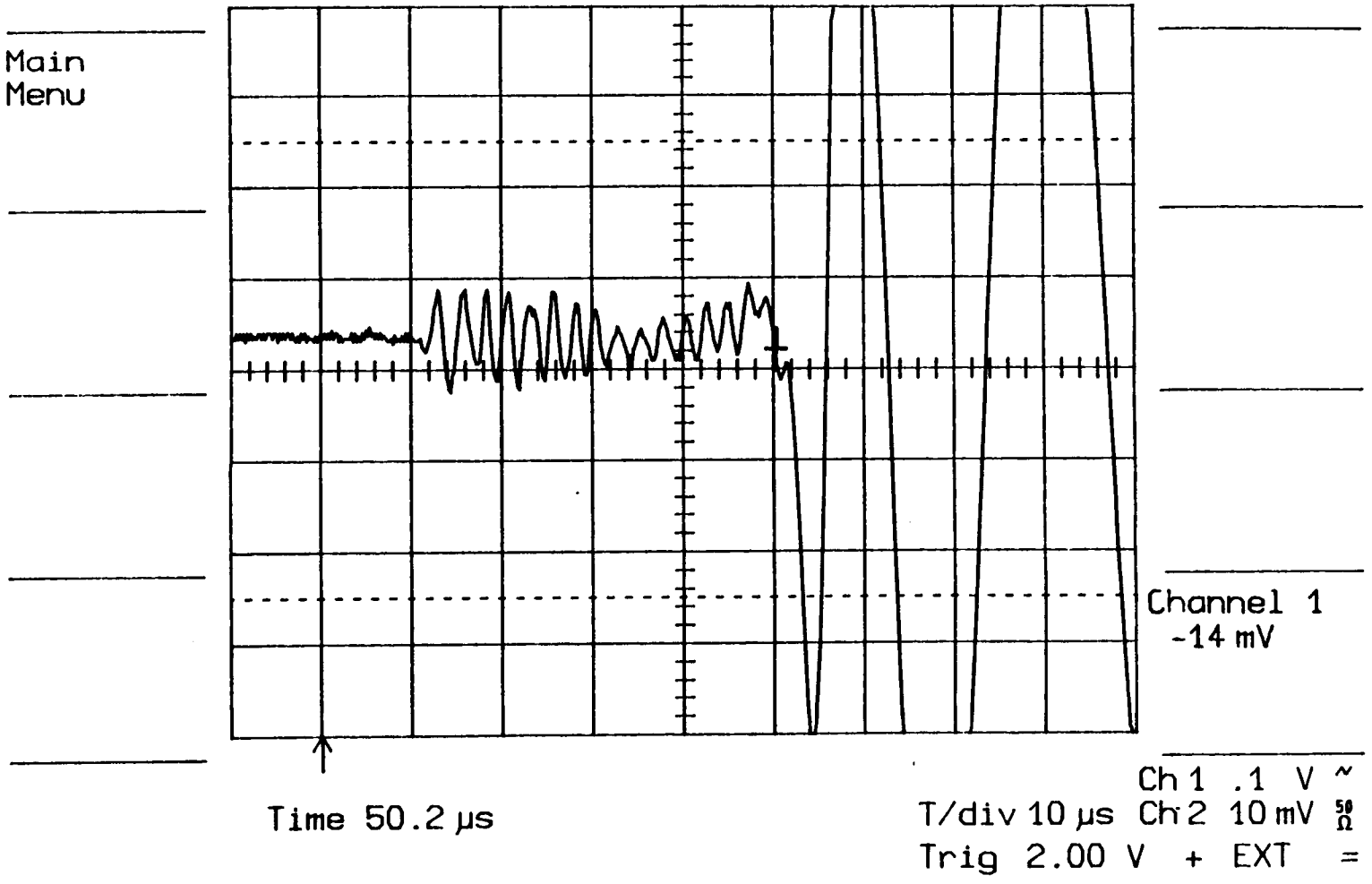
90-08684

Langley Research Center
Hampton, Virginia 23665-5225

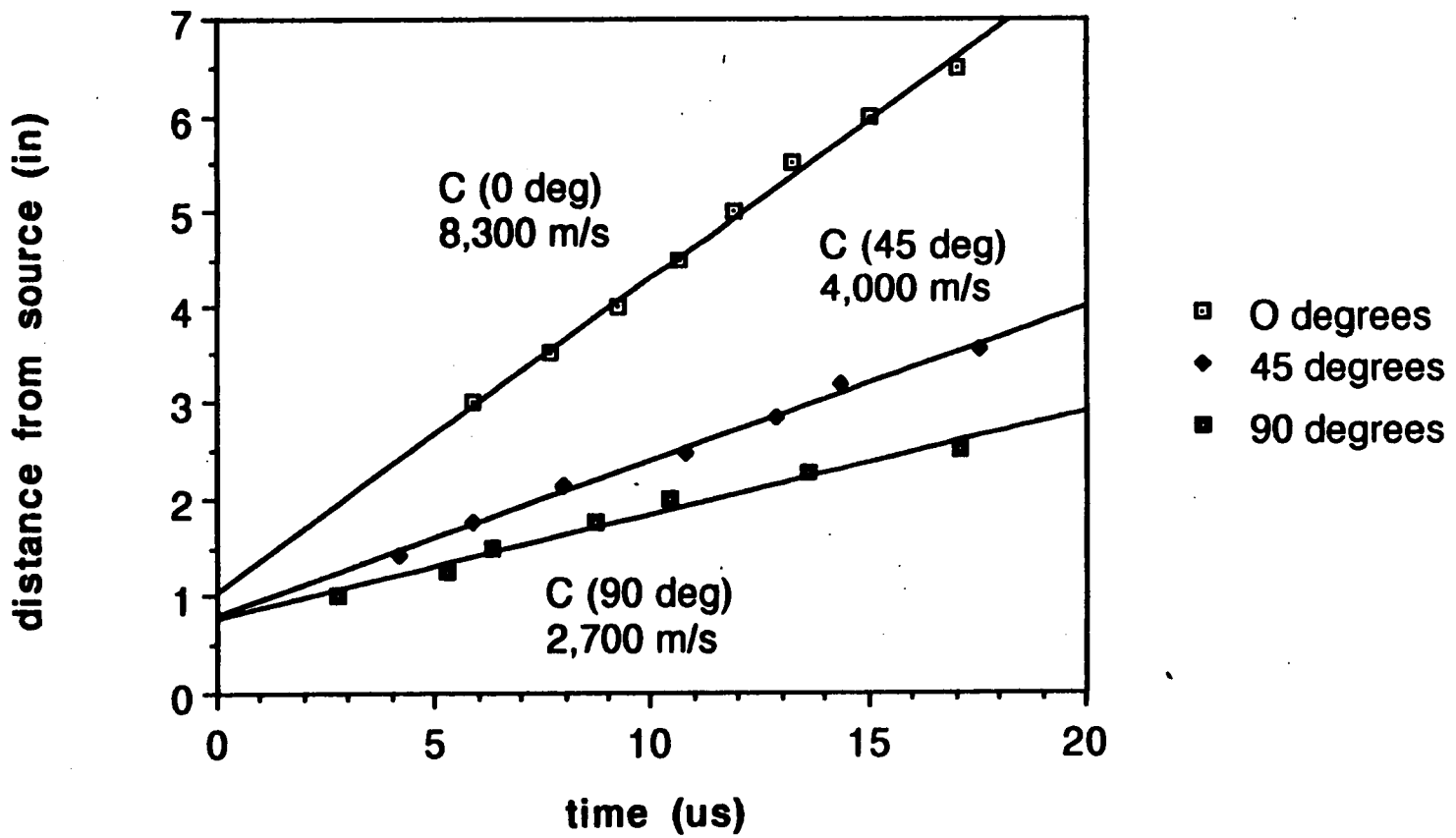


Typical Excited Waveform

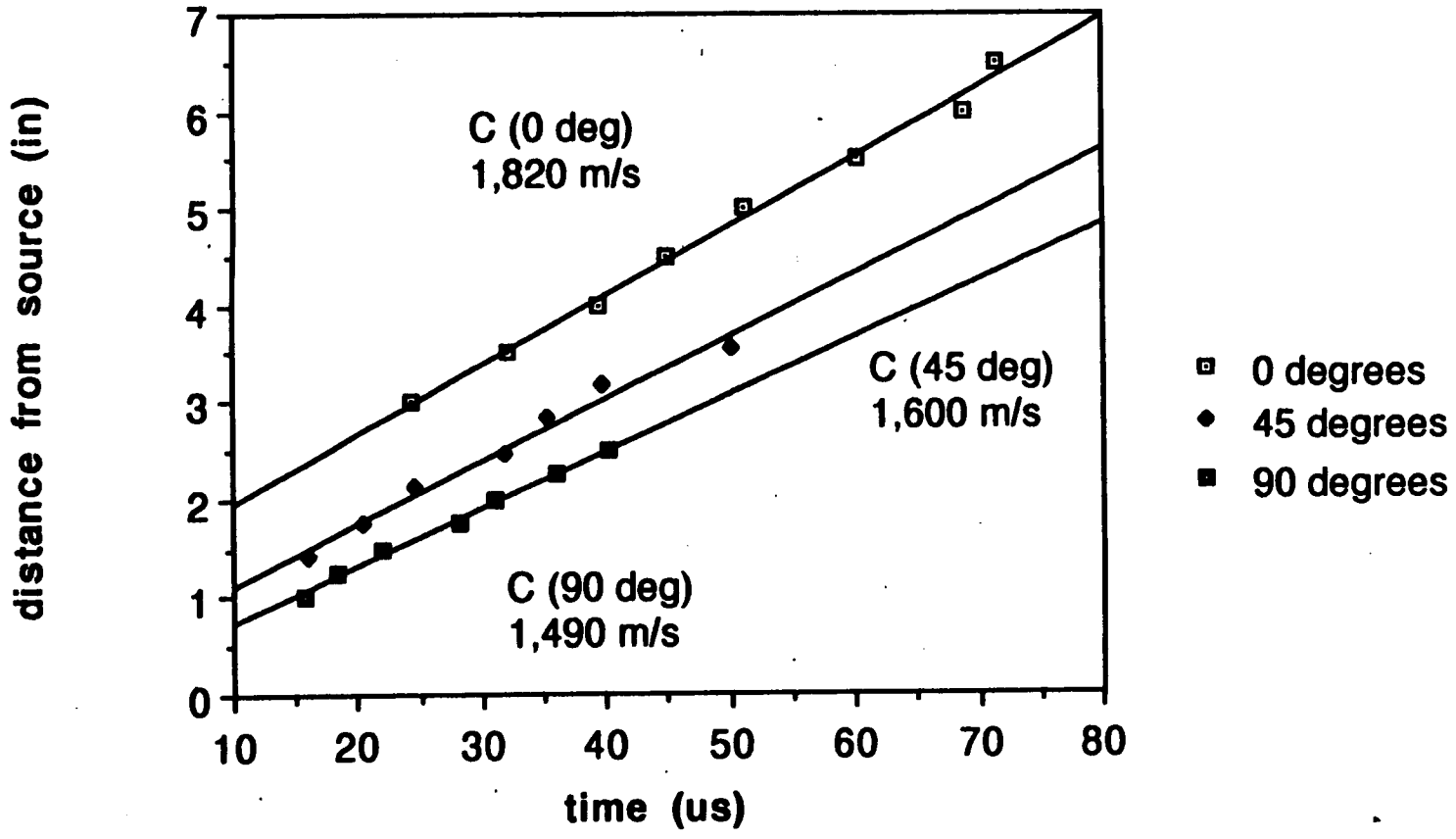



Main
Menu
Channel 1
-14 mV
Time 50.2 µs
Ch 1 .1 V ~
T/div 10 µs Ch 2 10 mV 50 Ω
Trig 2.00 V + EXT =

Extensional Wave Arrival Times



Flexural Wave Arrival Times



Extensional Wavespeeds

Theta	Classical Plate Theory (m/s)	Measured (m/s)
0°	8869	8300 ± 214
45°	5971	4000 ± 144
90°	2846	2700 ± 187

Flexural Wavespeeds

Theta	Classical Plate Theory (m/s)	Measured (m/s)
0°	5150	1820 ± 57
45°	4318	1600 ± 107
90°	2858	1490 ± 56

Conclusions

- Extensional and flexural wavespeeds can be accurately measured in composite tubes using simulated acoustic emmission

- Wavespeeds vary with fiber orientation

- Extensional wavespeeds can be predicted using Classical Plate Theory

- Flexural wavespeeds can not be predicted using Classical Plate Theory

N94-71019

Space Construction Requirements for Joining, Inspection, Development Testing, and Flight Check-Out

George W. Morgenthaler
Kendall M. Nii

Space construction poses new challenges not yet met in the space program to date: **New Materials:** High strength to weight ratio metal matrix composites and other kinds of composites have been developed. They have not been fully characterized as regards rolling, drilling, cutting, forming, joining, etc. **New Joining Methods:** Many types of joining methods are proposed for use in space construction. It is important to understand the key discriminators in choosing one method over another. Once the discriminators are known, one can rank the various methods of joining or connecting things in space. **New Constructors:** Astronauts frequently mention that EVA effort is very exhausting because of the suit inflexibility. For these reasons, as well as the inherent risk, hazards due to radiation and other concerns mentioned in the literature, it is likely that robot workers of various sorts will play a key role. Now one must consider the question of qualifying space joining methods that will be applied by robots as well as those being applied by humans. **New NDE Methods/Space Qualification of Detectors:** For every joining method that is used here on Earth, there are various non-destructive inspection techniques, such as ultrasonic inspection and x-ray inspection. It will be necessary to develop inspection techniques for all joining methods that will be approved for use in space. The detector must also me space qualified. **Development Testing:** As a new concept for space habitat goes through its conceptual phases, various development tests are anticipated for the first time. Some elements cannot be adequately tested except in space itself. How? **Flight Check-Out:** Assuming that one is assembling the Mars spacecraft in Earth orbit and that all of the preceding questions have been resolved, the day finally arrives when the fully assembled vehicle is ready for occupancy and journeying to Mars. It will be necessary to conduct a final flight readiness review, countdown procedure, and certification before the vehicle is permitted to depart for Mars with humans on board. When an error is found on Earth one can disassemble, go to a storeroom, pull a spare, or perform other readily available services to correct the anomaly. What and how shall we do this in space?

Space Construction Requirements for Joining, Inspection, Development Testing, and Flight Check-Out.

George W. Morgenthaler
Kendall M. Nii
Center for Space Construction, Systems Cluster

- SEI Missions will assemble/construct multiple payloads of subsystems and components.

- Construction must be developed for in-space use:
  - Joining
  - Inspection (NDE)
  - Development-Testing
  - Flight Check-Out
  - Diassemble and Repair

- These pose constraints on space construction and SEI mission architecture.

- Development of Apollo took 10 years; SSF will take 20+ years; to land on Mars by 2019 implies committing now to research.

- An overall Development and Test Philosophy (Facility?) is needed for space construction.

Space Construction Materials Lead Time

- Improvement Imperatives:
  - Higher termperature performance
  - Weight-reduction (15,000 lbs in Boeing 747)

- New Materials on the horizon:
  - Aluminum Lithium
  - Weldalite (6000 lbs saving in External Tank)
  - Metal Matrix composites
  - Non-metallic composites
  - XD alloys
  - Powder metallurgy
  - Inflatable materials

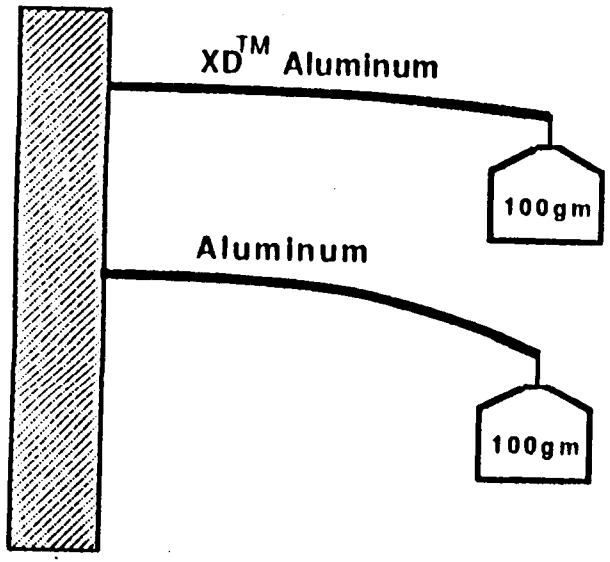
- Must Characterize and demonstrate for space-construction:
  - joining
  - heat-treat and processing
  - workability and forming
  - inspection
  - test programs

- Not available in repeatable, commercial quantities:
  - metal producer motivations
  - no standards
  - no certification procedures
  - no traceability

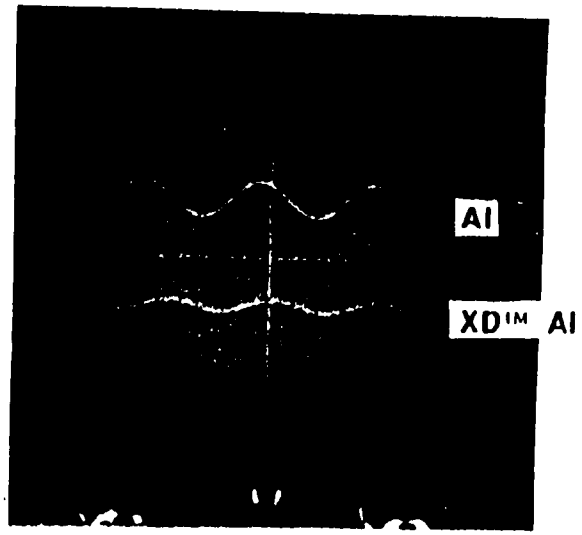
- Much work to be done

ALUMINUM BASED XD™ ALLOYS: DAMPING CHARACTERISTICS

TESTBED



OSCILLATION AMPLITUDE



RESULT

- XD™ ALLOYS SHOW INCREASED DAMPING CAPABILITY
- XD™ ALLOYS EXHIBIT HIGHER MODULUS

IMPLICATIONS

- REDUCED TIME
- REDUCED OSCILLATION FOLLOWING DISTURBANCE
- REDUCED DEFLECTION FOR GIVEN LOAD

MARTIN MARIETTA

Categories of Joining Methods

Adhesion

Bayonet

Bonding

- Weldbond
- Rollbond
- Explosively bond

Mechanical Fasteners

- Bolting/Turn Screws
- Clamping
- Riveting
- Snaps
- Threaded Joints
- Wire Ties

Swaging

- Explosive
- Mechanical

Welding

- Electron Beam
- Exothermic
- Explosive
- Laser
- Resistance
- Tungsten Inert Gas (TIG)
- Ultrasonic
- Brazing

General Information Database

A) Functional role of joint

B) Size and Mass of Equipment to make joint

C) Inspection/Test/Check-out procedure

D) Pros & cons of each method

Metric

	A	B	C	D	E	F	G	H
1		Purpose of	Quality of	Equipment	Tooling	Time to finish	Precision	External Force
2	Joining Method	Connector	Connection	Needed	Needed		Necessary	Necessary
3	Adhesion	S	B	1	10	10	10	2
4								
5	Bayonet -- SSF type	T	D	1	3	1	2	1
6								
7	Braizing -- Exothermic	B	B	8	10	7	9	1
8								
9	Mechanical -- Bolts	B	B	3	5	5	6	5
10	Mechanical -- Rivets	S	B	3	5	3	6	4
11	Mechanical -- Snap	S	D	1	3	1	2	1
12	Mechanical -- Threaded	B	B	1	6	5	6	5
13								
14	Swaging -- Explosive	B	D	2	10	1	8	1
15	Swaging -- Mechanical	B	D	2	4	1	6	6
16								
17	Weldbond	B	B	8	10			2
18								
19	Welding -- E-Beam	B	B	6	10	2	9	2
20	Welding -- Exothermic	B	B	6	10	2	8	1
21	Welding -- Explosive	B	B	3	10	2	10	1
22	Welding -- Laser	B	B	10	10	2	9	2
23	Welding -- Resistance	B	B	6	10	2	8	3
24	Welding -- TIG	B	B	6	10	2	8	2
25	Welding -- Ultrasonic	B	B	10	10	2	9	2
26								
27	Wire ties	S	D	1	2	3	1	1
28								
29	Legend:	(T)ension	(W)et or	1 - 10	1 - 10	1 - 10	1 - 10	1 - 10
30		(S)hear	(D)ry	1 = Little	1 = Little	1 = Little	1 = Little	1 = Little
31		(B)oth	(B)oth	10 = Much	10 = Much	10 = Much	10 = Much	10 = Much

Conclusions

Rules of Thumb

Use a well developed and mature technology

Use a simple method

Method of joining will depend heavily upon materials and the geometry

Design for modular assembly

Use pre-installed, and captured fasteners

Maximize commonality

Future Work

- More interaction with NASA and Industrial Associates
  - Experiment with explosive welding of metal matrix composites (characterize, evaluate using NDE, asses usage)
  - Discuss needs with designers
- Propose new methods
- Evolve NDE needs (perform survey)

Space Construction NDE Requirements

- Standard NDE Methods will need modification for space-use:

  - Working medium for ultrasonic methods?
  - Scarcity of gas supply for leak - tests?
  - Power supply needed for x-ray methods; shielding weight?
  - Insulate from space environment - e.g., thermographic methods
  - X-ray sources not adjustable - shielding?

- Need Miniaturization and Space Qualification of NDE Equipment

- Development of Standards for interpretation of NDE data

- Real-time interpretation of data mandatory during space-construction/assembly

- New techniques being developed:

  - laser interferrometry
  - holographic laser methods

Where/How Will Development-Testing Be Done?

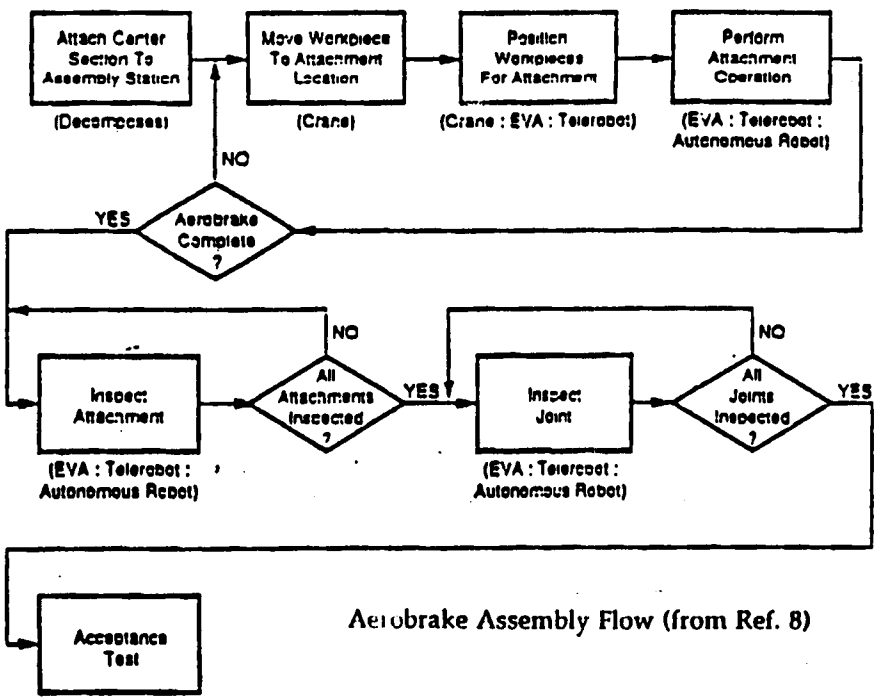
- Some structures too flimsy for Earth testing-chambers too small?
- Calibration and validity of Earth-based development tests?
  - environmental extremes?
  - representative times?
    (Example: LLNL sub-scale, Titan IV-delivered, inflatable Lunar base module.)
- Candidate locations:
  - Vicinity of SSF?
  - Separate On-Orbit Test Facility?
  - Lunar Test Facility?
- Collection of debris and return of test items to Earth?
- Development test philosophy; establish database; Use of AI Expert Systems.
- Trained test personnel?

Flight Readiness Check-Out and Certification

- Need comprehensive Test and Engineering Philosophy:

  - Shuttle Columbia hydrogen fuel leak
  - Commercial Titan III payload miscue
  - Hubble telescope flawed mirror problem

- Adapt Assembly Flow-Logic; pedigreed parts; component, sub-system, and system level tests.



Aerobrake Assembly Flow (from Ref. 8)

- Where do we disassemble and repair? Spares? Generic test equipment?

Conclusions

- Space construction constrained by space development - testing, NDE, and flight check-out

- NASA should accelerate research:

  - New materials for SEI
  - Joining methods
  - NDE methods
  - Development test philosophy and location
  - Flight check-out philosophy and location
  - Solution to in-space disassemble and repair problem

- Re-inspection/re-certification necessary due to materials degradation in space

- Development and certification of robotics joining techniques needed

omit
70 P541

Session Ten

CAE TOOLS FOR SPACE CONSTRUCTION

George W. Morgenthaler,
Chair

CAE Tools For Space Construction

Center for Space Construction
Thursday, October 18, 1:30 - 2:30 p.m.
George W. Morgenthaler, Chair (4min)

- The IDEAS**2 Computing Environment - Ugo Racheli, CSC (14min)
- DYCAM 1.0: A Tool to Enhance Constructability - Herb Schroeder, CSC (14min)
- DYCAM 2.0: An Expert System for Constructability Analysis - Steve Jolly, CSC (14min)
- On-Orbit Assembly Considerations of Manned Mars Transfer Vehicles: A Future DYCAM Application - Mark D'Amara, CSC (14min)

N94- 71020

The IDEAS**2 Computing Environment

Ugo Racheli

IDEAS**2 is the computing environment selected for system engineering (design and analysis) by the Center for Space Construction (CSC) at the University of Colorado (UCB). It is intended to support integration and analysis of any engineering system and at any level of development, from Pre-Phase A conceptual studies to fully mature Phase C/D projects.

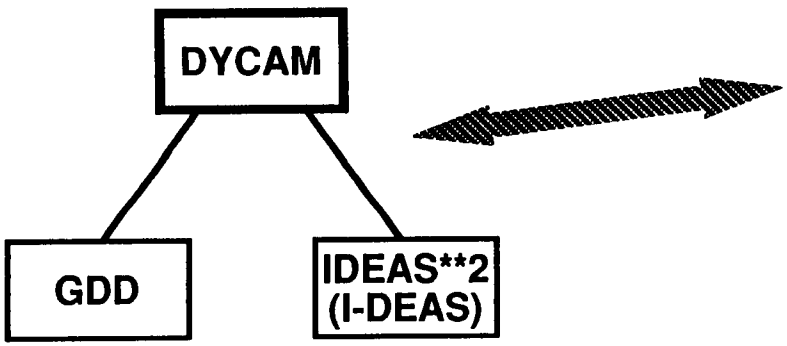
The University of Colorado (through the Center for Space Construction) has joined the Structural Dynamics Research Corporation (SDRC) University Consortium which makes available unlimited software licences for instructional purposes. In addition to providing the backbone for the implementation of the IDEAS**2 computing environment, I-DEAS can be used as a stand-alone product for undergraduate CAD/CAE instruction. Presently, SDRC is in the process of releasing I-DEAS level 5.0 which represents a substantial improvement in both the user interface and graphic processing capabilities.

IDEAS**2 will be immediately useful for a number of current programs within CSC (such as DYCAM and the "Interruptability Problem"). In the future, the following expansions of the basic IDEAS**2 program will be pursued, consistent with the overall objectives of the Center and of the College:

- Upgrade I-DEAS and IDEAS**2 to level 5.0.
- Create new analytical programs for applications not limited to orbital platforms.
- Research the semantic organization of engineering databases.
- Create an "Interoperability" testbed

PROGRAM	ACRONYM EXPLANATION	SOURCE
OL	ORBITAL LIFETIME	LaRC
ARCD	ARTICULATED RIGID-BODY CONTROL AND DYNAMICS	LaRC
ADASS		LaRC
ATTPRED	ATTITUDE PREDICTION	LaRC
SSPLIMP	SOURCE-FLOW PLUME IMPINGEMENT	JSC
SPASIS	SPACE SYSTEMS INTEGRATED SIMULATION	JSC
SDCM	SPACECRAFT DESIGN AND COST MODULE	
FRAME		SDRC
FATIGUE		SDRC
TDAS		SDRC
SYSTAN		SDRC
ADAMS		
NASTRAN		MSC
TRASYS	THERMAL RADIATION ANALYZER SYSTEM	JSC

DYCAM (DYnamic Construction Activities Model) is a database-driven Hypercard application designed to run on a Macintosh workstation. In order to run it needs an "executive" database (the GDD) and an analytical computing environment (IDEAS**2). Without the GDD, DYCAM will not run at all. Without IDEAS**2, DYCAM will not support the graphic representation of the objects listed in the GDD, nor perform any engineering analyses. It will however go through the selection of a construction scenario and an analysis of resource requirements.



The GDD (Global Database Directory) is a Hypercard document which drives the operation of DYCAM. There is only one DYCAM program, but every project must have its own GDD. Think of DYCAM as Microsoft Word and the GDDs as a Word documents.

IDEAS**2 runs on the VAX using the VMS operating system. In order for IDEAS**2 to be in the DYCAM loop, first the VAX must be connected to the Macintosh (presently through the RS 232 port), secondly there must be a set of files on the VAX that I-DEAS and IDEAS**2 can be operate on. Note that IDEAS**2 can operate in a standalone mode in term of graphics and analyses.

The CSCDC (Center for Space Construction Database Catalog) is a Hypercard stack that contains information relative to various projects/studies which have a bearing on the activities of the Center. It is intended as a general catalog of data, but it will specifically contain databases needed to support several programs developed by the Center, such as Interruptability, DYCAM, Vehicle Selection, Launch-on-time, and, eventually, SIMCON.
If the I-DEAS database is available (in the form of Universal files) then IDEAS**2 can be run on that project. If the GDD is available, construction planning can be done via DYCAM. If both are available, a full DYCAM run can be done, including graphics and engineering analyses.

CSCDC

CATEGORY	ITEM	CARD	GDD	I-DEAS
ET BASES	90 DAY STUDY	X	X	
	BOEING/SR STUDY	X		
	LLNL	X		
	LANGLEY	X		
ORBITAL PLATFORMS	SPACE STATION FREEDOM	X	X	X
	DUAL KEEL STATION			
	ATRIUM FACILITY			
LAUNCH VEHICLES	TITAN IV	X		
	ALS			
	SHUTTLE C	X		
	SHUTTLE Z			
ROBOTIC OPERATORS	FTS	X		
	RMS	X		
	FTS 1-G SIMULATOR			

NASA IDEAS

Interactive Design Evaluation of Advanced Spacecraft

- Multidisciplinary Spacecraft Analysis
- Truss Structure Synthesis
- Limited Graphics Support

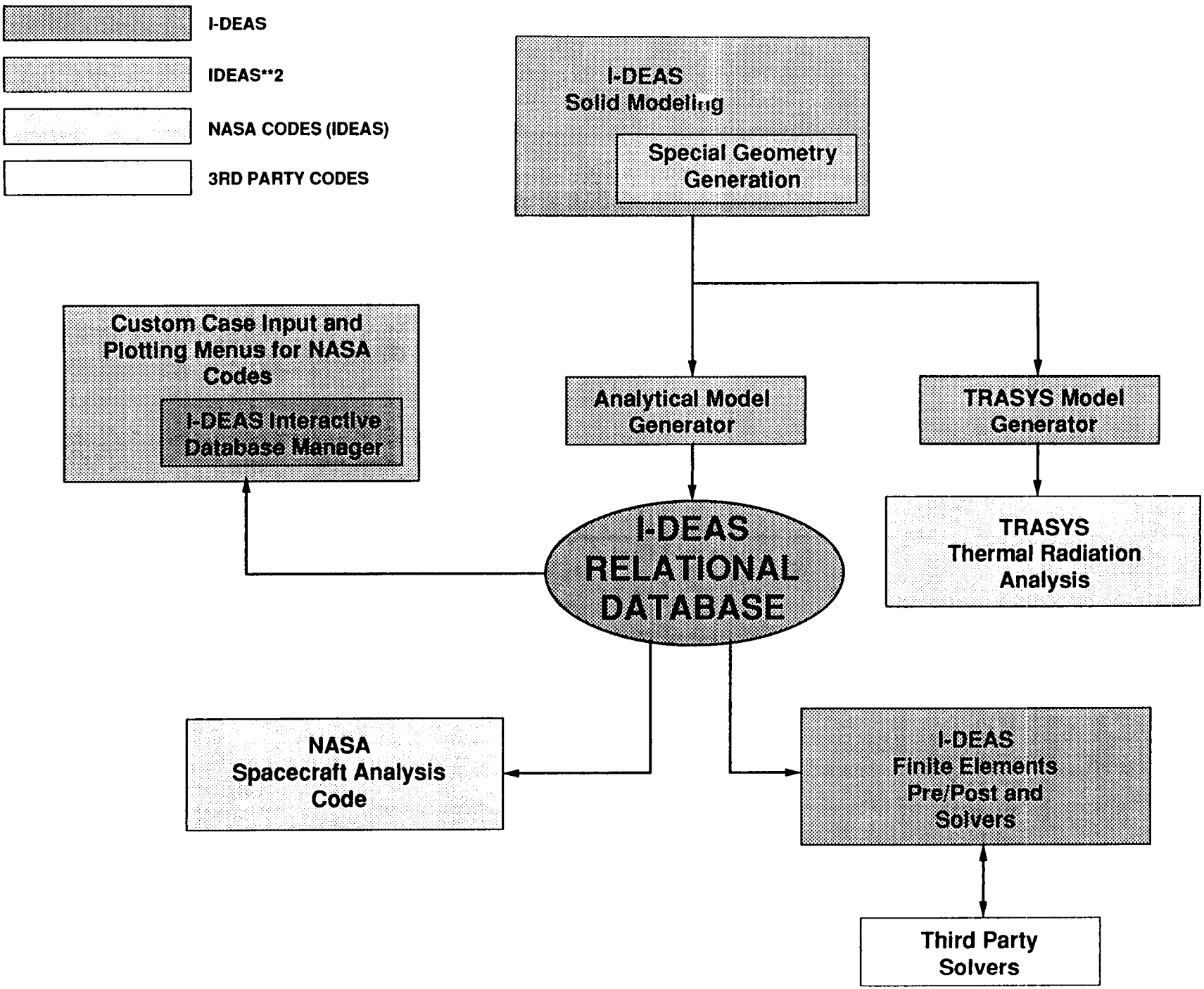
SDRC I-DEAS

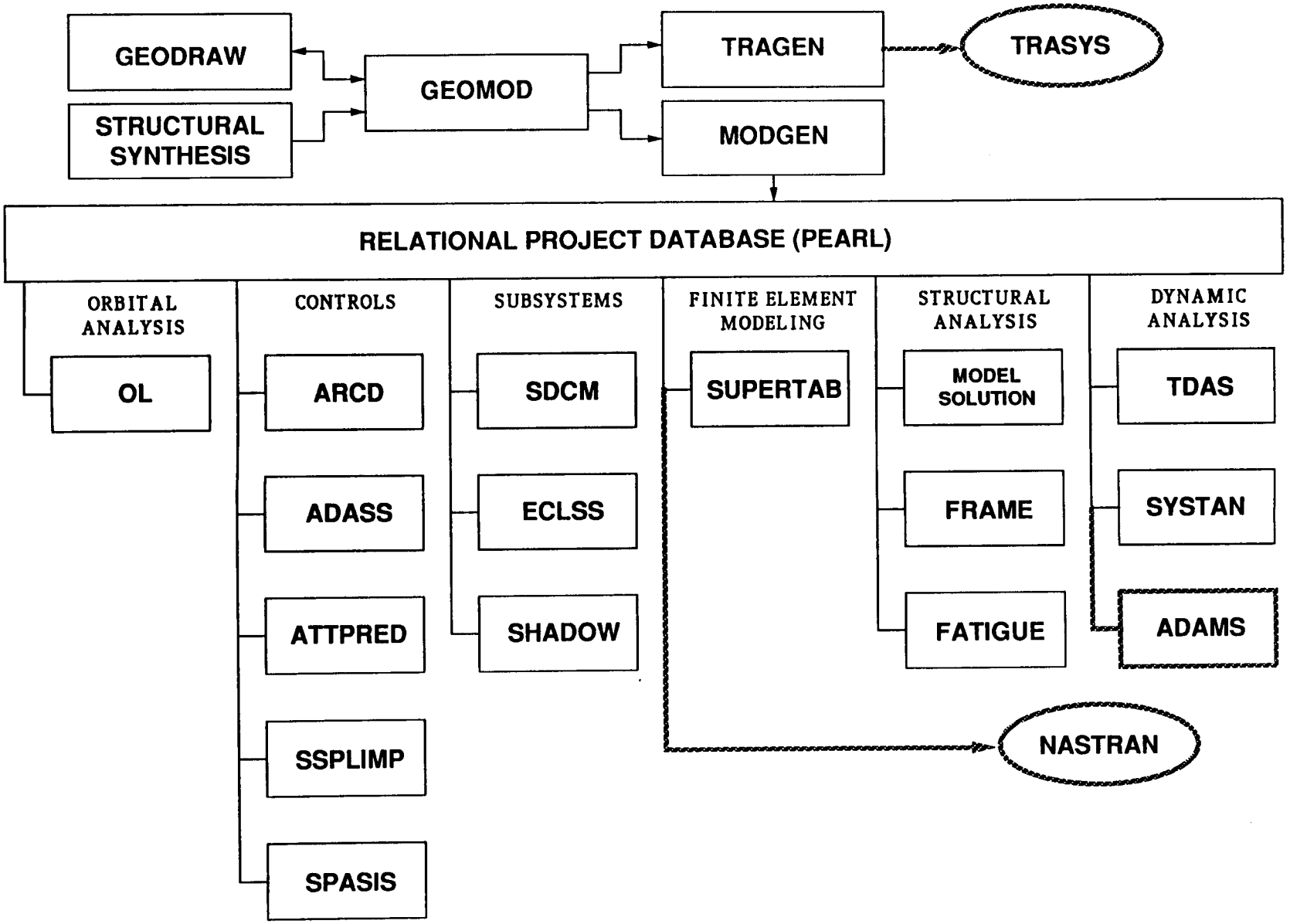
Integrated Design Engineering Analysis Software

- Interactive Graphics
- Solids and F.E. Modeling
- Relational Database
- Open Architecture

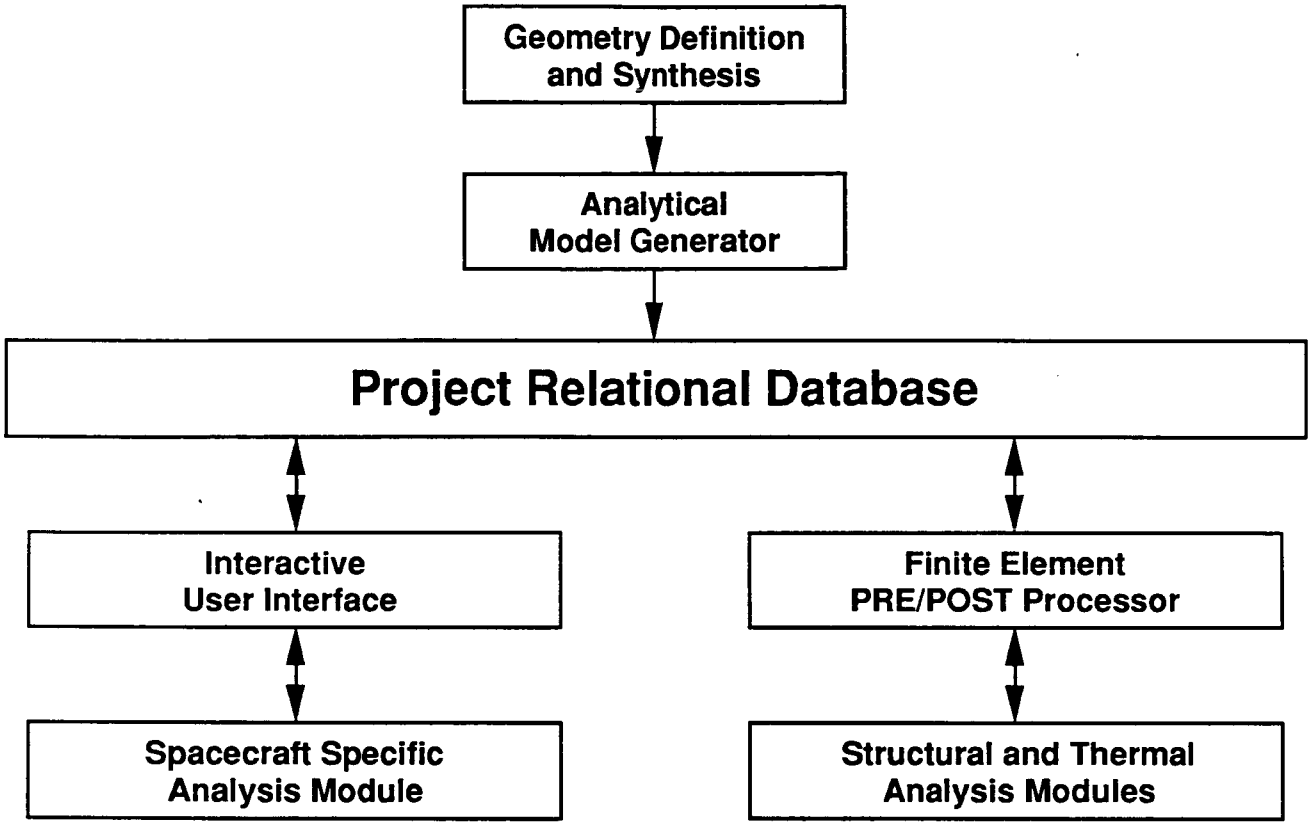
IDEAS**2

INTEGRATED, GRAPHICAL, INTERACTIVE ANALYTICAL TOOL


I-DEAS
IDEAS**2
NASA CODES (IDEAS)
3RD PARTY CODES
I-DEAS
Solid Modeling
Special Geometry
Generation
Custom Case Input and
Plotting Menus for NASA
Codes
I-DEAS Interactive
Database Manager
Analytical Model
Generator
TRASYS Model
Generator
I-DEAS
RELATIONAL
DATABASE
TRASYS
Thermal Radiation
Analysis
NASA
Spacecraft Analysis
Code
I-DEAS
Finite Elements
Pre/Post and
Solvers
Third Party
Solvers


GEODRAW
STRUCTURAL SYNTHESIS
GEOMOD
TRAGEN
MODGEN
TRASYS
RELATIONAL PROJECT DATABASE (PEARL)
ORBITAL ANALYSIS
OL
CONTROLS
ARCD
ADASS
ATTPRED
SSPLIMP
SPASIS
SUBSYSTEMS
SDCM
ECLSS
SHADOW
FINITE ELEMENT MODELING
SUPERTAB
NASTRAN
STRUCTURAL ANALYSIS
MODEL SOLUTION
FRAME
FATIGUE
DYNAMIC ANALYSIS
TDAS
SYSTAN
ADAMS

C-7


Geometry Definition and Synthesis
Analytical Model Generator
Project Relational Database
Interactive User Interface
Finite Element PRE/POST Processor
Spacecraft Specific Analysis Module
Structural and Thermal Analysis Modules

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p. 31

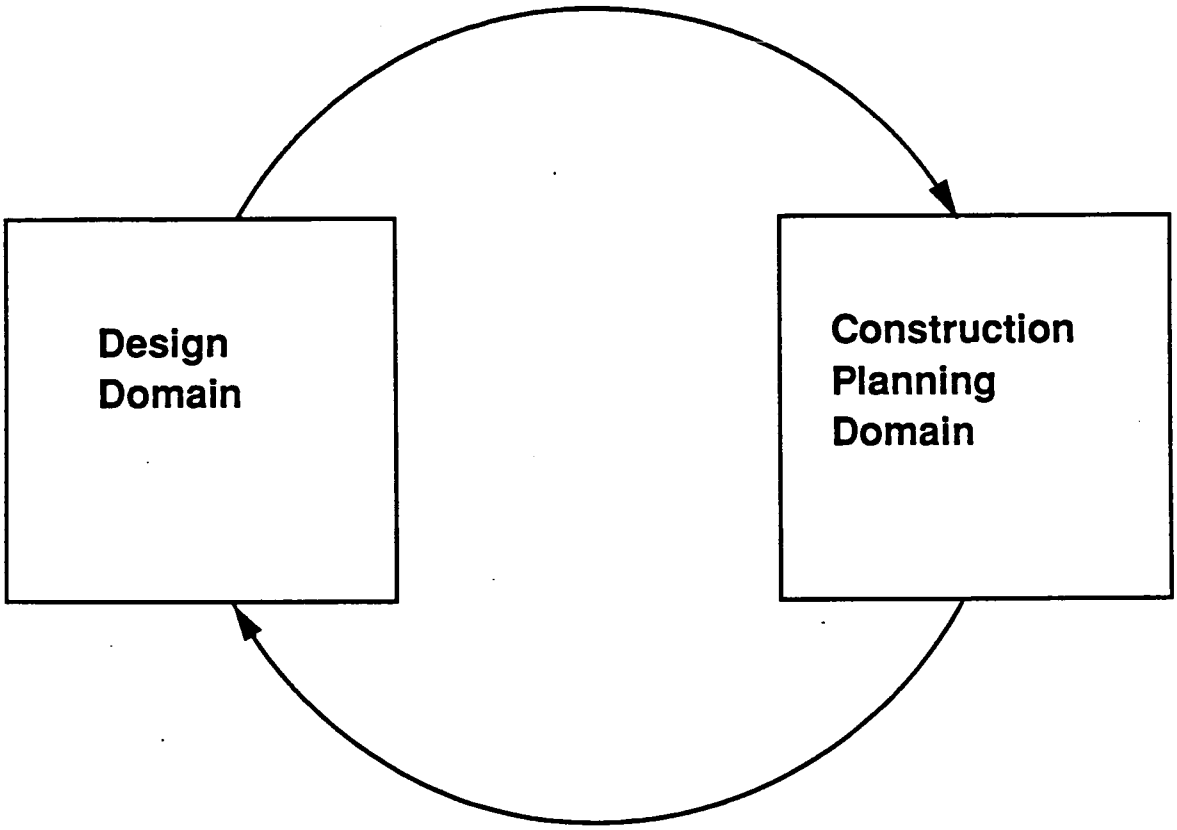
N94-71021

DYCAM 1.0 : A Tool to Enhance Constructability

Herb Schroeder

Those who plan the construction of large structures in space are presented with new challenges imposed by the constraints involved in such an operation. These constraints include those imposed by the assembly sequence itself, the available resources of time, money, manpower, equipment and material, and finally those constraints imposed by the physical nature of the environment. Design decisions ultimately affect the construction effort and inherent construction constraints affect the design. To enhance the constructability of these structures is important that the project planners be equipped with computer tools which will allow a rapid iterative analysis of many possible scenario for design and construction. DYCAM 1.0 provides the user with a computer tool to aid in the evaluation of Pre-Phase A and Phase A conceptual system designs and the identification of feasible construction scenario for these designs assuming various types and levels of construction technologies. The DYCAM 1.0 model interacts with a NASA utilized, commercially available computer model for conceptual system design, called IDEAS**2. DYCAM 1.0 incorporates the consideration of construction constraints as specified by the mission planner/system designer. This permits iteration of the system design with various construction sequences suggested by the user. The DYCAM 1.0 test case evaluates various construction sequences using IDEAS**2 data for the configuration of Space Station Freedom after two assembly flights..

Design and Construction Planning is an Iterative Process

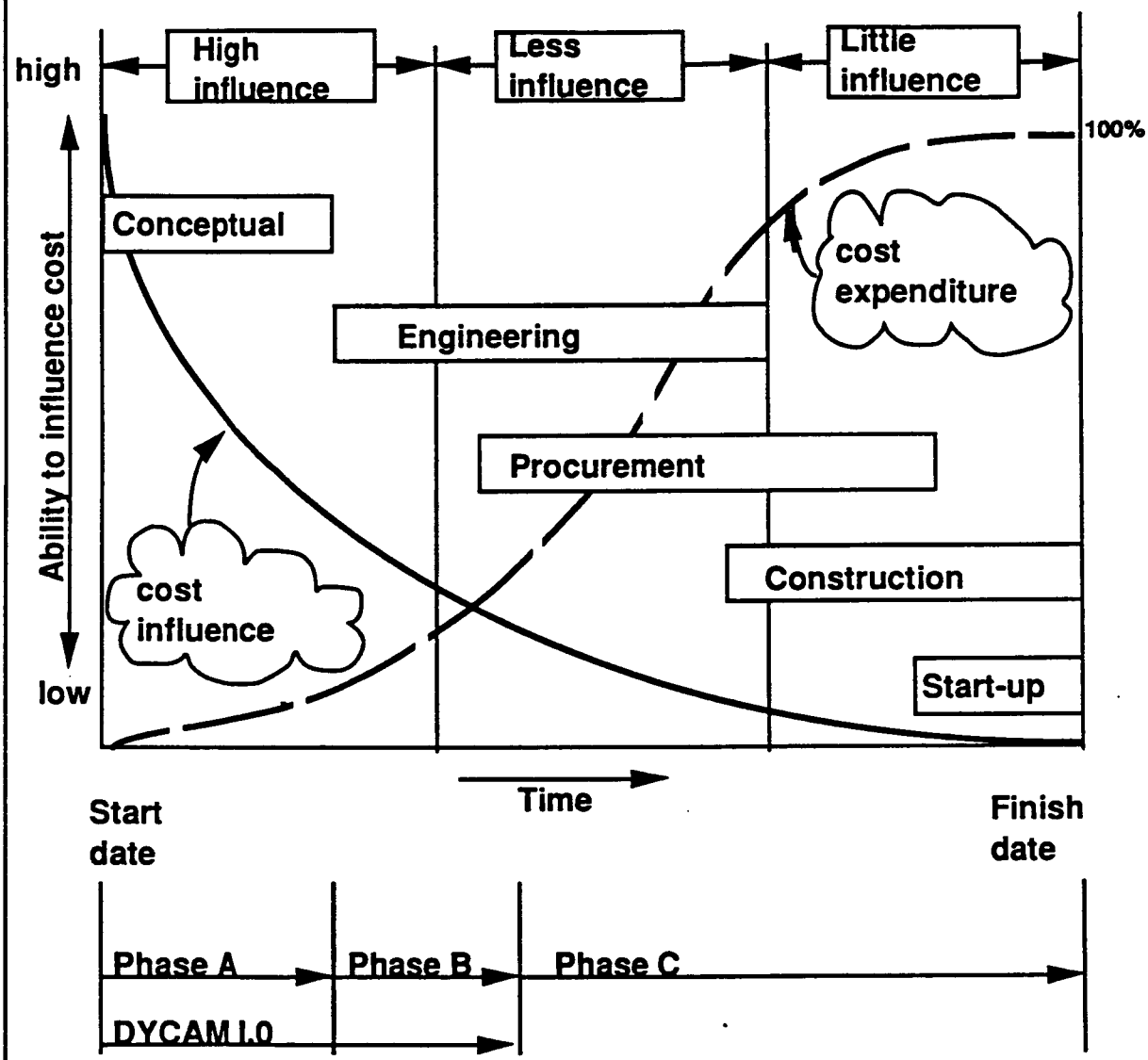


Decisions in design affect the assembly plan

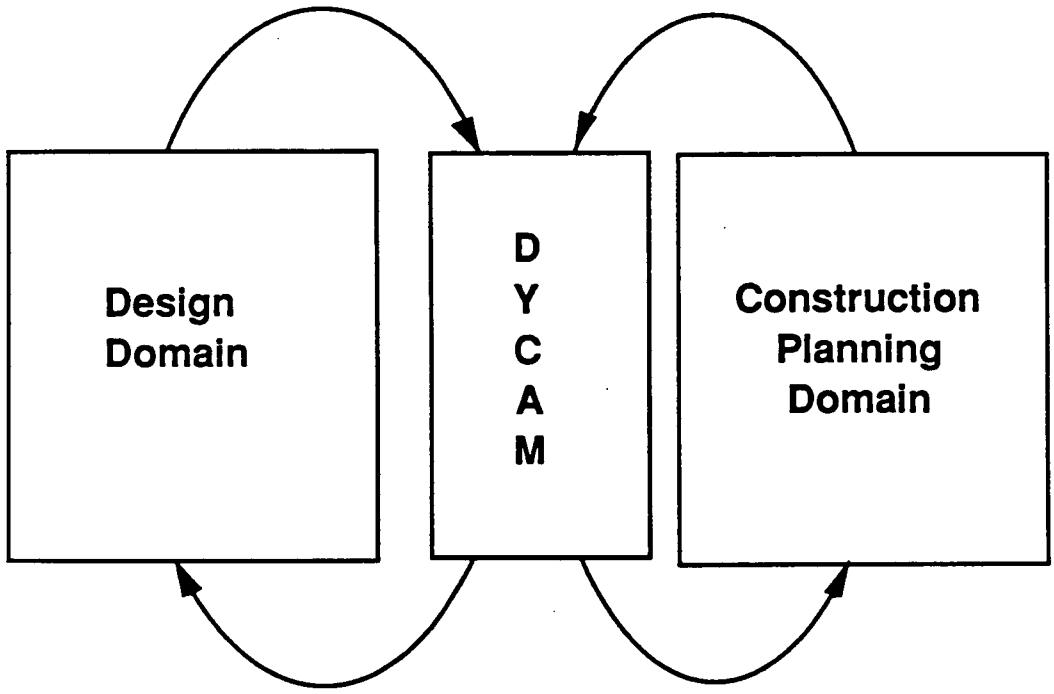
Inherent construction constraints affect the design

Iterations become ever more complicated as the design and assembly plans become more complex

Ability To Influence Cost Over the Life of a Project



DYCAM is a complexity manager



DYCAM Goals

1. Build a generic tool.

2. Graphically display the structure under consideration at any point in the construction stream.

3. Generate feasible construction sequences based on:

a. available resources
b. engineering data

Construction Constraints

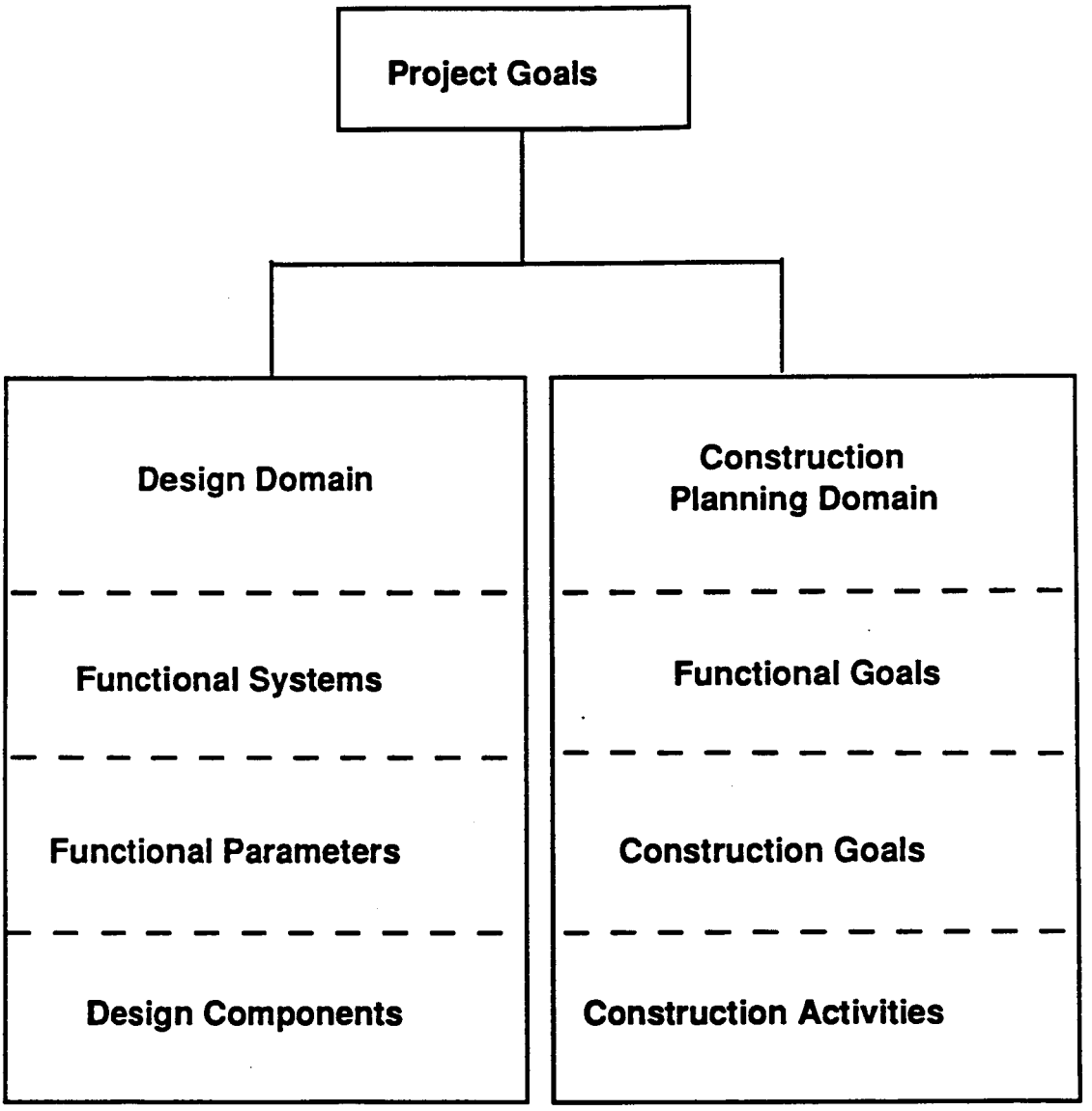
Construction activities are governed by certain constraints which can be grouped as follows:

1. Sequence dependent, i.e., is it logical?

2. Resource permitted, i.e., is it possible with the resources we have available?
   a. time
   b. money
   c. manpower: Astronauts available
   d. equipment: Tools, Telerobots
   e. material: Electric power

3. Mechanics feasible, i.e., will the physics let us do what we are planning?
   a. structural analysis
   b. dynamic analysis
   c. orbital lifetime
   d. control and stability
   e. thermal analysis
   f. etc.

Relationship of Project Goals to the Design and Construction Planning Domain



The System

Construction Planning Domain:

Macintosh IIci
Project Management Software

Construction Feasibility:

Macintosh IIci
DYCAM Software (Supercard)

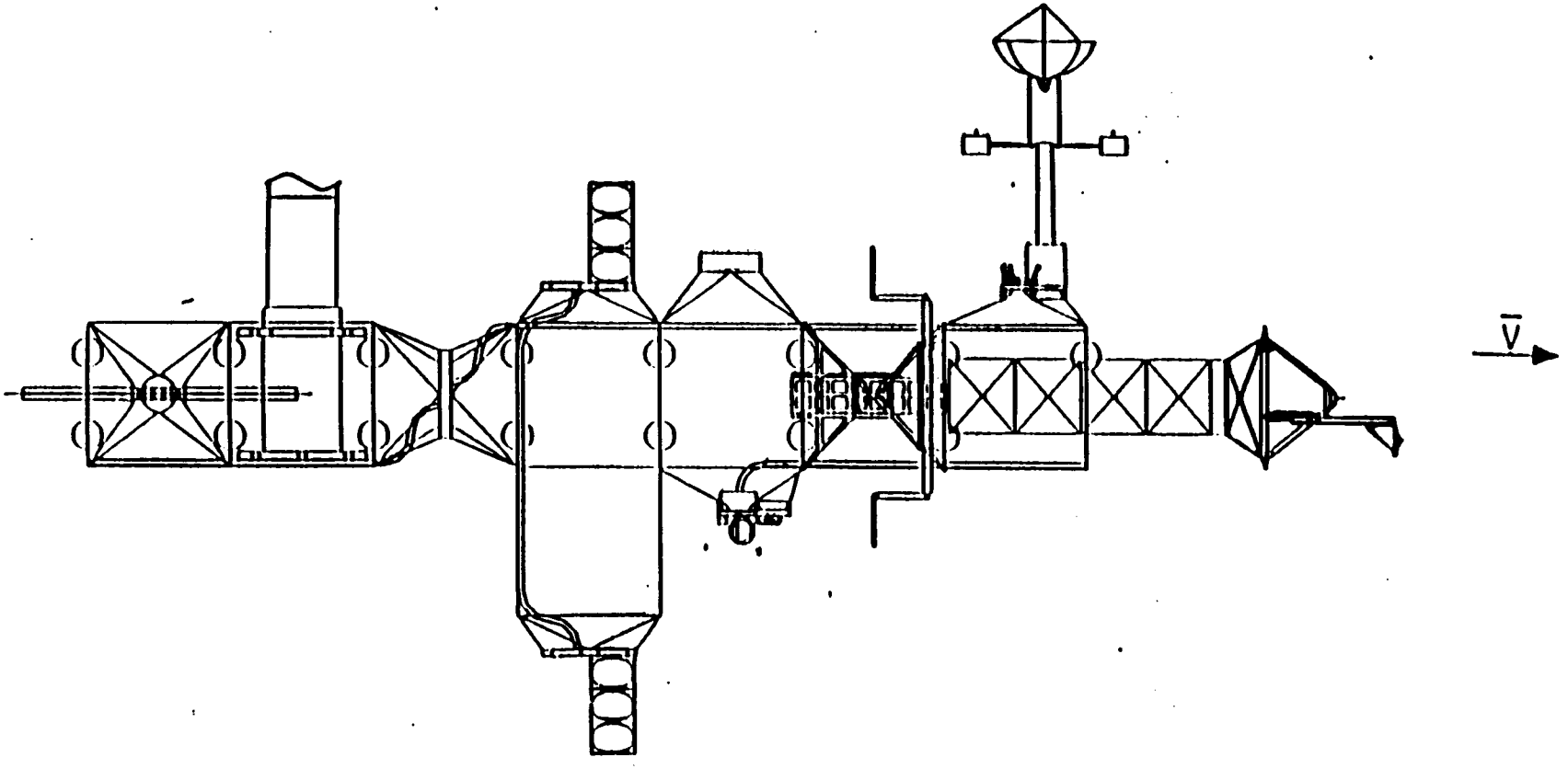
Design Domain:

VAXstation 3100
Ideas**2 software

PDR PLANNING BASELINE FLIGHT ORIENTATION
MB-2

DURING

* ASSEMBLY
* FREE FLIGHT
* DOCKING



The Test Case

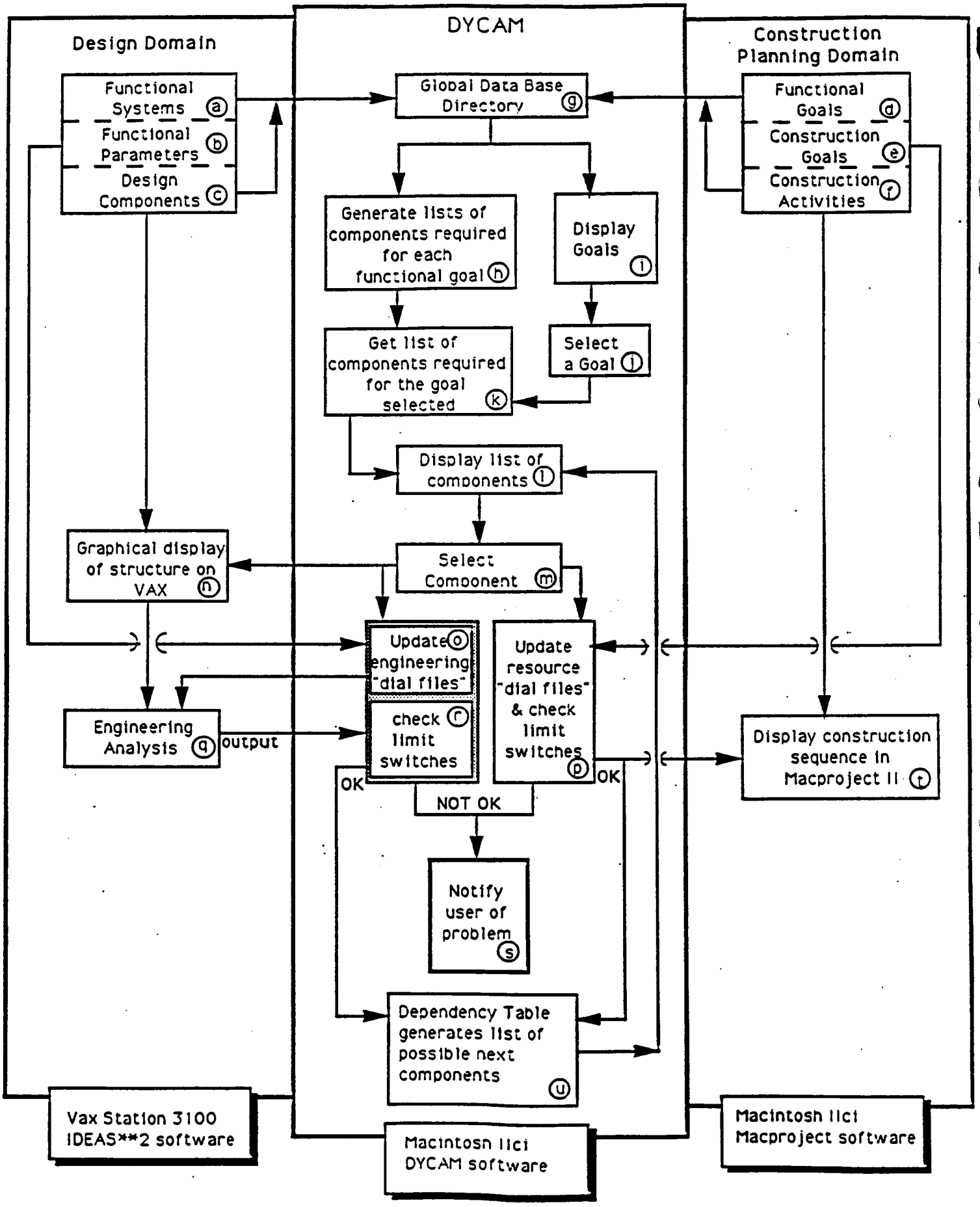
1. Install the assembly sequence for configuration MB-2 of Space Station Freedom.

2. Graphically display the structure at each activity junction.

3. Engineering: do articulated rigid body dynamics and orbital lifetime at each activity junction.

4. Construction: do resource analysis on time, manpower, equipment and material.

Domains Interfaces in DYCAM



DYCAM
DYnamic Construction Activity Model
System Level

Select a project by clicking on the appropriate box:

- Space Station Freedom
- Lunar Base A
- Mars Spacecraft Construction
- Lunar Cycler Construction
- Mars Cycler Construction
- Mars Aerobrake Construction
- Polar Platform

Quit

DYCAM

DYnamic Construction Activity Model

Project Level

Space Station Freedom

Select an operation by clicking on the appropriate box:

Construction Planning

Data Management

Quit

DYCAM

DYnamic Construction Activity Model

Data Management
Space Station Freedom

Select an operation by clicking the appropriate box:

Dial File Maintenance

Global Data Base Maintenance

Quit

DYCAM
DYnamic Construction Activity Model

Data Management
Dial File Maintenance

Move the arrow over a field and click once to edit the field

Resource	Limit Switch Information	
	Maximum Expenditure Available/Mission	Maximum Units Avail./Mission
EVA	10	1
RMS	10	1
FTS	10	1
AWP	10	1
SPDM	10	1

Quit

DYCAM

DYnamic Construction Activity Model

Data Management

Global Data Base Maintenance

Select an operation by clicking the appropriate button:

- Dependency Table
- Functional Systems
- Functional Goals
- Work Activities
- Functional Allocation Matrix

Quit

DYCAM

DYnamic Construction Activity Model

Data Management
Dependency Table

Double click on a component, select predecessor or connector, then double click on the predecessor/connector component to select:

Components

alpha joint
assembly work platfo
beta joint
end truss bay
solar panel 1
solar panel 2
truss bay 2
truss bay 3
truss bay 4
solar panel 3
beta joint 1

beta joint

Predecessors

end truss bay

Connectors

solar panel 1

Predecessor Components

alpha joint
assembly work platfo
beta joint
end truss bay
solar panel 1
solar panel 2
truss bay 2
truss bay 3
truss bay 4
solar panel 3
beta joint 1

Delete Predecessor or Connector

Quit

DYCAM

DYnamic Construction Activity Model

Data Management

Functional Allocation Matrix

Double click on a component then double click on a functional system or goal to select:

Components

alpha joint
assembly work platform
beta joint
end truss bay
solar panel 1
solar panel 2
truss bay 2
truss bay 3
truss bay 4
solar panel 3
beta joint 1

solar panel 1

Delete Functional Relationship

Functional Systems

solar power
active attitude control
structural
life support system
utilities

utilities

Functional Goals

manned habitation
attitude control
solar power generation

solar power generation

Quit

DYCAM

DYnamic Construction Activity Model

Data Management
Functional Systems

Type in a new functional system: [ ] OK to add

Select a functional system to edit or delete:

Functional Systems

solar power
active attitude control
structural
life support system
utilities

Delete

Quit

DYCAM

DYnamic Construction Activity Model

Data Management
Functional Goals

Type in a new functional goal:

OK to add

Select a functional goal to edit or delete:

Functional Goals

manned habitation
attitude control
solar power generation

Delete

Quit

DYCAM

DYnamic Construction Activity Model

Data Management
Work Activities

Select a component, the resources necessary, and the duration to install it:

Components
alpha joint
assembly work platform
beta joint
end truss bay
solar panel 1
solar panel 2
truss bay 2
truss bay 3
truss bay 4
solar panel 3
beta joint 1

Resources
EVA
RMS
FTS
AWP
SPDM

Duration:

OK

assembly work

RESOURCE	DURATION

Quit

DYCAM

DYnamic Construction Activity Model

Construction Planning
Functional Goals

Double click on a functional goal to get a list of the components available for installation:

Functional Goals

manned habitation
attitude control
solar power generation

Quit

DYCAM

DYnamic Construction Activity Model

Construction Planning

Functional Goal Components

Functional Goal: solar power generation

Make a selection by doubleclicking on the component:

Components	Resources				
	EVA	RMS	FTS	AWP	SPDM
truss bay 3	1	1	1	1	1
truss bay 2	1	1	1	1	1
end truss bay	1	2	3	4	5
alpha joint	3	5	5	5	5
truss bay 4	4	4	4	4	4

Resources available:					
Resources used:					

select a component

Select A New Functional Goal

Engineering Analysis

Quit

DYCAM

DYnamic Construction Activity Model

Construction Planning

Functional Goal Components

Functional Goal: solar power generation

Make a selection by doubleclicking on the component:

Components	Resources				
	EVA	RMS	FTS	AWP	SPDM
beta joint	1	1	1	1	1
beta joint 1	6	1	1	1	1
alpha joint	3	5	5	5	5

Resources available:	9	8	7	6	5
Resources used:	1	2	3	4	5

select a component

Select A New Functional Goal

Engineering Analysis

Quit

DYCAM

DYnamic Construction Activity Model

Construction Planning

Functional Goal Components

Functional Goal: solar power generation

Make a selection by doubleclicking on the component:

Components	Resources				
	EVA	RMS	FTS	AWP	SPDM
beta joint	1	1	1	1	1
alpha joint	3	5	5	5	5
solar panel 2	1	1	1	1	1

Resources available:	3	7	6	5	4
Resources used:	7	3	4	5	6

select a component

Select A New Functional Goal

Engineering Analysis

Quit

DYCAM

DYnamic Construction Activity Model

Construction Planning
Engineering Analysis

Select an analytical program:

- Articulated Rigid Body Control Dynamics
- Orbital Lifetime
- Attitude Predict
- Plume Impingement

Quit

DYCAM
DYnamic Construction Activity Model

Component Name:	truss bay 3
Component ID #:	
Mass:	
Shipping Volume:	
Shipping weight:	
Activity Duration:	

Resource	Duration
EVA	1
RMS	1
FTS	1
AWP	1
SPDM	1

Functional Systems

structural

Predecessor Components

Functional Goals

manned habitation
attitude control
solar power generation

Successor Components

truss bay 4
truss bay 2

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DYCAM 2.0: AN EXPERT SYSTEM FOR CONSTRUCTABILITY ANALYSIS

by Steve Jolly†

This presentation†† represents the first effort at defining the successor to DYCAM 1.0 which is the Center for Space Construction's Dynamic Construction Activities Model, Version 1.0. Version 1.0 is currently nearing the completion of its development phase, and now that its capabilities can be discerned, it is possible to envision the next step in Computer Aided Engineering Constructability Analysis tools. The presentation is a discussion of the "wish list" for future DYCAM versions, tempered by the very difficult reality, yet at the same time intrigued by the importance of modeling the Space Construction problems. This discussion of DYCAM 2.0's proposed capabilities remains a "living document" in that on-going research by the author and others may cause changes to the approach as well as to the architecture of Version 1.0. Similarly, as CSC gains experience with Version 1.0, one would expect to gain insight as to the positives and negatives of its general construction planning approach.

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††Discussed in detail in both CSC Systems Report #19 and CSC Systems Cluster Technical Note #68

DYCAM 2.0 :

AN EXPERT SYSTEM FOR CONSTRUCTABILITY ANALYSIS

CSC Systems Cluster
by Steve Jolly

10/19/90
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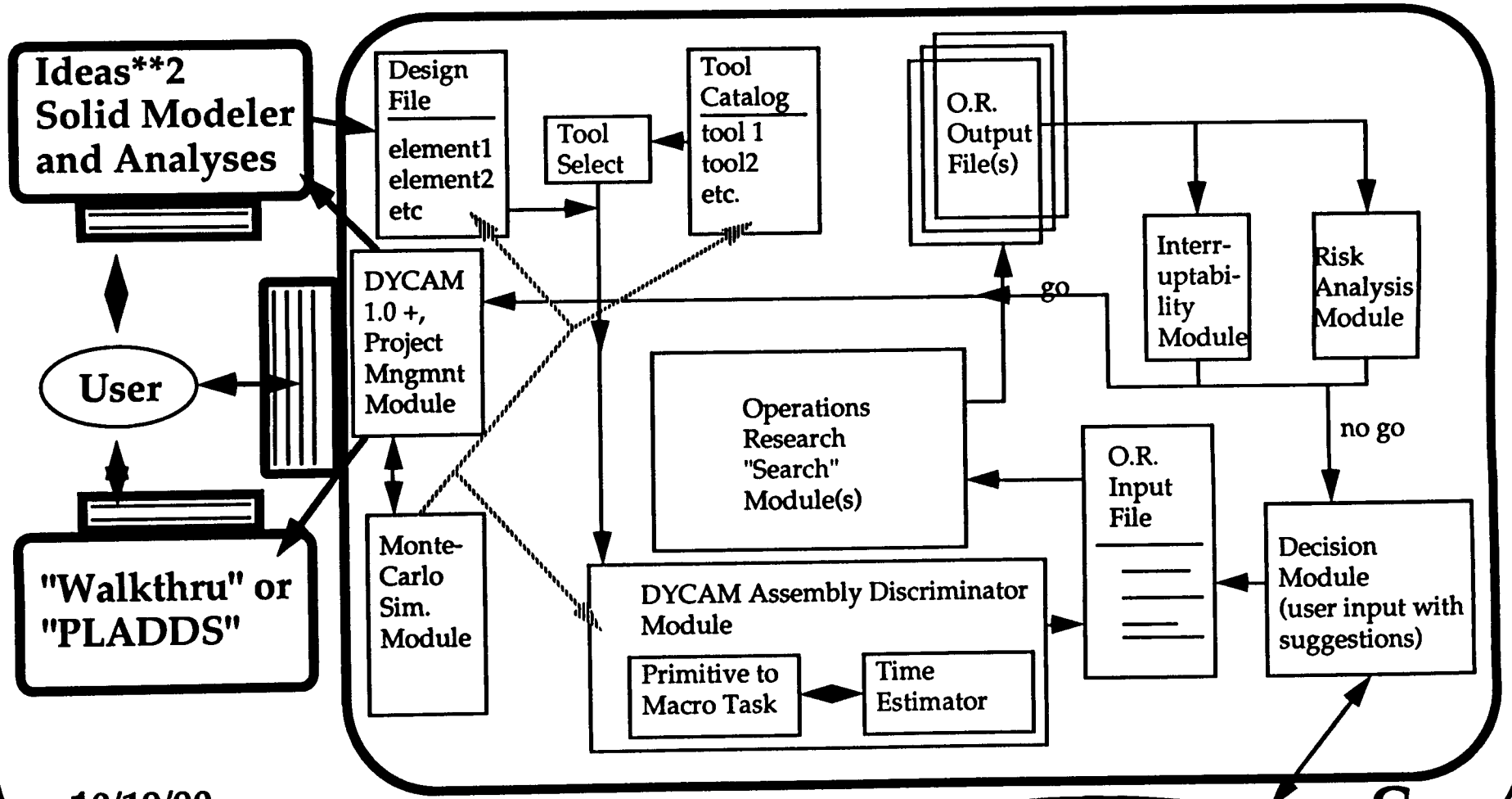
DYCAM Project Objectives Revisited

- **DYCAM is now and will continue to be** an engineering tool which enables the constructability analysis of many different mission designs by a single user. This analysis data can aid the user in decision making in the face of uncertainty and in the world of ever changing or ill defined top level (0.0) requirements.
- **DYCAM is targeted at** Phase A and pre- Phase A conceptual designs. Therefore it must be capable of operating in a domain where incomplete information and only high order definition prevail.
- **DYCAM should enhance, aid and preserve** what is best in humans and what is best in computational machines. For humans this is creativity and intuition, for computers this means modeling, analysis and relational database management.
- **Each evolutionary version of DYCAM should** strive to increase the number and quality of options available in the DYCAM interactive user environment such that each employ, as is possible, state-of-the-art analyses techniques. Thus the user is provided with new and increasingly better measures and indicators (through new DYCAM modules and peripherals), which can only serve to stimulate the intuitive process.

The Ultimate DYCAM Might Look Like:



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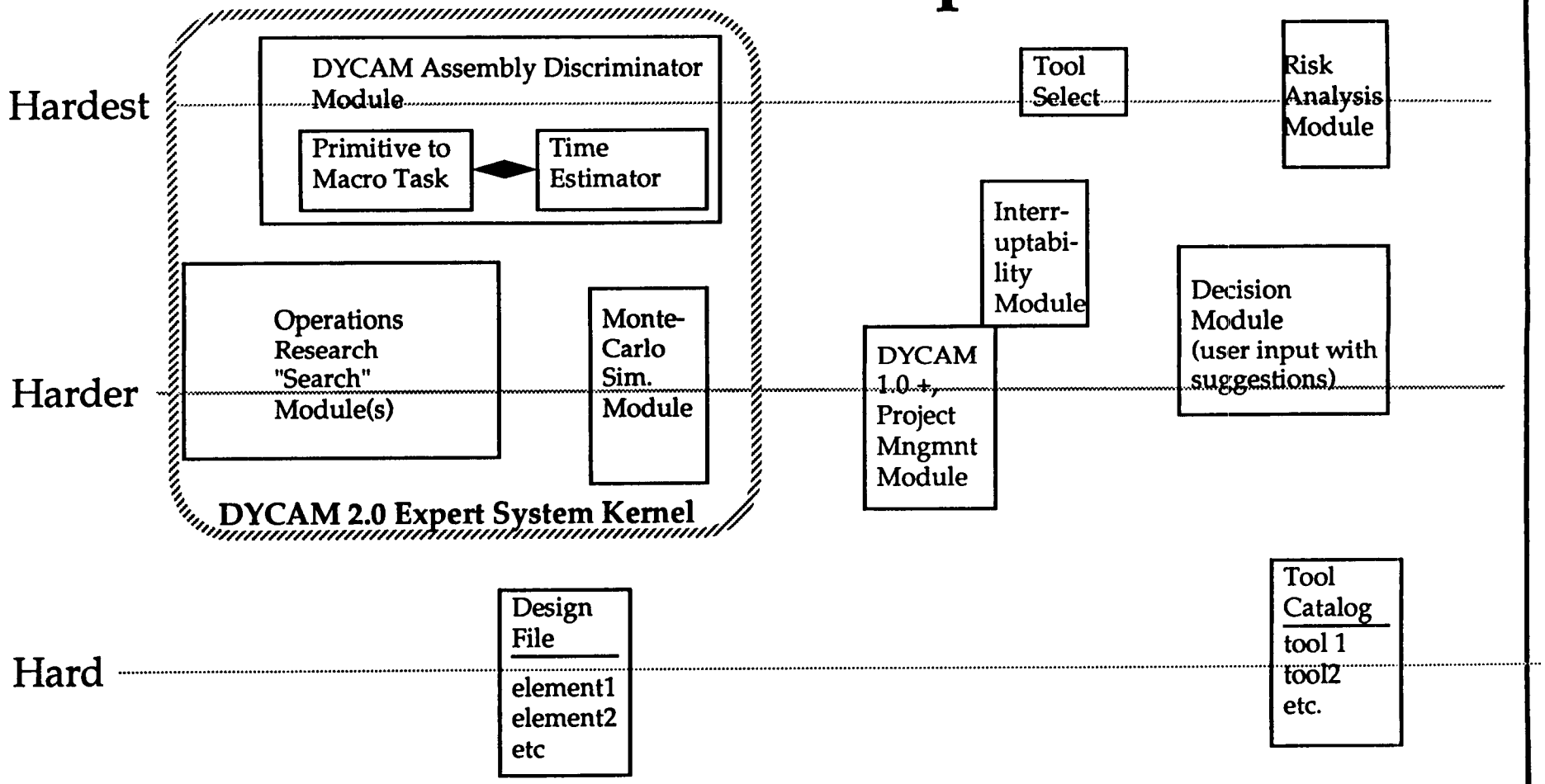
Scoping It Out, What Elements Appear Hardest to accomplish?



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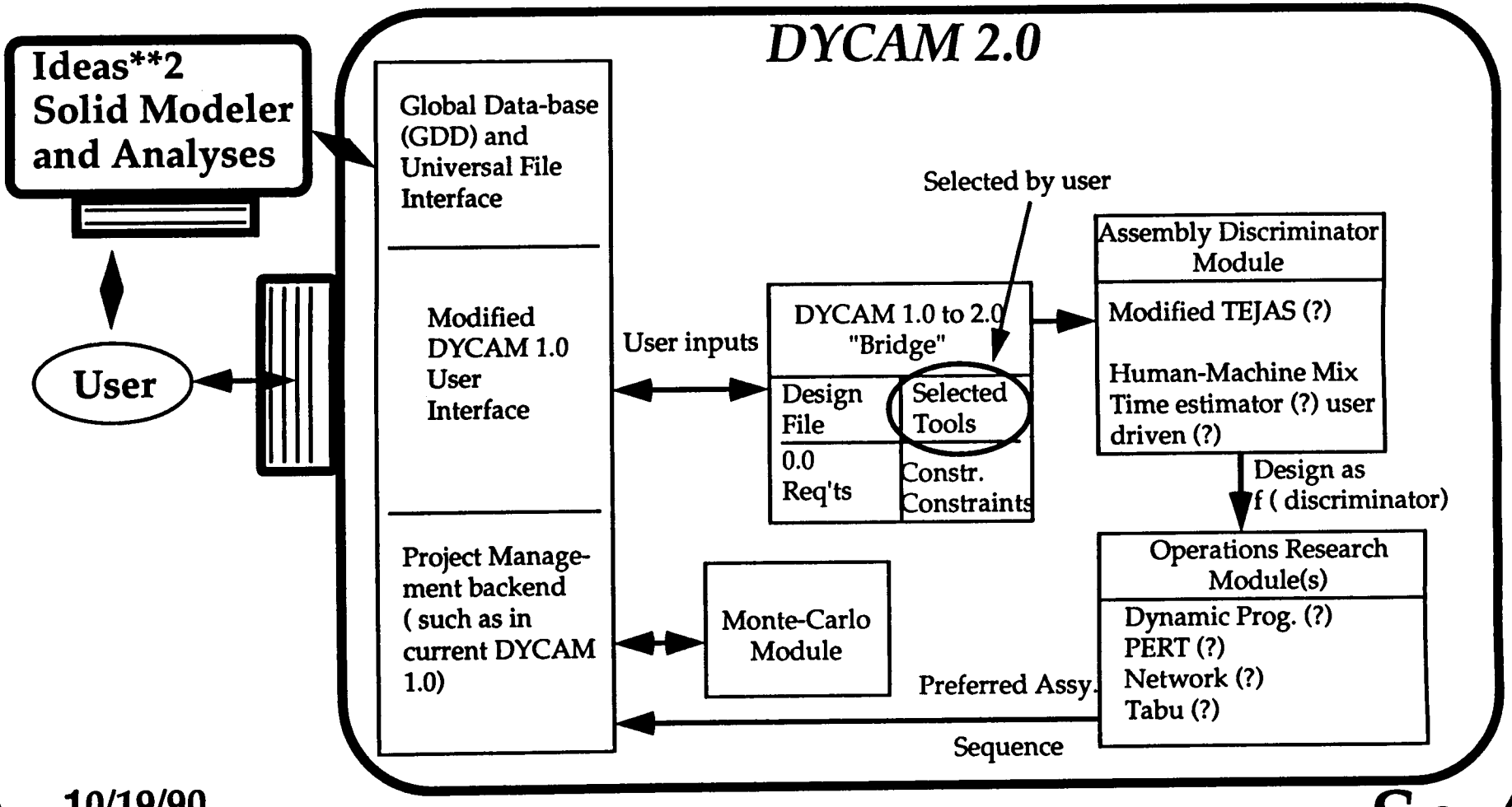
Proposed Reality



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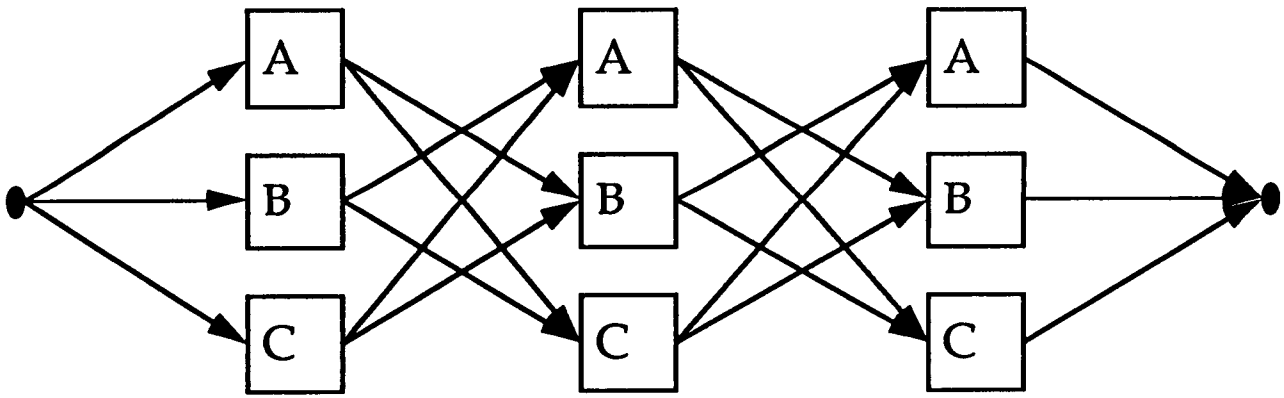
The Problem, Assembly Sequence Generation

° How does one distinguish between any two different assembly sequences ?



° What elemental discriminator(s) allow such distinctions , what are they ? What if we have "complete knowledge", i.e. Phase B/C design, what would a planner do? What would he use ?

If the Paths Between Nodes *Have* values that Differ from Each Other then:

- There exists state-of-the-art Operations Research algorithms and techniques which can illuminate the "preferred" feasible sequence among a set of feasible sequences - even for combinatorially explosive problems like those that exist in construction. Some candidates are:

  Dynamic Programming Approaches

  Tabu Search

  Generalized Network Models

  Synthetic Algorithms

- Monte-Carlo simulations, then, are also possible in a variety of approaches to assist in uncovering the sensitivities of both the design and in the construction of the design - including the study of the human-machine constructor mix.

Summary

- **Serious research** on DYCAM 2.0 is just beginning, but CSC is very optimistic about the outcome, particularly because of the recent success with DYCAM 1.0.

- **DYCAM 2.0 must be bounded** in such a way that appropriate, heavy focus can be carried otu on the really difficult challenges (the so-called Kernel), i.e. DYCAM 2.0 cannot be the "Ultimate DYCAM", but by making reasonable, stated assumptions and proceeding forward it could represent a productive, useful, large step in the right direction.

- **DYCAM 2.0 will not** "optimize" the solution or the design, but rather, it will use some "elegant" methods to provide the user with a more sophisticated and versatile computer aided engineering tool to assist in decision analysis.

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On-Orbit Assembly Considerations of Manned Mars Transfer Vehicles

Mark D'Amara

Ever since the United States space program started some forty years ago, there have been many ideas on how the U.S. should proceed to explore space. Throughout the years, many innovative designs have surfaced for transfer vehicles, space stations, and surface bases. Usually the difference in designs are due to differences in mission objectives and requirements.

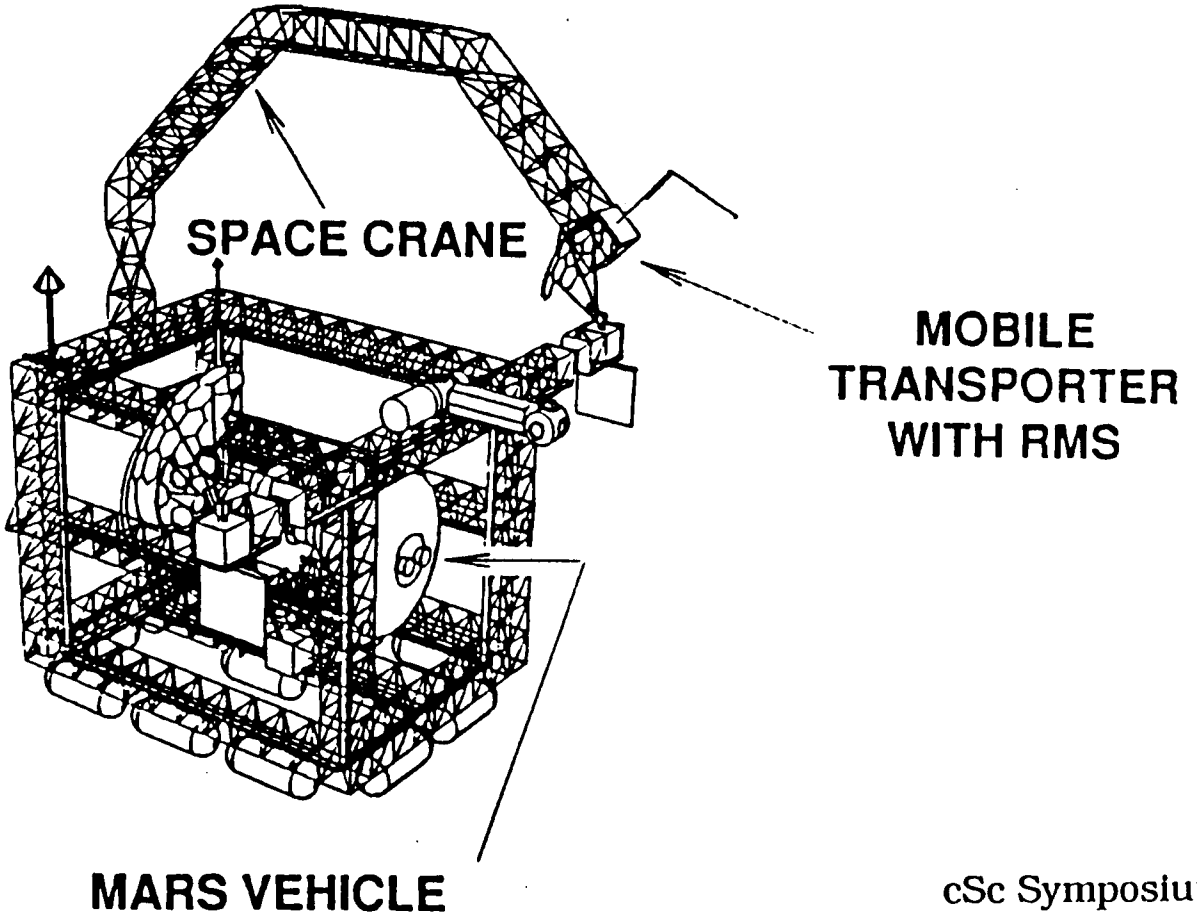
The problem for Mars is how to choose an architecture for human travel to Mars and what kind of base construction to design for Mars that will be reliable and cost-effective. Eventually, if the Space Exploration Initiative is to become a reality, NASA will have to select and fund a single mission architecture involving manned and unmanned Mars fly-by pre-cursors, a Mars landing vehicle, and, ultimately, the plan for constructing a Mars base. The decision to commit to a single architecture is a vital one and, therefore, the design issues, the decision-making process, and the analysis tools must be available to explore all of the options that are available.

A large part of any space mission architecture is the Earth-to-Mars transfer vehicle. The decision on the type of transfer vehicle to design is a crucial one. The many options must take into account the constraints encountered when assembling the vehicle in Earth-Orbit such as effective joining methods, test and evaluation methods, preventative maintenance measures, etc. Therefore, the process of trading off various designs must include every facet of that design. The on-orbit assembly/construction constraints will drive designs and architectures.

The goal of this paper is to highlight the above critical issues so that designs may be evaluated from these viewpoints. Evaluating designs from the issues contained in this paper will help decision-makers detect inadequate designs. Stressing these issues in the evaluation procedure will have a great impact on the decisions of future space mission transfer vehicles and consequent architectures.

On-Orbit Assembly Considerations of Manned Mars Transfer Vehicles

by Mark D'Amara



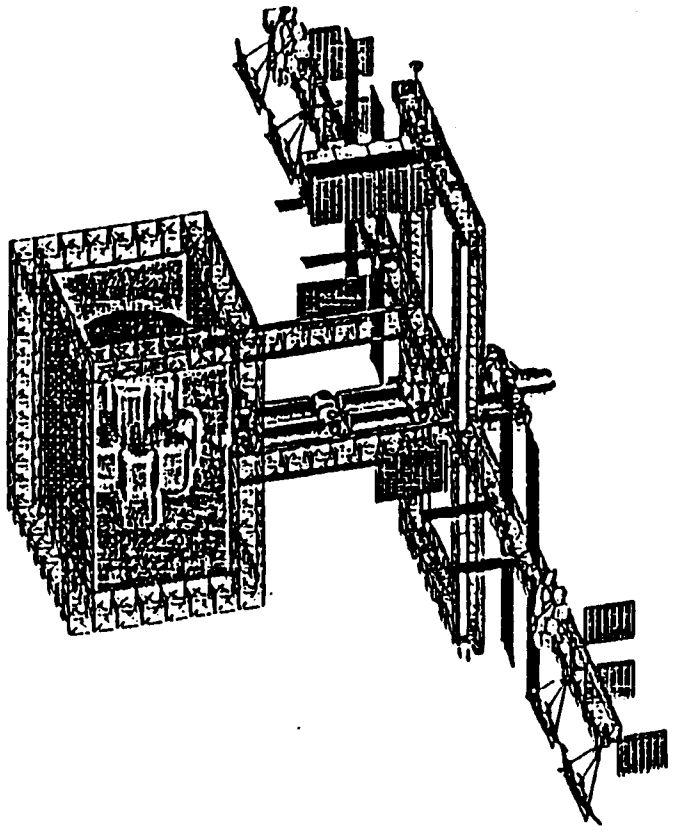
- **Three Main Concerns**
  - Integrity of the Design (CAE, IDEAS**2)
  - Impact of Assembly/Construction on Design
  - How do you choose the best design?

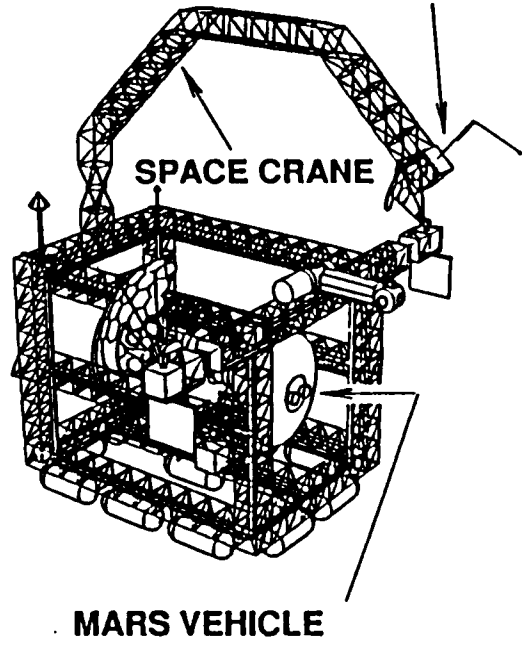
- **Goals of Paper**
  - Examine Major Issues of Orbital Construction Operations
  - Constraints in Orbital Construction of Spacecraft
  - Need for DYCAM to assist in Orbital Construction Planning
  - Develop Monte Carlo Tool for Evaluation of Alternative Spacecraft Designs and Selection of 'best' Design

Various Mars Spacecraft Concepts

- NASA 90-Day Study Concept (double aerobrake)
- Martin Marietta's Artificial-g Concept
- NASA MSFC Artificial-g Concept
- NASA's Office of Exploration Concepts
- Celdon Corp's Bruce Mackenzie's Allenmande Concept (tethers for artificial-g and momentum exchange)

Orbital Construction Site Options





Converting the Many Visions of On-Orbit Assembly Into Reality

- Space Structural Joining Methods
- Assembly Sequence Effects on Assembly Time
- Development Testing. Where? Scale?
- Inspection, Non-Destructive Evaluation (NDE), Form-Fitting Test
- Repair, Rework, Misfits, Preventative Maintenance
- Stability of Partially Constructed Facilities
  - Orbital Life Time
  - Attitude Control
  - Thermal Stability
  - Power Adequacy
  - Fluid Management
- Resource Management
  - Astronaut Work Hours
  - Robot Work Hours
  - Materials
- Command, Control, Communication Adequacy
- Interruptability Robustness
- ETO Capabilities
  - Shuttle Z (500k# to LEO) vs. smaller vehicles (50k# to LEO)
- Auxilliary Support System Benefits
- Multiple-Use Components (i.e. Shuttle External Tank)
  - Materials Storage
  - Fuel Storage Depots
  - Life Support Systems
  - Other

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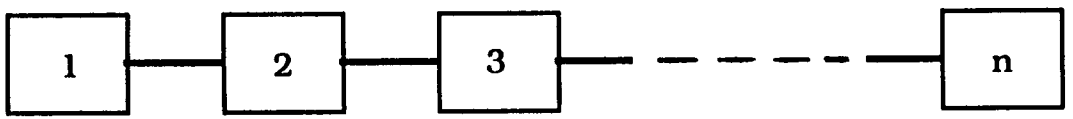
Assembly Time Sequence Implications

- Begin at left end with two crews
- 

  t = assembly time per link (no problems)

  τ = assembly time per link (with problems)

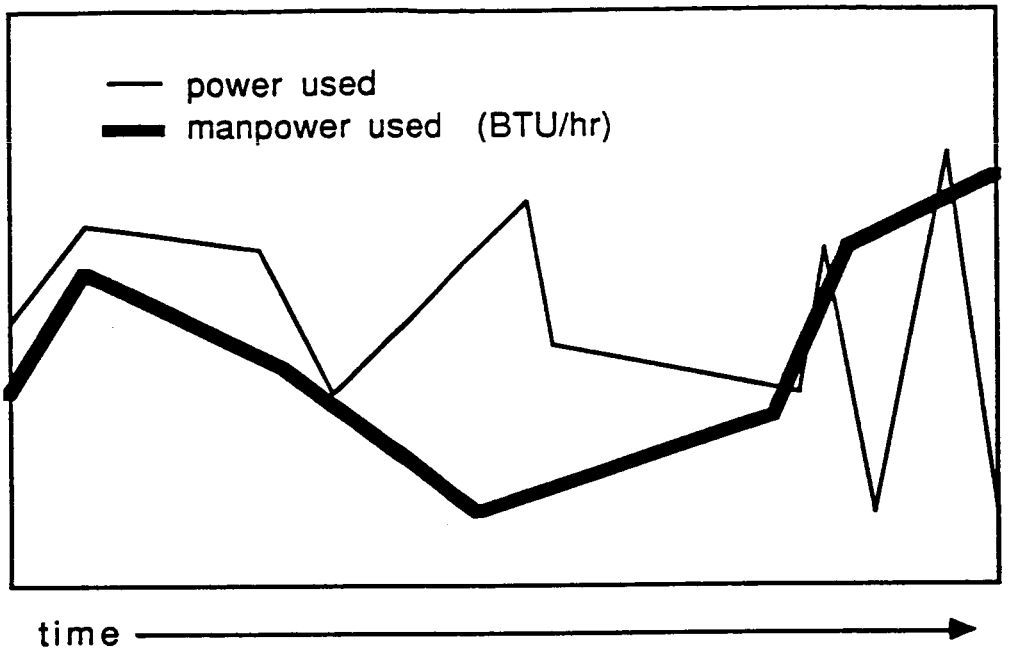
  p = probability of having a problem at each linkage

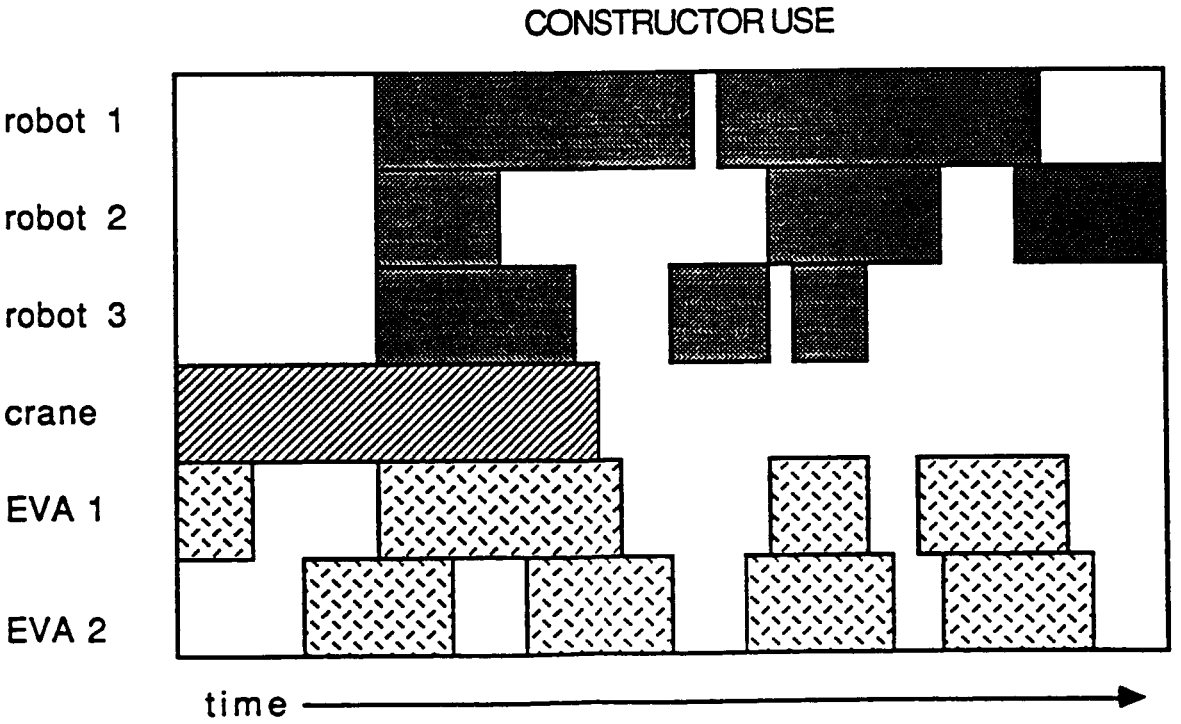
  Then, expected completion time with a crew of two is...

  $$E[T] = (n - 1)[\, t - p(\tau - t)] \quad , n \text{ odd}$$

- With what components do you begin assembly?
- What will it be if we begin at the middle and split the crews?
- What of three-dimensional assemblies?

Resource Management





Simulation of SSF Assembly Success and Average Program Delay

Calculation of SSF assembly success using reliabilities

R	P[No Failure]	P[≥1 failure]
0.95	0.324	0.676
0.96	0.407	0.593
0.97	0.512	0.488
0.98	0.641	0.359
0.99	0.802	0.198

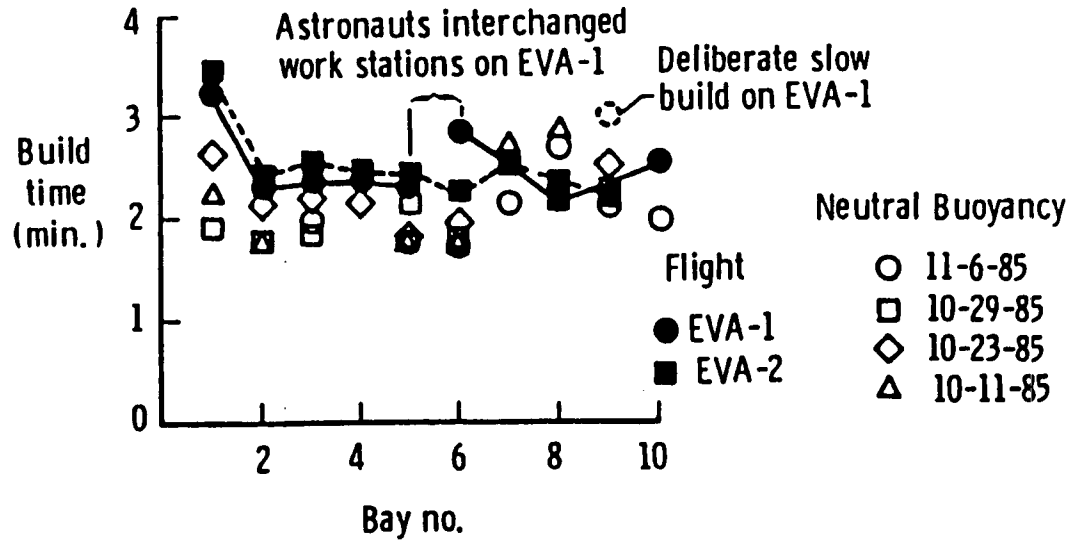
T_{av} with various reliabilities using the same Monte Carlo result for t_{av}:

Reliability (R)	P[no failure]	P[≥1 failure]	T_{av} (months)	n (months)
0.99	0.802	0.198	6.0	3.8
0.98	0.641	0.359	9.1	6.9
0.97	0.512	0.488	11.6	9.4
0.96	0.407	0.593	13.6	11.4
0.95	0.324	0.676	15.2	13.0

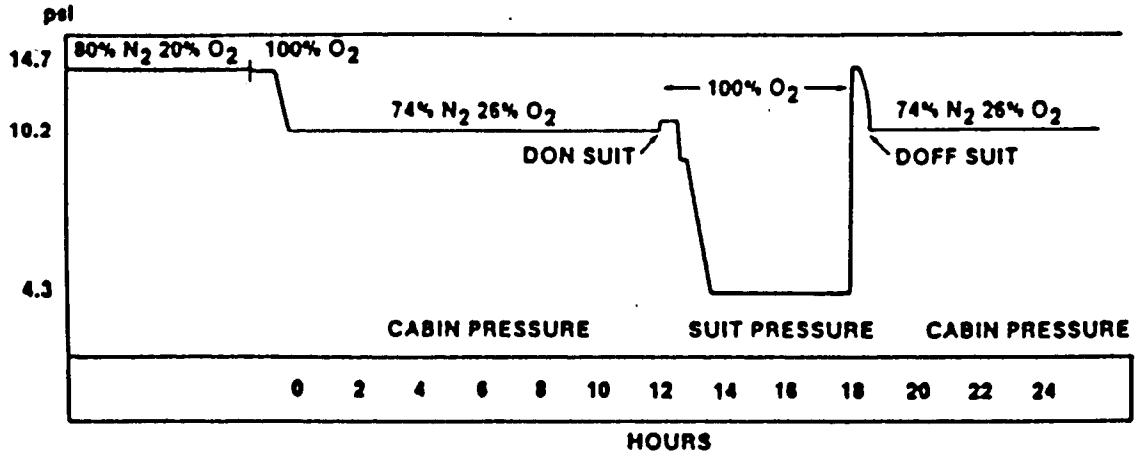
Human Constraints I

Baseline experiment average task times

Task	Time (min.)		
	NBS	WETF	FLIGHT
Setup	4.0	3.1	3.5
Assemble 10 bays	30.2	21.7	25.5
Disassemble 10 bays	18.7	15.7	18.9
Stow & close up	5.4	4.5	4.2
	58.3	45.0	52.1



Human Constraints II

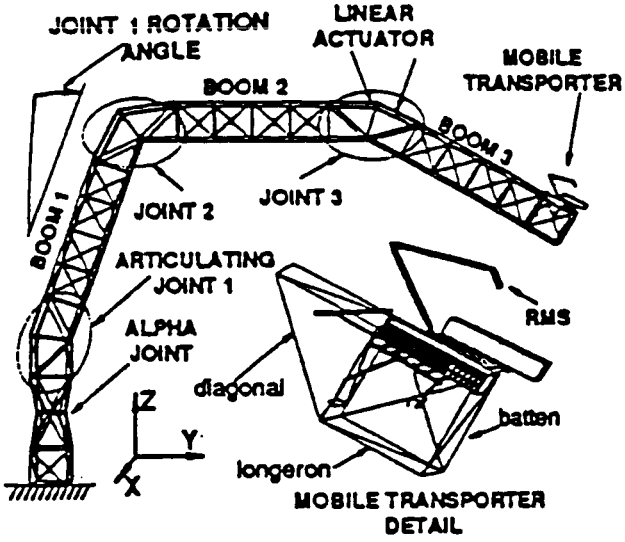


Combination of straight oxygen prebreathing and staged decompression.

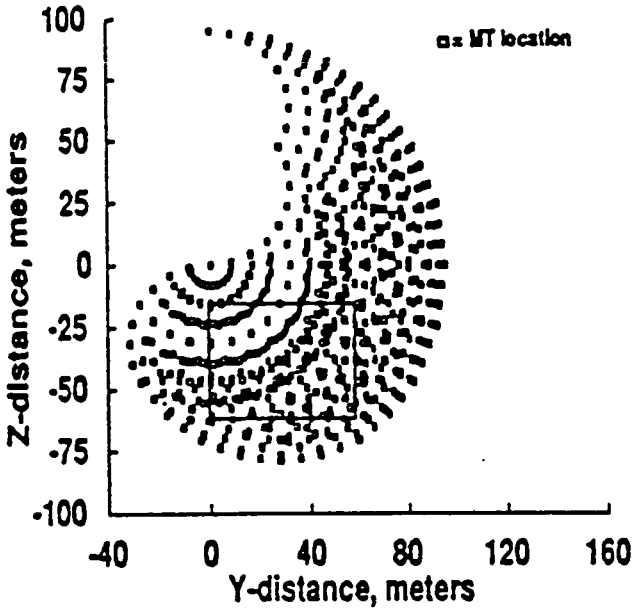
ZERO PREBREATHE OPTIONS OF SUIT AND CABIN PRESSURES

Cabin Pressure (psi)	Suit Pressure (psi)	Nominal O_2 Pressure (psi)	Constraints Prior to EVA
14.7	9.0	3.1-2.8	None
11.0	6.5	3.1-2.8	1 hr prebreathe prior to depress to 11.0 + 24 hrs at 11.0 psi.
10.2	6.0	3.1-2.8	1 hr prebreathe prior to depress to 10.2 + 24 hrs at 10.2 psi.
8.0	4.1	3.2-2.9	4 hrs prebreathe prior to depress to 8.0 + 24 hrs at 8.0 psi.

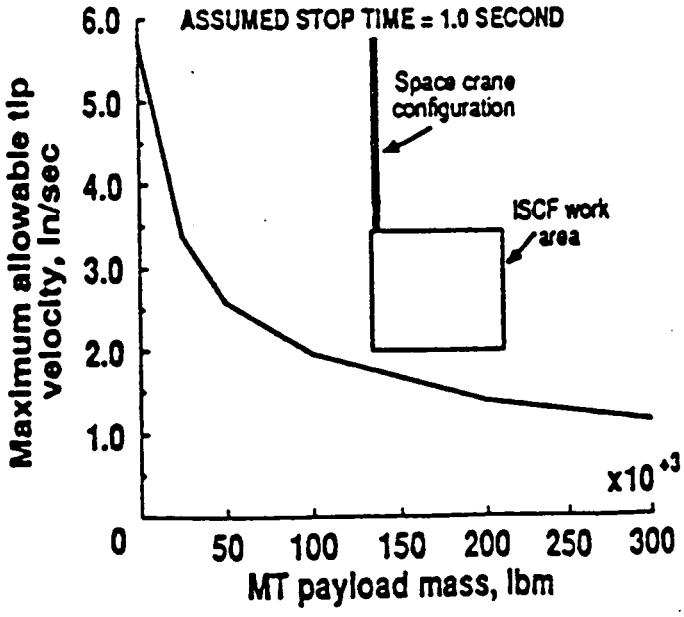
Hardware Constraints

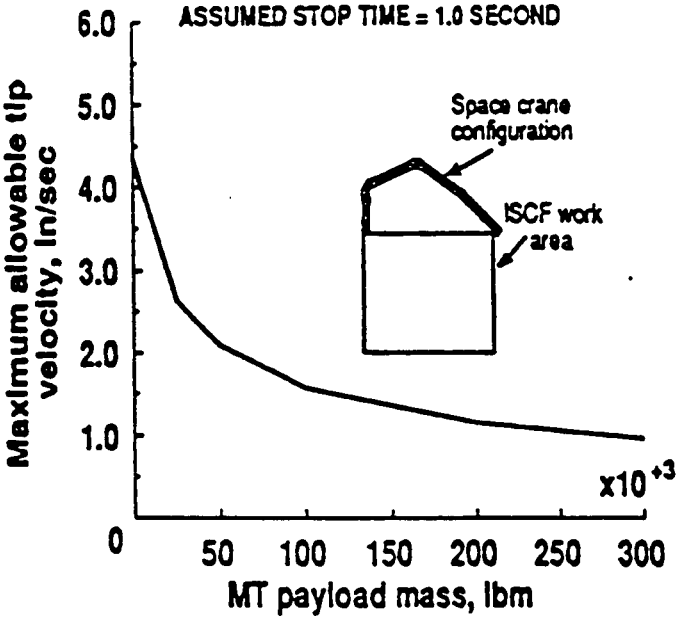


Space crane components.



MJRA of 120 degrees.





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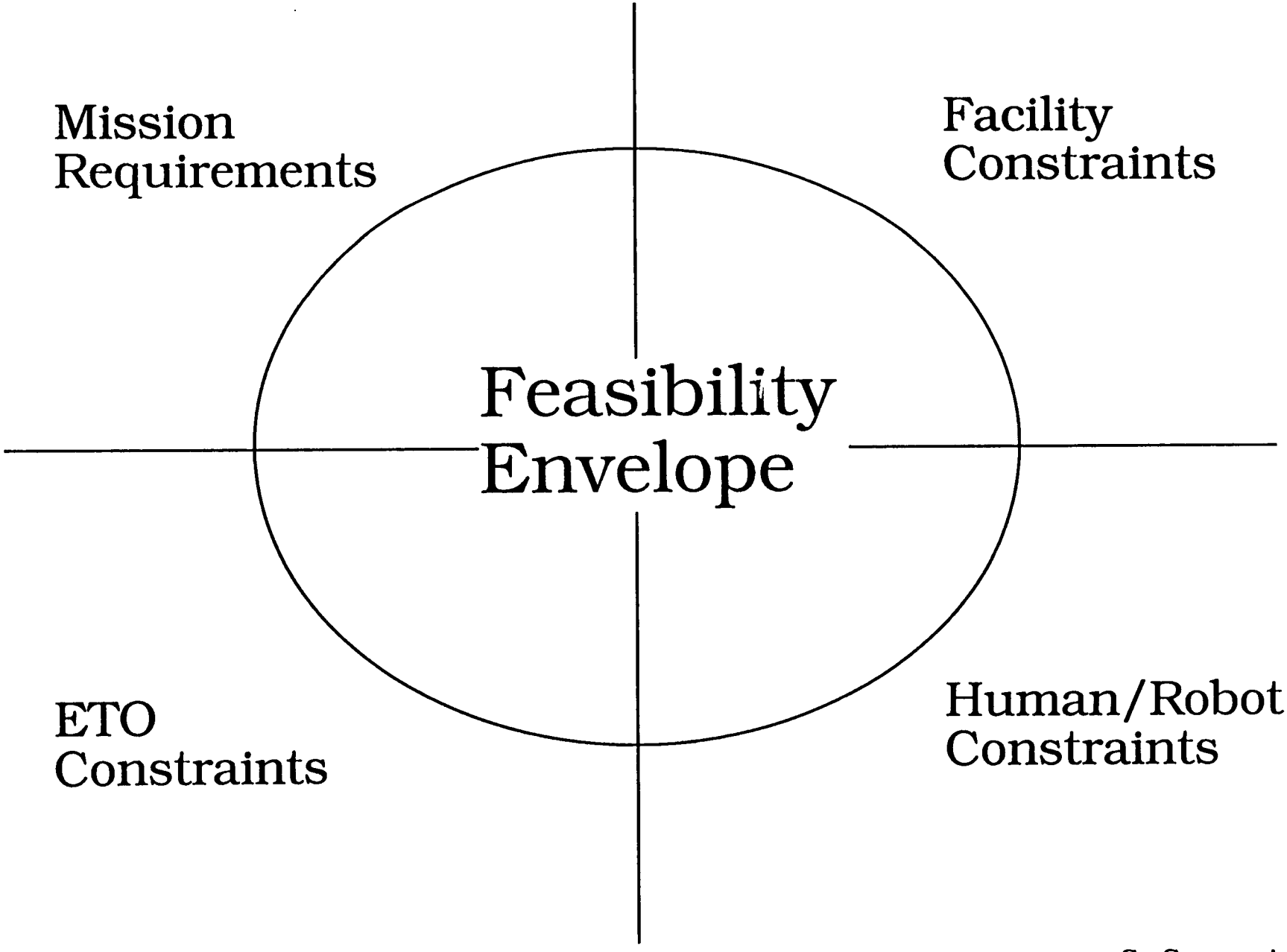

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Quantitative Evaluation Methods

PERT-CPM

mission timeline requirements
facilities operations
ETO scheduling
critical pacing technology development effects

Linear/Non-Linear Programming

resource allocation
global/subsystem reliability analysis

Probabalistic Models

risk analysis
Monte Carlo simulation

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Session Eleven

CHARACTERISTICS OF LUNAR REGOLITH

Stein Sture,
Chair

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Extraterrestrial Cluster: Characteristics of Lunar Regolith

Dr. Stein Sture
Dr. Hon-Yim Ko
Steven W. Perkins
Stephanie Popiel

A knowledge of the engineering characteristics of Lunar soils is essential in the design and construction of Lunar facilities. Some mechanical and physical properties of Lunar regolith are known from the Surveyor 3 and 7, and Apollo 11-17 as well as the USSR missions. To characterize the strength and deformation properties of Lunar regolith experiments have been conducted on a simulant prepared at the University of Minnesota and further processed at the University of Colorado, at various initial densities and environmental vacuum conditions. These experiments included conventional triaxial compression, extension, isotropic compression, direct tension, direct shear, and combined tension-shear.

Centrifuge modeling allows for the study of Lunar soil-structure interaction problems. As a test bed study a structure, representing a human habitat module, consisting of a cylindrical tube of relatively high stiffness resting on a level surface of Lunar regolith, is studied. Layers of regolith with thickness varying between 10 to 20 cm will be built up layer by layer under controlled compaction conditions adjacent to the horizontally aligned cylindrical structure so as to provide the 3 to 5 meter cover necessary for radiation shielding. Scale models will be studied in the centrifuge where the slope angle of the embankment cover's side surfaces and the regolith density will be the main variables.

A second test bed study involves the examination of the cause for the high density of the regolith immediately below the first 10 to 20 cm of the Lunar surface. Relatively loose Lunar simulant will be placed into a dynamic centrifuge model container and subjected to repeated cyclic loading under varying duration, frequency and amplitude. The density of the material will be monitored at various intervals throughout the experiments, by means of penetration testing.

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EXTRATERRESTRIAL ENGINEERING

CENTER FOR SPACE CONSTRUCTION

University of Colorado at Boulder

(Department of Civil, Environmental, and Architectural Engineering)

Faculty and Students

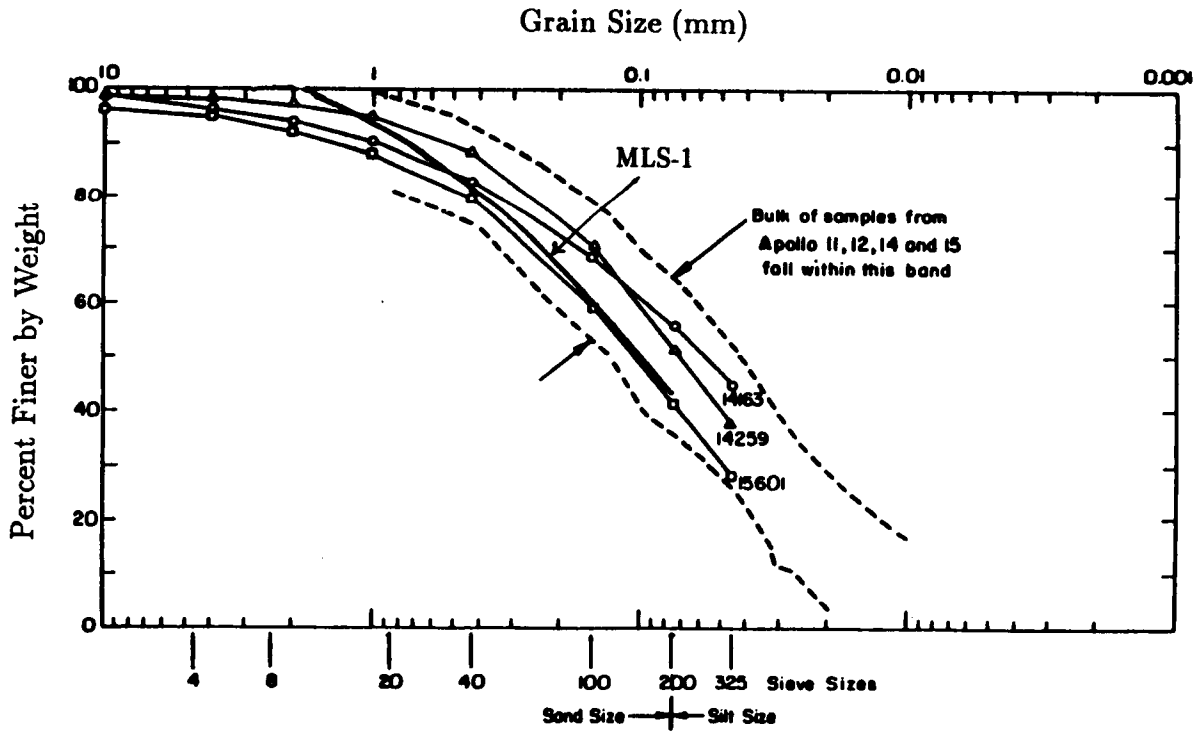
- Professor Stein Sture
- Professor Hon-Yim Ko
- Mr. Steven W. Perkins
- Ms. Stephanie Popiel

Extraterrestrial Cluster Objectives

Objective: To develop technology needed for constructing and maintaining the outposts and bases on the Moon and Mars including:

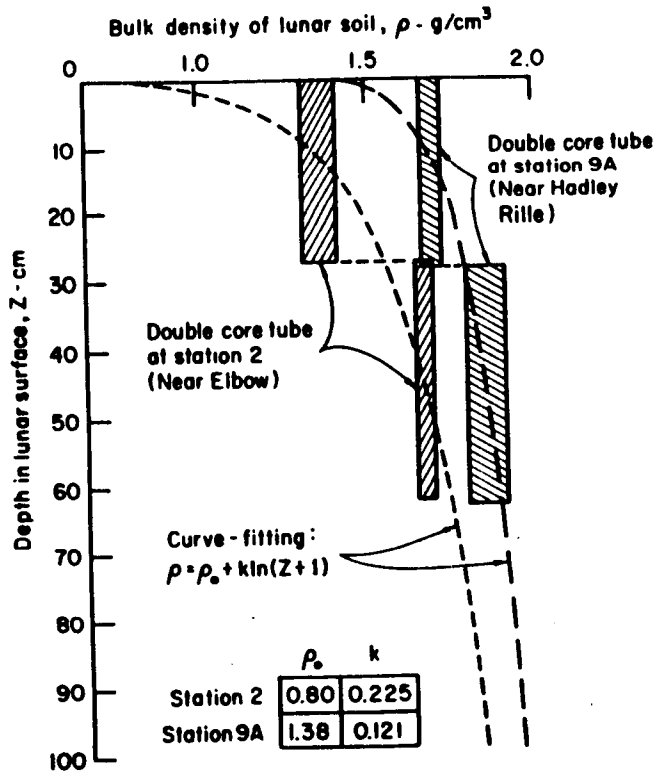
1. To characterize the mechanical properties of Lunar and Martian soils (regolith).
2. To develop analytical models of Lunar and Martian soils.
3. To analyze space system structure - soil interactions
4. To design foundation and support systems for constructed facilities.
5. To simulate and test foundation / support designs in geo-technical centrifuge.
6. To modify in-situ materials for construction purposes.

GRAIN SIZE DISTRIBUTION OF APOLLO LUNAR SOIL SAMPLES AND LUNAR SOIL SIMULANTS



(Carrier et al., J. Soil Mech. and Fnd. Div., ASCE, 1973)

PHYSICAL PROPERTIES OF LUNAR REGOLITH



DENSITY OF LUNAR REGOLITH AT APOLLO 15 CORE TUBE SITES
(Mitchell et al., Proc. 3rd Lunar Sci. Conf., 1972)

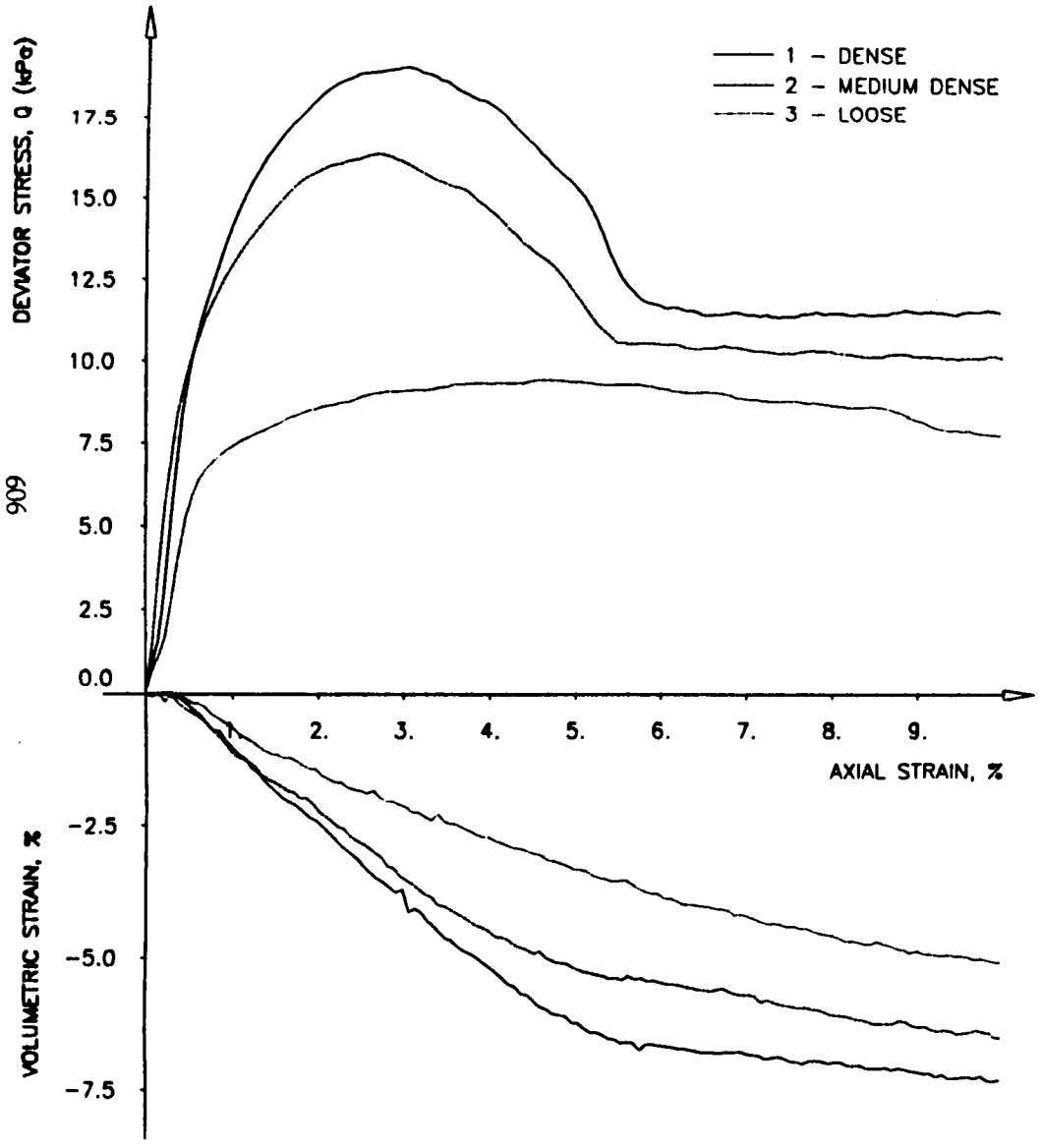
- SPECIFIC GRAVITY OF SOLIDS; $G_s = 3.1$
- POROSITY OF REGOLITH; $38\% \leq n \leq 56\ \%$
  - POROSITY IS THE MOST IMPORTANT SINGLE VARIABLE CONTROLLING COHESION AND FRICTION PROPERTIES OF THE REGOLITH

MECHANICAL PROPERTIES OF A SIMULATED LUNAR SOIL

CURRENT ACTIVITIES

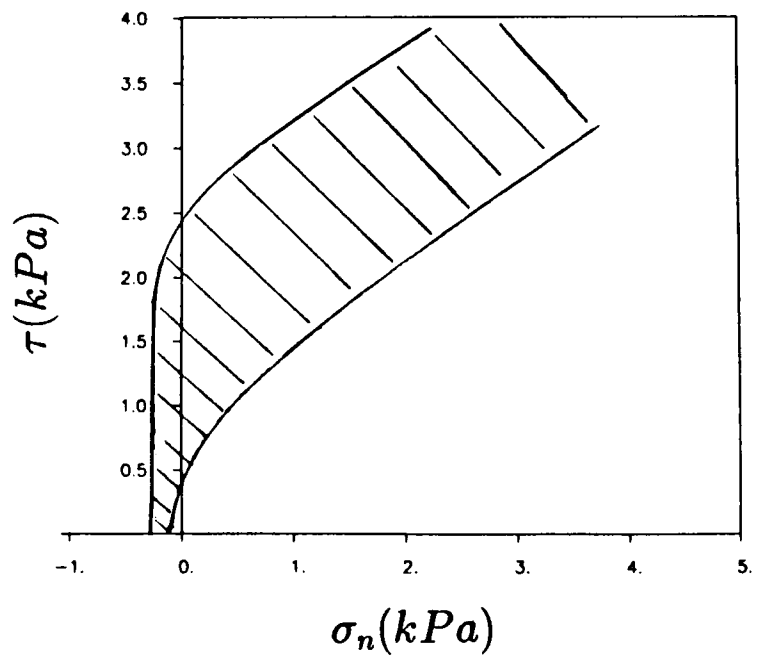
- EXPERIMENTS ON LUNAR SOIL SIMULANT AT VARIOUS INITIAL DENSITIES AND VACUUM LEVELS.
  - CONVENTIONAL TRIAXIAL COMPRESSION, EXTENSION AND ISOTROPIC COMPRESSION EXPERIMENTS ON CYLINDRICAL SPECIMENS.
  - DIRECT TENSION, DIRECT SHEAR AND COMBINED TENSION-SHEAR EXPERIMENTS ON CUBICAL SPECIMENS.

TRIAXIAL COMPRESSION EXPERIMENTS (MLS)

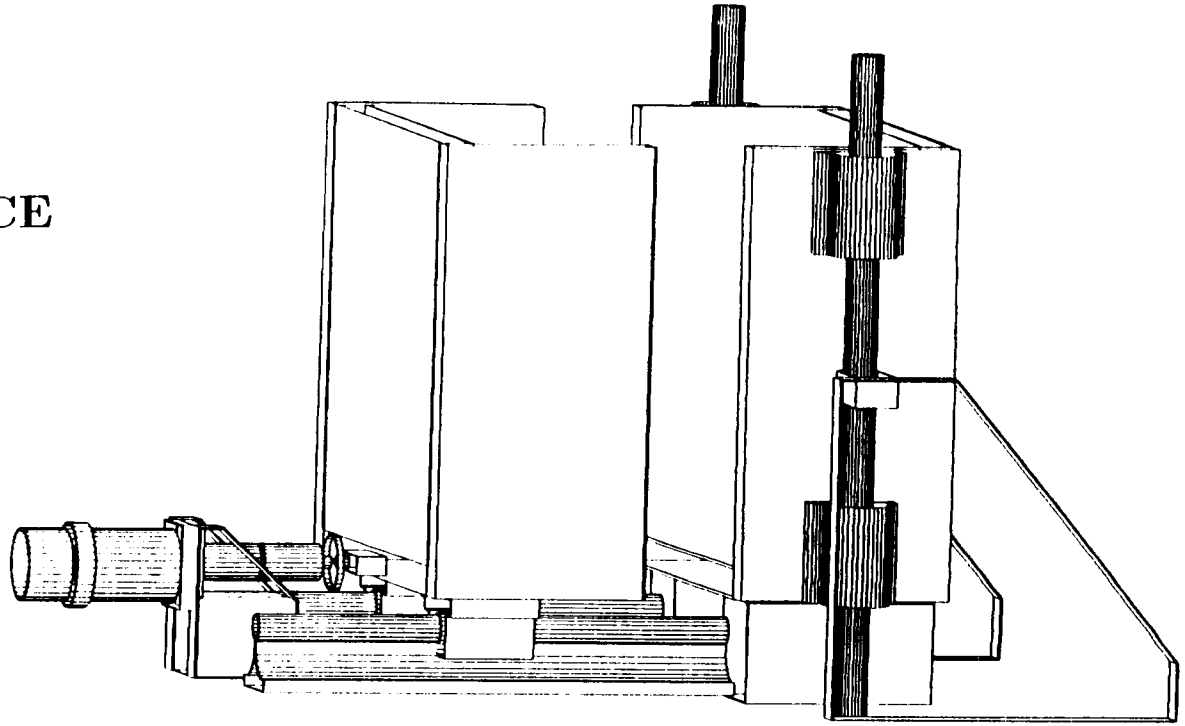


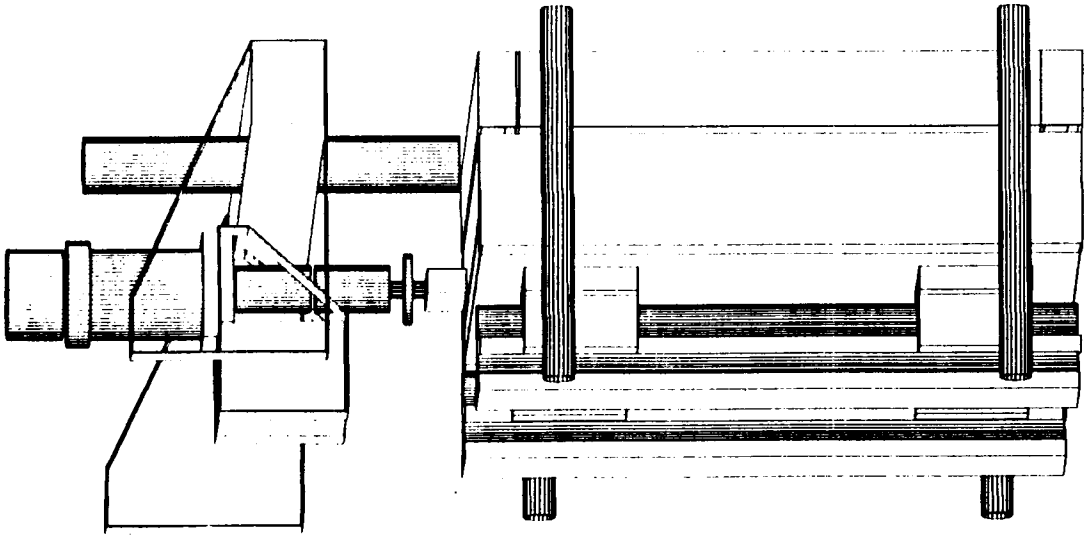
- COHESION (ADHESION); $0.05 \leq c \leq 2.5$ kN/m^2
- FRICTION (ANGLE OF INTERNAL FRICTION) $40° \leq \phi \leq 65°$
  - THE FRICTION ANGLE IS ALSO DEPENDENT ON MEAN STRESS LEVEL. IT DECREASES WITH INCREASING MEAN STRESS STATE

MOHR-DIAGRAM



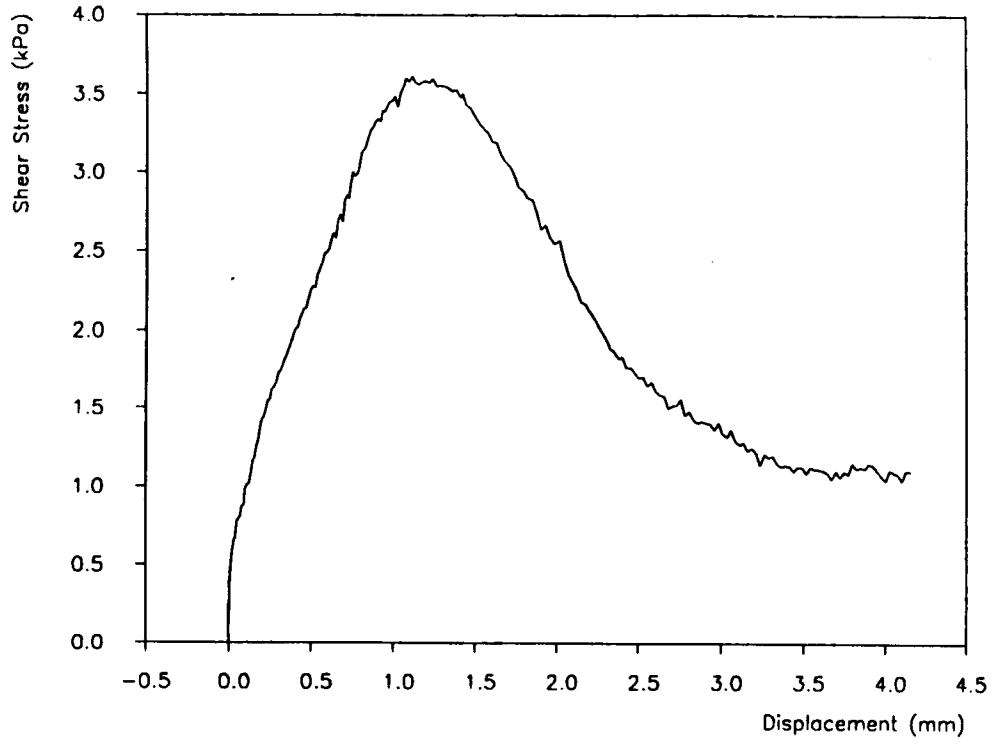
TENSION-SHEAR DEVICE

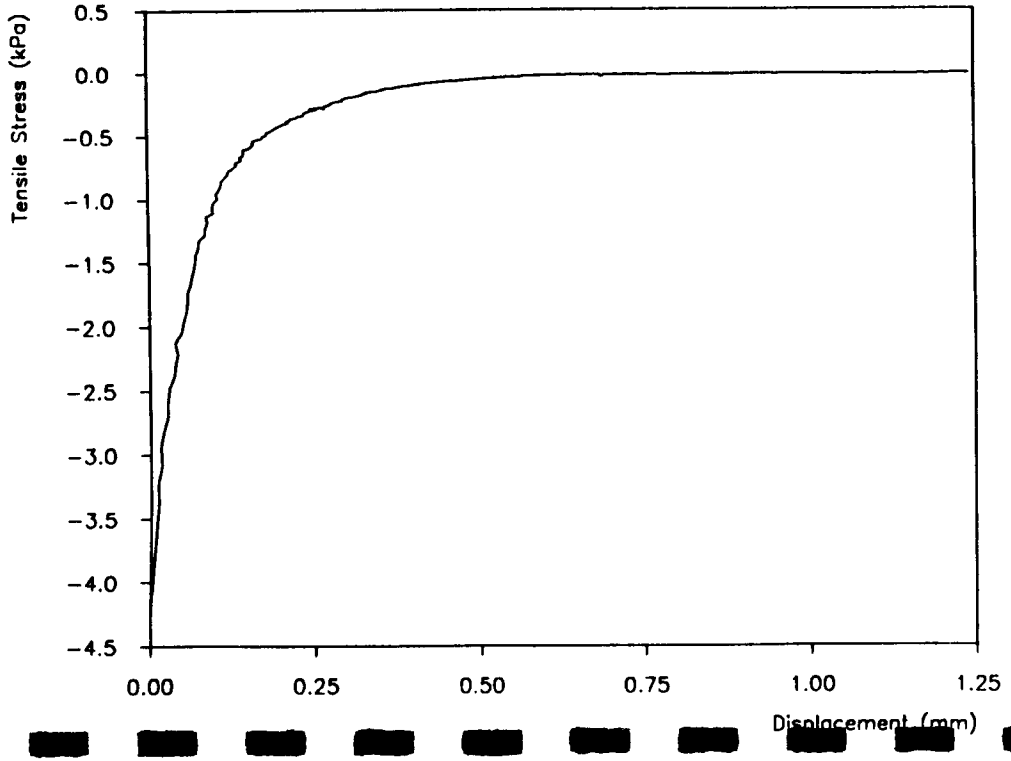




DIRECT SHEAR DEVICE

DIRECT SHEAR TEST, $\gamma = 2.17 g/cc$

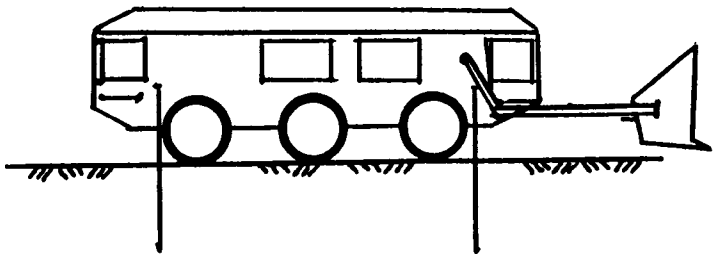




DIRECT TENSION TEST, $\gamma = 2.10 g/cc$

EARTH (REGOLITH) MOVING EQUIPMENT

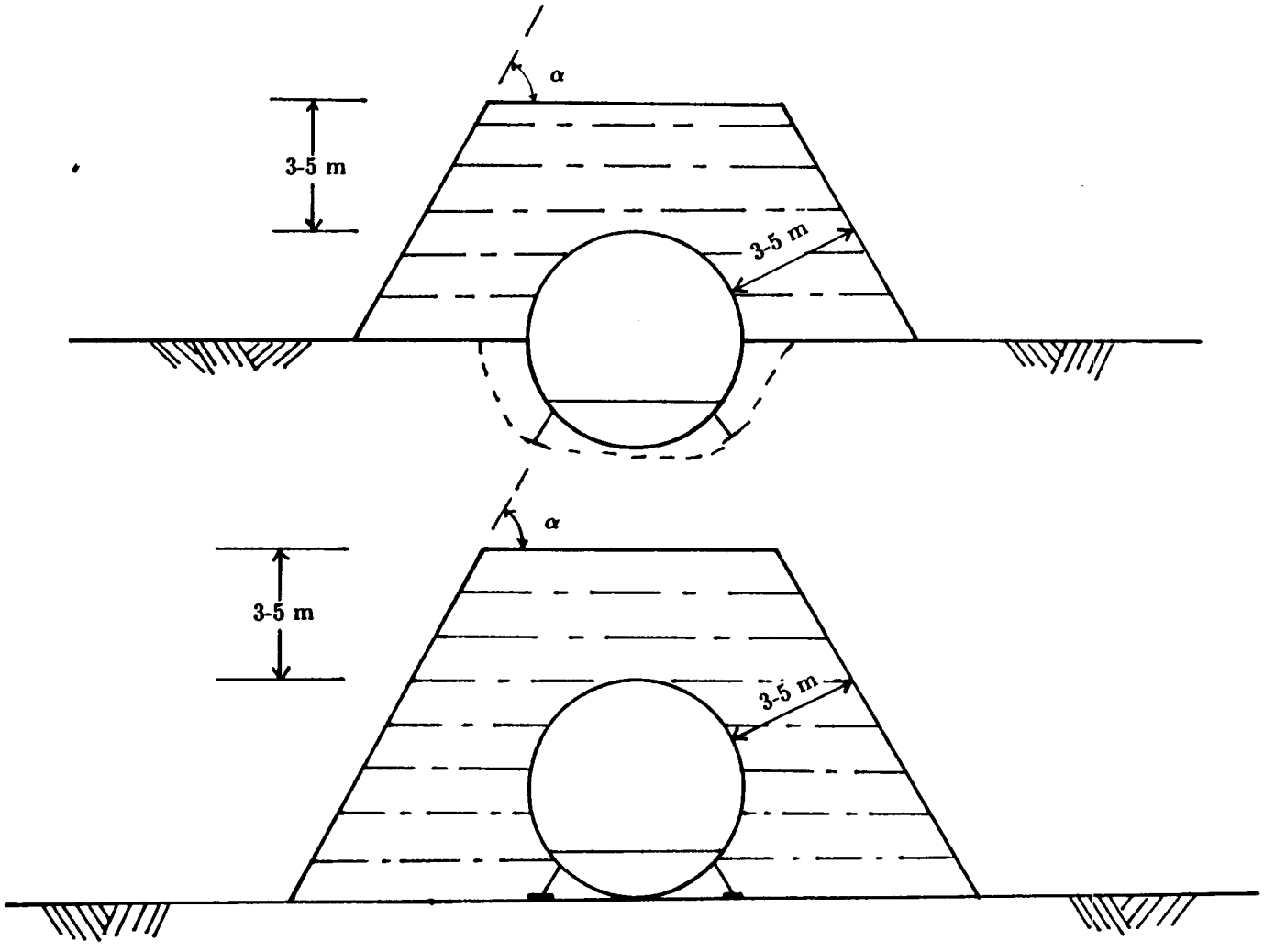
- CONVENTIONAL EXCAVATION, TRENCHING, GRADING, COMPACTION, ETC. EQUIPMENT:
  - Minimum Mass, 10,000 kg
  - Footprint (minimum): 3m X 6m
- USE OF PENETRATORS (ANCHORS), INSERTED BY VIBRATION, IS INVESTIGATED TO REDUCE REQUIRED EQUIPMENT MASS.



EARLY EMPLACEMENT HUMAN HABITAT AND OPERATIONS MODULE

- PROTOTYPE
  - The slope angle, α, will be limited by the embankment density, γ.
  - Compaction recommendations will consist of layer/lift thicknesses, densities, and required capacity of compaction equipment.
- MODEL (CENTRIFUGE)
  - Structure will consist of a rigid tube with a smooth exterior.
  - Stability of structure will be studied at various gravity levels.
  - Earth reinforcing systems (geogrids, geofabric, etc.) may possibly be used.
  - Construction (compaction) can be modeled in-flight.

HUMAN HABITAT AND OPERATIONS MODULE WITH REGOLITH SHIELDING



RADIATION SHIELDING ISSUES

1 SAND BAGS

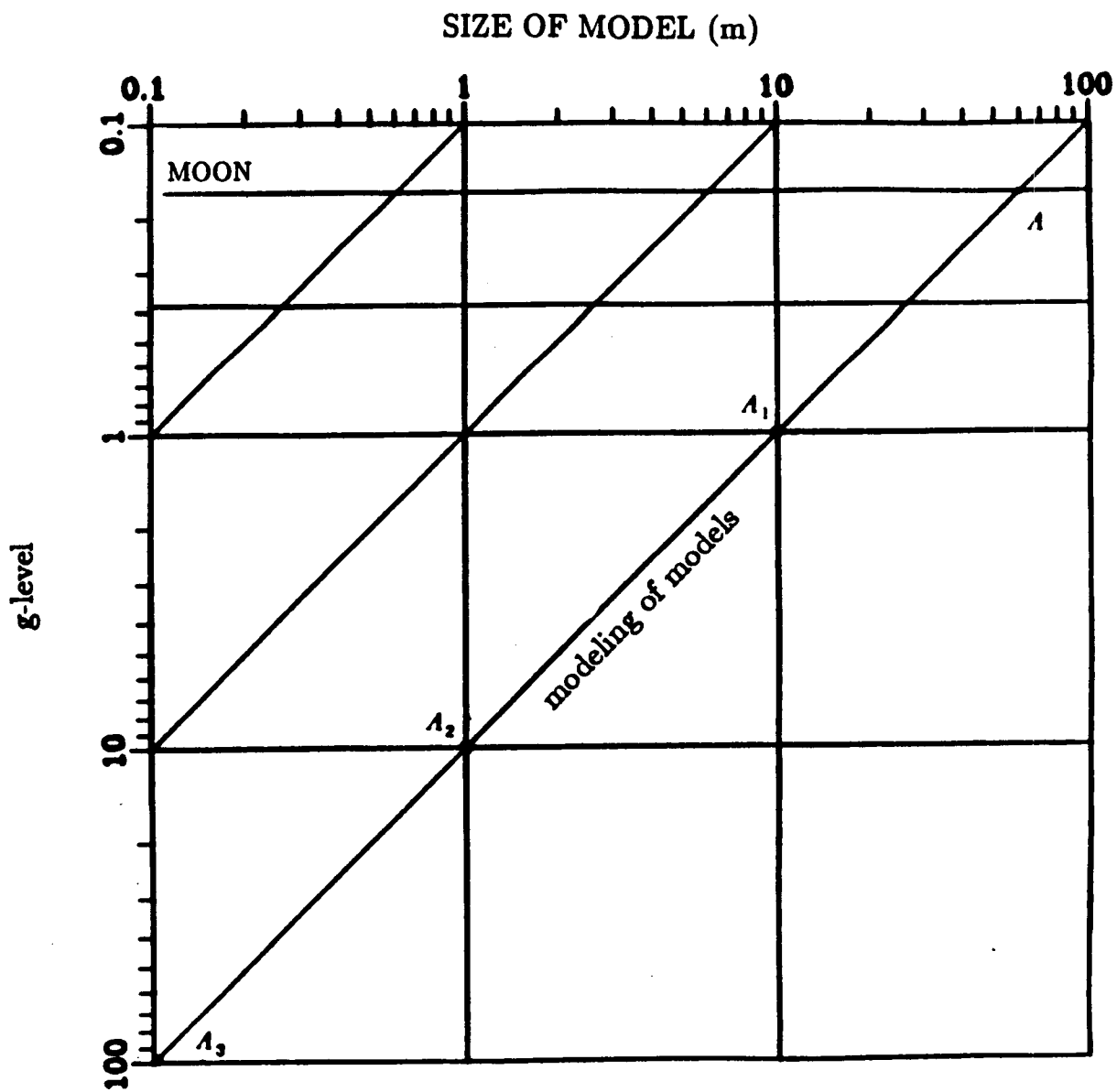
Fabric bags containing regolith, stacked around the exterior of habitable structures, are thought to possess several significant problems. The number of bags necessary to produce a cover of 3 to 5 m will be quite large and will need to be transported from earth, resulting in additional constraints on a transportation system. The regolith is highly angular and consists of very abrasive particles, and its friction angle and cohesive properties are far higher than dry terrestrial granular materials. It will be quite difficult to process the regolith in some type of a hopper for the purpose of bag filling and will certainly require innovative hopper designs. The bags will need to be thick and robust so as to maintain their integrity during filling, placement and possible removal in the case of module servicing. The bags will also be difficult to handle.

2 COMPACTED EMBANKMENT

Compacted embankments are seen as a more plausable alternative to radiation shielding. All construction materials, with the exception of geo-grids or other reinforcing materials for enhanced stability, if desired, are available on site. Embankment construction could proceed in a straightforward manner using bulldozers and vibrators, which could be used for other tasks as well. The properties of the regolith could be taken advantage of by vibration compaction to form relatively steep embankment slope angles.

For either alternative, one may consider a mass balance approach where the tubular habitat is buried sufficiently deep so that the excavated mass is just enough to provide the necessary cover. This will require excavation tools with enough power to excavate to depths of 3 to 5 m.

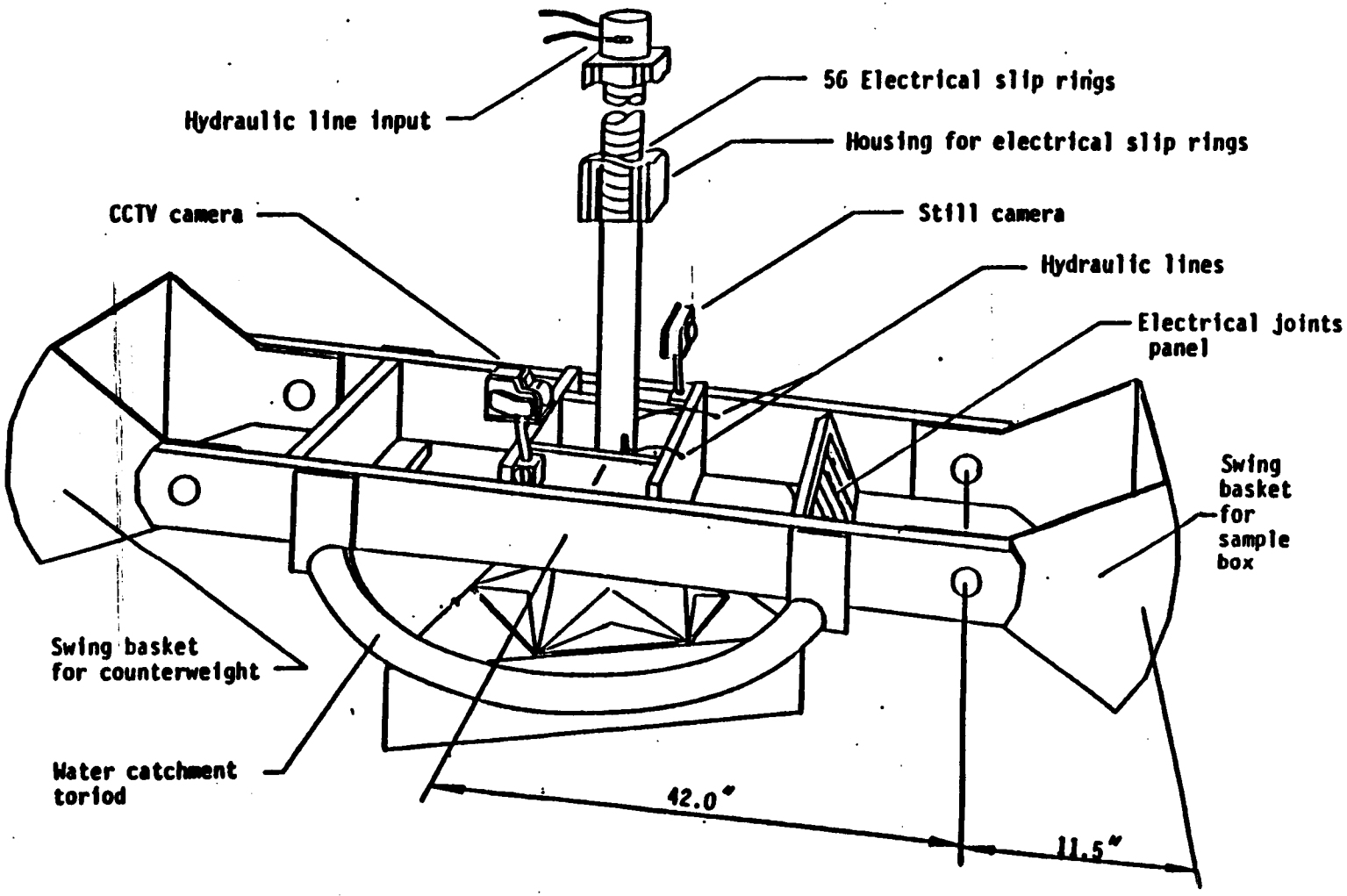
ILLUSTRATION OF THE CONCEPT OF MODELING-OF-MODELS



TEST BED

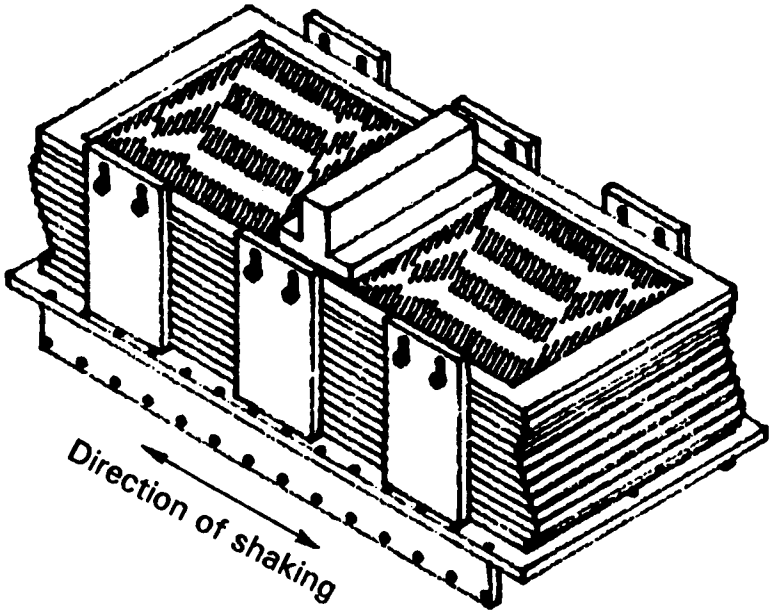
TO INVESTIGATE THE CAUSE FOR THE HIGH DENSITY OF THE LUNAR REGOLITH USING A VIBRATION SIMULATOR IN THE GEOTECHNICAL CENTRIFUGE

TO MEASURE, BY IN-FLIGHT PENETRATION TESTING, THE IN-SITU SOIL PROPERTY PROFILE AFTER DENSIFICATION

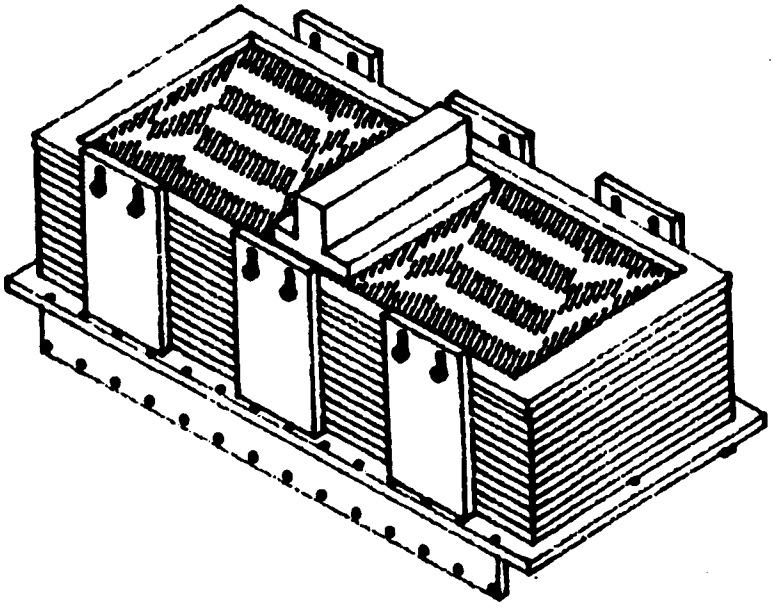


15 G-TON GEOTECHNICAL CENTRIFUGE

DURING SHAKING

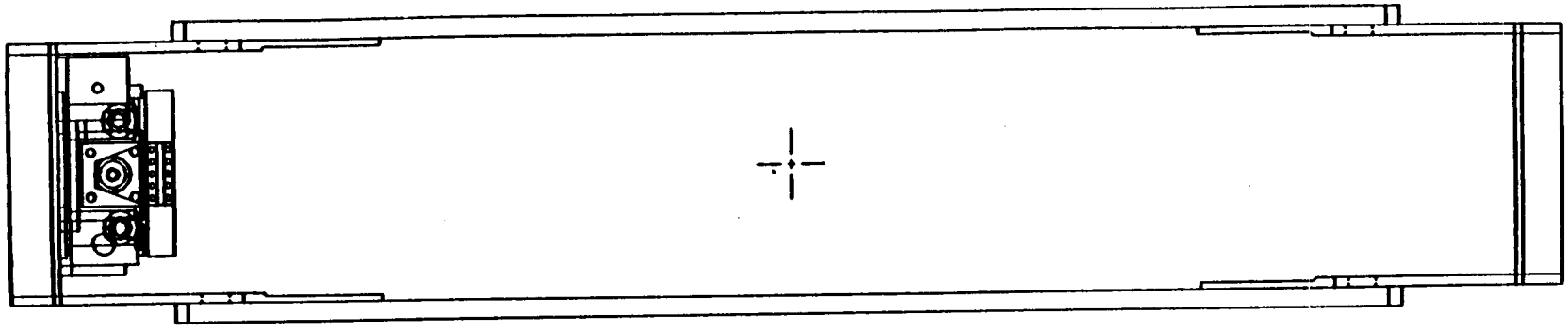


BEFORE SHAKING

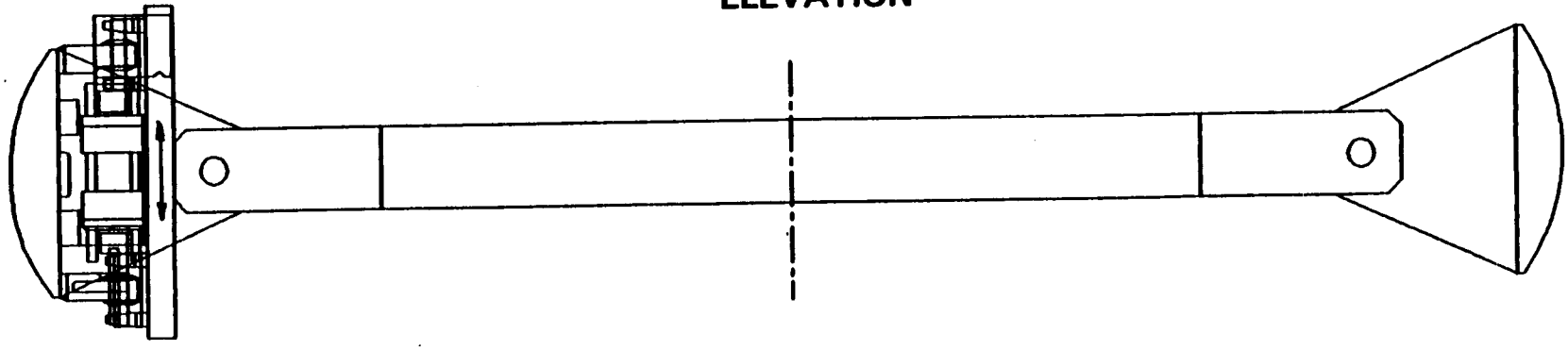


LAMINAR CONTAINER TO SIMULATE FREE FIELD MOTION

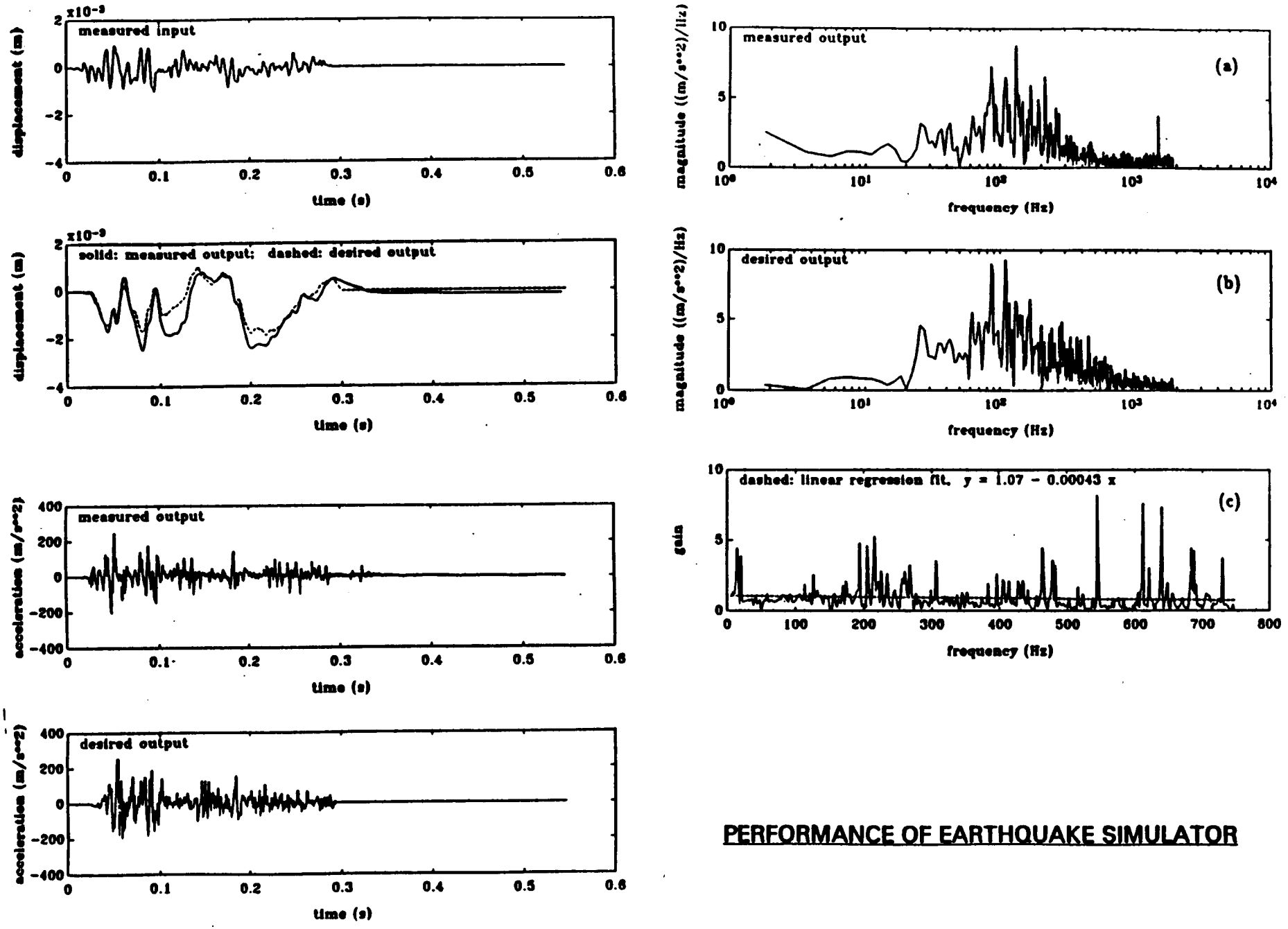
PLAN



ELEVATION



EARTHQUAKE SIMULATOR (SLIP TABLE) FOR 15 G-TON CENTRIFUGE



PERFORMANCE OF EARTHQUAKE SIMULATOR

Session Twelve

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CONSTRUCTION OF A LUNAR BASE

James R. Stuart,
Chair

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CONSTRUCTION OF A LUNAR BASE

Dr. James R. Stuart

This session will cover one of the most important issues surrounding the Space Exploration Initiative missions, the issue of constructing complex assemblies in space, in particular a Lunar Base. The term *constructibility* has become a buzz word throughout the industry, and here at CSC it has become the paramount phrase used to describe the probability of success in an SEI endeavor. This is not to say that the design of the hardware is less of an issue, indeed, design and construction are interwoven, dependent on one another.

The individual presentations in this session have been chosen and ordered in such a way as to consider the construction in a logical manner. First, a discussion of what construction requirements really are, and how they are derived will be presented as the results of an intensive six month exercise that CSC has conducted with it s Industrial Associates. Next, a presentation by a CSC University Associate on the kinds and types of equipment to perform Lunar construction/Lunar mining will be delivered. Thirdly, CSC's prototype design of a liquid oxygen storage facility on the Moon accompanied by the critical issues involved. Lastly, a presentation on Lunar Base construction planning using a design reference mission to uncover the principles and patterns of constructibility.

CSC Annual Symposium:

CONSTRUCTION OF A LUNAR BASE

Session Chairman:
Dr. James R. Stuart
October 19,1990
9:00 AM - 10:30 AM

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Agenda

- 9:00 AM - 9:05 AM *Introduction and Opening Remarks,* Dr. James Stuart
- 9:05 AM - 9:30 AM *Lunar Base Construction Requirements,* Steve Jolly and Brent Helleckson
- 9:30 AM - 9:45 AM *Lunar Construction/Mining Equipment,*Dr. Levent Ozdemir
- 9:45 AM - 10:00 AM *Liquid Oxygen Prod. and Storage ,* Gary Mills
- 10:00 AM - 10:30 AM *Lunar Base Construction Planning,* Dr. Stuart and Others

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LUNAR BASE CONSTRUCTION REQUIREMENTS

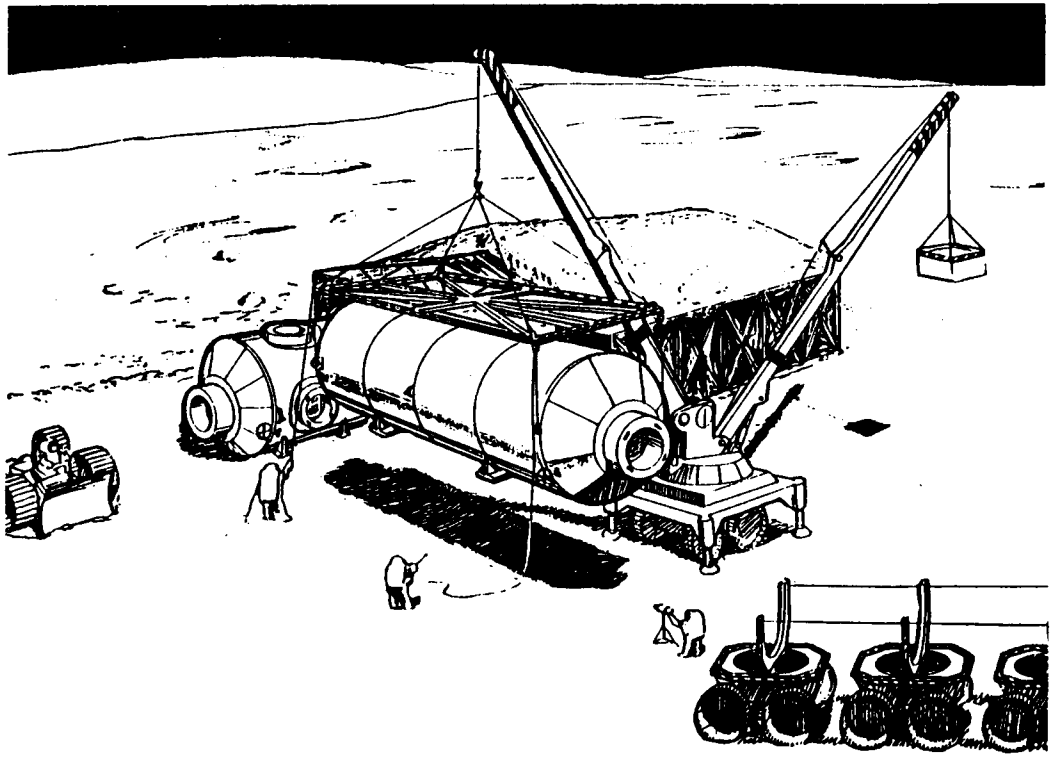
Steve Jolly
Brent Helleckson

The following presentation is a review of the Lunar Base Constructibility Study† carried out in the Spring and Summer of 1990. The objective of the study was to develop a method for evaluating the constructibility of Phase A proposals to build facilities on orbit or on extraterrestrial surfaces. Space construction was broadly defined as all forms of assembly, disassembly, connection, disconnection, deployment, stowage, excavation, emplacement, activation, test, transportation, etc., required to create facilities in orbit and on the surfaces of other celestial bodies. It was discovered that decisions made in the face of stated and unstated assumptions early in the design process (commonly called Phase A) can lock in non-optimal construction methods. Often, in order to construct the design, alterations must be made to the design during much later phases of the project. Such "fixes" can be very difficult, expensive, or perhaps impossible. *Assessing constructibility should thus be a part of the iterative design process, starting with the phase A studies and continuing through production.*

This study assumes that there exists a minimum set of key construction requirements (i.e. questions whose answers form the set of discriminators) that must be implied or specified in order to assess the constructibility of the design. This set of construction requirements, constitutes a "constructibility filter" which then becomes part of the iterative design process. Five inherently different, dichotomous design reference missions were used in the extraction of these requirements to assure the depth and breadth of the list.

† See Lunar Base Construction Requirements Review, May 8,1990 for detailed analysis and note that this project involved many more CSC personnel and Industrial Associates than the two presenters listed above

LUNAR BASE CONSTRUCTION REQUIREMENTS



by Steve Jolly and Brent Helleckson

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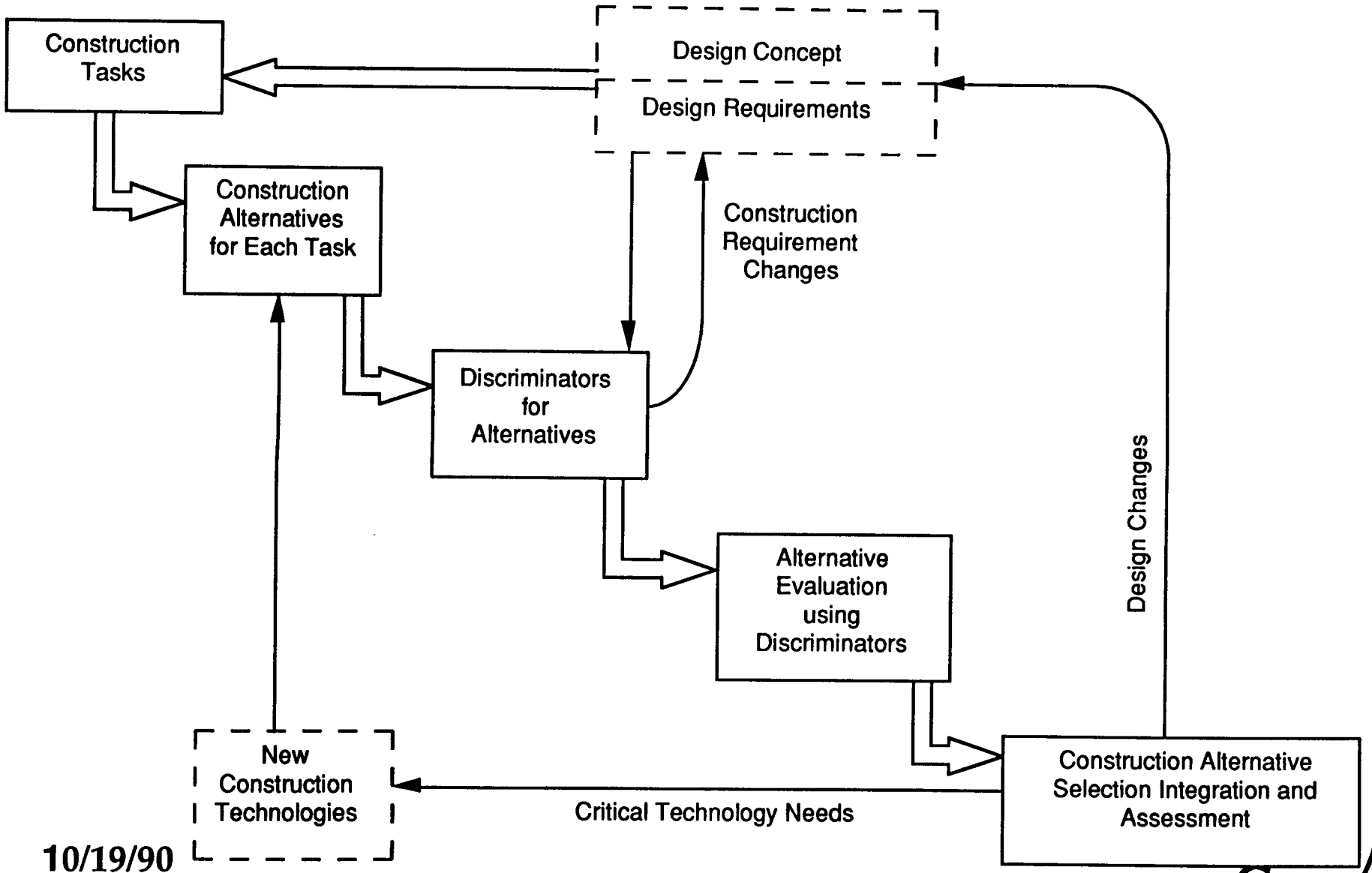
Lunar Base Construction Study

Lunar Base Construction Team Study Goals (Long Term)

- Develop the initial lunar base preliminary design requirements necessary to baseline the proper construction alternatives for design and evaluation
- Develop the methodology, information base, and techniques to determine and assess the constructability of lunar base preliminary designs
- Develop the capability to assess and compare the constructability of lunar base preliminary designs (e.g. required resource estimation)
- Develop the capability to recommend construction improvement modifications to reference lunar base preliminary designs and recommend critical construction technology development needs

Construction Assessment Methodology



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Design Reference Studies

Four main studies (1-3 and 5), one category of "other studies" (4) :

Case Study #1: "Report of the 90-Day Study on Human Exploration of the Moon and Mars" (NASA - JSC)

Case Study #2: "An American-Traditional Space Exploration Program: Quick, Inexpensive, Daring and Tenacious" (Lawrence Livermore National Laboratory)

Case Study #3: "A Lunar Habitat Configuration Derived From a National Space Transportation System External Tank" (NASA - LaRC)

Case Study(s) #4: "Moon and Space Development Current Research and Technology: Lunar Base Related Papers Proposed By Shimizu" (Shimizu)

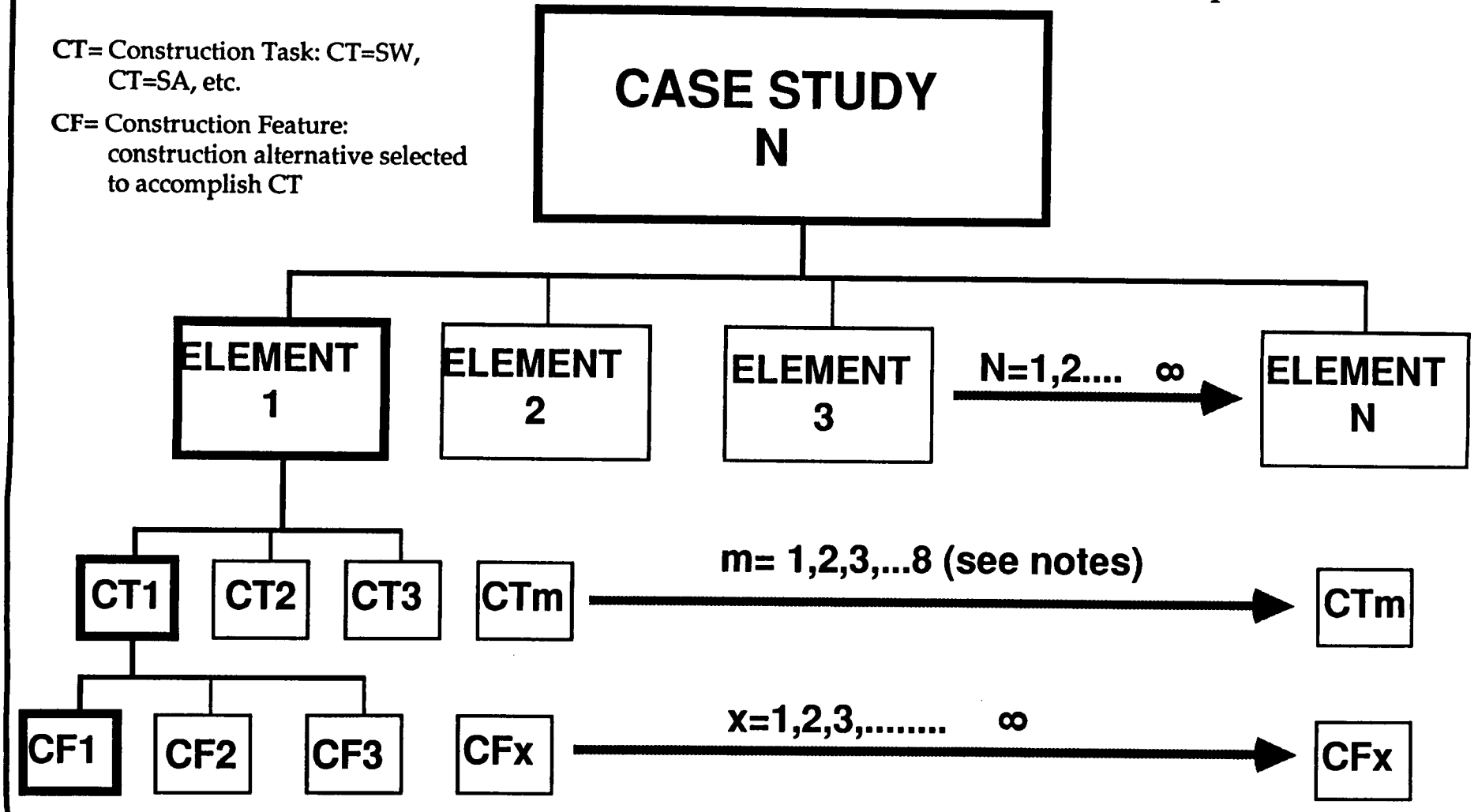
Case Study #5: " Robotic Lunar Surface Operations" (Boeing for NASA-Ames)

Construction Task Codes

element of dissection + set of construction tasks -> construction requirements

CT= Construction Task: CT=SW, CT=SA, etc.

CF= Construction Feature: construction alternative selected to accomplish CT



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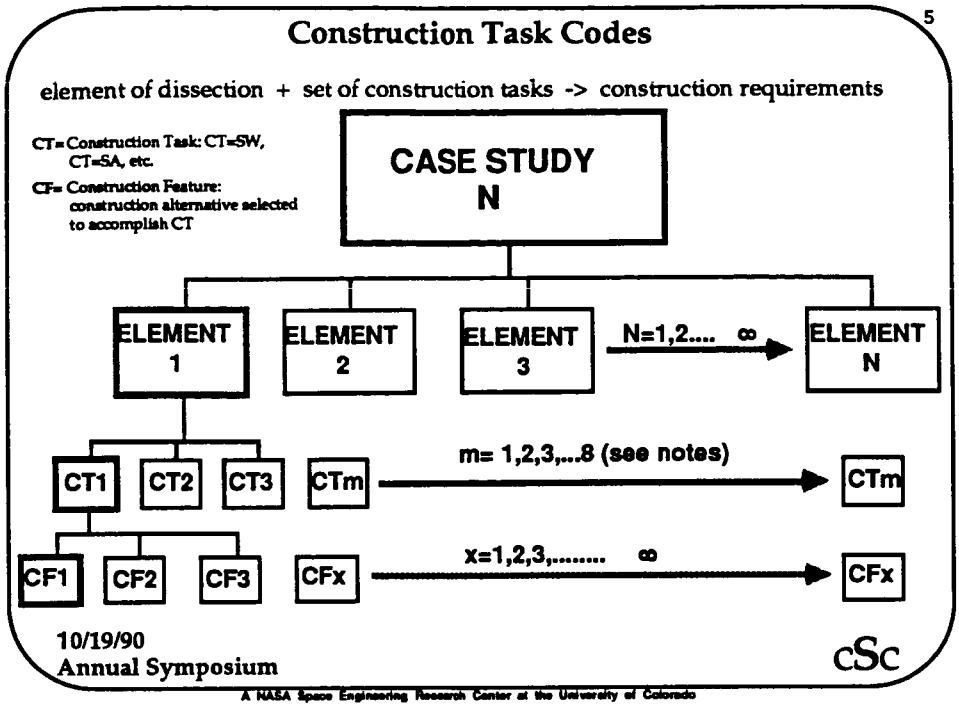


Eight General Construction Task Categories

Site Work (SW)

- Grading/Levelling
- Digging Holes
- Piling Regolith
- Transporting Regolith

Surface Transport (ST)

- Cargo
- Personnel
- Regolith

Offloading (OL)

- From Lander
- From Surface Transporter

Emplacement (Em)

- Cargo
- Regolith

Orbital Assembly (OA)

- Connect/Disconnect
- Deploy/Stow
- Managing Of Scrap

Surface Assembly (SA)

- Connect/Disconnect
- Deploy/Stow

Shirt-sleeve Assembly (ShA)

- Connect/Disconnect
- Deploy/Stow
- Managing Of Scrap

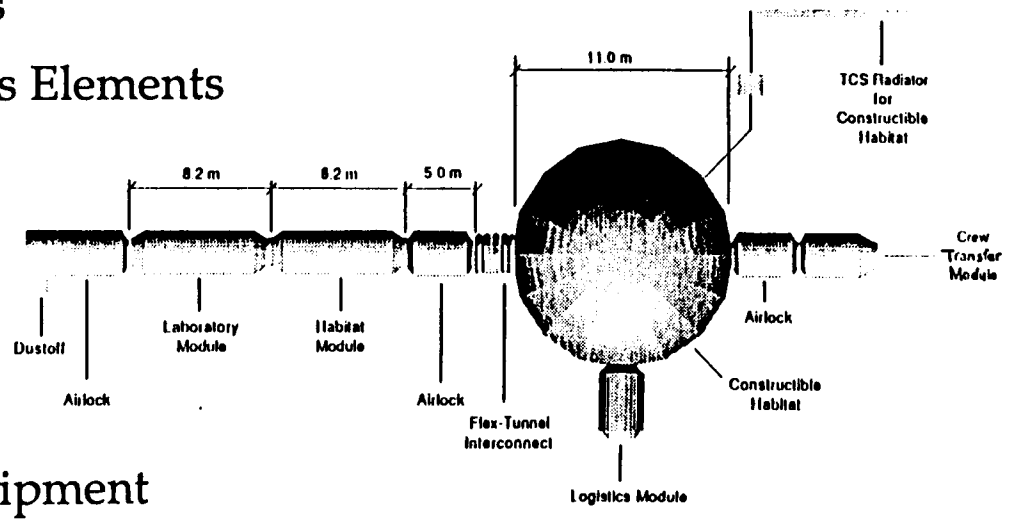
Test and Verify (Tst)

- Activate
- Test/ Verify

NASA 90-DAY Study
Case Study #1
Summary of Derived Construction Requirements

The study was broken down into 9 categories:

1. Structure Elements
2. Power System Elements
3. Thermal Control Systems
4. Communications Systems Elements
5. Shielding Elements
6. Launch/Landing Pads
7. Lunar Roads
8. Site Topography
9. Vehicles and Mobile Equipment



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NASA 90-DAY Study
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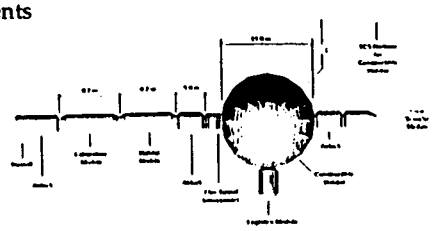

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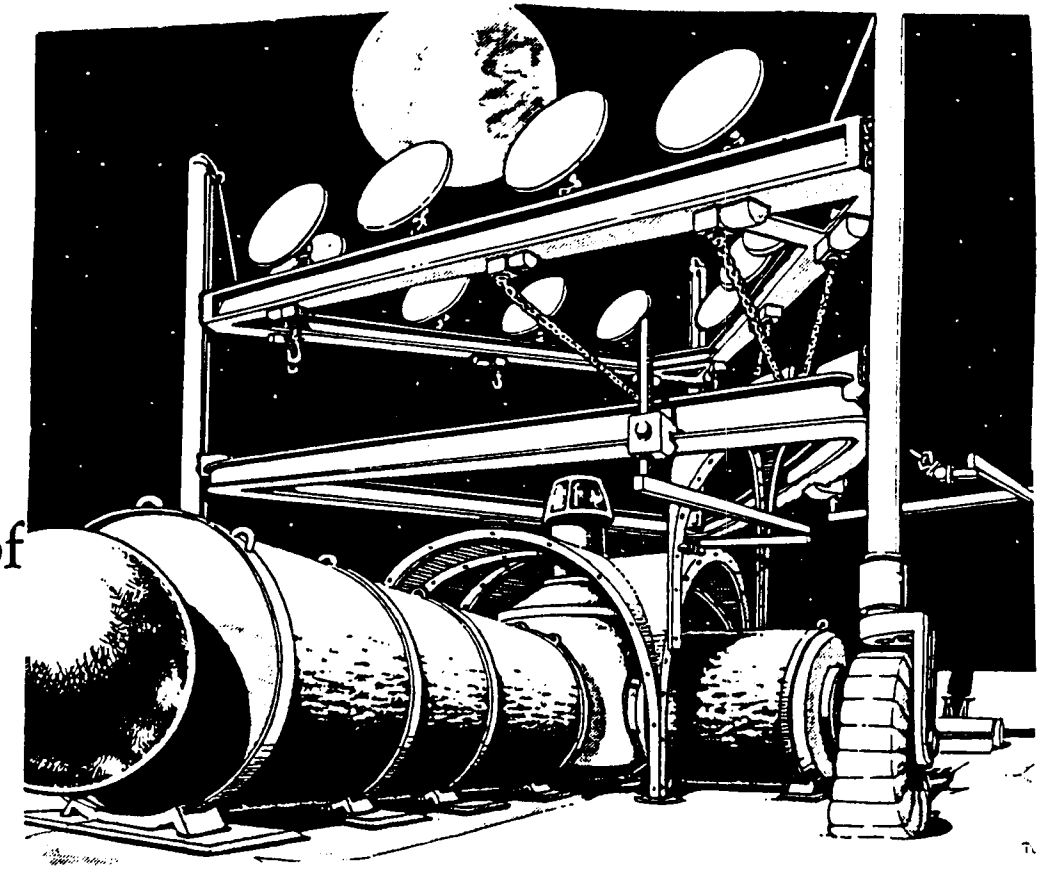
Category	Element (flights 01 -08)	Construction Task Code
Structures	SSF Habitation Module	OL, ST, Em, SW, SA,Tst
	Airlock	OL, ST, Em, SW, SA,Tst
	LEV Servicer	OL, ST, Tst
	Optical Telescope	OL, ST, Em, SW, SA,Tst
	UV-Visible Telescope	OL, ST, Em, SW, SA,Tst
	Constructible Tunnel	OL, ST, Em, SW, SA,Tst
	ISRU	OL, ST, Em, SW, SA,Tst
	UV Visible Telescope	OL, ST, Em, SW, SA,Tst
	Const Hab LSS	OL, ST, Em, SW, SA,Tst
	Const. Log. Module	OL, ST, Em, SW, SA,Tst
	Const. Hab / Air supply	OL, ST, Em, SW, SA,Tst
	Const. Hab Outfitting	OL, ST, Em, SW, ShA,Tst
	Const. Hab Structure	OL, ST, Em, SW, SA,Tst
Power	Three PV array / Regen. Fuel Cell	OL,ST, SA,Tst
	SP-100 reactor (Dynamic)	OL, ST , Em , SW, SA,Tst

Category	Element (flights 01 -08)	Construction Task Code
Thermal Systems	Module TCS	OL,ST,ShA,Tst
	Hab Module Radiators	OL,ST,Em,SW,SA,Tst
	Const. Hab TCS	OL,ST,Em,SW,SA,Tst
	Thermal Tents	OL,ST,SA,Tst
Communications	Communication equipment	OL,ST,Em,SW,SA,OA,Tst
Shielding	Regolith in bags hanging from modules	Em,SW,SA
	Regolith in bags wrapped around Hab	Em,SW,SA
Pads	Preliminary Site Preparation	SW
	Service Site Preparation	SW
Roads	Hab.Landing Pad Road (1km)	SW
	Hab/ Power Site Road (1km)	SW
	ISRU Road (750m)	SW
Site Topography	00 Hab Module Site Preparation	SW
	00 PV Site Preparation	SW
	00 Preliminary SP100 Site Preparation	SW
	02 Lab/ Airlock Site Preparation	SW
	04 ISRU Site Preparation	SW
	08 Const Hab Site Preparation	SW
Vehicles and Mobile Equipment	LEVPU	OL
	Attachments	OL, SA
	Unpressurized Rovers	OL

Combined Construction Alternatives (Case Studies 1 - 4)

The Process

- Gathered stated construction methods from each study
- Eliminated redundancies
- Described in terms of standard set of construction operations.



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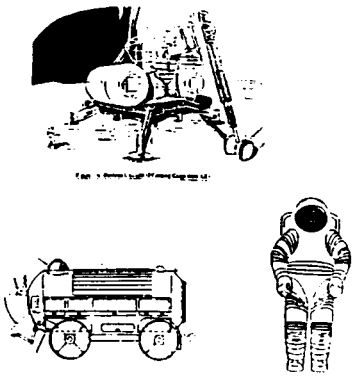

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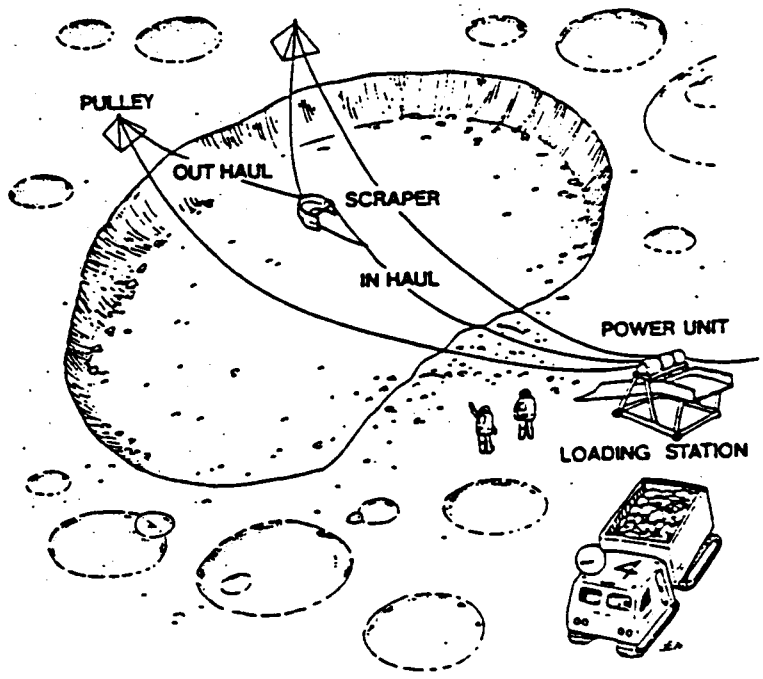
Category	Method / Alternative	Source
Emplacement	LEVPU (mobile crane)	90-Day
	Auto-deploy, EVA Crew	LLNL
	Self landing, Adjustable footpads	LaRC ET, Other (SICSA)
Site Work	LEVPU (mobile crane, grader, front-end loader backhoe, drill rig)	90-Day
	EVA Crew, Trenching machine	LLNL
	Bucket scoop conveyor	LaRC ET
	Bucket type mining machine	Other (Shimizu)
Shirt Sleeve Assy.	Shirt-sleeve Crew	90-Day, LLNL, LaRC, Other (Shimizu)
Offload Material	LEVPU (mobile crane, manipulators)	90-Day
	Air bag eject, EVA Crew	LLNL
Orbital Assembly	Auto-deploy	LLNL
	EVA Crew, Shirt-sleeve crew, Telerobots	LaRC ET

Category	Method / Alternative	Source
Surface Assy.	EVA Crew, Shirt-sleeve Crew, Telerobots	LaRC ET
	LEVPU (mobile crane, manipulator arms)	90 Day
	Pre-fab, Inflatables, Air bag eject	LLNL
	EVA Crew	90 Day, LLNL, LaRC ET
Surface Transport	LEVPU (mobile crane)	90 Day
	Snow blower, EVA Crew, Hop-about, Tractors	LLNL
	Bucket scoop conveyor	LaRC ET
	Conveyor belt assembly	Other (Shimizu)
Test and Verify	Crew	90 Day, LLNL
	Automated	LLNL



Now What ?

- **With all this combined information** the Team sat down and brainstormed every possible construction requirement

- **Each "requirement" was then tested for criticality** by asking the following question: " Does the fulfilling of this so-called requirement in of itself enable the choice of one construction method over another or one tool (system) over another, i.e. does the requirement represent a discriminating parameter?"

- **If the answer to the question was "yes"** then the requirement was retained as being significant to constructability analysis of a Phase A design. **Likewise if the answer was "no"** then it is not a critical issue to the constructabiltiy analysis of Phase A designs.

- **Each requirement that survived this "screeening"** (and there weren't many compared to the original list) was then cast in the form of a question to ask of the Phase A design, as will be seen in the remaining presentation.

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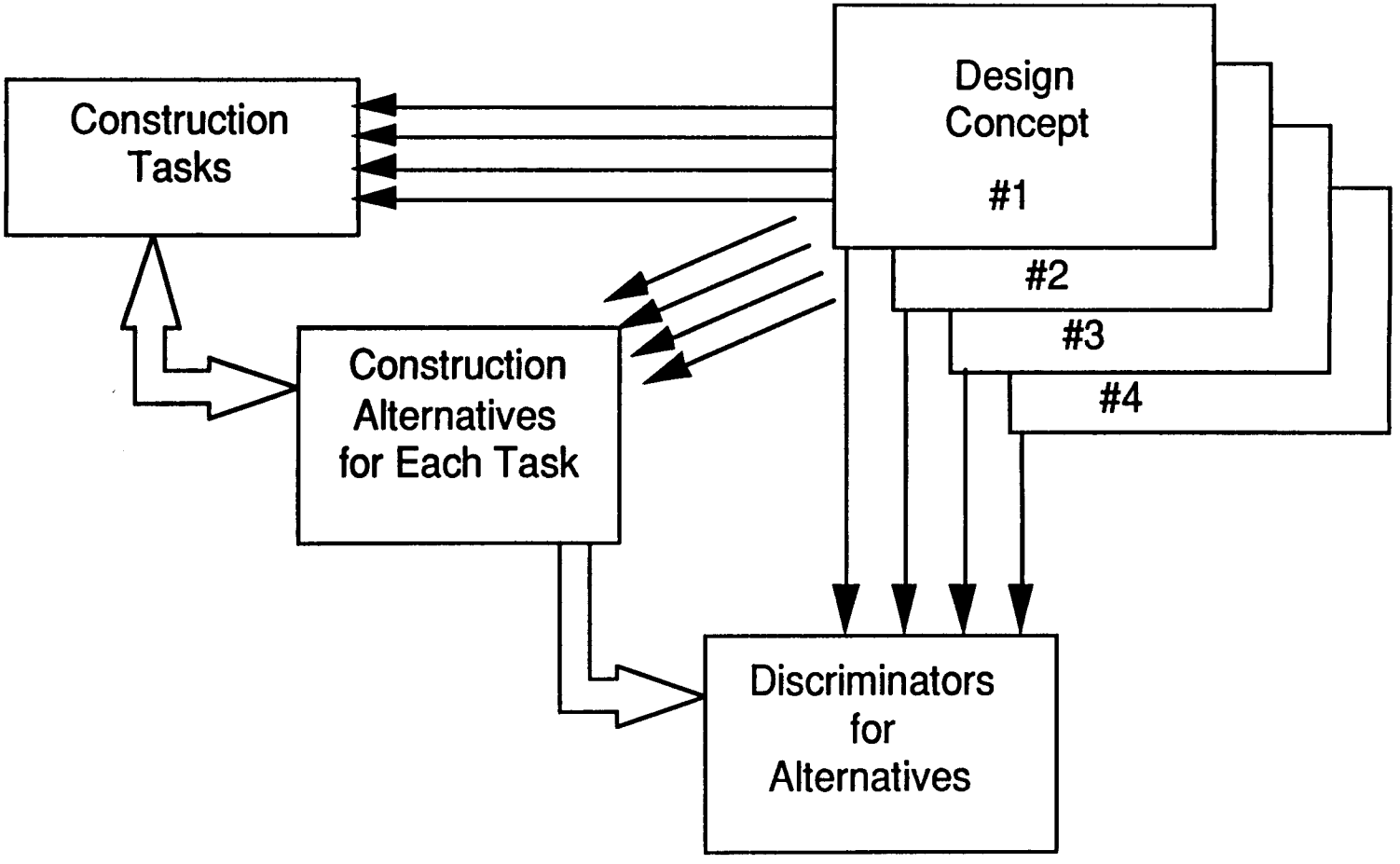
Process

- Review the entire list of questions
- Identify the discriminators which allow a comparison among alternatives
- For each discriminator, identify the breakpoints (if any) that force the choice of one alternative over another
- Evaluate each study on the basis of completeness

  (i.e. is there enough information contained in the study to assess its constructibility relative to the other studies being considered?)

Lunar Base Construction Study: Discovery of Discriminators



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Example of a Discriminator

Task	Possible Alternatives	Discriminators
Surface Transport of Regolith	Bucket (LEVPU) (90-Day) Conveyors (Shimizu, LaRC) Dump Truck (CSC) Sno-Blower (LLNL) EVA Human	Volume Max. Distance

Example of Discriminator Questions

- What volume of regolith must be transported on the surface?
- What is the maximum distance it must be moved?

These are legitimate questions to be asked at the Phase A level.

Furthermore, they must be answered in order to design and select a construction system for a given mission design.

Evaluation of Existing Studies

Construction Requirement / Study	90-Day	Lawrence Livermore	Langley External Tank
1.1.1 Area to be graded/levelled	Specified	NA	
1.1.2 Surface variance less than **X**	Derivable		
1.1.3 Max. Surface Density (Bearing Capacity)			
1.2.1 Total volume to be excavated	Derivable	Derivable	Derivable
1.2.2 Max. depth to be excavated	Specified	NA	NA
1.2.3 Type of material to be excavated	Specified	Derivable	Derivable
1.2.4 Vertical and horizontal base layout	Specified		
2.1.1 Max. dimensions of cargo to be surf. trans.	Specified		
2.1.2 Max. mass of cargo to be surf. transported	Specified		Derivable
2.1.3 Types of cargo to be surface transported	Specified		Derivable
2.1.4 Max. distance cargo is to be surf. trans.	Specified		
2.2.1 Max. distance to transport humans	Derivable		
2.2.2 Max. time to transport humans	Derivable		
2.3.1 Volume of regolith to be transported		Derivable	Derivable
2.3.2 Max. distance regolith is to be transported	Derivable	Derivable	Derivable

Evaluation of Existing Studies

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Construction Requirement / Study	90-Day	Lawrence Livermore	Langley External Tank
1.1.1 Area to be graded/levelled	Specified	NA	
1.1.2 Surface variance less than X	Derivable		
1.1.3 Max. Surface Density (Bearing Capacity)			
1.2.1 Total volume to be excavated	Derivable	Derivable	Derivable
1.2.2 Max. depth to be excavated	Specified	NA	NA
1.2.3 Type of material to be excavated	Specified	Derivable	Derivable
1.2.4 Vertical and horizontal base layout	Specified		
2.1.1 Max. dimensions of cargo to be surf. trans.	Specified		
2.1.2 Max. mass of cargo to be surf. transported	Specified		Derivable
2.1.3 Types of cargo to be surface transported	Specified		Derivable
2.1.4 Max. distance cargo is to be surf. trans.	Specified		
2.2.1 Max. distance to transport humans	Derivable		
2.2.2 Max. time to transport humans	Derivable		
2.3.1 Volume of regolith to be transported		Derivable	Derivable
2.3.2 Max. distance regolith is to be transported	Derivable	Derivable	Derivable

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Evaluation of Existing Studies

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Construction Requirement / Study	90-Day	Lawrence Livermore	Langley External Tank
3.1.1 Max. mass of cargo offloaded from lander	Specified	Specified	Derivable
3.1.2 Max. dim. of cargo offloaded from lander	Specified		
3.1.3 Types of cargo to be offloaded from lander	Specified	Derivable	Derivable
3.1.4 Dimensions of lander	Specified		
3.2.1 Max. mass of cargo offloaded from surf. tran.	Specified		
3.2.2 Max. dim. of cargo offloaded from surf. trans.	Specified		Derivable
3.2.3 Types of cargo offloaded from surf. trans.	Specified		Derivable
3.2.4 Dimensions of surface trans. vehicle	Specified		
4.1.1 Max. mass of cargo to be emplaced	Specified	Specified	Derivable
4.1.2 Cargo placement precisions less than X			
4.1.3 Max. dimensions of cargo to be emplaced	Derivable		
4.1.4 Types of cargo to be emplaced	Specified		Derivable
4.1.5 Vertical and horizontal base layout	Specified	NA	
4.2.1 Volume of regolith to be emplaced	Specified	Derivable	Specified
4.2.2 Vertical and horizontal base layout	Specified	NA	

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Construction Requirement / Study	90-Day	Lawrence Livermore	Langley External Tank
4.2.3 Regolith emplacement precision less than X	Derivable	Derivable	Derivable
4.2.4 Density of placed regolith greater than X	Derivable	Specified	
4.2.5 Dust Tolerance of base component			
5.1.1 Type and number of surf. assy. connections			
5.1.2 Force req. for surf. assy. conn. less than X			
5.1.3 Surf. assy. connection precisions less than X			
5.1.4 Communication available (bandwidth, RTLT)	Specified		
5.2.1 Type and num. of surf. assy. disconnections			
5.2.2 Force req. for surf. assy. discon. less than X			
5.2.3 Surf. assy. discon. precisions less than X			
5.2.4 Communication available (bandwidth, RTLT)	Specified		
5.3.1 Type and num. of deploy. meth. of surf. assy.	Specified	Specified	
5.3.2 Force req. for surf. assy. deploy less than X			
5.3.3 Surf. assy. deploy. precisions less than X			
5.3.4 Communication available (bandwidth, RTLT)	Specified		

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Construction Requirement / Study	90-Day	Lawrence Livermore	Langley External Tank
5.4.1 Type and num. of surf. assy. stow methods			
5.4.2 Force req. for surf. assy. stowage less than X			
5.4.3 Surf. assy. deploy. precisions less than X			
5.4.4 Communication available (bandwidth, RTLT)	Specified		
6.1.1 Type and number of ss. assy. connections			
6.1.2 Force req. for ss. assy. connects less than X			
6.1.3 Ss. assy. connection precisions less than X			
6.1.4 Communication available (bandwidth, RTLT)	Specified		Derivable
6.2.1 Type and num. of ss. assy. disconnections			
6.2.2 Force req. for ss. assy. discon. less than X			
6.2.3 Ss. assy. discon. precisions less than X			
6.2.4 Communication available (bandwidth, RTLT)	Specified		Derivable
6.3.1 Type and num. of deploy. meth. of ss. assy.			
6.3.2 Force req. for ss. assy. deploy. less than X			
6.3.3 Ss. assy. deploy. precisions less than X			

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Evaluation of Existing Studies

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Construction Requirement / Study	90-Day	Lawrence Livermore	Langley External Tank
6.3.4 Communication available (bandwidth, RTLT)	Specified		Derivable
6.4.1 Type and num. of ss. assy. stow methods			
6.4.2 Max. force required for ss. assy. stowage			
6.4.3 Ss. assy. stowage precisions less than X			
6.4.4 Communication available (bandwidth, RTLT)	Specified		Derivable
7.1.1 Type and number of orb. assy. connections	NA	NA	
7.1.2 Force req. for orb. assy. conn. less than X	NA	NA	
7.1.3 Orb. assy. connect. precisions less than X	NA	NA	
7.1.4 Communication available (bandwidth, RTLT)	NA	NA	Derivable
7.2.1 Type and num. of orb. assy. disconnects	NA	NA	Specified
7.2.2 Force req. for orb. assy. discon. less than X	NA	NA	Derivable
7.2.3 Orb. assy. discon. precisions less than X	NA	NA	
7.2.4 Communication available (bandwidth, RTLT)	NA	NA	Derivable
7.3.1 Type and num. of deploy. meth. of orb. assy.	NA	NA	
7.3.2 Force req. for orb. assy. deploy. less than X	NA	NA	Derivable

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Evaluation of Existing Studies

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Construction Requirement / Study	90-Day	Lawrence Livermore	Langley External Tank
7.3.3 Orb. assy. deploy. precisions less than X	NA	NA	
7.3.4 Communication available (bandwidth, RTLT)	NA	NA	Derivable
7.4.1 Type and num. of orb. assy. stow methods	NA	NA	
7.4.2 Force req. for orb. assy. stowage less than X	NA	NA	
7.4.3 Orb. assy. stowage precisions less than X	NA	NA	
7.4.4 Communication available (bandwidth, RTLT)	NA	NA	Derivable
7.5.1 Volume of orb. assy. scrap to be managed	NA	NA	Derivable
7.5.2 Particle dimensions of orb. assy. scrap	NA	NA	
7.5.3 Worksite volume	NA	NA	
7.5.4 Assembly orbit	NA	NA	Specified
8.1.1 TBD			
9.1.1 TBD			

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The Addition of the Boeing "Robotic Lunar Surface Operations" Study

- Only one of the studies to address logistics, spares, etc., in any detail
- Good treatment of issues dealing directly with robotics (e.g. connection types, material handling, etc.)
- From the point of view of a constructibility analysis, the study is indeterminate

Conclusions

- Studies vary greatly in their degree of completeness
- None may be considered complete enough to assess constructibility
- The use of a list of discriminator questions would place competing missions on common ground
- The breakpoints within the discriminator classifications must be identified and, if possible, quantified

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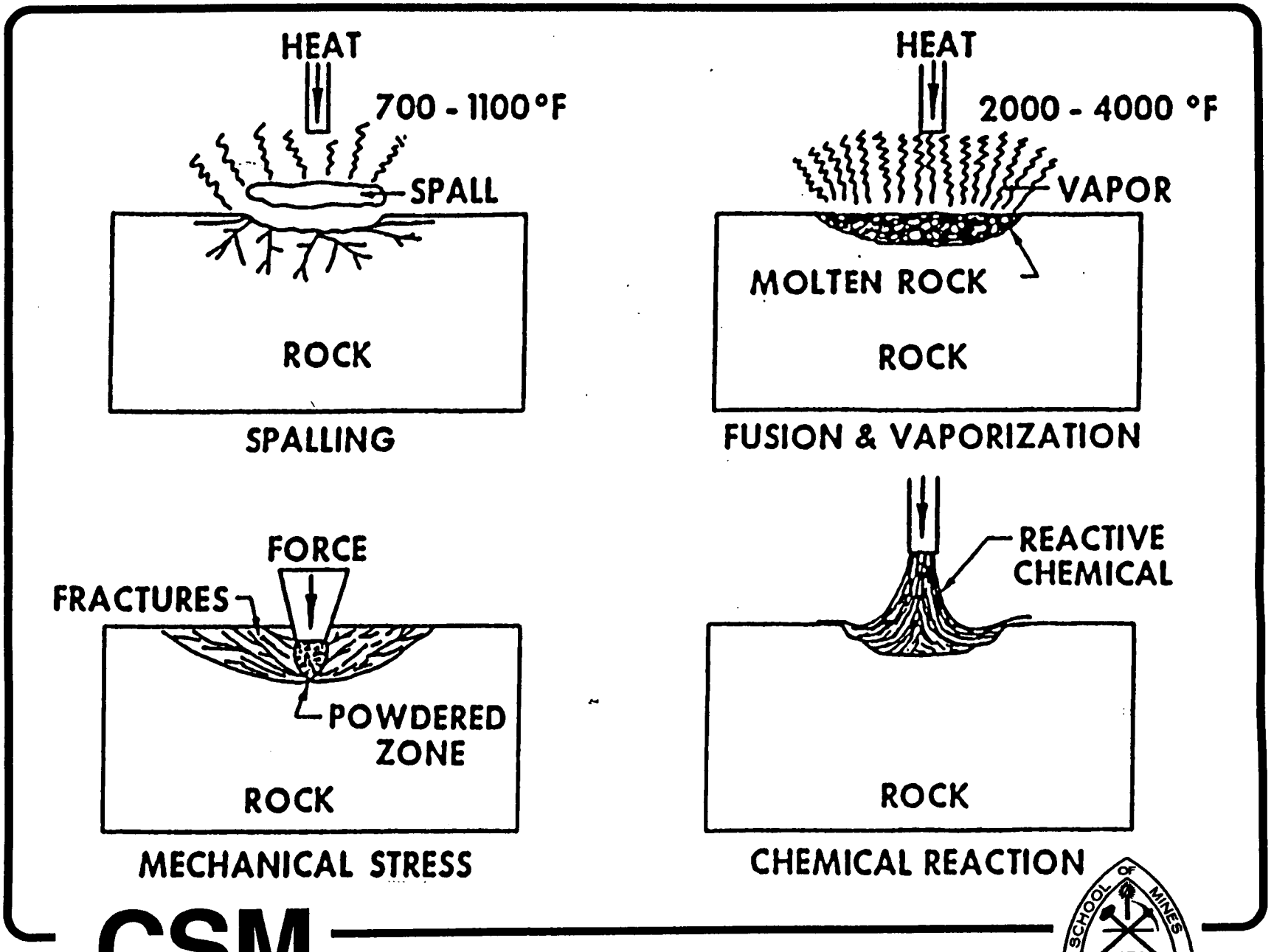
LUNAR CONSTRUCTION/MINING EQUIPMENT

Dr. Levent Ozdemir†

For centuries, mining has utilized drill and blast as the primary method of rock excavation. Although this technique has undergone significant improvements, it still remains a cyclic, labor intensive operation with inherent safety hazards. Other drawbacks include damage to the surrounding ground, creation of blast vibrations, rough excavation walls resulting in increased ventilation requirements and the lack of selective mining ability.Perhaps the most important shortcoming of drill and blast is that it is not conducive to full implementation of automation or robotics technologies. Numerous attempts have been made in the past to automate drill and blast operations to remove personnel from the hazardous work environment. Although most of the concepts devised look promising on paper, none of them was found workable on a sustained production basis. In particular, the problem of serious damage to equipment during the blasting cycle could not be resolved regardless of the amount of charge used in excavation. Since drill and blast is not capable of meeting the requirements of a fully automated rock fragmentation method, its role is bound to gradually decrease. Mechanical excavation, in contrast, is highly suitable to automation because it is a continuous process and does not involve any explosives..

Many of the basic principles and trends controlling the design of an Earth-based mechanical excavator will hold in an extraterrestrial environment such as on the Lunar surface. However, the economic and physical limitations for transporting materials to space will require major rethinking of these machines. In concept, then, a Lunar mechanical excavator will look and perform significantly different from what one would design for use here on Earth.

† Dr. Ozdemir is a Professor at the Colorado School of Mines, Department of Mining Engineering; Golden, Colorado 80401


HEAT
700 - 1100 °F
SPALL
ROCK
SPALLING
HEAT
2000 - 4000 °F
VAPOR
MOLTEN ROCK
ROCK
FUSION & VAPORIZATION
FORCE
FRACTURES
POWDERED ZONE
ROCK
MECHANICAL STRESS
REACTIVE CHEMICAL
ROCK
CHEMICAL REACTION
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ADVANTAGES OF MECHANICAL MINING

- Improved Safety
- Minimal Ground Disturbance
- Reduced Ground Support
- No Blast Vibrations
- Uniform Muck Size
- Reduced Ventilation Reguirements
- Increased Ore Recovery
- Selective Mining Capability
- Continuous Operation
- Conducive to Automation
- Higher Production Rates
- Reduced Mining Costs

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PRESENT SHORTCOMINGS OF HARD ROCK MECHANICAL MINERS

- Rate of Penetration
- Cutter Costs
- Adaptability to Changing Ground
- Shape of Opening
- Mobility
- Flexibility of Operation
- Capital Cost
- Adaptability of Current Mine Designs

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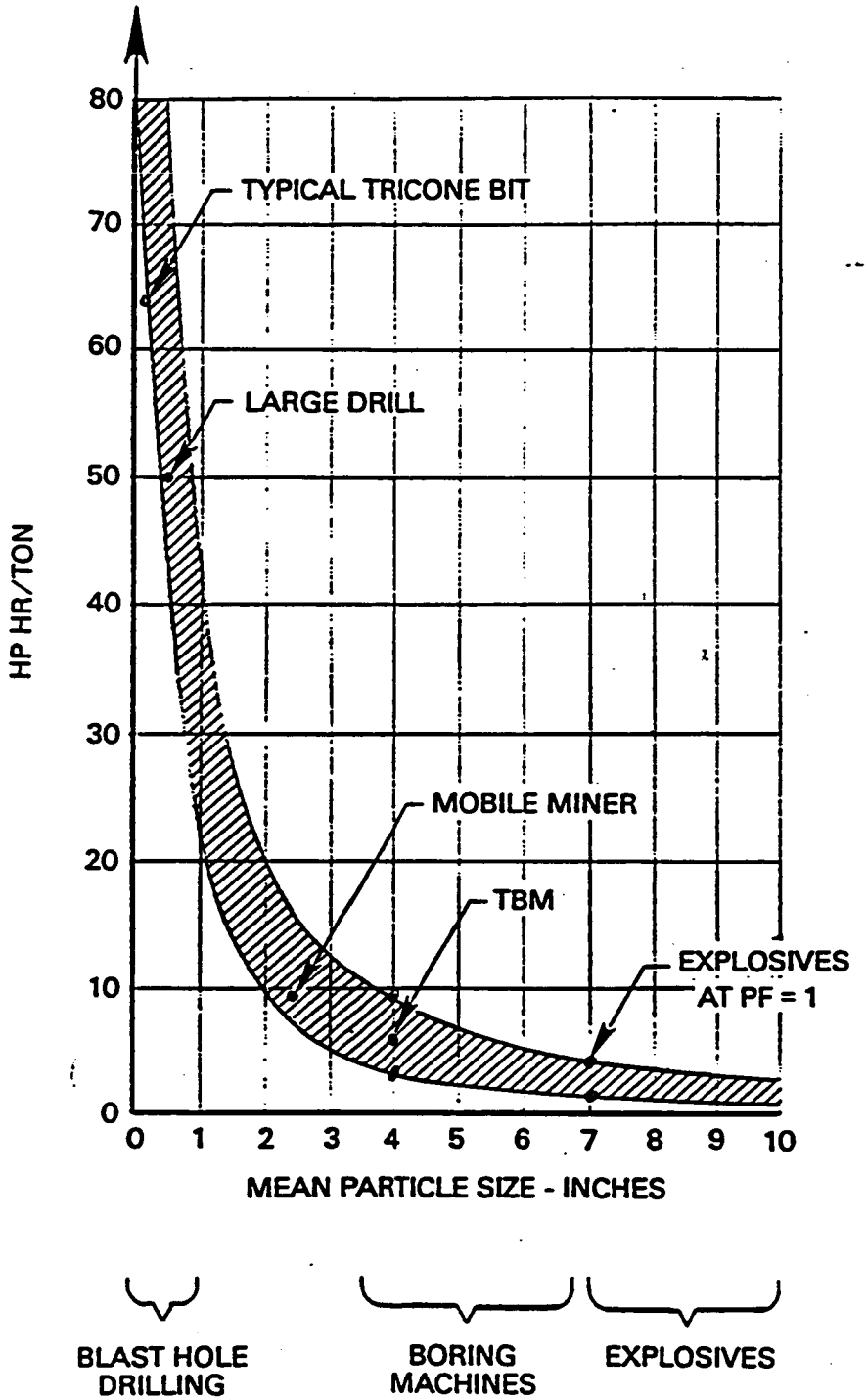
EXCAVATION POWER RELATED TO PARTICLE SIZE



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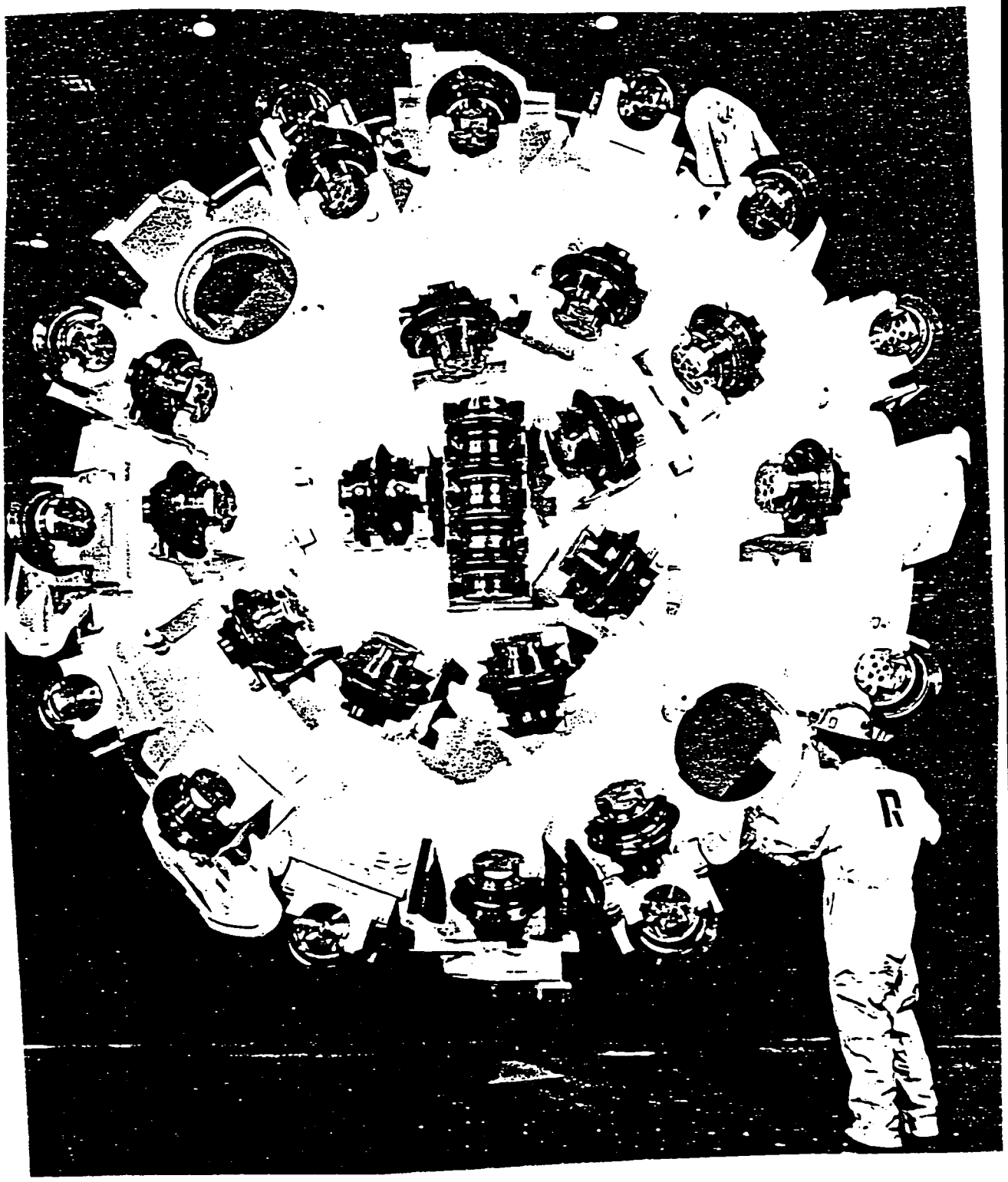

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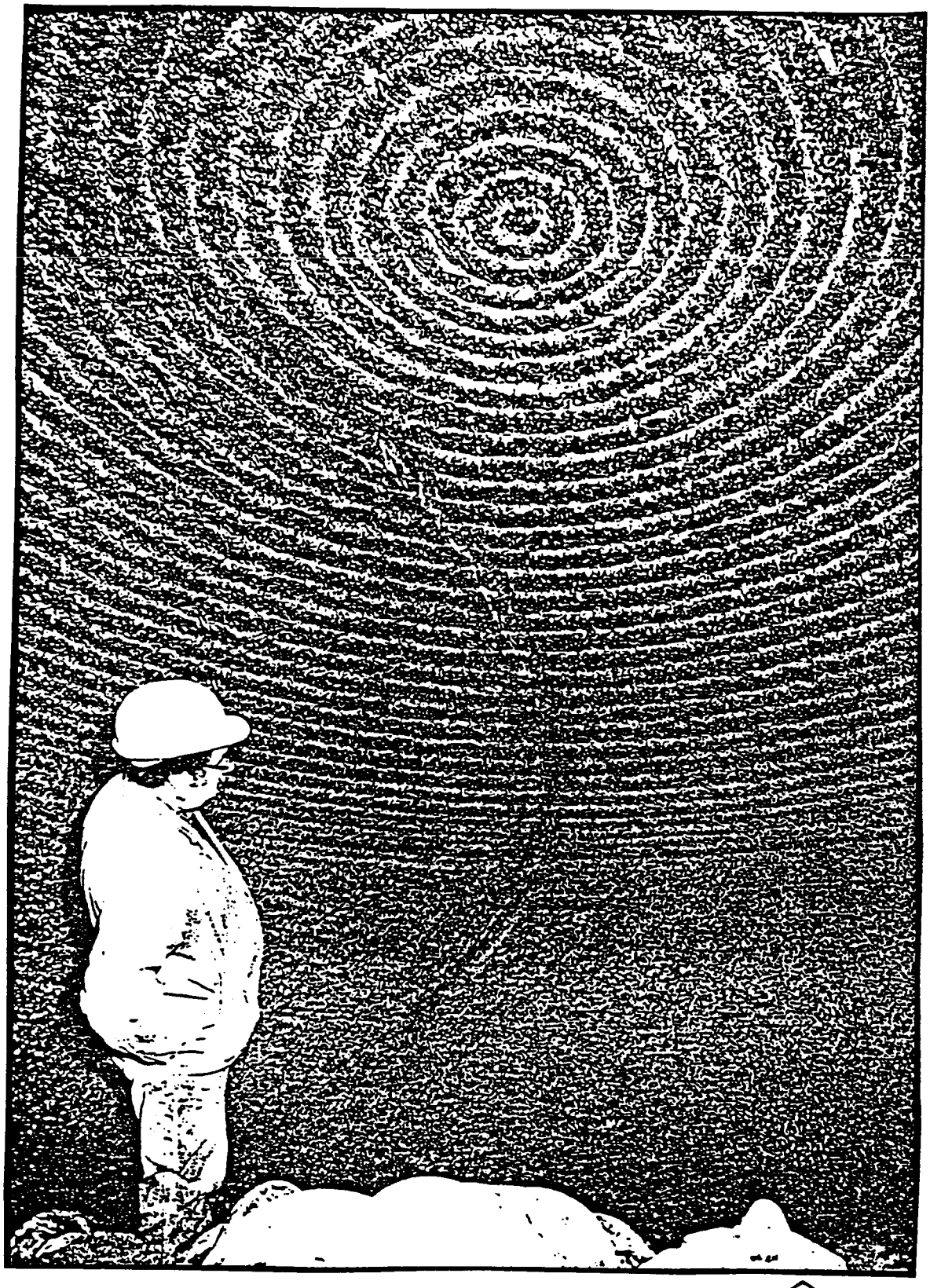

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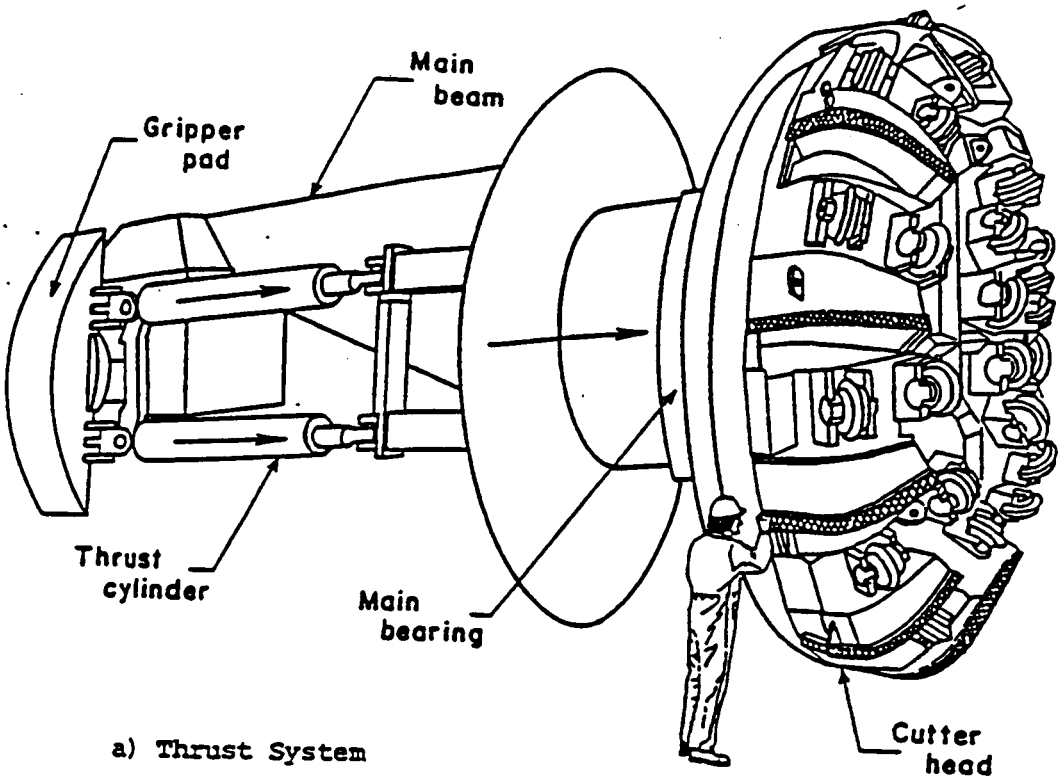
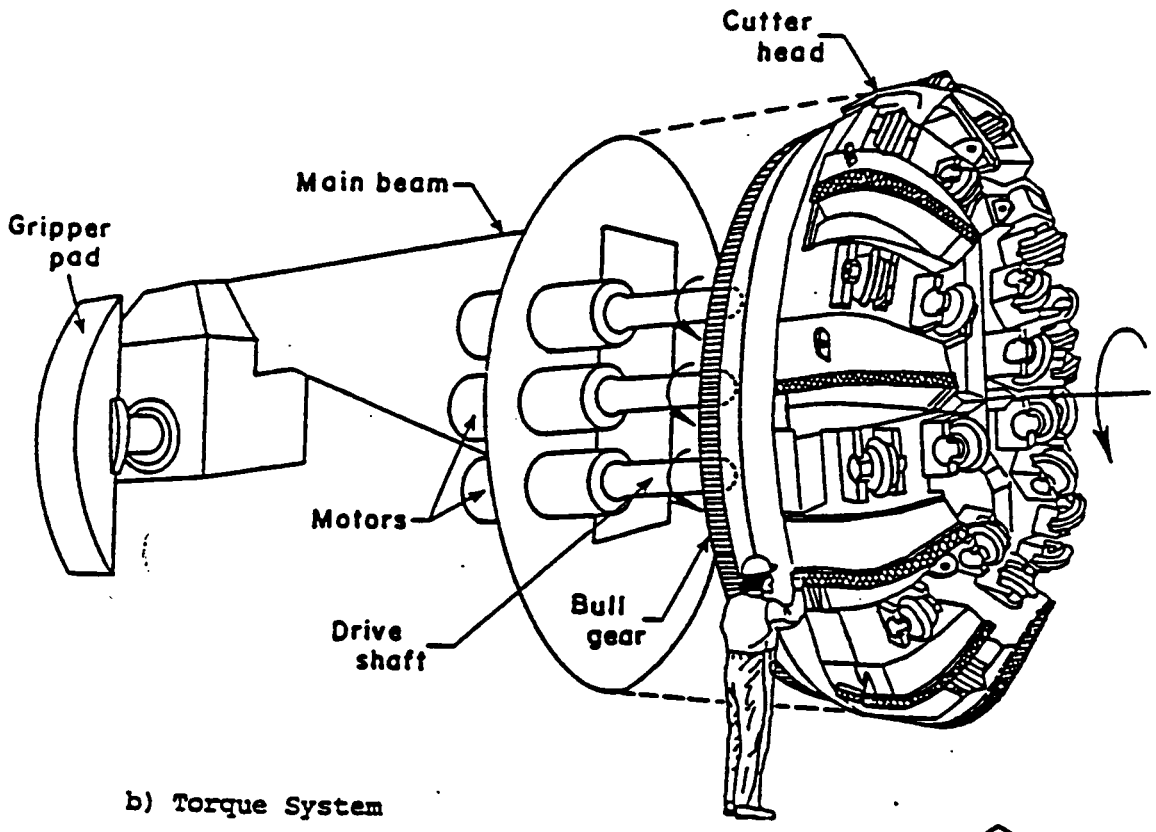


a) Thrust System



b) Torque System

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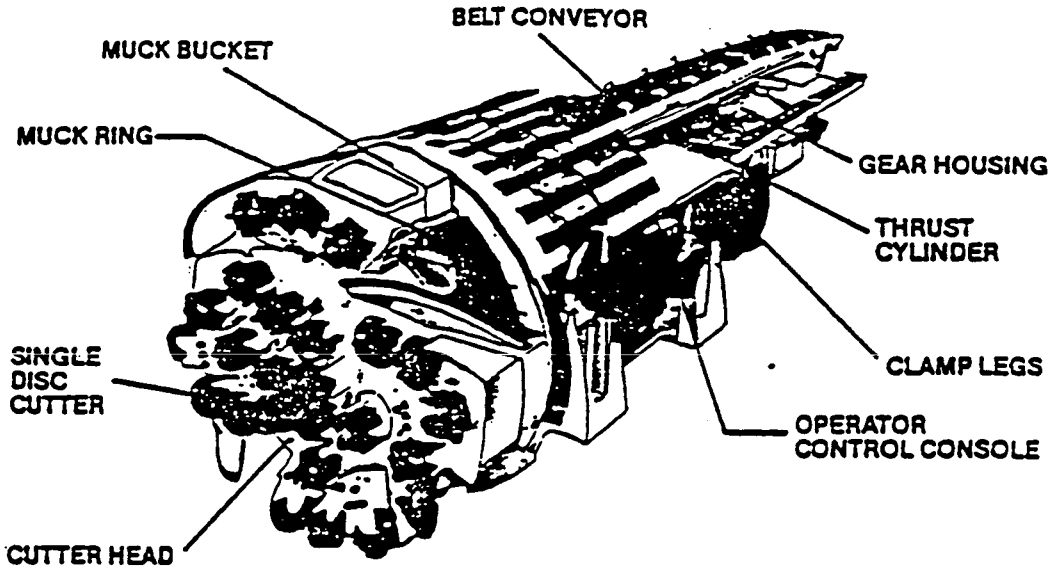
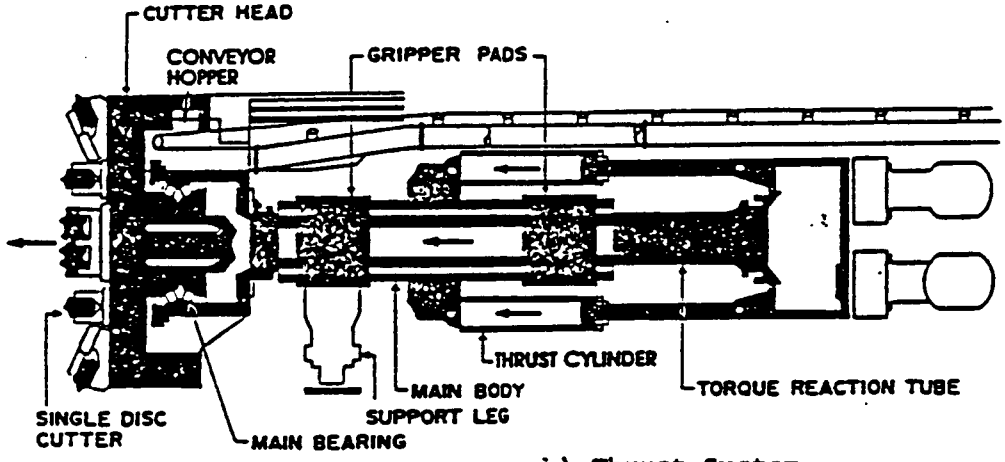
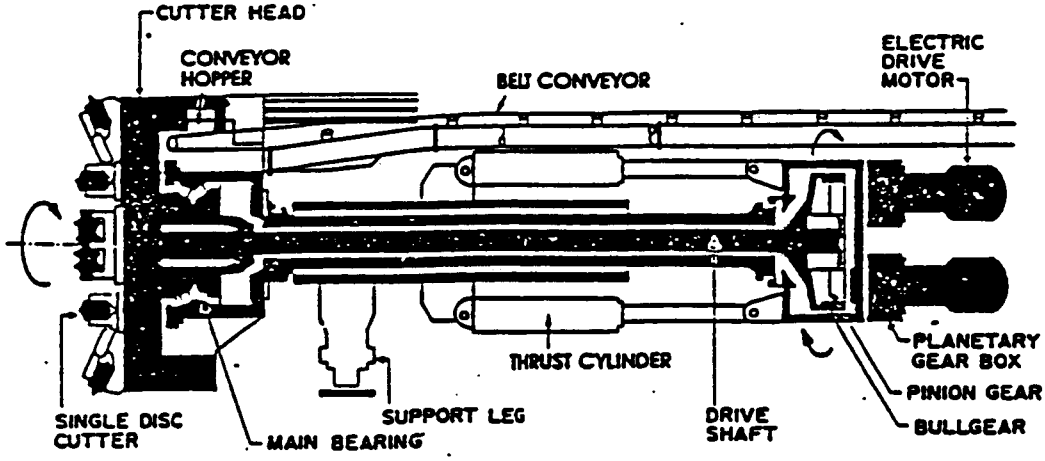


a)

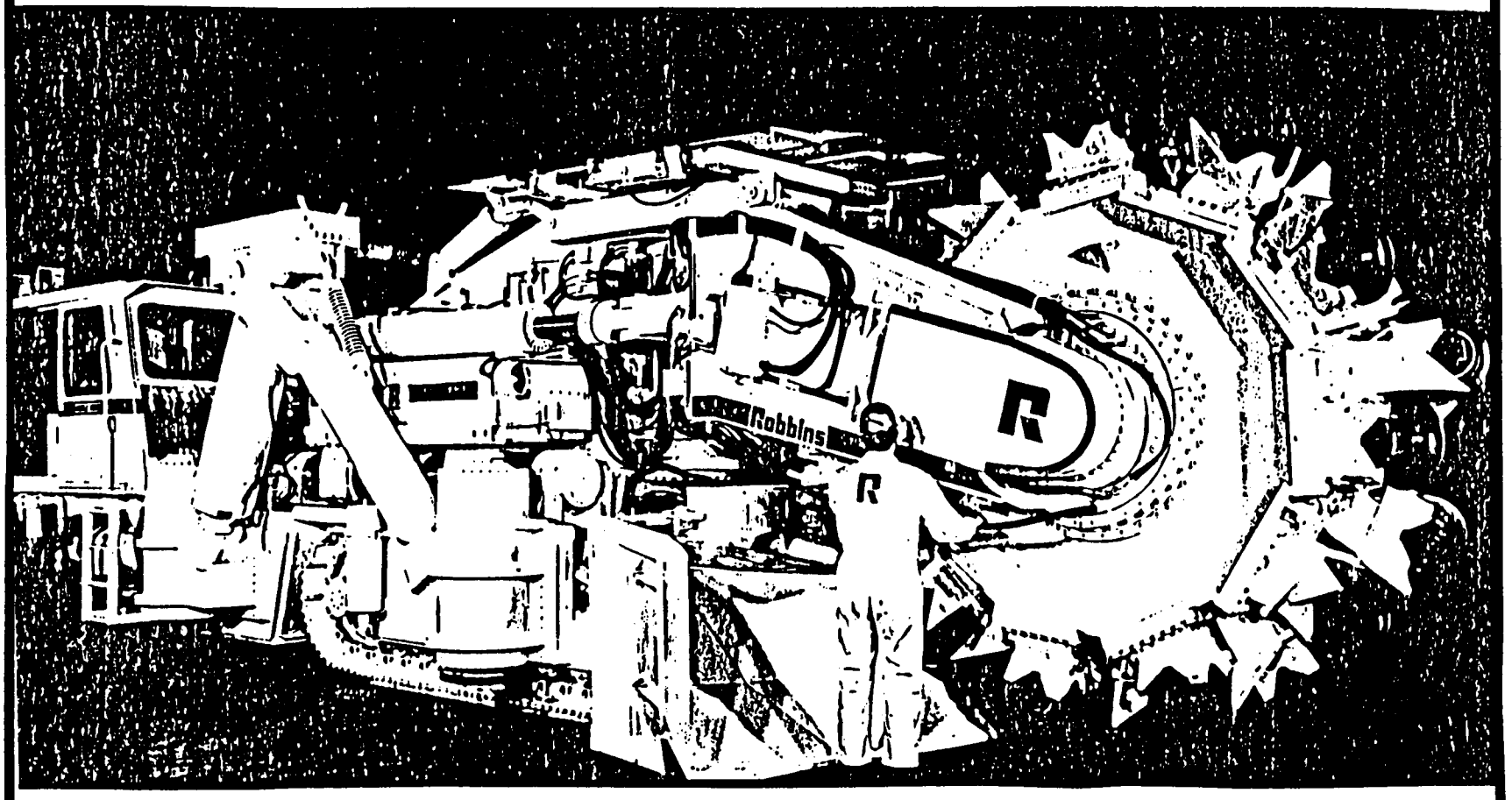


b) Thrust System



c) Torque System

CSM



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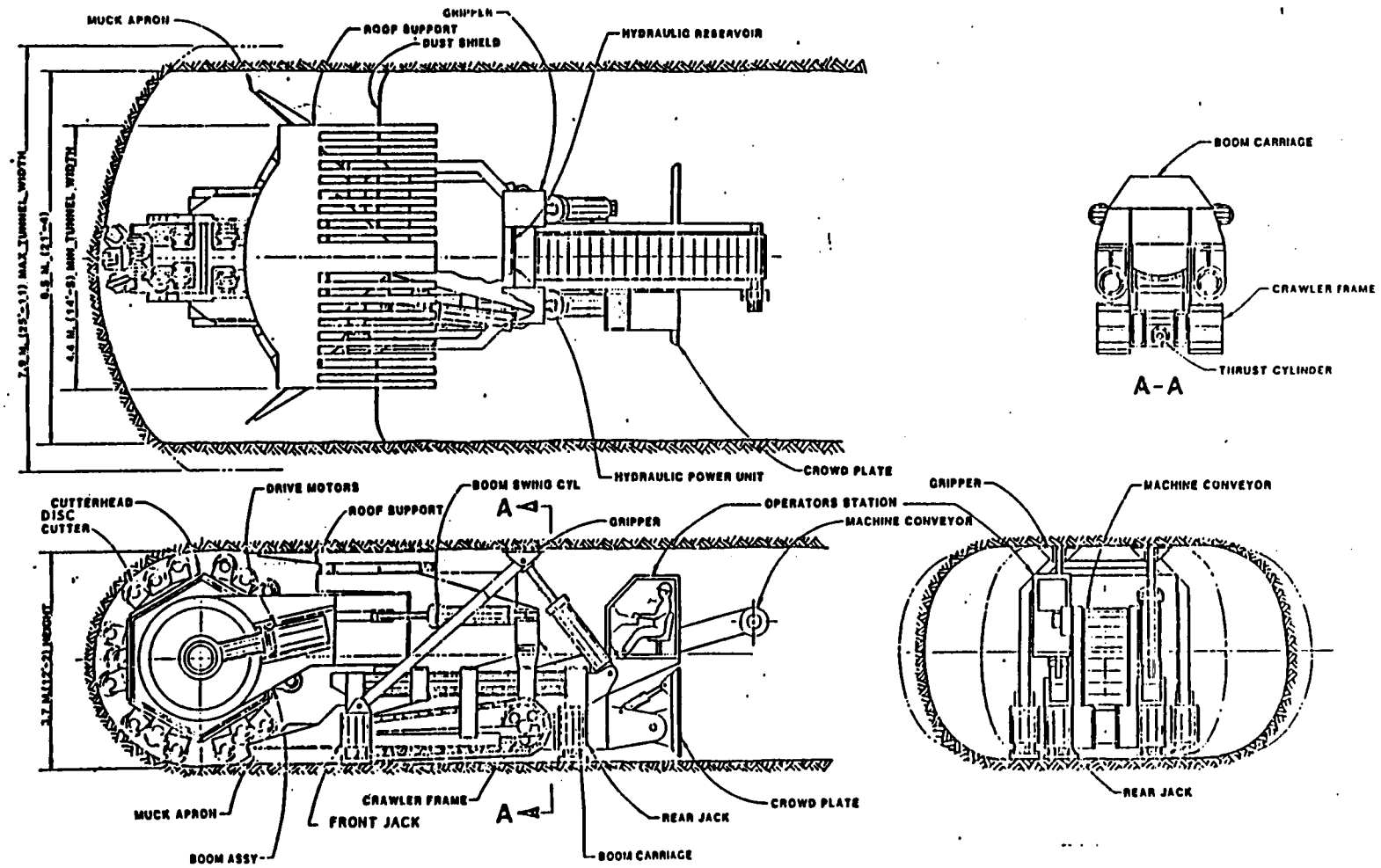
MUCK APRON
ROOF SUPPORT
DUST SHIELD
GRIPPER
HYDRAULIC RESERVOIR
HYDRAULIC POWER UNIT
CROWD PLATE
BOOM CARRIAGE
CRAWLER FRAME
THRUST CYLINDER
A-A
CUTTERHEAD
DISC
CUTTER
DRIVE MOTORS
ROOF SUPPORT
BOOM SWING CYL
A
GRIPPER
OPERATORS STATION
MACHINE CONVEYOR
MUCK APRON
FRONT JACK
CRAWLER FRAME
A
BOOM ASSY
BOOM CARRIAGE
REAR JACK
CROWD PLATE
GRIPPER
MACHINE CONVEYOR
REAR JACK

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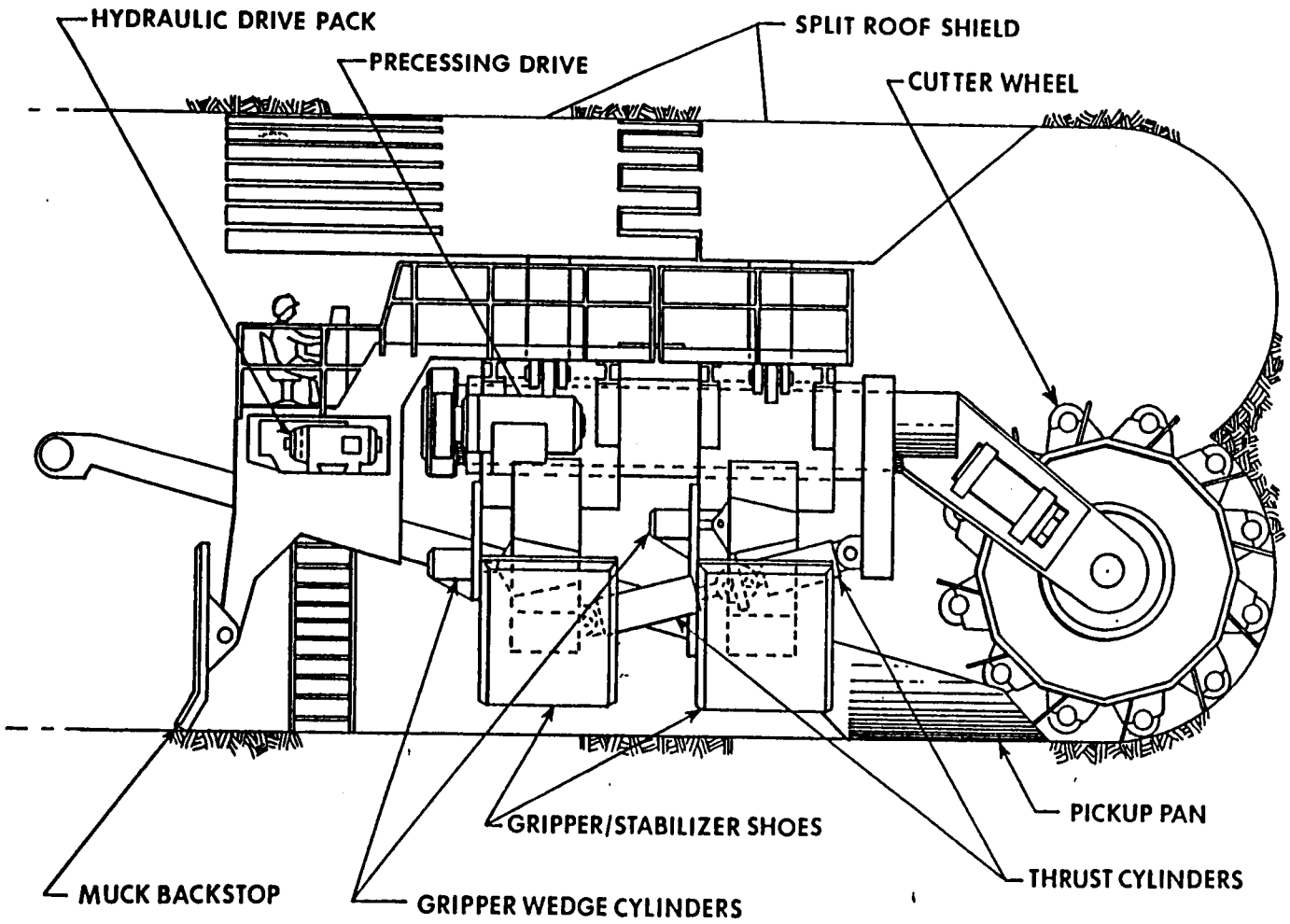
ROTARY MOBILE MINER



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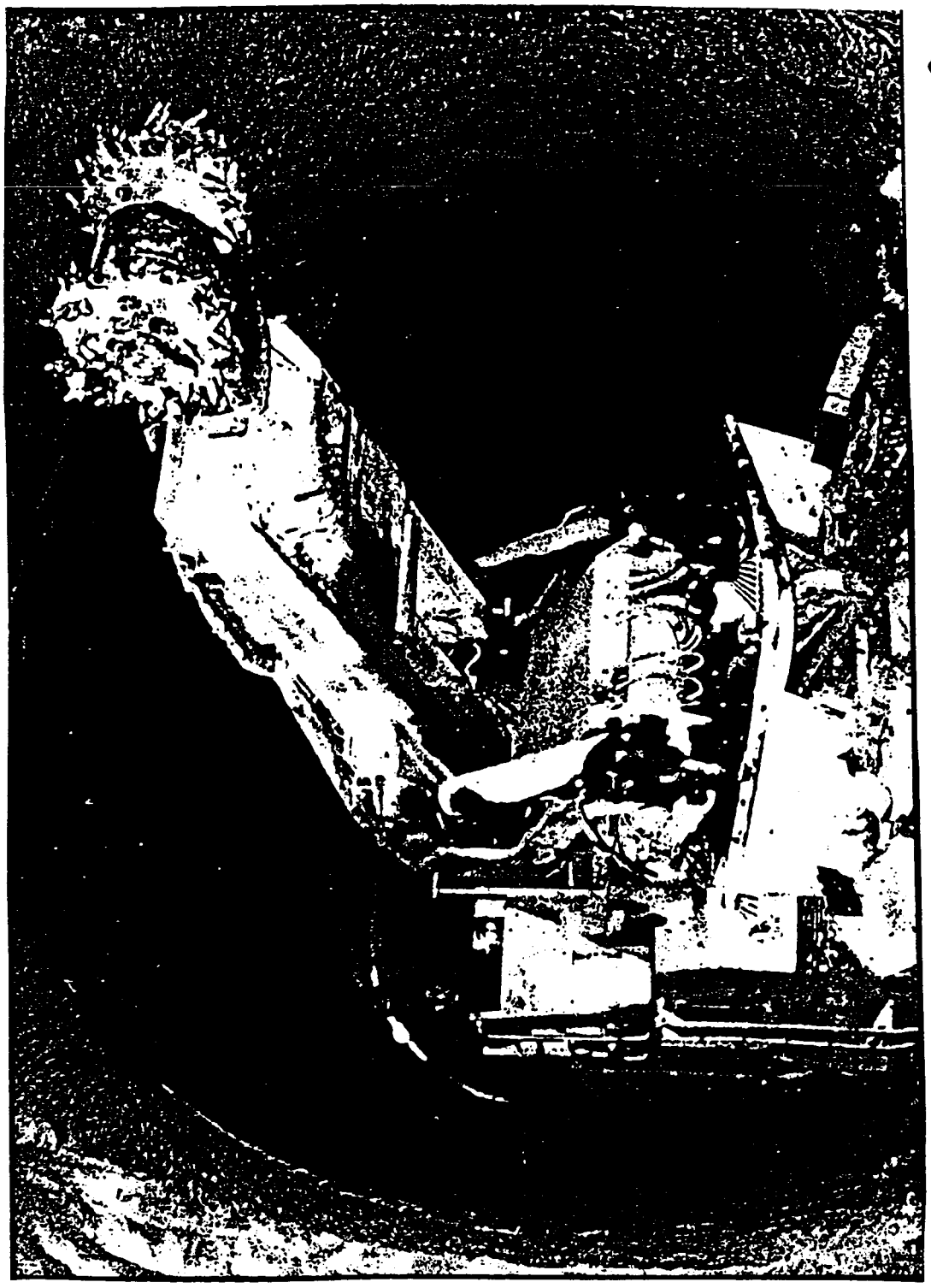

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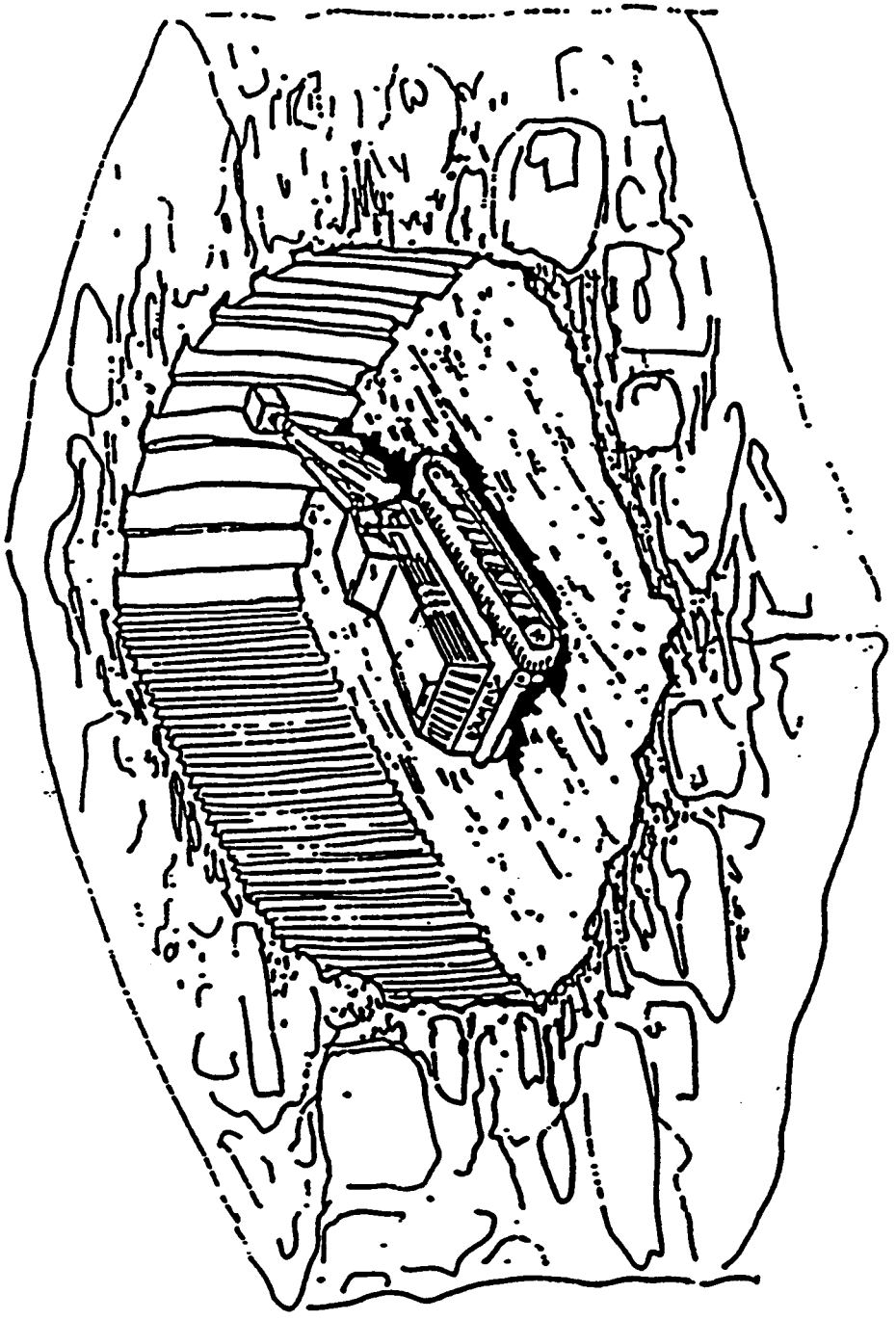

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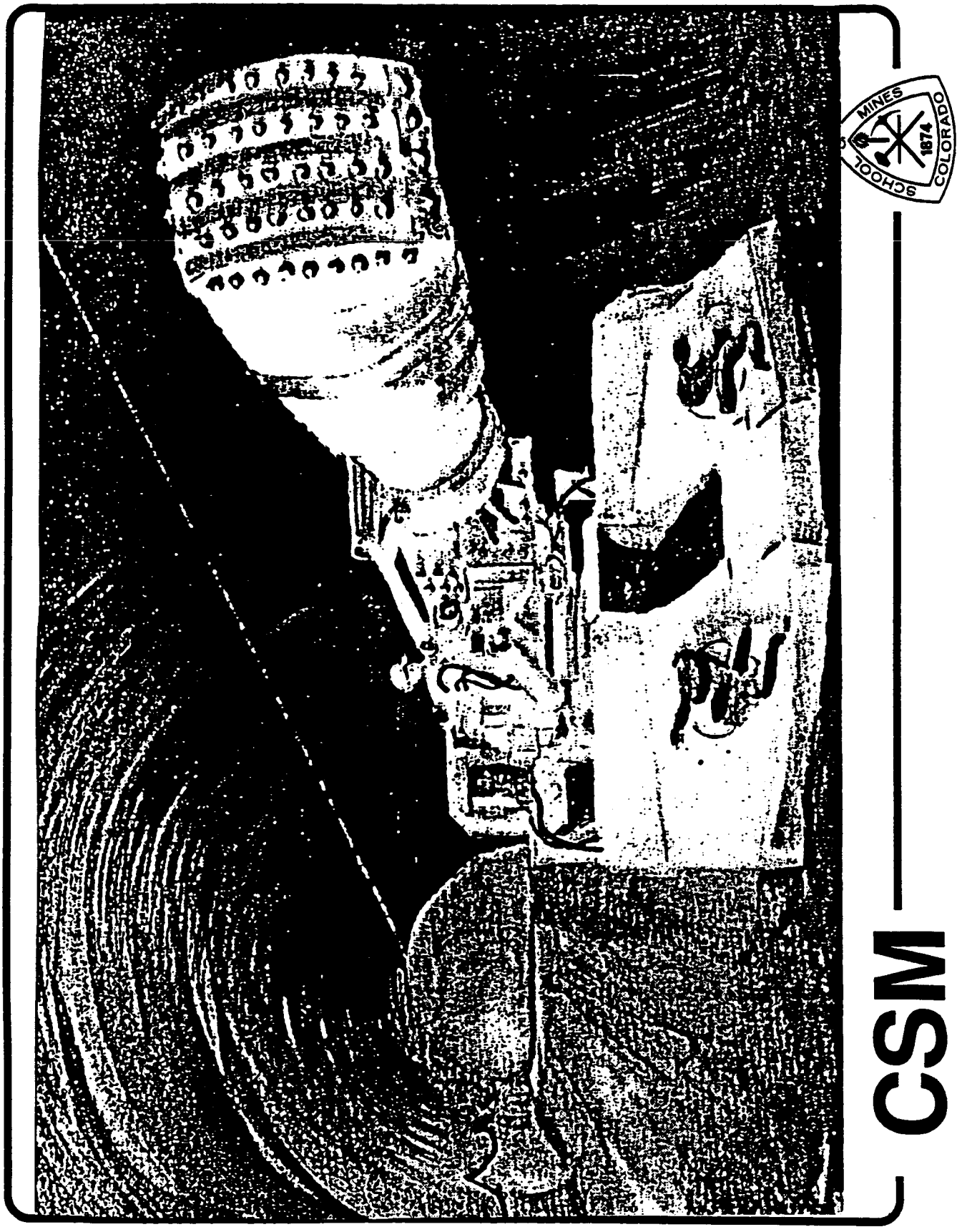
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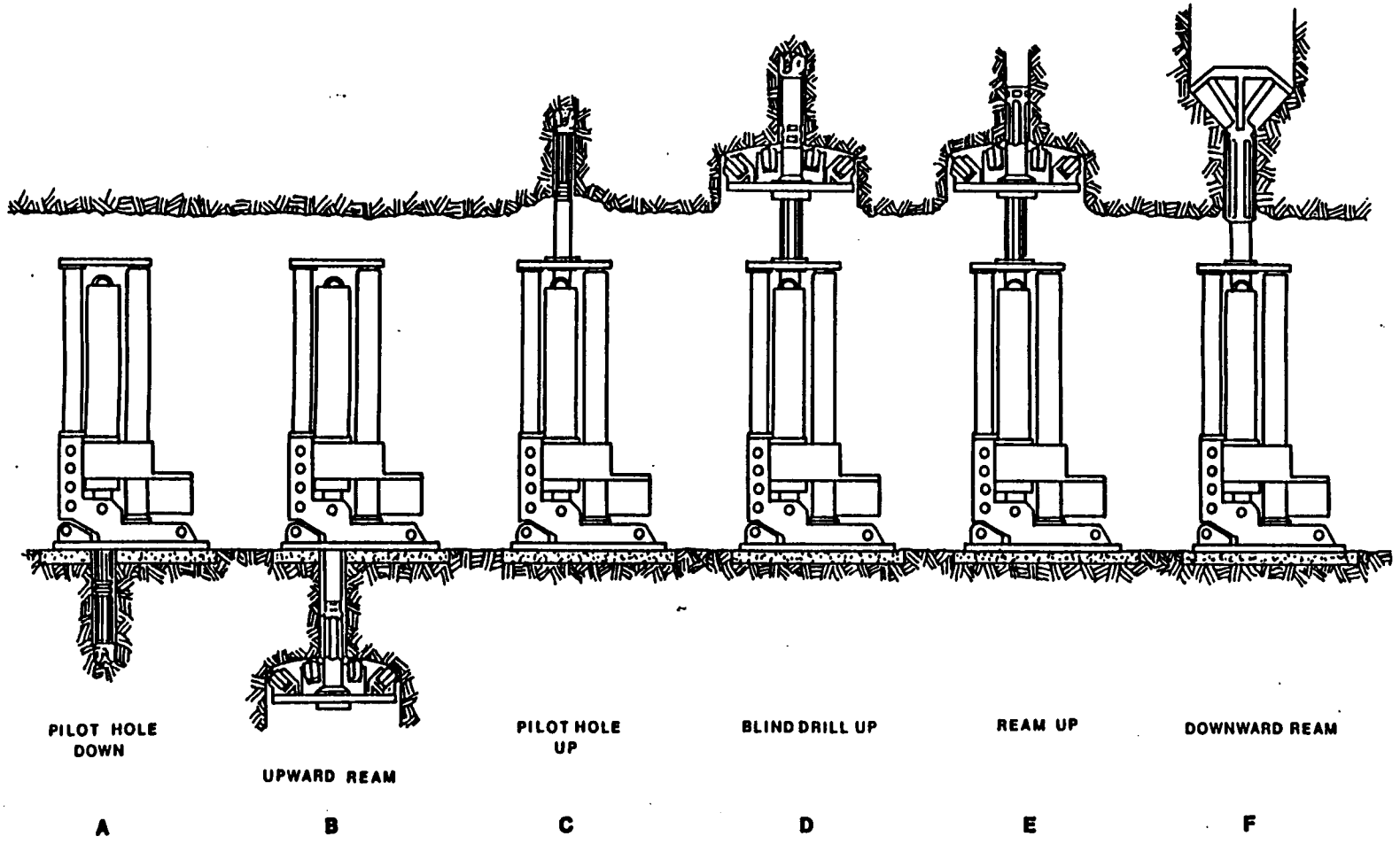
THE VARIOUS OPERATING MODES OF THE ROBBINS 53R



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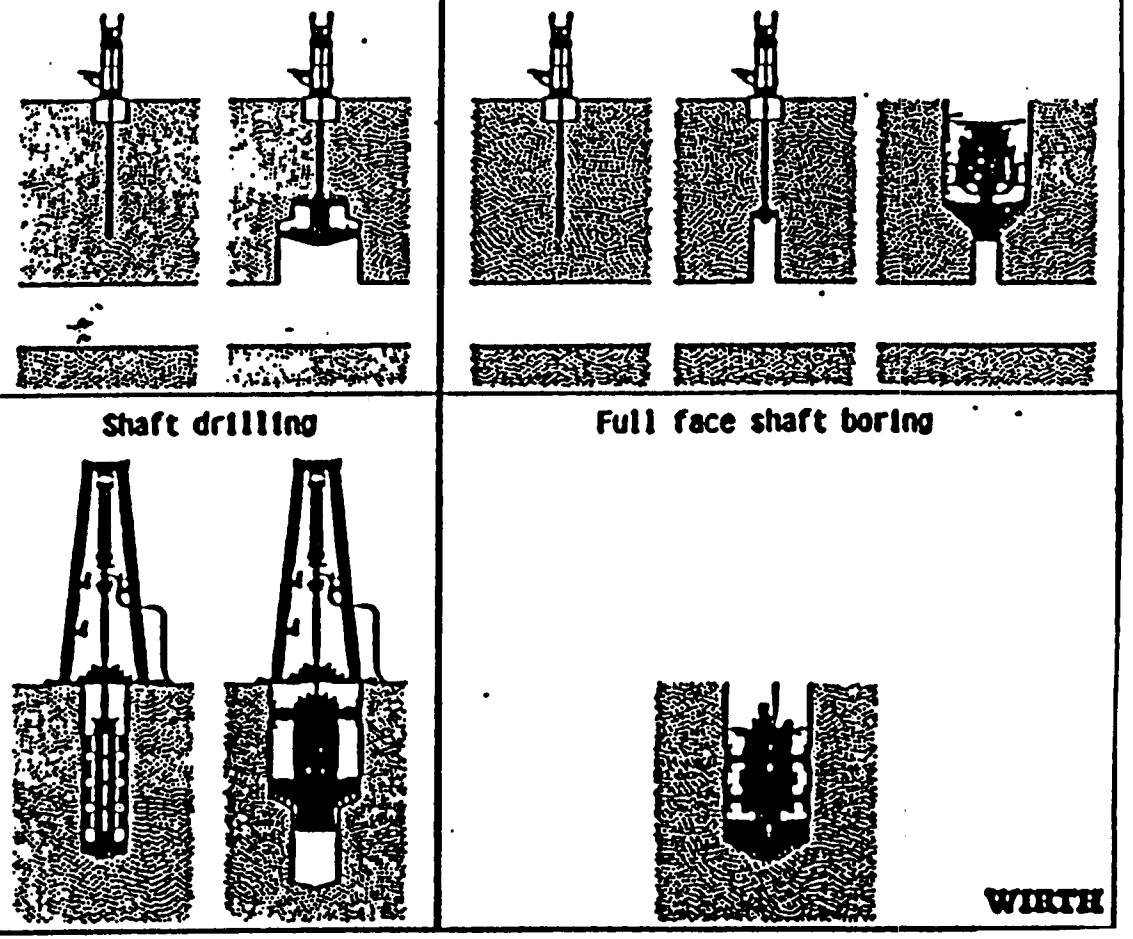
Direction of cuttings-transportation	Methods	
A Cuttings transport to lower level	Raise boring	Raise boring with down reaming
B Cuttings transport to upper level or surface	Shaft drilling	Full face shaft boring



Various methods of shaft drilling and boring

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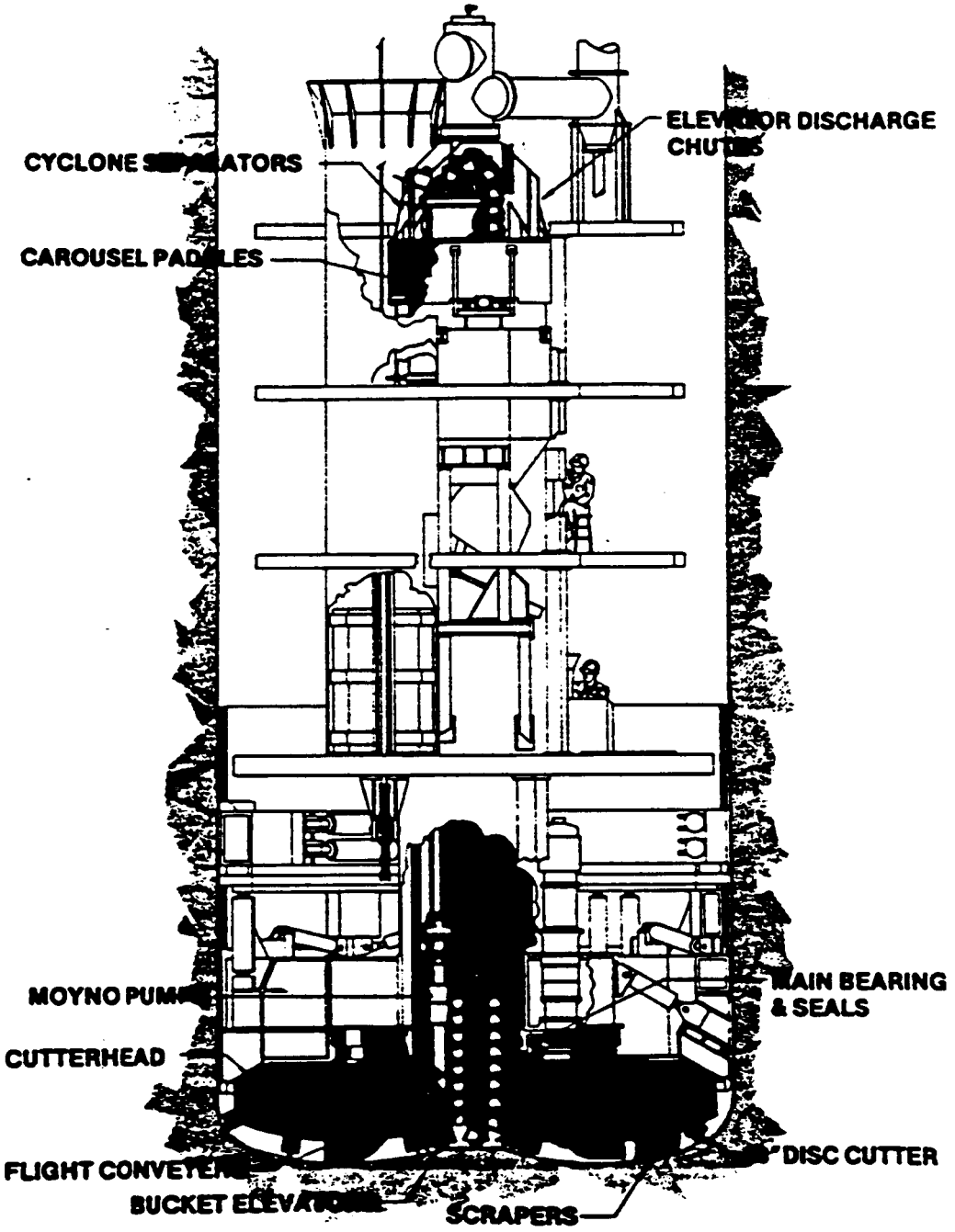
BLIND SHAFT BORER
ROTATING COMPONENTS



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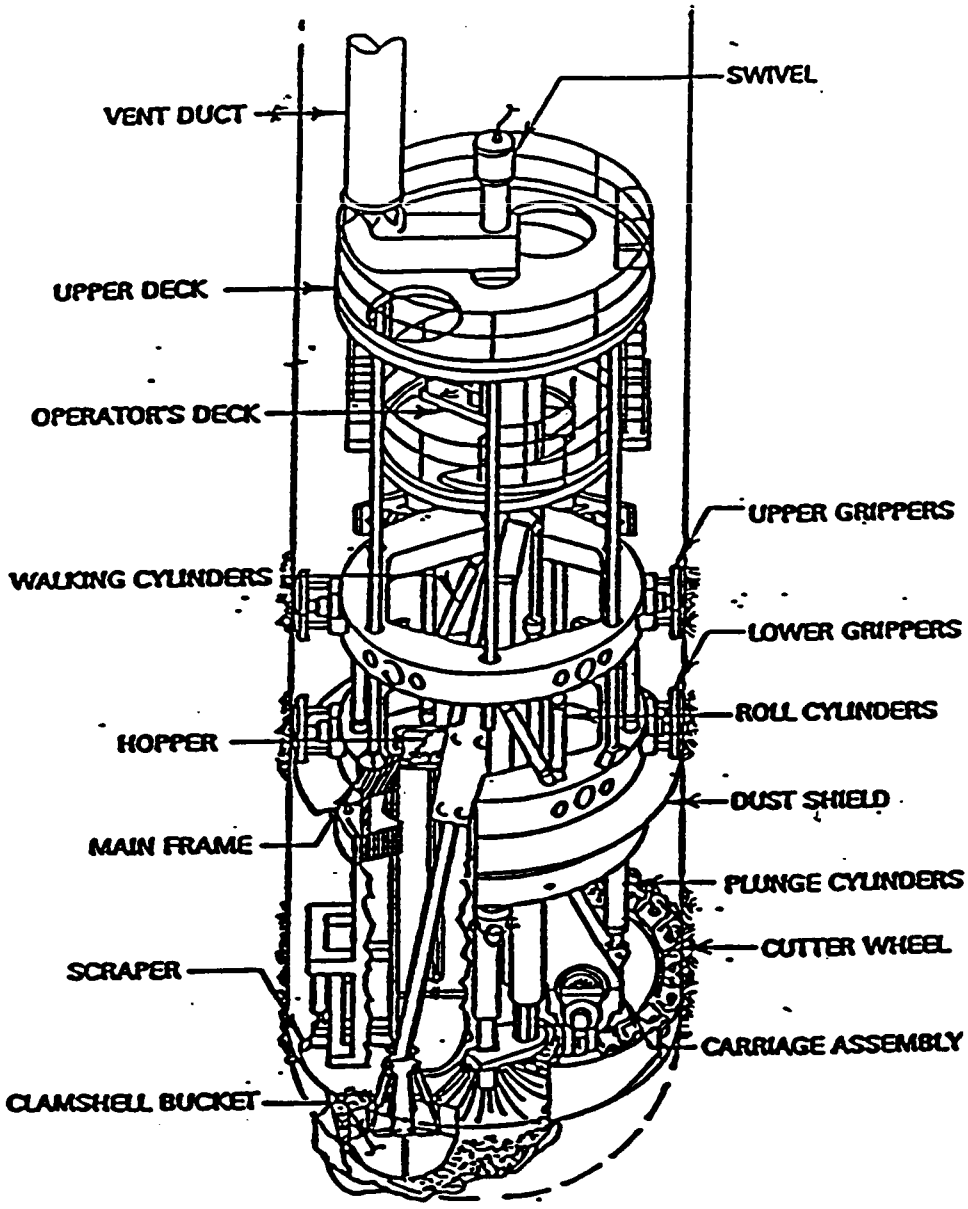

Robbins-Redpath partial-face shaft boring machine

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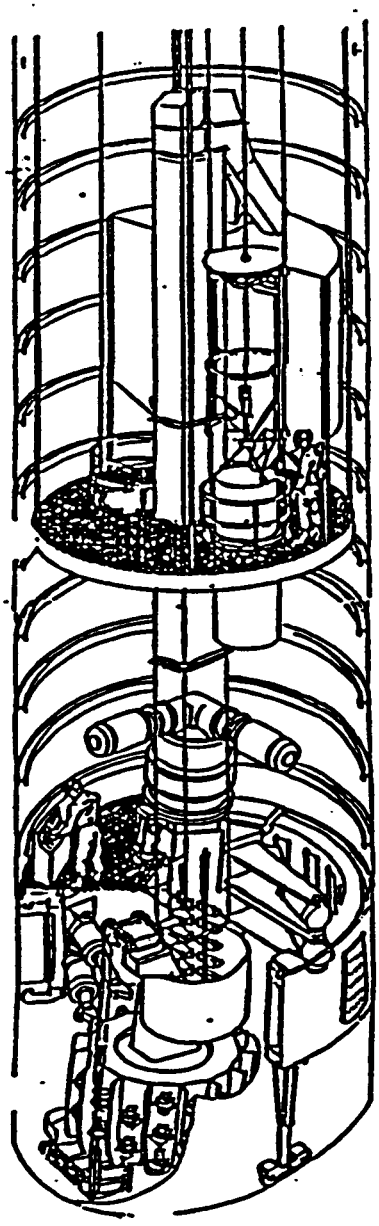

Snyder Engineering partial-face shaft boring machine

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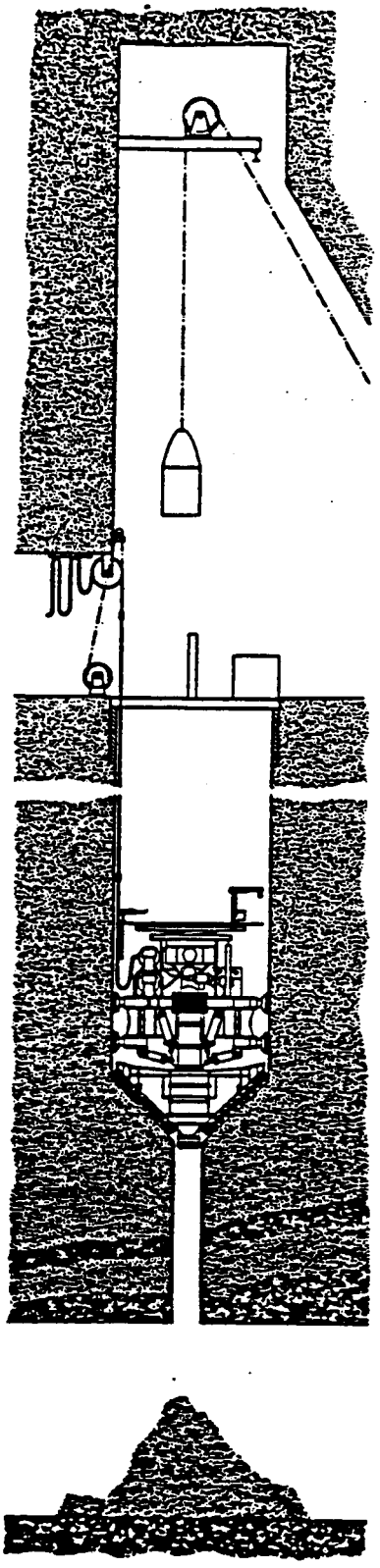

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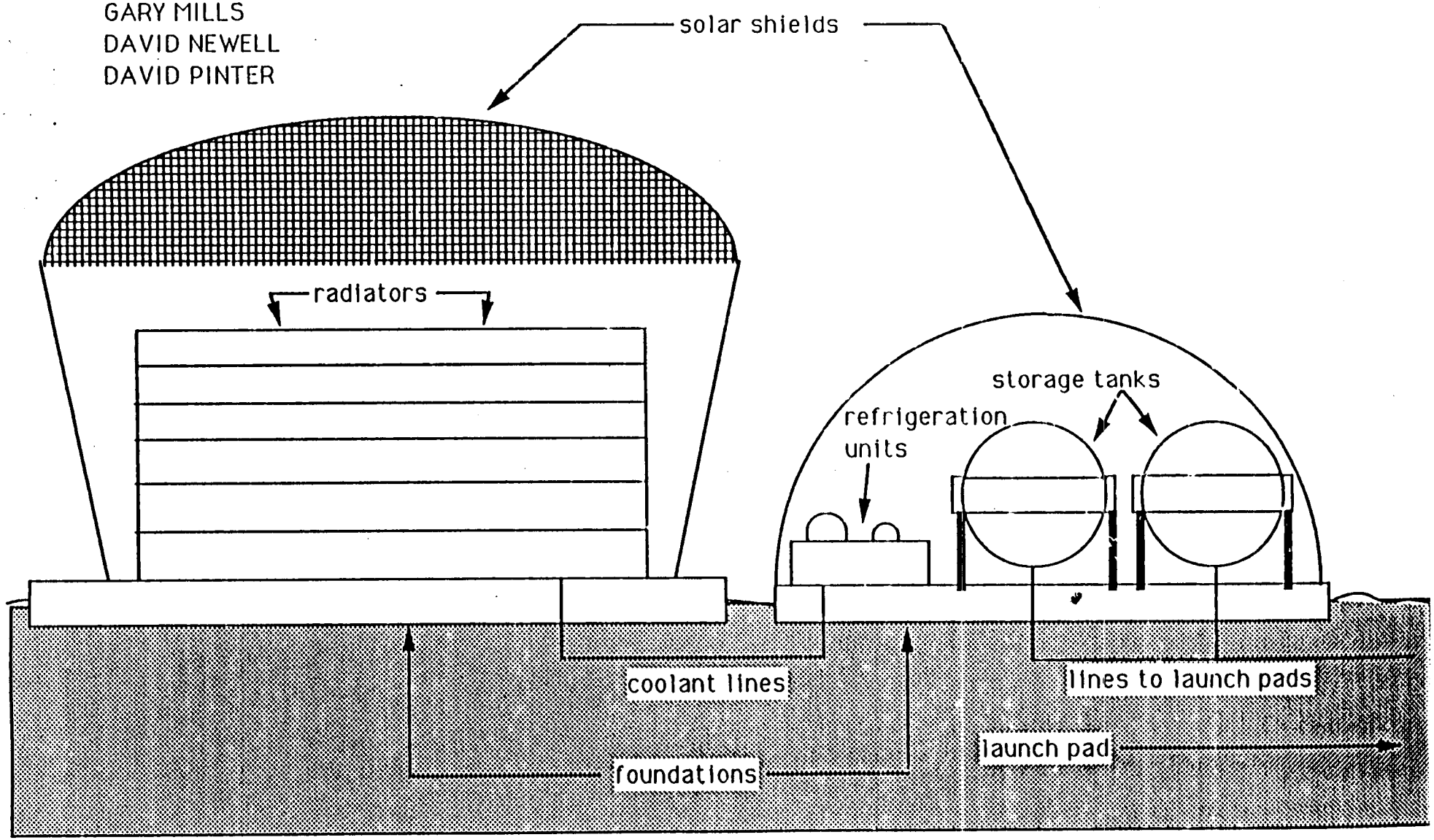
LIQUID OXYGEN PRODUCTION AND STORAGE ON THE LUNAR SURFACE

Gary Mills
Dave Newell
Dave Pinter
Dr. Howard Snyder

Once oxygen is produced on the Lunar Surface, it must be liquefied and stored for use by the lander vehicle. CSC has performed a preliminary design for the cyrogenic storage depot for this liquid oxygen (LOX). Estimates have been made of the refrigeration power and equipment weight required for the liquefication and storage. The determination is that the system is compatible with solar power limitations and will require little new technology development.

LIQUID OXYGEN PRODUCTION AND STORAGE ON THE LUNAR SURFACE

PROF. HOWARD SNYDER
GARY MILLS
DAVID NEWELL
DAVID PINTER



The Ilmenite Process

A practical application of:

$$H_2 + FeTiO_3 \rightleftharpoons Fe + TiO_2 + H_2O \rightleftharpoons H_2 + \tfrac{1}{2}O_2$$

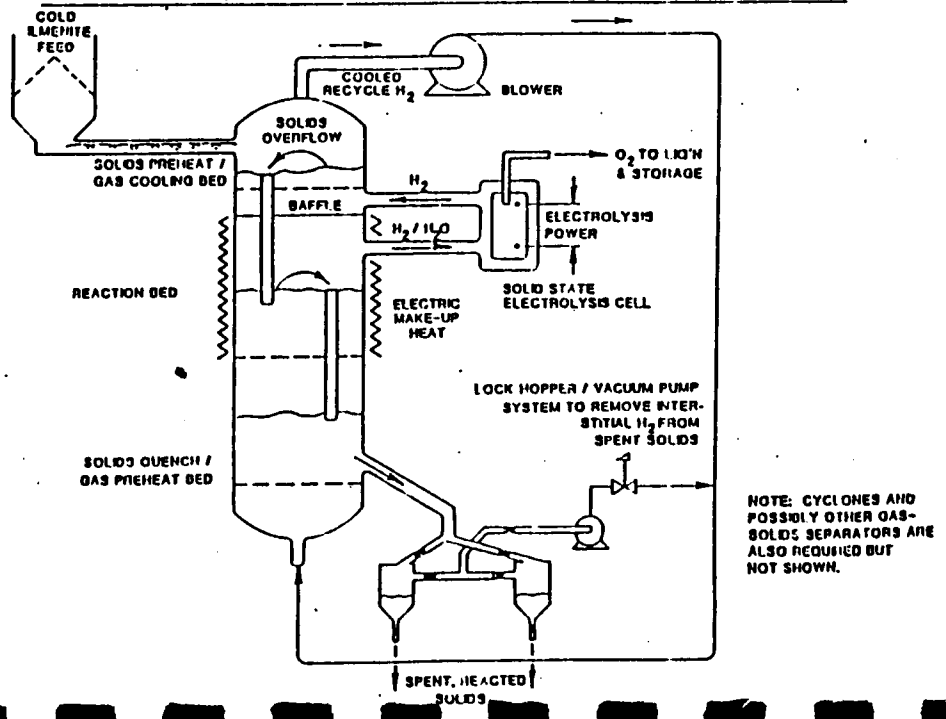
At 900°C

Δh = +9.7 kcal/g·mole
= 1212.5 kcal/kg O_2
= 5.1 Gigajoule/metric ton O_2

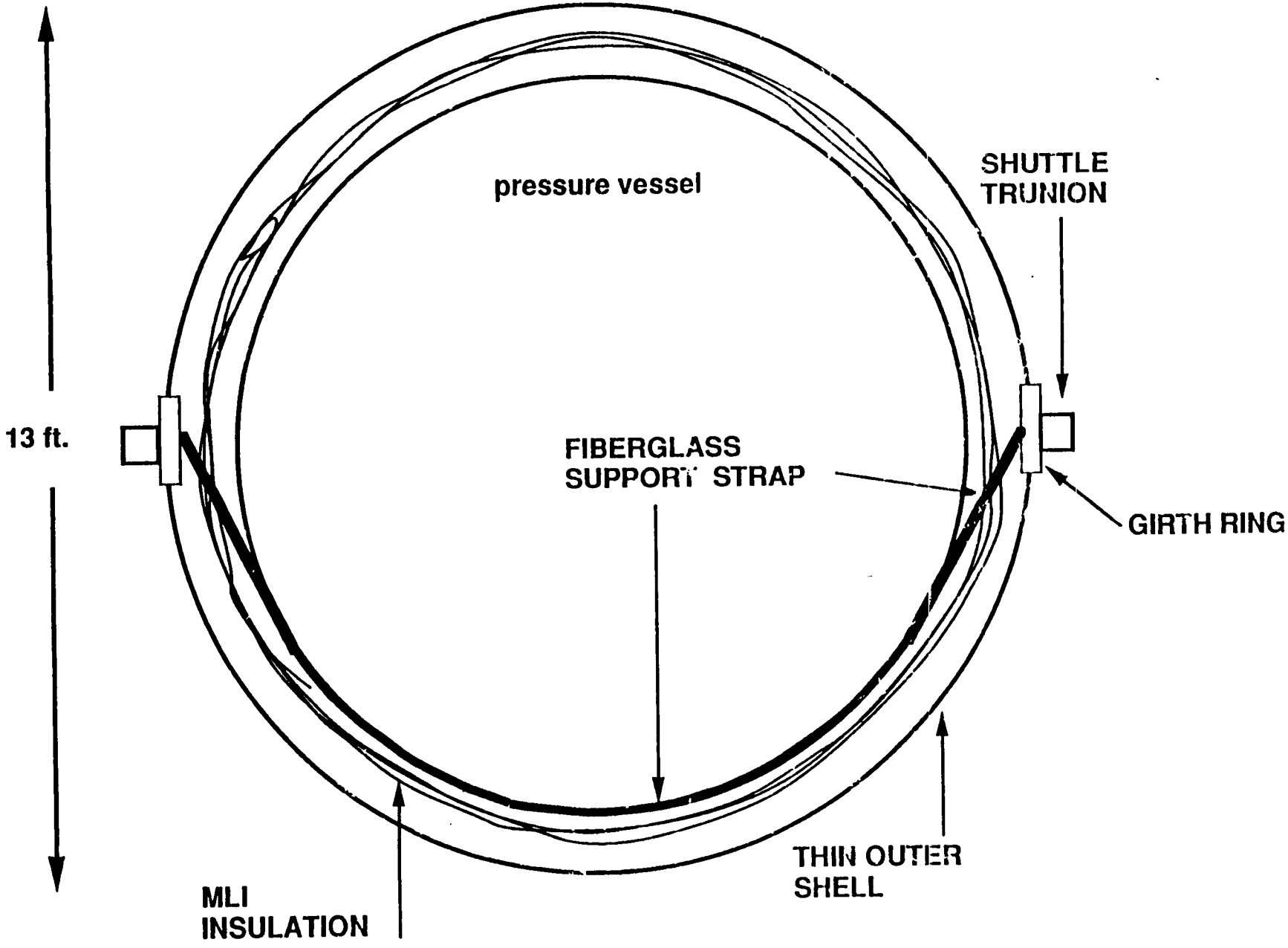
Technical Difficulties

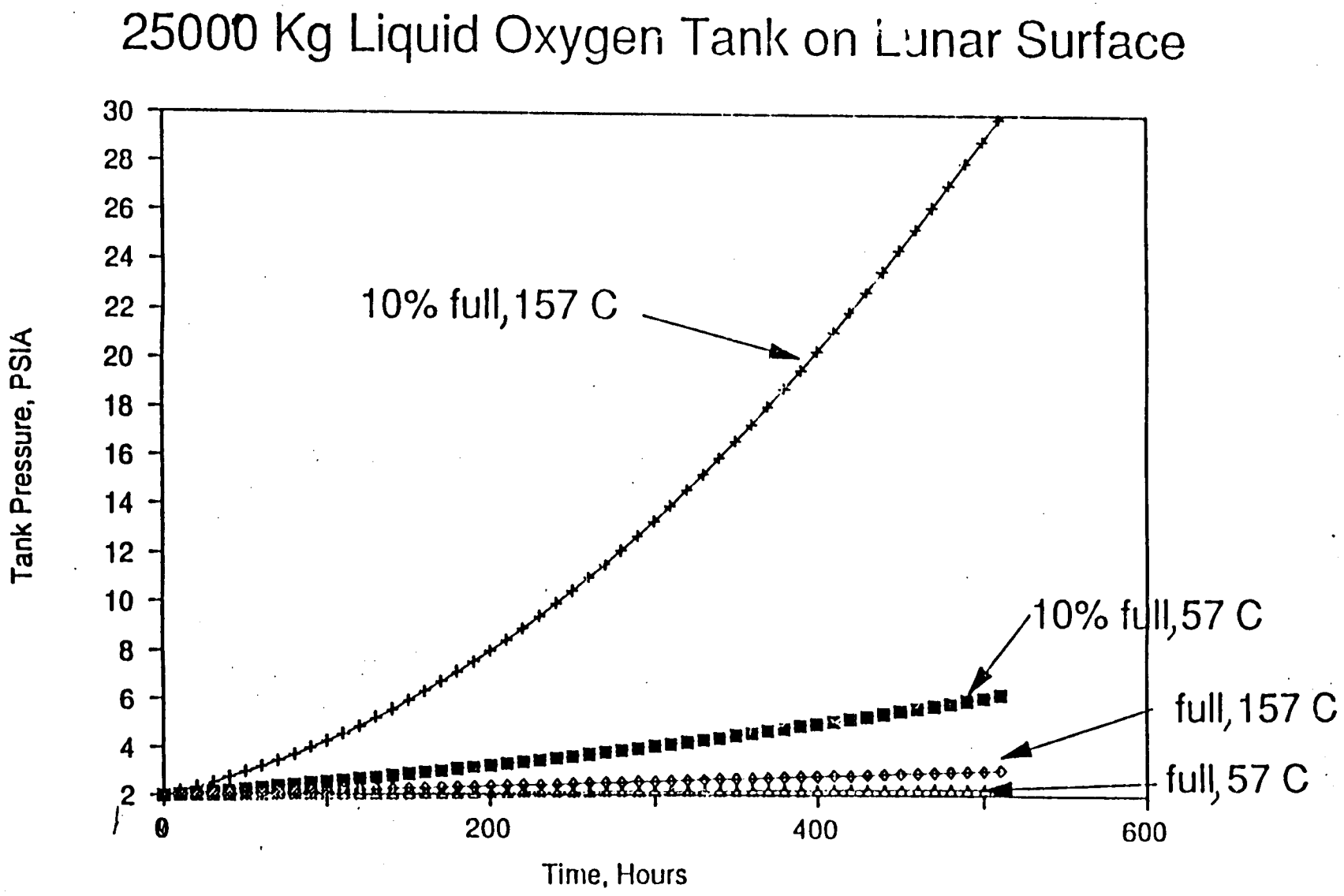
1. Maintaining a reaction temperature of 900°C.
2. Providing 1.41 MegaWatt-Hours per metric ton O_2 to drive reaction.
3. Providing 19 metric tons of Ilmenite per metric ton O_2.
4. Providing for 18 metric tons of Fe and TiO_2 per metric ton O_2.
5. Development of a (water) vapor phase electrolysis device. (Cooling and condensing of water vapor should be avoided)
6. Obtaining a very high production rate (approx 25 Kg/hr).

CONTINUOUS, FLUID BED ILMENITE REDUCTION / O_2 PRODUCTION



LIQUID OXYGEN STORAGE TANK




25000 Kg Liquid Oxygen Tank on Lunar Surface
Tank Pressure, PSIA
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
200
400
600
Time, Hours
10% full,157 C
10% full,57 C
full,157 C
full,57 C

CONCLUSIONS:

- Storage and handling of liquid oxygen in lunar gravity requires little technology development.

REQUIREMENTS:

-POWER
  Storage tank can operate with no refrigeration for 3/4 of the lunar day.
  43 kilowatts required to liquify 100 M tons of oxygen.
  1.2 kilowatts required each lunar day to eliminate boil-off.
-WEIGHT
  Dry weight of tanks approximately 1700 lbs.
-SIZE
  Tank diameter of thirteen feet will fit in shuttle bay.

OPEN ISSUES:

- Recovery of large quantities of oxygen gas from cooldown and fueling operations.
- Siting of radiators and oxygen depot.
- Micro-meteorite protection.
- Dust contamination of machinery and fluid couplings.

OMIT TO END

LUNAR BASE CONSTRUCTION PLANNING

Dr. James R. Stuart
Dr. Martin Mikulas
Independent Study students of ASEN 5906†

The latest CSC research is a continuation of the study that was began in the spring of 1990 and continued further in the summer of 1990 called the *Lunar Base Construction Requirements Review*. The latest focus is, however, on trying to understand the methodology of space construction planning by producing an implementation plan for a design reference mission. For this purpose CSC has chosen as its reference mission the NASA "90 Day Study" with the latest input from JSC in the form of draft "White Papers". Presented in this last session will be the very latest in this ongoing project, particularly in the area of understanding "functional planning goals" and the hierarchy of elements to satisfy those functional goals. One of the rules for this exercise is to not only state all the assumptions required to make a decision at each assembly node but to also "fill" and record the holes in the study with reasonable "mortar". Ultimately, it is hoped that this process will lead to the uncovering of the critical construction technological issues that have up to now eluded discovery. These critical "issues" can lead to the development of necessary countermeasures or what have been called "high leverage technologies".

† The Center for Space Construction's Fall 1990 Lunar Base Construction Study Team under the direction of Dr.Stuart and Dr.Mikulas. In alphabetical order the participants are: Chris Grasso, Wayne Jermstad, Steve Jolly, Michael Kazmierski, Allison Kipple, Alex Montoya, Jane Pavlich, Steve Perkins, Scott Ruta, Dane Spangler and Pete Warren.

LUNAR BASE CONSTRUCTION PLANNING

by Dr. James Stuart, Dr. Martin Mikulas
and the Independent Study students of
ASEN 5906

10/19/90
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TBD
HANDOUTS WILL BE AVAILABLE
AT THE SESSION

Appendix One:

POSTERS AND DEMONSTRATIONS RELATED TO SESSIONS TWO - SEVEN

APPENDIX ONE:
ABSTRACTS OF POSTERS AND DEMONSTRATIONS, SESSIONS 2 - 7

Session Two
Lunar Base Concepts
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REQUIREMENTS DEFINITION FOR A TRANSLUNAR EXPLORATION PROGRAM

Brent Helleckson
Mike Loucks

Many of the space exploration strategies put forward in documents such as the 90-Day Study (NASA), Beyond Earth's Boundaries (NASA), Robotic Lunar Surface Operations (Woodcock et al), A Lunar Habitat Configuration Derived from a Space Transportation System External Tank (NASA), etc., provide innovative technical solutions to specific problems associated with the exploration of the moon and Mars. However, the overarching rationale for such strategies is often unconvincing or absent. Such a rationale, if it can be developed, provides the framework in which programmatic decisions must be made. The lack of such a rationale makes the necessary technical trade-offs difficult to make. There is no framework available to define terms such as "low cost", "optimal", "politically acceptable", etc.

This project makes use of the system engineering approach (specifically the use of "and" and "or" trees) to discover and define the requirements, both technical and political, that must be satisfied in order for a successful Space Exploration Initiative to be undertaken.

Lunar Base Computer Demo

M. Kazmierski/D. Spangler
Center for Space Construction

From an architectural standpoint, the presentation of Lunar base design lacks in the display of fully-rendered, three-dimensional depiction. Thus, the creation of full-color, computer-generated, (and possibly fully-animated) 3-D models of Lunar base designs will be implemented. Such graphic displays will be of great assistance to mission planners, base designers, and base constructors (astronauts and robot teams). The display shall portray views of transfer, emplacement, and deployment of three different configurations of Lunar bases: inflatable, pre-fabricated, and Shuttle External Tank derived scenarios. Each respective sequence shall consist of three to five frames, depending on the Lunar base type. The purpose of this demo is to convey a graphic architectural understanding of how a Lunar base is packaged and how it is deployed.

Lunar Base Systems Requirement Study

Dalton Pont
Martin Marietta Astronautics and
Center for Space Construction

In response to several recent government initiatives the United States scientific, academic, and industrial communities have begun development of a Lunar Base which could potentially provide a wide range of capabilities with respect to future space exploration activities. Hence the US Space Exploration initiative (SEI) has stimulated a variety of independent research activities which to this point, has been accomplished without any specific direction or program level guidance. This document reports on a study to provide top level system guidance, as is required to organize and systemize the SEI related development effort. The Space Exploration System (SES) is a system level concept, defined to tie together the miscellaneous elements/components of research associated with the SEI. Specifically, this document consists of the highest level Lunar Base design parameters to include mission, functional performance, interface, and other related system requirements (survivability/habitability/maintainability/testability/etc.) needed to adequately develop and evaluate candidate Lunar Base concepts. Likewise, the document may serve as a baseline for new conceptual/design efforts which are in need of a system guidance document. In conclusion, the SES approach designed herein, is simply a traditional systems engineering tool provided to enhance and coordinate ongoing Lunar Base research and related development effort.

Cost Modeling for SEI Systems Analysis

Dalton Pont
Martin Marietta Astronautics and
Center for Space Construction

An internally consistent method of relative cost estimation is needed for the evaluation of trade-offs in the SEI mission Architecture and in-space construction design approaches. Cost estimation Relationships (CERs) exist for some categories of space hardware such has engines, structures, power systems, etc. Additional cost data is needed for items such as construction tools, robotics, and advanced structural components. These newly-developed CERs can then be incorporated into the overall cost of space-constructed systems such as the Space Station Freedom. Learning curve theory predicts a gradual cost reduction after repetitive construction activity, and this needs to be accounted for. Such cost analysis must highlight the need for new tests and data.

Lunar Mission Architecture Evaluation Using a Decision Analysis Approach

Janet Gleave

Center for Space Construction, Systems Cluster

President Bush's call for a return to the Moon, followed by the human exploration of Mars, has spawned numerous ideas for implementing what has been called the Space Exploration Initiative (SEI). Because a return to the Moon has been designated as the first step of SEI, the time is rapidly approaching to select one of the many mission architectures proposed for the exploration, settlement, and exploitation of the Moon. The evaluation of alternative architectures, and the subsequent selection of the "best" alternative will be critical to the success of this, and other, space programs.

A poster presentation is used to demonstrate the application of *systems analysis* to the evaluation and selection of a Lunar outpost mission architecture. The role of a *decision model* in the evaluation/selection process is discussed, and different types of decision models are presented. A simple "probability of mission success" decision model is applied to three Lunar outpost mission architecture alternatives. Although this model is too simplistic to be used in the actual evaluation/selection process, it does provide insight into the requirements for a more sophisticated decision model.

Simulation of Shuttle Launch Operations for the SSF Assembly Sequence.

George Morgenthaler
Kadett Chan
Kendall Nii
Center for Space Construction, Systems Cluster

With the increasing importance placed on the Shuttle to transport payloads such as the Space Station Freedom (SSF) components into orbit, it is essential that the Shuttle launch operation enables the Shuttle to perform reliable transport missions. Unfortunately, various mishaps and delays in recent Shuttle launches have indicated the need to strongly consider space logistics reliability in planning space construction. Now that complex space structures require multiple cargo deliveries, we cannot afford to have unduly delayed deliveries that might jeopardize the survival of the space structure. Shuttle processing and launch resources must be analyzed in the face of delays and interruptions to numerically assess the probability, duration, and cost of delayed launches.

To provide an accurate measure of processing capability, a detailed Monte Carlo simulation will be used to model Shuttle processing and launch behavior during SSF Assembly. The same kind of model can be used to analyze other Space Exploration Initiative (SEI) space construction tasks.

Vehicle delay and failure times will be the main focus in this simulation to determine how an interruption or failure will affect SSF Assembly schedule. Two cases will be presented. The first case will be to determine the effectiveness of current space logistics resources to handle random interruptions. Various data on quantity and quality of the resources from this first case will be statistically analyzed. The second case will incorporate modifications to alleviate time delay problems encountered in the first case. Further runs of this simulation on more cases can provide valuable insight into how interruptions and proposed improvements affect each component in Shuttle processing. This simulation can be a tool to provide the types of improvements that can make the current logistic system better suited to handle the Shuttle's increasing role in space logistics. The model can be applied to other proposed Heavy Lift Launch vehicles such as ALS, Shuttle C, Shuttle Z, and the Zenith Star Launch System.

LAUNCH VEHICLE SELECTION MODEL POSTER BOARD SESSION

Alex J. Montoya
Center for Space Construction, Systems Cluster

Over the next 50 years, man will be heading for the Moon and Mars to build scientific bases to gain further knowledge about the universe, and to develop rewarding space activities. These large scale projects will last many years and will require large amounts of mass to be delivered to Low Earth Orbit (LEO). It will take much planning to complete these missions in an efficient manner. The preferred selection of a transportation fleet to move these large masses to LEO and beyond becomes necessary, because of the trade-offs and the vast differences in cost depending upon which vehicle fleet is chosen. Furthermore, the planning of a future Heavy Lift Launch Vehicle (HLLV) will significantly impact the overall multi-year launching cost for the vehicle fleet, depending upon when the HLLV will be ready for use.

It is desirable to develop a model in which many trade studies can be performed. In one sample multi-year space program analysis the total launch vehicle cost of implementing the program reduced from 50% to 25%. This indicates how critical it is to reduce space logistics costs. A linear programming model has been developed to answer such questions. The model is now in its second phase of development and this paper will address the capabilities of the model and its intended uses.

The main emphasis over the past year was to make the model user friendly and to incorporate additional realistic constraints that are difficult to represent mathematically. We have developed a methodology in which the user has to be knowledgeable about the mission model and the requirements of the payloads. We have found a representation that will cut down the solution space of the problem by inserting some preliminary tests to eliminate some infeasible vehicle solutions. The paper will address the handling of these additional constraints and the methodology for incorporating new costing information utilizing learning curve theory. The paper will review several test cases that will explore the preferred vehicle characteristics and the preferred period of construction, i.e., within the next decade, or in the first decade of the next century. Finally, the paper will explore the interaction between the primary mission model (all payloads going from Earth to low Earth orbit (LEO), and the secondary mission model (all payloads from LEO to Lunar and LEO to Mars and return).

Analysis and Application of Launch-On-Time Model

Kendall M. Nii
CSC Symposium Poster, October 17-19, 1990
Center for Space Construction, Systems Cluster.

During 1989 the Center for Space Construction developed the Launch-On-Time (L-O-T) Model. The model chose a reference by which the L-O-T probability and improvements to L-O-T probability can be judged. The measure of improvement was chosen as the percent reduction in $E[S_N]$, the total expected amount of unscheduled "hold" time. We have also previously developed an approach to determining the reduction in $E[S_N]$ due to reducing some of the causes of unscheduled holds and increasing the speed at which the problems causing the holds may be "fixed". We provided a mathematical (binary linear programming) model for measuring the percent reduction in $E[S_N]$ given such improvements. In this poster we will exercise the model which was developed, and draw some conclusions about: methods used, data available and needed, and make suggestions for areas of improvement in "real world" application of the model.

Seasonal and Time Variations to Launch-On-Time Probability

Kendall M. Nii
CSC Symposium Poster, October 17-19, 1990
Center for Space Construction, Systems Cluster.

During 1990 the Center for Space Construction explained the general Launch-On-Time Problem and its importance to future space program success. In this Tech note we explore the Seasonal effects on the average number of holds per launch, $\overline{X}$. Using Statistical hypothesis testing techniques we find that there is a statistically significant variation of $\overline{X}$ for different seasons.

We also explore the "learning curve" effect. That is, as a launch vehicle system becomes more mature, does $\overline{X}$ decrease? The "Learning Curve" theory suggests that as one accumulates more experience, one should become more adept at doing a certain job. It seems that $\overline{X}$ is not decreasing with time as we might expect from the theory of "Learning Curves". We statistically test the hypothesis that there is no learning curve and seek to determine why this might be so.

ARTIFICIAL GRAVITY MARS SPACESHIP

Benton C. Clark
Martin Marietta Astronautics

Recent studies have provided a variety of concepts for the artificial gravity approach to human travel to Mars. This paper culminates the experience gained and presents Concept Six, a "snowflake"-configured interplanetary vehicle cluster of habitat modules, descent vehicles, and propulsion system. Habitats are derived from Space Station Freedom cylindrical modules. Within the 10-m diameter payload shroud of a heavy lift launch vehicle, the core spaceship can be launched together. Propulsion systems are derivable from existing, proven engines. An evolutionary design is provided that allows sequential upgrading from 5 to 9 crewmembers, an increase of landers from one to as many as three per mission, and the orderly, phased incorporation of advanced technologies (aerocapture, nuclear thermal rocketry, and spaceship recovery at Earth) as they become available. A Mars program can therefore be initiated on an earlier time scale. Joint international participation is facilitated by the mix-and-match building block approach of the snowflake cluster, made possible by the "decoupling" of elements in the basic concept.

Assessing the Feasibility of a Mars Cycling Transportation System

Michel E. Loucks
University of Colorado
Center for Space Construction
Systems Cluster

This presentation examines the feasibility of a Mars cycling space vehicle in terms of Initial Mass to Low Earth Orbit (IMLEO) and rendezvous constraints. A minimum of two cycling spacecraft are used with the associated 'taxi' vehicles. Spacecraft designs are adapted from the 1988 NASA Office of Exploration "Exploration Studies Technical Report" and other reports. The cycler trajectories used are the 'Split-Cycler' or 'Escalator' trajectories documented by Hoffman et. al. of SAIC in 1989. The cycler concept is compared to the "Exploration Studies Technical Report" scenario and other concepts on the basis of IMLEO. The associated 'taxi' rendezvous logistics are assessed as are the sizing sensitivities of the 'taxi' vehicle with respect to the associated rendezvous launch windows.

This mission is compared to various other Manned Mars Mission concepts and the various construction issues are discussed. Also discussed are possible further topics of study for CSC with respect to this concept.

MODELING BOTTLENECKS IN LUNAR BASE CONSTRUCTION

Peter A. Warren

Constructing a lunar base involves sophisticated choreography of payload delivery, assembly in earth orbit and on the lunar surface, robotic and manned operations and resupply/repair of the partially assembled base. Understanding the bottlenecks in this process is vital to developing an efficient assembly and construction plan. By modeling the end to end construction process, the CSC Operations Group is identifying those "high leverage" areas where small increases in component performance yields large improvements in the overall system efficiency.

This presentation demonstrates a complex model of a lunar base construction system developed from the intuitive and explicit relationships between groups of two and three parameters. This model can be easily altered to show the impacts of changing component performance and alternate operations concepts.

DISPLAY TECHNIQUES FOR VISUALIZATION OF REMOTE TASKS

Allison Kipple
Andy Meiman

The performance of remote tasks requires displays to inform the user of the configuration of the work space. Much work has been done with video links to provide this visualization of the work site. For many tasks that are well defined there are simpler and less expensive methods for displaying this information.

OASIS/TAE (Operations and Science Instrument Support/Transportable Applications Executive) software allows telemetry items to activate graphical displays. In this testbed the operator selects objects whose location is determined by a local vision system and uses a robot to put them into preselected locations. The displays provide feed back to which locations have been filled and whether the robotic arm can insert a block without collision. As the robot performs each step, the computer screen provides a graphical representation of what the robot is doing. In the event of a failure the software will halt the sequence and inform the operator who can then abort, take corrective action or resume.

TROTER SIMULATION USING SMALLTALK

Chris Grasso

TROTERs are small, inexpensive robots which act together as a group to accomplish sophisticated remote tasks. To fully understand the issues involved in designing and operating a team of TROTERs, the robots and their components must be modeled . This poster board describes introduces a strawman TROTER system featuring standardized component behavior. An object-oriented modeling scheme implemented in the Smalltalk programming language is demonstrated on a Mac II. Preliminary results and new issues uncovered are presented.

GENERATING EVENT SEQUENCES USING DEDS MODELS AND TABU SEARCH METHODOLOGIES

Dan Hunter

With a Discrete Event Dynamical System (DEDS) model of a machine ensemble, a control strategy can be implemented such that the machine ensemble performs a given set of tasks. The control strategy uses a scheduler to construct the event sequence and a controller that runs concurrently with the machine ensemble to enforce the event sequence. The scheduler uses a TABU search that utilizes the DEDS model for the tree generation, the cost function, and the aspiration values. With the event sequence defined, simulations can be performed on the DEDS model to monitor system performance and schedule robustness.

Partially Decentralized Formation of a Circle of Robots

Mark P. Nathan
Renjeng Su

Methods for forming a circle of small independent robots have been investigated at the Center for Space Construction. The search has continued through implementation of a centralized control algorithm to the difficult case of finding a decentralized control algorithm. In the case presented here, a hybrid of the two forms of control is demonstrated. We shall show that random oriented and positioned robots with no knowledge of the position and orientation of other robots can coordinate to form a single circle of robots if each robot has a proximity sensor. A centralized controller is used to form a circle from a group (arbitrary number of robots in close proximity), and a decentralized controller is used to combine a group with other groups.

USING A SPREADSHEET TO MODEL TROTERS

Nicholas P. Wilde
Clayton Lewis

The CSC Operations branch has been actively exploring the concept of using teams of small, relatively inexpensive robots (TROTERs) cooperating together to do construction in space. We have been exploring some of the issues involved in controlling teams of such robots using the NoPumpG spreadsheet based interactive graphics system.

NoPumpG is a system that attempts to combine the simplicity and ease of use of spreadsheets with the power of interactive graphics. It does this by allowing the user to implement interactive graphical simulations using a spreadsheet-like framework to control the individual graphical elements on the screen.

Using the NoPumpG system, we have been able to program simulations of several different elementary TROTER tasks. Some of the demonstrations shown today include one TROTER homing in on a target, a collection of TROTERS forming a circle around another target, and a team of TROTERS pushing a bar towards a different target.

MUSICAL INSTRUMENT DIGITAL INTERFACE (MIDI) CONTROL FOR PROXIMITY OPERATIONS

Brent Helleckson
Wayne Jermstad
Steve Monk

Musical theory and notation serves as a useful analogy for the control of multiple, independent but coordinated, remote operations. The conductor and orchestra, through aural feedback, a small set visual cues and a complex, agreed upon notation for events over time, execute multiple, independent, highly complex, and coordinated actions. MIDI, the standardized protocol for communication between electronic instruments, is used to explore the relationship of musical sound, theory, and notation to the execution of remote tasks. Building upon previous Center for Space Construction work on robotic control via MIDI interface, the MIDI concept is applied to the problem of proximity operations for rendezvous and docking.

An electronic keyboard using MIDI protocol is evaluated against two other types of hand controllers in simulated rendezvous and docking operations. Several parameters, including fuel usage, rendezvous time, and operator comfort are evaluated for the MIDI keyboard, a six degree of freedom (DOF) hand controller, and two three DOF hand controllers. Results from multiple test runs at the Martin Marietta Space Operations Simulation (SOS) Laboratory in Denver, Colorado are displayed. A videotaped test run will be presented and a hands on demonstration of usage of the keyboard to guide a rendezvous simulation will be available.

NEURAL NETWORKS FOR IDENTIFICATION AND CONTROL

Noureddine Kermiche
(Department of Electrical Engineering,
University of Colorado)

In this poster presentation, Neural Networks, which have been proven to be a good approximating tool for nonlinear mappings are used to achieve:

1. Restoration of unknown functions of the form $y = f(x)$ using randomly observed values $(x_i, f(x_i))$.

2. Networks are updated using randomly generated initial conditions of the dynamical system.

Learning algorithms are derived for both cases. Two computer program simulations are presented, one for the restoration of nonlinear functions and the other for the control of an inverted pendulum system.

MODELING DECENTRALIZED CONTROL ALGORITHMS

Steve Monk

The purpose of this testbed is to test decentralized control algorithms in the real world. Each train has a position sensor and a separate process on the PC. At the beginning of the experiment, the trains are given a general description of the task, "move bar", which they are to perform autonomously; communication between trains in minimized as much as possible and global knowledge of the task is given only to a designated "leader". The behaviors programmed for moving the bar are general, and can be used for other tasks as well.

REMOTE CONTROL OF A MULTI-ARM TESTBED

Jane Pavlich
Steve Monk
Jack Faber
Wallis Harrison†
Don Soloway†

The Center for Space Construction in cooperation with the Automation Technology Branch of the Nasa Langley Research Center provides remote control for a dual robot arm testbed. The testbed consists of two 6 DOF Unimate Puma 560 Mark I arms. Both arms have wrist mounted force/torque sensors and parallel jaw end-effectors. Remote control of the arms is accomplished with the Operations and Science Instrument Support software (OASIS). Commands constructed by OASIS communicate with control software running at the Langley testbed site. A robotic simulation package called Cimstation provides a 3-D display of the testbed for visual confirmation.

† Nasa Langley Research Center

A Portable Hyperbaric Oxygenation Chamber for Space Mission

Dr. Aldona A. Siczek,
Dr. R. Igor Gamow,
Department of Chemical Engineering
University of Colorado

Plans for the Space Station Freedom call for greater emphasis on maintenance of crew health and productivity.

During Extra Vehicular Activities (EVA), astronauts work in space using a space suit which presently provides only a pressure of 4.3 psi (pounds per square inch). High pressure suits (up to 9 psi) are being considered, for future missions, providing the engineering limitations can be overcome.

Astronauts are expected to undergo transition from cabin pressure of 1 atm (14.7 psi) to the much lower pressures of a space suit. This transition poses a substantial risk of decompression sickness (DCS) even though denitrogeneration procedure is conducted. For the Shuttle the following protocol was adopted: a one-hour period of breathing 100% oxygen at a cabin pressure of 14.7 psi (1 atm) followed by cabin decompression to a pressure of 10.2 psi for at least 12 hours prior to EVA to further reduce nitrogen concentration in the tissue; this is then followed by a 40-minute period in the space suit at 10.2 psi breathing pure oxygen, and finally decompression of the space suit in the airlock down to 4.3 psi (Waligora, 1984). In order to prevent some aspects of altitude sickness, the oxygen in the cabin is increased to 26% during the time that the barometric pressure is lowered to 10.2 psi.

Ideally, one would like to shorten or eliminate completely the need for the denitrogeneration procedure.

Traditionally, hyperbaric oxygenation (HBO) chambers holding pressures as high as 2.8 atm or higher are used for treating DCS. It is not clear from the literature that these pressures are absolutely necessary. A recent USAF (1988) report suggested that pressures less than 10 psi would be sufficient to eliminate the occurrence of bends.

Appendix Two:

POSTERS AND DEMONSTRATIONS RELATED TO SESSIONS EIGHT - TWELVE

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APPENDIX TWO:
ABSTRACTS OF POSTERS AND DEMONSTRATIONS, SESSIONS 8 - 12

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HYBRID ACTUATION FOR PRECISION CONTROL OF LARGE SPACE STRUCTURE (HAPCLSS)

Ali A. Gooyabadi

High level of expectation from Large Space Structures (LSS) such as shape fidelity, line of site pointing accuracy, etc., puts stringent condition on their performance. The only means of achieving such performance expectations is active control of these Large Space Structures. A fundamental problem in the actual implementation of such control schemes is the physical limitations of actuators. All of the available, as well as proposed, actuators tend to have physical limitations. Two of the major limitations with suitable actuators both LSS are effective band width and power output limitations. Achievement of the precision performance requirement dictates the need for both low as well as high frequency active vibration damping of the structures.

One of the most commonly foreseen actuators to be used in LSS applications is the jet thruster, because it is the simplest type of vibration control device. It acts as an active damper that emulates ideal coulomb friction. This type of actuator is ideal for large amplitude vibration. However, due to the time delay associated with jet thrusters their effective used is limited to low frequency vibrations, and their reaction to high frequency vibrations could cause instability. Thus, a need for high frequency actuators is warranted. The inherent problem of high frequency actuators is limited output force capability. The most feasible high frequency actuator is the reaction mass actuator (RMA). Also, the power source for high force actuators is usually some sort of propellant, that requires storage and is limited in supply. On the other hand, electricity is more abundant due to the availability of solar energy. This suggests the use of actuators such as RMA's whenever possible. However, it is important to keep in mind that high power actuators are essential to control large amplitude vibration. Thus, the case of Hybrid actuation provides a sensible solution to the problem of precision control of LSS.

We are using a planar truss test bed as the basis for our study on the effect and interaction of hybrid actuation with a Flexible Structure. This experimental planar truss is currently housed in the Air Force Academy at Colorado Springs, CO. We propose to do an in depth study on the effect of hybrid actuation which includes closed loop stability analysis, optimal "on" time actuator management and dynamical interaction of these linear/nonlinear actuators.

VERIFICATION OF A MODEL OF CRYOGENIC HELIUM TRANSFERS

David Newell

A computer model has been developed for the optimization of cryogenic transfers in space, including the resupply of SSF from the shuttle and in the storage and handling of cryogenic helium on the moon. The model is currently being validated through comparison with relevant experimental data in the literature. A few cases where the data is sufficiently detailed to test the theory have been identified. Preliminary results indicate the model's predictions are within 5% of the experimentally measured values. This is better than was expected considering the assumptions inherent in the model.

IDENTIFICATION OF CLOSED LOOP LARGE SPACE STRUCTURE MODELS THROUGH NUMERICAL SIMULATION AND SYSTEM IDENTIFICATION

Ralph Quan

A software package (written in the C language) has been developed within the Center for Space Construction, which simulates controlled large space structures. The more accurate finite element representation of the structure is used in the simulation, instead of the less accurate reduced order modal representation. This software also features an efficient matrix storage scheme, which effectively deals with the asymmetric system matrices which occur when control is added to the structure. Also, an integration algorithm has been chosen so that the simulation is a reliable indicator of system stability or instability.

The software package is fairly general in nature. Linearity of the finite element model and of the controller is the only assumption made. Actuator dynamics, sensor dynamics and disturbances can be handled by the package. In addition, output feedback of displacement, velocity and/or acceleration signals can be simulated. Kalman state estimation has also been implemented.

The closed loop modes are needed for evaluating the performance of the controller. However, large finite element models have as many modes as degrees of freedom. An open loop model can be analyzed with methods such as subspace iteration, which can yield the first hundred or so modes. These methods take advantage of the symmetry of the open loop matrices. However, the matrices are asymmetric for controlled large space structures. Subspace iteration does not apply in this case.

We therefore look to other techniques, such as the Eigensystem Realization Algorithm (ERA). This algorithm computes a finite dimensional discrete time model from impulse response data. The discrete time model is then converted into a continuous time one. For determining the dominant modes of a linear system, ERA is an effective method. This algorithm has been incorporated into the software package described above.

This software has been tested on a finite element model of a real large space structure: The Mini-Mast Truss at NASA-Langley. A 714 degree of freedom finite element model was computed, and the latest torque wheel dynamics were added to the model. A 16 state controller was designed for this model, and the entire closed loop system was simulated with the software package. Closed loop performance was then determined with the use of the Eigensystem Realization Algorithm.

PRELIMINARY DESIGN AND ANALYSIS OF A COUNTER-BALANCED LUNAR BASE CONSTRUCTION CRANE

Li Farn Yang
Martin M. Mikulas, Jr.

Construction of a Lunar base will require a large mechanical device for off loading components from the landing site and for positioning and assembling these components into an operational base. This talk presents one concept for accomplishing these tasks, a counter-balanced mobile crane. The two major features of this particular concept are: 1) an actively controlled counter weight to offset tipping moments, and 2) control of the pay load with multiple cables to provide positive, precision positioning capability. Results are also presented of a dynamic analysis which is currently being conducted to understand optimal cable attachments to the payload. Preliminary results indicate that varying the geometry of cable attachments to the pay load can significantly alter the resultant dynamic response. The long range goal of this research is to identify and quantify the characteristics of a lightweight mobile crane which is capable of conducting stable, automated construction tasks at a lunar base.

SPACE ASSEMBLY INTERRUPTABILITY WITH APPLICATIONS TO SPACE STATION FREEDOM*

James W. Wade
Center for Space Construction, Systems Cluster

The task of assembling large structures in space creates the possibility of construction interruptions. The unscheduled interruption of the assembly process may require abandoning the Station and returning to Earth. This interruption may be due to: crew illness/injury, Shuttle Orbiter mechanical failure, Orbiter or Station pressure loss, space debris damage etc. If not handled properly, these interruptions may jeopardize crew safety, Orbiter operations and the recoverability of the structure being assembled. The problem of space assembly interruptability was first addressed in January 1989 by astronaut Vance Brand (NASA-JSC) to Dr. George Morgenthaler at the University of Colorado - Boulder, at which time an Interruptability Team was organized at the University to study the problem of Space Station Freedom assembly interruptability.

The approach which is being undertaken at the University of Colorado is to create a methodology capable of analyzing generic structures. This is being accomplished by developing a software tool, DYCAM, to plan assembly sequences, and will be used in conjunction with INTERPRO, the INTERrupatbility PROgram, to analyze the Space Station Freedom assembly interruptability problem. Using an automated networking approach with some human interaction, the most favorable near-term safing† options will be calculated in the event of an interruption. PERT network techniques are employed to analyze which of these near-term improvements provide the optimal long-term response, as far as impact on the time and cost of the overall project are concerned.

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* Prepared for the University of Colorado, Center for Space Construction (CSC) 1990 Symposium, Boulder, CO.

† Safing options or tasks are defined as those activities which are performed after an interruption in order to stabilize the configuration.

Assembly Sequence Rescheduling in the Event of Interruption

Jack Hwang
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The task of assembling structures such as the Space Station Freedom in space creates the possibilities of construction interruptions. If not handled properly, these interruptions may jeopardize crew safety, Orbiter operations, and survival of the structures being assembled. When a preliminary analysis indicates that an interruption would be catastrophic (instability or loss would result) there must be alternatives available to "safe" the questionable assembly operation. Therefore, one of the goals is to create a method that will generate all feasible "safing" options at each Assembly Junction (AJ) in rescheduling the assembly sequence for the space structure so as to select feasible alternatives which will improve "stability" in the face of interruption.

A Fortran computer model for re-manifesting the Orbiter, but which considers both Orbiter constraints and construction limitations, is being developed. This task is part of the several Phase III activities described in Jim Wade's paper at this Symposium.

Interruptability Team - State Expansion

Lawrence (Robbie) Robertson III
Center for Space Construction Systems Cluster

During any flight into space there is always the chance that the duration of the flight has to be cut short due to some problem. This could be caused by anything from crew illness, to total or partial loss of battery power, to whatever. During Space-based assembly, these interruptions would be critical if they were to occur at a time when either the Orbiter could not re-enter, or the structure was unstable in some manner. Therefore, the identification of such instabilities in the assembly sequence is important. Presently, only the Orbiter c.g. and the passive and active stability have been considered in the Interruptability model. A more robust analysis of the overall station stability will include Orbital Lifetime (OL), thermal control, power, and propulsion. These will greatly expand the realism of the SSF active stability model.

Interruptability Expanding "Safing" Options

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When constructing large space structures such as the Space Station Freedom (SSF), the possibility for unscheduled and unavoidable interruptions arises. If such interruptions endanger the astronauts involved in the construction or interfere with the project to the point of having to abandon the assembly of the project temporarily, then large scale space ventures face the possibility of failure unless stability measures are preplanned. Thus, it is important for this Interruptability Problem to be addressed. Indeed, it is essential that a space construction project is able to recover from unexpected interruptions in order to ensure its success.

The Interruptability Team at the University of Colorado is working on the second of a three phase approach. The first phase, which was completed in the Spring of 1990, examined only the stability of an assembly sequence specified by JSC. If the Orbiter or the SSF were unstable, then phase one produced the option to either proceed forward or go back to the nearest stable point in the assembly sequence. During the summer of 1990, the Phase 2 Temporary Options were completed. These options concentrate on finding improvements to the station's Stability State. The Temporary response provides tasks to stabilize an unstable assembly junction. Phase 2 is currently being expanded to provide additional options to improve an unstable state. These new options include Throw Away Options and Hybrid Options. By expanding the safing options, the crew will have a greater selection of tasks to choose from which will improve an unstable state, and thus, a greater selection of options to minimize cost and time.

REFLECTIONS AND MODAL FILTERING IN FREQUENCY DOMAIN ANALYSIS OF PULSE PROPAGATION IN COMPOSITE TUBES

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Tubes of finite length are modeled in dynamic pulse propagation using a modal expansion derived from a wave propagation based finite element method. Complete 3-D dynamic solution may be obtained at any position in the tube. The elastic waves are considered to be plane harmonic and the modal distribution gives the variation of displacements, strains and stresses over a tube cross section perpendicular to the axis of symmetry. The dispersive nature of the elastic waves in such problems implies that different segments of a disturbance propagating in the form of elastic waves will propagate along the length of the tube at different rates. Depending on the part of the response of interest and the position along the tube, it is often necessary to consider the effect on the response by reflections of modes propagating at higher speeds. These reflections may overlap and thereby seem to influence the response observed due to more slowly propagating waves in the initial wave train. The method used in this analysis allows for modeling of these reflections for a given set of time varying tube end conditions. The incident and reflected phenomenon are superimposed solutions for a "semi-infinite" tube. Solution is obtained in the frequency domain and a fast Fourier transform is used to obtain the time response. However, the highly dispersive nature of guided waves in composite tubes may create numerical difficulties in obtaining the time domain response unless some modal filtering is applied to the solution. The problem stems from modes which propagate too slowly to be observed within the time window of the solution obtained from performing the fast Fourier transform. If a mode which propagates too slowly to fall within the given time window is included in the solution, the result is a distortion of the time response obtained. The solution is skewed in the sense that components of the disturbance which should occur after the given time window now appear at the beginning of this window. A mode at a given frequency can be shown to propagate at its group velocity $d\omega/d\gamma$ where ω is the circular frequency and γ is the wavenumber. By approximating the group velocity as $\Delta\omega/\Delta\gamma$, it can be determined whether contribution from a given mode at a specified frequency is physically realizable from the time window used. Physically unrealistic modes are filtered or removed from the solution. The method is clearly successful as all distortion of the time response is removed and physically realistic results are obtained.

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LOW-GRAVITY FLUID SLOSH

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Low-gravity fluid slosh dynamics are an important part of spacecraft dynamics, due to the large amount of fluid which must be stored in space. Fluid slosh dynamics must be known to accurately control the spacecraft. One can group fluid slosh problems into three categories by the type of analysis required to model the fluid flow. If the fluid is highly excited, then a time-dependent analysis which tracks the fluid particles around the tank is required. However, once chaotic motion settles and the fluid oscillates about an equilibrium position, then either a linear or a nonlinear modal analysis is required. The present work involves calculating the linear fluid slosh modes about the equilibrium position. The equilibrium equation and equation of motion are derived from energy expressions. The important energy terms are the fluid kinetic energy, the gravitational potential energy and the surface tension potential energy. The direct boundary element method is used to derive the expression for the fluid kinetic energy throughout the volume in terms of surface variables only. The divergence theorem is used to derive the expression for the gravitational potential energy throughout the volume in terms of surface variables only. The surface tension potential energy is inherently a function of surface coordinates. Since all energy terms are expressed using coordinates which are attached to the fluid surface, the equations are valid for arbitrary geometries. A two-dimensional analysis has been completed to ascertain the effectiveness of this approach. Where analytical solutions exist, the method yields accurate results. A strength of this approach is the simple surface discretization which is required instead of a much more complex volume discretization. Much effort has been dedicated to finding the simplest numerical schemes which yield good results. A three-dimensional analysis is currently in progress, which will be compared to both analytical solutions and experimental data.

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DEVELOPMENT OF PVDF PIEZOELECTRIC TRANSDUCERS FOR ACOUSTIC EMISSION STUDIES IN COMPOSITES

Wayne P. Rogers
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A new PVDF (polyvinlidene flouride) piezoelectric transducer was developed for acoustic emission detection in composite materials. The new sensor is well suited to remote, in-space nondestructive evaluation of space based structures. The transducer has good potential for use in sensor arrays which will monitor vibration, damage to composite structural materials, and changes in elastic moduli.

Sensor characteristics were studied using waveforms generated by a controlled acoustic emission source in a long glass plate. The sensor was found to be capable of measuring displacements over the range from nanometers to millimeters and frequency over the range from Hz to MHz. Special construction techniques were developed to minimize the sensor size while retaining good sensitivity and signal-to-noise ratio.

Experiments-in-progress are intended to demonstrate the applicability of the sensors to monitor acoustic emission in graphite/epoxy composites in four-point bending. Acoustic emission waveforms will be correlated with macroscopic stress and strain, and with microstructural damage events, such as matrix cracking and fiber breakage.

† United States Air Force Academy, Colorado Springs

Analysis of Alternative Joining Methods for Space Technology

Kendall M. Nii
CSC Symposium Poster, Oct 17-19, 1990
Center for Space Construction, Systems Cluster.

There are many different types of joining methods available for use in space construction. It is important to understand the key qualifiers or discriminators in choosing one method over another. Once the discriminators are known, one can rank the various methods of joining or connecting things in space. This is an important step in determining which method is the most "effective" -- cost saving, reliable, feasible, etc.. The purpose of this presentation is to expand upon the construction requirements model developed by CSC, specifically in the area of orbital assembly. We will begin by developing a database of information on each candidate technology. Then we will develop a metric which gives a preliminary ranking to each of the candidate joining methods.

Non-Destructive Evaluation and Testing Requirements for Non-Terrestial Assembly

By Jeff Wells

As currently configured, the size of the proposed Space Station Freedom (SSF) is such that it cannot be deployed in a single launch. Estimated sizes for the proposed Mars Mission Vehicle and Lunar Base are also too large for any single launch system. These projects will therefore require some non-terrestial assembly. Methods of joining and bonding will have to be developed for nonterrestial construction. This necessarily will require the co-development of space qualified test and inspection procedures and equipment.

The nature of the construction that occurs outside of the Earth's atmosphere will generally dictate what type of testing is necessary. However, many questions relating to what means of testing, how to test, what to test, and what equipment is essential will have to be answered. The testing equipment itself will have to be space qualified. Concerns over the size, weight, flexibility and what or whom will be using the test equipment will have to be addressed. Additionally, the calibration, maintenance and repair of the test equipment will have to be considered.

DYCAM 1.0 : A Tool to Enhance Constructability

Center for Space Construction, Systems Cluster
by Herb Schroeder

Those who plan the construction of large structures in space are presented with new challenges imposed by the constraints involved in such an operation. These constraints include those imposed by the assembly sequence itself, the available resources of time, money, manpower, equipment and material, and finally those constraints imposed by the physical nature of the environment. Design decisions ultimately affect the construction effort and inherent construction constraints affect the design. To enhance the constructability of these structures it is important that the project planners be equipped with computer tools which will allow a rapid iterative analysis of many possible scenarios for design and construction.

DYCAM (DYnamic Construction Activity Model) provides the user with a computer tool to aid in the evaluation of Pre-Phase A and Phase A conceptual system designs and the identification of feasible construction scenarios for these designs, assuming various types and levels of construction technologies. The DYCAM model has been designed to interact with a NASA utilized, commercially available computer model for conceptual system design, called IDEAS**2. This permits iteration of the system design with various alternative construction sequences suggested by the user. DYCAM also incorporates the consideration of construction constraints as specified by the mission planner/system designer. The DYCAM test case will evaluate the feasibility of various construction sequences using IDEAS**2 data for the configuration of Space Station Freedom(SSF) after two assembly missions. The DYCAM system has been designed to assist the planner/designer in the interactive development of feasible construction plans. In doing this, DYCAM manages data, manages the interfaces between design and construction planning, performs bookkeeping chores on resource limitations, keeps track of project elements which are available for assembly, executes scheduling and analytical engineering routines, and presents graphic representations of the project as construction and assembly proceed. In designing DYCAM, we have recognized the fact that humans are good at synthesizing information and that computers are good at keeping score. DYCAM is a tool that leverages planner intelligence by providing the planner with a means to deal with the complexities involved in construction planning.

DYnamic Construction Activities Model (DYCAM) Computing System Implementation

by Stephen Maurich
Center for Space Construction, Systems Cluster

To solve the problem of construction planning in space, the DYnamic Construction Activities Model (DYCAM), a Pre-Phase A and Phase A construction planning tool, integrates software from both the design and construction planning domains to provide a unified package for both engineering analysis and construction planning. Using graphics tools common to computer aided engineering, DYCAM assists the planner in the generation of a feasible construction sequence. Being a complexity management tool, DYCAM manages the data between the subsidiary software packages and itself. With the ability to store various scenarios, DYCAM provides a convenient way for the user to examine the trade-offs of design decisions. This Posterboard gives a brief overview of the hardware and software used in the implementation of DYCAM 1.0 including a section on NCS and how it can be used by the Center for Space Construction.

IMPLEMENTATION OF NCS

By Stephen Maurich
Center for Space Construction, Systems Cluster

In large technical projects, where data and computational resources are distributed among a number of companies and organizations, complex problems in networking, information management, and data processing arise. With the technology in place for computer networking over high speed data links, distribution of applications and data across a variety of widely scattered computer systems has become feasible. Distributed processing is not a reality due to hardware availability alone. Software protocols, such as Network Computing System (NCS), are specifically designed to handle the interoperability problems that are seen in a distributed environment. Using both the hardware and software tools that are on the market today, distributed computing can be used as part of the solution to the problem of management of complex and data intensive ventures.

The computerized DYnamic Construction Activities Model (DYCAM) at the Center for Space Construction (CSC) will use NCS over a local ethernet to simulate the distributed environment in which it may be used. Three applications of NCS are being investigated by CSC. First, the feasibility of accessing a network of workstations to make all the resources on the network available to DYCAM. Second, creating a distributed computing environment among the NASA centers so that data and applications available at one center can easily be accessed by the others. Finally, a distributed workstation environment will be created for DYCAM to be used in an educational setting. Although not all networking problems can be solved using NCS, it is one software solution to the problem of improving hardware performance without increasing hardware costs.

Characteristics of Lunar Regolith

Dr. Stein Sture
Dr. Hon-Yim Ko
Steven W. Perkins
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Knowledge of the properties of Lunar regolith was obtained through the Surveyor 3 and 7, and Apollo 11-17 as well as the USSR missions. These properties, including material cohesion, friction, in-situ density, grain-size distribution and shape, and porosity, were determined by indirect means of trenching, penetration, and vane shear testing. Several of these properties were shown to be significantly different from those of terrestrial soils, such as an interlocking cohesion and tensile strength formed in the absence of moisture and particle cementation. A summary of these properties is provided in the extraterrestrial engineering posters.

To characterize the strength and deformation properties of Lunar regolith experiments have been conducted on a Lunar soil simulant at various initial densities, and environmental vacuum levels. These experiments included conventional triaxial compression, extension, isotropic compression, direct tension, direct shear, and combined tension-shear. Experiments have been conducted at low levels of effective confining stress. External conditions such as membrane induced confining stresses, end platten friction and material self weight have been shown to have a significant effect on the strength properties at low levels of confining stress. The solution has been to treat these external conditions and the specimen as a full-fledged boundary value problem rather than the idealized elemental cube of mechanics. More detailed results of the above listed experiments are provided.

Centrifuge modeling allows for the study of Lunar soil-structure interaction problems. In recent years centrifuge modeling has become an important tool for modeling processes that are dominated by gravity and for verifying analysis procedures and studying deformation and failure modes. Centrifuge modeling is well established for terrestrial engineering activities and applies equally well to Lunar engineering. Principles of centrifuge modeling are outlined in the posters.

Numerical modeling is a powerful tool for analyzing proposed Lunar constructed facilities. Numerical models are initially calibrated using the experiments described above. Additional calibration is accomplished through the centrifuge model experiments. Details of the model used along with notes on the rationale behind numerical modeling are provided.

EXPERIMENTAL STUDIES ON THE MECHANICS OF LUNAR EXCAVATION

Leonhard E. Bernold†

One of the first construction operations for building a stationary habitat on the Moon or on Mars will be excavation of soil. The reasons for this necessity are manyfold and reach from the need to protect inflatable habitats from radiation to creating an underground space to build electrical power plants. Despite the fact that tremendous amount of earth moving has taken place on this globe, a sound theoretical basis for designing soil moving machines does not exist. The interaction between soil and tools or machines is still not clearly understood because of the complexity of the earth material. This fact has to be recognized when one tries to design excavation operations on the moon. Despite the fact that there exists a theory of soil mechanics, the theory of soil-machine mechanics has not been established. This paper describes the results of experiments which were developed to evaluate empirically if and how soil could be excavated on the moon. Explosive blasting was used to loosen the very dense (100% relative density) lunar simulant to the point where a microrobot backhoe and a cableway excavator were able to cut through the soil. No attempt has been made to optimize or to promote a particular method. The goal of the presented study is rather to establish a sound knowledge base to be useful for further more detailed studies needed to design an operational system which will be successful on the moon.

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MARS MISSION SPACE CONSTRUCTION COMMUNICATION SYSTEMS NEEEDS

Center for Space Construction, Systems Cluster

by Waleska Peraza†

A communications system to support the exploration and establishment of a permanent base on Mars is one of the necessities for the success of this mission. Several studies in the literature deal with the Mars mission communication system and investigate research problems in telecommunications for the steady-state communications problem during the journey to Mars. Steady-state means that the astronauts, on a journey to Mars and when operating the Mars base, must have a daily line of communications for all the activities that must be performed. To accomplish this, the communications requires some mechanisms such as links from the Mars surface to Mars orbit, from Mars Orbit to Earth, etc., and also requires services and functional requirements. The long signal delays of 20 to 40 minutes cause severe operating and base construction problems.

Few studies discuss the communication problem during the Mars base construction phase. This poster presentation†† deals with Construction phase requirements and the constraints imposed by the Mars communications system. Special focus is placed on the assembly and construction period and provides suggestions based on several referenced studies. It is intended to select the best communications techniques for use during this construction/ assembly period, and to identify the system's respective physical requirements and constraints.

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† Undergraduate Student in the Electrical Engineering Dept. of the University of Puerto Rico; Summer Research Student for the University of Colorado's Center for Space Construction (Systems Cluster) under the US Dept. of Education's SUMMER MINORITY ACCESS to RESEARCH TRAINING (SMART).

††For details see CSC Systems Cluster Technical Note #64

OMNIDIRECTIONAL PLATFORM FOR UNSTRUCTURED SURFACES

James W. Brazell†

This unique work vehicle is intended for tasks essential to the construction of outposts and early bases on the Moon and Mars. These tasks include unloading landers, cargo handling, facility assembly, emplacement of infrastructure elements and regolith reconfiguration work such as leveling, trenching and drilling. It provides mobility, manipulation and power for a variety of interchangeable implements to accomplish these and other tasks. The vehicle is comprised of a central body and struts and that each terminate in a wheel. Each strut includes a hip joint, a femur, a knee joint, a tibia, an ankle joint and a wheel. Two particularly favorable configurations are presented. The first uses three struts mounted equally spaced around the body. The other is a six strut configuration having three struts along each side. Potentially, two three strut machines could be merged to form a six strut configuration. The ankle joint, made of rotatable oblique sections of a tubular structure, provides steering and alignment of the wheel which is driven by the last section. Reorientation of this joint places the wheel in a horizontal position as a footpad for the walking mode of mobility. The hip and knee joints are similar in construction to the ankle joint. This arrangement provides struts having tubular structures which approach the ideal cross-section for strength/weight and stiffness/weight ratios in bending and torsion. The vehicle as conceived utilizes design principle which include mechanical simplicity, fault and accident tolerance, minimal mass, commonality of parts, adaptability to mission changes, and control by microprocessors which use uploadable, task specific software. The six strut vehicle not only provides dexterity and power for the associated implements, but can essentially emulate the rolling mobility of the familiar six wheel drive vehicles or, in the walking mode, emulate the mobility of the familiar six legged walking machines.

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Appendix Three:

CENTER FOR SPACE CONSTRUCTION PERSONNEL

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Appendix Four:

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