NASA-CR-192688

UNIVERSITY OF COLORADO
AT BOULDER

CENTER FOR SPACE CONSTRUCTION

THIRD ANNUAL SYMPOSIUM

General Comments:

1. Only 2 students gave presentations during 1st day.
2. The two NASA presentations took ~~up~~ valuable time away from CSC activities.
3. How is the CSC doing in striving to reach established goals?

Goal 1 - interdisciplinary research: I didn't see that much interdisciplinary activity. Each prof. simply doing their own thing.

Goal 2 - educate students w/ vision and tech. skills: No direct evidence in symposium that revealed CSC doing anything out of the ordinary here.

November 21 - 22, 1991

(NASA-CR-192688) CENTER FOR SPACE CONSTRUCTION THIRD ANNUAL SYMPOSIUM (Colorado Univ.) 298 p

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Dynamics of On-Orbit Construction Process

K.C. Park

This study looks at three aspects of on-orbit construction: perturbations of the orbiter due to changes in configuration of the structure being deployed, the effects of flexibility on the dynamics of the orbiter and the deployed structure, and interaction dynamics of the structures being assembled. Once the interaction dynamics are understood, appropriate strategies for control and maneuvering of manipulators can be formulated.

Interaction Dynamics and Control for Orbital Assembly

Renjeng Su

Building structures and spacecraft in orbit will require technologies for compliant contact of subassemblies. Satisfactory compliant contacts must be secured for various joining operations to take place. Compliant interactions between mechanical structures may be defined by the dynamics of position and contact forces. The basic problem here is how to use active and passive control mechanisms to achieve stable interactions and a specified level of compliance. Results will be presented on stability analysis, compliance control design, and steady-state contact dynamics specification.

Controls for Orbital Assembly of Large Space Structures

Mark Balas

To assemble large space structures, on-orbit control algorithms must deal with the berthing of flexible substructures while maintaining stability and meeting basic performance goals. No doubt these operations will be carried out with the aid of flexible robot manipulators. Controlling such complex dynamics will require reduced-order model-based algorithms for rapid response; however, stability is easily compromised by interaction with unmodeled dynamics. Analytical and numerical results will be presented in three areas: the stable berthing of actively controlled substructures; direct model reference adaptive control of distributed flexible structure models; and control design for flexible structures with slow actuator dynamics.

Structural Load Control During Construction

Martin Mikulas

For many large space structures, the major design loads can occur during the construction phase or during subsequent maintenance or augmentation operations which involve moving large masses. In the absence of gravitational loadings, all major loadings on space structures are transient in nature, unlike the traditional static loadings associated with Earth structures. This fact requires the introduction of concepts for structural elements designed to absorb load impulses. This talk will present a new strut concept for a "fuse" in the structure which can release at prescribed levels of loading and return to the nominal position at a controlled rate after the loading has passed. A discussion is presented of the general application of the strut to several space structures, including the recent Space Shuttle thruster pressure blast on the Space Station solar arrays.

Systems Engineering Studies of On-Orbit Assembly Operations

George W. Morgenthaler

Systems engineering studies of orbital assembly operations at CSC focus on the issues of subassembly partitioning, packaging and delivery to LEO, cost trade-offs, operation simulation, analysis of interruptability and constructibility, and expert systems for construction sequence planning and evaluation. A simplified cost trade-off model will be presented which relates size of Heavy Launch Lift Vehicles, number of subassemblies to be delivered to LEO, and the probability of mission success.

Expert Systems for Assembly Sequence Evaluation

Steve Jolly

Complexity of orbital assembly will ultimately stem from the actual physical properties and behavior of the delivered subassemblies. To reduce this complexity it is desirable to launch the largest possible pre-integrated, pre-assembled, pre-tested subassemblies, while simultaneously conforming to launch vehicle, construction tool and resource constraints. A simulation model which combines numerical and symbolic engineering knowledge with heuristic reasoning will be presented. The main function of this model is to decompose a representative SEI "Phase A" space vehicle into deliverable orbital subassemblies. The model employs state-of-the-art constraint propagation techniques developed at Stanford University for terrestrial construction to create a potentially powerful space research tool. Simulation results will be presented.

Lunar Regolith and Structure Mechanics

Stein Sture

Lunar regolith is unlike terrestrial unconsolidated soils. Its unusual strength and stiffness properties simplify design and construction of embankments, shielding structures and foundations, but make it more difficult to perform excavations and cuts than on Earth. In this presentation we focus on construction of regolith-structure facilities, and characteristics of scale-model experiments. Fundamental mechanical properties of regolith and density variations on the lunar surface are also described.

Indigenous Lunar Construction Materials

Wayne Rogers

The utilization of local resources for the construction and operation of a lunar base can significantly reduce the cost of transporting materials and supplies from Earth. The present study is an investigation of the feasibility of processing lunar regolith to form construction materials and structural components. A scenario will be presented which integrates a processing method with the design for a lunar base shelter and potential construction techniques.

Design Concepts for Pressurized Lunar Shelters Utilizing Indigenous Materials

John Happel

Two design concepts for pressurized lunar shelters are presented together with an in-depth analysis of primary and secondary load conditions and arguments for the utilization of cast basalt as the principal construction material. The first design is comprised of cast cylindrical segments which are post-tensioned in the longitudinal direction. The second design is based on arch-slabs and post-tensioned ring girders which are also post-tensioned longitudinally to create a structure dominated by compression. Construction sequences are outlined for rapid assembly of the two pressurized shelters.

Configuration Optimization of Space Structures

Carlos Felippa

The suitability of Kikuchi's homogenization method for the configuration-shape-size optimization of space structures is investigated. A "design domain block" filled initially with finite elements is gradually "sculpted" into an optimal structure. This new method promises to be a powerful tool in helping the conceptual designer. We focus on its application to planetary structures.

Telerobotic Rovers for Extraterrestrial Construction

Jim Avery

Robotic rovers will play a crucial role in extraterrestrial construction. They will substitute for humans in many operations such as surveying, sensing, signaling and load handling. Rover systems must be versatile so that they can perform a wide variety of jobs, and robust to parts failures. To this end, the ideas of software modularity and multi-robot coordination are being investigated. The current focuses include the development of three telerobotic platforms, infrared positioning systems, and a 4-degree-of-freedom manipulator. Design concepts and telerobotic development will be presented.

Lunar Surface Structural Concepts and Construction Studies

Martin Mikulas

A preliminary design for a heavy lift crane capable of positioning 30,000 kg masses on the surface of the moon will be presented. This crane will enable remote or autonomous precision positioning of large masses without the manual aid of astronauts. The crane concept makes use of three cables instead of one to maintain positive, precise control of the payload. The presentation will include crane mass, stiffness, and control, and will describe an ongoing experimental program to evaluate the concept.

Agenda

Center for Space Construction - Third Annual Symposium

University of Colorado, Boulder
November 21 & 22, 1991

November 21, 1991 — Coors Events/Conference Center, Rooms 3 & 4

7:45 - 8:10	**Registration**	
8:10 - 8:15	**Welcome** A. Richard Seebass, Dean of Engineering	
8:15 - 8:45	**Introduction** Renjeng Su, CSC Director	
8:45 - 10:00	**Orbital Construction**	
	Dynamics of On-Orbit Construction Process	*K.C. Park*
	Interaction Dynamics and Control for Orbital Assembly	*Renjeng Su*
	Controls for Orbital Assembly of Large Space Structures	*Mark Balas*
10:00 - 10:15	***break***	
10:15- 12:05	**Orbital Construction (continued)**	
	Structural Load Control During Construction	*Martin Mikulas*
	Systems Engineering Studies of On-Orbit Assembly Operations	*George Morgenthaler*
	Expert Systems for Assembly Sequence Evaluation	*Steve Jolly*
	Assembly and Joining Methods for Large Space Structures	*Harold Bush, NASA*
12:05 - 1:15	***lunch and poster session***	
1:15 - 3:15	**Lunar Construction**	
	Lunar Regolith and Structure Mechanics	*Stein Sture*
	Indigenous Lunar Construction Materials	*Wayne Rogers*
	Design Concepts for Pressurized Lunar Shelters	*John Happel*
	Configuration Optimization of Space Structures	*Carlos Felippa*
3:15 - 3:30	***break***	
3:30 - 5:00	**Lunar Construction (continued)**	
	Telerobotic Rovers for Extraterrestrial Construction	*Jim Avery*
	Lunar Surface Structural Concepts and Construction Studies	*Martin Mikulas*
	Robotic Technology Application Plan for JSC	*Reg Berka, NASA*
5:00 - 5:15	**Summary** Renjeng Su	
5:15 - 7:00	**Wine/Cheese Reception and Poster Session**	

November 22, 1991 — Engineering Center

Meet at Main Lobby

8:00 - 10:00	**Experimental and Simulation Demonstrations**
	Lunar Crane Testbed
	Lunar Regolith and Structures
	Lunar Rover and Local Positioning System
	Dynamics of Orbital Structures
	Expert Systems for Assembly Sequence Evaluation

Introduction

Renjeng Su
CSC Director

Third Annual Symposium
November 21 & 22, 1991

OMIT

CSC GOALS

1. To conduct interdisciplinary engineering research which is critical to the construction of future space structures and systems

2. To educate students who will have vision and technical skills to advance the new engineering culture of space construction

The Purpose of Space Construction Engineering

The purpose of Space Construction Engineering is to enable the establishment of structures in Earth orbit, on the Moon, and on planetary surfaces to provide for habitation, exploration and other scientific and engineering activities.

Characteristics Of Space Construction

- Remote construction sites and difficult access
- High cost of transportation, construction, and maintenance
- Limited human resources

In Orbit

- Large volume and mass
- Free flying in reduced-gravity environment
- Fragility

On the Moon

- Extremely different and hostile construction environment

Orbital Structures and Systems

Space Station, Interplanetary Spacecraft, Earth Observation Satellite, Planetary Exploration Vehicle

Technical Challenges of Orbital Construction

1. Design :
   - Integrated process for structural design and construction methods
2. Analysis:
   - Construction dynamics and evolving structures
   - Systems trade-off models
3. Construction equipment:
   - Autonomous and telerobotic equipment
   - Supporting fixtures for construction
4. Mechanisms:
   - Joining devices and processes
   - Load absorption and stabilization devices
5. Experimentation:
   - Earth-based and space-based methods
6. Testing and Maintenance methods and facilities

CSC Orbital Construction Tasks

1. Design:
   - Expert systems for assembly sequence evaluation (Jolly)
   - Control for evolving structures during construction (Balas)
2. Analysis:
   - Multi-body dynamics simulation capability (Park)
   - Component mode synthesis methods (Farhat)
3. Construction equipment:
   - Space crane control (Balas)
   - Robotic positioning and attachment of structural payloads (Su)
4. Mechanisms:
   - Passive/active load control mechanisms (Mikulas)

Lunar Structures and Systems

Pre-assembled Lunar Shelters

Indigenous Lunar Shelters

Lunar Outpost Infrastructures: Roads, Landing Pads, Communication Facilities, Power systems, etc.

Technical Challenges Of Lunar Construction

1. Understanding of soil conditions (Sture)
2. Structural designs using indigenous materials (Rogers)
3. Construction equipment with increased efficiency, teleoperation capabilities, flexibility, and reliability (Haggard)
4. Rigorous analysis of performance and energy consumption for construction equipment
5. Systems analysis

CSC Lunar Construction Tasks

1. Lunar regolith condition and structures (Steve)
2. Indigenous material processing for structural elements (Rogers)
3. Lunar shelter design using indigenous materials (Hoppel)
4. Lunar crane system (Mikulas)
5. Robotic construction workers (Avery)
6. Lunar regolith penetration tools (Steve, Barnes)
7. Systems analysis of construction equipment and structural concepts

Space Construction: A New Engineeing Culture

A new engineering culture will emerge which is characterized by an unprecedented level of

- planning and analysis
- integration of design and construction
- telerobotic operation
- reliability

and innovative approaches to experimentation, testing and maintenance

CSC - A Miniature Of The New Culture

- A faculty with diversified background leads the students to define and develop the field of space construction.
- The students are the prime mover of the new culture.
  - course work from multiple departments
  - interdisciplinary research projects on space construction
- Weekly CSC seminars provide an educational forum.

ORBITAL CONSTRUCTION

Throughout this session, there was no discussion of efforts addressing deployable [illegible] structures.

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Dynamics of On-Orbit Construction Process

Good progress in only 5 months of effort.

K.C. Park

Third Annual Symposium
November 21 & 22, 1991

Participants:

J.C. Chiou, S. Alexander, M.C. Natori,
M. Mikulas and K.C. Park

Contents of Presentation

- Problem Definition and Motivation
- Survey of Current Technology
- Focus Problems
- Approach
- Progress/Discussion
- Future Direction and Anticipated Results

Problem Statement and Motivation

- In-space structural construction technology is yet to be demonstrated even for the planned space station.
- Construction procedures, logistics, the shuttle deployment duration for each flight are criticallydictated by how well we understand the interaction dynamics when two modules are assembled together.
- The interaction dynamics is, from the outset, an interdisciplinary problem, involving the multibody dynamics, the dynamics of the RMS, the control of maneuvering and contact/impact surge forces, and possibly also the shuttle attitude dynamics and control.

Existing Applicable Technology

- Truss Assembly Experiment in Buoyancy Tank
- In-Space Shuttle-Based Deployment of Solar Panel and Truss
- Den Hartog-Like Shock Isolation Elements
- Contact/Impact Predictability via Simulation ***Ren Su**
- High-Precision Flexible Multibody Simulation
- Adaptive Elements for Localized Shock Mitigation
- Fast Real-Time Control and Simulation

The Present Focus Problem

"Dynamics of On-Orbit Structural Construction"

- To identify the required forces for structure-structure rendezvous vs. construction/maneuvering speed

- To perform accident scenarios for safeguarding of unanticipated human/RMS operational mistakes

- To conduct trade-off studies between passive and active control of contact/impact mechanisms

- To perform integrated simulations involving the structural dynamics, RMS control maneuvering, and the shuttle orbital attitude dynamics/control

- And, finally, to assist the designers of "structural-structural rendezvous" mechanism devices in the evaluation of candidate devices.

Objectives

- Librational Motion of the Space Shuttle
- The Interaction of SRMS Motions and Attitude Dynamics
- Transient Vibrations of Shuttle/SRMS Combination
- The Starting and Stopping Strategies While Maneuvering SRMS
- Contact/Impact Behavior of SRMS with/without Payload
- Identify Possible Dynamic Instability and/or Control Requirements

Present Approach

1. Conduct the orbital perturbation effects of the shuttle due to rendezvous/disengagement of the shuttle from the space station and/or the structural payload to be assembled.

2. Construct RMS model (both rigid and flexible) and study the dynamics of RMS maneuvering scenarios.

3. Perform simple rigid-rigid, rigid-flexible, flexible-flexible contact/impact analysis vs. rendezvous speeds.

4. Establish dynamics/control operational requirements from the above three studies.

5. Develop "rendezvous" elements or concepts.

6. Develop simulation modules for others to use for the study of in-space construction procedures.

Progress (June – November, 1991)

- Modeling of shuttle perturbations due to possible construction disturbances
- SRMS modeling as an integral part of structural cargo maneuvering
- Study of a simple rendezvous dynamics model
- Development of 3-D special-purpose dynamics simulation
- Parameter study of assembly speeds vs. contact forces

Findings and Discussion

- For Trajectory/Motion Study only, one can employ rigid SRMS, rigid structural cargo models; however, for controlling multiple-contact assembly, dynamic flexible models of both SRMS and structural modules are necessary.

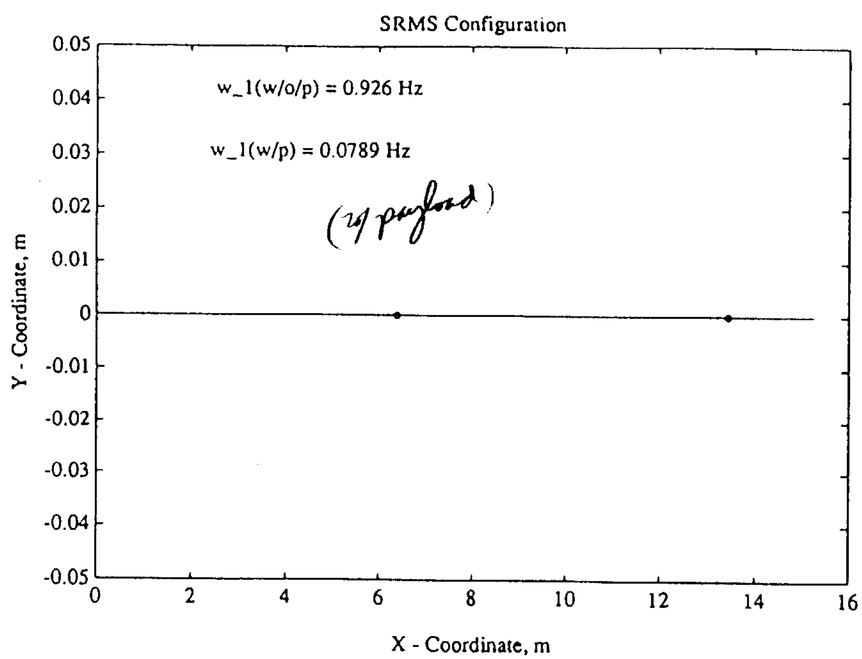
- If high-precision assembly is of primary concern, adaptive devices that absorb the contact surge stresses, and at the same time self-correct the dimensional errors can significantly improve the in-space structural assembly.

- No matter how slowly and carefully the assembly is to be carried out, an integrated dynamics model is important for assessing 'unwanted' abort maneuvering, accidents, safety margin (operational) evaluations.

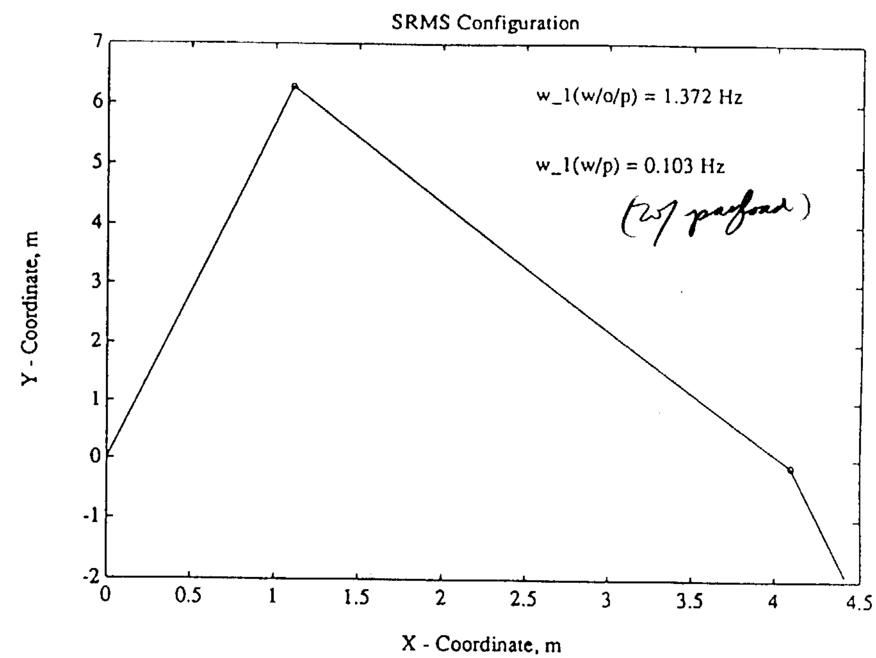
Future Activities and Anticipated Results

- Make our Multibody Simulator available to NASA/Langley team for shuttle-based structural assembly evaluations as an alternative tool.
- 3-Dimensional flexible multipoint assembly contact evaluations.
- Integrated simulation of structures, SRMS, shuttle orbital attitude motions.
- Development of Design Concepts for structure-structure Rendezvous Mechanism Devices.

Frequency Variations During Manuevering of SRMS



Straight Position



Intermediate Position

Question: How effective can linear control strategies be for changing frequencies and mode shapes?

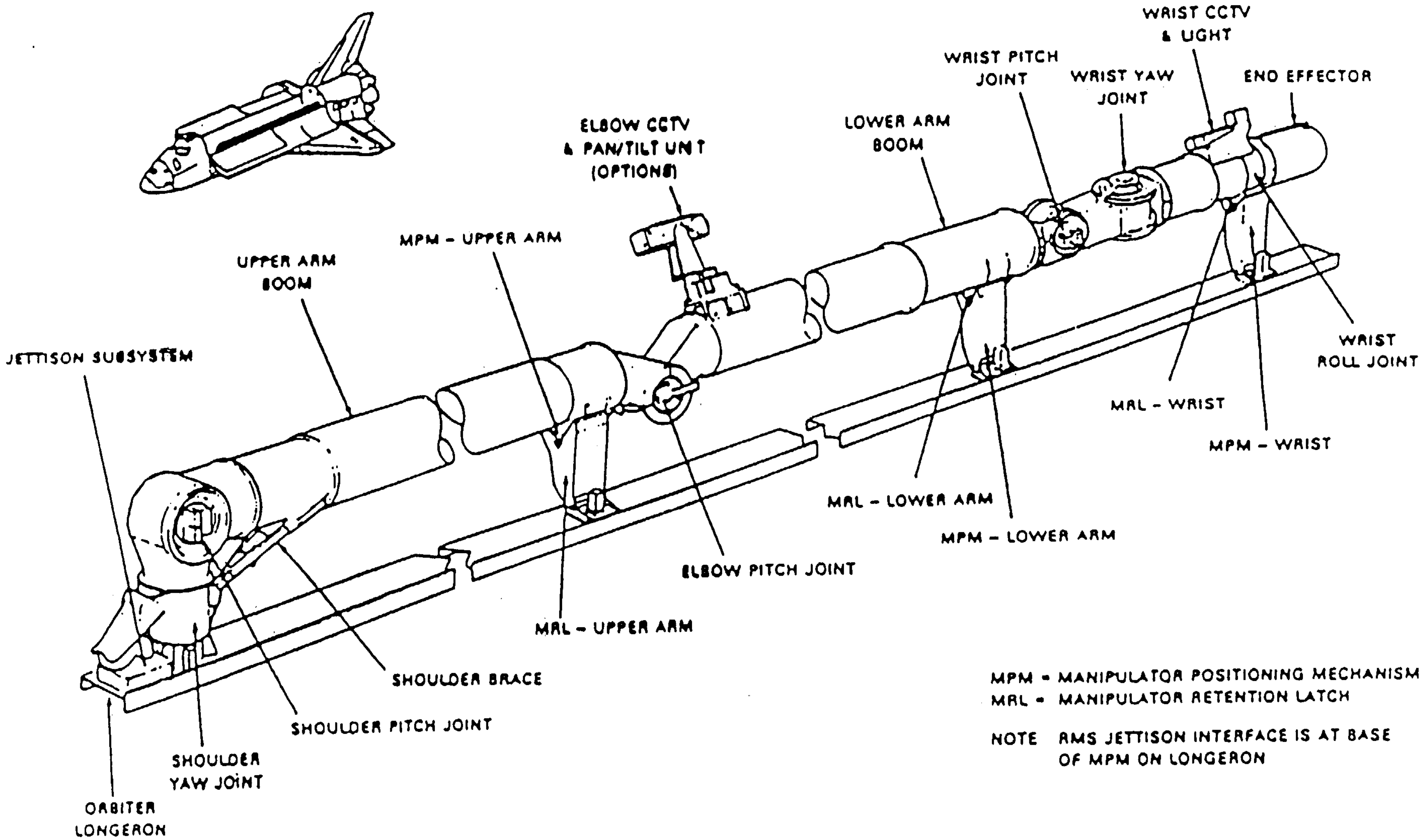


Figure 1 SRMS Mechanical Arm in Stowed Position

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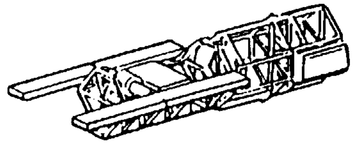
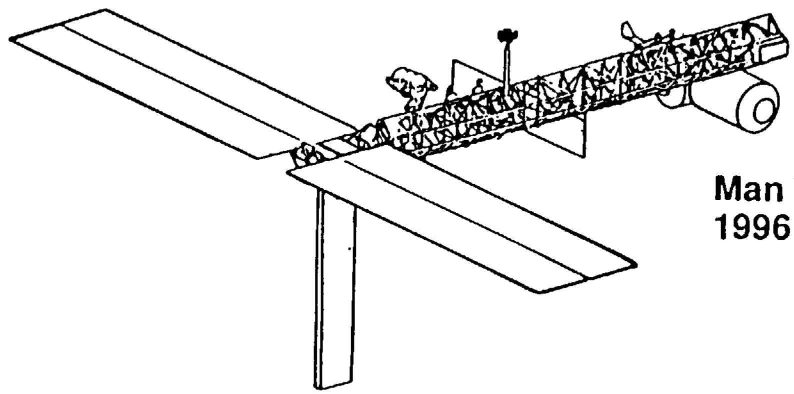
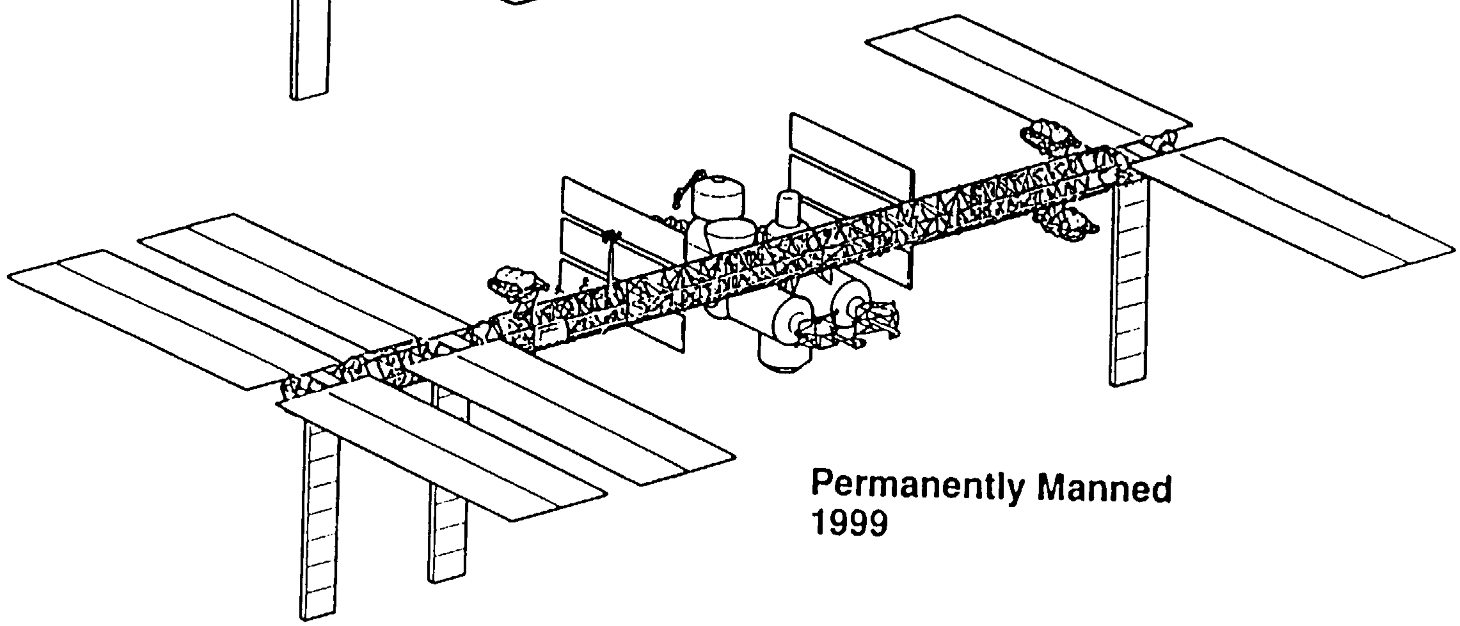
SPACE STATION FREEDOM ASSEMBLY SEQUENCE



First Element Launch
1995

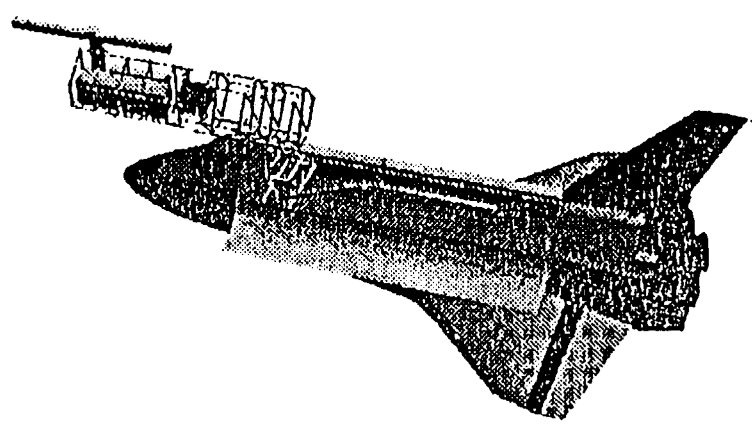


Man Tended Capability
1996



Permanently Manned
1999

MB-1



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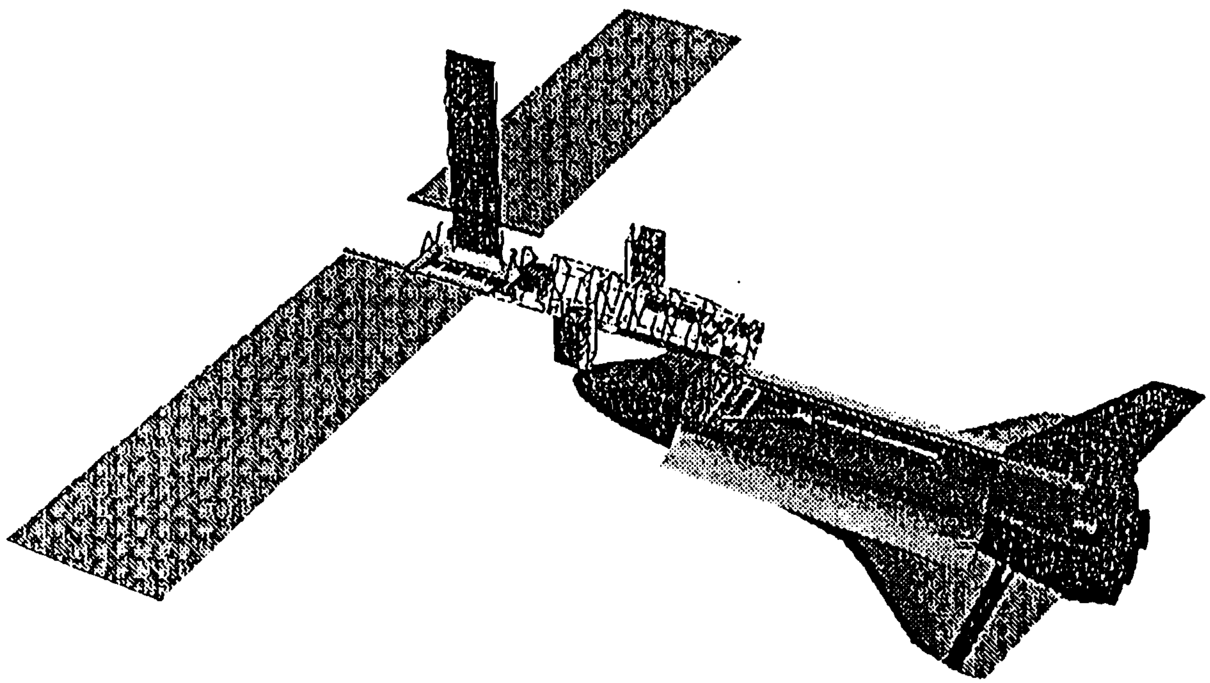
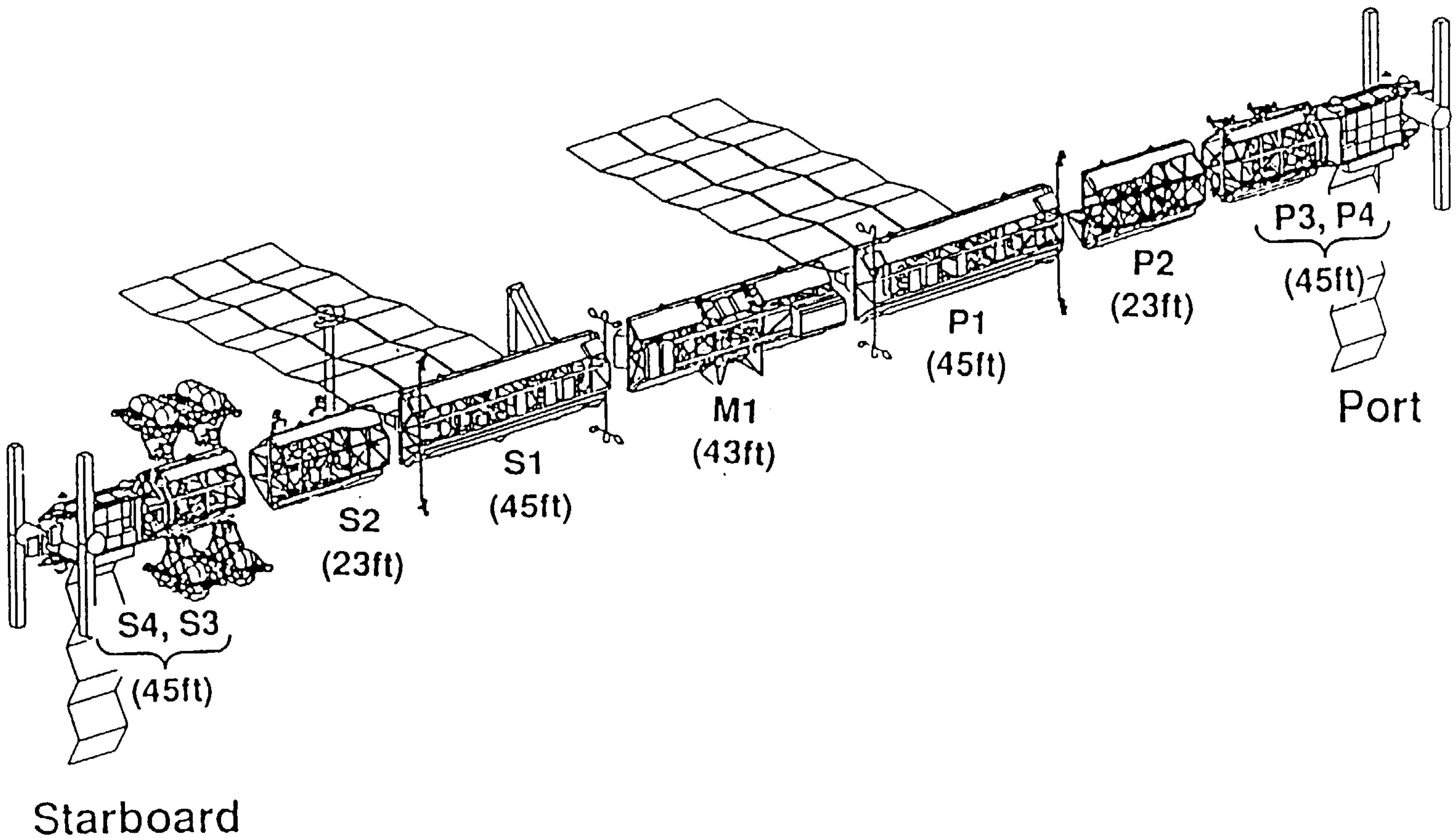


THE SEGMENTS

VKB253 M3EL



Librational Motion of a Space Shuttle

- 100 minutes circular orbit
- $(I_{xx} - I_{zz})/I_{yy} = 1$
- Initial Disturbance: $\omega_1 = \omega_3 = 0, \omega_2 = -0.105$ deg/s

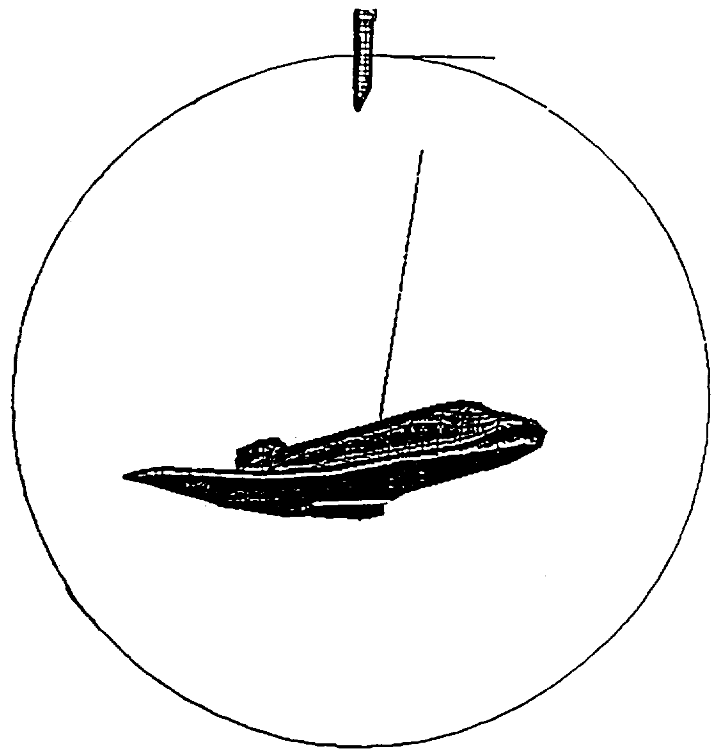


Fig. 1 Orbiting Space Shuttle with MRMS

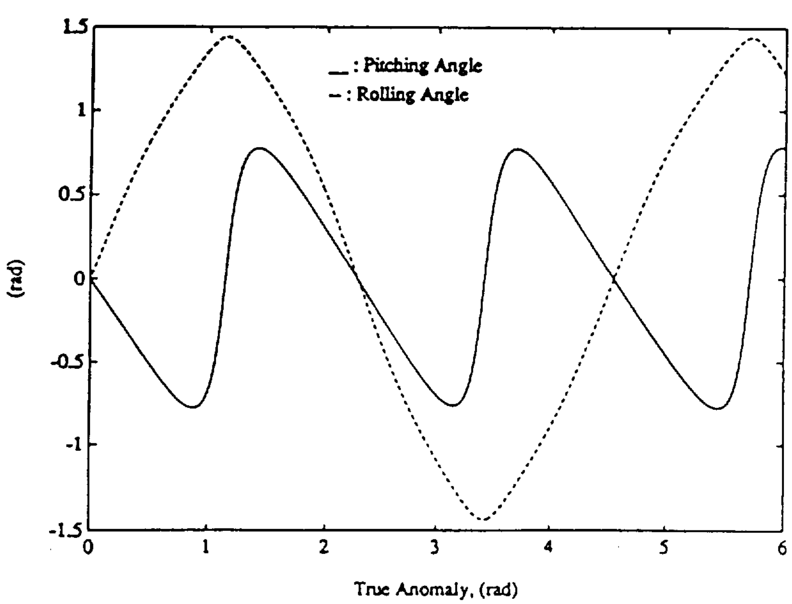


Fig. 2 Three Dimensional Librational Response

Librational Motion of a Space Shuttle

- $I_{xx}/I_{yy} = 0.958, \quad I_{zz}/I_{xx} = 0.126$
- (1) Initial pitching, rolling, yawing angles = 10 deg.
- (2) Initial pitching, rolling, yawing angles = 25 deg.

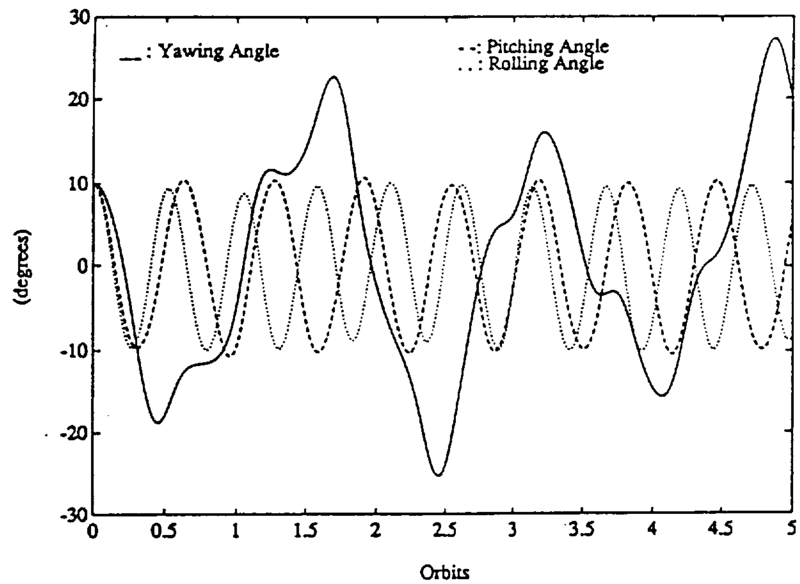


Fig. 3 Librational Response of a Space Shuttle Under Small Disturbances
Pitching Angle = Rolling Angle = Yawing Angle = 10 degrees

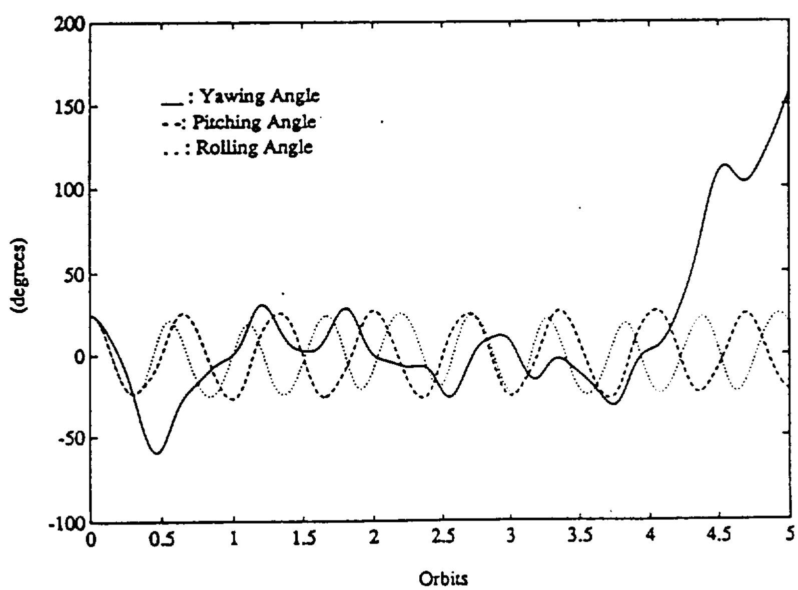
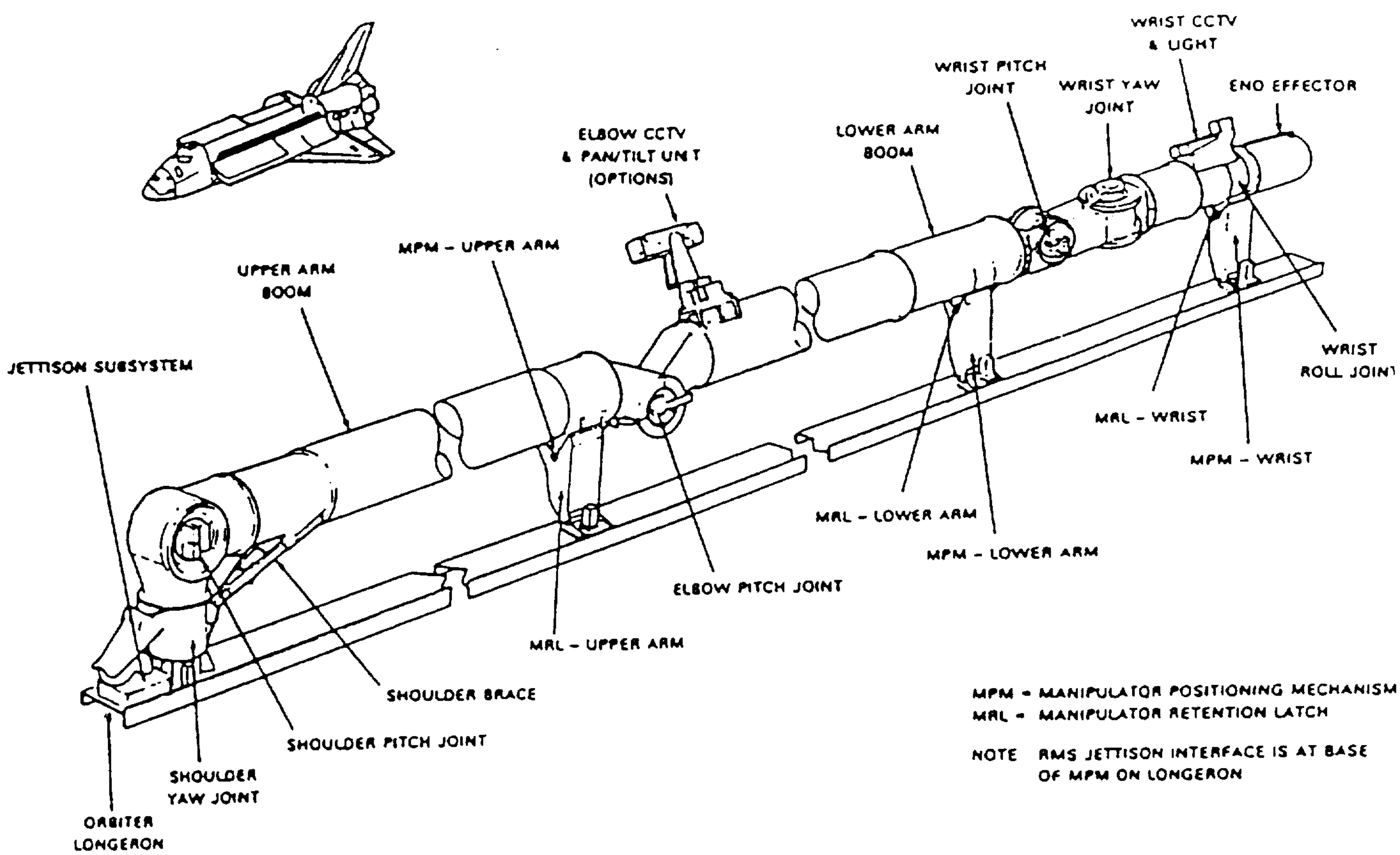


Fig. 4 Librational Response of a Space Shuttle Under Small Disturbances
Pitching Angle = Rolling Angle = Yawing Angle = 25 degrees

Maneuvering of Shuttle Remote Maneuverno Systems (SRMS)

Properties of SRMS:

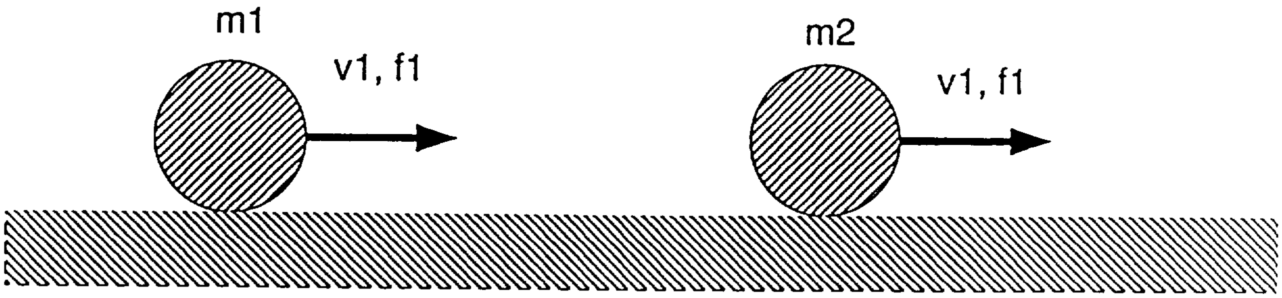
- Weight = 410 Kg
- Length = 15 m
- Cross Section Area = 0.0022 m^2
- Young's Module = 1.27 X 10^{11} Pa
- Shear Module = 3.18 X 10^{10} Pa
- Density = 1.2 X 10^4 Kg/m^3
- Tip Maneuvering Speed (without payload) = 0.6 m/s

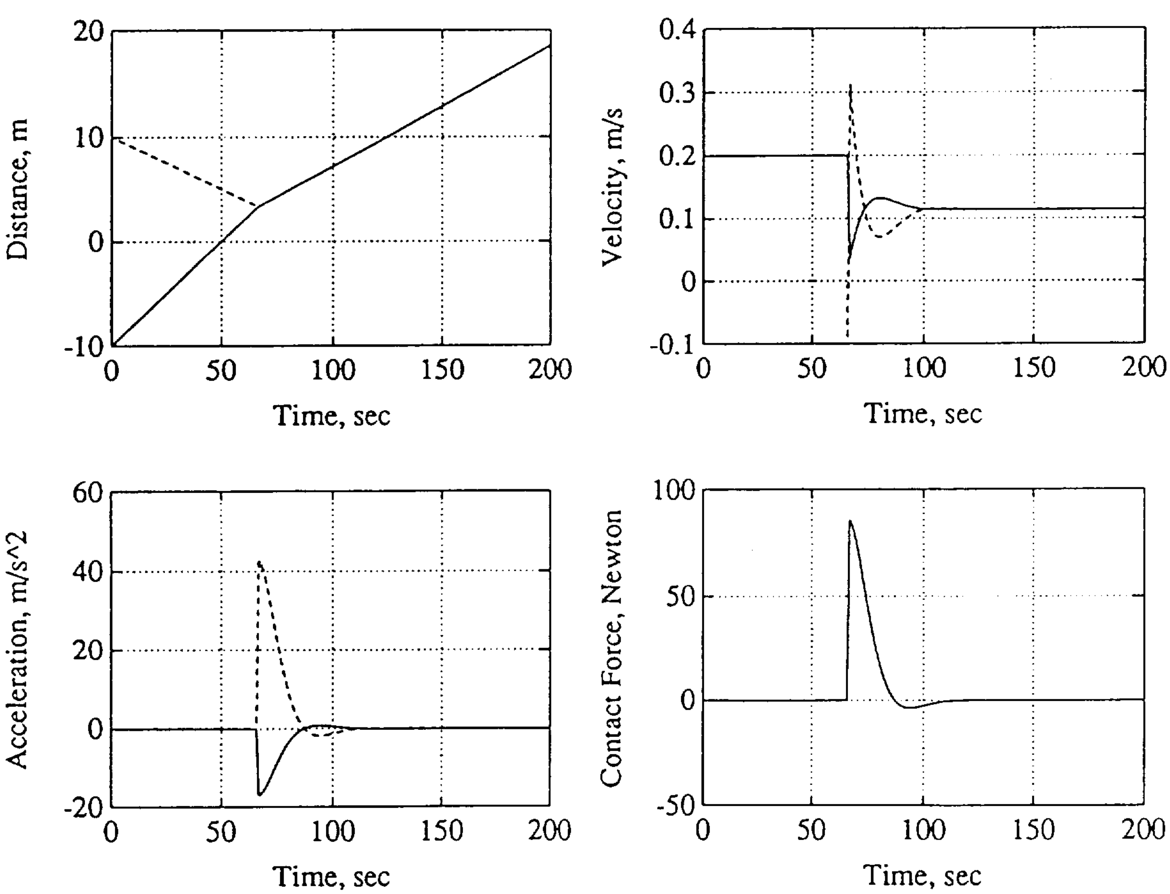


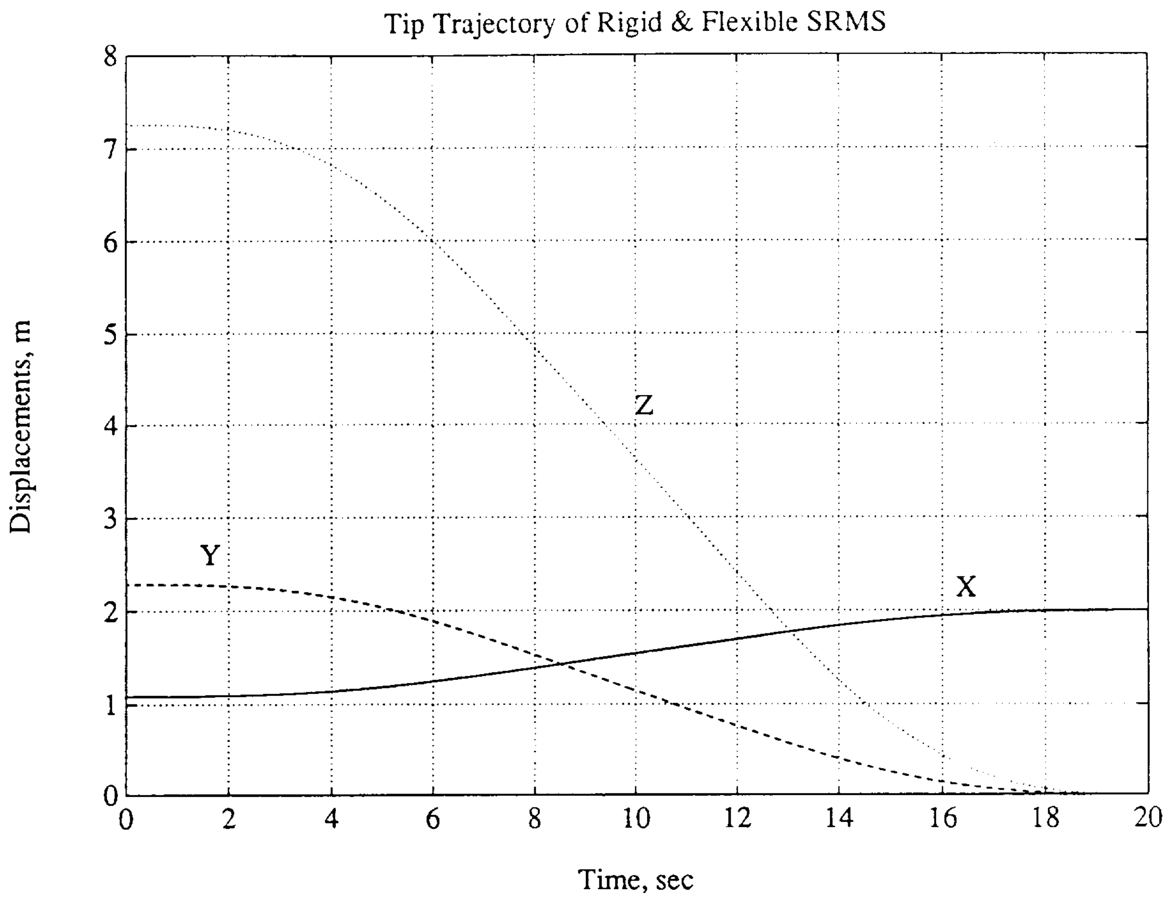
CONTACT/IMPACT OF 2 RIGID BALLS

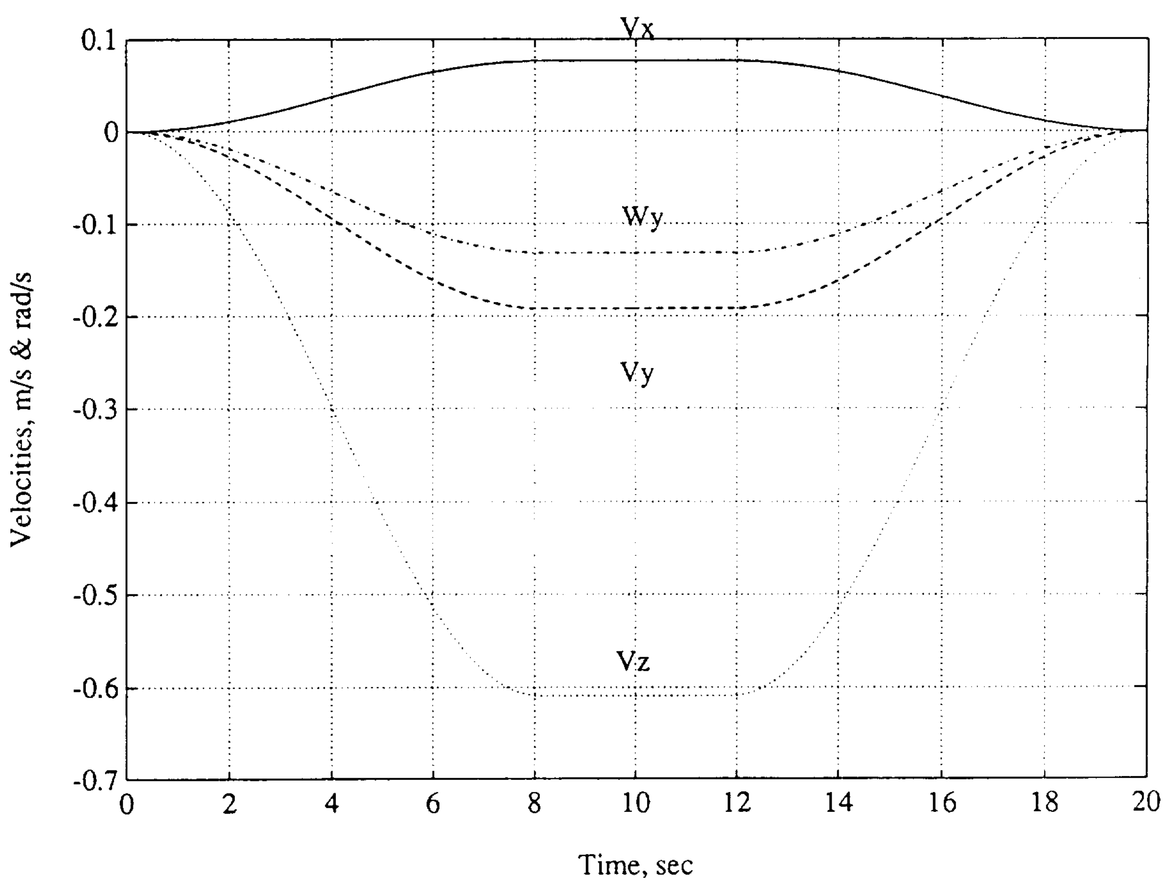
m1 = 5 kg,   m2 = 2 Kg

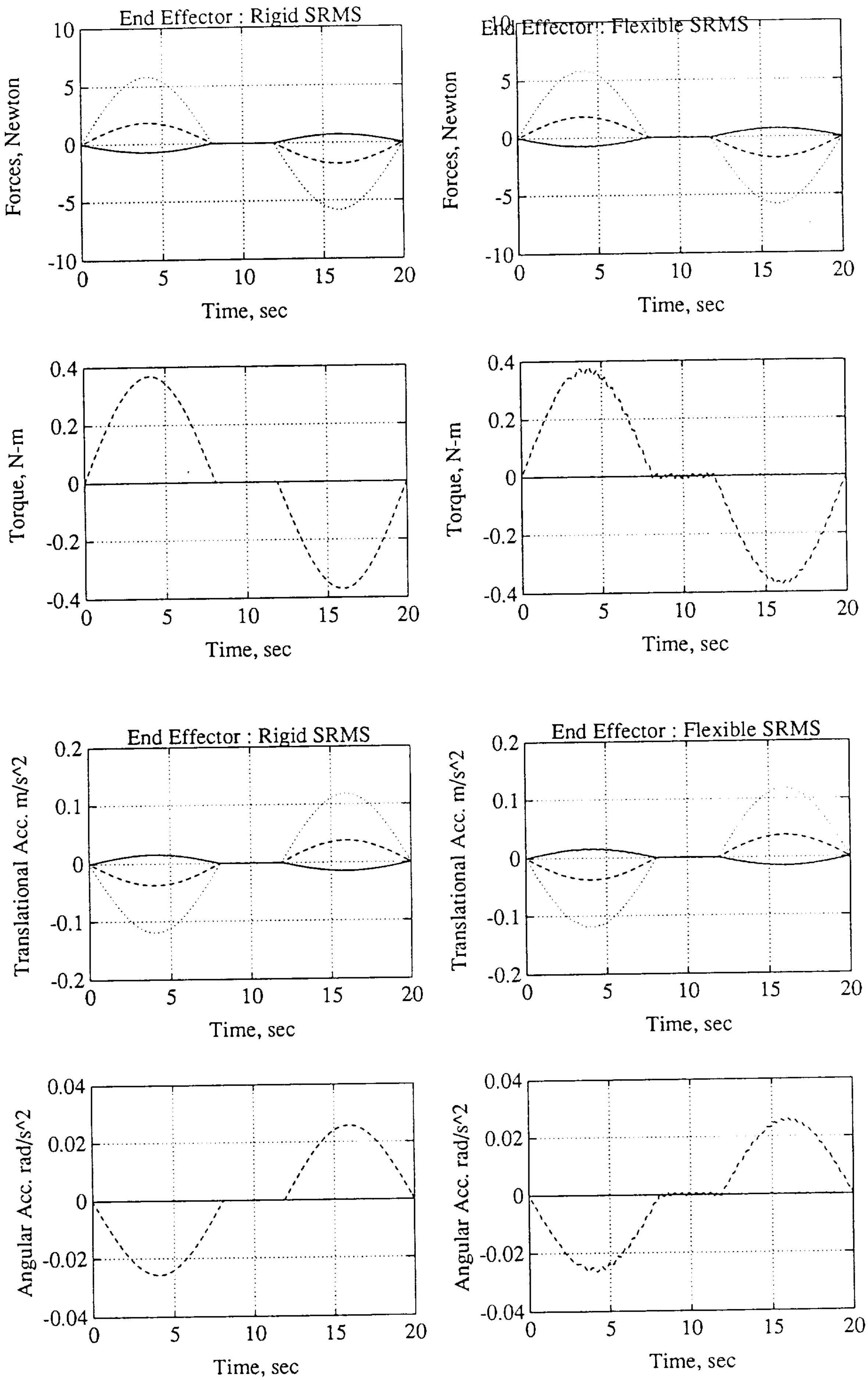
1) v1 = 0.2 m/s, v2 = - 0.1 m/s
2) f1 = 0.01 N,   f2 = - 0.008 N
3) v1 = 0.1 m/s, v2 = - 0.05 m/s, f1 = 0.01 N, f2 = -0.001 N



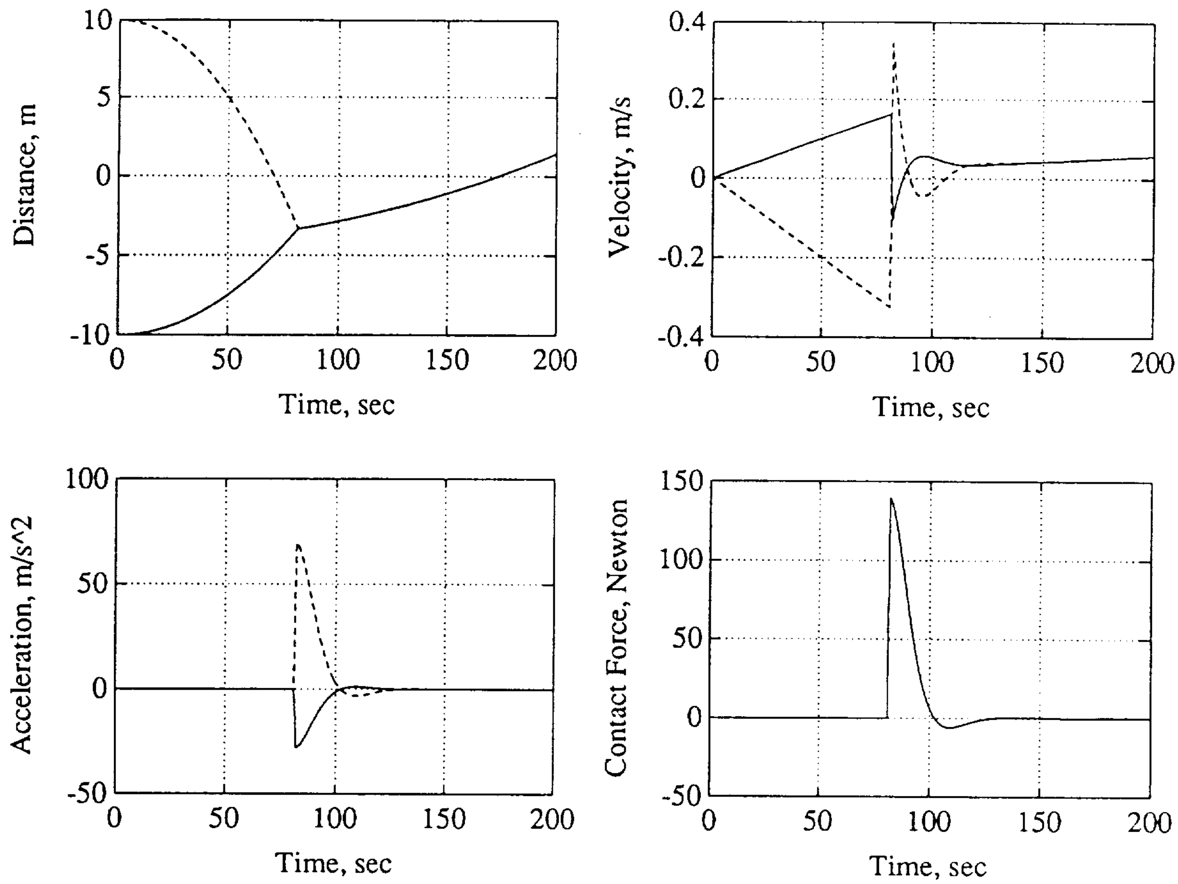


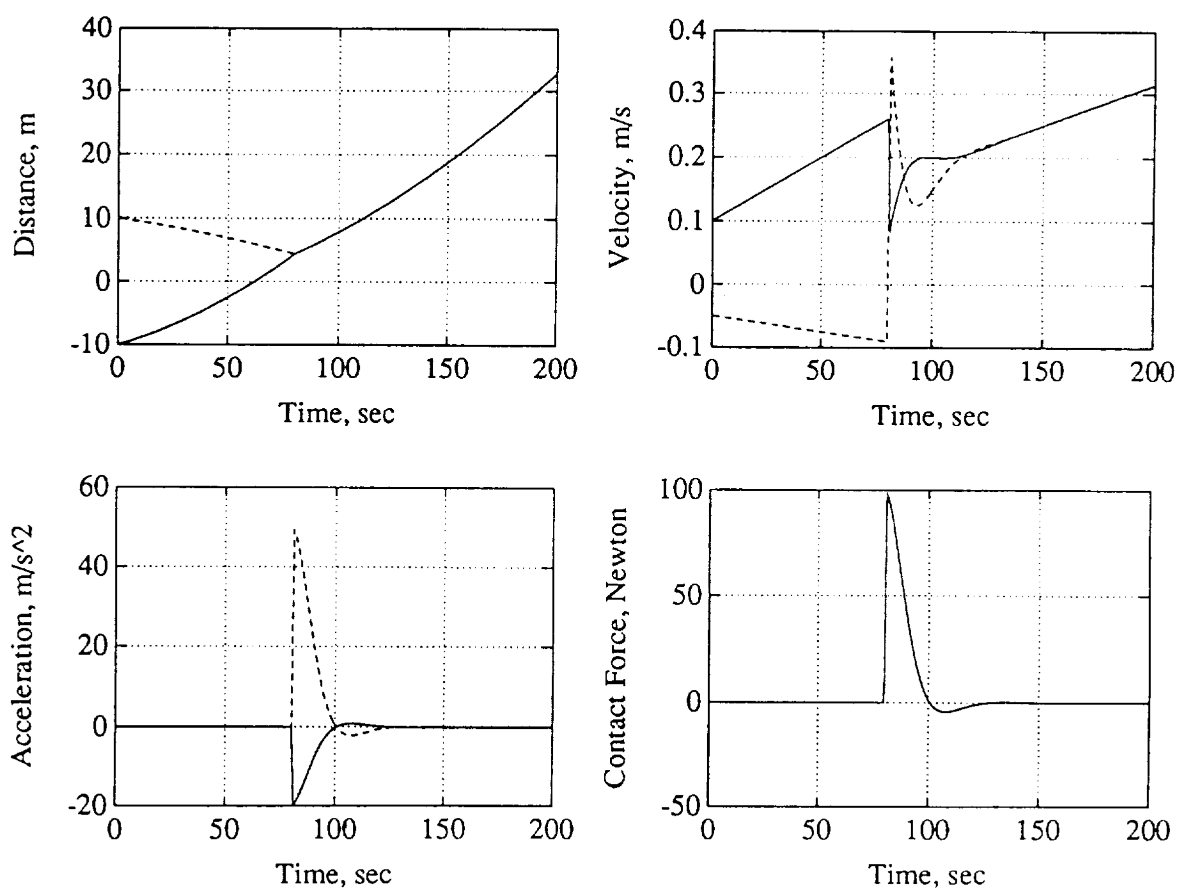

Tip Trajectory of Rigid & Flexible SRMS
Displacements, m
Time, sec
X
Y
Z
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10
12
14
16
18
20

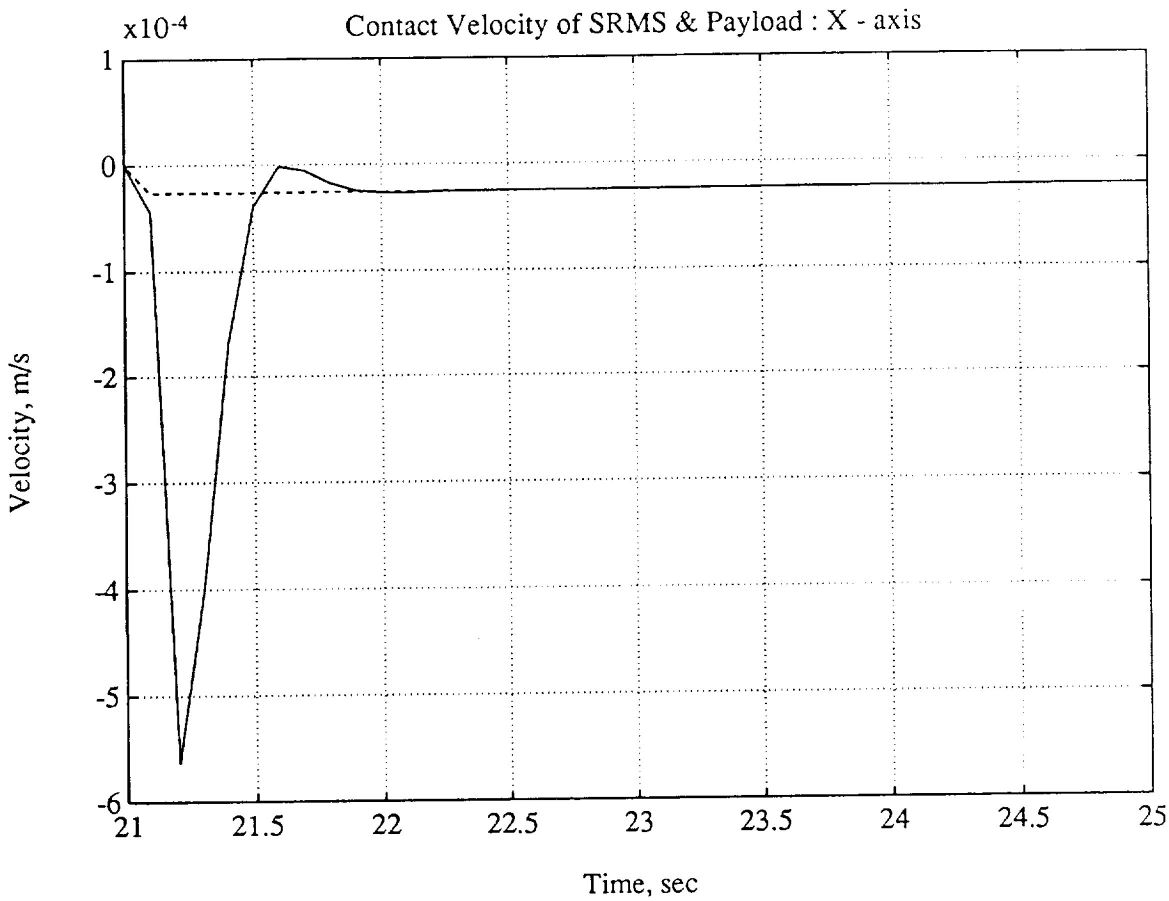

Velocities, m/s & rad/s
Time, sec
Vx
Wy
Vy
Vz
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
0
2
4
6
8
10
12
14
16
18
20



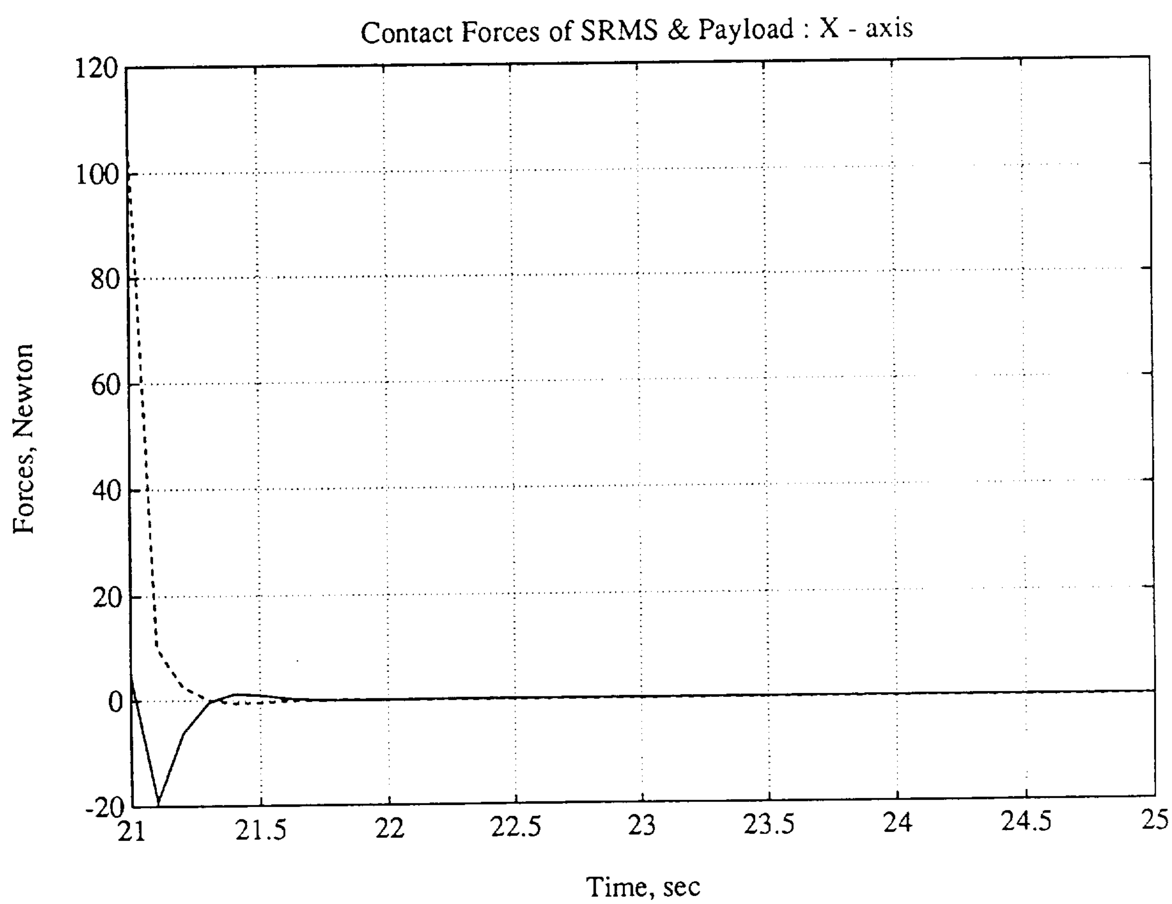
End Effector : Rigid SRMS
Forces, Newton
10
5
0
-5
-10
0
5
10
15
20
Time, sec
End Effector : Flexible SRMS
Forces, Newton
Time, sec
Torque, N-m
0.4
0.2
0
-0.2
-0.4
Time, sec
Torque, N-m
Time, sec
End Effector : Rigid SRMS
Translational Acc. m/s^2
0.2
0.1
0
-0.1
-0.2
Time, sec
End Effector : Flexible SRMS
Translational Acc. m/s^2
Time, sec
Angular Acc. rad/s^2
0.04
0.02
0
-0.02
-0.04
Time, sec
Angular Acc. rad/s^2
Time, sec


Distance, m
Time, sec
Velocity, m/s
Time, sec
Acceleration, m/s^2
Time, sec
Contact Force, Newton
Time, sec

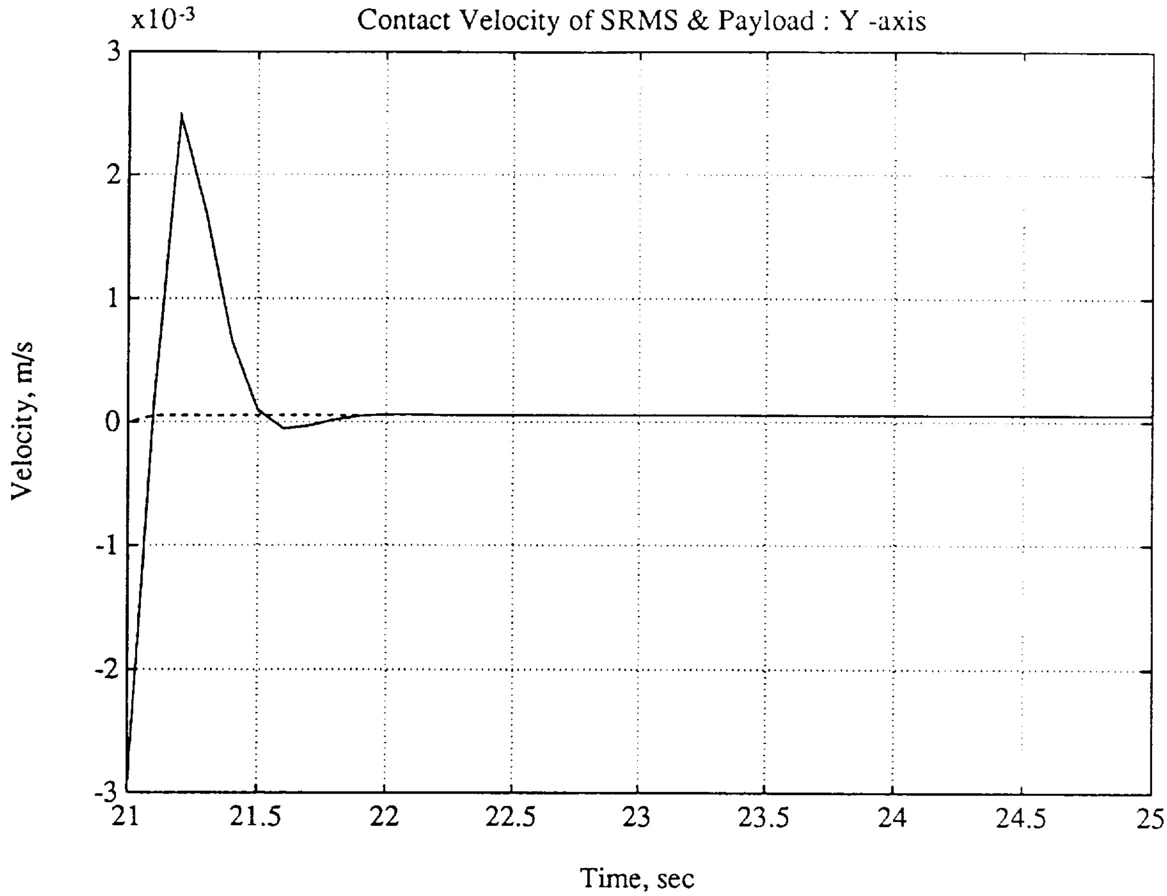

Distance, m
Time, sec
Velocity, m/s
Time, sec
Acceleration, m/s^2
Time, sec
Contact Force, Newton
Time, sec

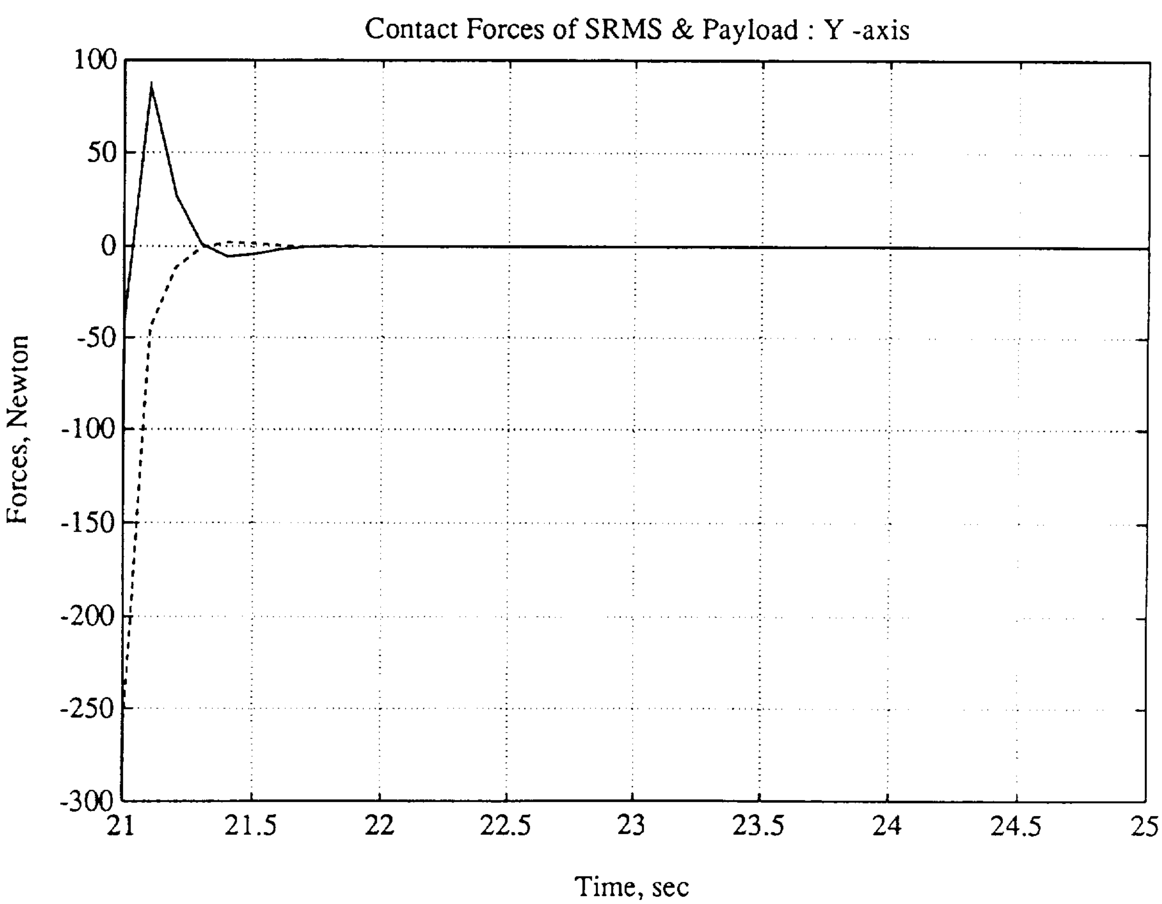


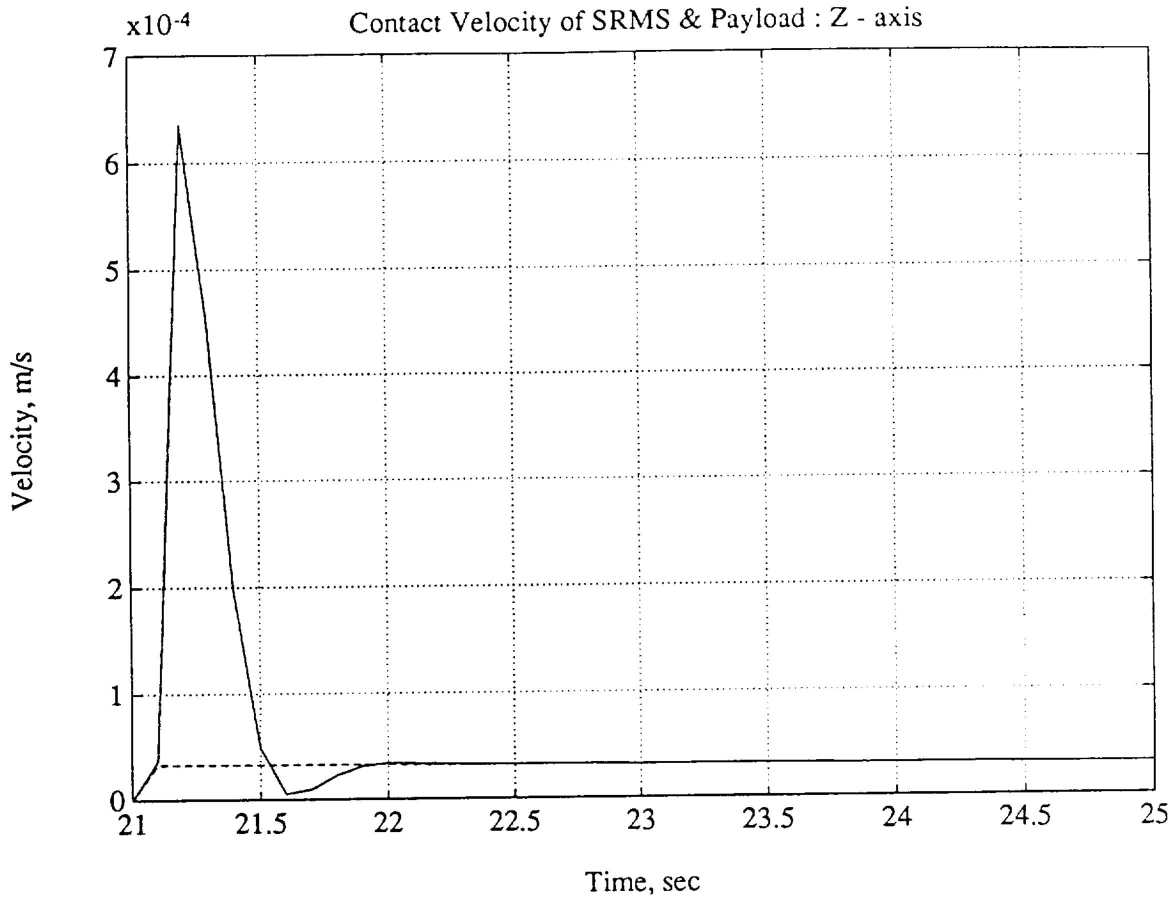
Contact Velocity of SRMS & Payload : X - axis
x10^-4
1
0
-1
-2
-3
-4
-5
-6
Velocity, m/s
21
21.5
22
22.5
23
23.5
24
24.5
25
Time, sec

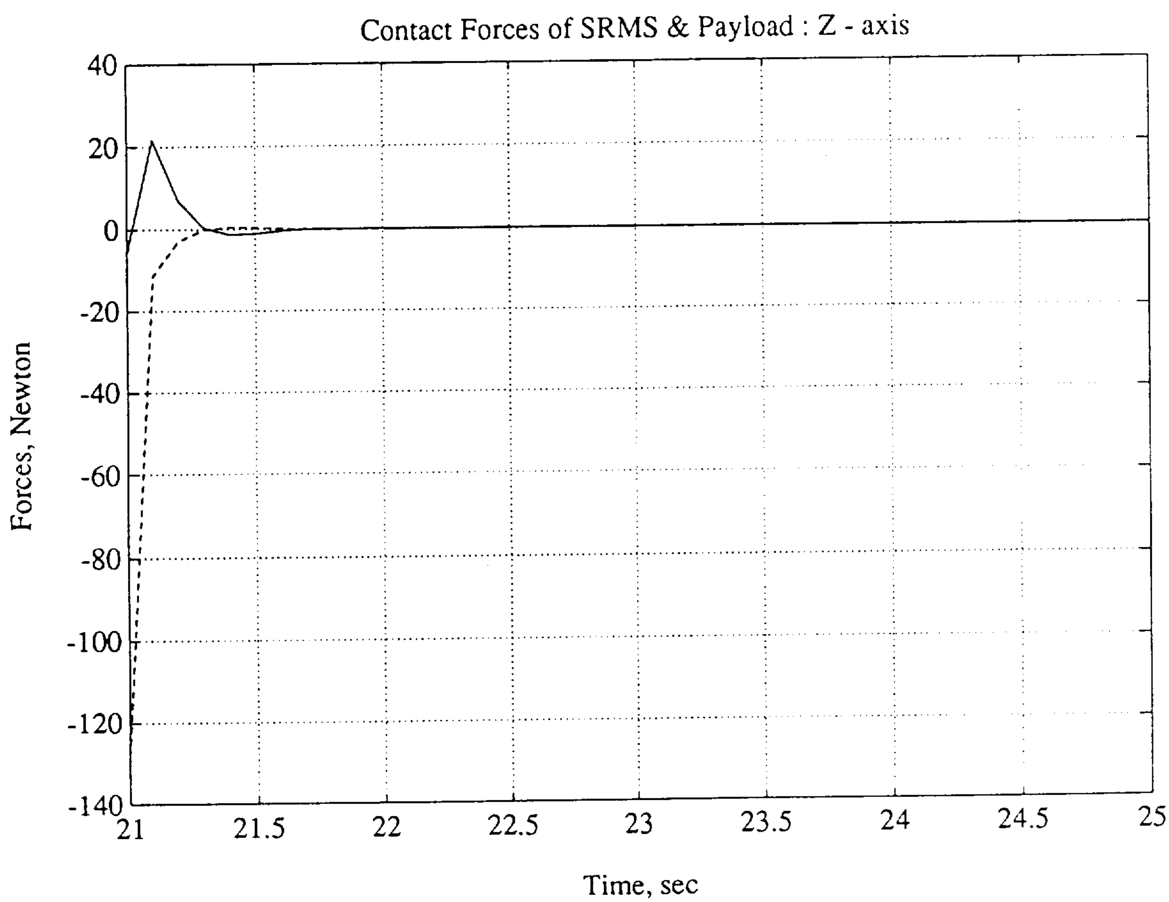


Contact Forces of SRMS & Payload : X - axis
120
100
80
60
40
20
0
-20
Forces, Newton
21
21.5
22
22.5
23
23.5
24
24.5
25
Time, sec


x10-3
Contact Velocity of SRMS & Payload : Y -axis
3
2
1
0
-1
-2
-3
Velocity, m/s
21
21.5
22
22.5
23
23.5
24
24.5
25
Time, sec


Contact Forces of SRMS & Payload : Y -axis
100
50
0
-50
-100
-150
-200
-250
-300
Forces, Newton
21
21.5
22
22.5
23
23.5
24
24.5
25
Time, sec


Contact Velocity of SRMS & Payload : Z - axis
x10-4
Velocity, m/s
Time, sec
0
1
2
3
4
5
6
7
21
21.5
22
22.5
23
23.5
24
24.5
25


Contact Forces of SRMS & Payload : Z - axis
Forces, Newton
Time, sec
40
20
0
-20
-40
-60
-80
-100
-120
-140
21
21.5
22
22.5
23
23.5
24
24.5
25

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P-14

cSc

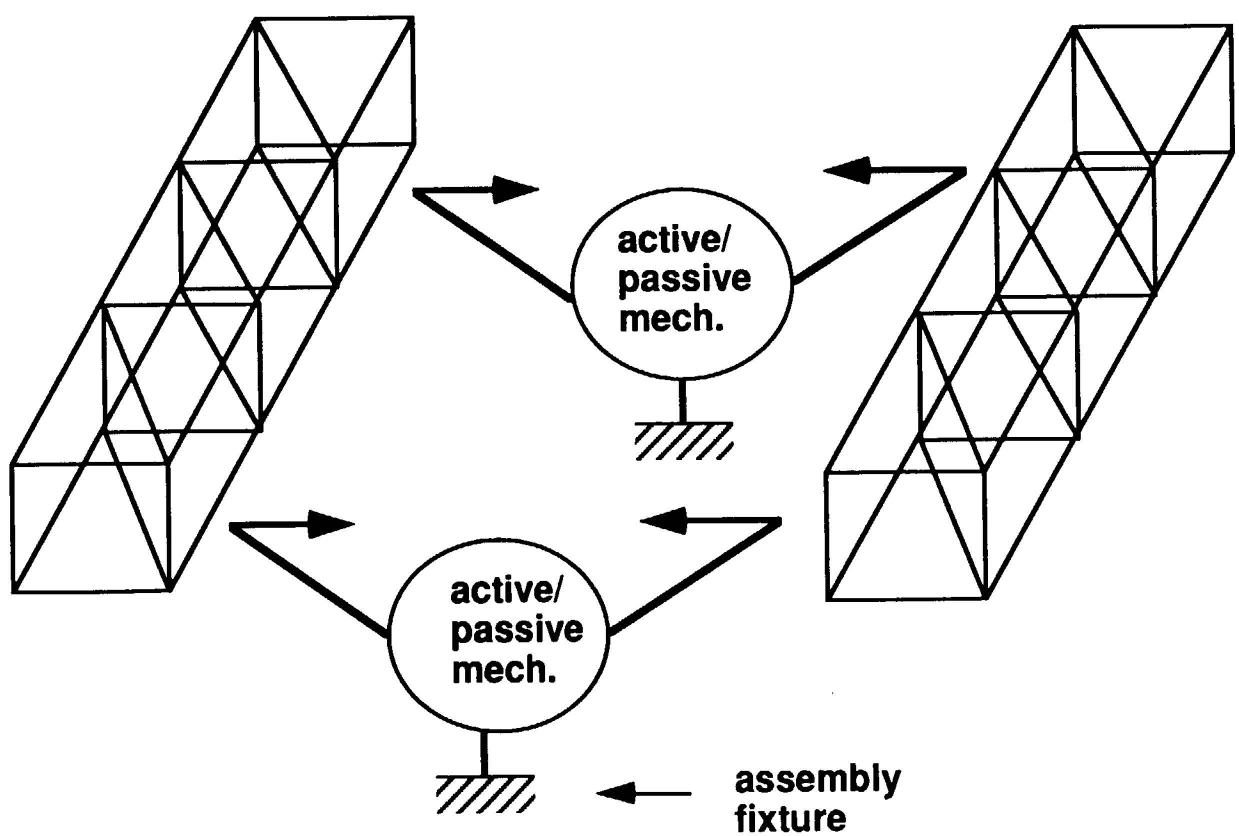
Interaction Dynamics and Control for Orbital Assembly

Very simplistic models. Good starting point. Should be further along at 3rd annual review.

Renjeng Su
Jim Chapel, M.M. PhD student

Third Annual Symposium
November 21 & 22, 1991

Dynamics and Control Problems of Joining Structures in Orbit



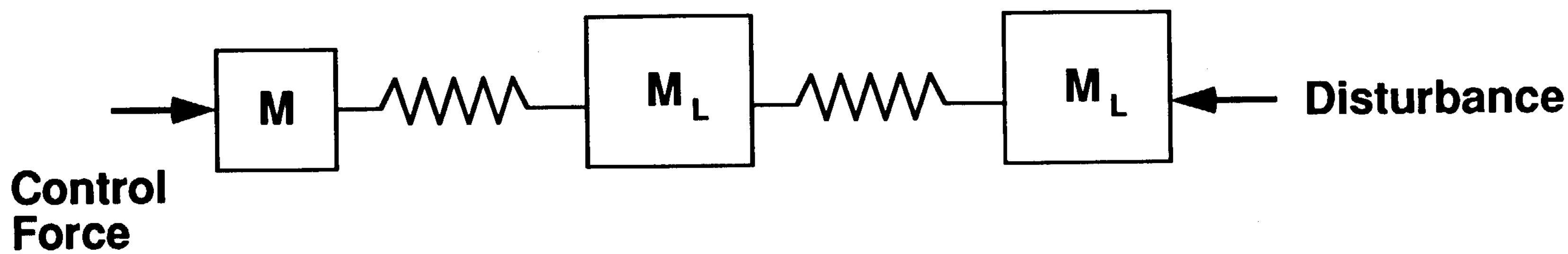
- structural vibrations
- multiple-point joining
- compliant contact

BASIC PROBLEMS

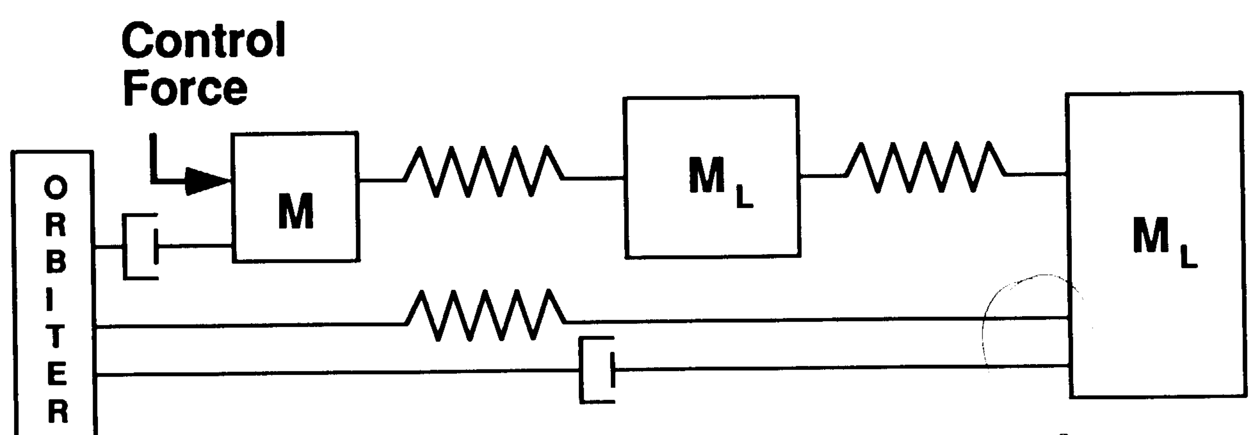
1. How will a payload controlled by active positioning devices interact dynamically with its environment?
2. How can closed-loop control be designed to achieve desired interactive dynamics?

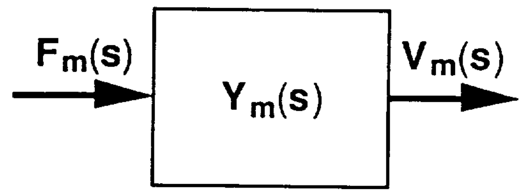
Spring-and-Mass Models

1)



2)

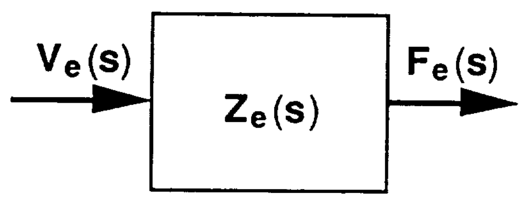




Admittance model of the manipulator.

$$\int_{t_0}^{T} F_m^T(t)\, V_m(t)\, dt \geq 0$$

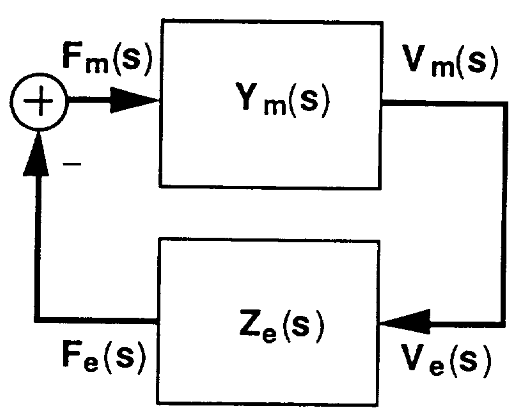
Condition for manipulator passivity



Impedance model of the environment.

$$\int_{t_0}^{T} F_e^T(t)\, V_e(t)\, dt \geq 0$$

Condition for environmental passivity



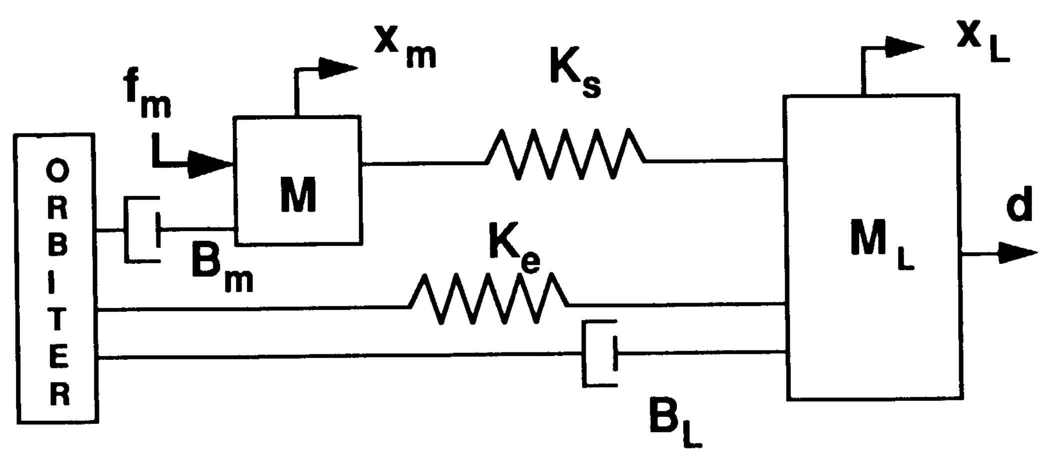
Model of manipulator coupled to environment.

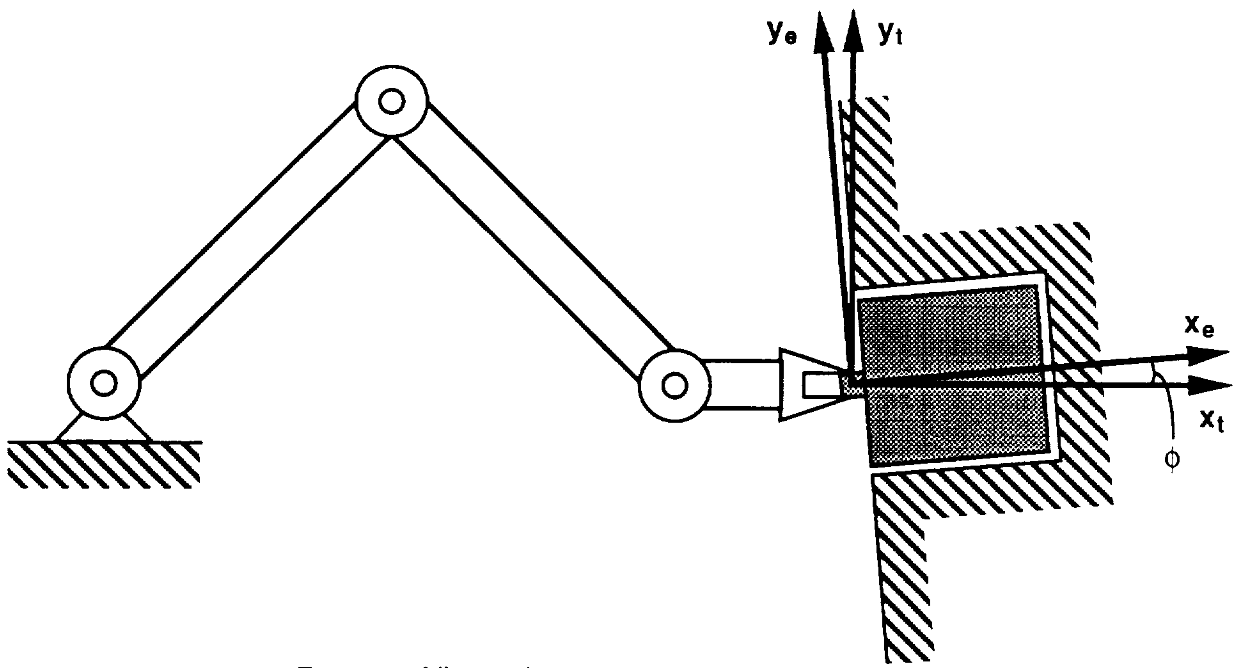
A Simple Example

$$\begin{bmatrix} x_m \\ x_m \\ x_L \\ x_L \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -K_s/M & -B_m/M & K_s/M & 0 \\ 0 & 0 & 0 & 1 \\ -K_s/M_L & 0 & dK/M_L - B_L/M_L \end{bmatrix} \begin{bmatrix} x_m \\ x_m \\ x_L \\ x_L \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -1/M & 0 \\ 0 & 0 \\ 0 & -1/M \end{bmatrix} \begin{bmatrix} f_m \\ d \end{bmatrix}$$

Feedback controls:

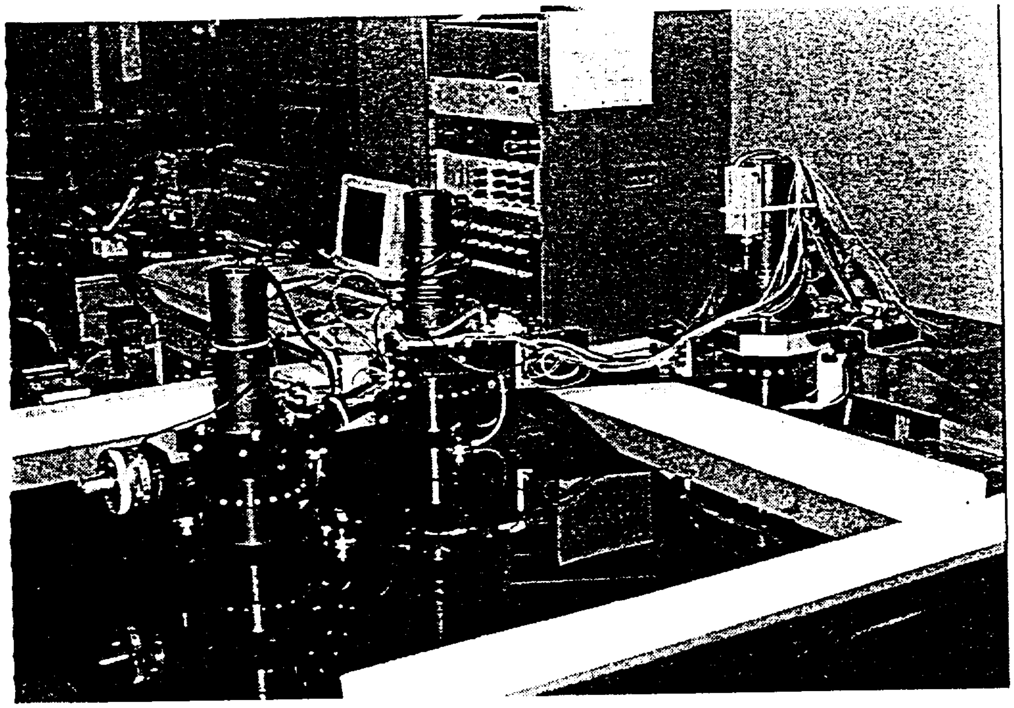
1. simple PD control
2. Torque loop
3. Impedance shaping

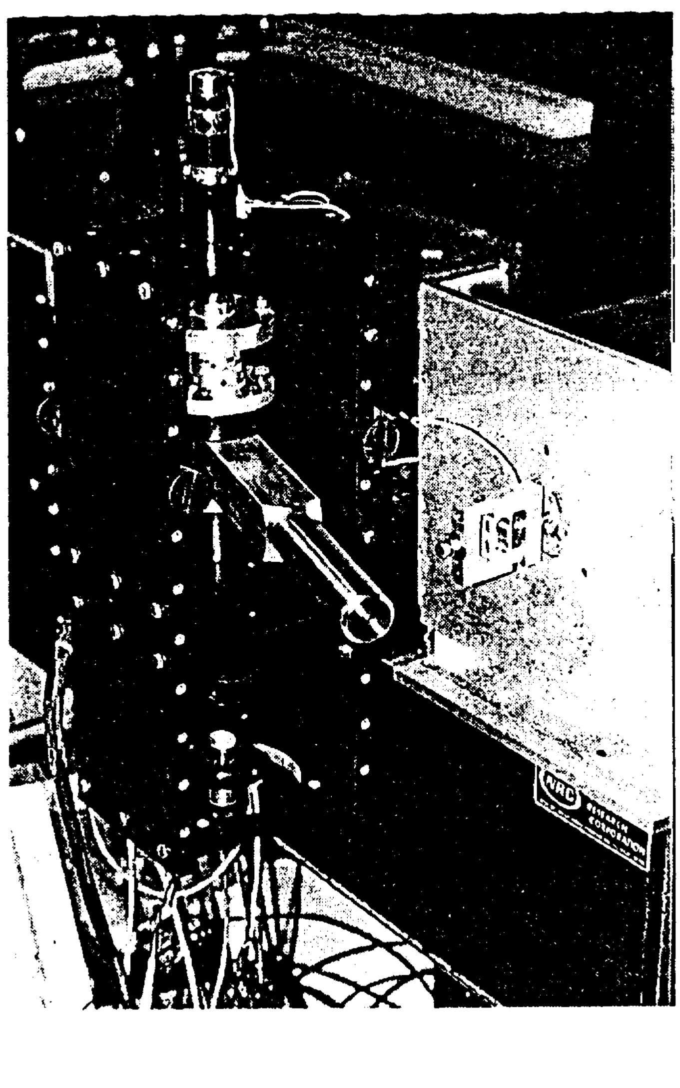


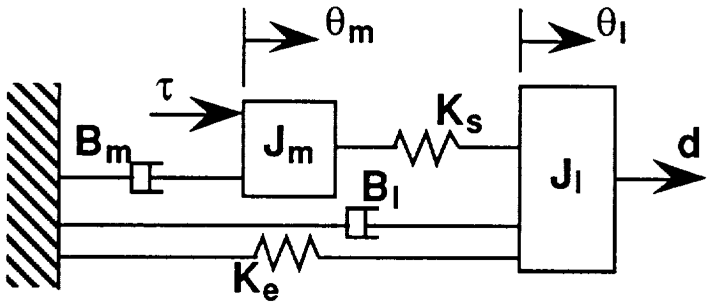


Removal/insertion of a misaligned module.

ORIGINAL PAGE IS
OF POOR QUALITY



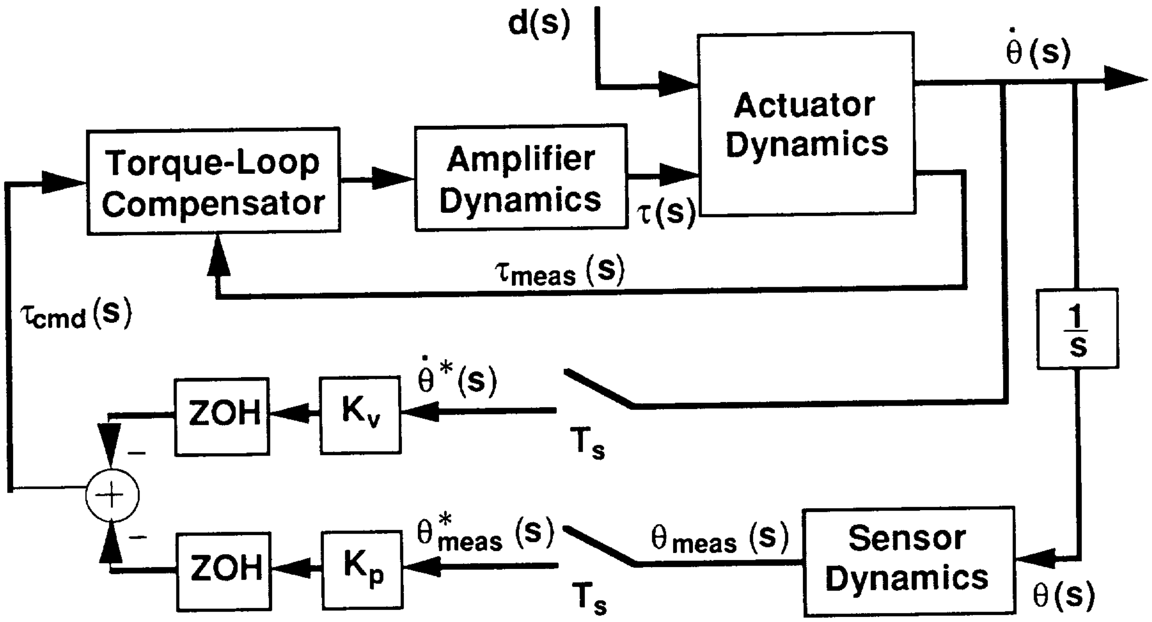




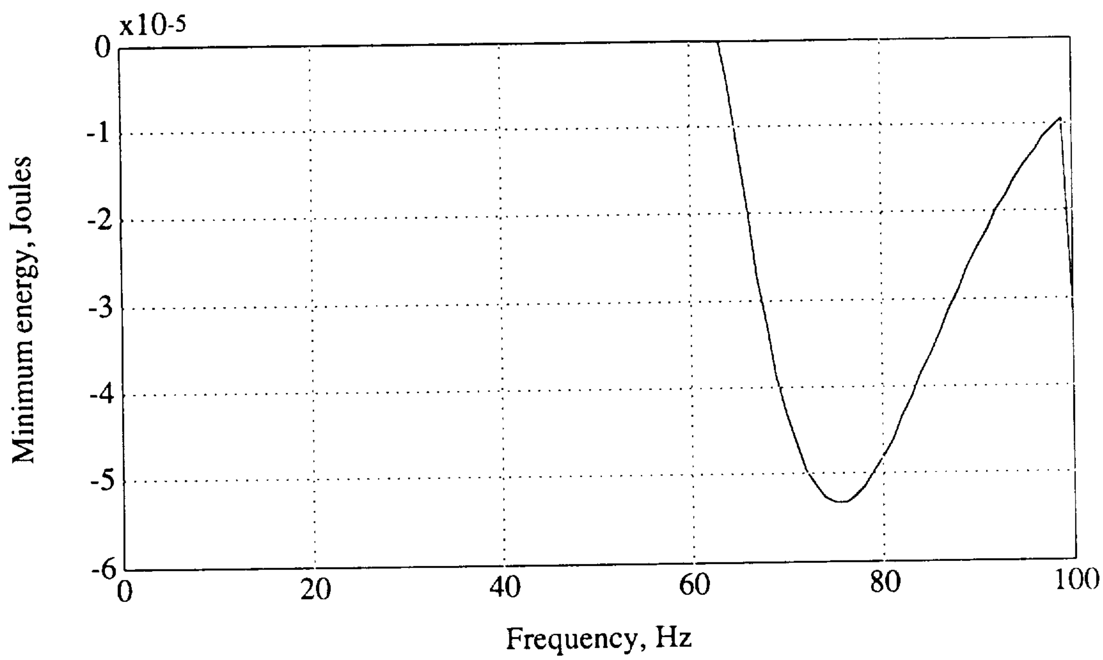
Model of a "typical" actuator.

Parameter	Value	Units
Motor Inertia, J_m (reflected to output side)	0.0934	kg-m^2
Motor Viscous Damping, B_m (reflected to output side)	3.4	N-m/(rad/s)
Harmonic Drive Stiffness, K_s	1600	N-m/rad
Load Viscous Damping, B_l	0.7	N-m/(rad/s)
Representative Load Inertia, J_l	0.64	kg-m^2
Gear Ratio	100:1	N/A

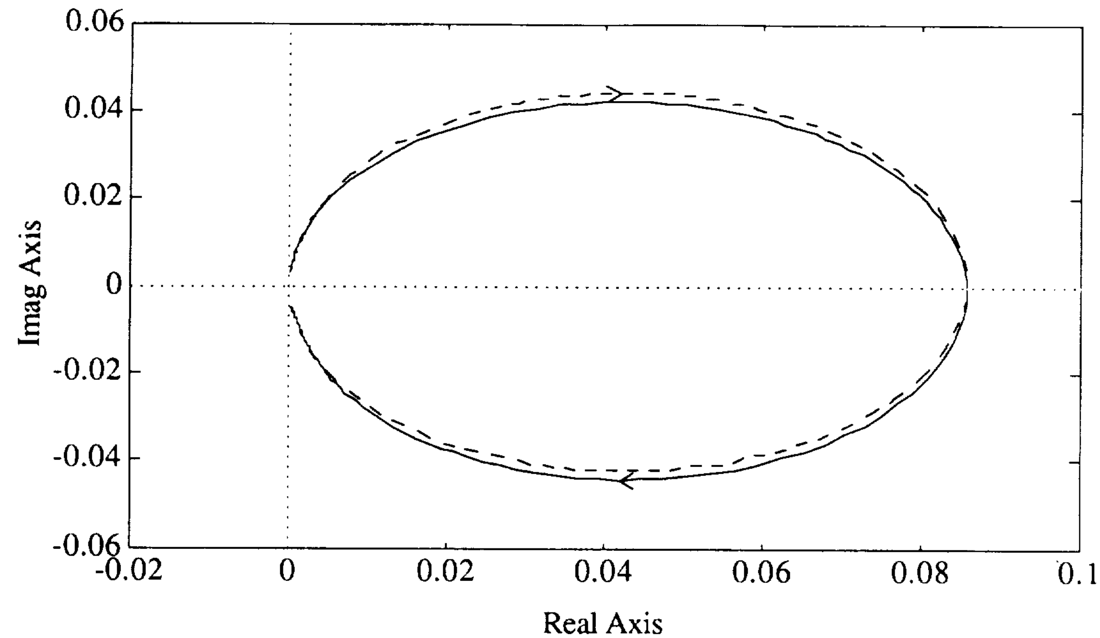
Representative Actuator Parameters



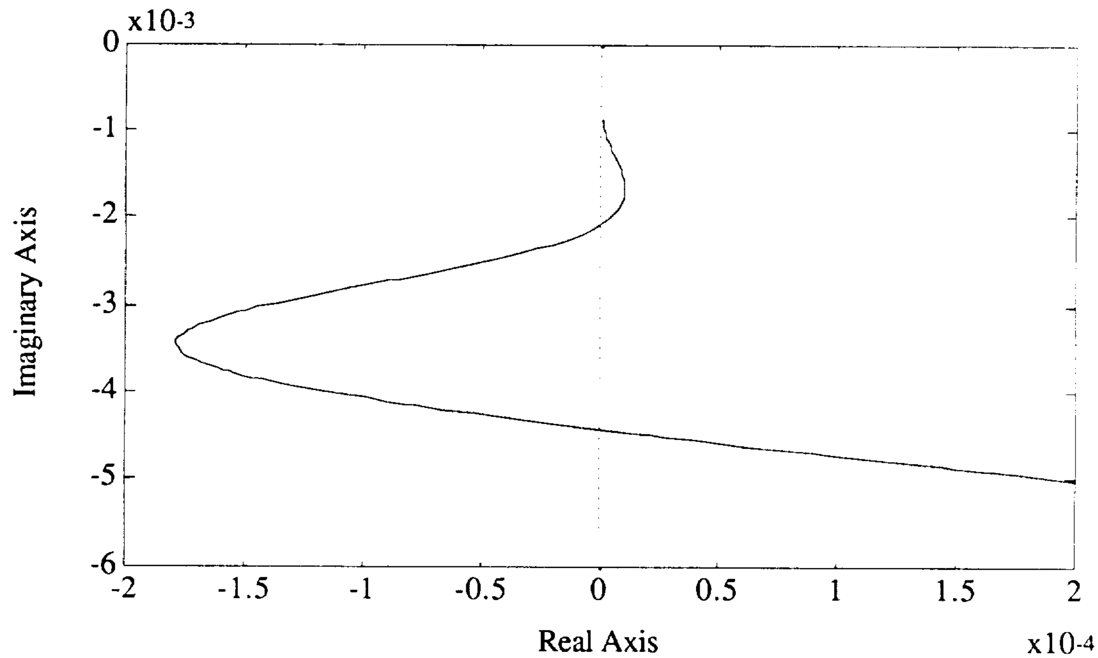
Moderate fidelity model of PD position-controlled actuator.



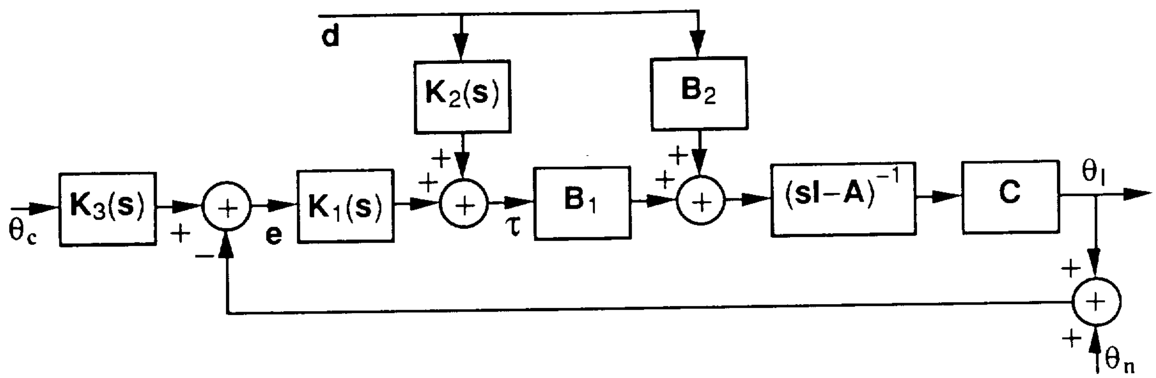
Minimum total energy delivered to the system over 1 second for a 1 N-m amplitude sinusoid disturbance torque (100 Hz bandwidth torque loop, 100 Hz bandwidth sensor dynamics, 1000 Hz bandwidth amplifier dynamics, 200 Hz sample rate, Kp=116, Kv=12.5)



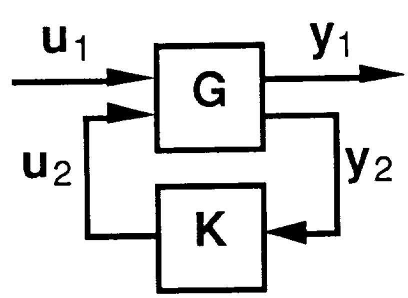
Nyquist diagram of the admittance response for the PD position-controlled actuator (sampling and ZOH modeled by time delay of half the sampling period).



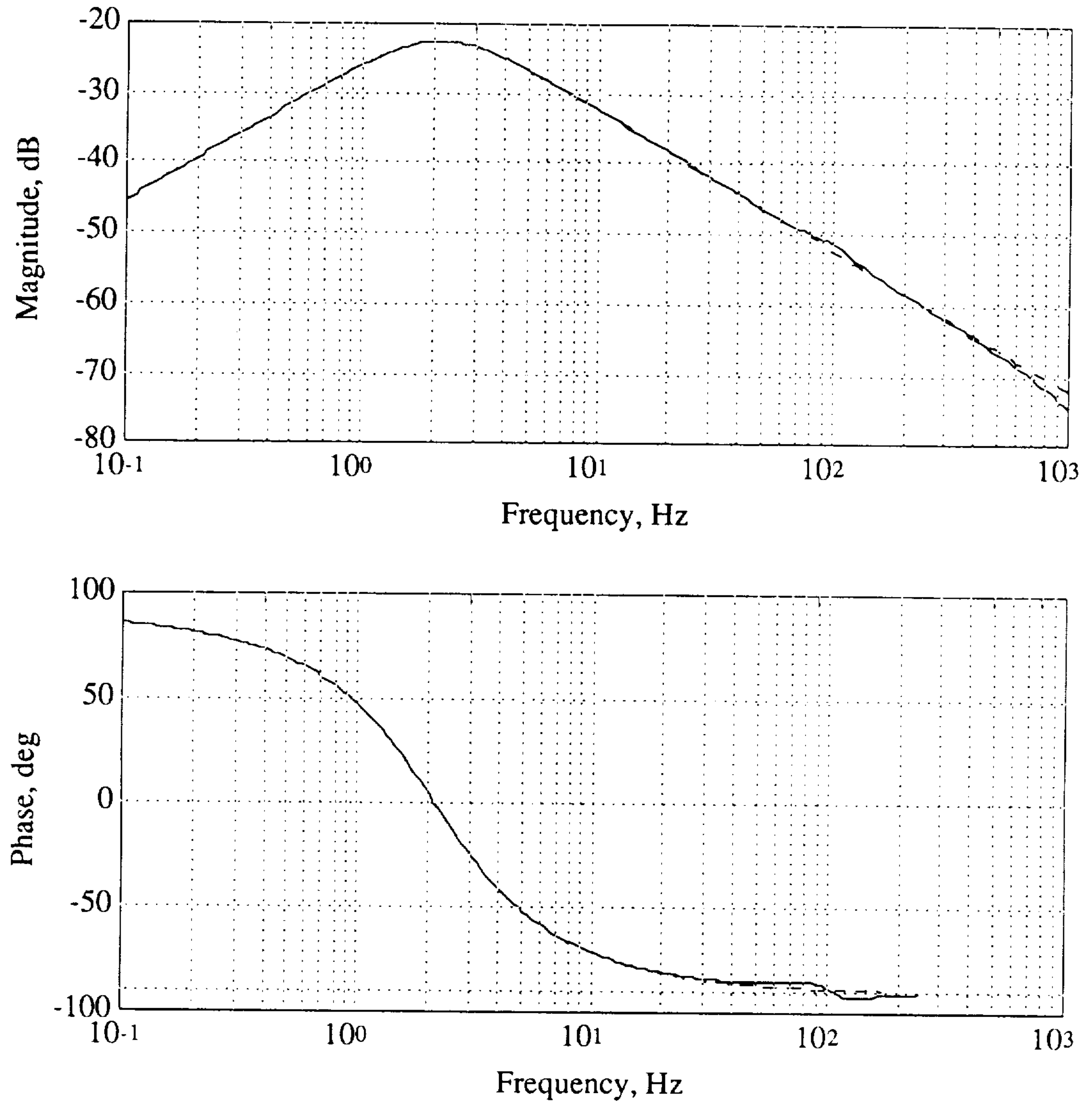
Nyquist diagram of the admittance response above 50 Hz for the PD position-controlled actuator (sampling and ZOH modeled by time delay of half the sampling period).



Generalized Actuator Control Block Diagram.



Standard H_∞ minimization problem.



Achieved (solid line) and target (dashed line) admittance responses for example H_∞ design using $K_1(s)$.

Fuzzy logic - Ken Su working

Conclusions

1. Absolute passivity is not practical as a design goal for the active devices which bring the structural payloads into contact.

2. A method has been developed for estimating the environment stiffness above which the operation of attachment may become unstable.

3. Preliminary results have been obtained in a procedure for feedback control design to achieve desired contact compliance.

N93-26408

cSc

Controls for Orbital Assembly of Large Space Structures

Mark Balas

Good activity and effort. General applicability to on-orbit construction. Great to get a [illegible] in the laboratory.

Third Annual Symposium
November 21 & 22, 1991

Flexible Structure Control

PROF. MARK J. BALAS

Roger Davidson — PhD Completed 1990

Ali A. Gooyabadi

Ralph Quan — PhD Completed 1991

Brian Reisenauer

L. "Robbie" Robertson

Jim Mohl (Ball Aerospace)

Philip Good (Martin Marietta)

Loren Vredevoogd

Jose Galvez — PhD Completed 1991

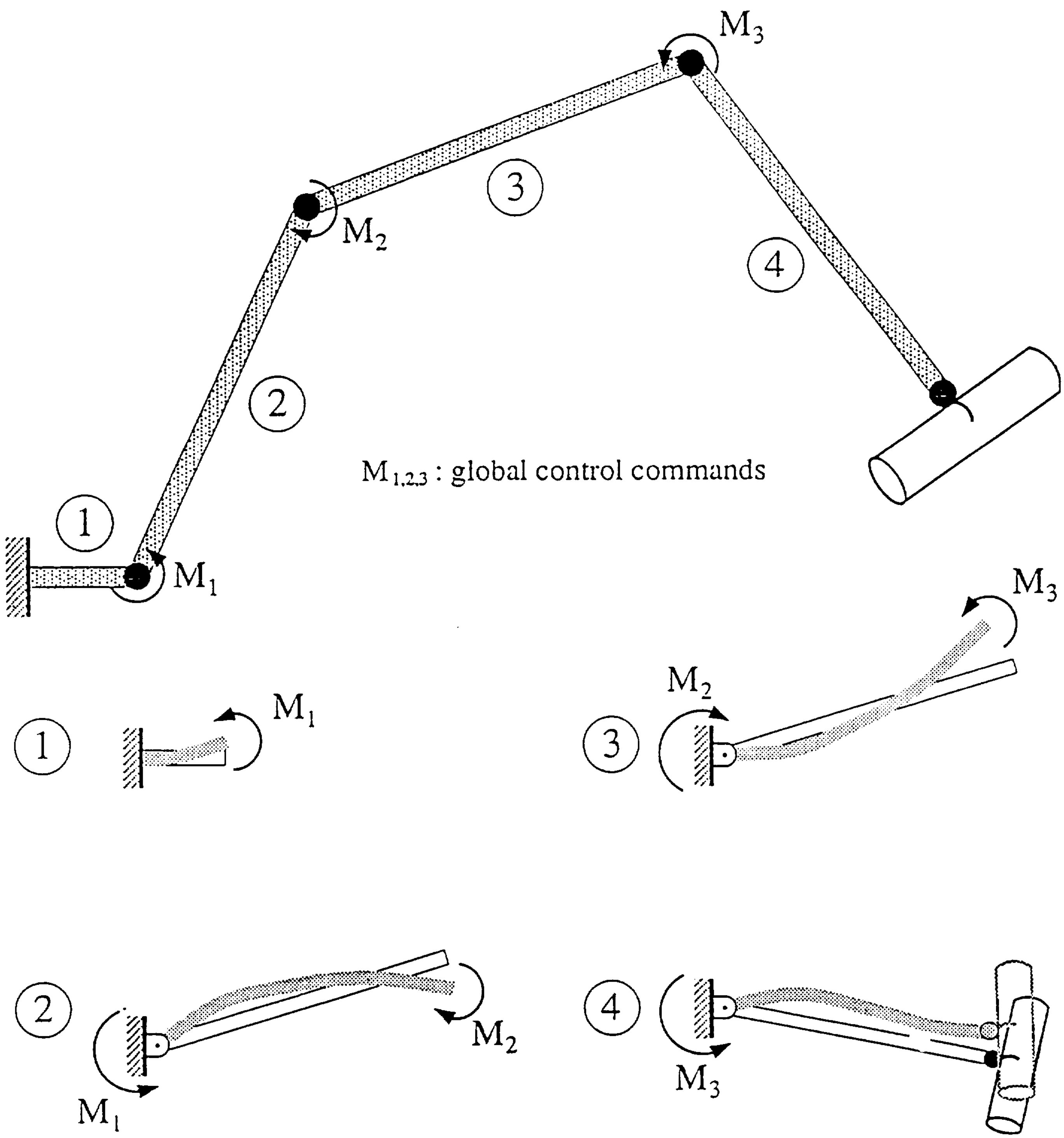
Shin-Ching Liang — PhD Completed 1991

NASA Center for Space Construction
Univ. of Colorado, Boulder

Industrial affiliates

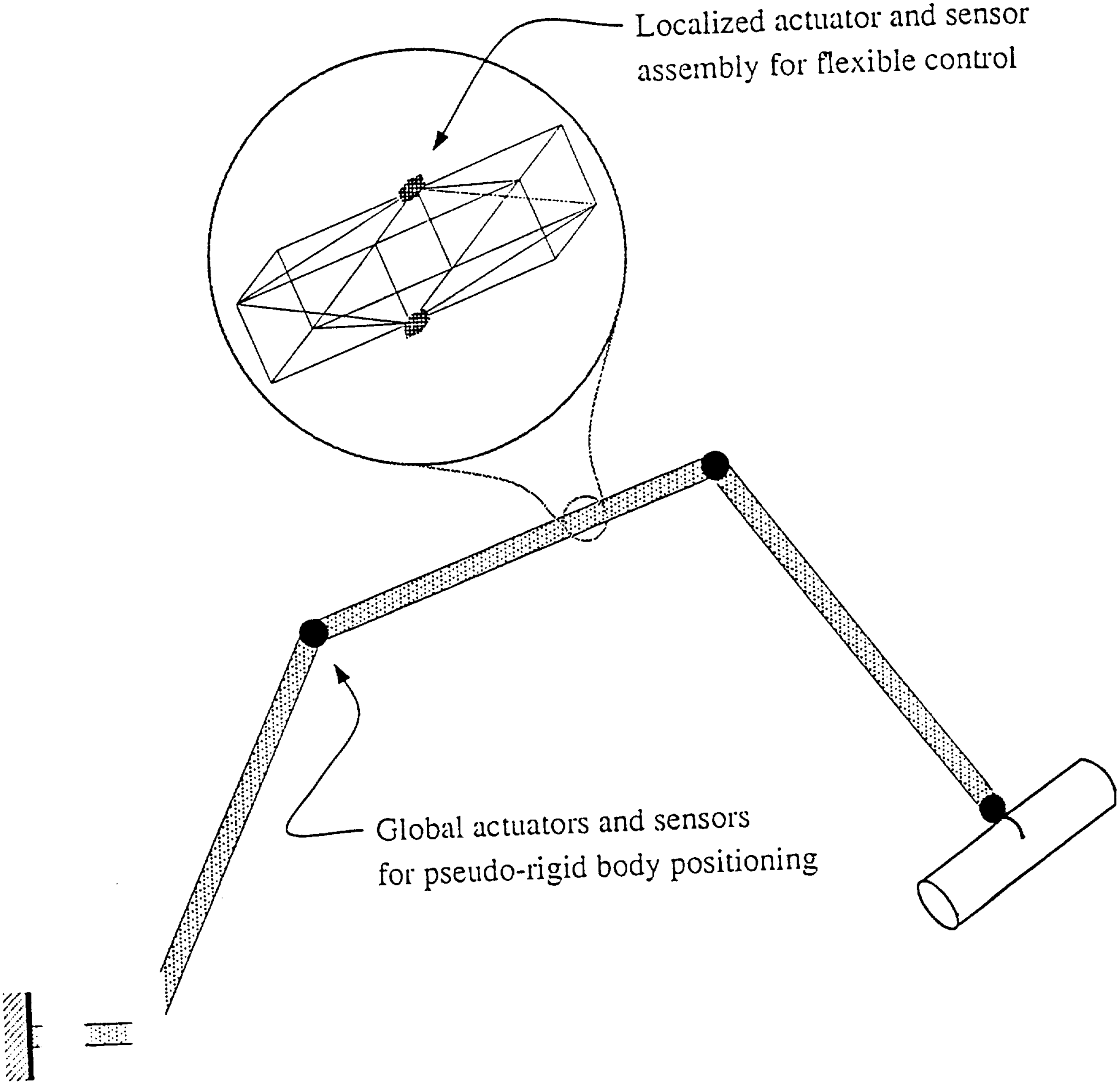
De-centralized Control for Flexible Multi-body Systems

Flexible Sub-system Division

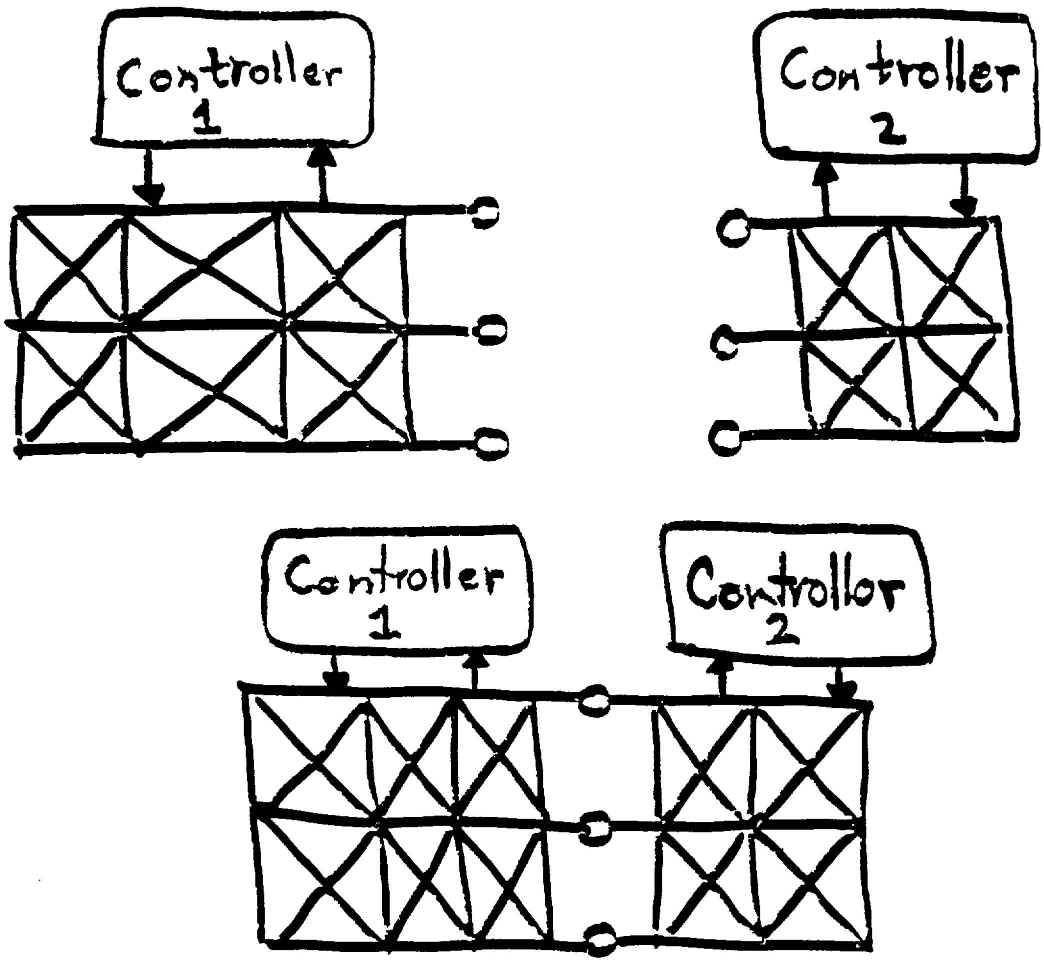


De-centralized Control for Flexible Multi-body Systems

Local and Global Control



L. (Robbie) Robertson

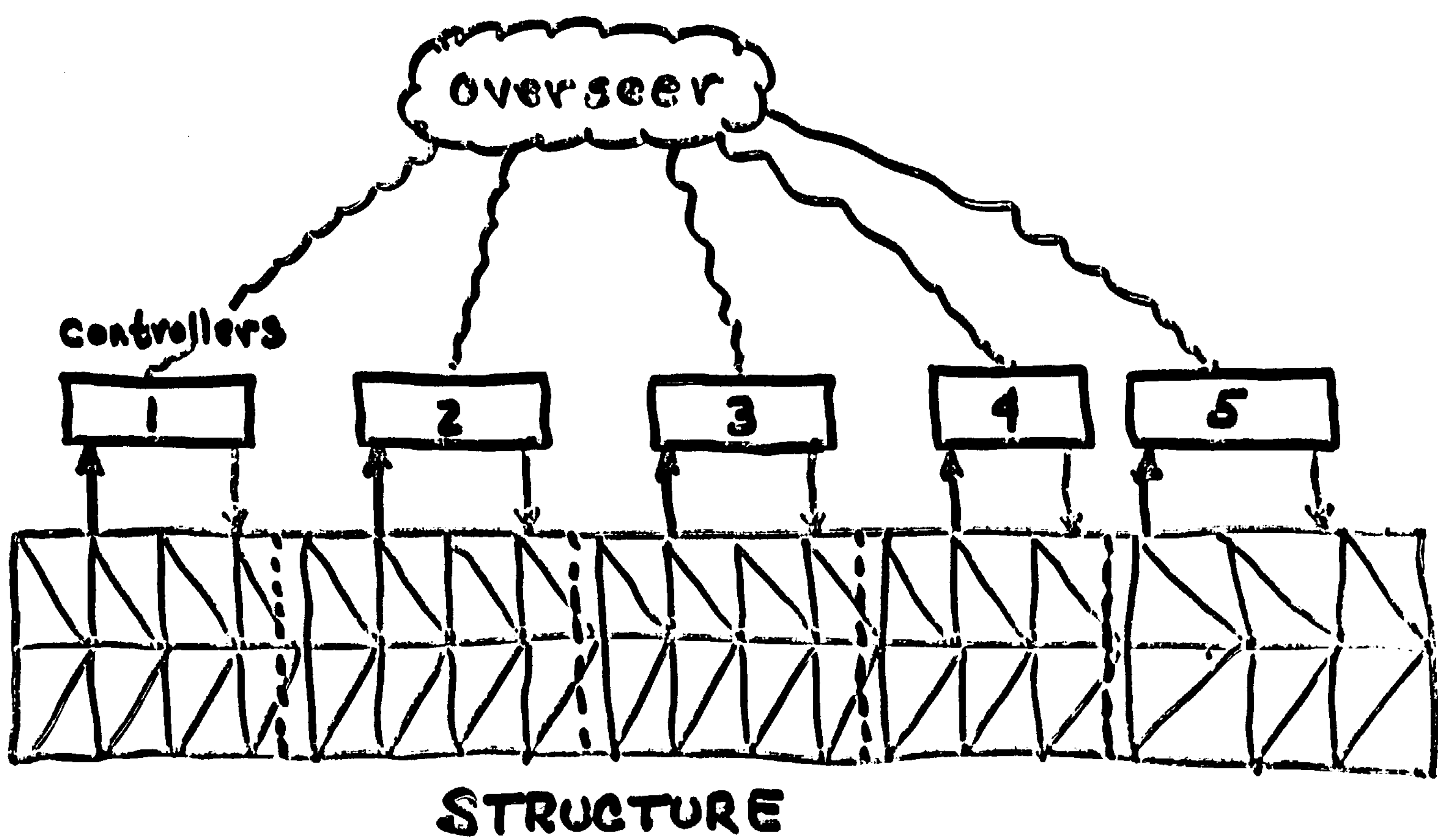


Control of Structures During Assembly

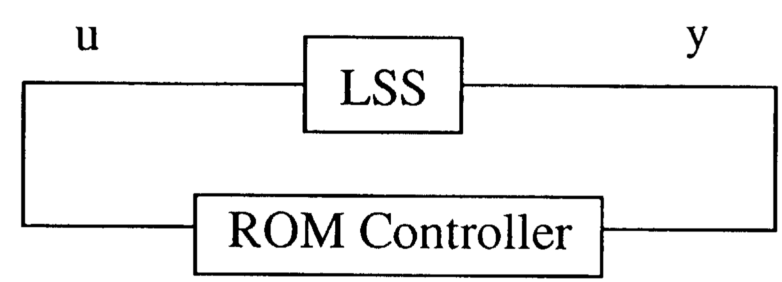
Normal (Planned) Assembly
Emergencies (F^3U)

Docking & Berthing / Contact

Decentralized Control Using Structural Partitioning



Reduced-Order Model-Based Controller Design



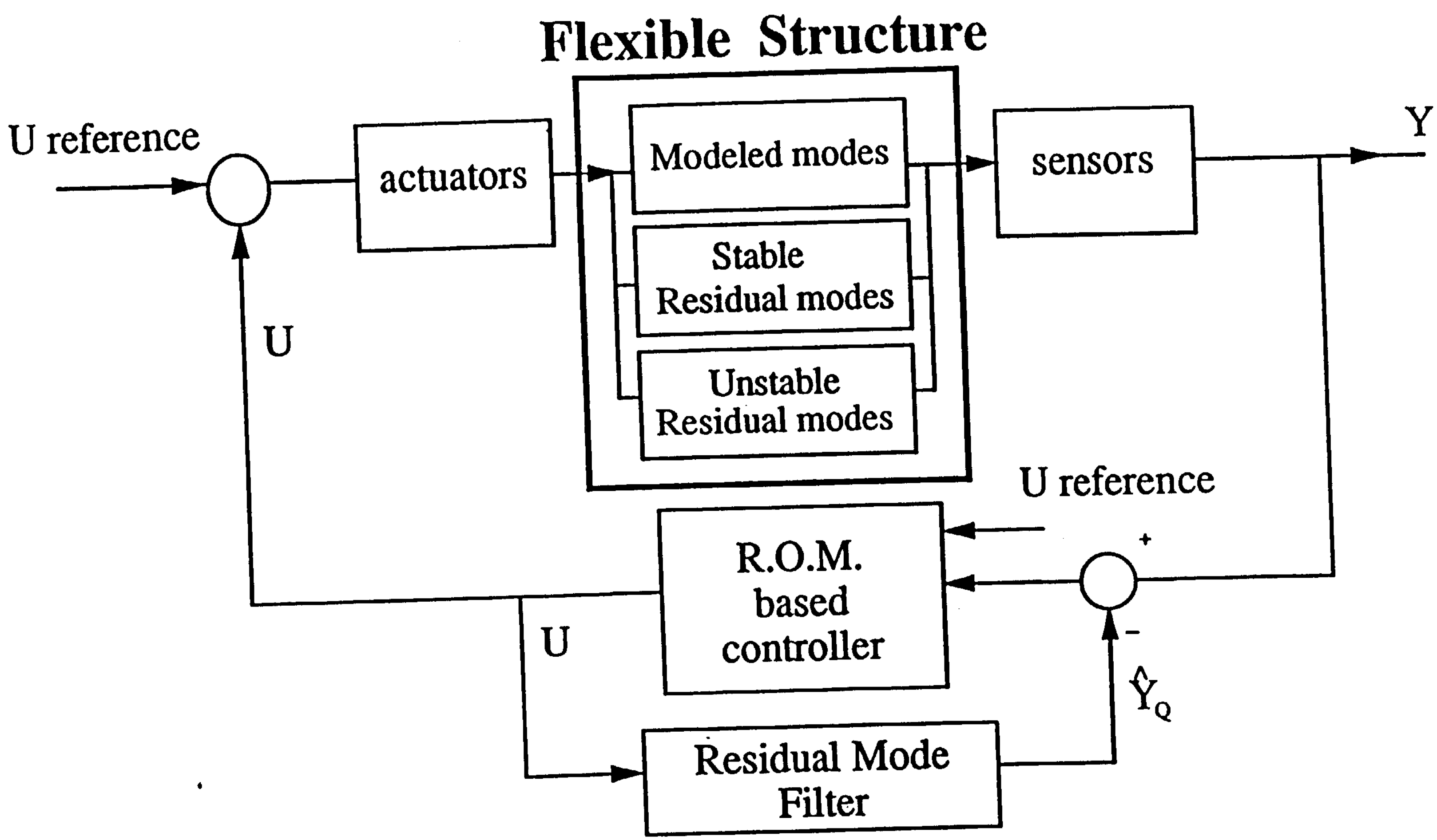
Closed Loop: $L_n = A_n + B_n G_n - K_n C_n$

$$\begin{bmatrix} \dot{x}_n \\ \dot{\hat{x}}_n \\ \dot{x}_r \end{bmatrix} \quad \underbrace{\begin{bmatrix} A_n & B_n G_n & 0 \\ K_n C_n & L_n & K_n C_r \\ 0 & B_r G_n & A_r \end{bmatrix}}_{A_c} \begin{bmatrix} x_n \\ \hat{x}_n \\ x_r \end{bmatrix}$$

OR

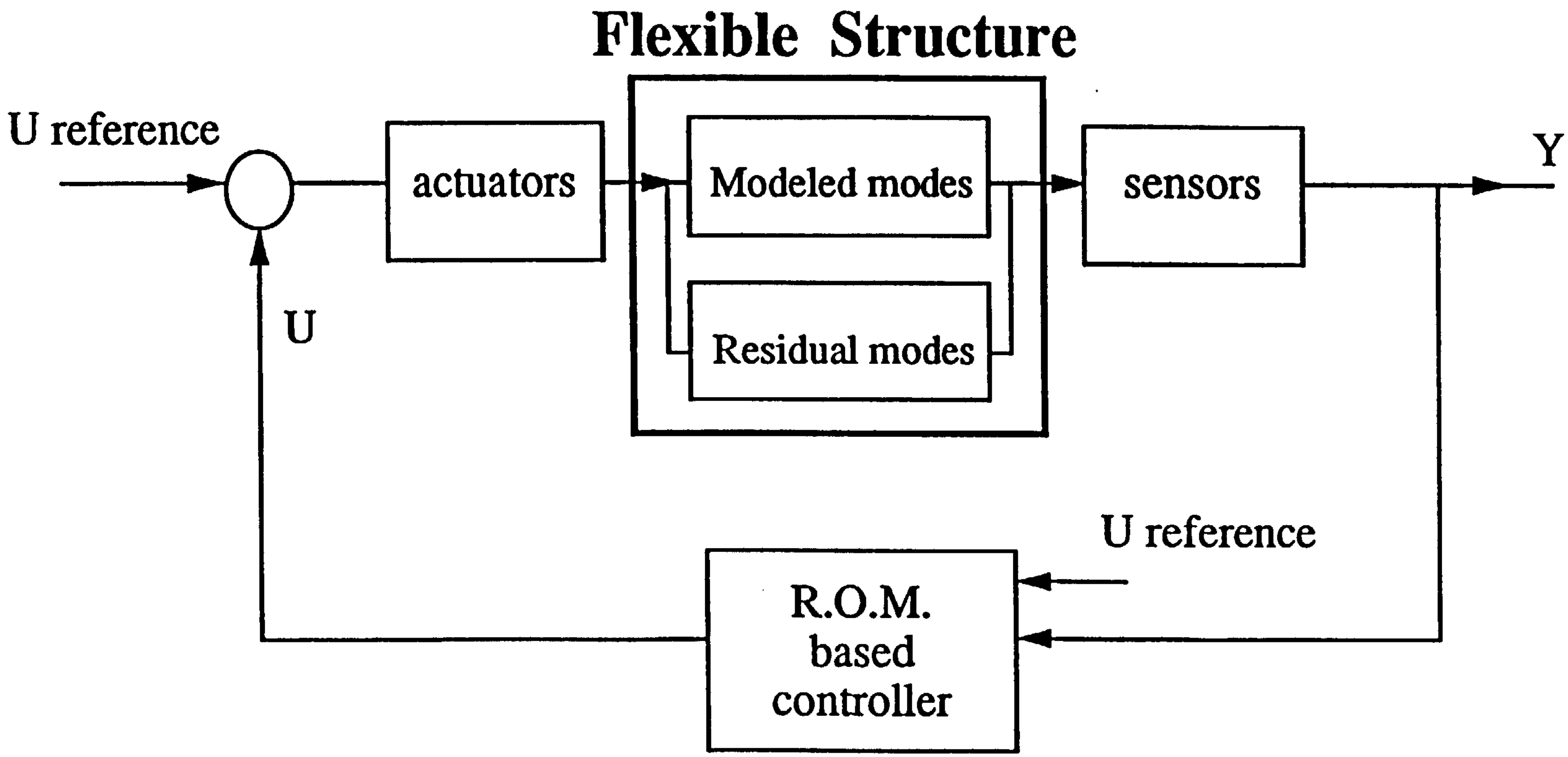
$$\begin{bmatrix} \dot{x}_n \\ \dot{e}_n \\ \dot{x}_r \end{bmatrix} = \begin{bmatrix} A_n + B_n G_n & B_n G_n & 0 \\ 0 & A_n + K_n C_n & K_n C_r \\ B_r G_n & B_r G_n & A_r \end{bmatrix} \begin{bmatrix} x_n \\ e_n \\ x_r \end{bmatrix}$$

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



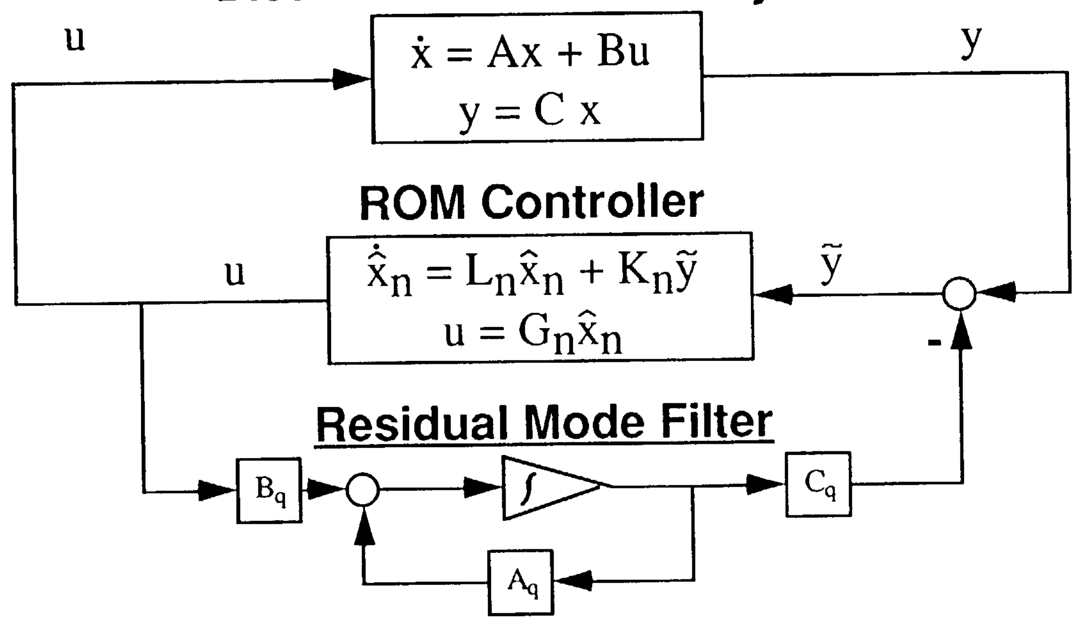
- **Develop a R.O.M. controller, designed for performance.**
- **Dimension of the controller << dimension of the structure.**

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.)**

Residual Mode Filters (RMF) in a Distributed Parameter System (DPS)

Balas: JMAA 1988



$$A = \begin{bmatrix} A_n & 0 & 0 \\ 0 & A_q & 0 \\ 0 & 0 & A_r \end{bmatrix}$$

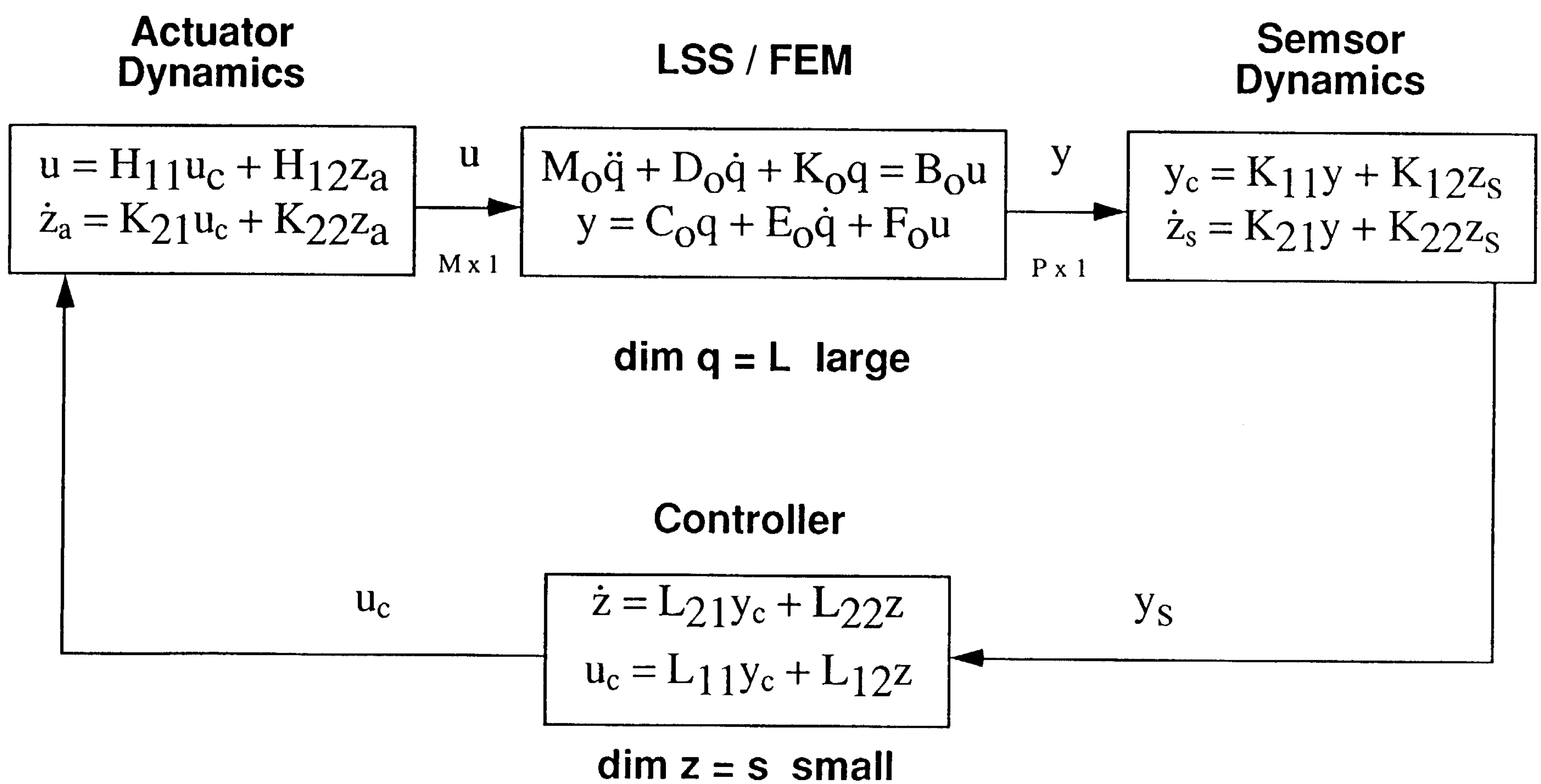
- A_n ← open-loop unstable modes
- A_q ← closed-loop unstable modes
- A_r ← unaffected residual modes (unmodelled dynamics)

DPS + Rom Controller ⟶ unstable (q modes)

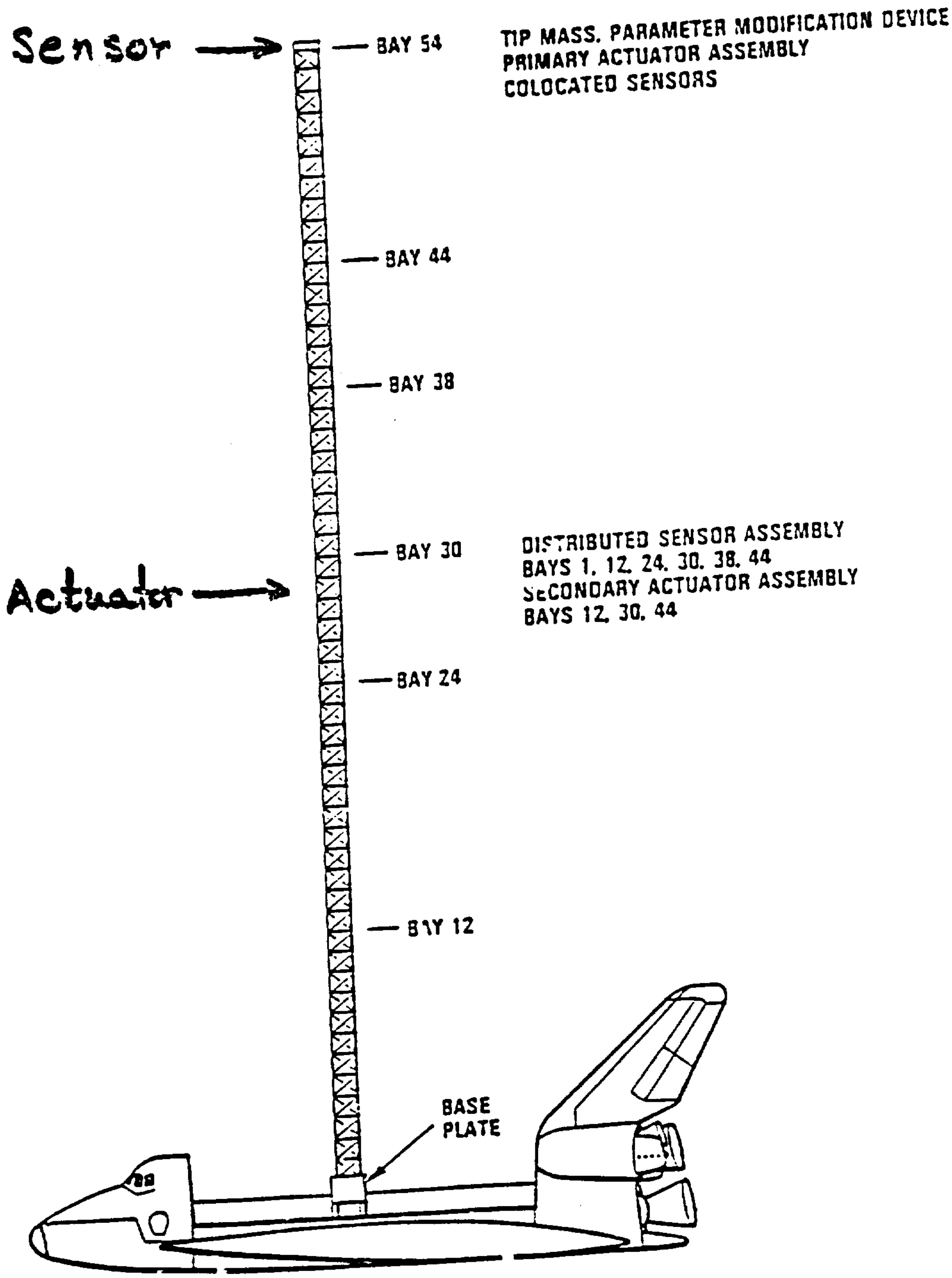
DPS + ROM Controller + RMF ⟶ exponentially stable

LSS Active Control Simulation

(Ralph Quan)

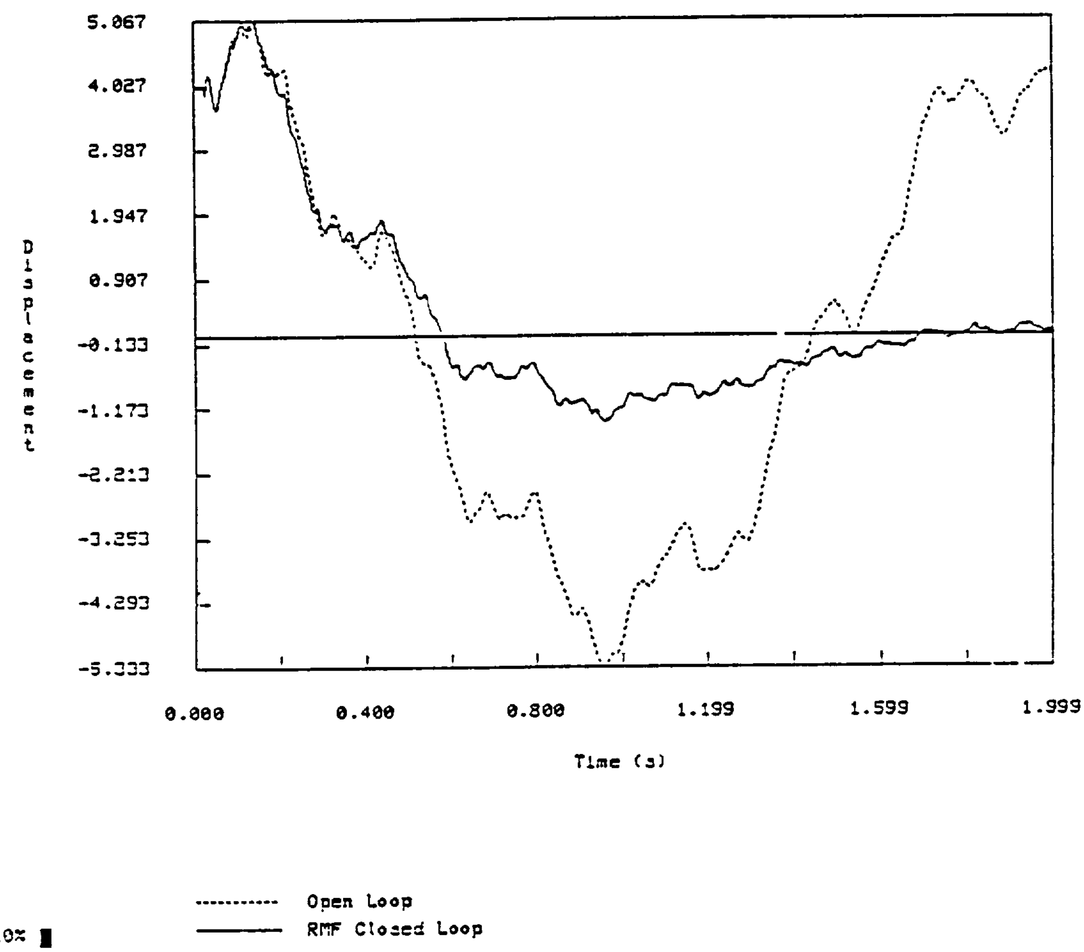


3-Dimensional Truss Beam



~1000 degree of freedom
CSSC simulation
Ralph Quan
"Quanware"

OPEN LOOP versus RMF CLOSED LOOP



jupiter20%

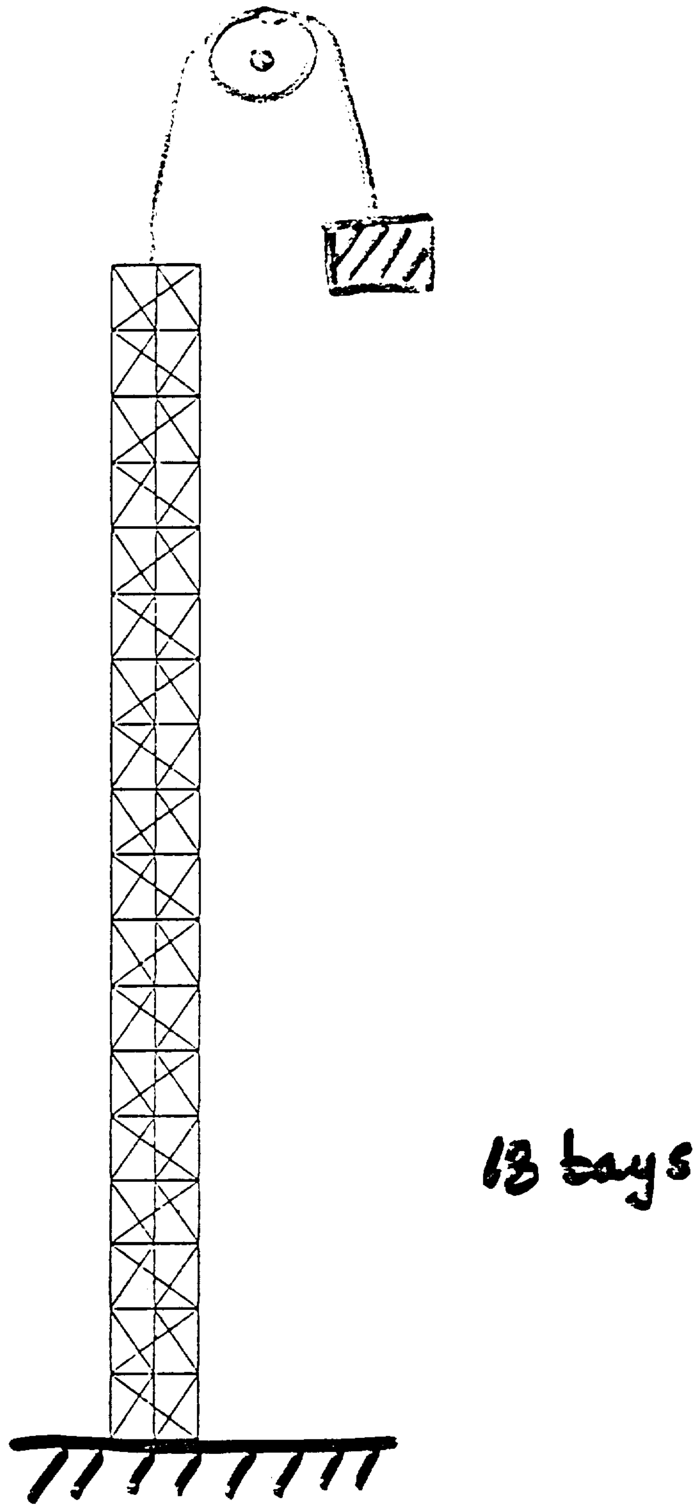


Figure 8.7 The Mini-Mast Truss

Langley

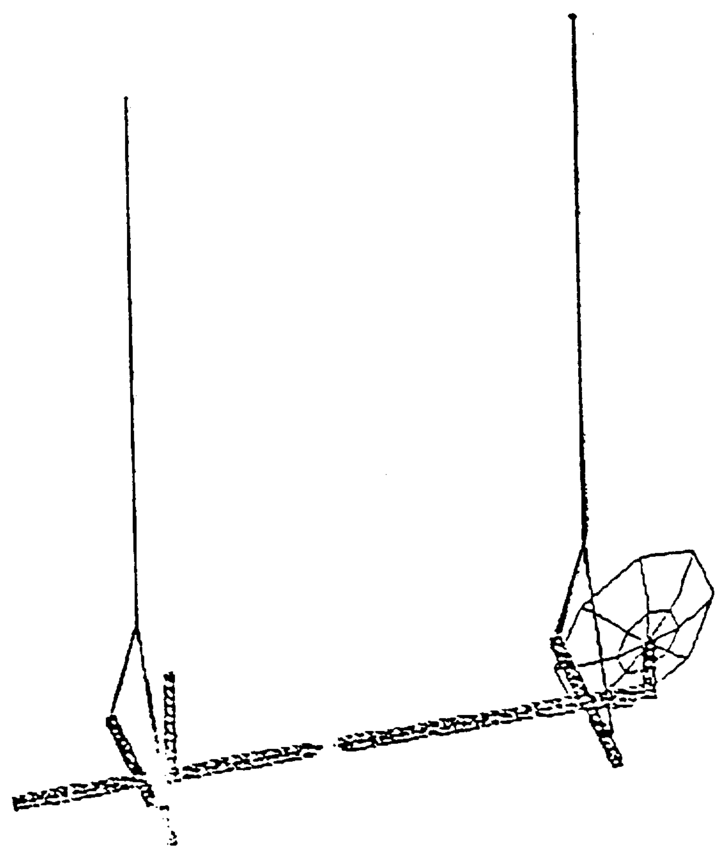
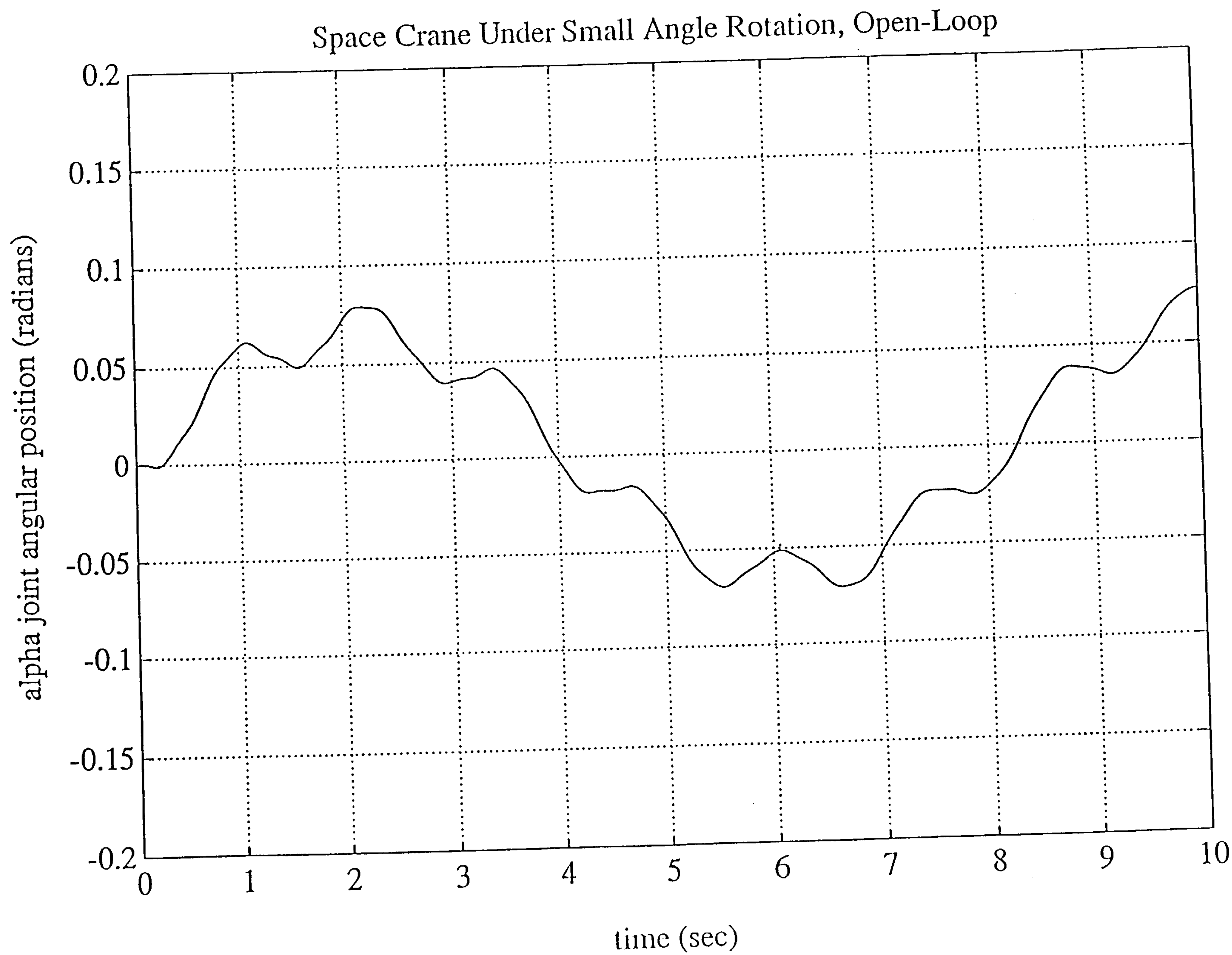
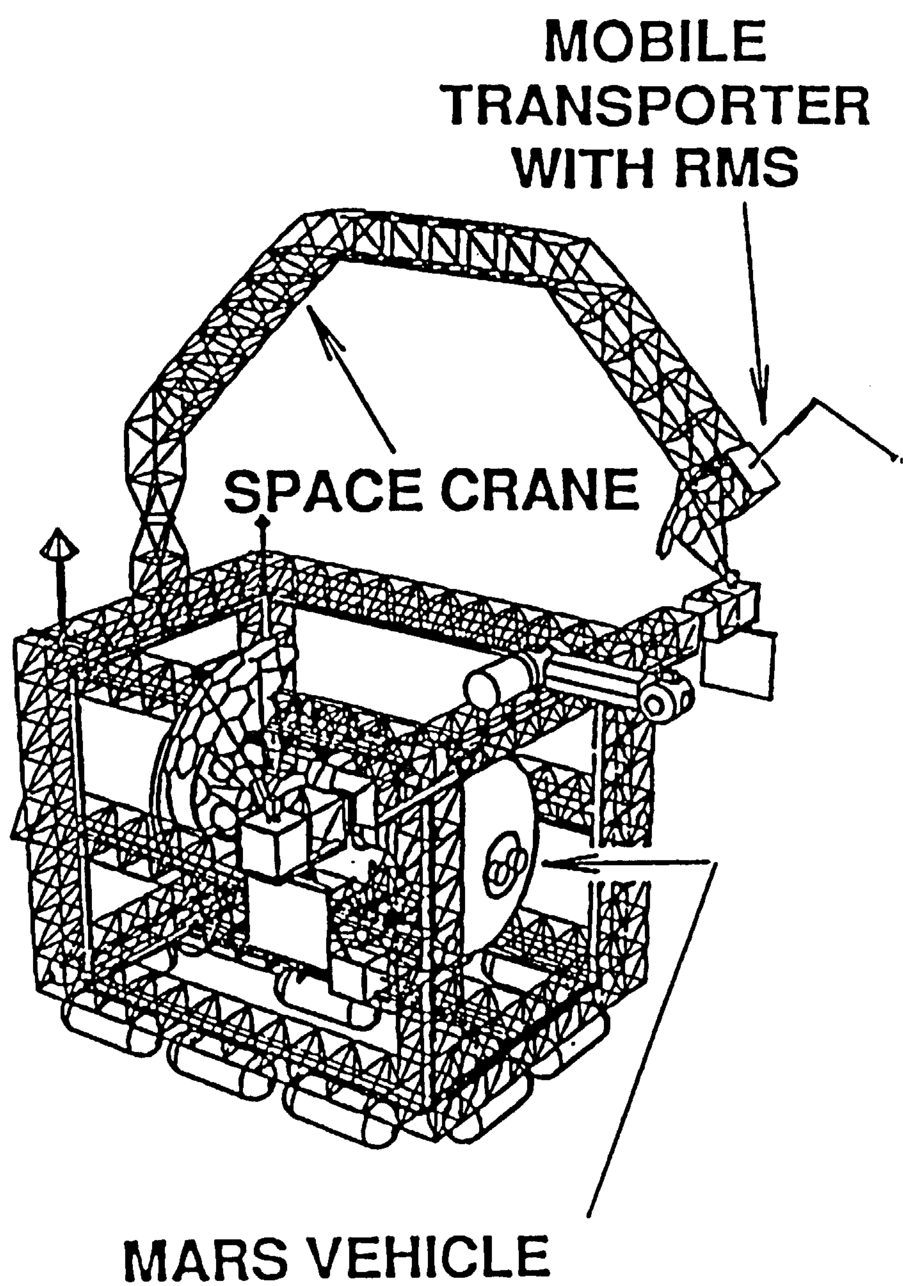
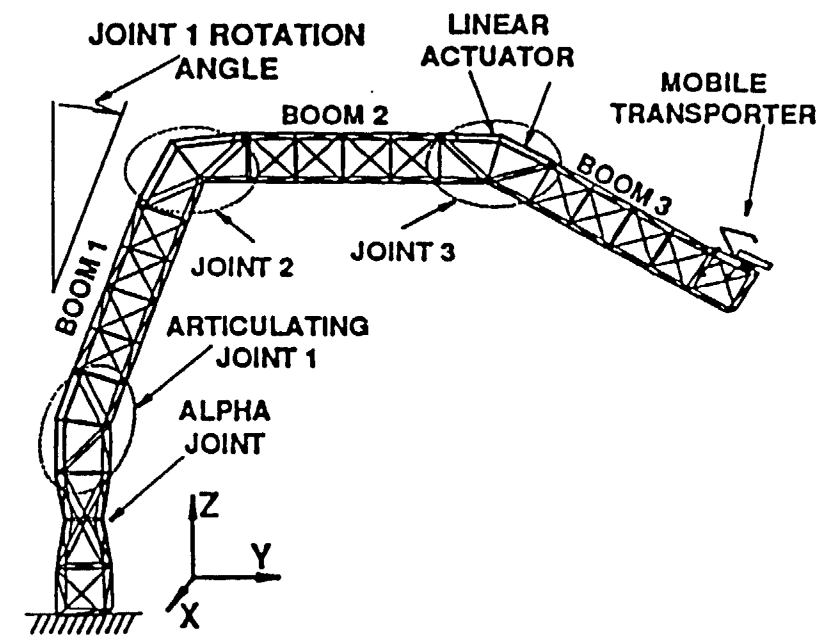
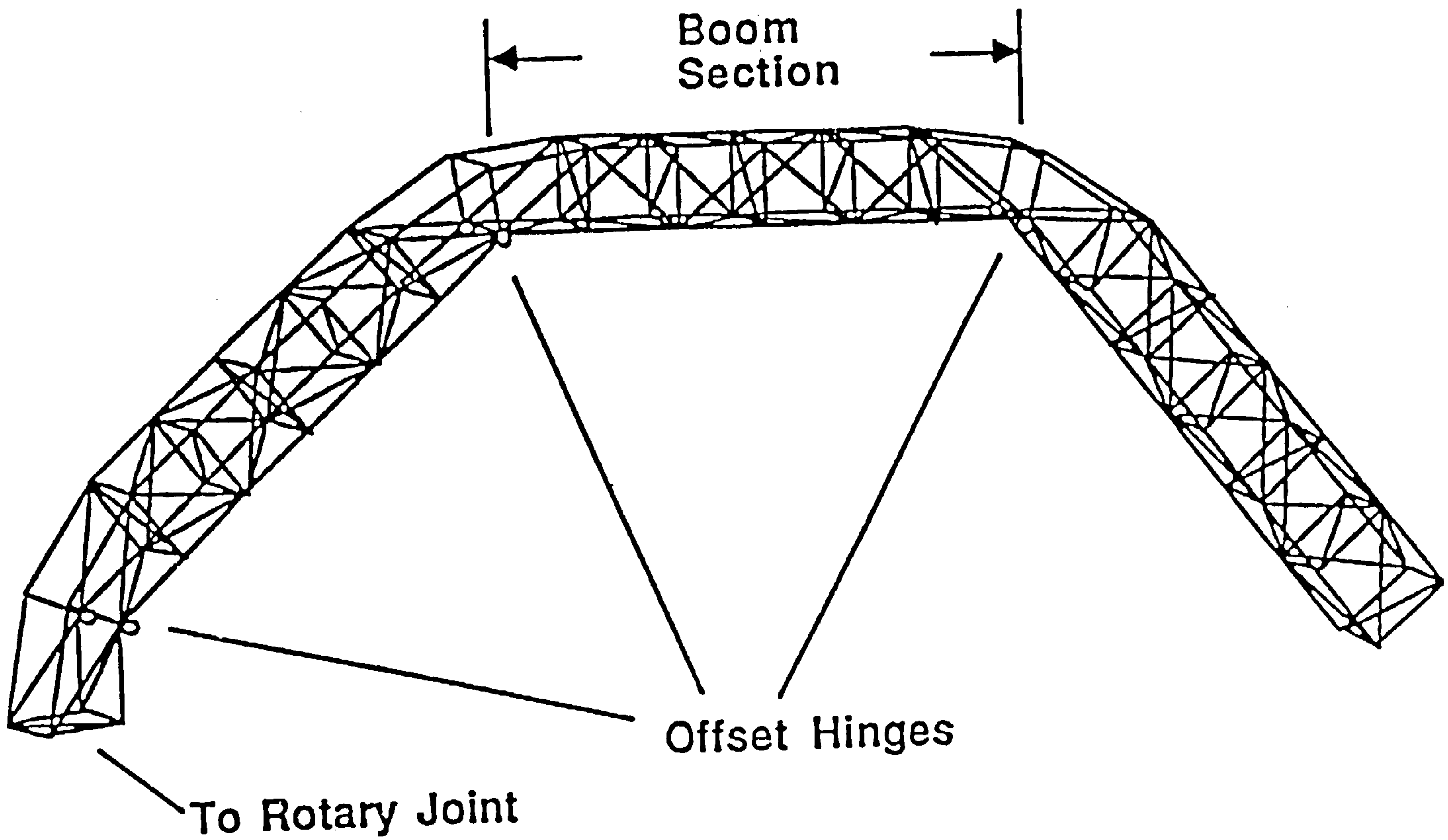


Figure 8.22 Phase o Evolutionary Model

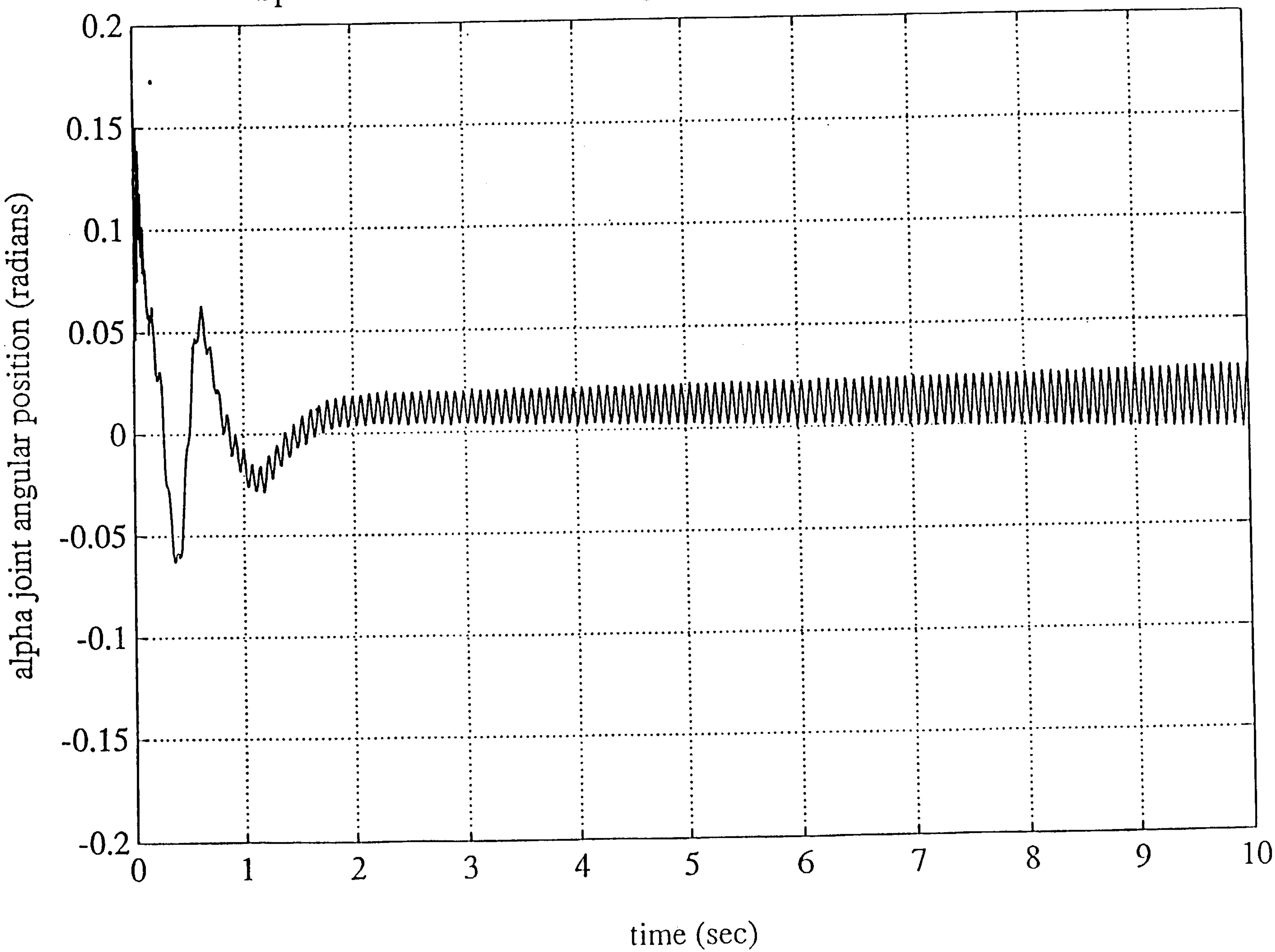

Space Crane Under Small Angle Rotation, Open-Loop
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
alpha joint angular position (radians)
0
1
2
3
4
5
6
7
8
9
10
time (sec)


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

Space Crane Under Small Angle Rotation without Compensation



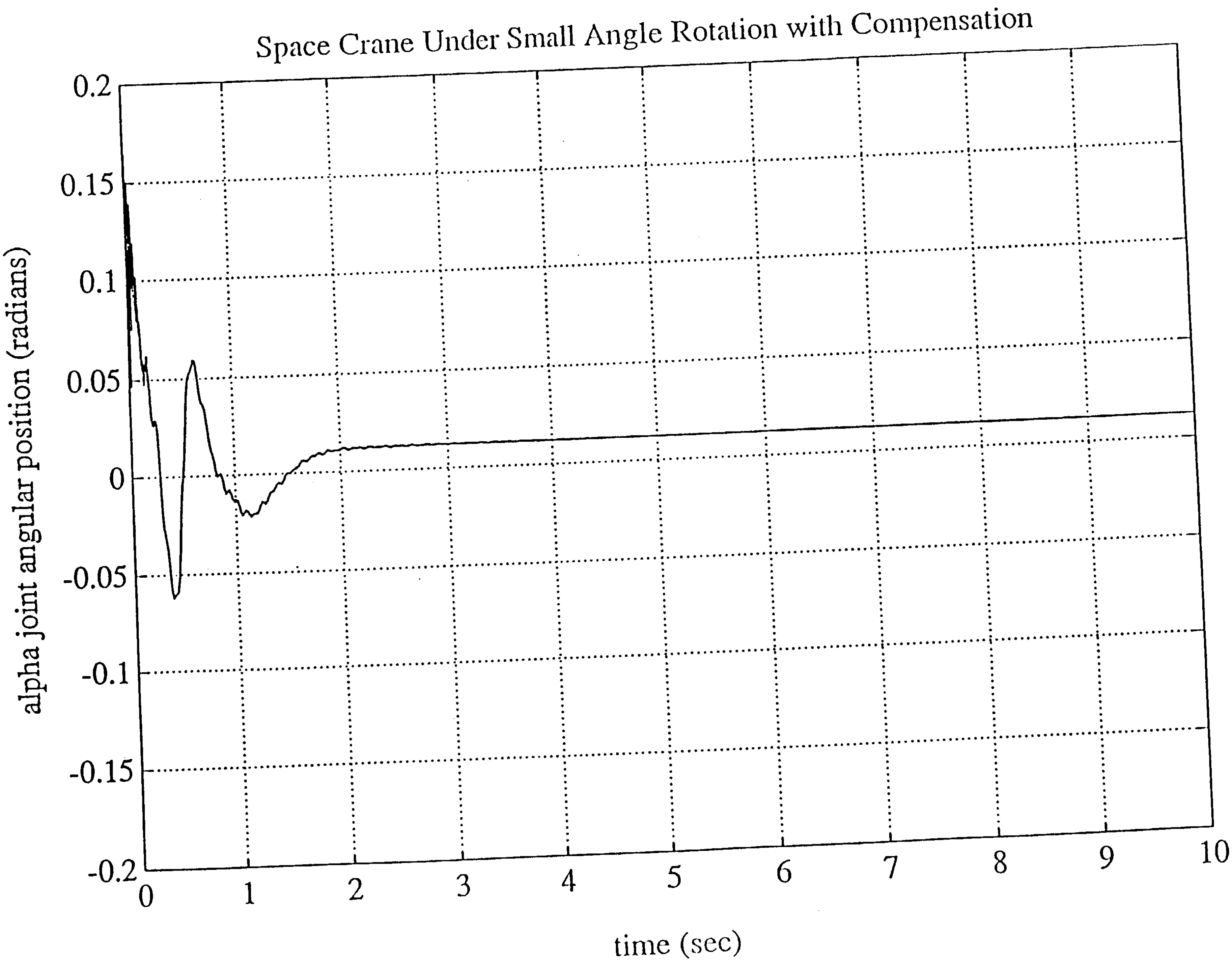

Space Crane Under Small Angle Rotation with Compensation
alpha joint angular position (radians)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
1
2
3
4
5
6
7
8
9
10
time (sec)

Figure 3 : Flexible Robot Manipulator at Martin Marietta

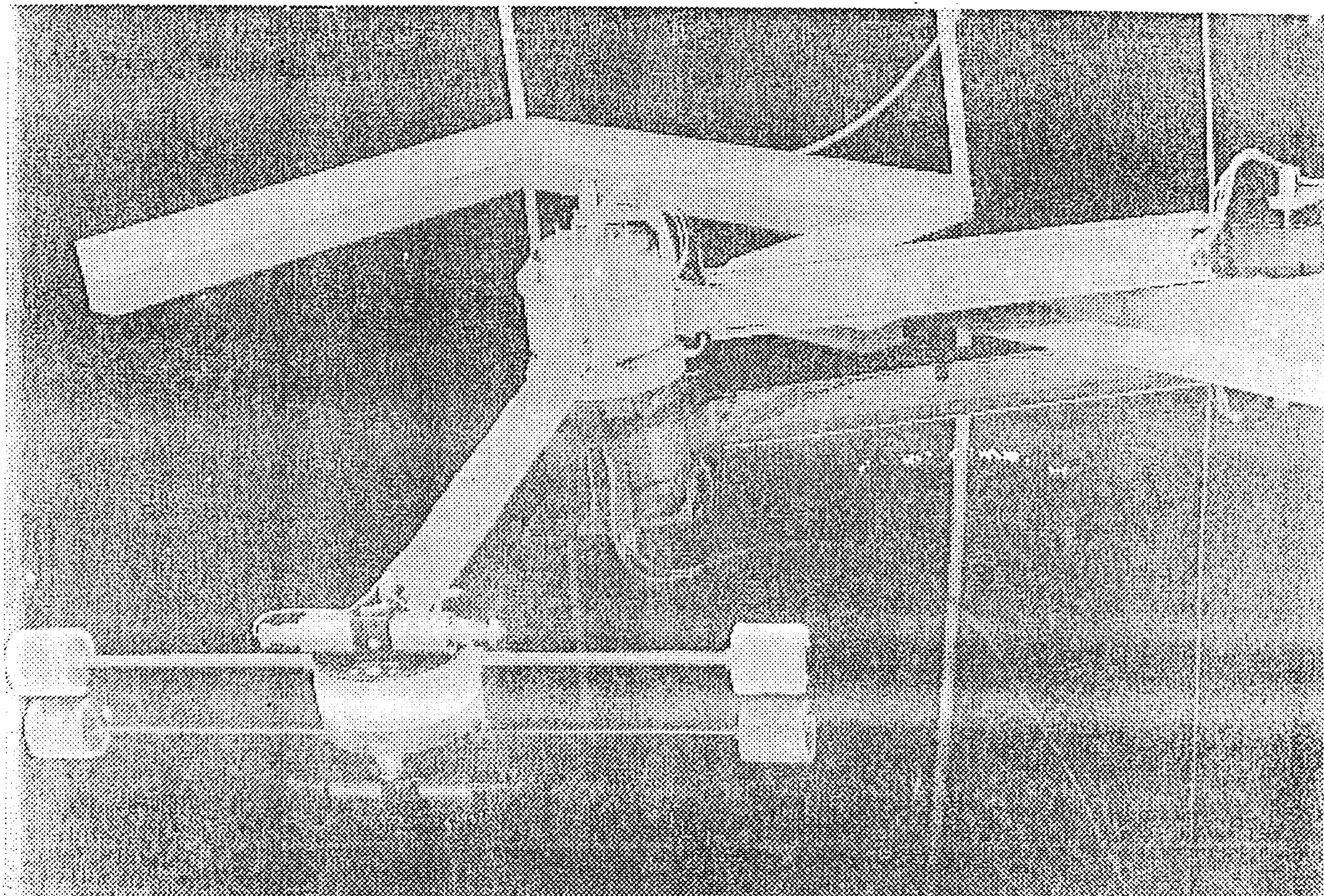


Figure 7 : Hub Position Without CSI Compensation

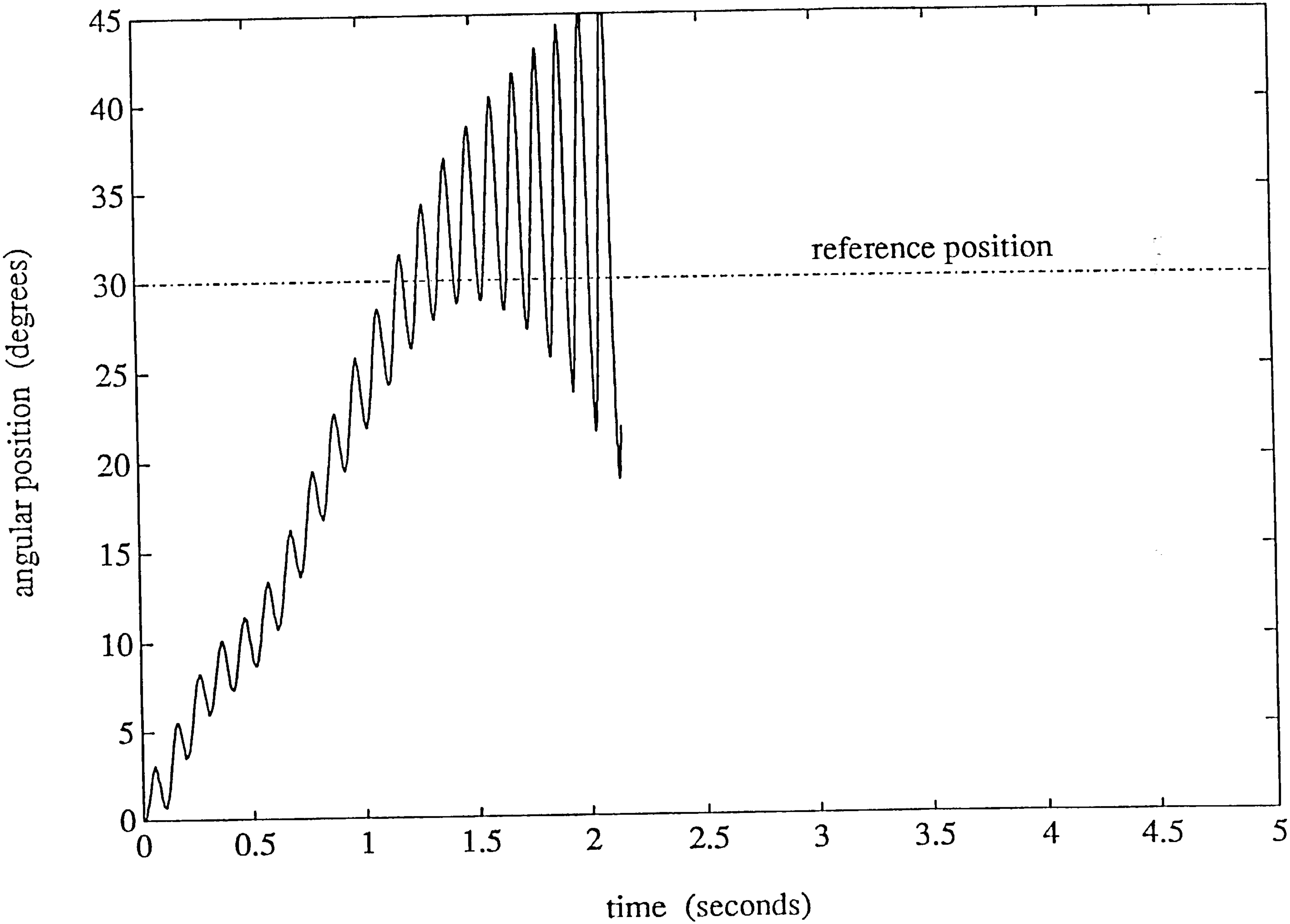
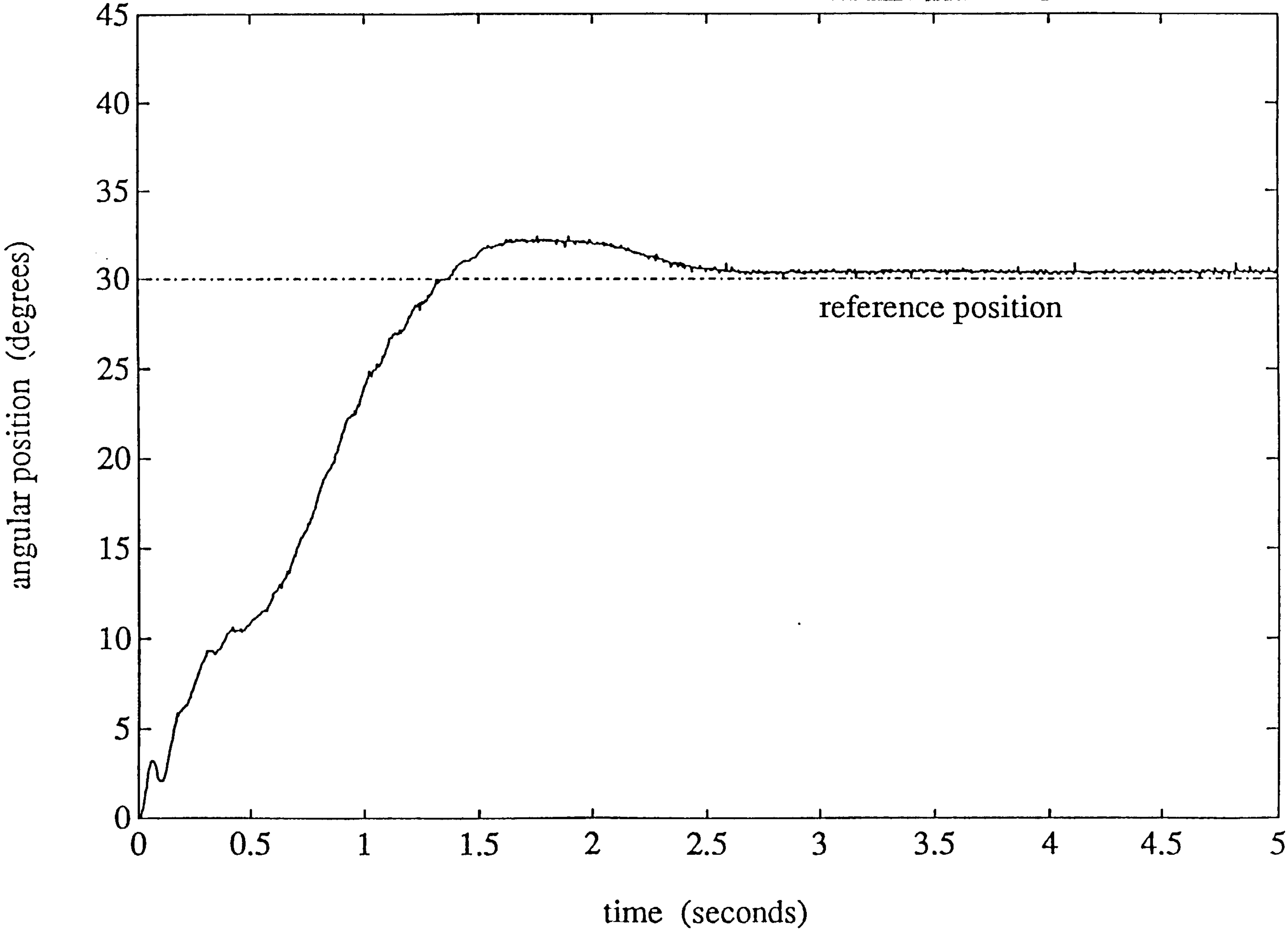


Figure 10 : Hub Position With CSI Compensation



Perturbation Analysis

Ali Gooyabadi
SPIE 1992

$$A_c(\epsilon) = \underbrace{A_0}_{\text{well known}} + \underbrace{\epsilon\,\Delta A}_{\text{Small Perturbation}}$$

well known

Small Perturbation

Asymptotic Eigenvalue Series:

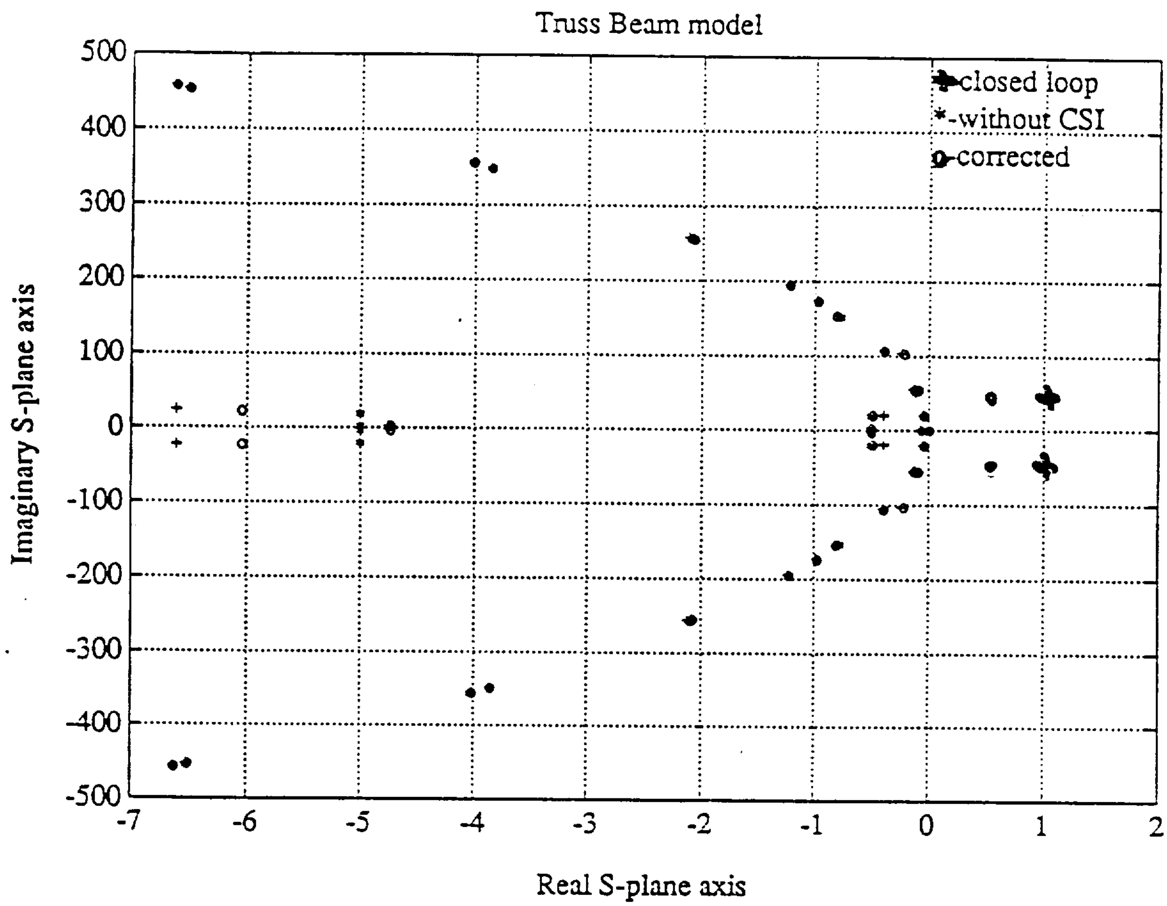
$$\hat{\lambda}_c(\epsilon) = \lambda_0 + \epsilon\lambda_1 + \epsilon^2\lambda_2 + \cdots$$

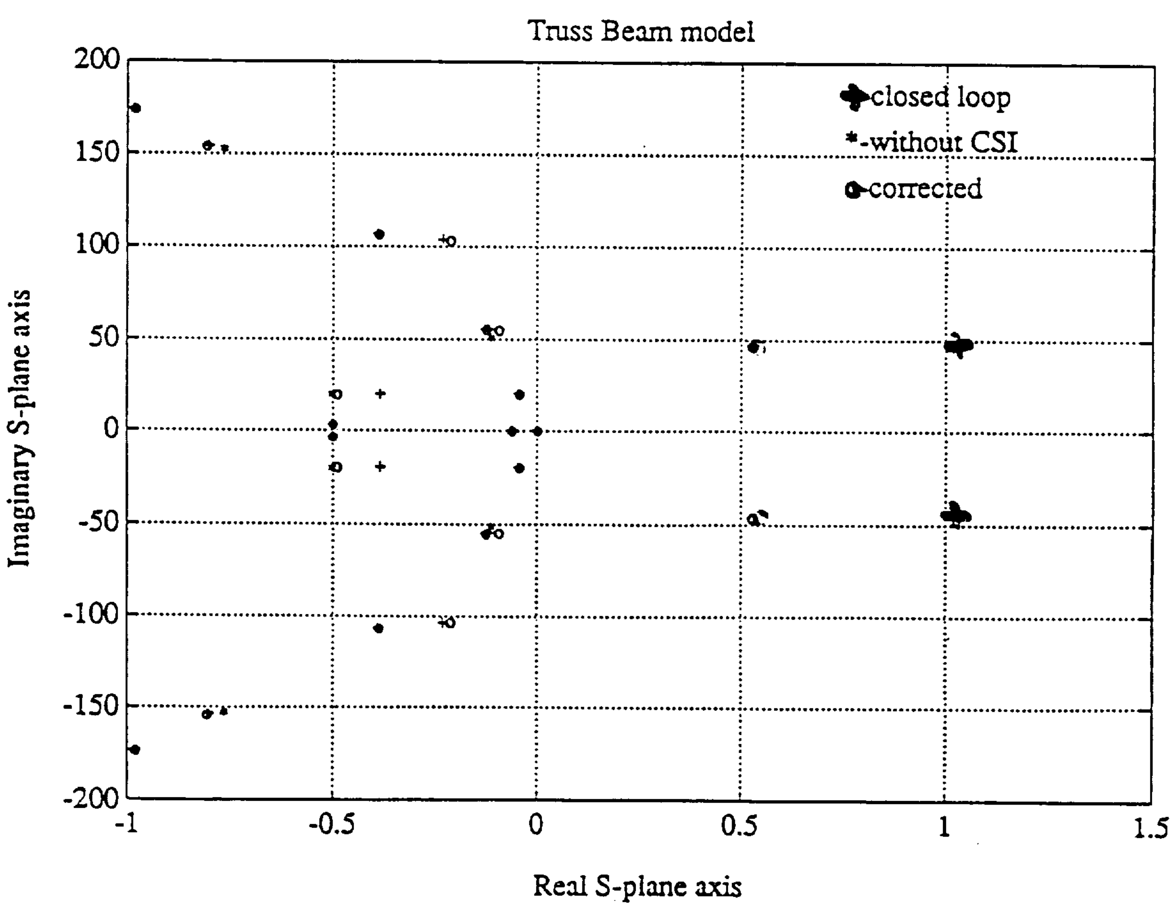
Closed-Loop (LSS + ROM Controller):

$$A_c(\epsilon) = \begin{bmatrix} A_M & B_M G_M & 0 \\ K_M C_M & L_M & \epsilon K_M C_R \\ 0 & \epsilon B_R G_M & A_R \end{bmatrix}$$

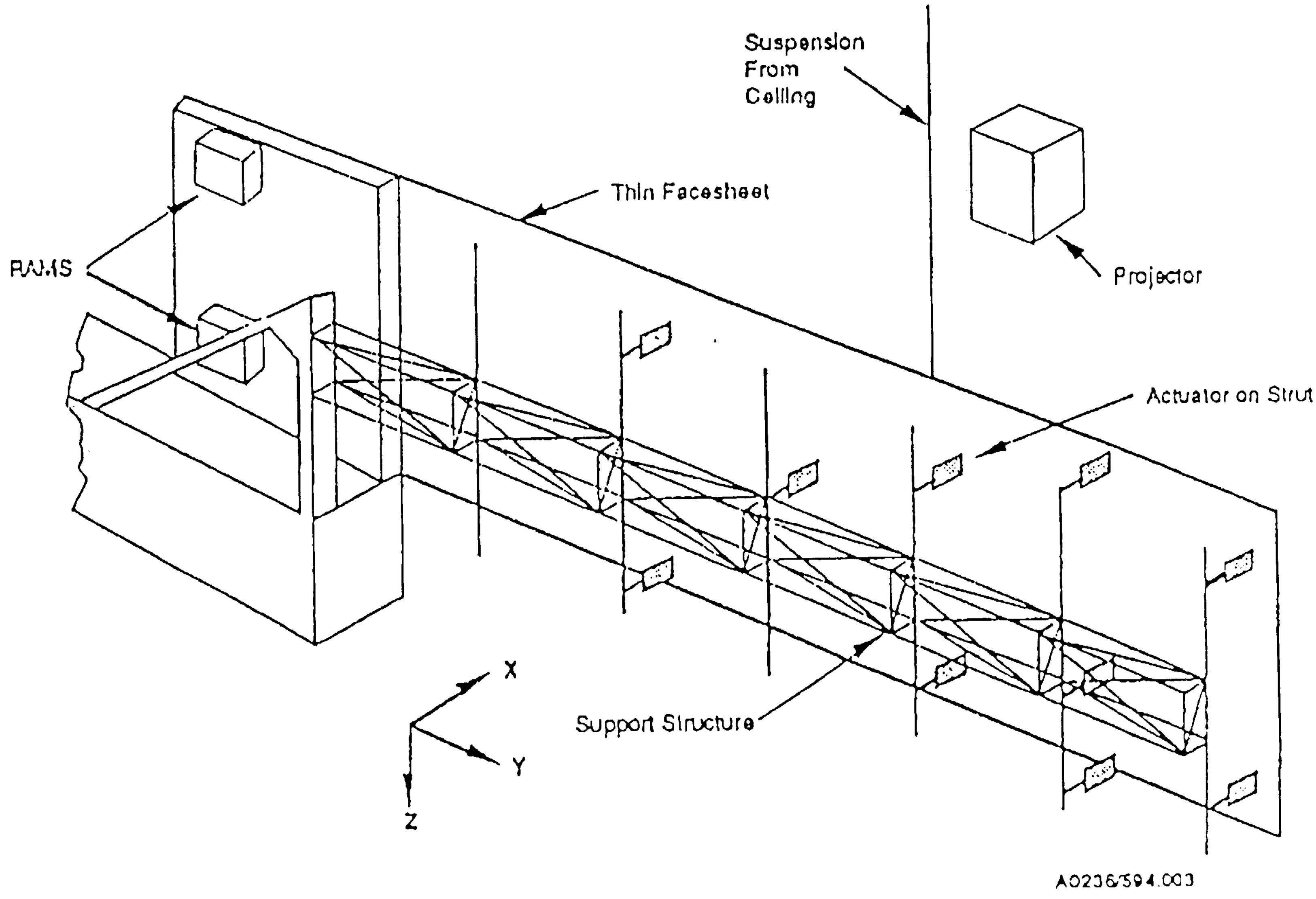
$$\therefore \quad \hat{\lambda}_c(\epsilon) = \lambda_0 + \epsilon^2 \lambda_2$$

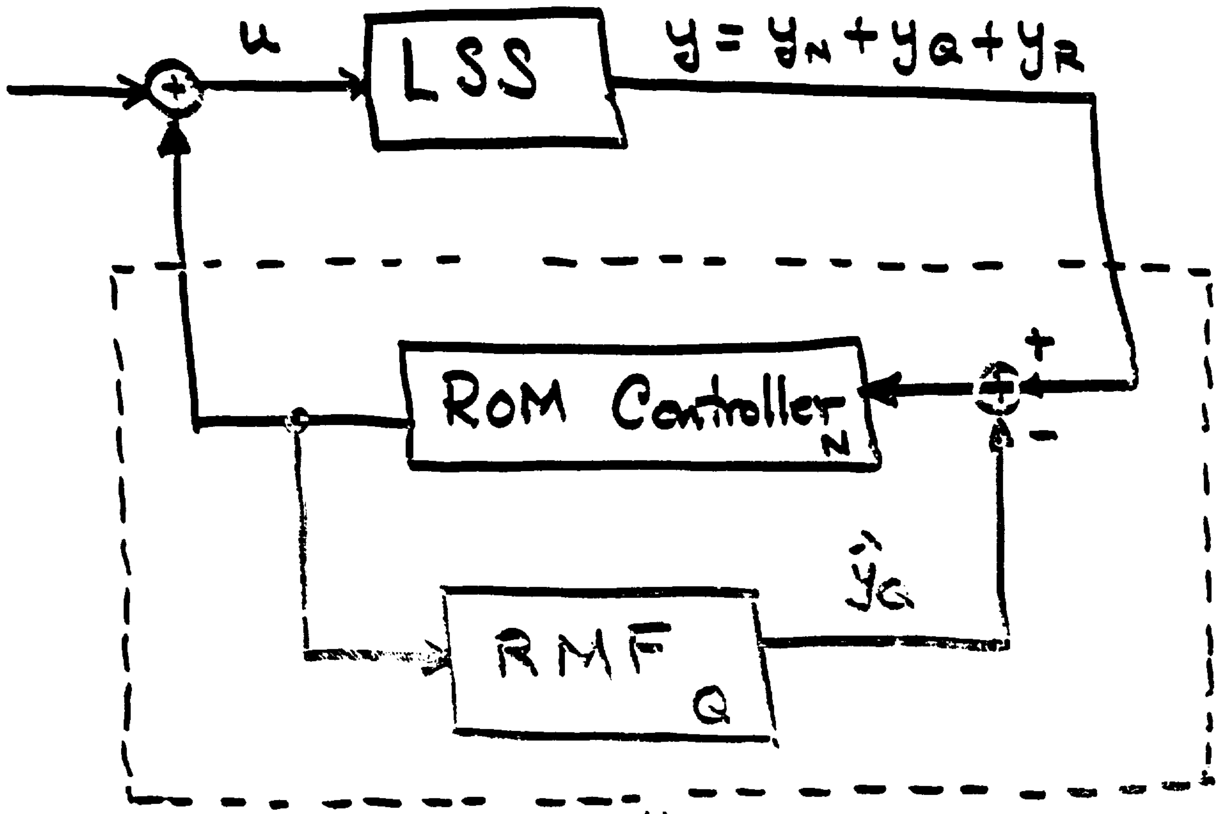
<u>Note:</u> $\lambda_1 = 0$ & $\lambda_3 = 0$


Truss Beam model
closed loop
*-without CSI
o-corrected
Imaginary S-plane axis
Real S-plane axis
500
400
300
200
100
0
-100
-200
-300
-400
-500
-7
-6
-5
-4
-3
-2
-1
0
1
2


Truss Beam model
closed loop
*-without CSI
o-corrected
Imaginary S-plane axis
Real S-plane axis
200
150
100
50
0
-50
-100
-150
-200
-1
-0.5
0
0.5
1
1.5

Testbed Concept Has Thin Facesheet Controlled From Support Truss





New Controller

Good Stuff:

- Add-on: No Controller ReDesign
- RMF: simple Hardware Implementation
- Restores: Stability + Performance

Difficulties:

- What Are Q modes?
- RMF sensitive to frequency
- Actuator/Sensor Dynamics
- Nonlinearities

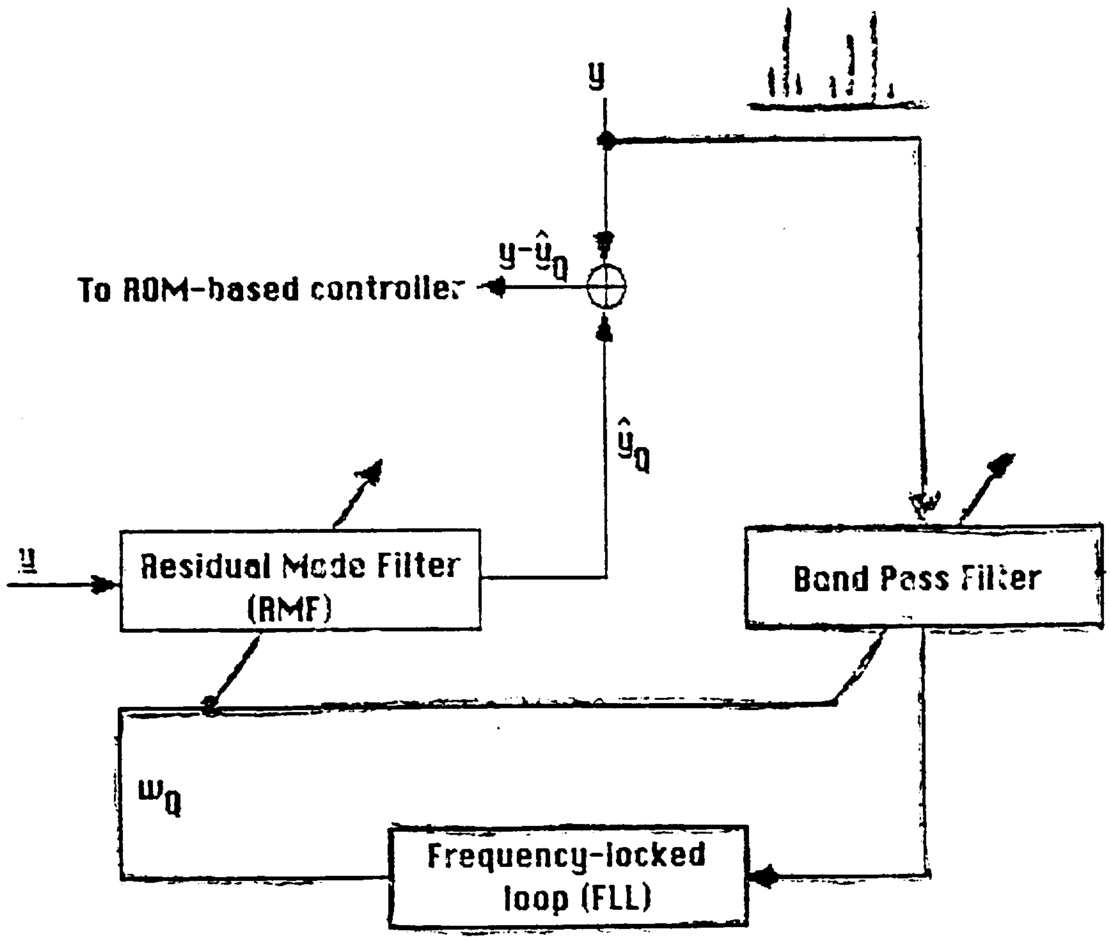


Figure 4. The adaptive, self-tuning RMF.

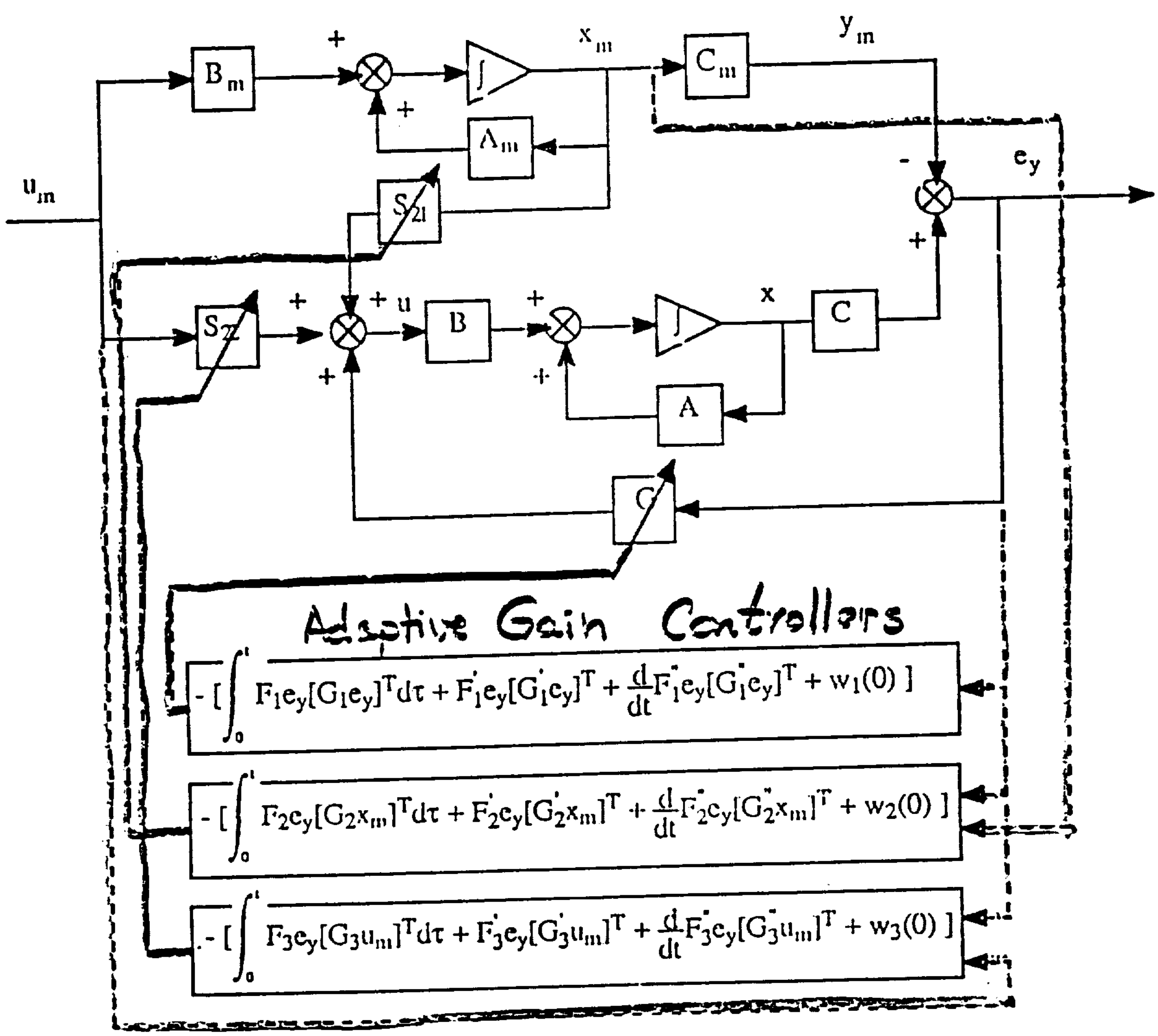
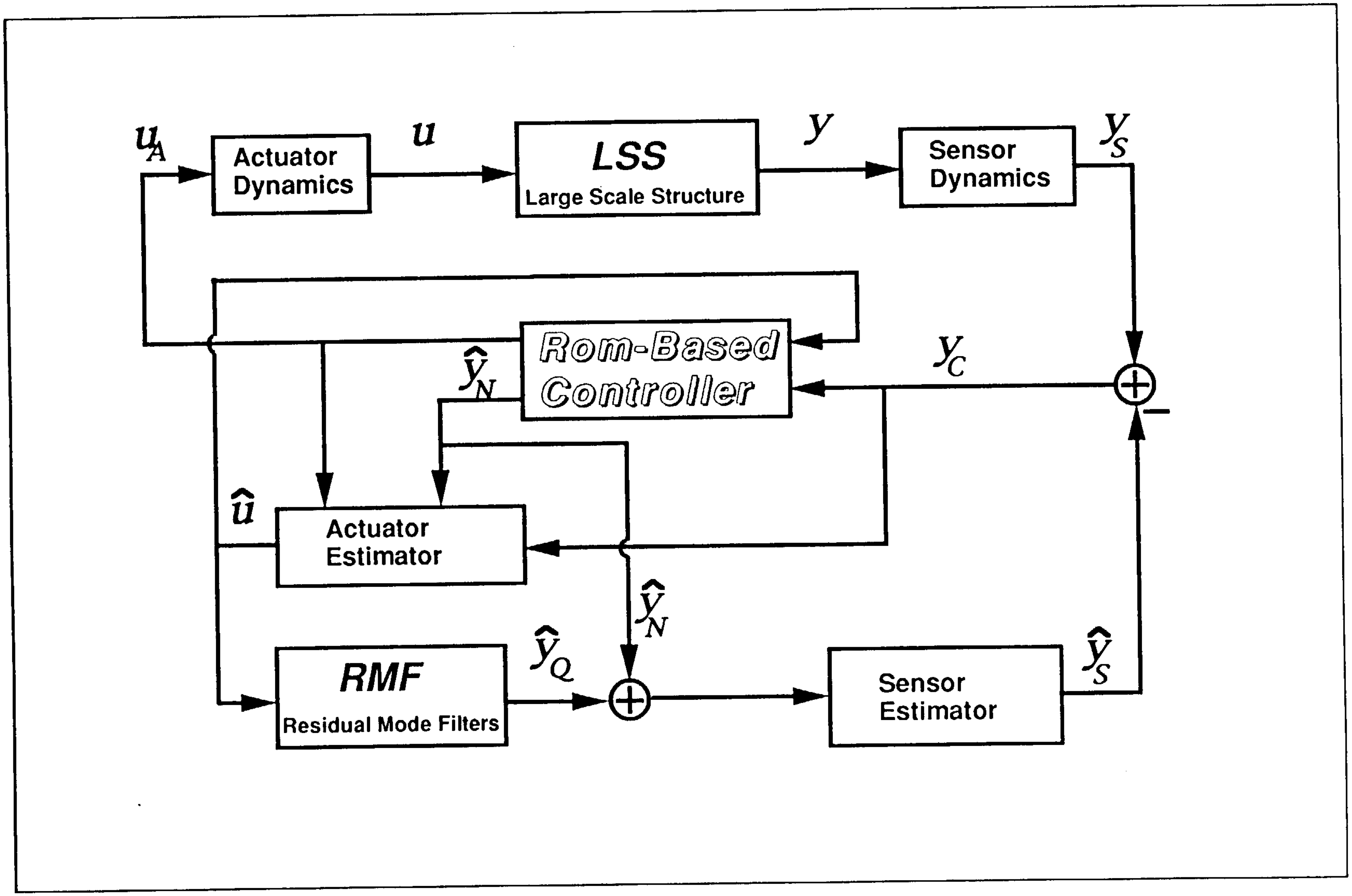
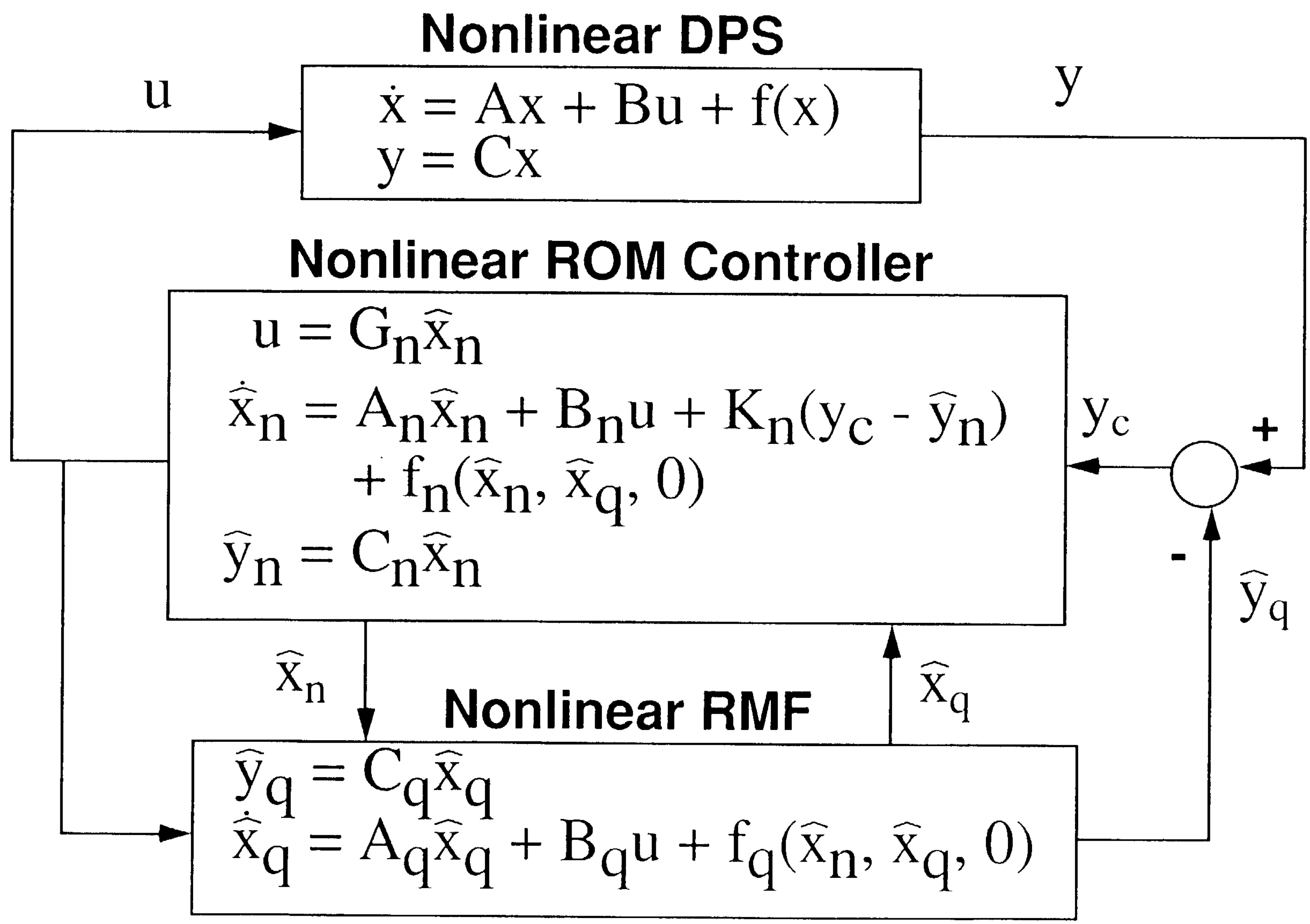


Figure 3-1. The structure of the adaptation mechanism

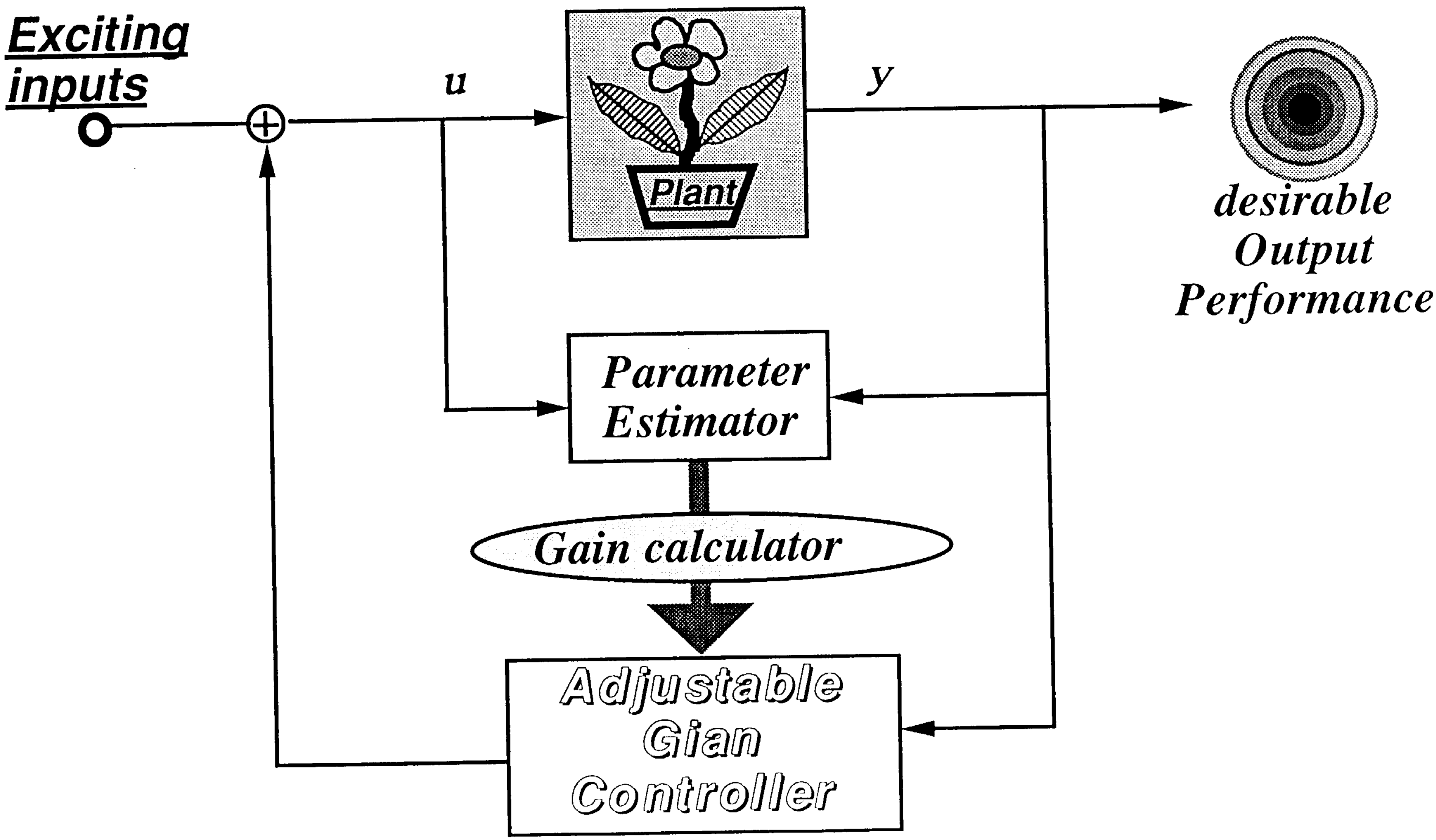
ROM/RMF with actuator/sensor dynamics



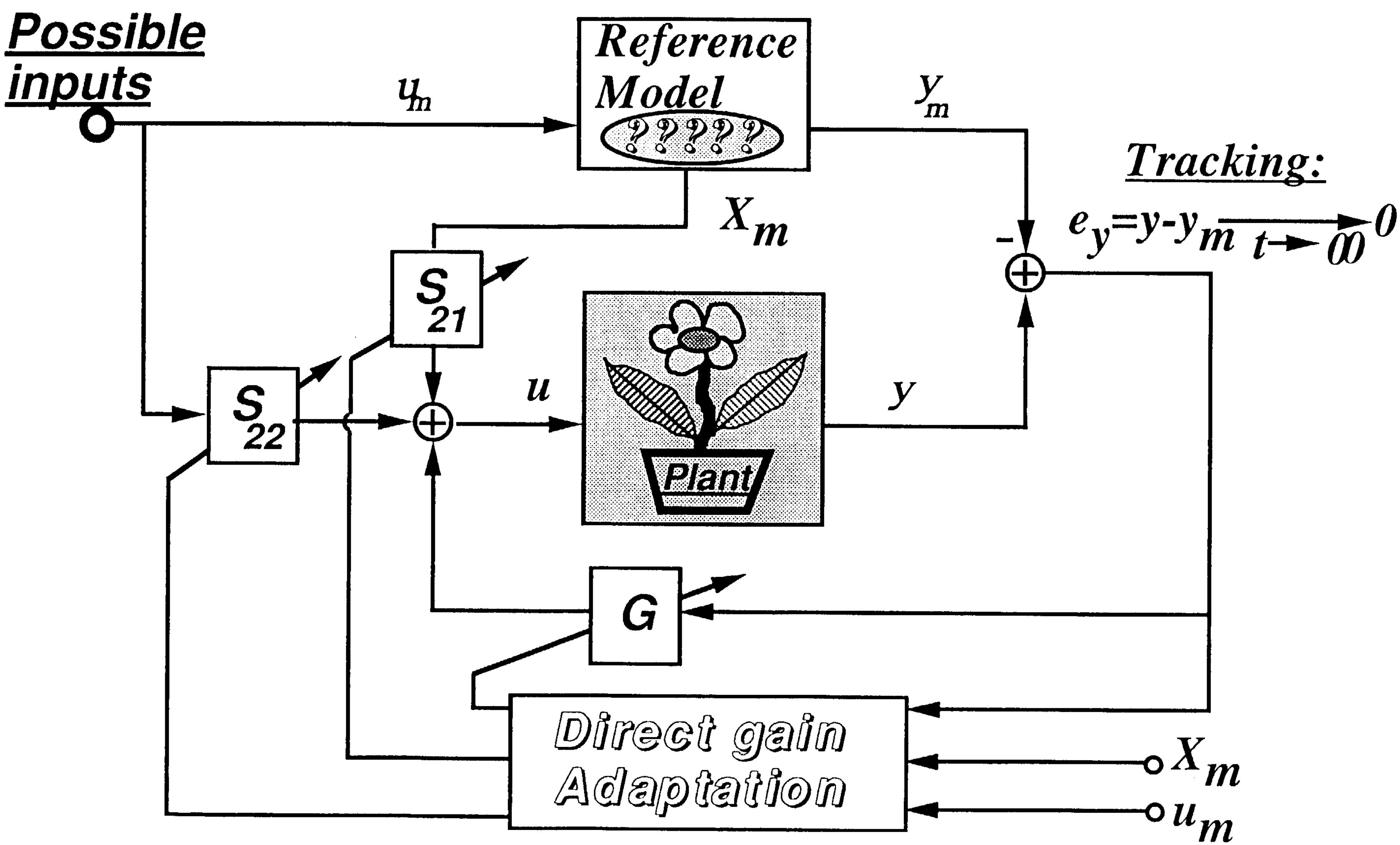
Modifications For Nonlinear ROM/RMF Control JMAA 1991

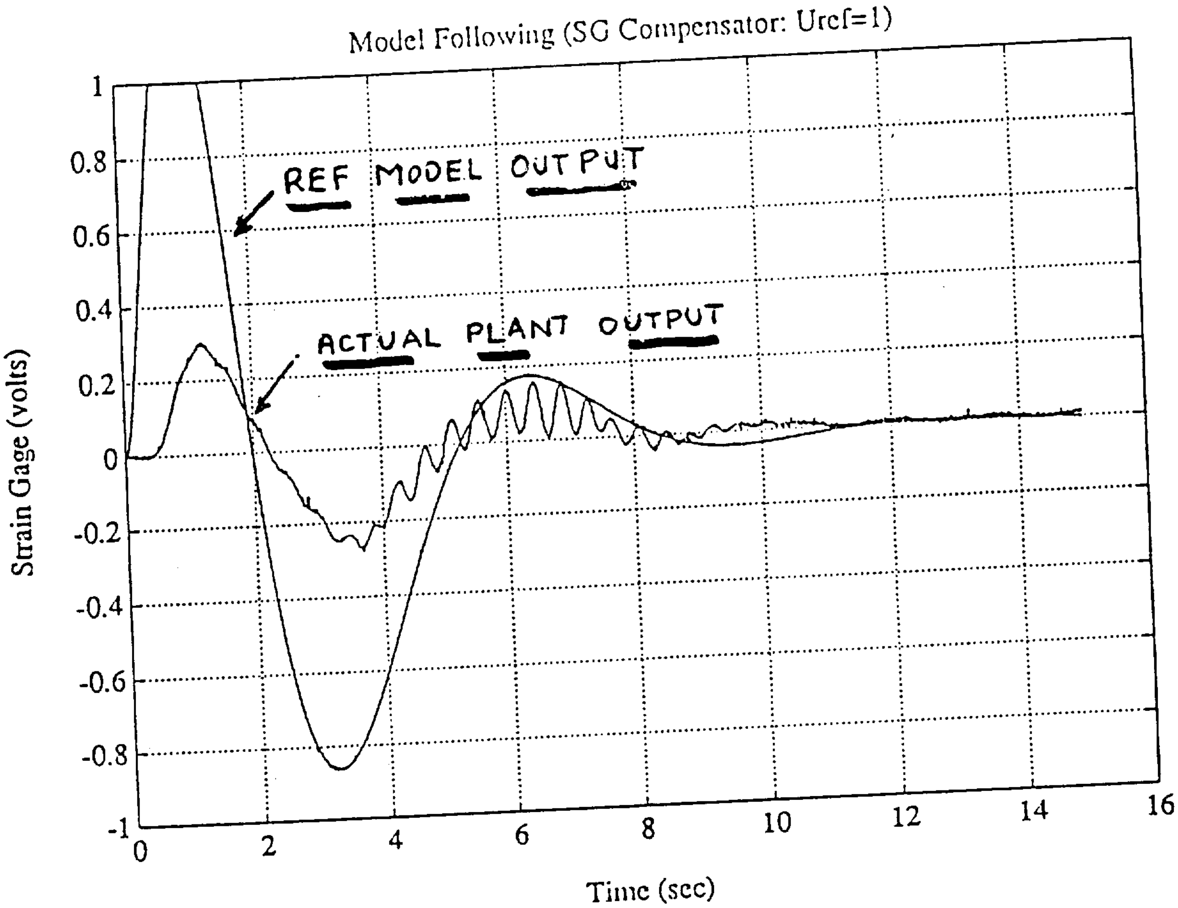


Indirect Adaptive Control



Direct Adaptive Control





Flexible Manipulator Experiments (SC Liang)

Hub Control - Strain Gauge Sensor

(Not Collocated)

Decentralized Controller Design

→ **Performance** ←

Controller 1

$$u_1 = K_1^o y_1 + K_1^1 z_1$$
$$\dot{z}_1 = L_1^o z_1 + L_1^1 y_1$$

Controller 2

$$u_2 = K_2^o y_2 + K_2^1 z_2$$
$$\dot{z}_2 = L_2^o z_2 + L_2^1 y_2$$

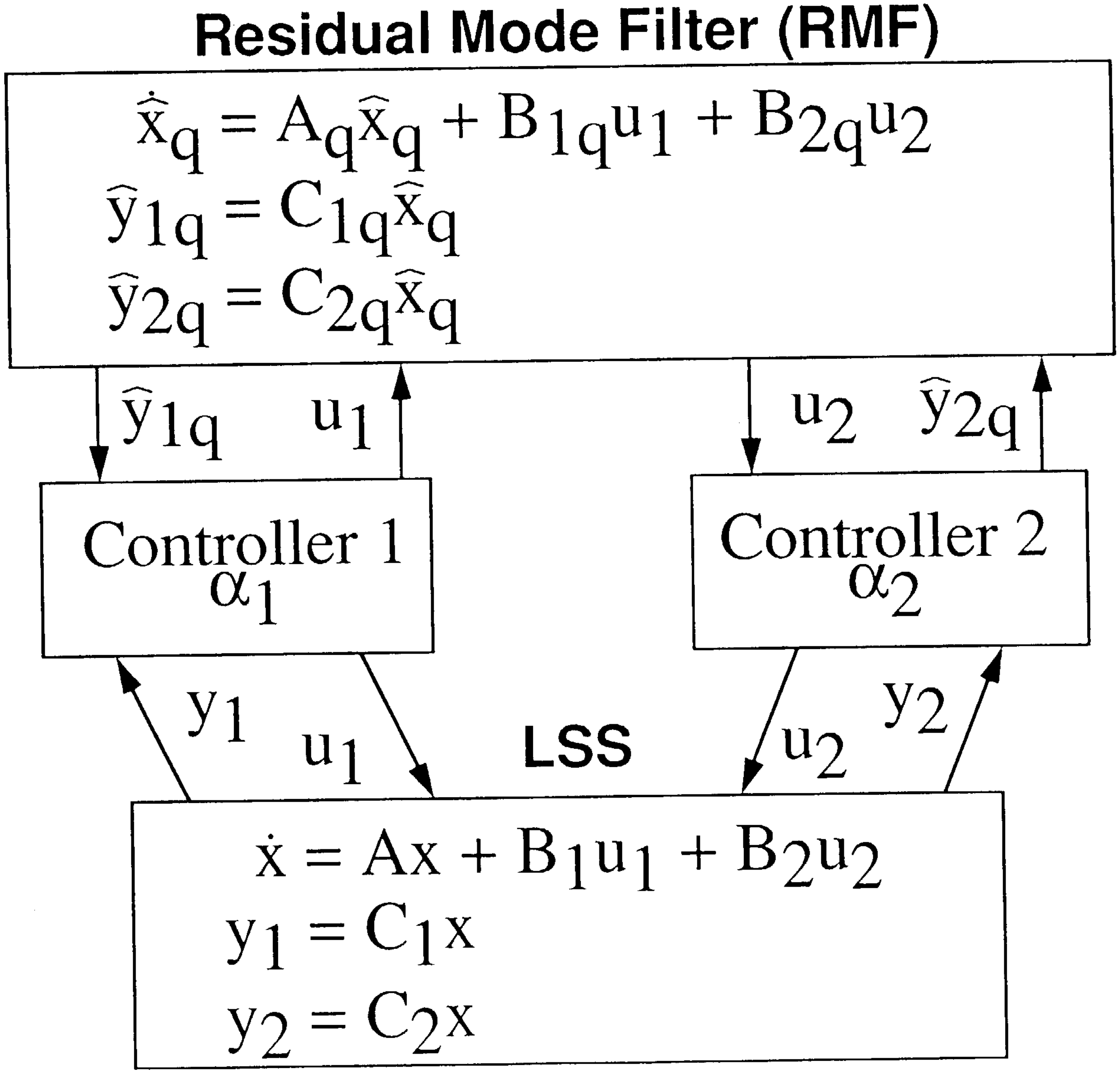
y_1 ↑ u_1 ↓ y_2 ↑ u_2 ↓

Large Space Structure (LSS)

ROM :

$$\dot{x}_n = A_n x_n + B_{1n} u_n + B_{2n} u_2$$
$$y_1 = C_{1n} x_n + \text{residuals}$$
$$y_2 = C_{2n} x_n + \text{residuals}$$

RMF Compensation for Stable Control



N93-26409

cSc

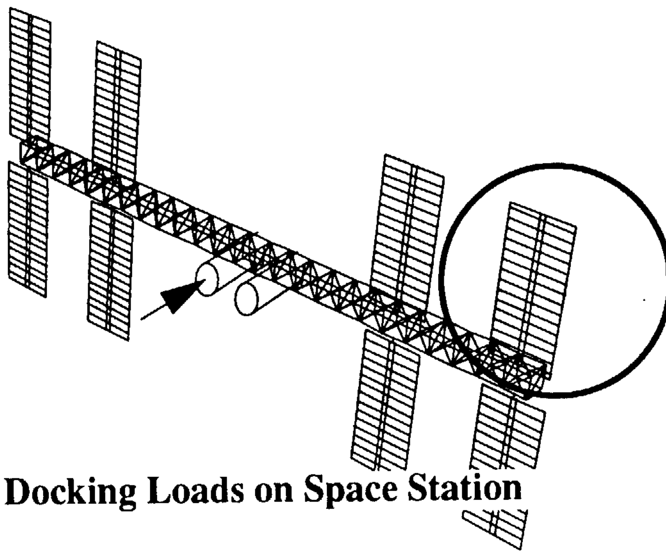
Structural Load Control During Construction

Martin Mikulas

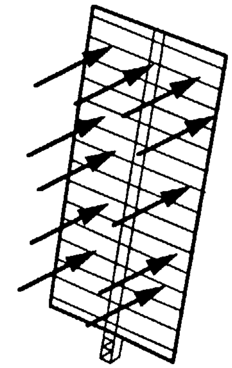
Third Annual Symposium
November 21 & 22, 1991

A NASA Space Engineering Research Center at the University of Colorado

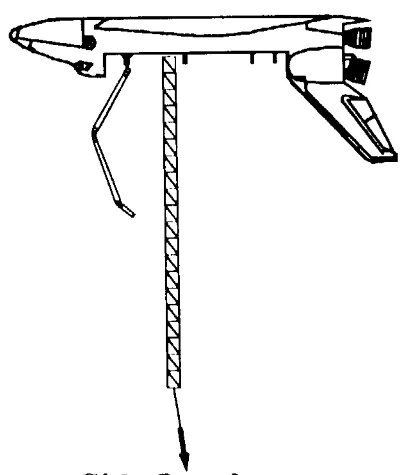
EXAMPLES OF HIGH TRANSIENT LOADINGS ON LARGE SPACE STRUCTURES



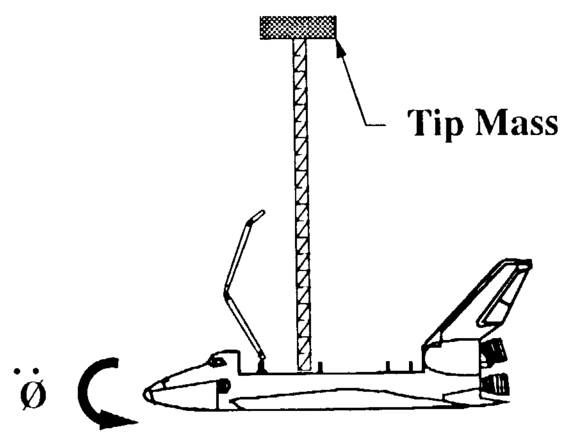
Docking Loads on Space Station



Shuttle Thruster Impingement on Solar Arrays



Side Loads From Tethers



Shuttle Accelerations Applied to Attached Beam

ENERGY ABSORBING/LOAD LIMITING STRUT RESEARCH OBJECTIVES

Explore feasibility of using energy-absorbing/load-limiting struts in large space structures subjected to transient loadings

Develop analytical and design capability for energy absorbing struts

Develop several energy absorbing strut concepts (passive & active)

Experimentally demonstrate application of energy absorbing struts

SCOPE OF RESEARCH ON ENERGY ABSORBING STRUTS TO DATE

Rigid body analysis developed to scope problem

Intial contacts made with LeRC to understand solar array problem — Kornel Nagy

Visit made to JSC to understand their effort on energy absorbers

Preliminary finite element analysis conducted on uniform beam solar array model

Studies conducted to size springs in energy absorbers

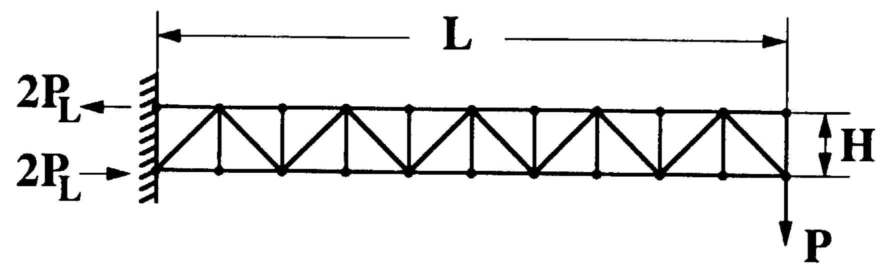
Test bed for energy absorbers designed and under construction

Porter Davis

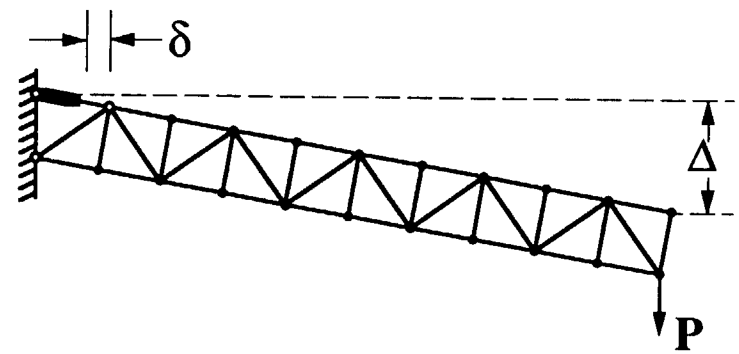
Cooperative agreement made with Honeywell to co-develop an energy absorber

ENERGY CHARACTERISTICS OF CANTILEVERED TRUSSES WITH A TIP LOAD.

Standard Truss



Energy Absorbing Truss



$$2P_L H = PL \quad \Rightarrow \quad P_L = \frac{PL}{2H}$$

Truss strain energy is:

$$\Pi = \frac{1}{2} P \Delta$$

Where

$$\Delta = \frac{PL^3}{3EI}$$

$$\frac{\delta}{H} = \frac{\Delta}{L} \quad \Rightarrow \quad \Delta = \frac{L}{H}\delta$$

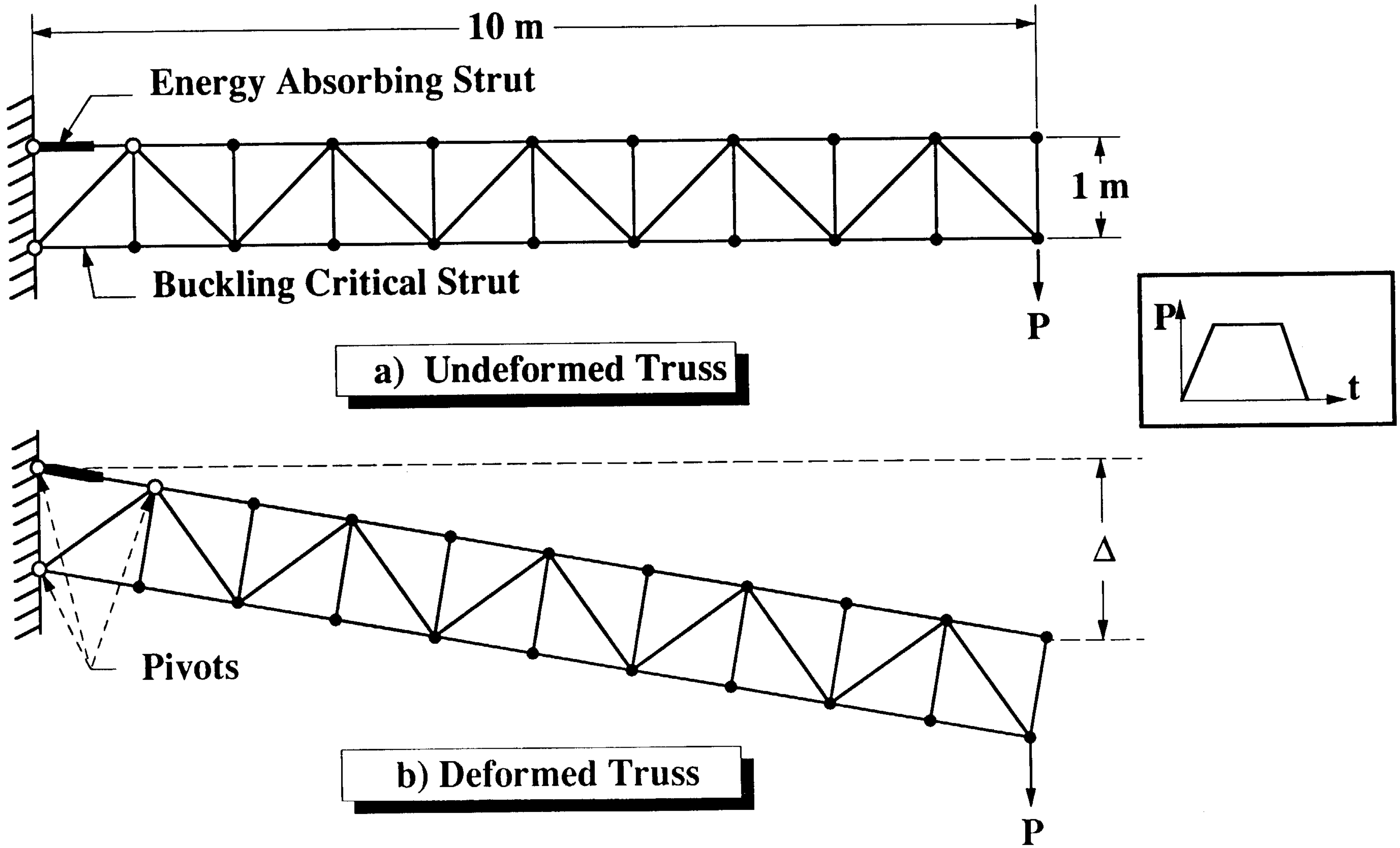
Truss absorbed energy is:

$$E = P\Delta$$

or

$$E = P\frac{L}{H}\delta = 2P_L\delta$$

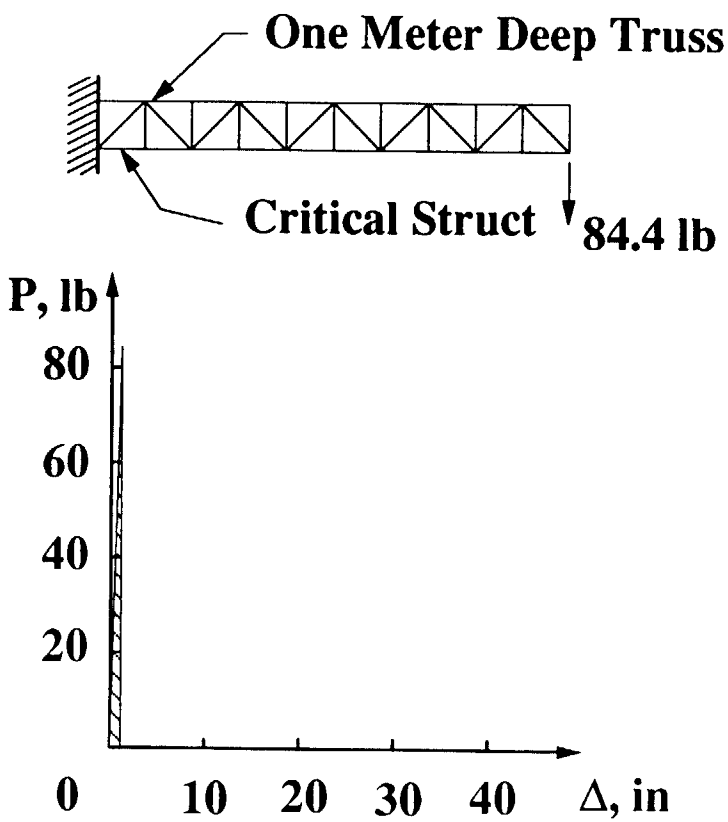
TEN BAY LONG RESILIENT TRUSS EXAMPLE



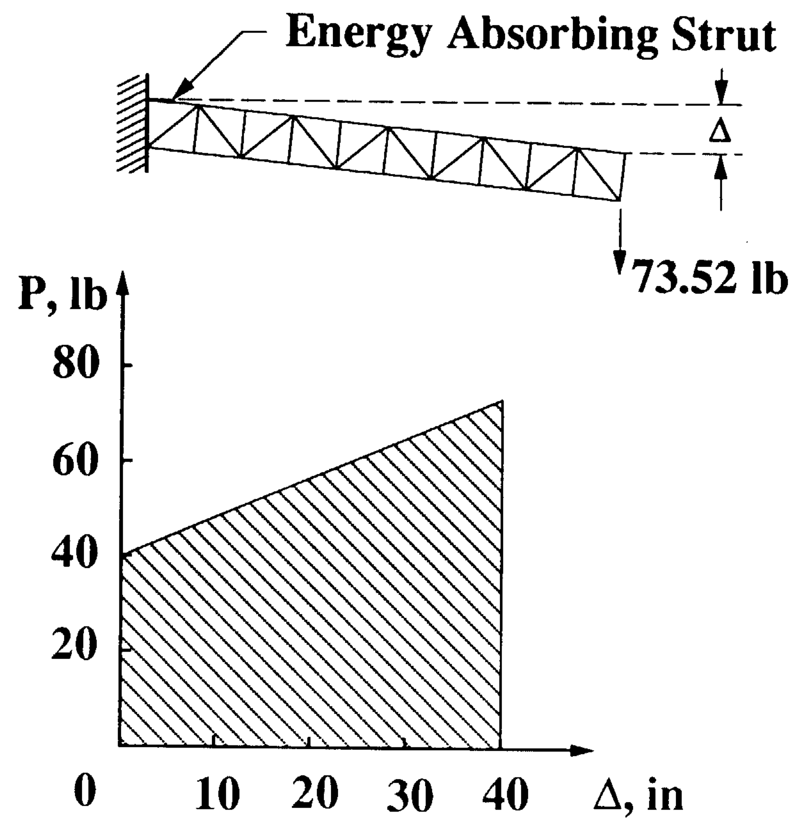
a) Undeformed Truss

b) Deformed Truss

STORED ENERGY CHARACTERISTICS OF ONE METER DEEP TRUSS.

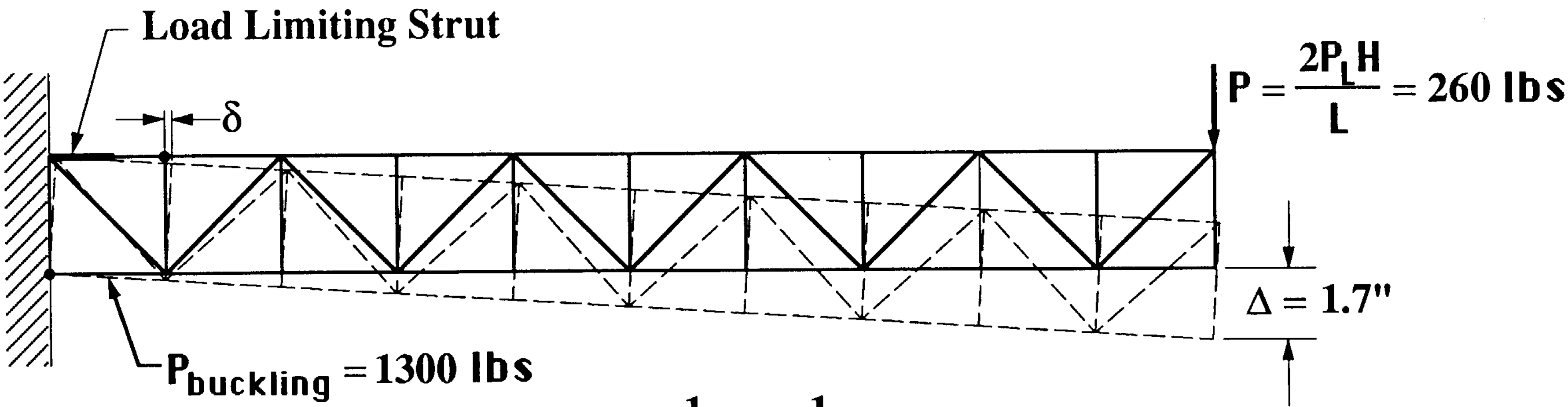


a) Strain energy stored in regular truss (50 in-lb)



b) Energy absorbed by resilient truss (2300 in-lb)

ENERGY ABSORBING POTENTIAL FOR 10-BAY 5-METER DEEP TRUSS



$$E = \frac{1}{2}P\Delta = \frac{1}{2}260 X 1.7 = 220 \text{ in-lb}$$

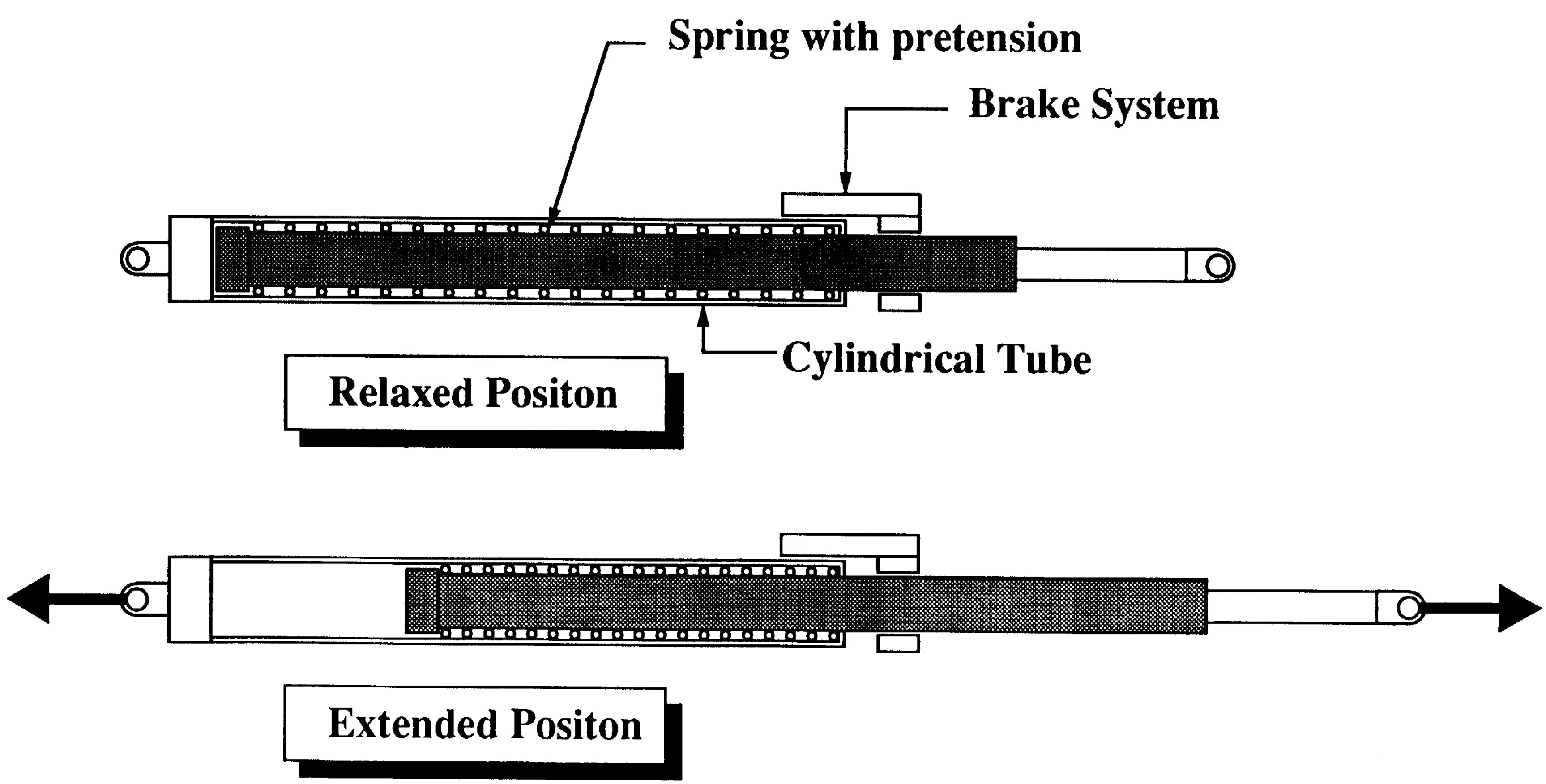
For load limiting strut with preload of 500 lbs and $\delta = 4''$

$$E = 2P_L\delta = 2X500X4 = 4000 \text{ in-lb}$$

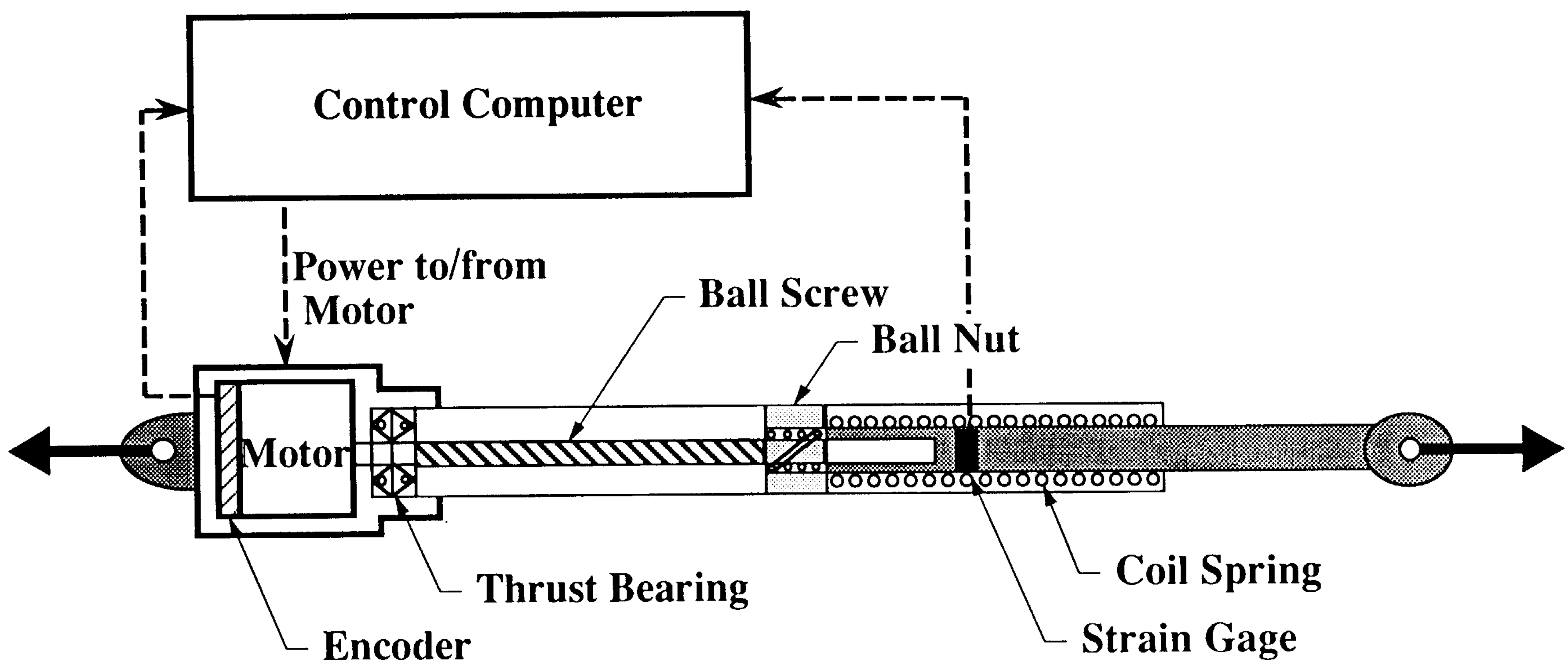
$$\Delta = 10\delta = 40''$$

$$\frac{\Delta}{H} = \frac{40}{196} = .2$$

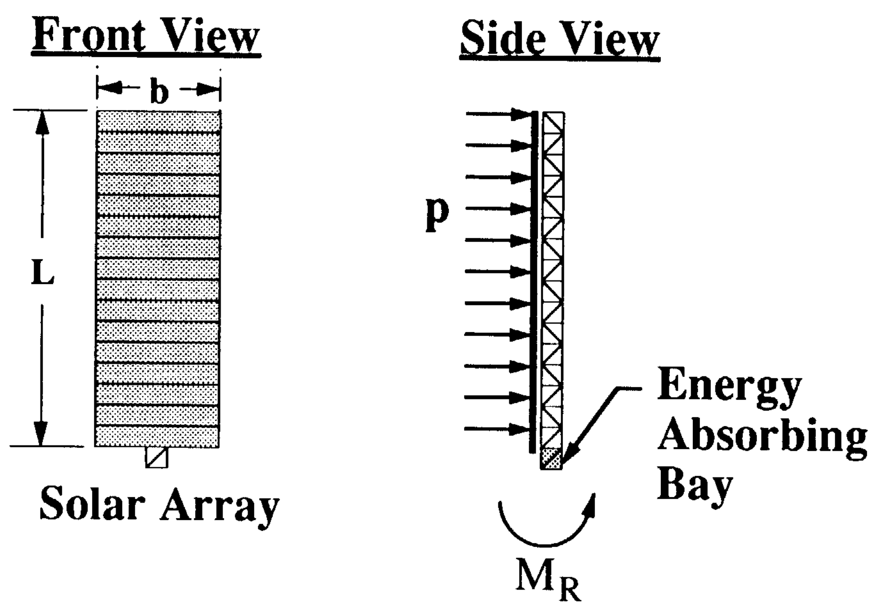
SCHEMETIC OF ENERGY ABSORBING STRUT

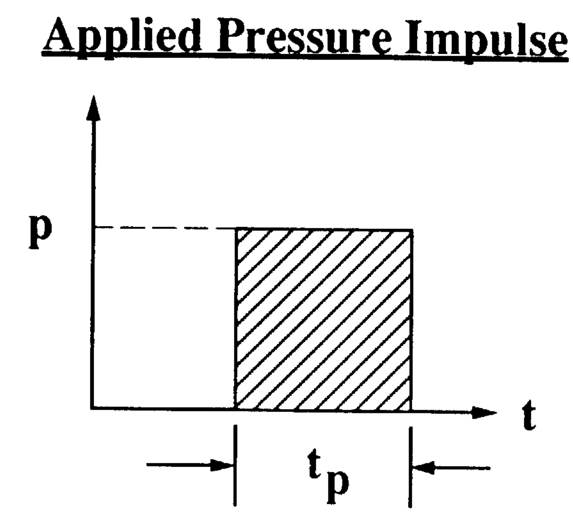


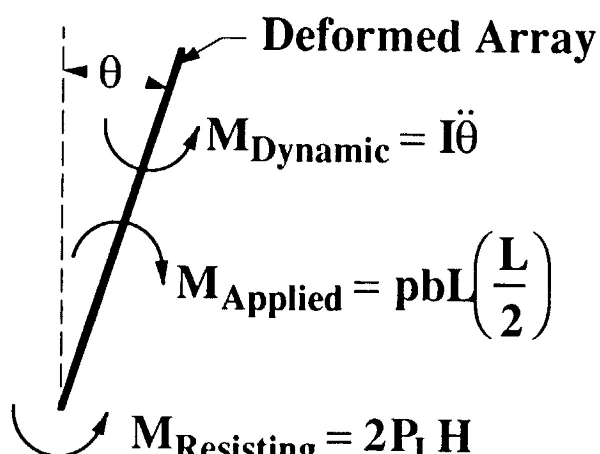
LINEAR LOAD AND MOTION CONTROL ACTUATOR
(Energy Absorbing Strut)



RIGID BODY RESPONSE OF A SOLAR ARRAY TO THE SHUTTLE THRUSTER PRESSURE IMPINGEMENT.







$M_{Dynamic} = I\ddot{\theta}$

$M_{Applied} = pbL\left(\frac{L}{2}\right)$

$M_{Resisting} = 2P_L H$

(1) $M_A - M_R = I\ddot{\theta}$

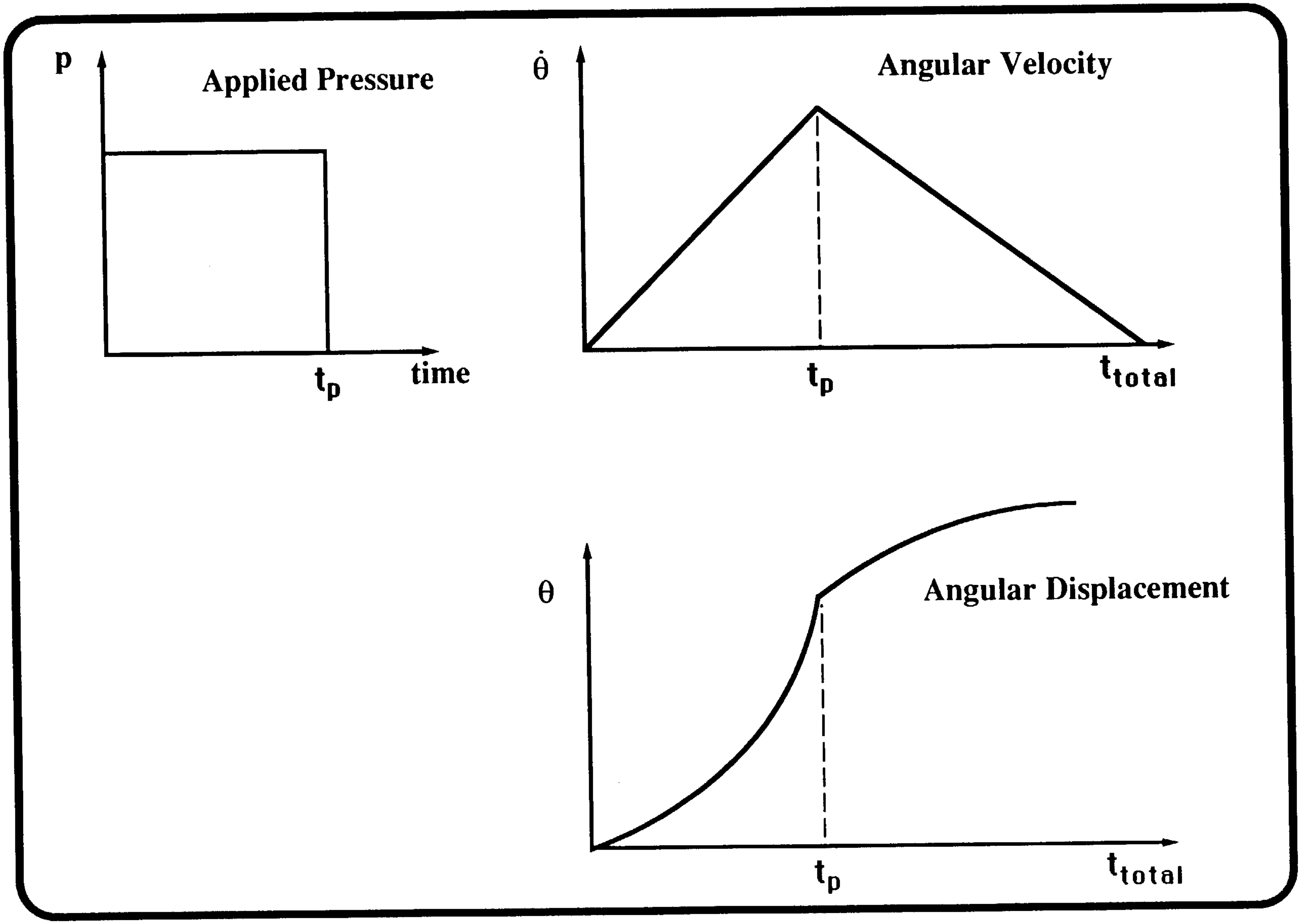
<u>Integration Yields:</u>

(2) $\theta = \frac{M_A t_p^2}{2I}\left(\frac{M_A}{M_R} - 1\right)$

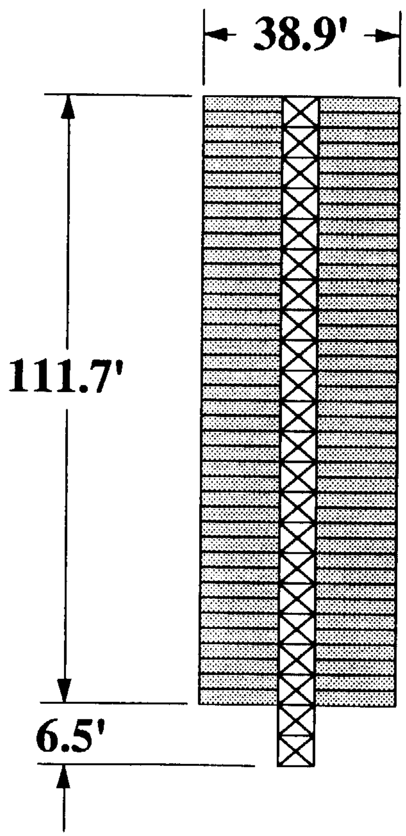
or

(3) $\delta = \frac{M_A t_p^2}{2I} H\left(\frac{M_A}{M_R} - 1\right)$

SOLAR ARRAY PIECEWISE LINEAR RESPONSE

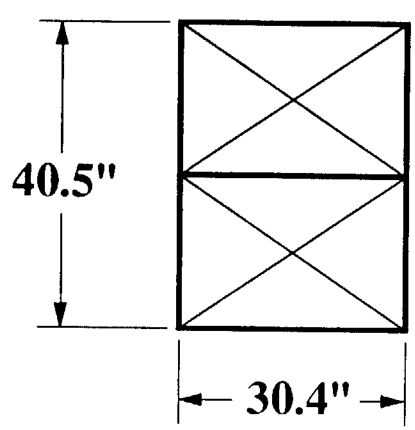


SOLAR ARRAY CHARACTERISTICS



Array Weight, lbs	
Tip	31
Truss beam	315.78
Canister	534.65
Array Blanket	1246.57
Total	2128

Array Beam (one bay)



Longeron properties

Area = .5x.5 = .25 in^2
E = 10e6
Pcrit = 1250 lbs

Truss bending stiffness

EI = .43x EI(theoretical)
= 98 lb-in^2 (Tom Irvine)

SOLAR ARRAY TIP DEFLECTION AND REQUIRED ACTUATOR STROKE

$$\delta = \frac{M_A t_p^2 H}{2I}\left(\frac{M_A}{M_R} - 1\right)$$

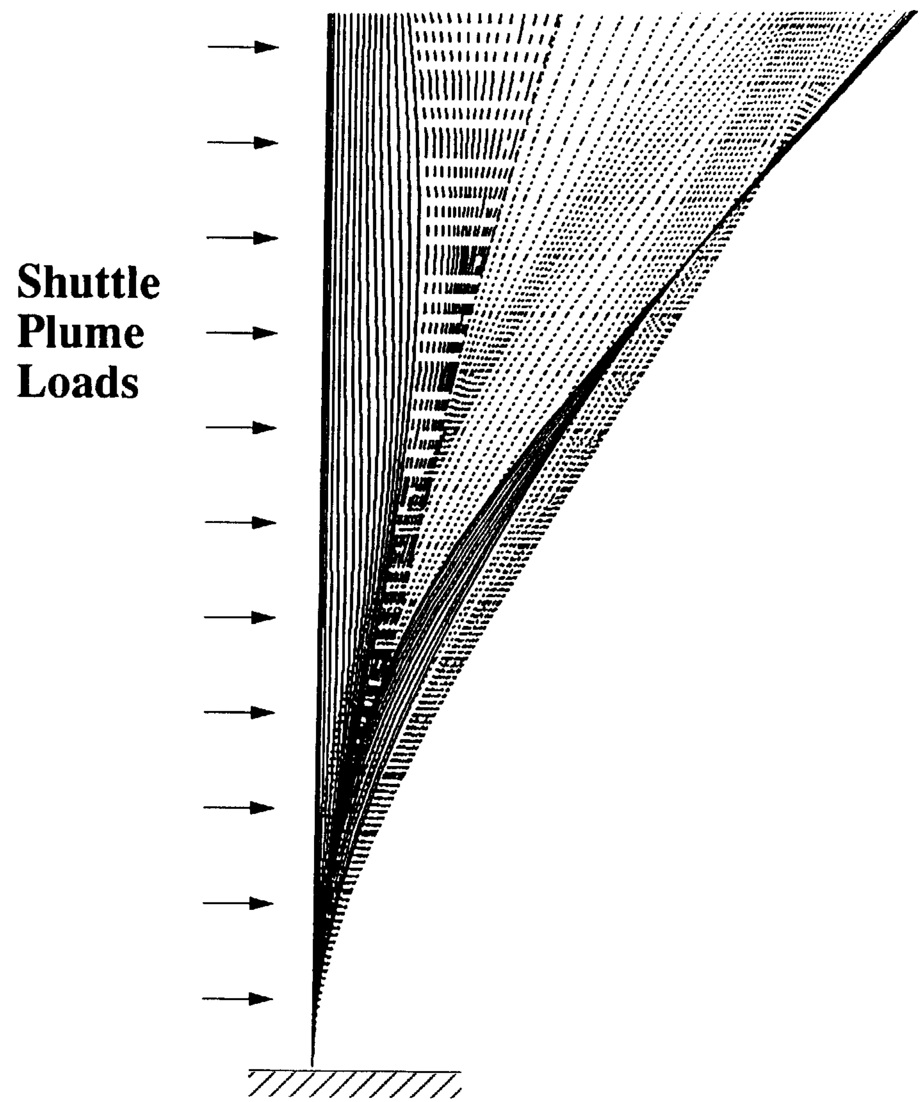
<u>Array input quantities</u>

tp = .75 sec
Plume pressure = .0002 psi
Total load on array = 104 lbs
Assumed actuator preload = 300lb

<u>Tip displacement</u>

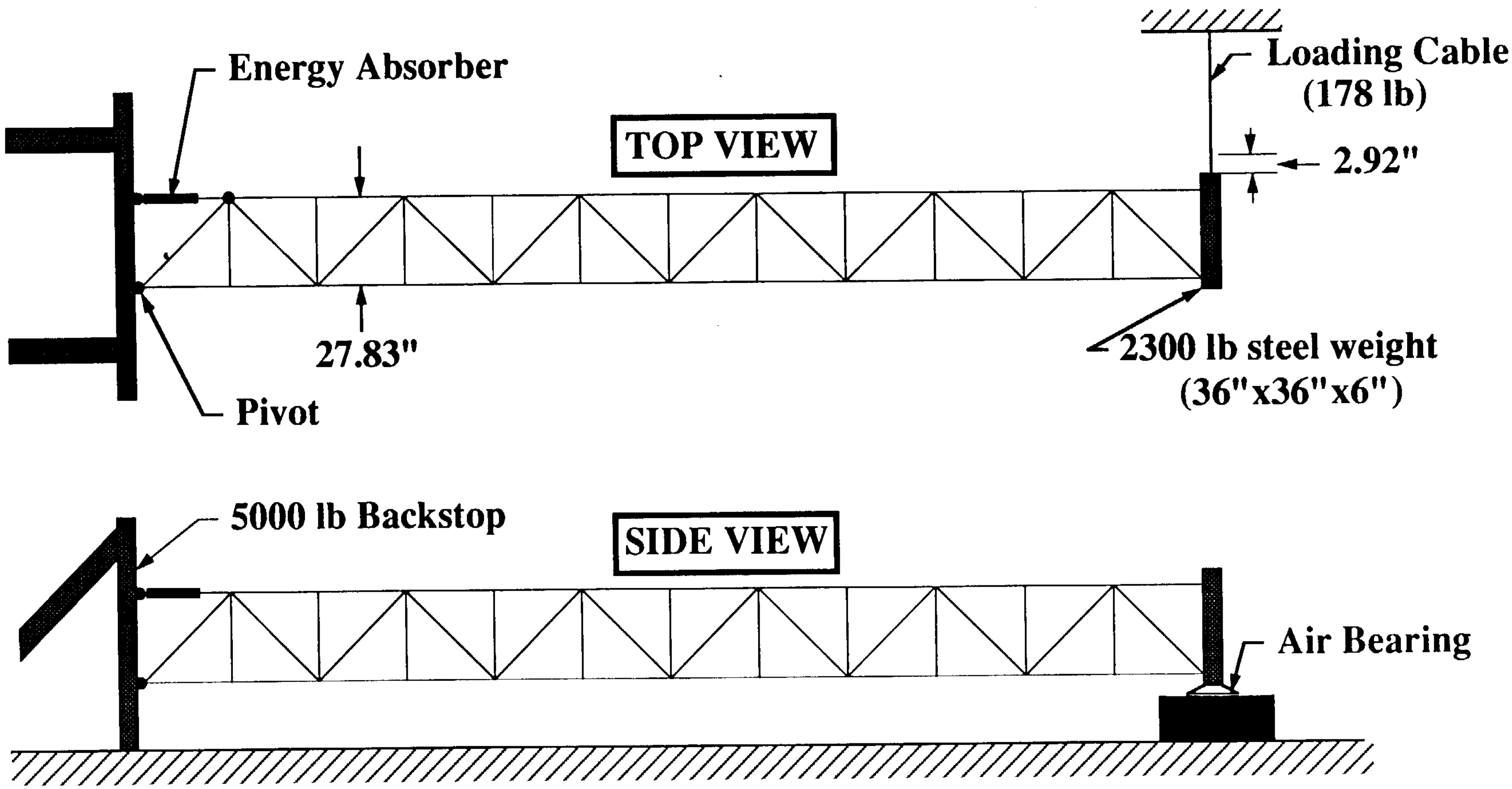
Rigid body - 31"
Finite Element - 98"; Actuator stroke = 2.1"

SOLAR ARRAY RESPONSE FROM FINITE ELEMENT ANALYSIS



12 BAY ENERGY ABSORBING TEST BED

(Beam Length = 27.83')

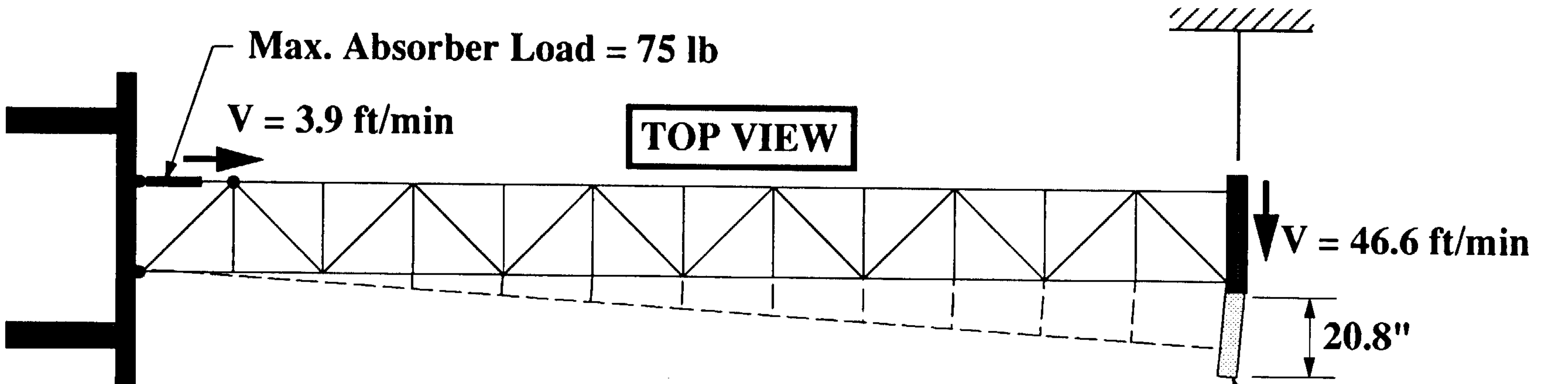


Beam Weight = 75.47 lb   Beam Frequency = . 5 Hz

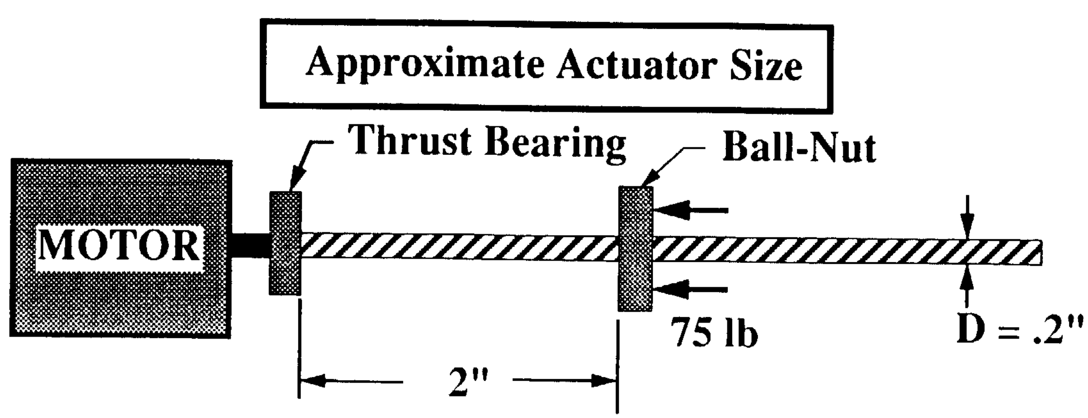
12 BAY ENERGY ABSORBING TEST BED DYNAMICS

(Beam Length = 27.83')

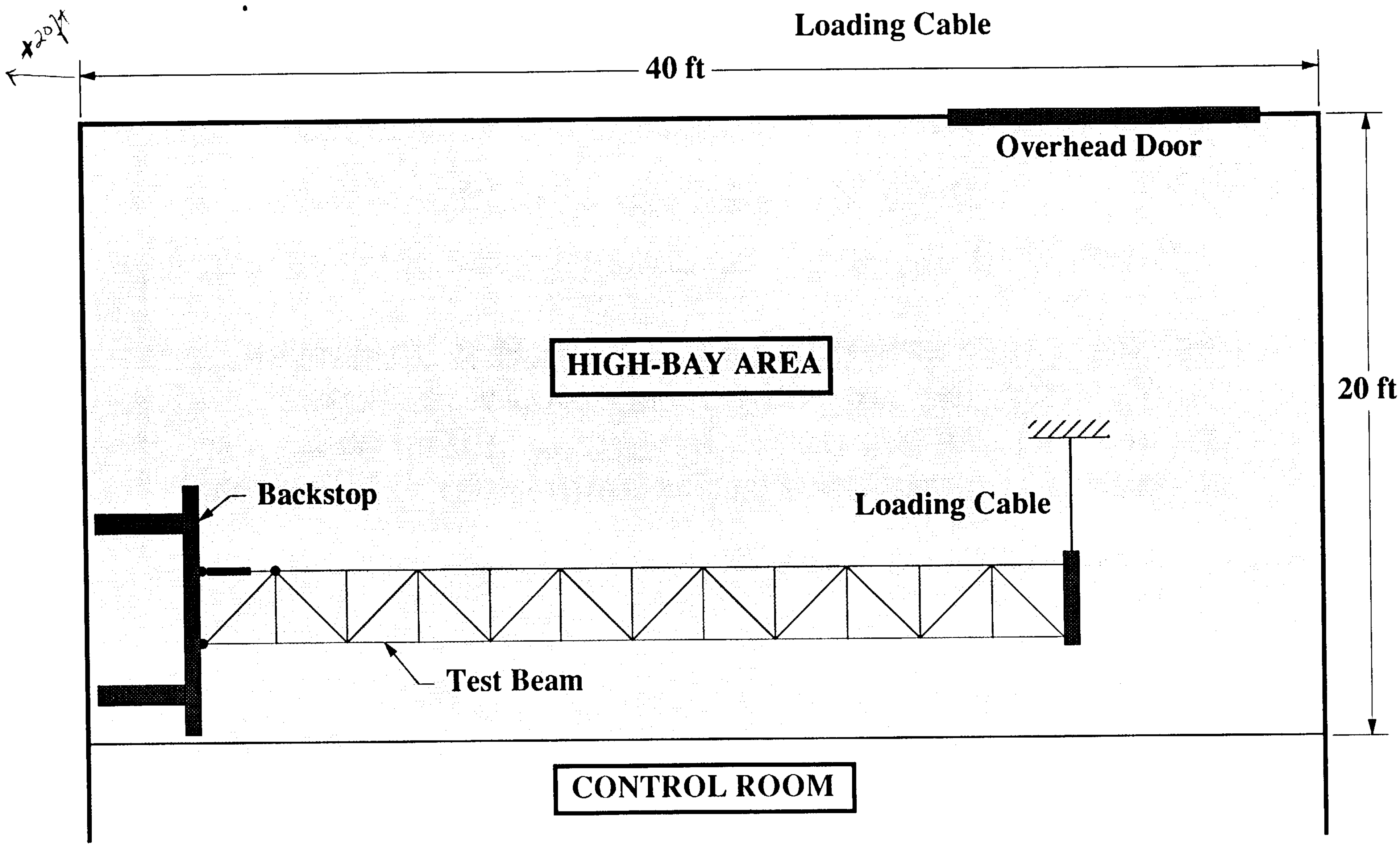
Beam Strain Energy = 260 in-lb = 22 ft-lb



Horsepower = (FxV)/33,000 = (75x3.9)/33,000 = .0088



NEW AERO-LAB WITH 12-BAY TEST BEAM



CONCLUDING REMARKS

All example cases analyzed to date indicate that there is a large payoff in efficiency and fail-safety by using energy absorbers as a "fuse"for limiting and absorbing transient loadings on space structures

Large scale experiments are needed to demonstrate the application of these devices

N93-26410

cSc

Systems Engineering Studies of On-Orbit Assembly Operations

George W. Morgenthaler

Third Annual Symposium
November 21 & 22, 1991

Center for Space Construction

The Theory of Space Construction

Progress Report

George W. Morgenthaler

PART I: DEFINITION AND SCOPE OF SPACE CONSTRUCTION

PART II: ORBITAL ASSEMBLY AND CONSTRUCTION

PART III: LUNAR BASE CONSTRUCTION

PART IV: MARS BASE CONSTRUCTION

(11/23/91)

Constructability Definition

"Constructability is defined as the optimum use of construction knowledge and expertise in the conceptual planning, detail engineering, procurement, and field operations phases to achieve the overall project objectives."

N. Eldin, "Constructability Improvement Of Project Designs", Journal of Construction Engineering and Management, American Society of Civil Engineers (ASCE), Vol. 114, No. 4, pp. 631-640, December 1988

Theory of Space Construction

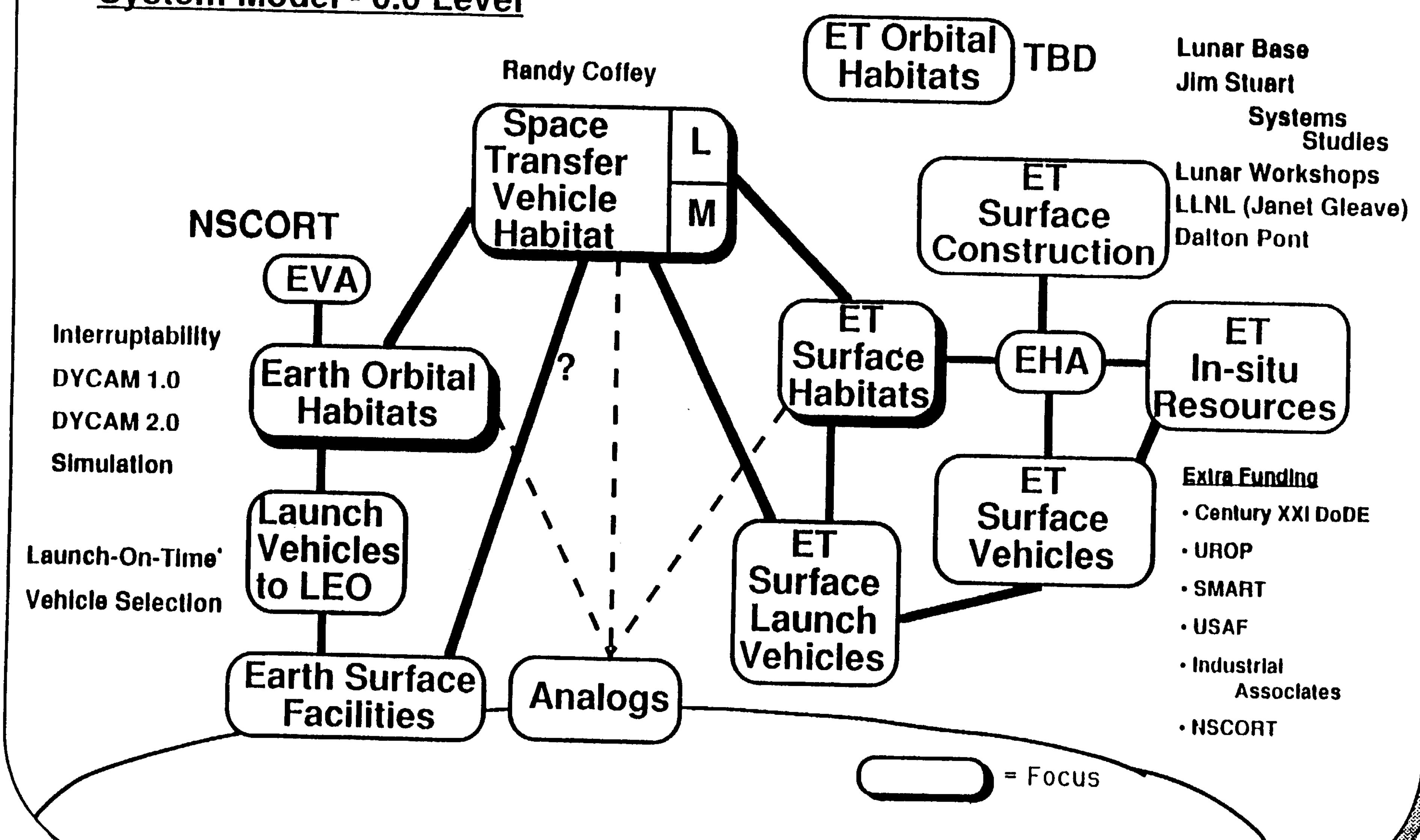
- Construction is Old; Construction Theory is young.
- The literature is filled with construction "war stories" and "Sea Bee" epics, but little quantitative analysis and optimization of construction.
- Strong parallels exist between Manufacturing and Construction:
  - — Requirements are critical (confused requirements lead to waste)
  - — Good design is critical; concurrent engineering requires iterations between Engineering and Manufacturing.
  - — Material selection is critical (failure, weight, hazards)
  - — Procurement (logistics) is critical
  - — Manufacturing Engineering is critical
  - — Inspection, QC, NDE are critical
  - — Cost and schedule analysis is critical
  - — A Systems Approach is required for success
- Analytical tools have been developed for terrestrial manufacturing and construction, but not for Space-based applications. (Synthesis tools do not as yet exist for either domain)
- We need to approach a Theory of Space Construction in the same way

(Space construction is not as forgiving as manufacturing)

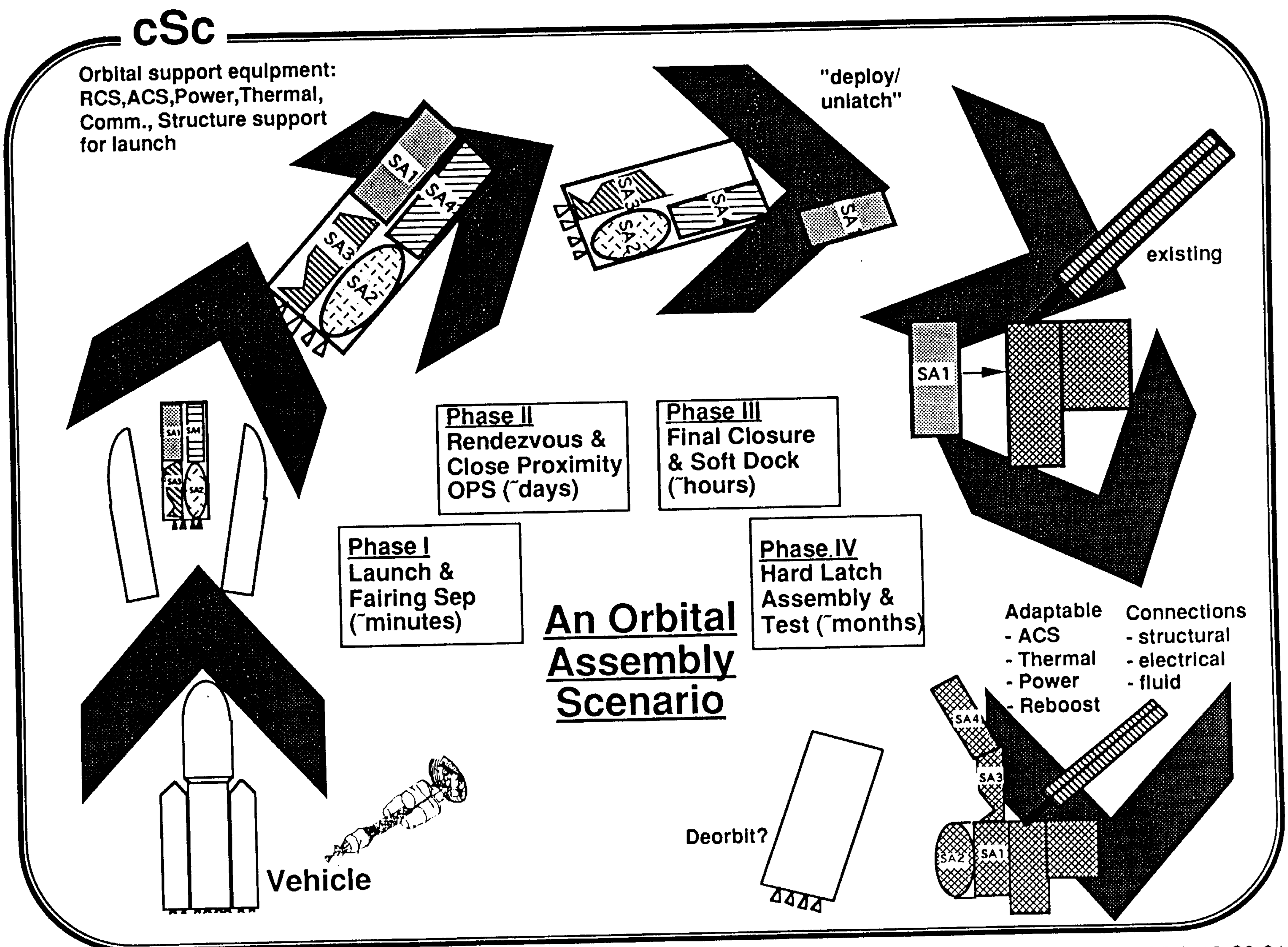
Center for Space Construction

Theory of Space Construction

System Model - 0.0 Level



An Orbital Assembly Scenario



Center for Space Construction

In-Space Construction Research (AY 1990-1991)

Introduction
- Theory of Space Construction
- A Systems Approach
- Develop Construction Model Theory of CAE/Constructability Tools

Logistics to LEO
- Launch-on-time- GWM, K.Nii (Compound Distribution)
- Vehicle Selection Model- GWM, A. Montoya
- Simulation Models- K. Chan, K .Nii
- System Study: Need HLLV- GWM

Interruptability
- NASA Requests , Early Work
- The General Model - (Network Theory + Stability Matrices) J. Wade, H. Sato, K. Chan (Ph. D Thesis)

DYCAM
- Early Definition- U. Racheli
- DYCAM 1.0 (IDEAS**2 + resource allocation)-H. Schroeder (Ph. D Thesis)

Orbital Assembly
- Problem Definition- S. Jolly, M. Loucks, GWM
- Simulation Model- M. D'Amara (Simulation + Monte Carlo)
- Rendezvous + Docking D. Mackison, K. Nii, D. Lawrence, GWM

Logistics to SEI Destinations
- Optimal Supply of GEOS- R. Coffey (Ph. D Thesis)
- Lunar/ Mars Cyclers C. Uphoff, M. Loucks

Joining, Test and NDE
- Joining- K. Nii, B. Nguyen
- Test and NDE- R. Nici

Center for Space Construction

On-Orbit Assembly

- Evaluation of Logistics Supply Needs
- Evaluation of Assembly Sites
- Evaluation of On-Orbit Assembly Operations
- Evaluation of On-Orbit Assembly Support Equipment Designs and Performances
- Evaluation of Space Transfer Vehicle Designs

A COST TRADE-OFF MODEL FOR ON-ORBIT ASSEMBLY LOGISTICS

George W. Morgenthaler

(11/23/91)

All is not well with SEI logistics

- Ability to deliver on-time constrains space construction — logistics trade-offs limit specialized construction equipment.
- Data analysis of US LEO launch capability shows:

— Reliability high; L.O.T. low; need L.O.T. improvement model
— Incapable of supporting existing missions plus SEI

$$\frac{\text{2,100,000 Lbs/yr to LEO for SEI}}{\text{50,000 Lbs/Shuttle launch}} = \text{42 Shuttle launches/yr}$$

— Need HLLV $$\frac{\text{2,100,000 Lbs/yr to LEO}}{\text{330,000 Lbs/HLLV launch}} = \text{6.4 HLLV launches/yr}$$

- Need HLLV Vehicle Requirements Model

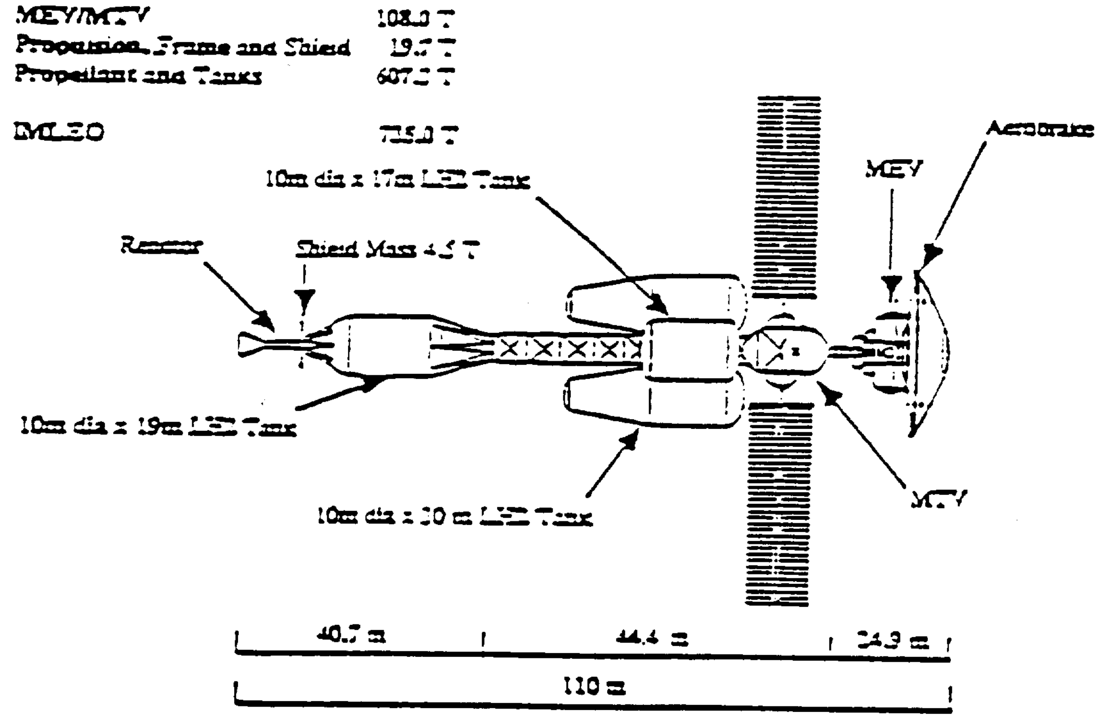


Figure 2-1 Reference Boeing NTR Vehicle

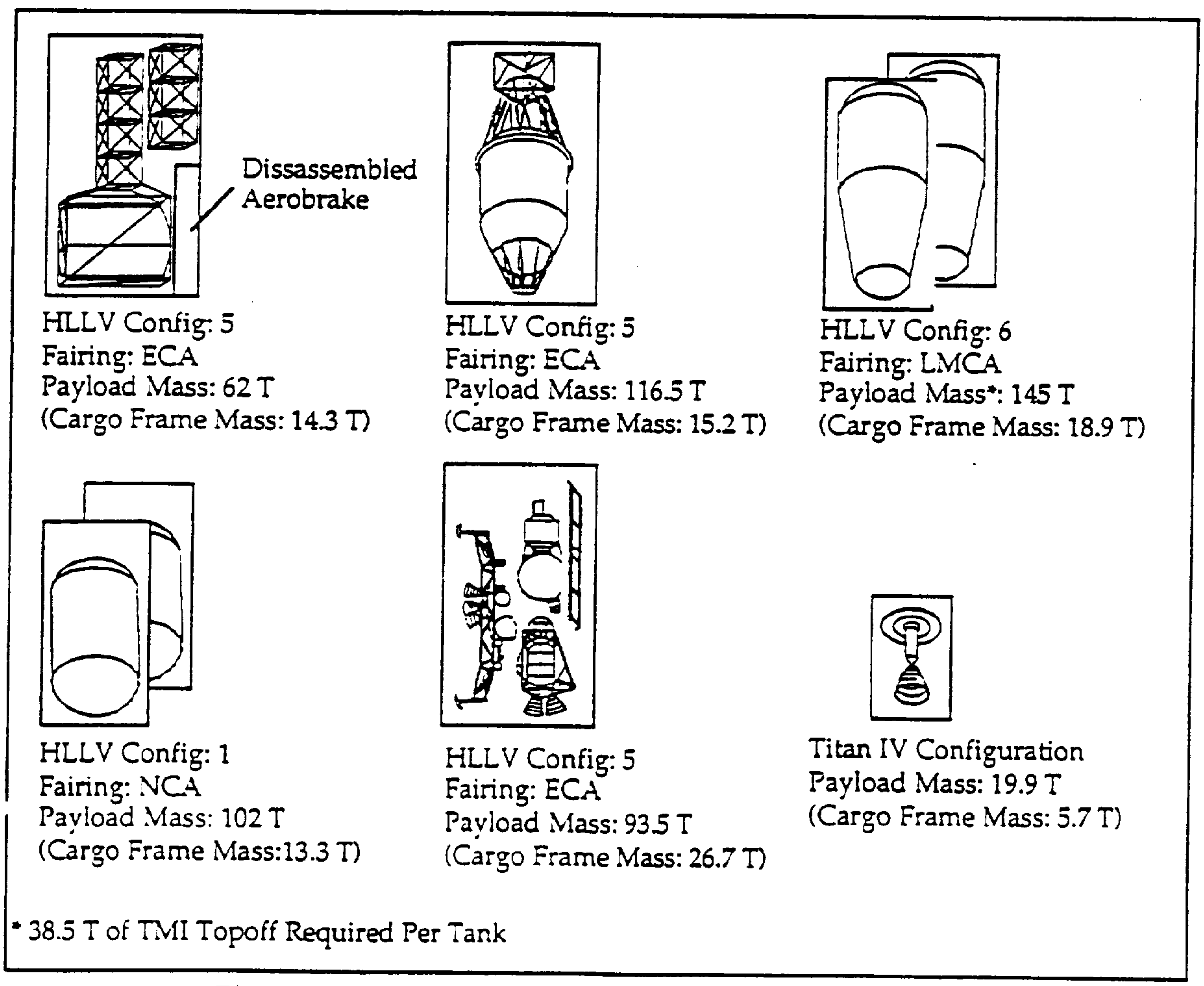


Figure 3-5 Initial HLLV Cargo Delivery Manifests

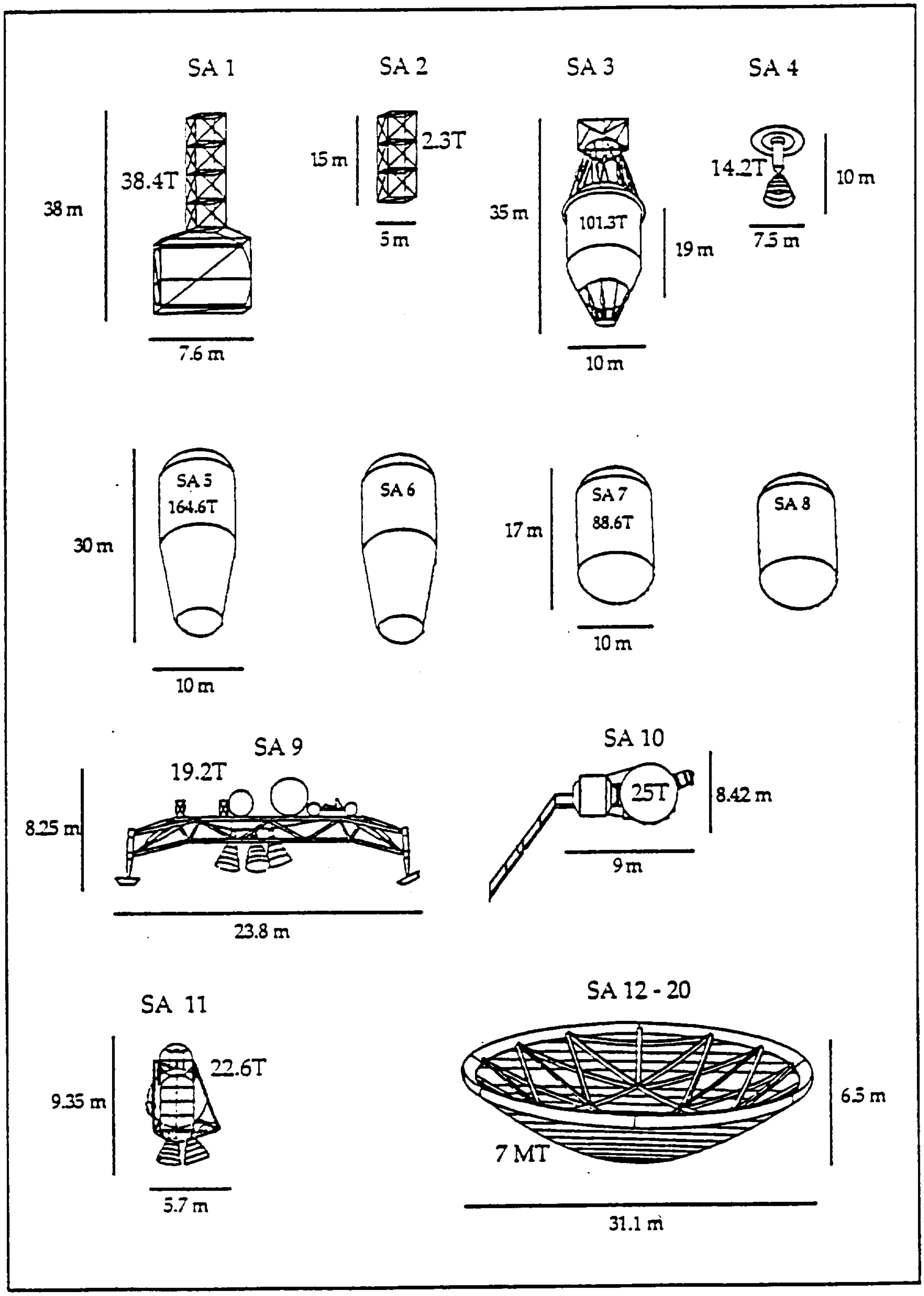


Figure 3-6 Subassemblies for Delivery to Low-Earth Orbit

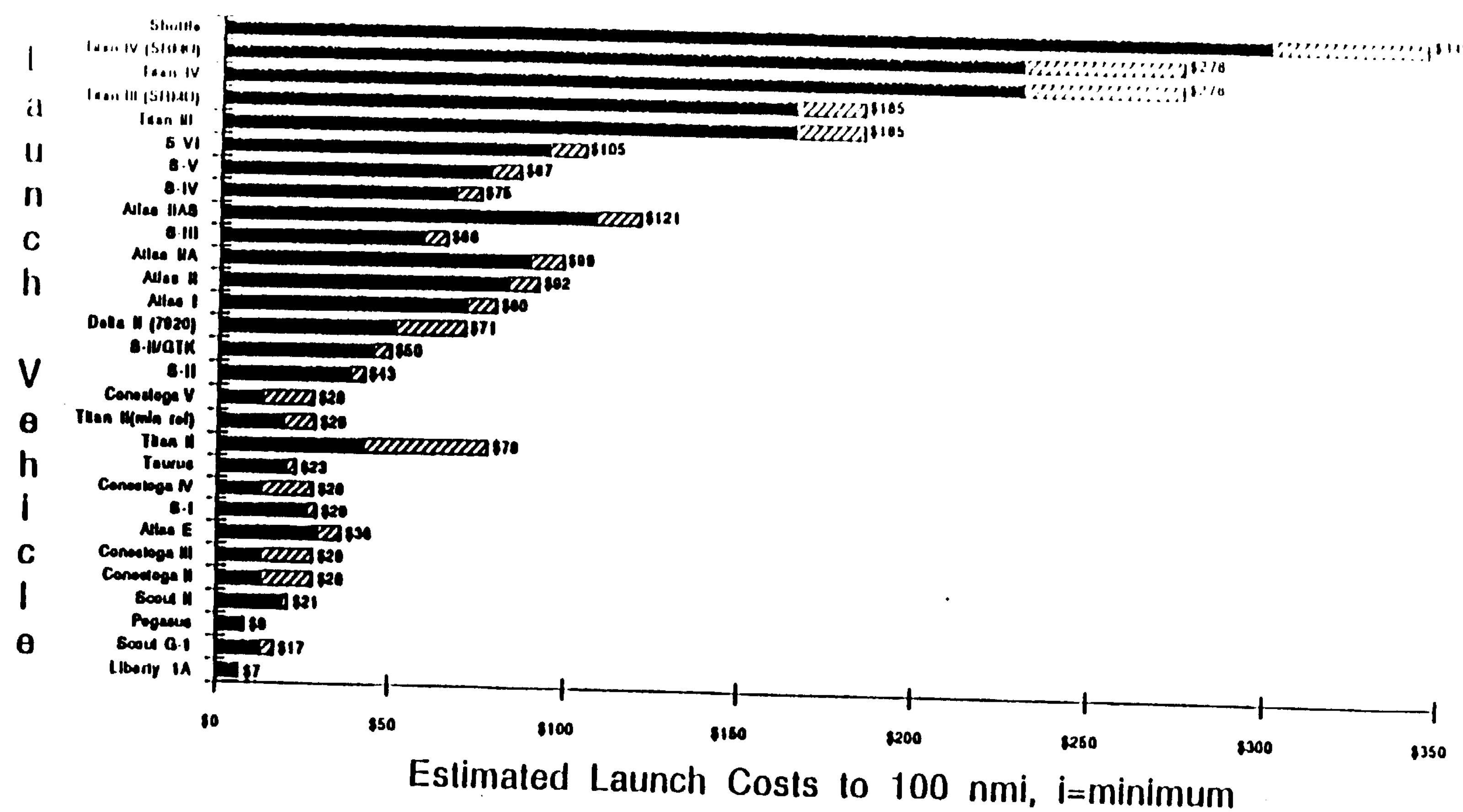
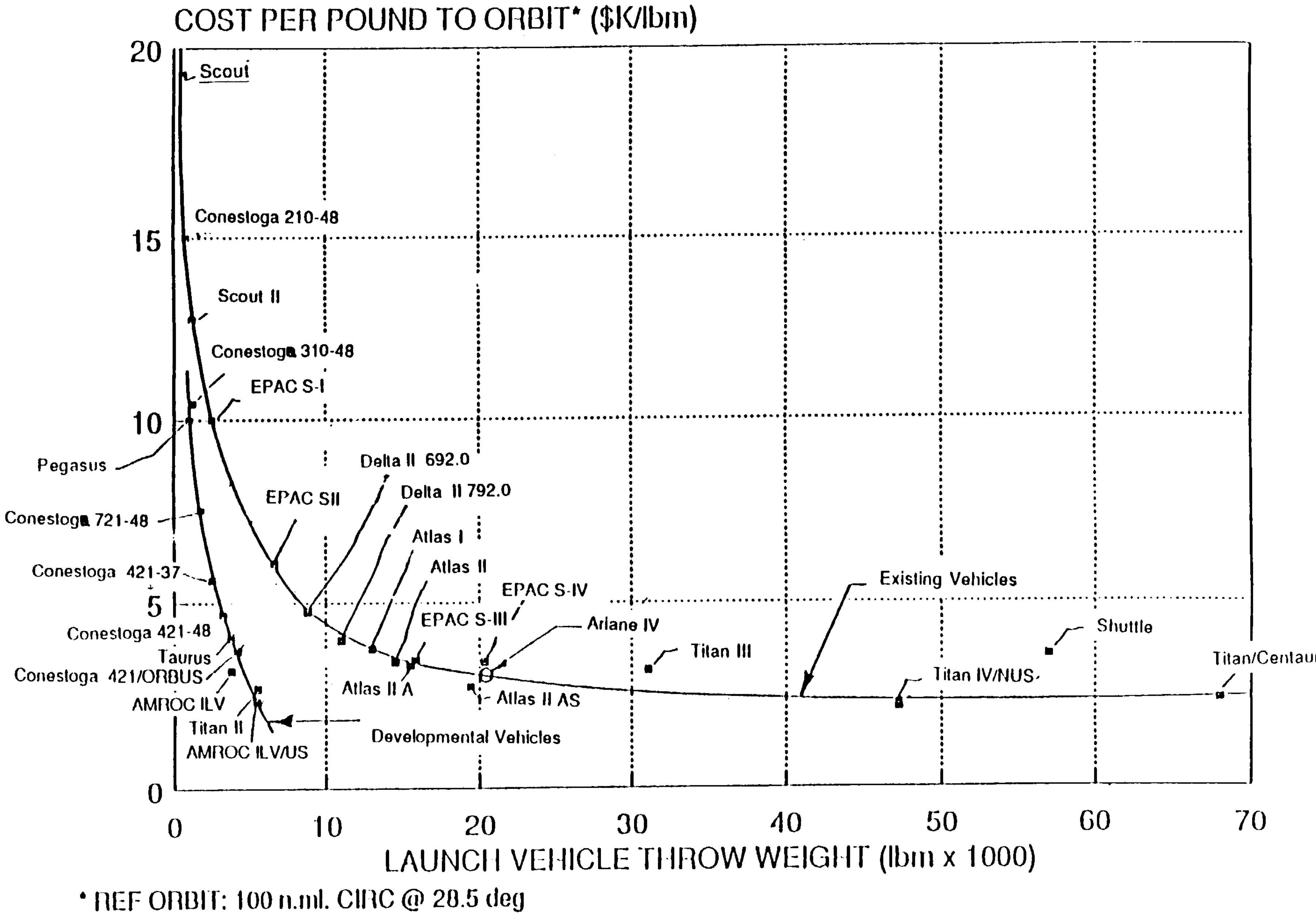


Figure 1 Launch Costs in Order of Performance (U.S. Launch Vehicles)

From Reference 10.

Figure 3

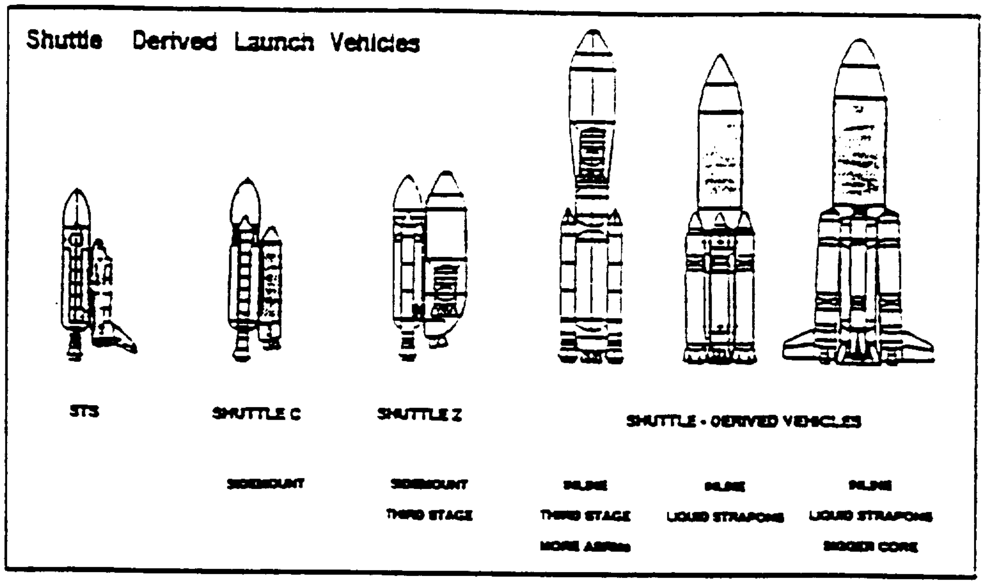
U.S. LAUNCH VEHICLES



From Reference 10.

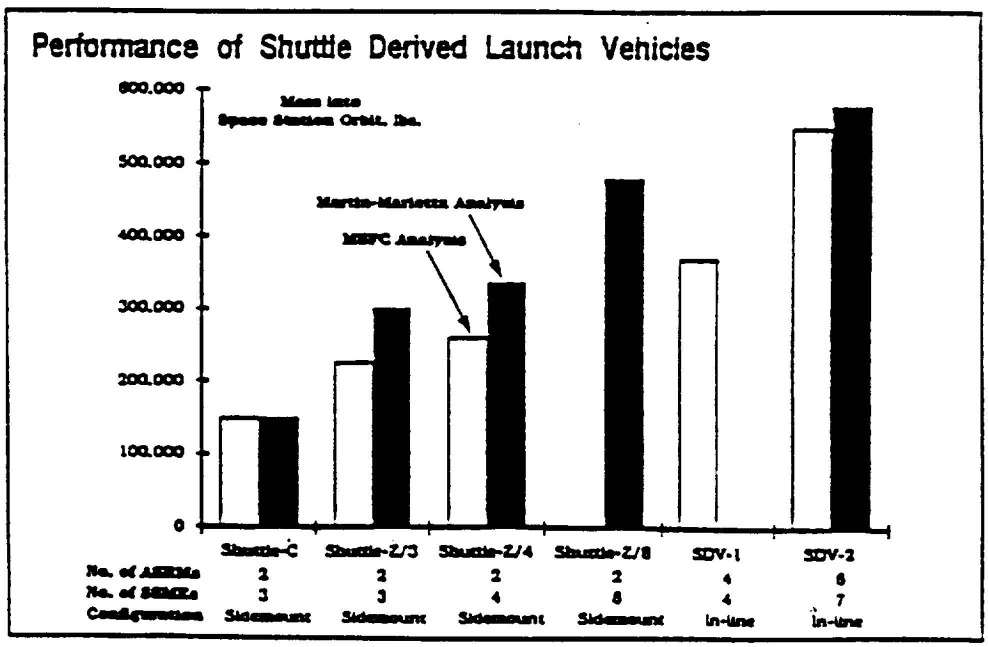
Shuttle C Performance

Figure 5



SPACEFLIGHT, Vol. 31, September 1989

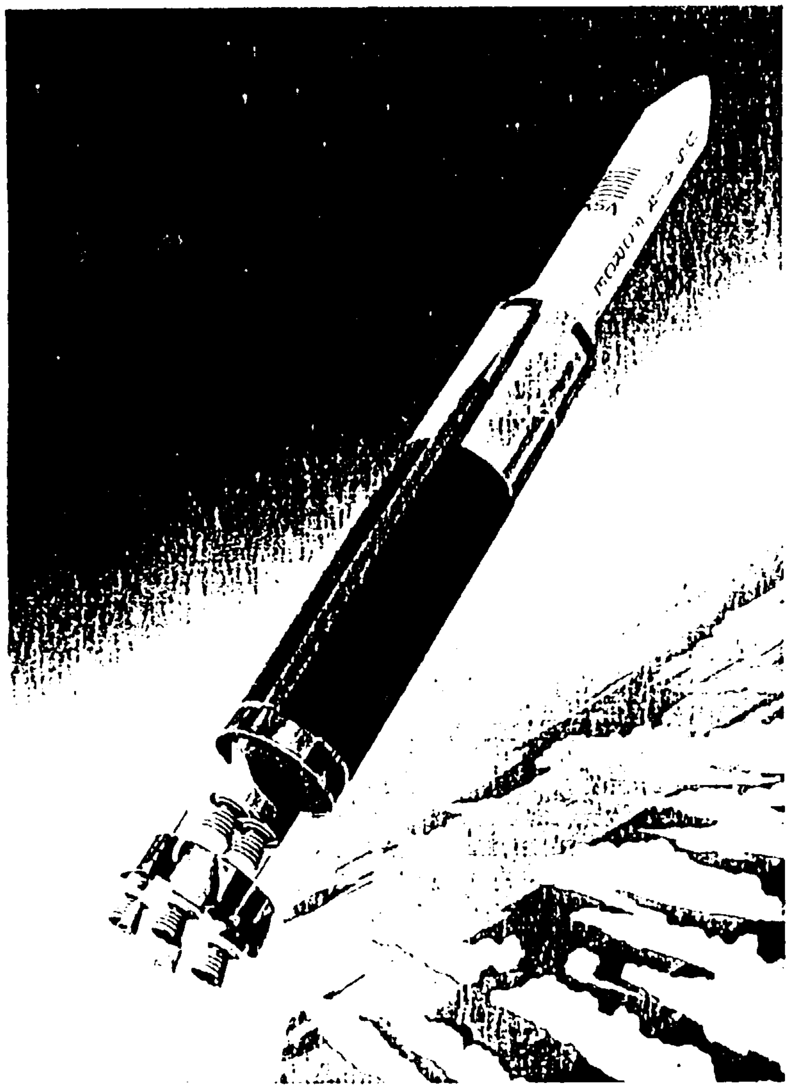
Figure 6

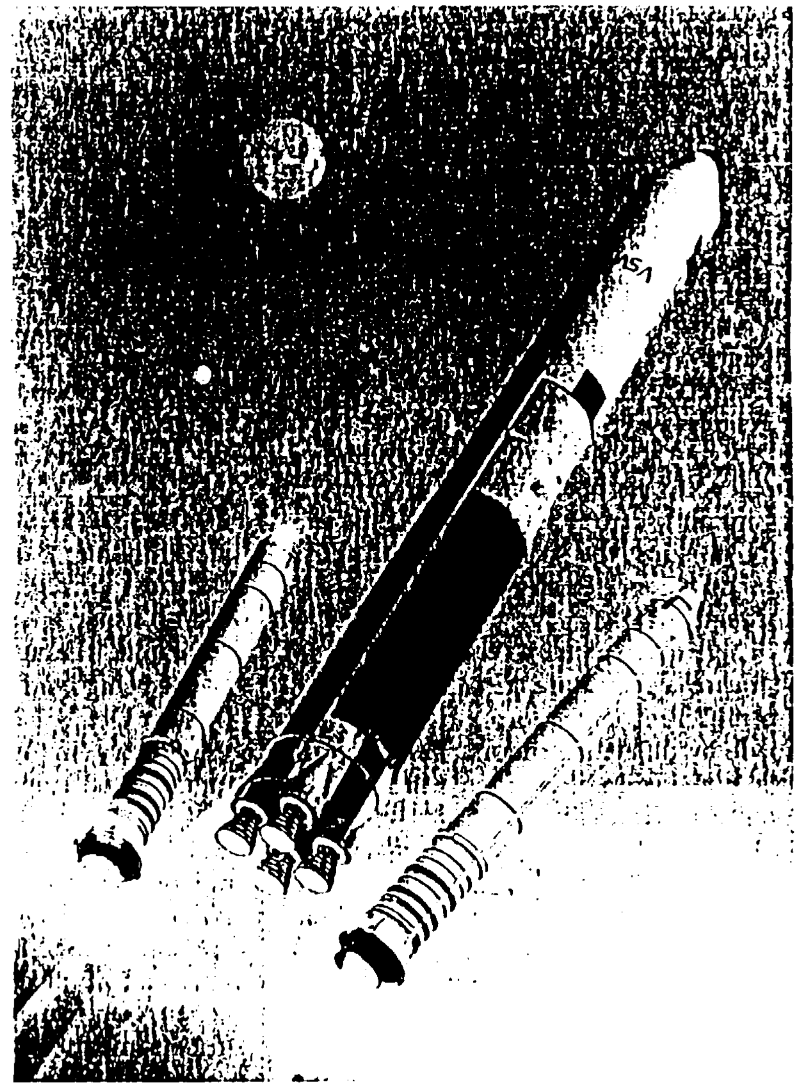


SPACEFLIGHT, Vol. 31, September 1989

From Reference 10.

NLS - SHUTTLE E.T. CORE





These are two configurations envisioned for the National Launch System that use the Martin Marietta space shuttle external tank as the vehicle core. Concept at left is of the One and One-Half Stage Vehicle and at right is the concept for the Heavy-Lift Launch Vehicle.

AVIATION WEEK & SPACE TECHNOLOGY/August 26, 1991

ORIGINAL PAGE IS
OF POOR QUALITY

Table 1. Vehicle Cost Performance (Thousands of 1990 dollars)

Vehicle	Cost (Millions)	Pounds to LEO	Kg to LEO	Cost/Kg (thousands)
Scout	17	574	261	65.13
Conestoga	28	1397	635	44.09
Scout II	21	1184	538	39.03
EPAC S-I	29	2499	1136	25.53
EPAC S-II	43	6600	3000	14.33
Delta II 6920	42	8700	3955	10.62
Delta II 7920	71	11086	5039	14.09
Atlas I	80	12980	5900	13.56
Atlas II	92	14916	6780	13.57
EPAC S-3	66	15862	7210	9.15
EPAC S-4	75	20328	9240	8.12
EPAC S-5	87	24640	11200	7.77
EPAC S-6	105	29920	13600	7.72
Atlas IIa	99	15664	7120	13.90
Atlas IIas	121	18942	8610	14.05
Ariane IV	65	20500	9318	6.98
Titan III	185	32432	14742	12.55
Titan IV	276	46900	21318	12.95
Shuttle C	240	150000	68182	3.52
Shuttle Z	343	250000	113636	3.02
Titan IV/Cent	276	68000	30909	8.93
Saturn V	600	308000	140000	4.29

Shuttle 1	345	54386	24721	13.96
Shuttle 2	200	54386	24721	8.09
Shuttle 3	345	303600	138000	2.50
Shuttle 4	200	303600	138000	1.45

Note: There are four Shuttle data entries here because the Shuttle is the only one of these launch vehicles whose payload compartment, the Orbiter, is recoverable and reusable. This makes it difficult to compare it with expendable launch vehicles. Saturn V data are from Ref. 11.

Shuttle 1 this is the data entry for the standard Shuttle from Ref. 10.

Shuttle 2 this entry shows a reduction of the cost of the Shuttle "launch vehicle" by an estimate of the cost of the Orbiter, which is assumed to be replaced by a fairing. The amortized cost used was the $4.1 billion Orbiter cost divided by a 28 launch utilization lifetime, i.e., approximately $145 million per launch, reducing the $345 million to $200 million per launch.

Shuttle 3 this entry keeps the $345 million cost per launch of the Shuttle but assumes that the Orbiter is replaced by a payload bay. The LEO delivery weight is thus (24,721 + 113,279) = 138,000 kg.

Shuttle 4 this entry shows a reduction of the per launch cost by $145 million and an increase of the payload delivered to LEO to 138,000 kg.

Figure 7 includes a "rectangle of uncertainty" with the Shuttle entries at the four corners.

Figure 7: Cost vs. Pounds to LEO (100 nmi @ 28.5 deg)

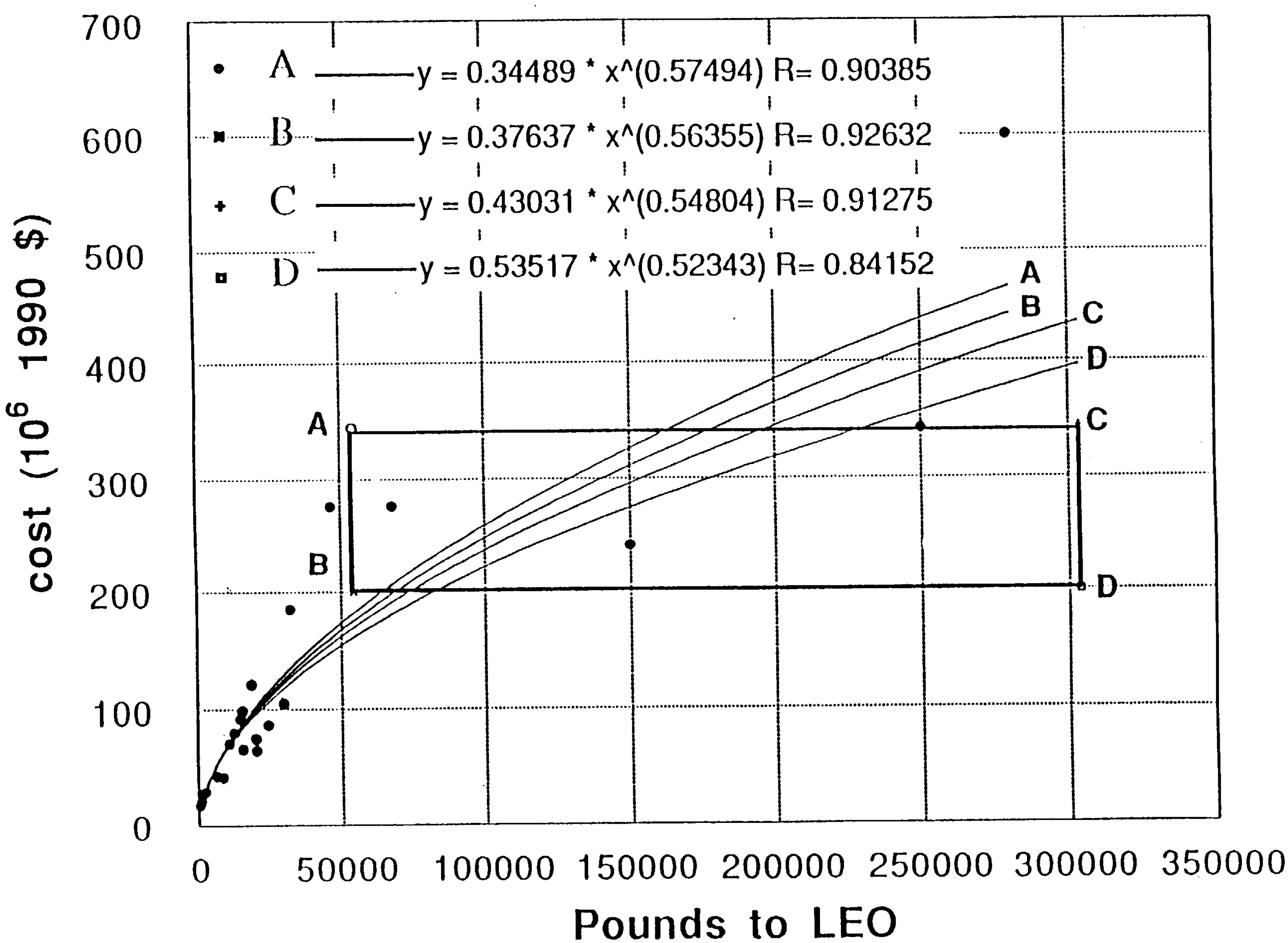


Figure 8: Cost/kg vs. kg to LEO

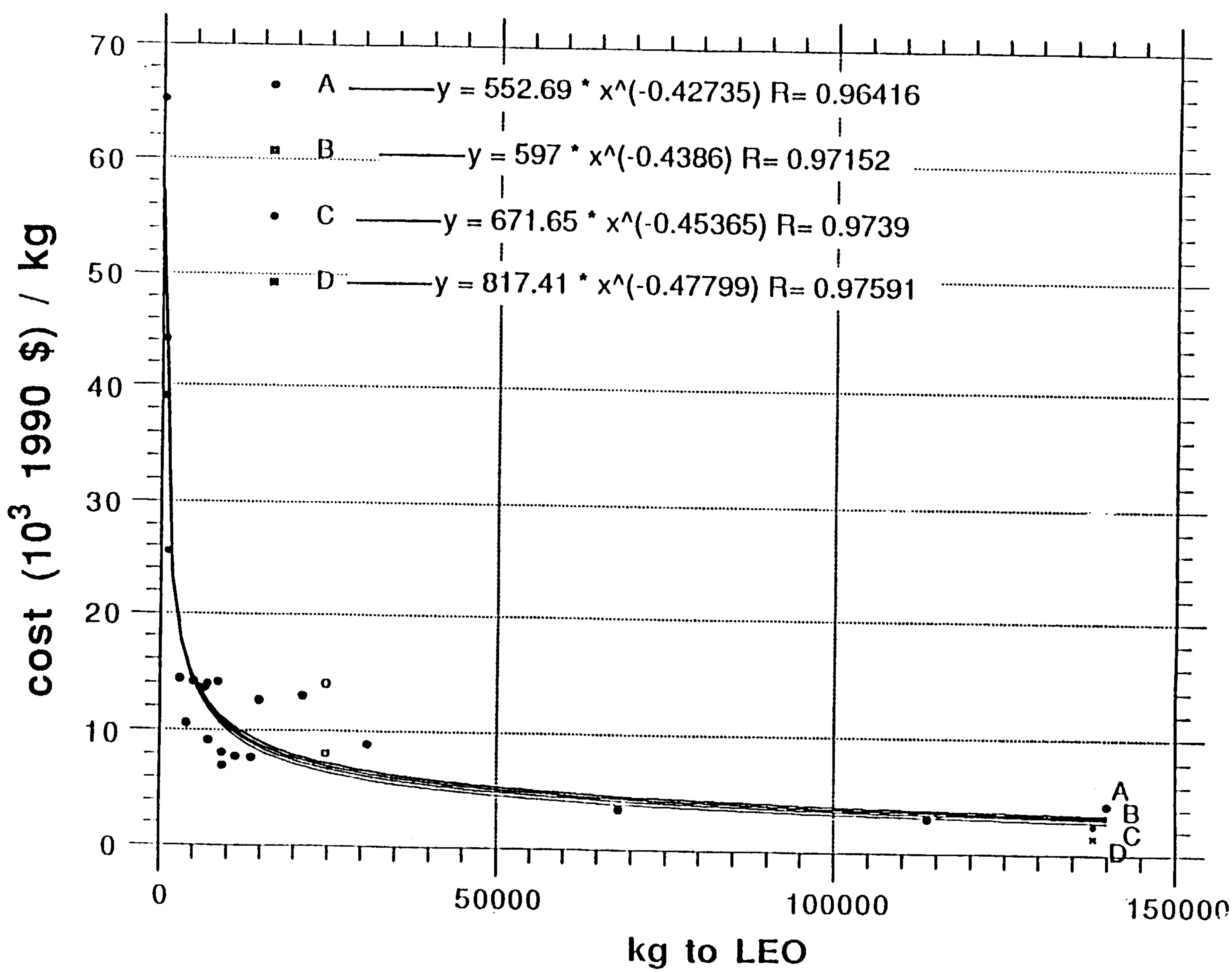
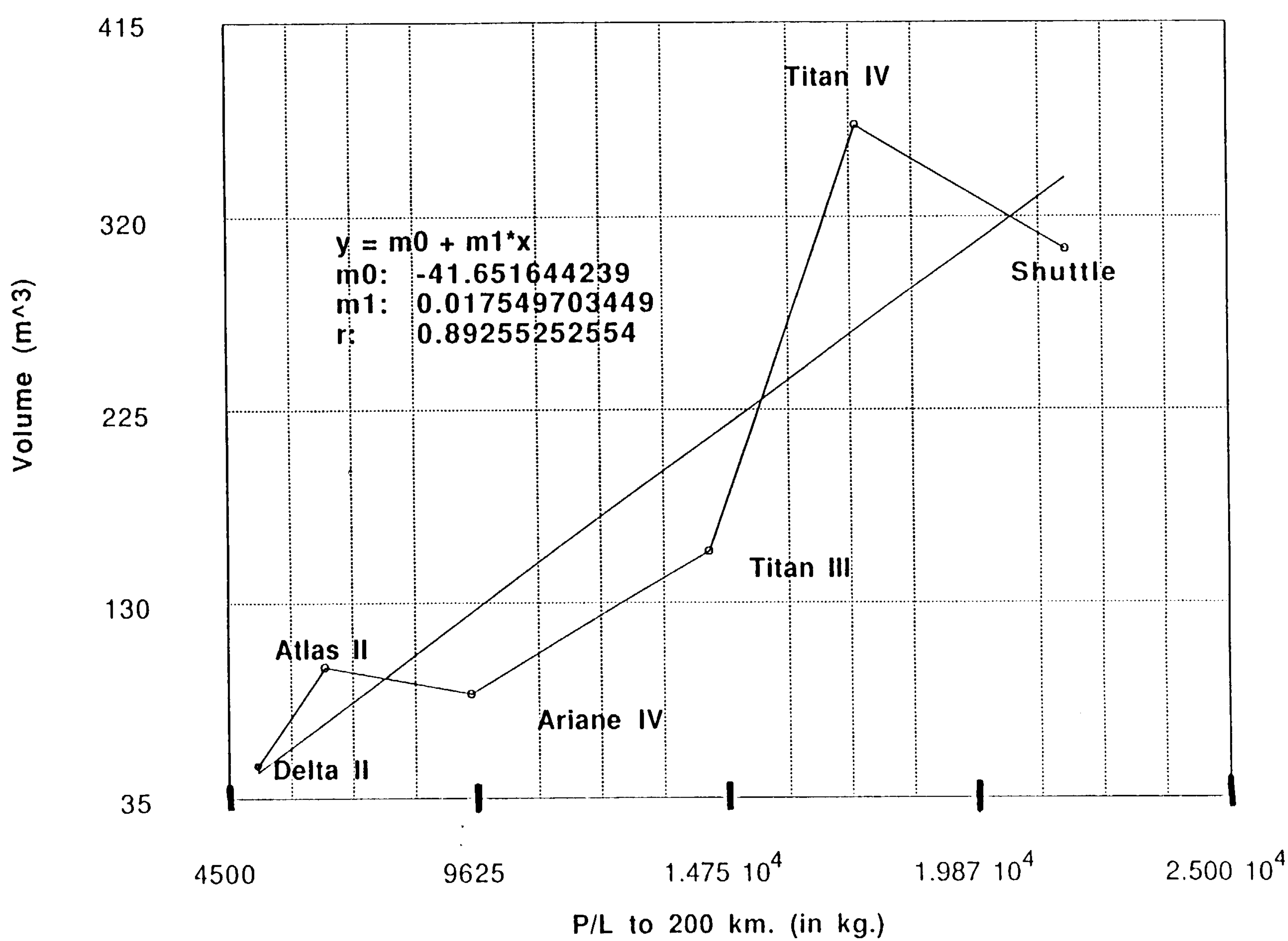


Figure 9: "Useful" Volume vs. Payload



NUMBER OF PAYLOADS NEEDED

$$N_L(w) = [W_o/w] + (1/2)\{1 + sgn(W_o/w - [W_o/w])\}\, sgn(W_o/w - [W_o/w])$$

$$N_V(w) = [V_o/V_H(w)] + (1/2)\{1 + sgn(V_o/V_H(w) - [V_o/V_H(w)])\} \times sgn(V_o/V_H(w) - [V_o/V_H(w)])$$

$$N(w) = Max\ \{N_L(w), N_V(w)\}$$

LAUNCH VEHICLE RELIABILITY

Then the probability of a successful launch to LEO, i.e. not more than h units out of n failing, is

(12) $$P_n(n-h) = \sum_{j=0}^{h} (n!/(n-j)!j!)p^{n-j}q^j,$$

If we let r be the conditional probability that an engine fails catastrophically, given that it fails, then

(13) $$q = qr + q(1-r),$$

where q(1-r) = probability of that an engine fails, but not catastrophically.

Hence,

(14)
$$P_n(n) = p^n q^0 (1-r)^0 = p^n$$
$$P_n(n-1) = np^{n-1}q(1-r) + p^n$$
$$P_n(n-2) = (n(n-1)/2)p^{n-2}q^2(1-r)^2 + np^{n-1}q(1-r) + p^n.$$

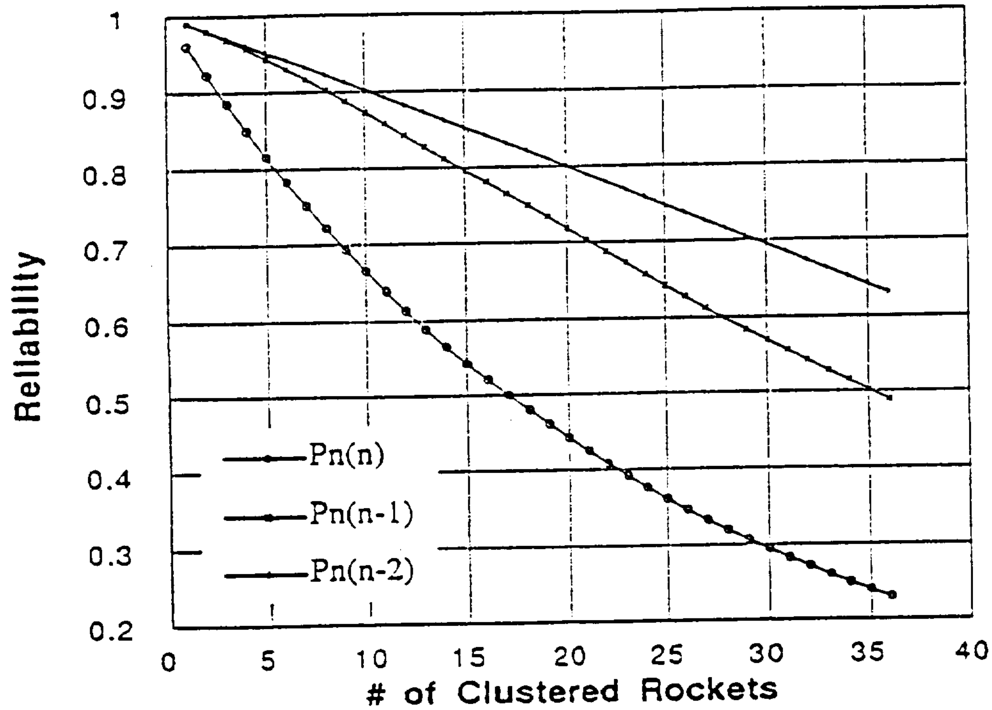


Figure 10. Launch Vehicle Reliability as a Function of Clustered Rockets
($p = 0.96$, $r = 0.25$)

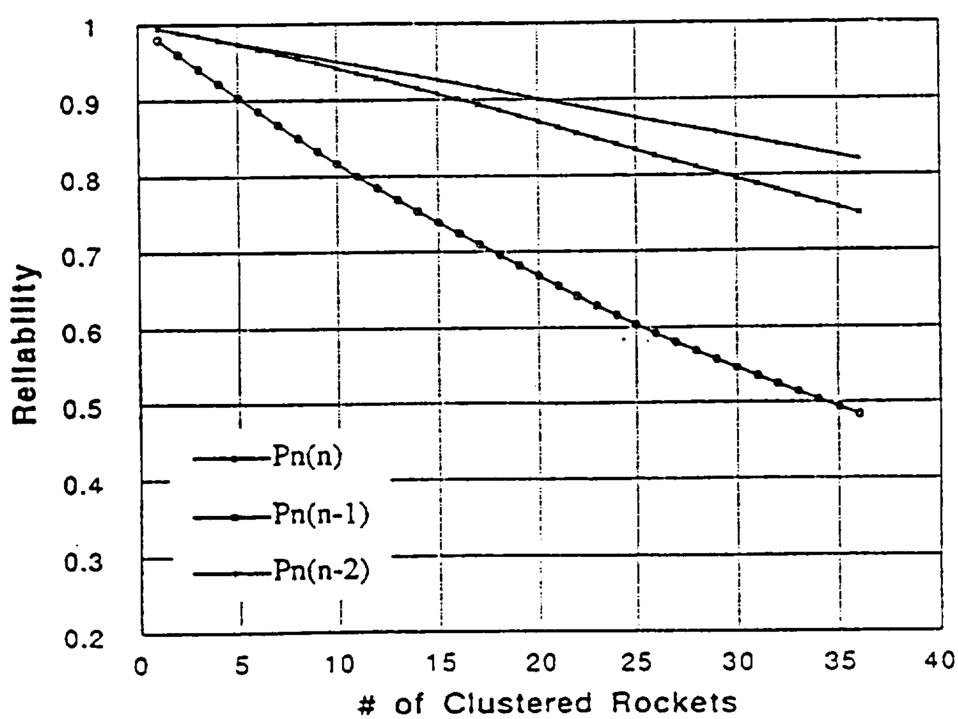


Figure 11. Launch Vehicle Reliability as a Function of Clustered Rockets
($p = 0.98$, $r = 0.25$)

MAKING THE LAUNCH WINDOW?

If $N = N(w)$ payload deliveries are needed to assemble the spacecraft and if time for up to j additional launches is included in the schedule to compensate for up to (j - 1) launch failures, then, assuming no political launch hiatus after any failure,

$$p^* = P\begin{bmatrix}\text{make launch window}\\ \text{in } j \text{ extra launches}\end{bmatrix} = p^N + C_1^N p^N q + C_2^{N+1} p^N q^2 + \ldots + C_j^{N+j-1} p^N q^j$$

where

$$C_i^{N+i-1} p^N q^i = \frac{(N+i-1)(N+i-2)\ldots(N)}{i!} p^N q^i$$

is the negative binomial density which gives the probability that the Nth success is achieved precisely at the $(N + i)$th launch.

LIMITATIONS ON HLLV SIZE

1. Limitations on the usable size and shape of payload bays and the limited deployability of space structures;
2. Limitations on the size of propellant tankage domes (currently around 10 to 15 meters in diameter) that can be built with current methods of metal forming, spinning, welding, etc;
3. Limitations on the size of loads that can be transported by air, rail, truck, and barge;
4. Limitations on the size of facilities and handling ability of cranes, transports, and "strongbacks" at launch sites;
5. Limitations on the safety considerations for handling and launching very large quantities of cryogenic or hypergolic propellants, particularly with respect to the population living in the local abort zone;
6. Limitations on the reliability of HLLVs that are made of a large number of clustered tanks;
7. Limitations of cost and risk in concentrating too many resources in a single launch of the HLLV.

ORBITAL ASSEMBLY EXPECTED COST MODEL

(15)

$$C(w) = [\text{Expected Cost}] = \overbrace{N(w)C_H(w)/P_H(w)}^{\text{HLLV Costs}} + \overbrace{(SC)_\$ + (SC)_\$/N(w)\left\{N(w)/P_H(w) - N(w)\right\}}^{\text{Spacecraft Costs}}$$

$$+ \overbrace{(N(w)-1)(k)(C_{\$c})}^{\text{Connection Costs}} + \overbrace{(N(w)-1)(C_s/P_s)}^{\text{Crew Transport Costs}} + \overbrace{(N(w)-1)C_{\$D}}^{\text{Docking Costs}} + \overbrace{\left\{1 + [N(w)/15]\right\}C_{\$F}}^{\text{Facility Costs}}$$

(18) $C^*(w)$ = {Expected cost including probability of missing one launch window}

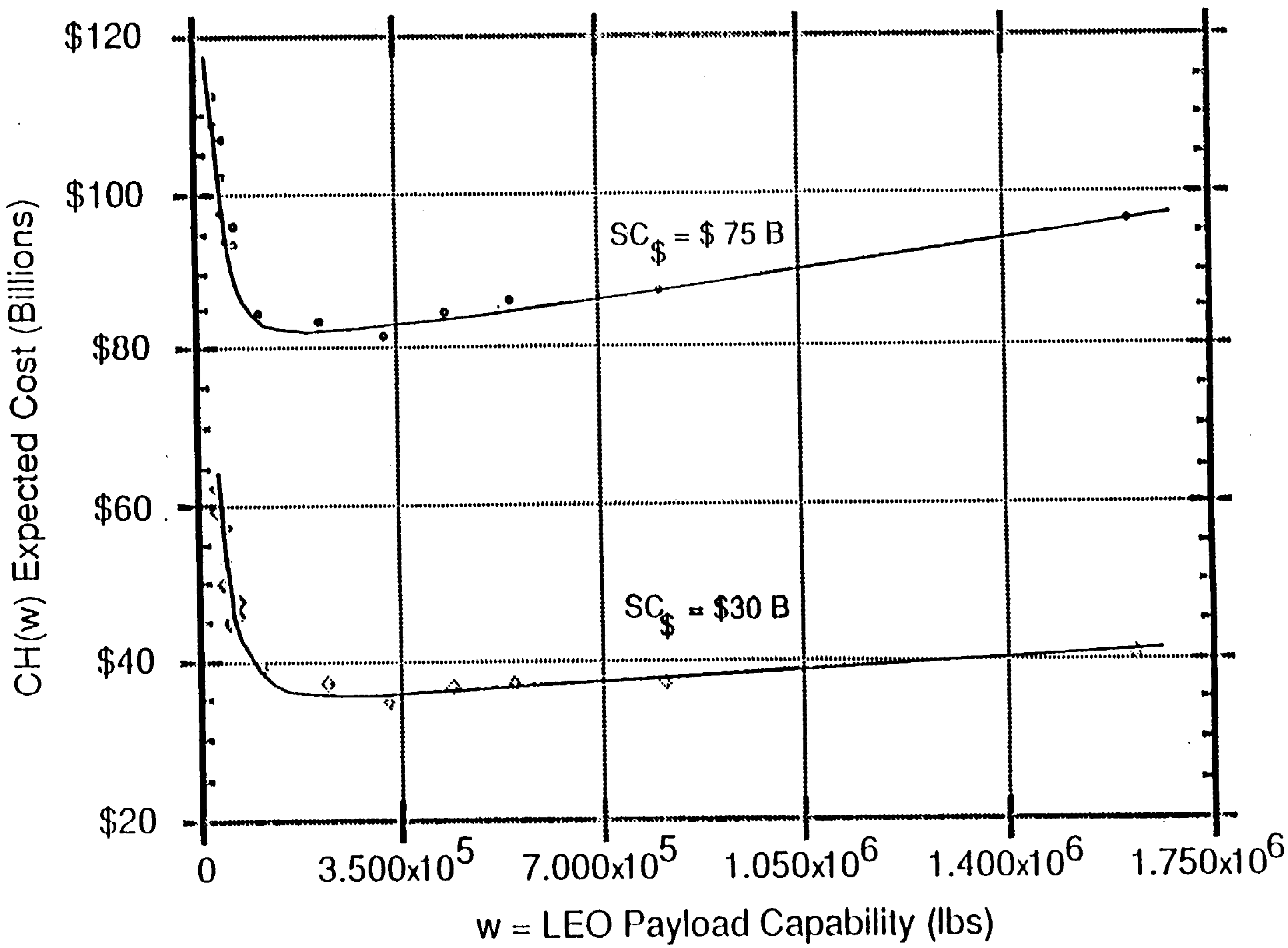
$$= C(w)\,[\,1 + (1 - P^*)R\,],$$

where C(w) is found in (15).

Table V: Parameter Values Used with Equations (15) and (18) for Figure 14.

HLLV Payload (lbs.)	h	N(w)	# Cluster	PII(w)	k	C$c	Ps	Cs ($10^6)	C$D ($10^6)	FII(w) ($10^9)	# Bases	P*	R	C*(w) calc ($10^9)	CII(w) list ($10^6)	C* list ($10^9)
$75 BILLION CASE																
1620000	2	1	36	0.82	100	0		0	0	2	1	.9676	0.5	96.3		
810000	2	2	18	0.91	100	100000	0.98	170	10	2	1	.9771	0.5	87.2		
550000	2	3	14	0.93	100	100000	0.98	170	10	2	1	.9733	0.5	86.1		
440000	2	4	10	0.95	100	100000	0.98	170	10	2	1	.9774	0.5	84.7		
330000	1	5	6	0.97	100	100000	0.98	170	10	2	1	.9875	0.5	82.9		
220000	1	8	5	0.98	100	100000	0.98	170	10	2	1	.9869	0.5	83.4		
110000	1	15	3	0.99	100	100000	0.98	170	10	2	1	.9891	0.5	84.7		
68000 Titan IV/Cent		24		0.98	100	100000	0.98	170	10	2	2	.9114	0.5	93.6	276	95.8
55000 Shuttle		30		0.98	100	100000	0.98	170	10	2	3	.8723	0.5	93.9	345	99.6
46900 Titan IV		35		0.98	100	100000	0.98	170	10	2	3	.8382	0.5	102.3	270	107
32432 Titan III		50		0.98	100	100000	0.98	170	10	2	4	.8220		109	185	112.2
$30 BILLION CASE																
1620000	2	1	36	0.82	100	0		0	0	2	1	.9676	0.5	96.3		
810000	2	2	18	0.91	100	100000	0.98	170	10	2	1	.9771	0.5	37.2		
550000	2	3	14	0.93	100	100000	0.98	170	10	2	1	.9733	0.5	37		
440000	2	4	10	0.95	100	100000	0.98	170	10	2	1	.9774	0.5	36.8		
330000	1	5	6	0.97	100	100000	0.98	170	10	2	1	.9875	0.5	36.3		
220000	1	8	5	0.98	100	100000	0.98	170	10	2	1	.9869	0.5	37.1		
110000	1	15	3	0.99	100	100000	0.98	170	10	2	1	.9891	0.5	38.9		
68000 Titan IV/Cent		24		0.98	100	100000	0.98	170	10	2	2	.9114	0.5	45.7	276	47.8
55000 Shuttle		30		0.98	100	100000	0.98	170	10	2	3	.8728	0.5	45.1	345	50.8
46900 Titan IV		35		0.98	100	100000	0.98	170	10	2	3	.8382	0.5	52.7	276	57.3
32432 Titan III		50		0.98				170	10	2	4	.8220	0.5	59.3	185	62.4

Figure 14: Total Expected Cost vs. LEO Payload Capability



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Expert Systems for Assembly Sequence Evaluation

Steve Jolly

Third Annual Symposium
November 21 & 22, 1991

EXPERT SYSTEMS FOR ASSEMBLY SEQUENCE EVALUATION

PRESENTATION FOCUS:

- ❑ RESEARCH GOALS
- ❑ METHODOLOGIES
- ❑ RESULTS
- ❑ CONCLUSIONS & PLANS

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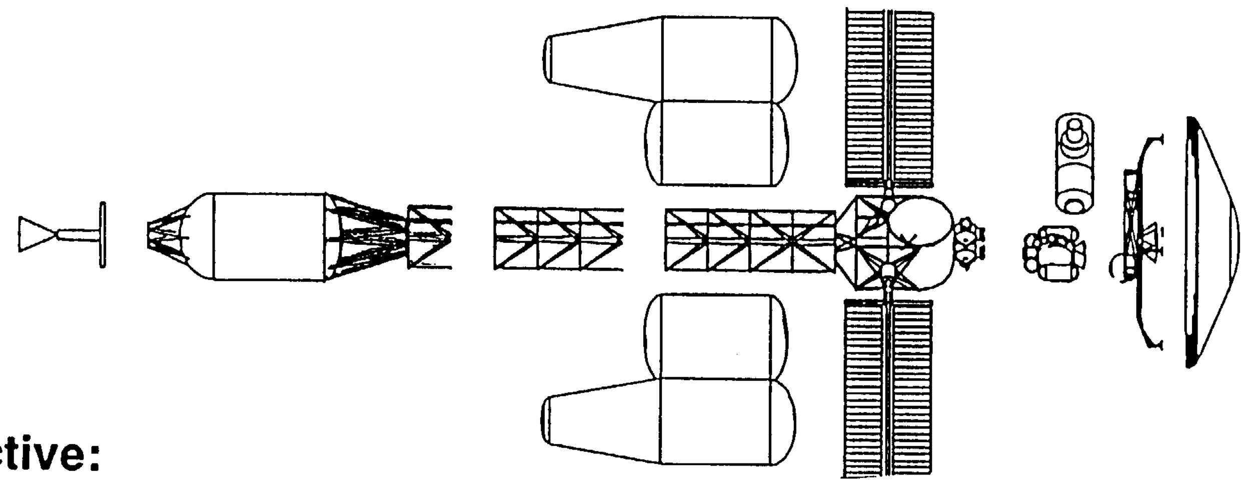
RESEARCH GOALS

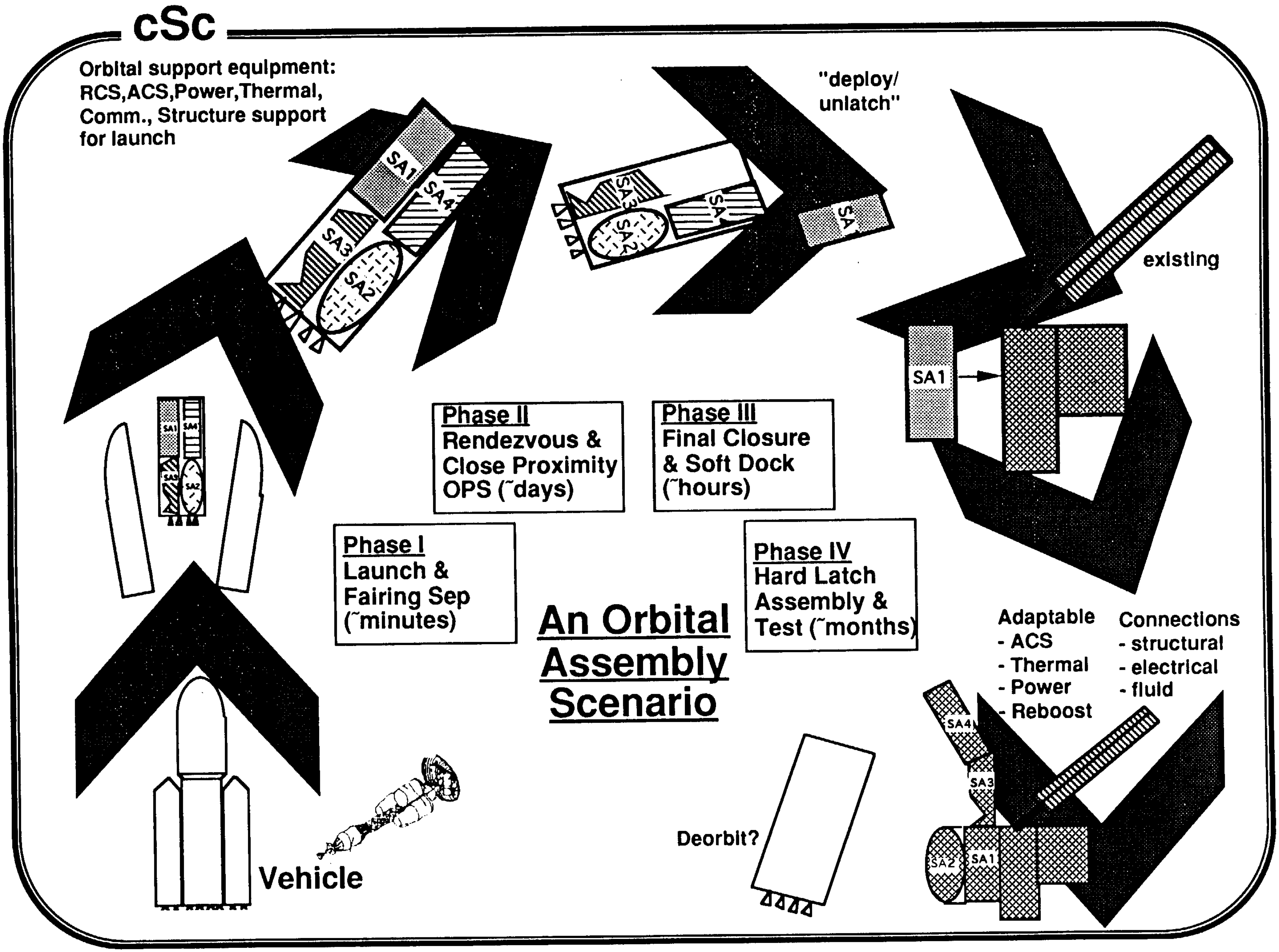


Objective:

Identify delivered orbital subassemblies derived from a Phase A conceptual space vehicle design while minimizing on-orbit assembly complexity.

Primary Constraints:

- ❑ Payload Shroud mass and volume (allowing for rendezvous stage)
- ❑ Geometric Feasibility
- ❑ Connection-technology Limitation
- ❑ Tool Performance Limitations
- ❑ Minimal Crew Hazard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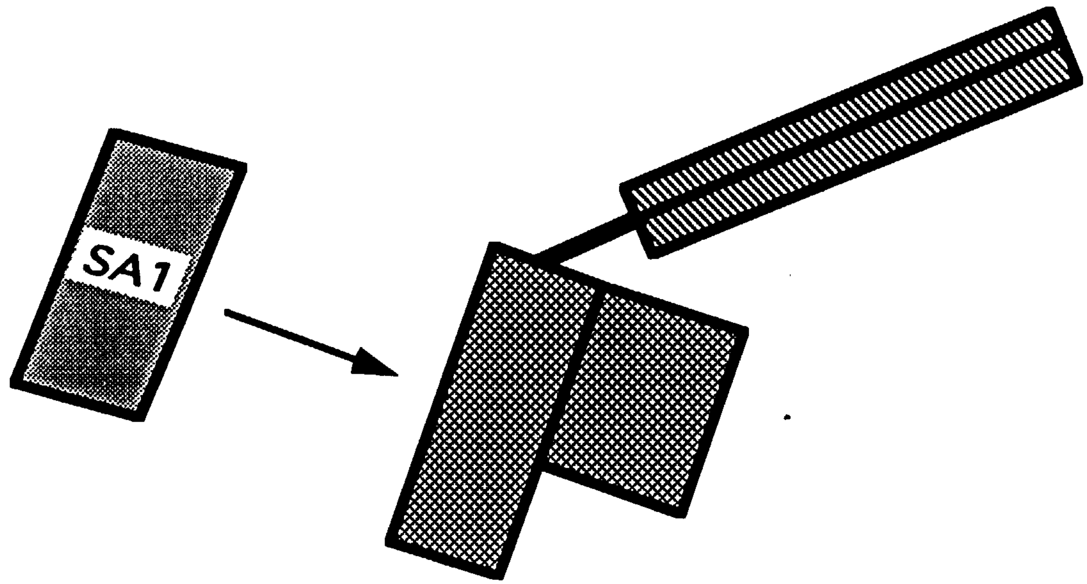
Orbital support equipment: RCS,ACS,Power,Thermal, Comm., Structure support for launch
"deploy/ unlatch"
existing
SA1
SA2
SA3
SA4
Phase I
Launch & Fairing Sep (~minutes)
Phase II
Rendezvous & Close Proximity OPS (~days)
Phase III
Final Closure & Soft Dock (~hours)
Phase IV
Hard Latch Assembly & Test (~months)
An Orbital Assembly Scenario
Adaptable
- ACS
- Thermal
- Power
- Reboost
Connections
- structural
- electrical
- fluid
Deorbit?
Vehicle

SUBASSEMBLIES

Attributes

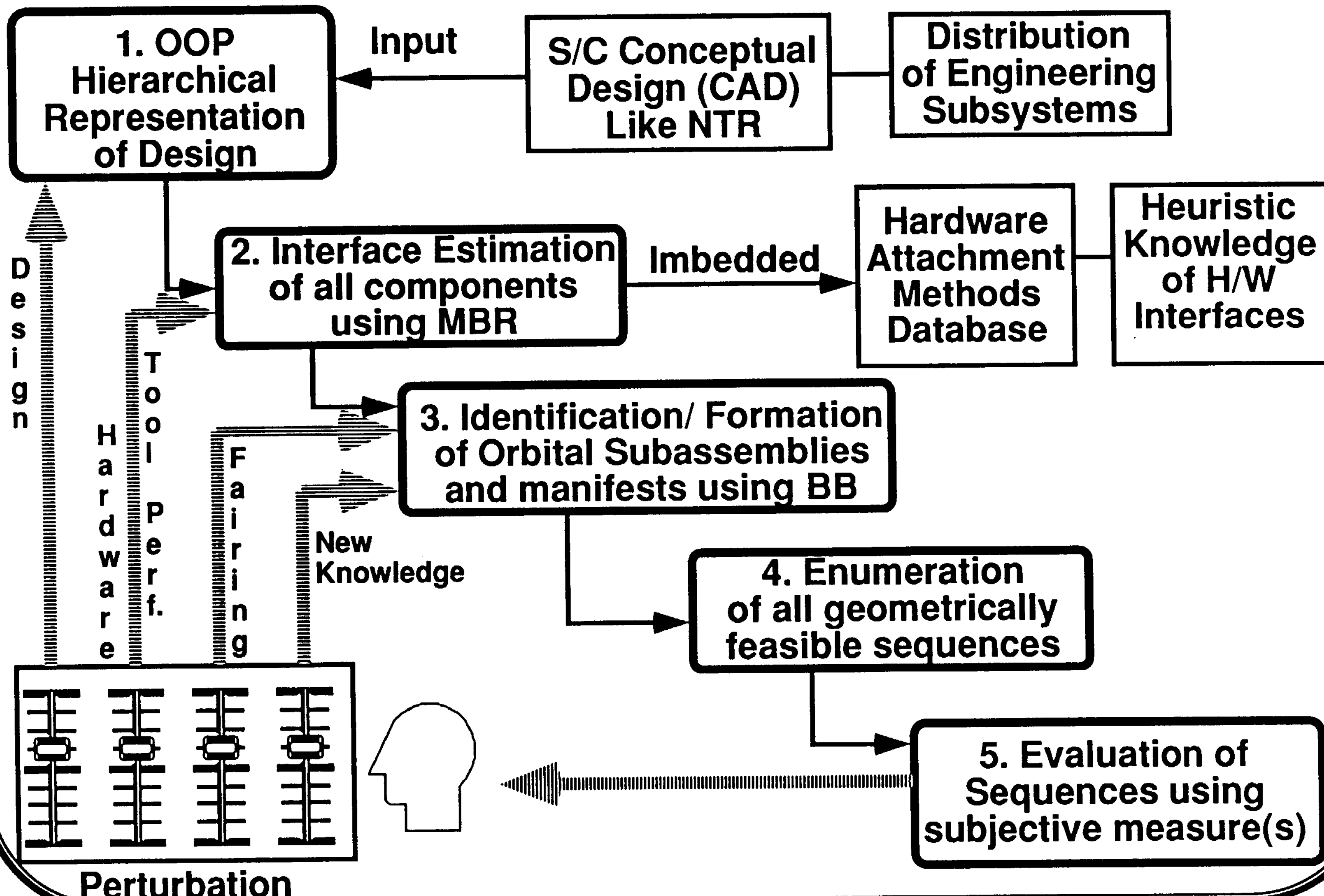
- Geometric Characteristics
- Special Hazards
- Inertial Properties
- Control Response
- Engineering Subsystems
- External Interfaces



A Beginning Taxonomy of Subassemblies:

Tanks	Crew
Partial Spacecraft	Avionics
Complete Spacecraft	Propulsion
Structural	Power

SUBASSEMBLY IDENTIFICATION SIMULATION MODEL



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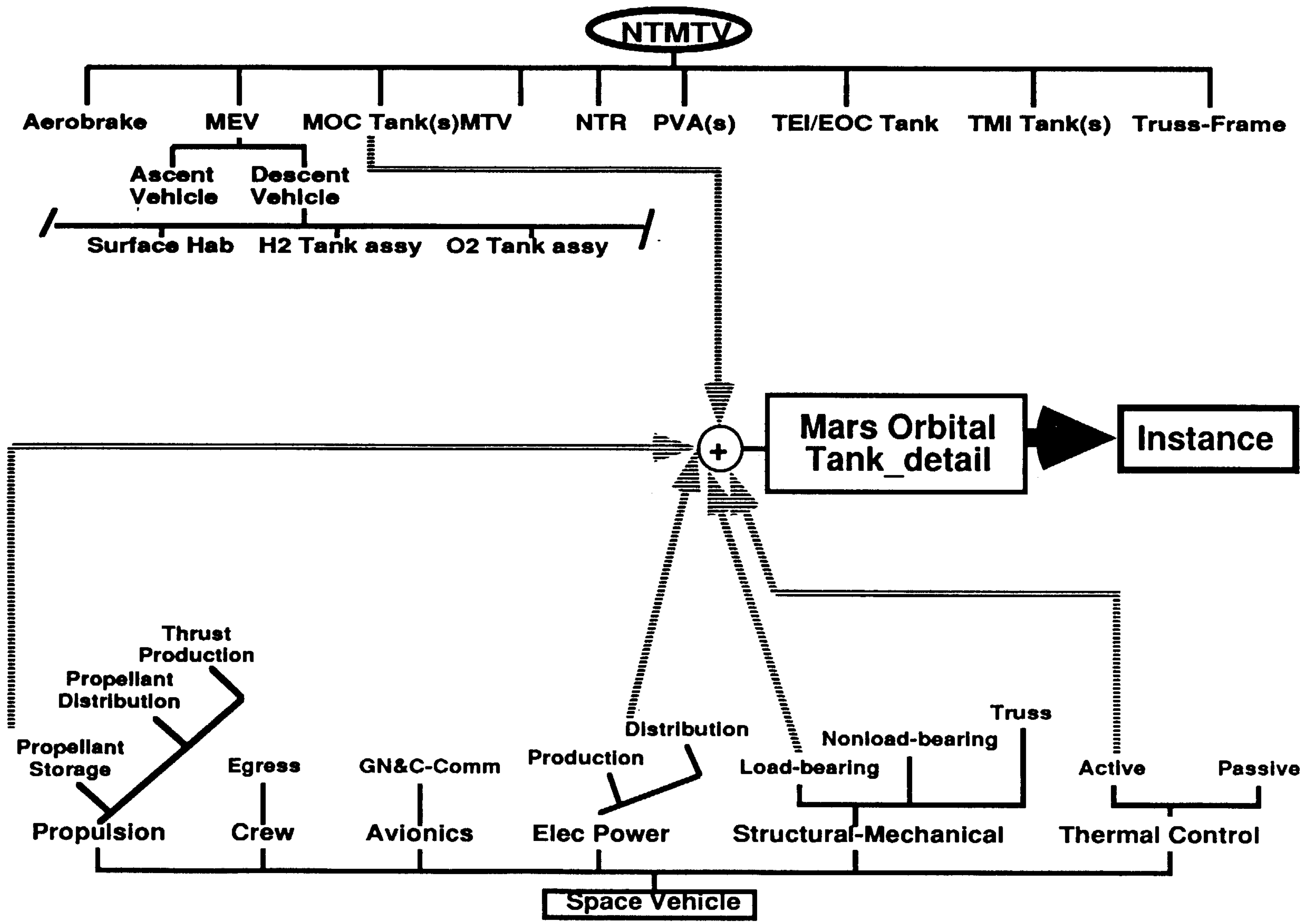
ESTIMATING SUBASSEMBLY INTERFACES BY ENGINEERING FUNCTIONAL ALLOCATION USING MBR



REPRESENTATIVE DATA BASE OF INTERFACE CONNECTIONS

- Should reflect current Aerospace Industry practice, but can be upgraded for in-space construction connection technologies
- Each type of attachment method has codes which indicate the capabilities and constraints of such method
- A representative normalized "index" of connection difficulty has been ascribed using MIL-Std Handbook-472 (Maintainability) TER's and MDSSC inspection and testing company standards, as penalties
- Data base is not yet rigorous, nor has it been modified for in-space construction, but it is a starting point
- Desperately need data on human EVA interface connection primitives

Cleanliness Codes:
L- LOX Clean
F- Fuel Clean
E- Electrical Clean
H- Hydraulic Clean
B- Biologically Clean

Insp/ Ver Codes:
V- Visual
M- Mechanical
L- Leak Check
E- Electrical
A- Automatic
X- X-ray
U- Ultrasonic

Process Physics Codes:
T- Thermal Producing
O- Outgassing
C- Caustic/contaminating solvents
E- Electromagnetic Interference
V- Vibration/shock
S- Electrostatic
D- Debris/projectile

Temporal Codes:
I- Instantaneous
F- Fast setting, < 1 minute
M- Medium setting, < 30 minutes
S- Slow setting, > 30 minutes

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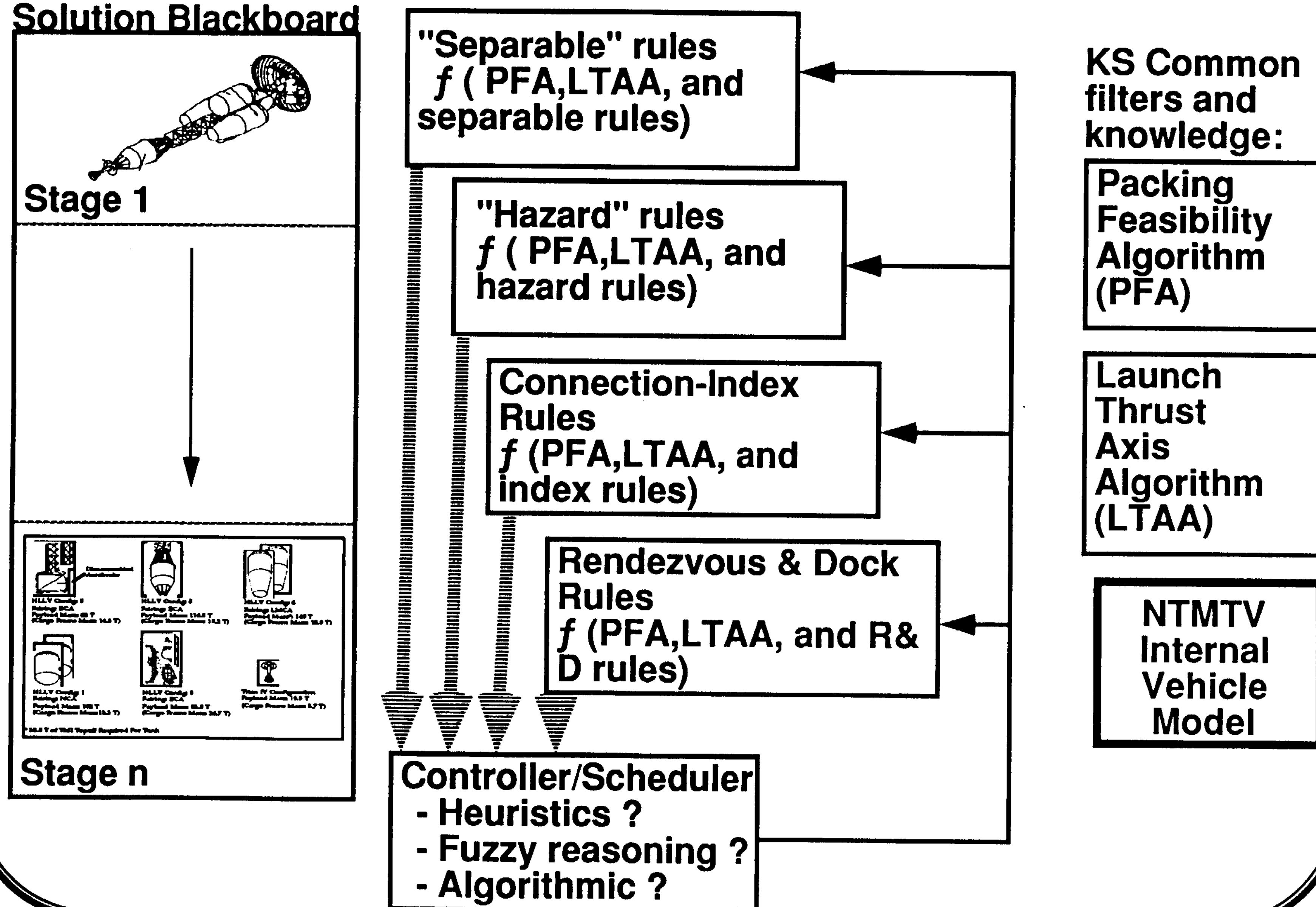
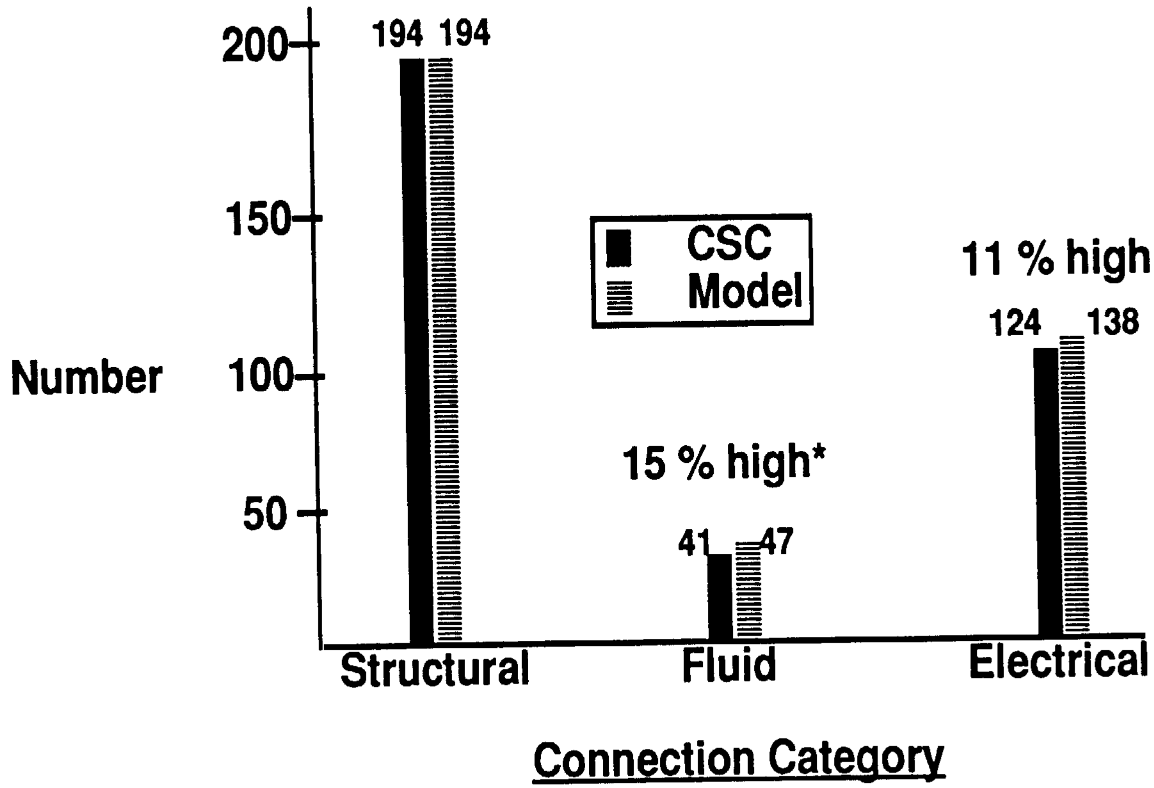
VEHICLE DECOMPOSITION MODEL



CONNECTION INTERFACE ESTIMATION MODEL RESULTS



Mars Vehicle Interface Estimation Results, Model vs. CSC study

Total Connections (10 Subassemblies, Boeing NTR-2016) = 379

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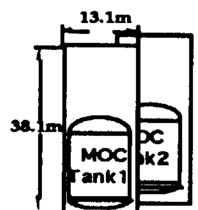
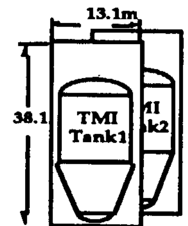
KNOWLEDGE-SOURCE 1 AND 2 RESULTS

KS1



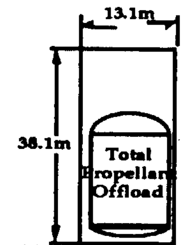
Subassembly mass = 88.59 metric tons
Mass efficiency = 69.76 %
Volumetric efficiency = 26 %

+



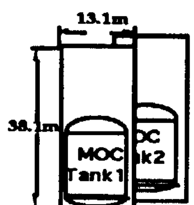
Subassembly mass = 110.5 metric tons
Mass efficiency = 87 %
Volumetric efficiency = 45.88 %

+



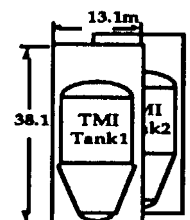
Subassembly mass = 108 metric tons
Mass Efficiency = 85 %
Volumetric efficiency = not calculated

KS2



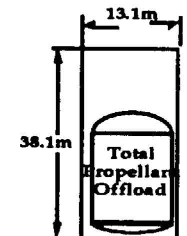
Subassembly mass = 88.59 metric tons
Mass efficiency = 69.76 %
Volumetric efficiency = 26 %

+



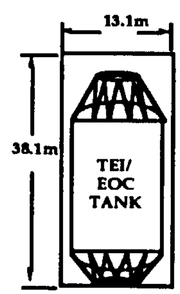
Subassembly mass = 110.5 metric tons
Mass efficiency = 87 %
Volumetric efficiency = 45.88 %

+



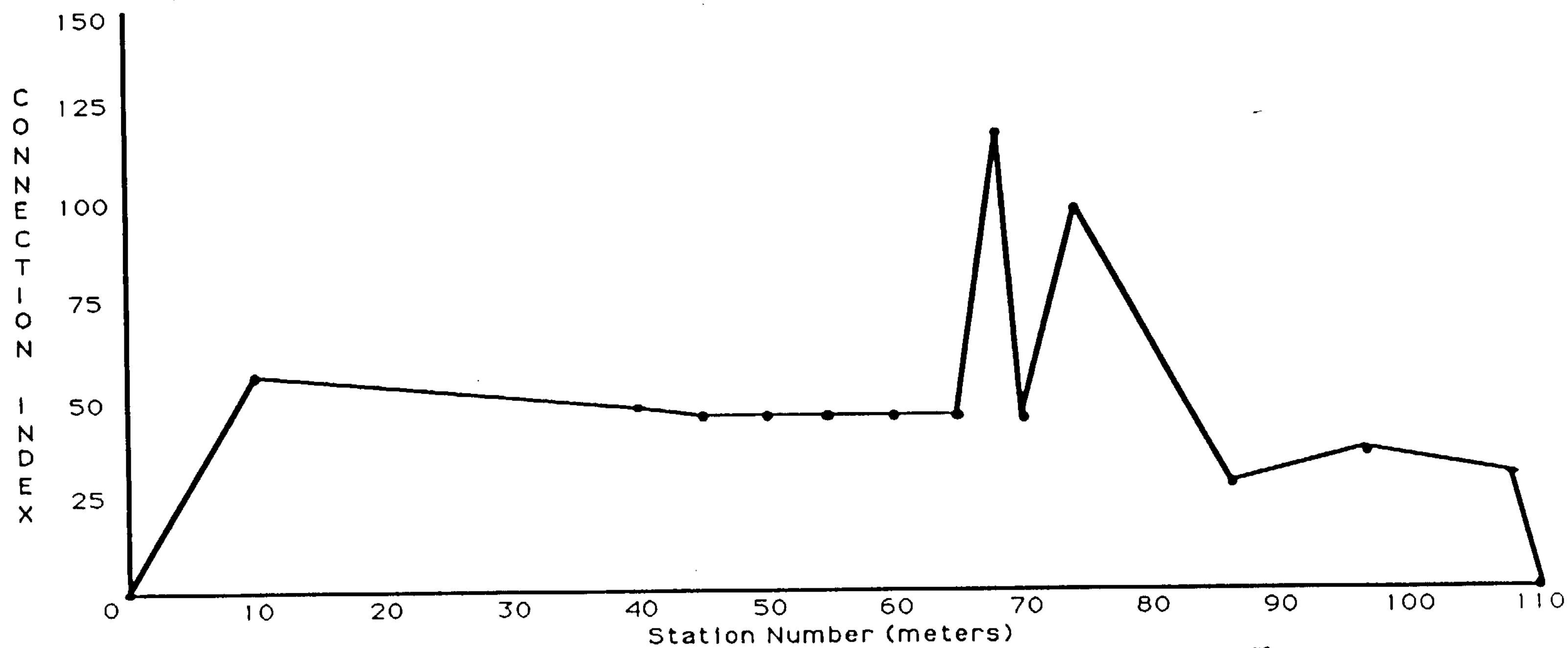
Subassembly mass = 108 metric tons
Mass Efficiency = 85 %
Volumetric efficiency = not calculated

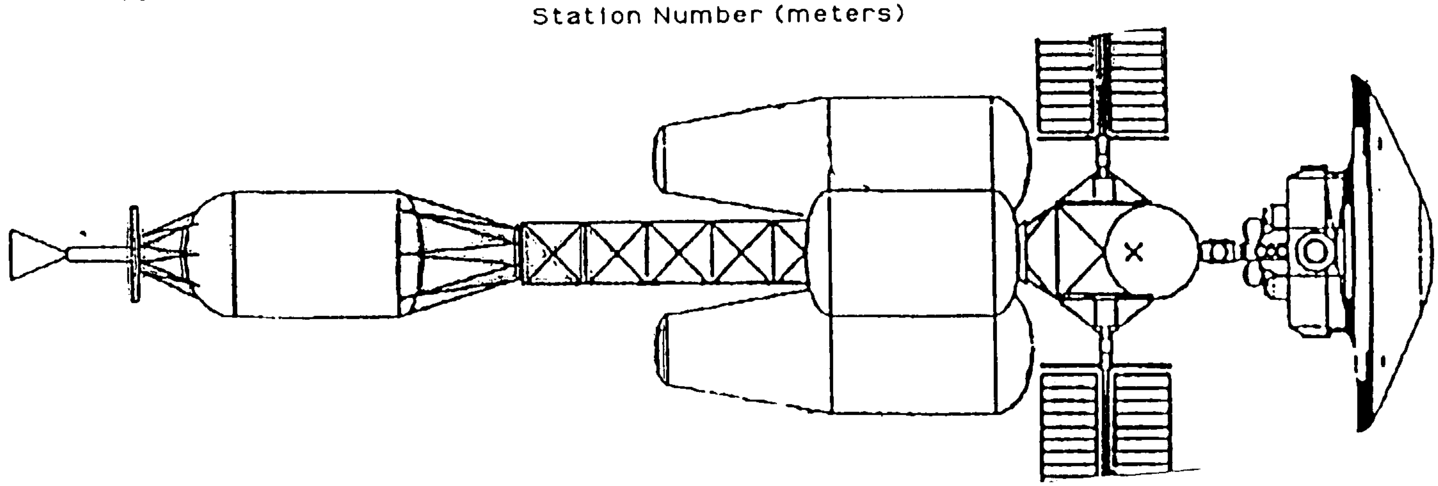
+



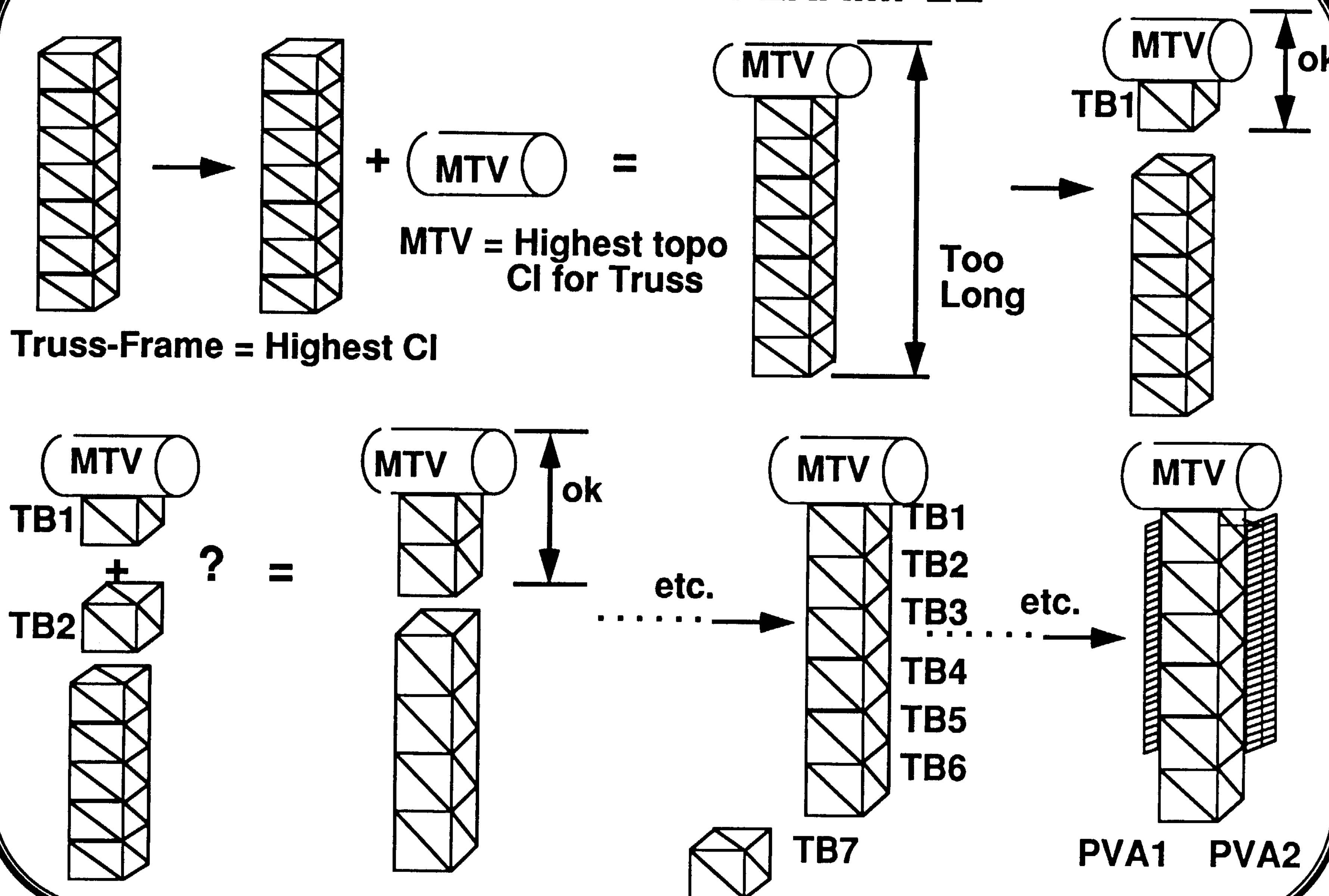
Subassembly mass = 100.33 metric tons
Mass efficiency = 79 %
Volumetric efficiency = 53.53 %

KNOWLEDGE-SOURCE 3 =====> CONNECTION-INDEX RESULTS: BOEING NTR-2016 CI-PROFILE



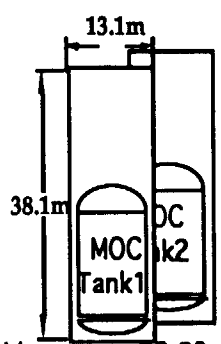


KS3 ALGORITHM: EXAMPLE



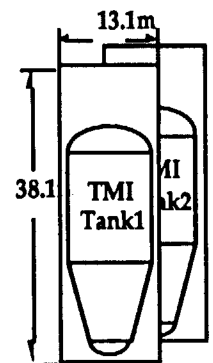
KS3: Flight Manifest Results

- Two New Aggregates Created
- True Synthesis



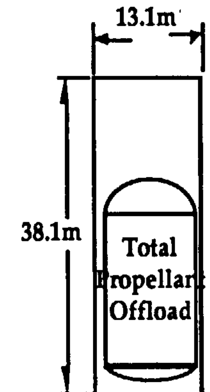
Subassembly mass = 88.59 metric tons
Mass efficiency = 69.76 %
Volumetric efficiency = 26 %

+



Subassembly mass = 110.5 metric tons
Mass efficiency = 87 %
Volumetric efficiency = 45.88 %

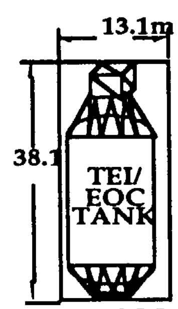
+



Subassembly mass = 108 metric tons
Mass Efficiency = 85 %
Volumetric efficiency = not calculated

New Subassembly 2 (TEI/EOC Tank + Truss-Bay 1)

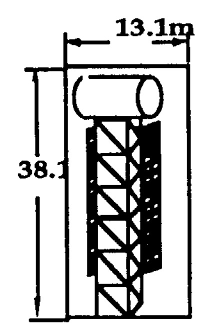
+



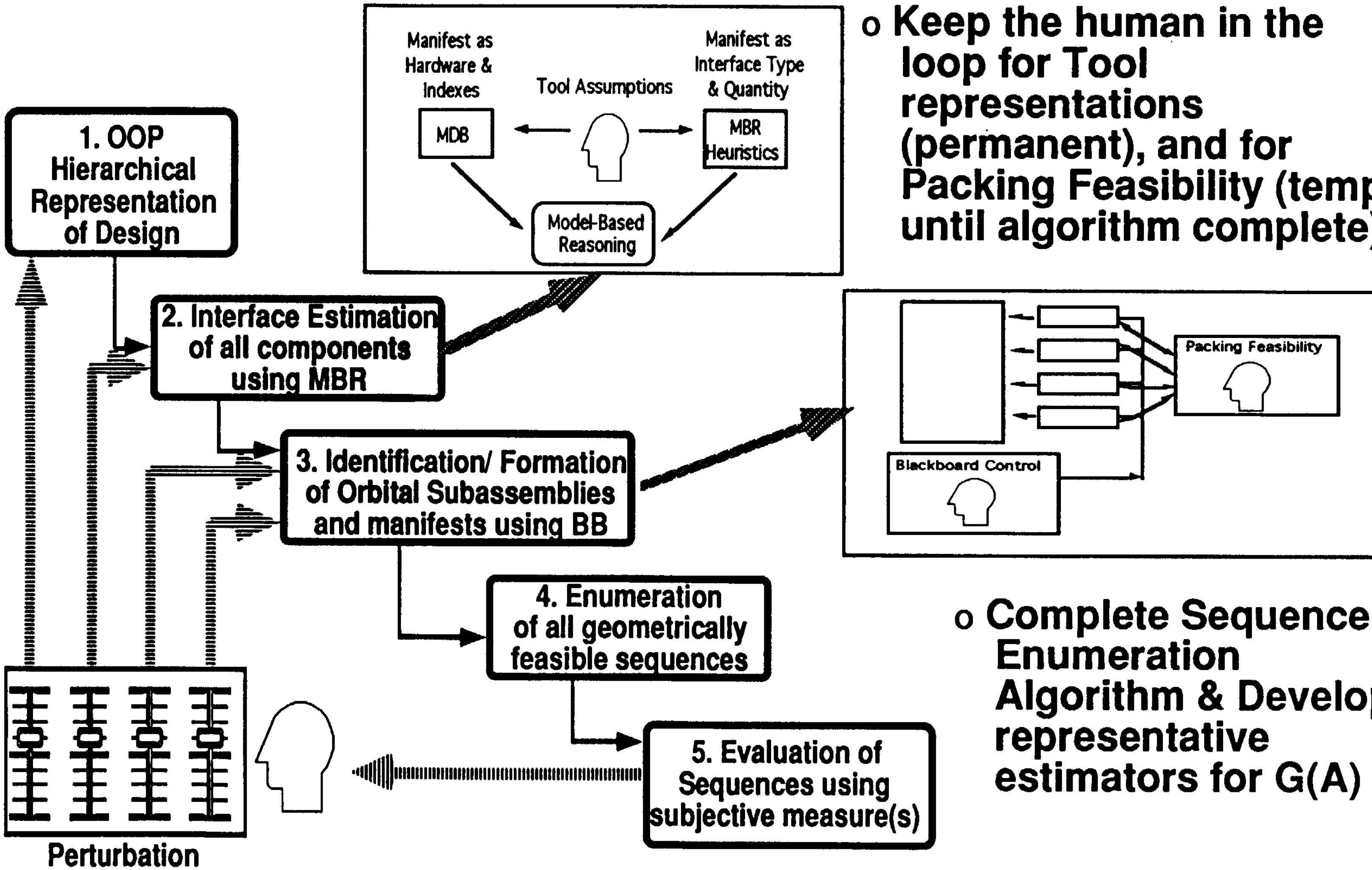
Subassembly mass = 100.33 metric tons
Mass efficiency = 79 %
Volumetric efficiency = 53.53 %

(+)

New Subassembly 1 (MTV + Truss-Bays 1-6 + PVAs 1 & 2)



Conclusions and Plans



- Keep the human in the loop for Tool representations (permanent), and for Packing Feasibility (temp. until algorithm complete)
- Complete Sequence Enumeration Algorithm & Develop representative estimators for G(A)
- Evaluate simulation stability through perurbation analyses of inputs, and introduction of other orbital assembly designs

LUNAR CONSTRUCTION

ORIGINAL PAGE
COLOR ~~PHOTOGRAPH~~
PAGE.

N93-26412

cSc

Lunar Regolith and Structure Mechanics

Stein Sture

Third Annual Symposium
November 21 & 22, 1991

cSc

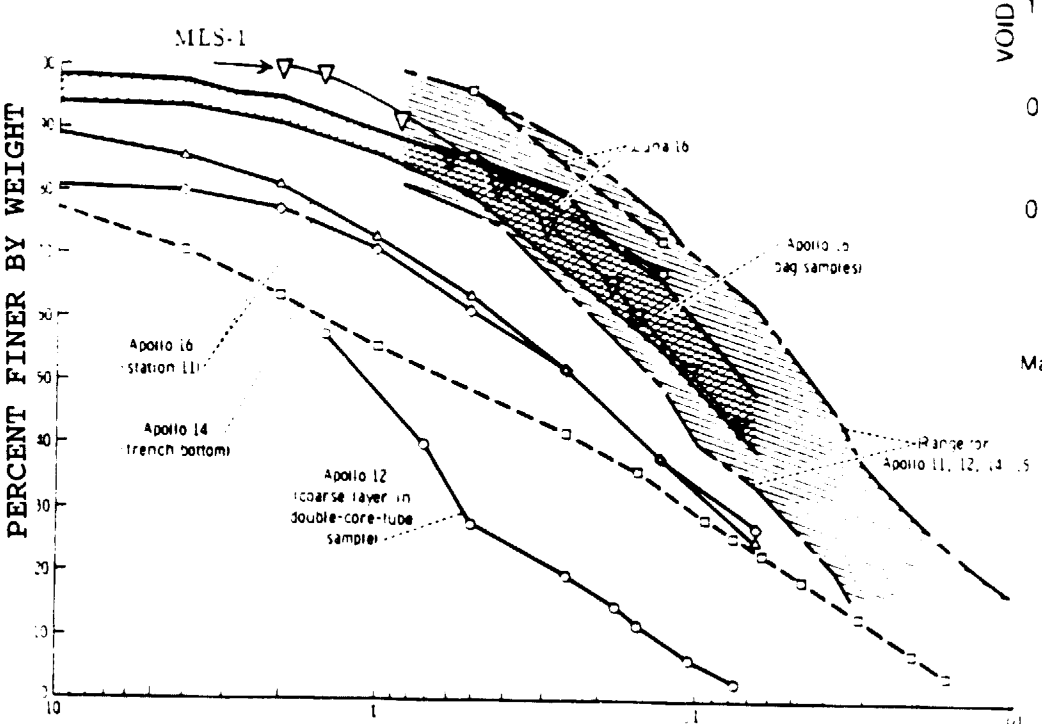
LUNAR REGOLITH AND STRUCTURE MECHANICS

Frank Barnes
Hon-Yim Ko
Stein Sture

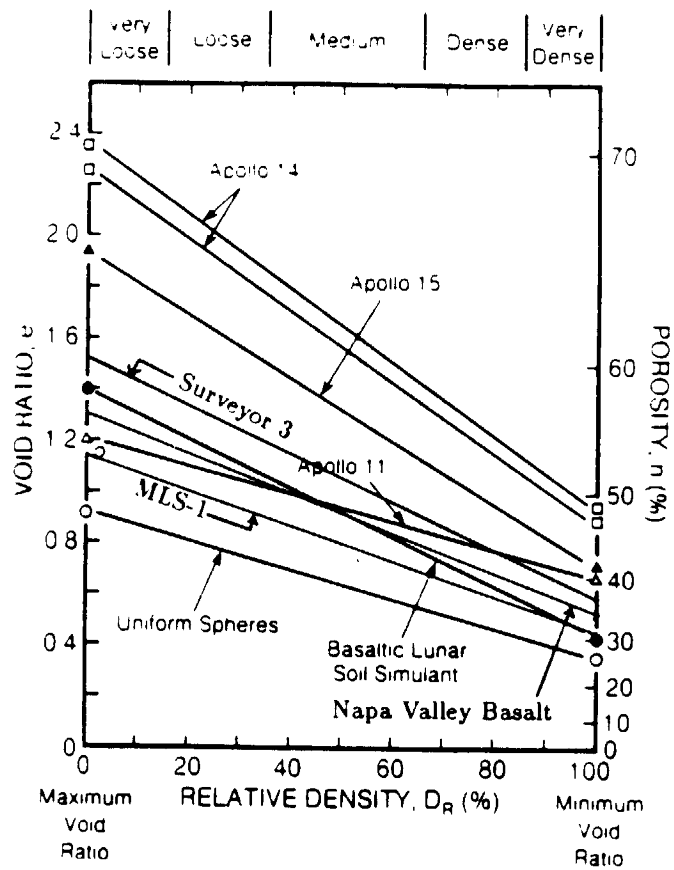
Tyrone R. Carter
Kraig A. Evenson
Mark P. Nathan
Steve W. Perkins

- MODELING OF REGOLITH-STRUCTURE INTERACTION IN EXTRATERRESTRIAL CONSTRUCTED FACILITIES
- DENSIFICATION OF LUNAR SOIL SIMULANT
- VIBRATION-ASSISTED PENETRATION OF LUNAR SOIL SIMULANT

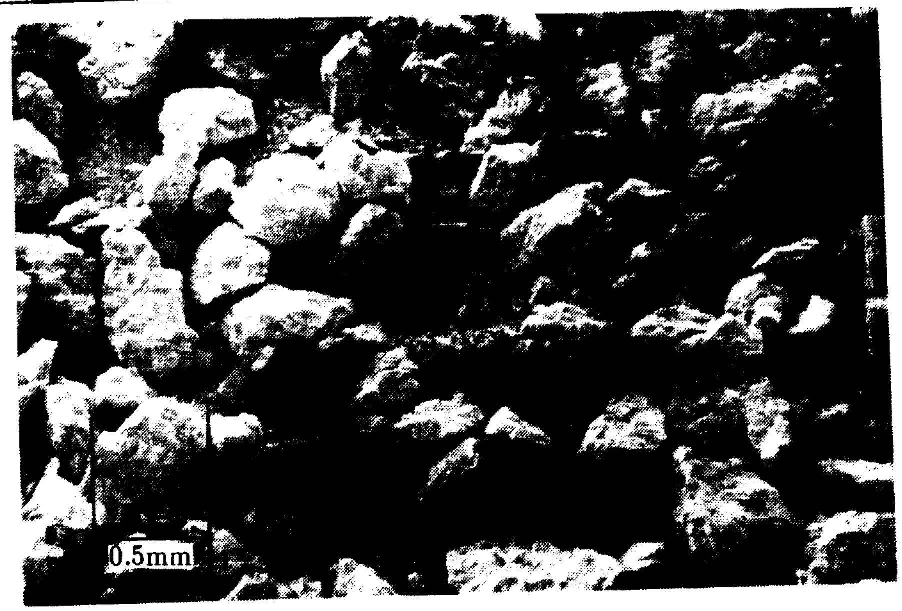
MINERALOGY AND PHYSICAL PROPERTIES OF LUNAR REGOLITH AND MLS ARE VERY CLOSE



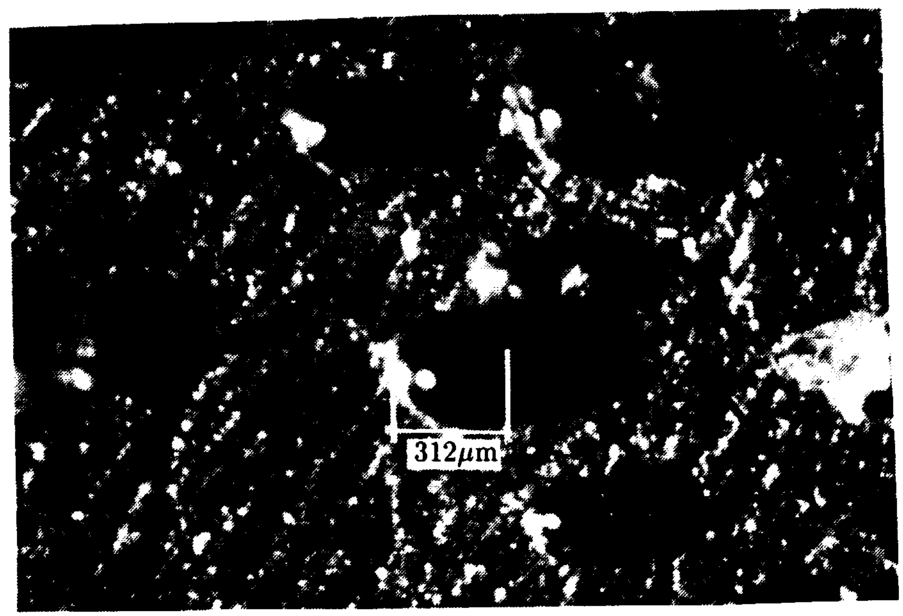
Grain Size Distribution Curves for Apollo Samples and Recombined MLS-1



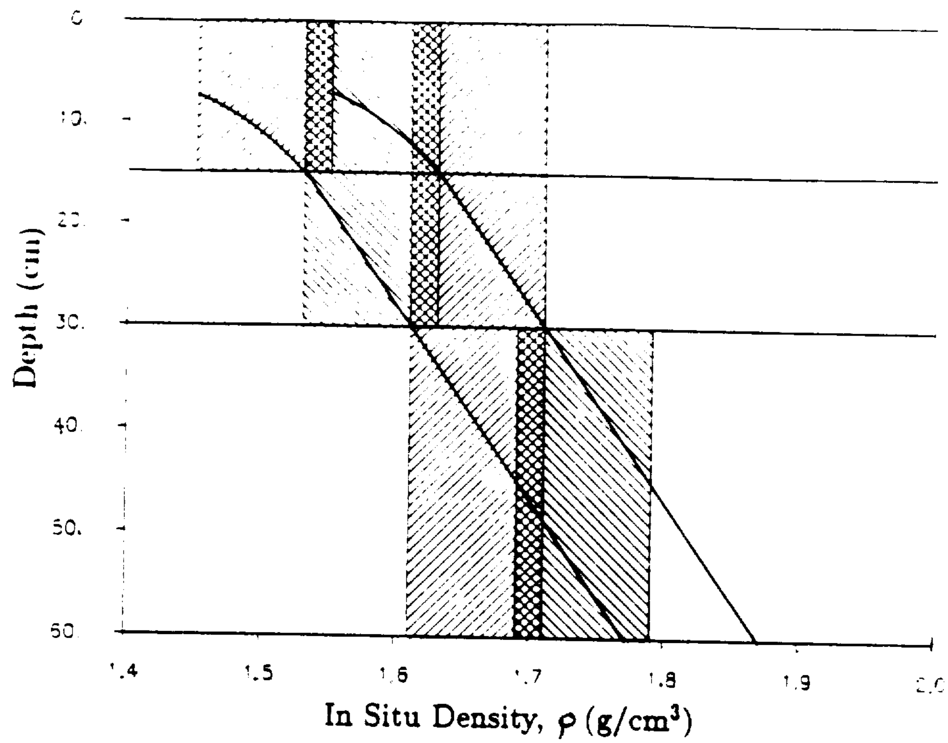
Maximum and Minimum Void Ratio for Lunar Soil and Simulants



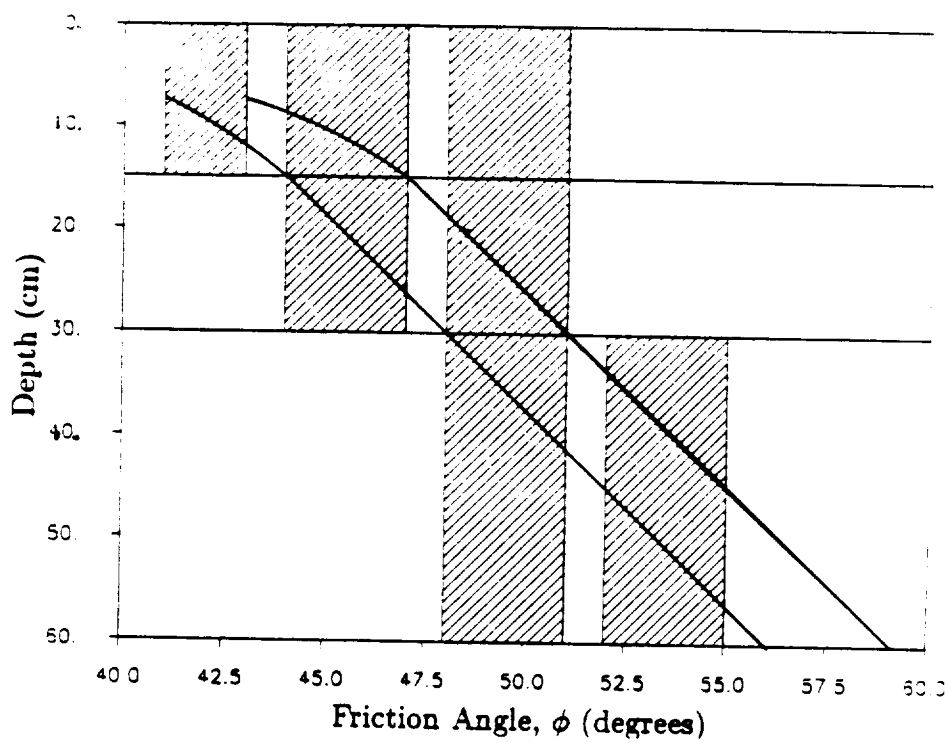
REGOLITH



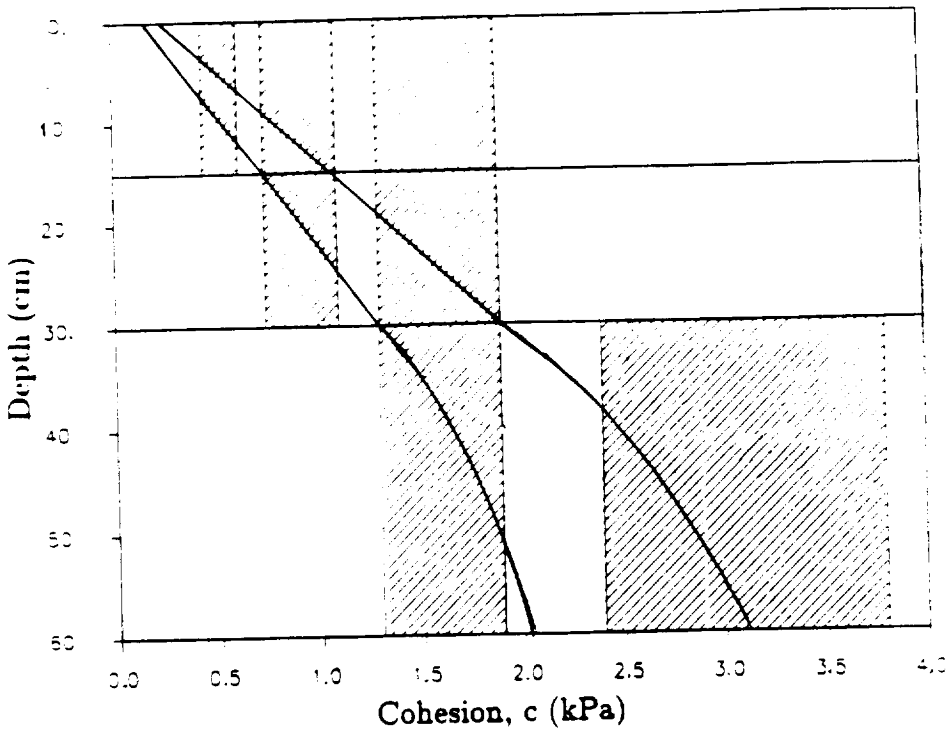
SPHERULES



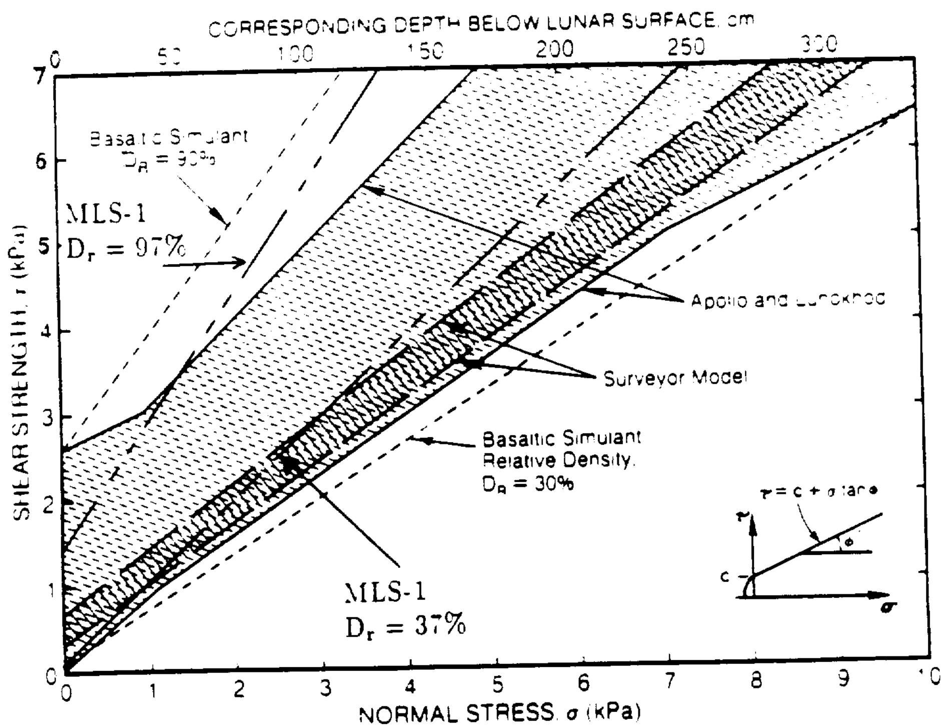
Best Estimates of Lunar Soil In Situ Density Versus Depth (data after Carrier, 1990)



Best Estimates of Lunar Soil Friction Angle Versus Depth (data after Carrier, 1990)



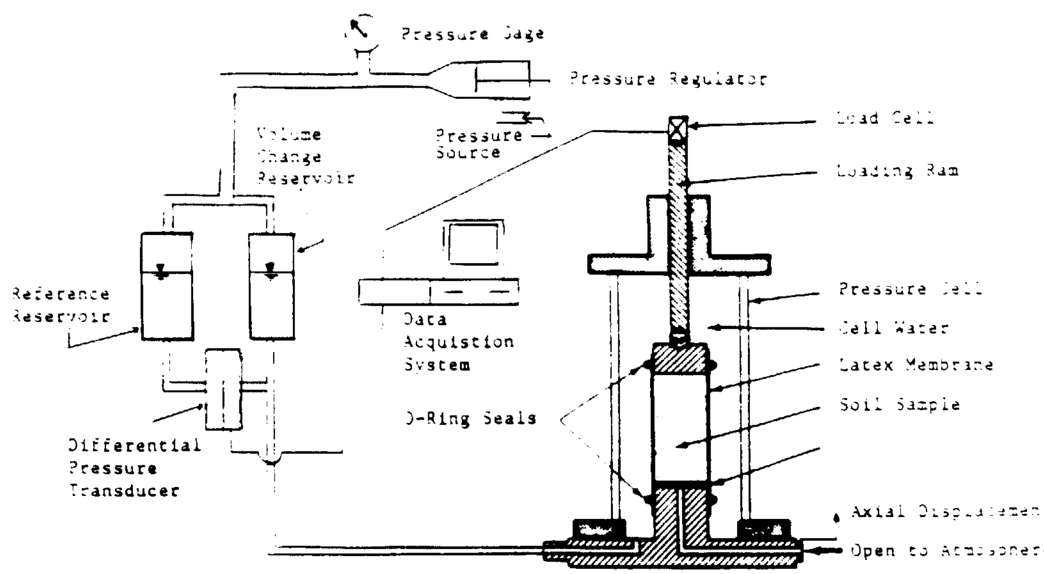
Best Estimates of Lunar Soil Cohesion Versus Depth (data after Carrier, 1990)



Mohr-Coulomb Peak Strength Envelopes for Lunar Regolith and MLS-1 (after Carrier et al., 1991)

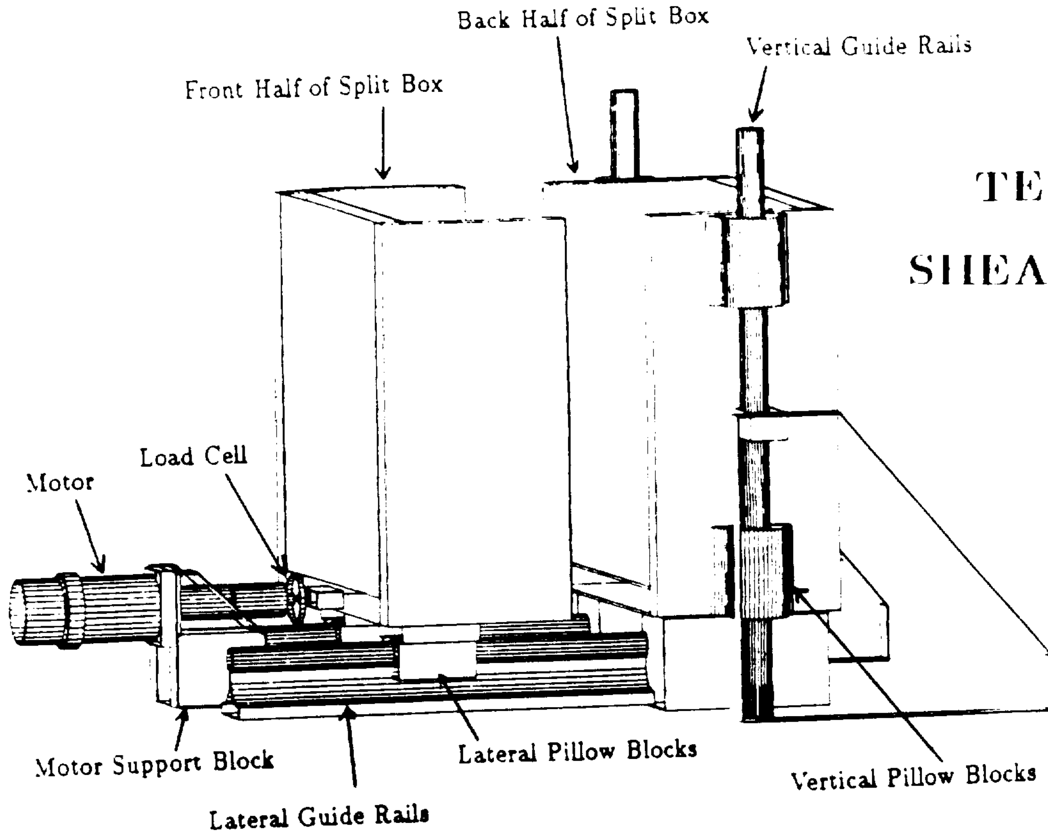
MECHANICAL PROPERTIES OF A SIMULATED LUNAR SOIL

TRIAXIAL COMPRESSION EXPERIMENTS (MLS)

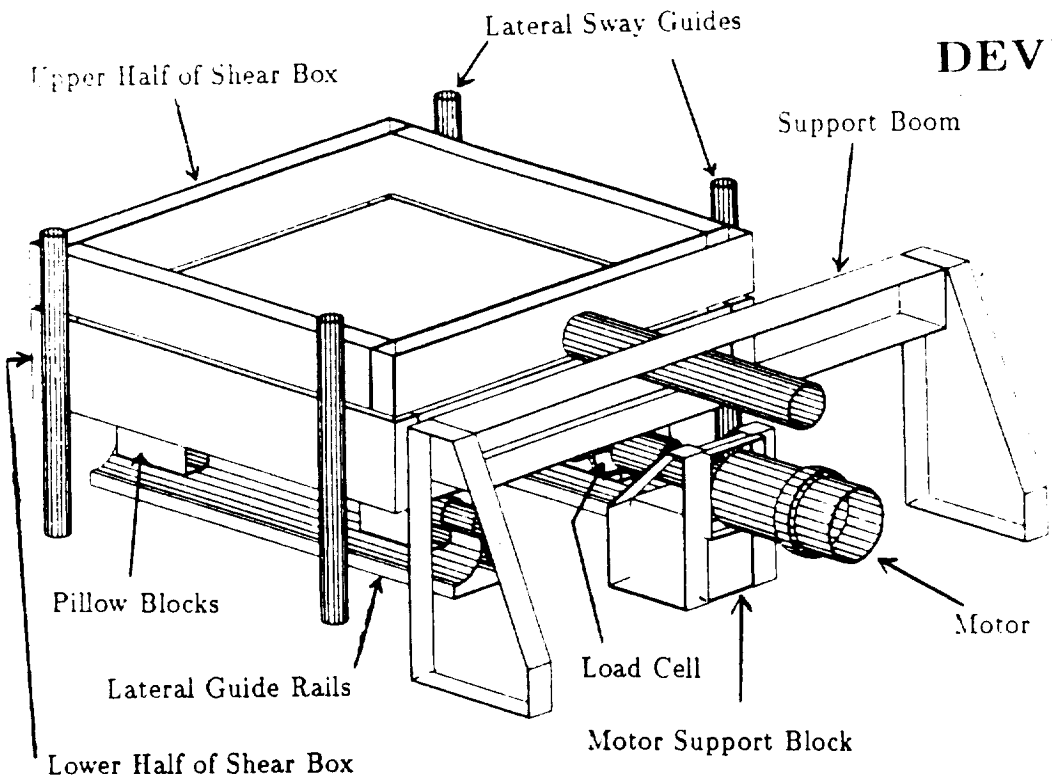


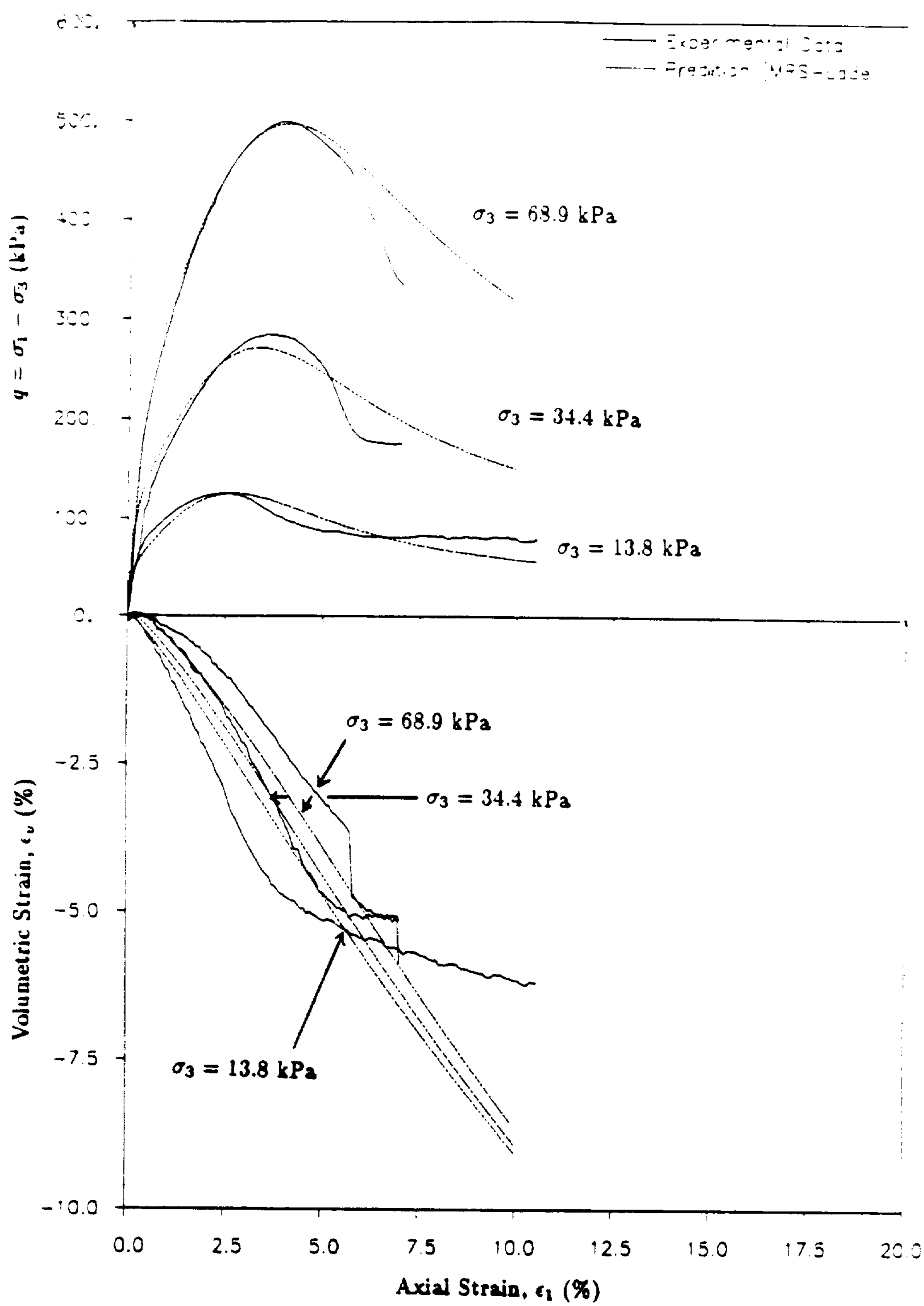
Schematic Diagram of the Triaxial Testing System

TENSION-SHEAR DEVICE

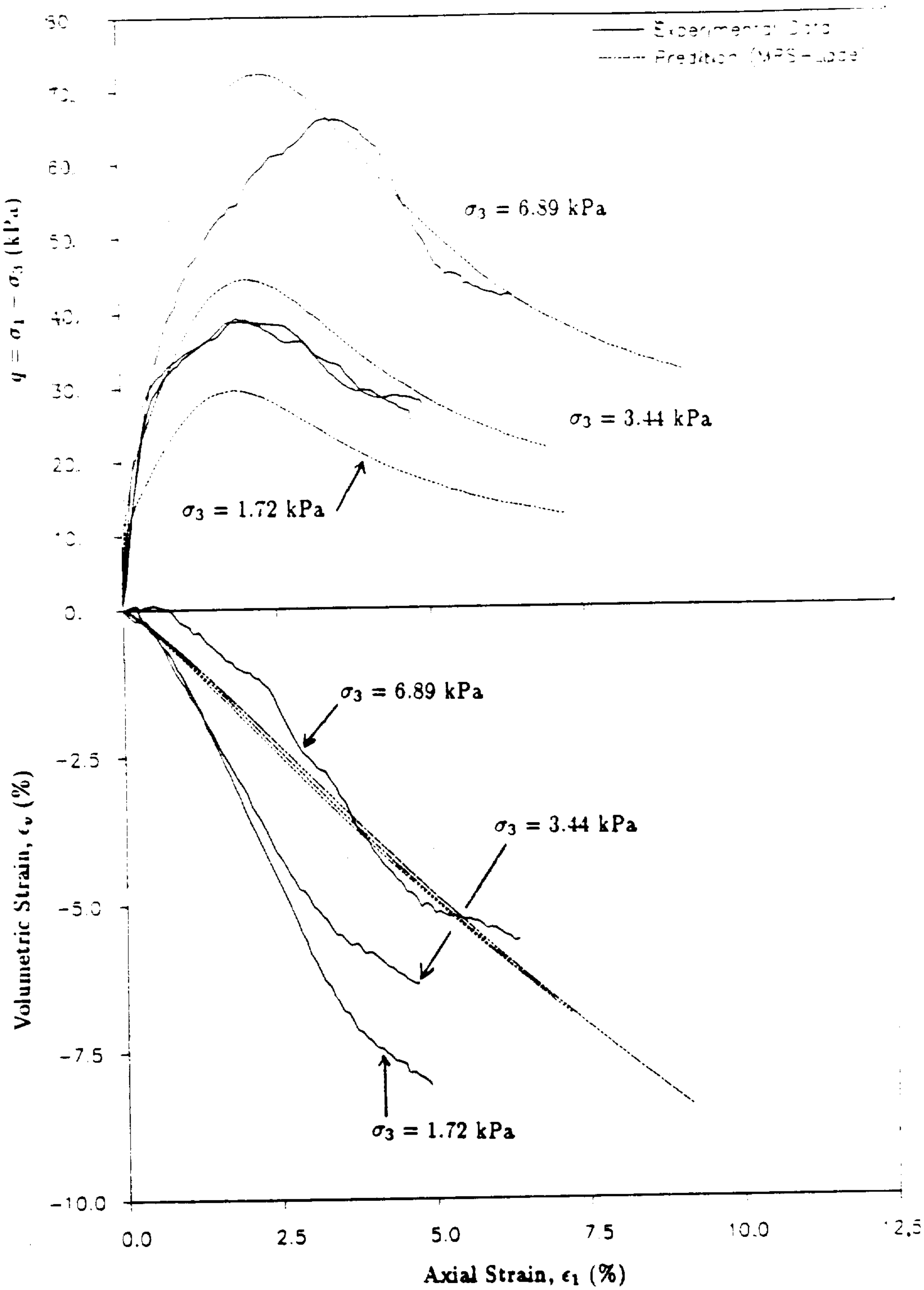


DIRECT SHEAR DEVICE





CTC Experimental Results and Predictions For "High" Confining Stress Levels (Dense)



CTC Experimental Results and Predictions For "low" Confining Stress Levels (Dense)

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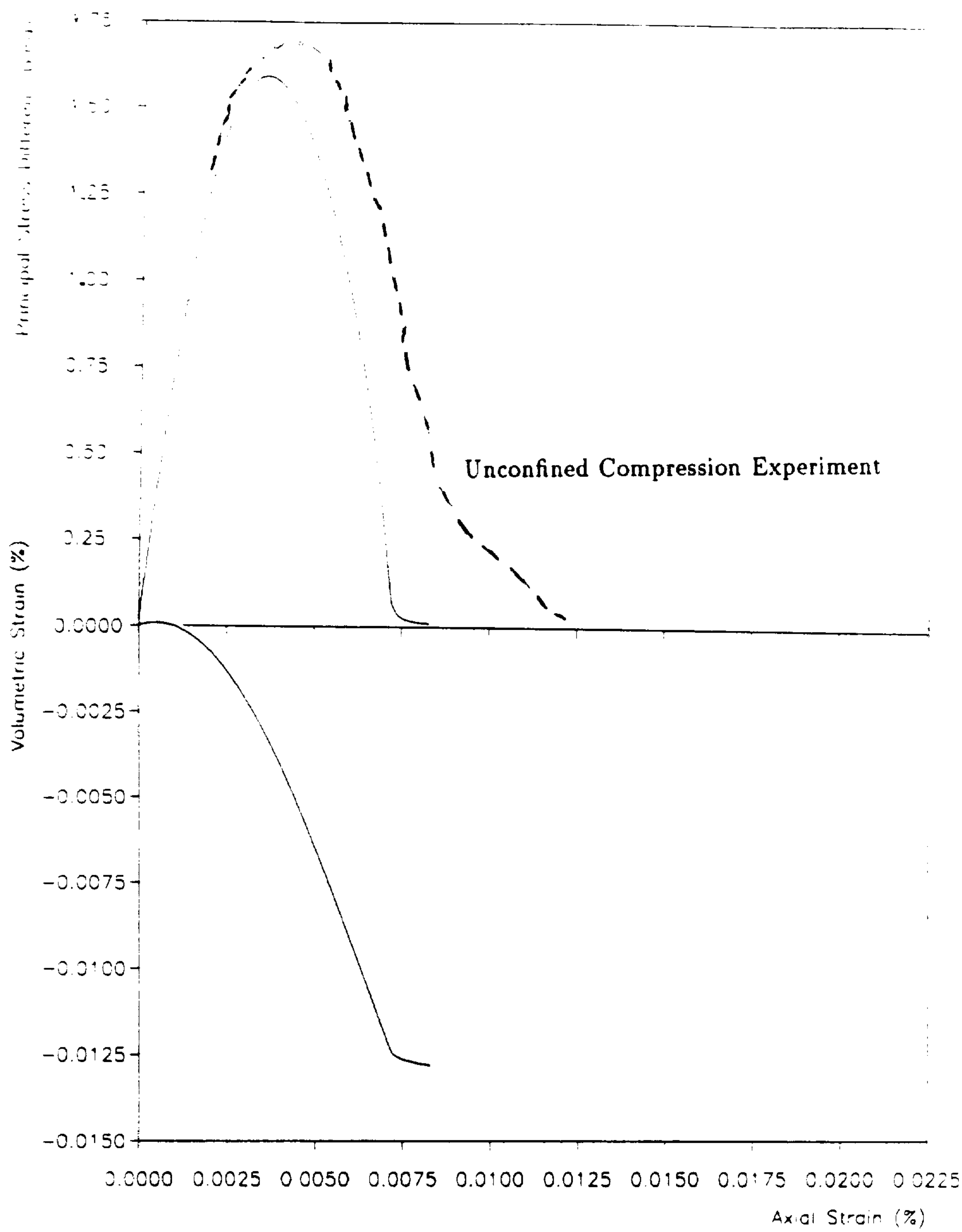

MRS-Lade Prediction for Unconfined Compression Test From Calibration at Ultra-Low Stress Levels

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A NASA Space Engineering Research Center at the University of Colorado

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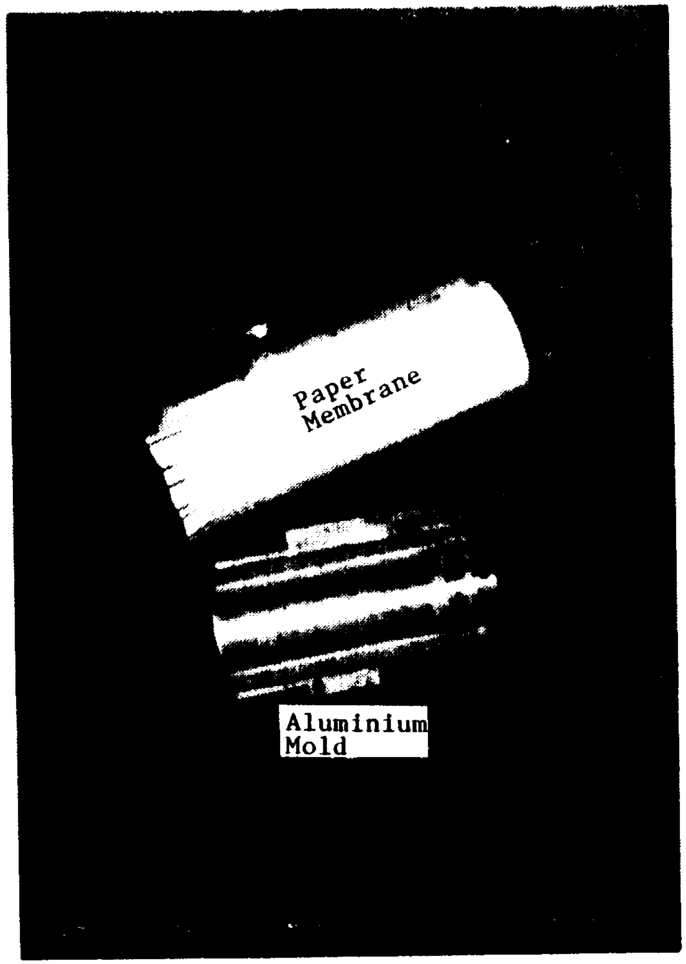
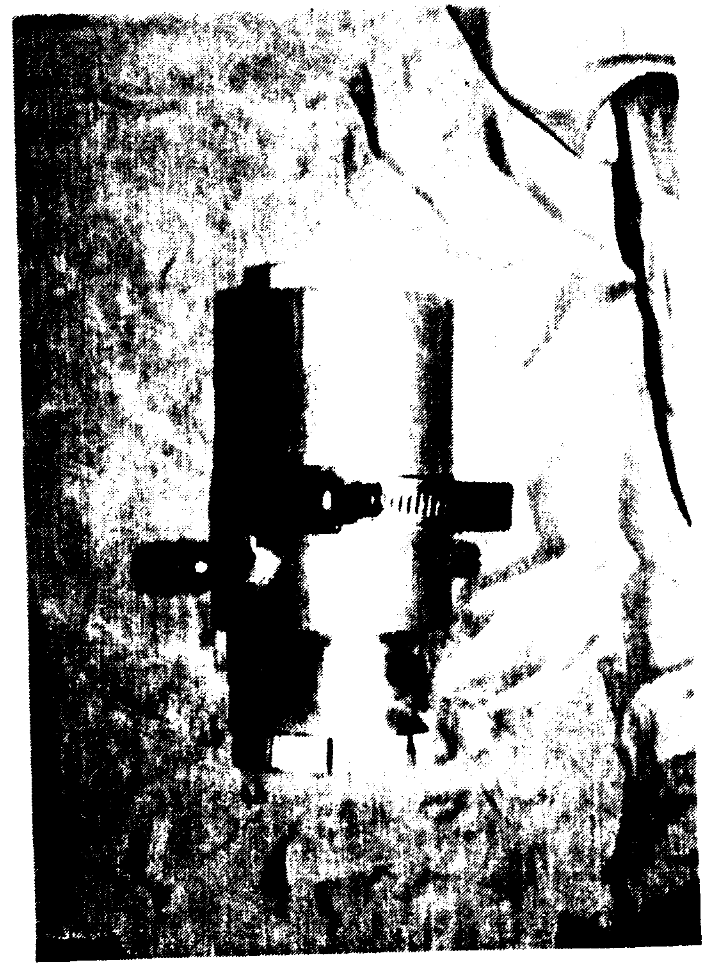
TENSILE STRENGTH EXPERIMENT





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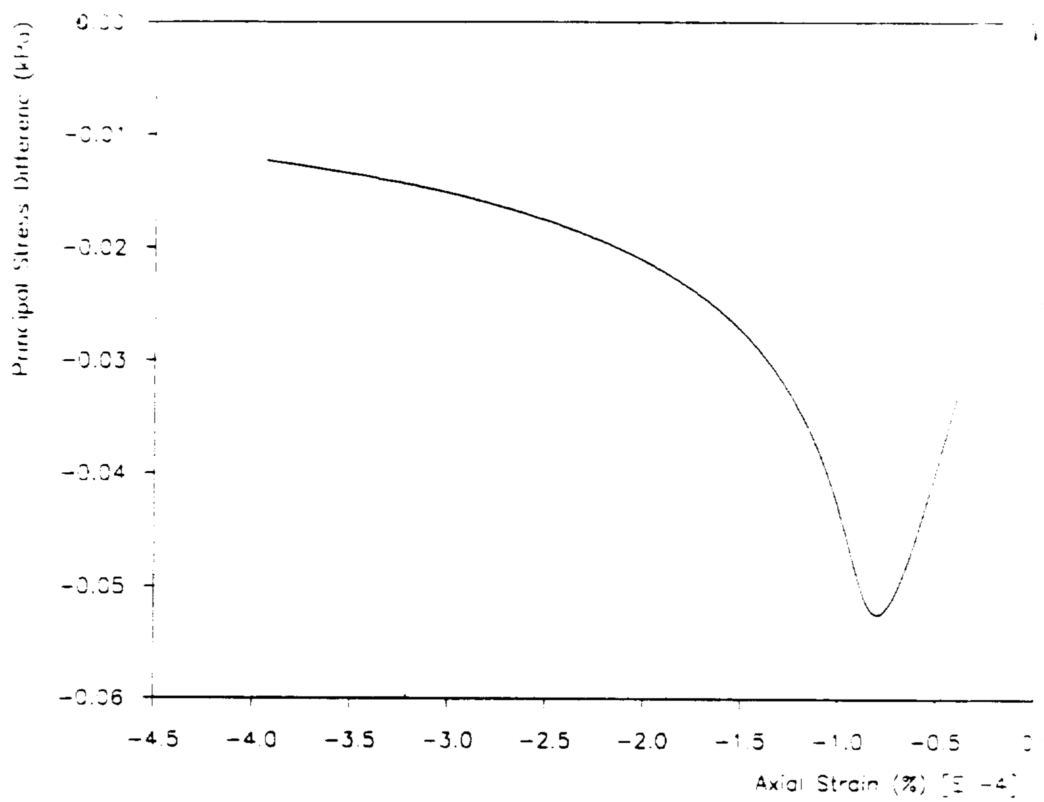
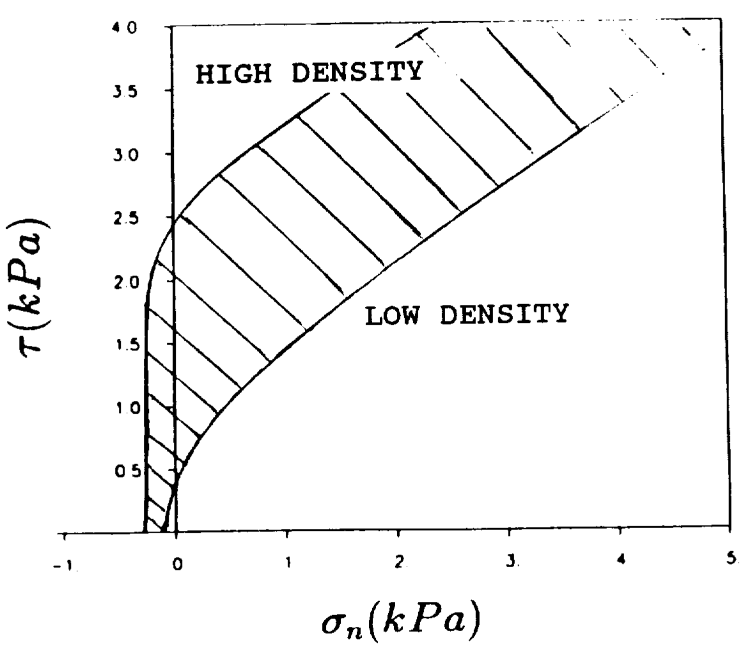
BLACK AND WHITE PHOTOGRAPH



MRS-Lade Prediction for Unconfined Tension From Calibration at Ultra-Low Stress Levels



ULTIMATE STRENGTH ENVELOPE FOR MLS-1

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A NASA Space Engineering Research Center at the University of Colorado

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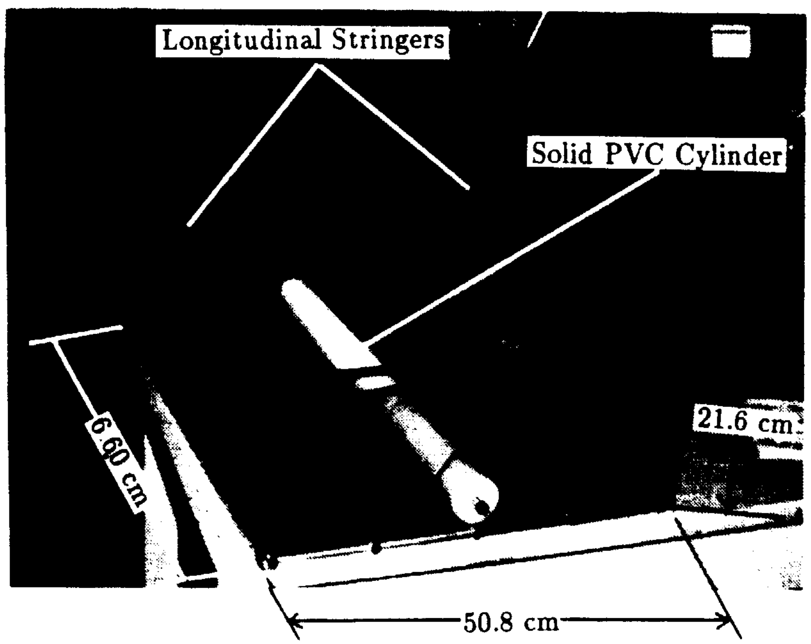
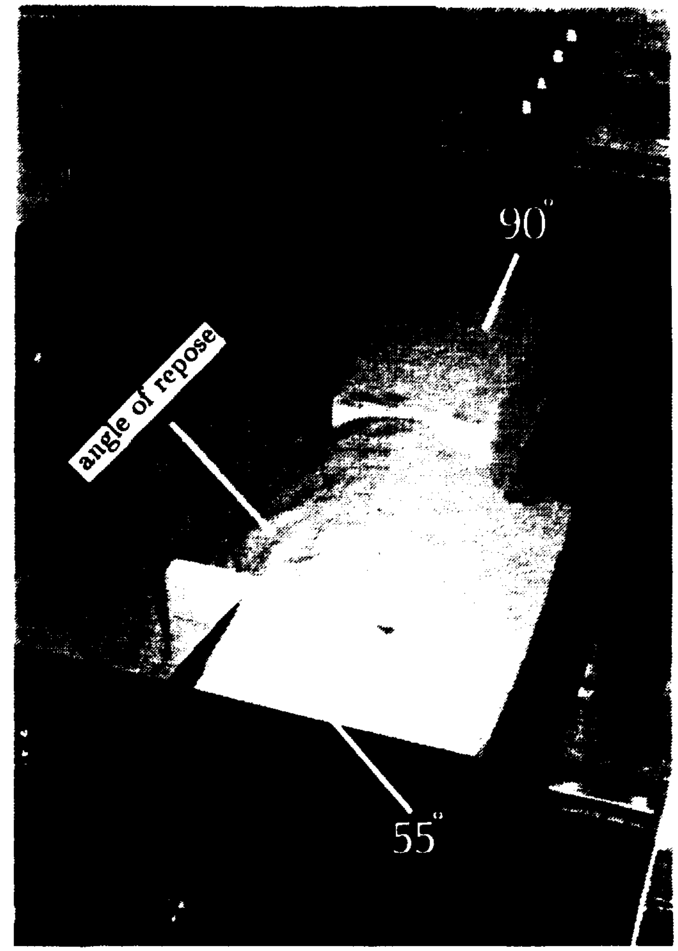
TYPICAL RANGES OF ENGINEERING PROPERTIES FOR DRY TERRESTRIAL COHESIONLESS SOILS AND LUNAR REGOLITH (REAL AND SIMULATED)

- ADVANTAGES
  - Increased Strength
  - Increased Stiffness
  - Subsurface Homogeneity
- DISADVANTAGES
  - Electrostatic Attraction To All Non-Geologic Matter
  - Difficult To Excavate

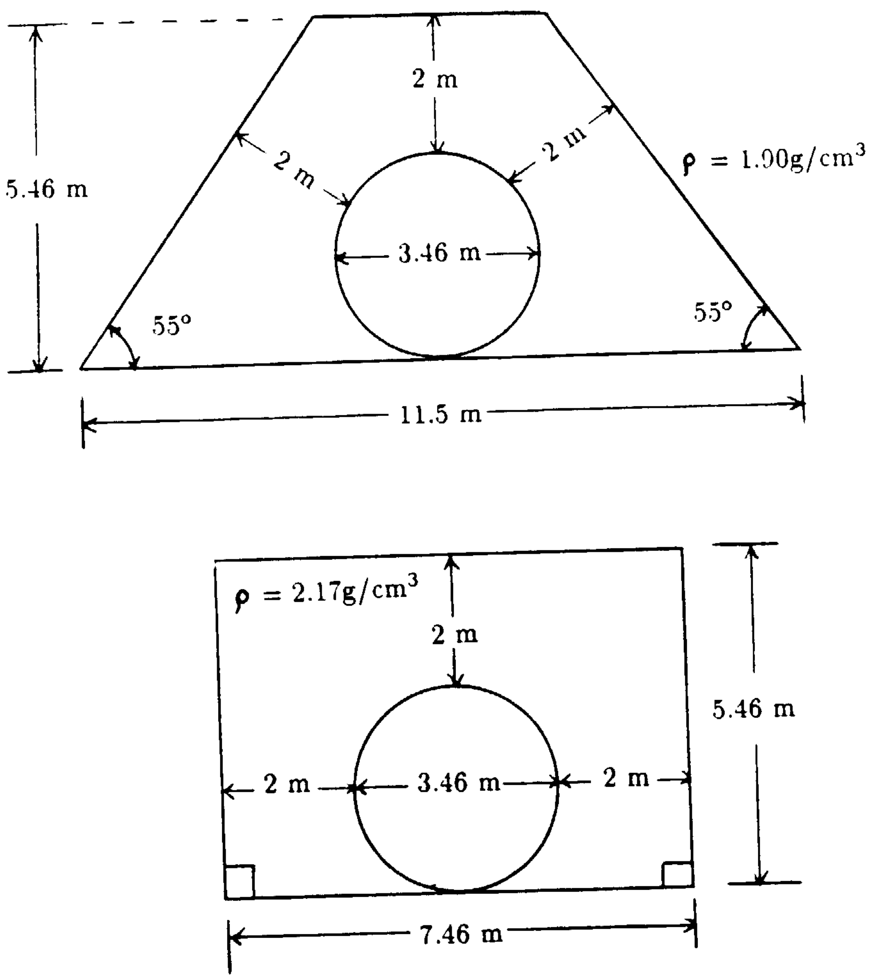
	Terrestrial Soils	Lunar Regolith and MLS
Friction Angle (ϕ, °)	30-38	44-66
Cohesion/Adhesion (c, $\frac{kN}{m^2}$)	0	0.05-4.50
Specific Mass of Solids (ρ_s, $\frac{g}{cm^3}$)	2.7	3.1
Mass Density of Particulate Void-Solids Composite (ρ, $\frac{g}{cm^3}$)	1.4-1.9	1.8-2.2
Unit Weight (γ, $\frac{kN}{m^3}$)	14-19	2.9-3.6
Bearing Capacity of a 0.10 m by 0.10 m Footing on Level Ground (q_f, $\frac{kN}{m^2}$)	8-45	27-1840
Modulus of Subgrade Reaction (est.) (k_s, $\frac{MN}{m^3}$)	0.5-15	$1\text{-}10^4$

CENTRIFUGE MODELING OF REGOLITH-STRUCTURE INTERACTION



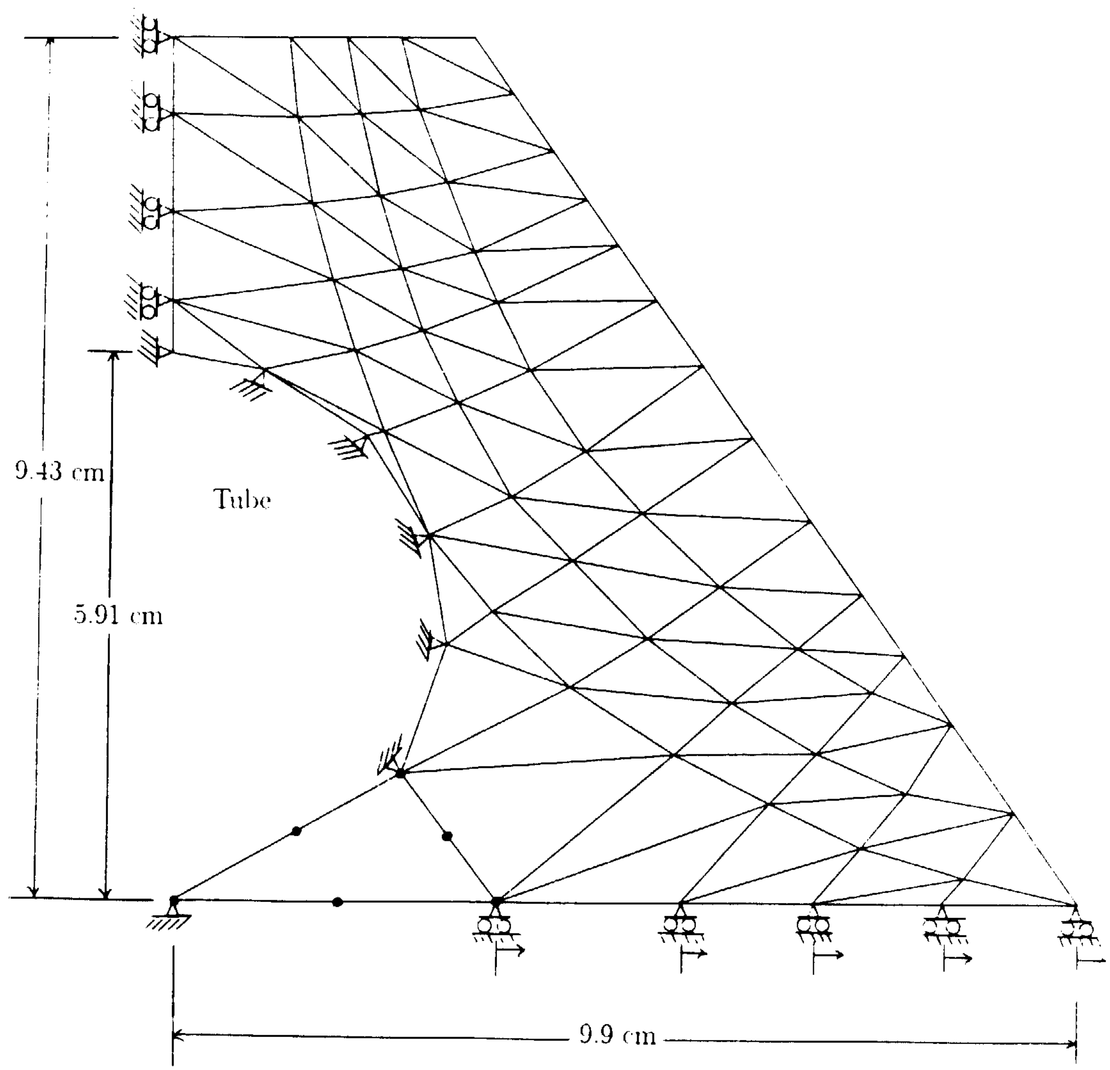


MODEL



Lunar Prototype II.II.M. Dimensions

SLOPE ANGLE	VOLUME [m^3]
30°	1,245
55°	705
90°	690


9.43 cm
5.91 cm
Tube
9.9 cm

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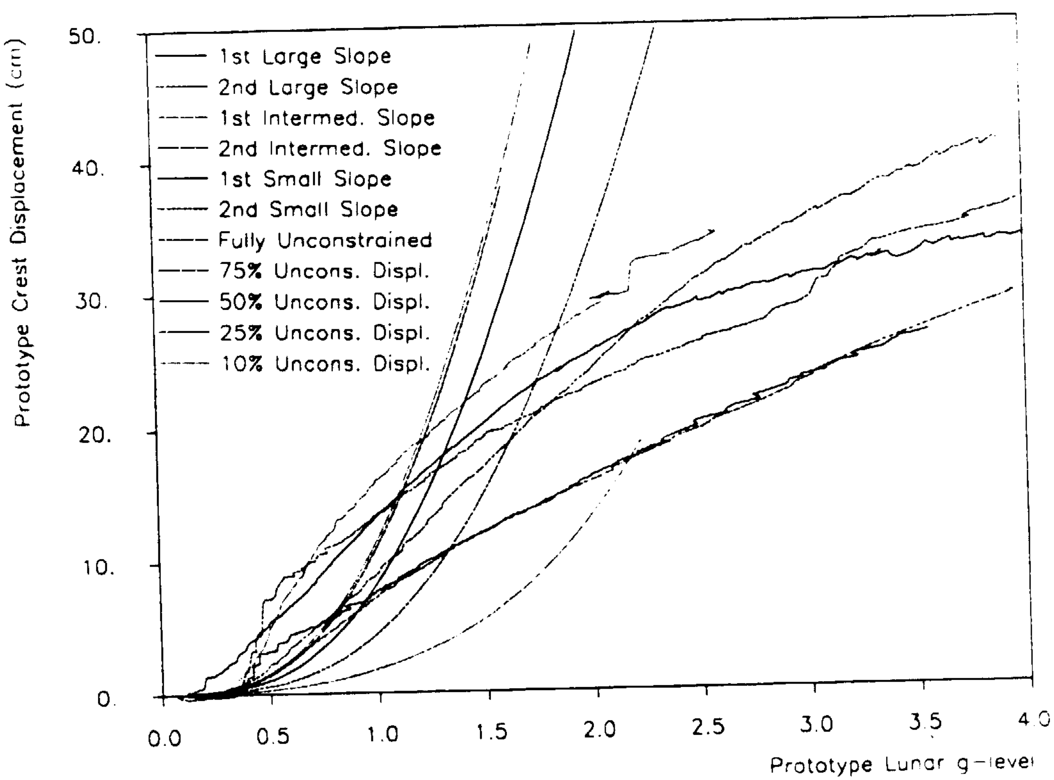
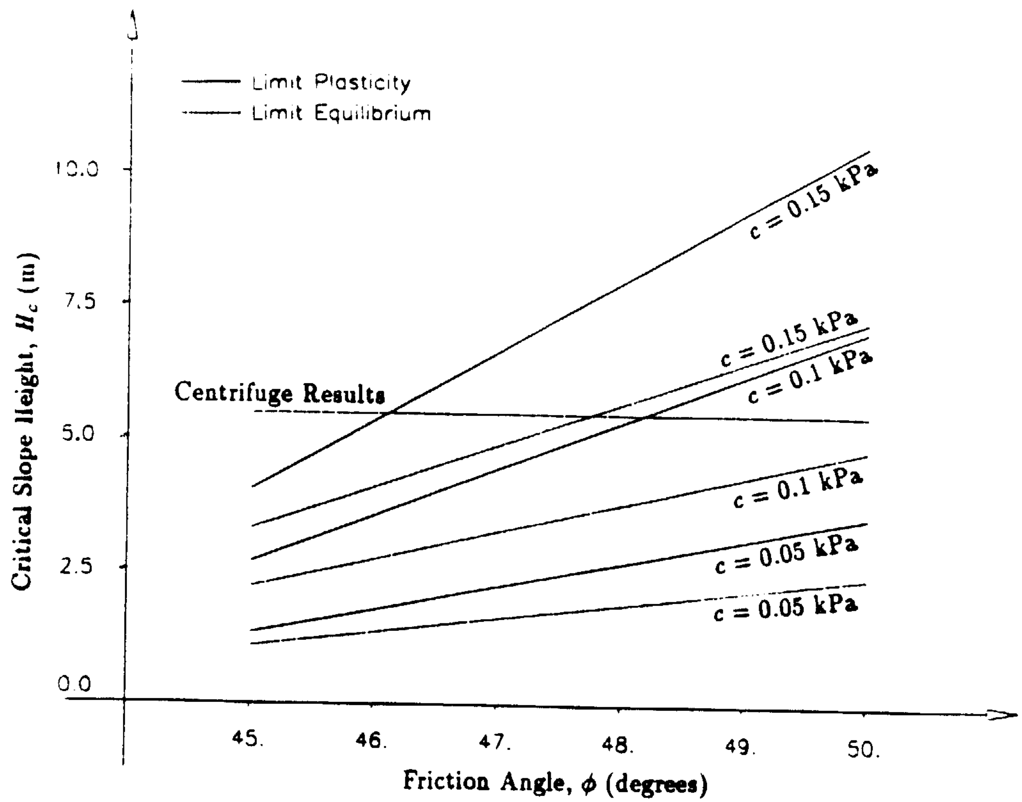


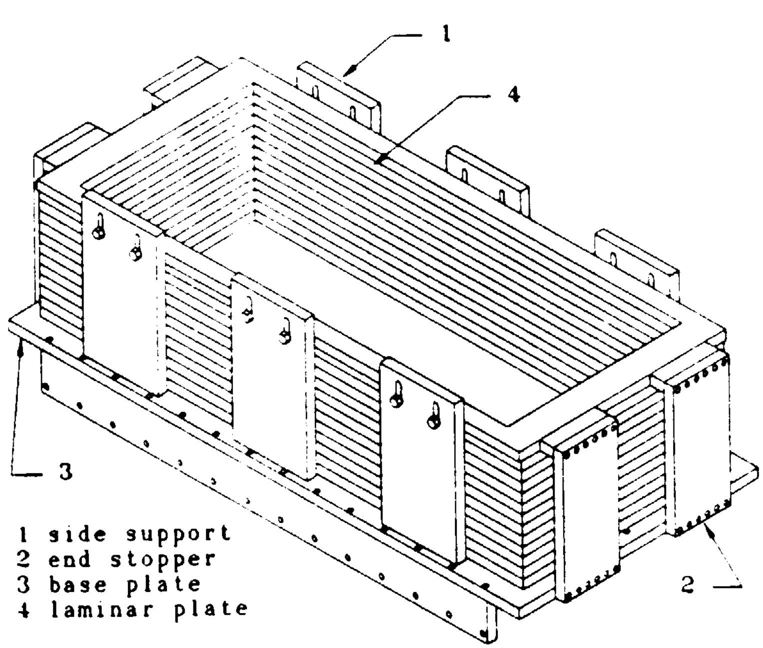
Prototype Crest Displacement (cm)
50.
40.
30.
20.
10.
0.
1st Large Slope
2nd Large Slope
1st Intermed. Slope
2nd Intermed. Slope
1st Small Slope
2nd Small Slope
Fully Unconstrained
75% Uncons. Displ.
50% Uncons. Displ.
25% Uncons. Displ.
10% Uncons. Displ.
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Prototype Lunar g-level



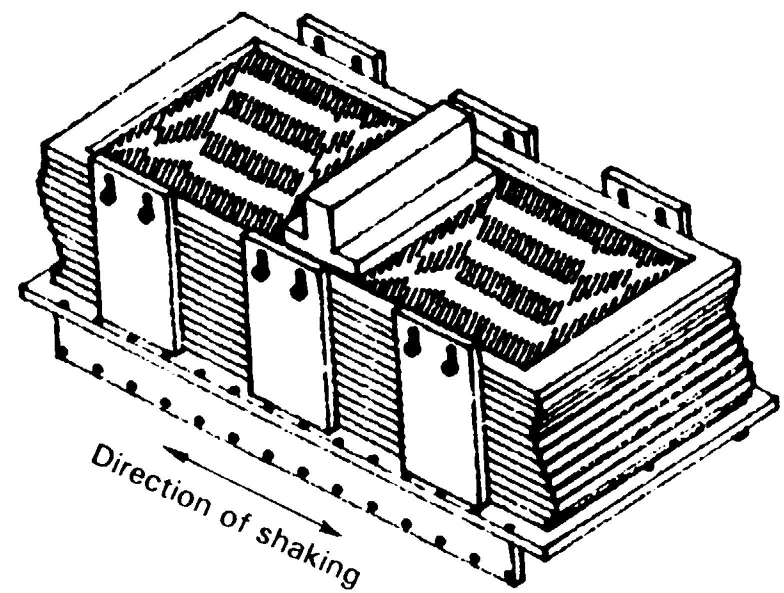
Comparison of Conventional Slope Stability Solutions To Centrifuge model

DENSITY OF LUNAR REGOLITH

LAMINAR CONTAINER TO SIMULATE FREE FIELD MOTION

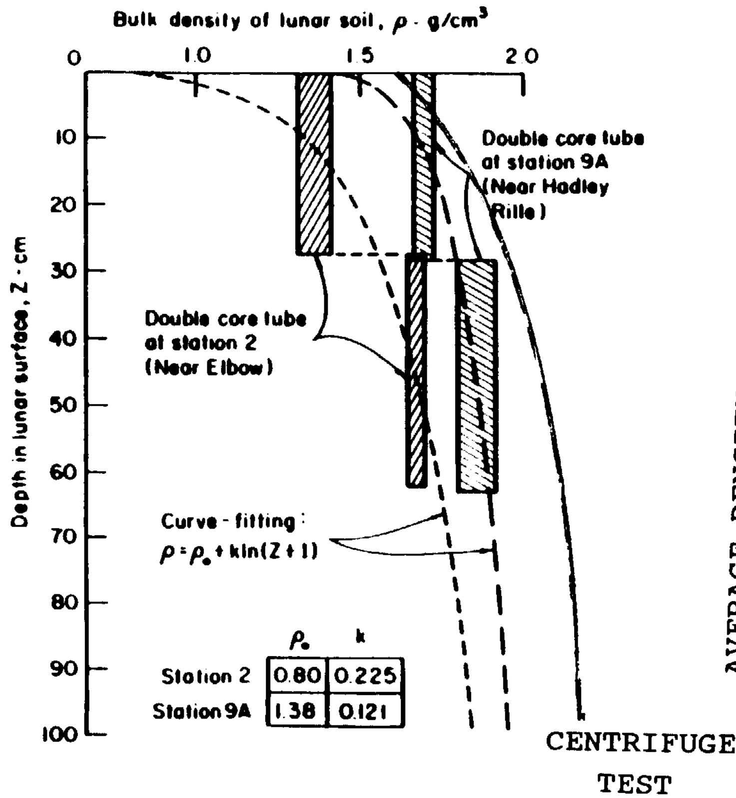


BEFORE SHAKING



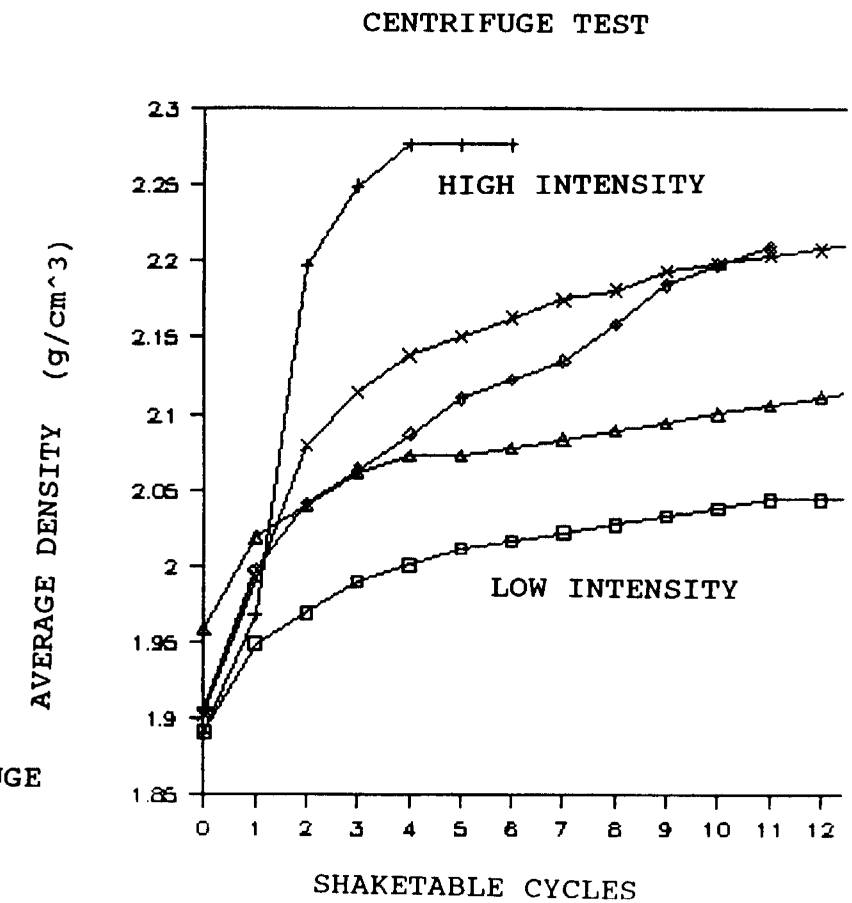
DURING SHAKING

PHYSICAL PROPERTIES OF LUNAR REGOLITH



APOLLO 15 CORE TUBE SITES

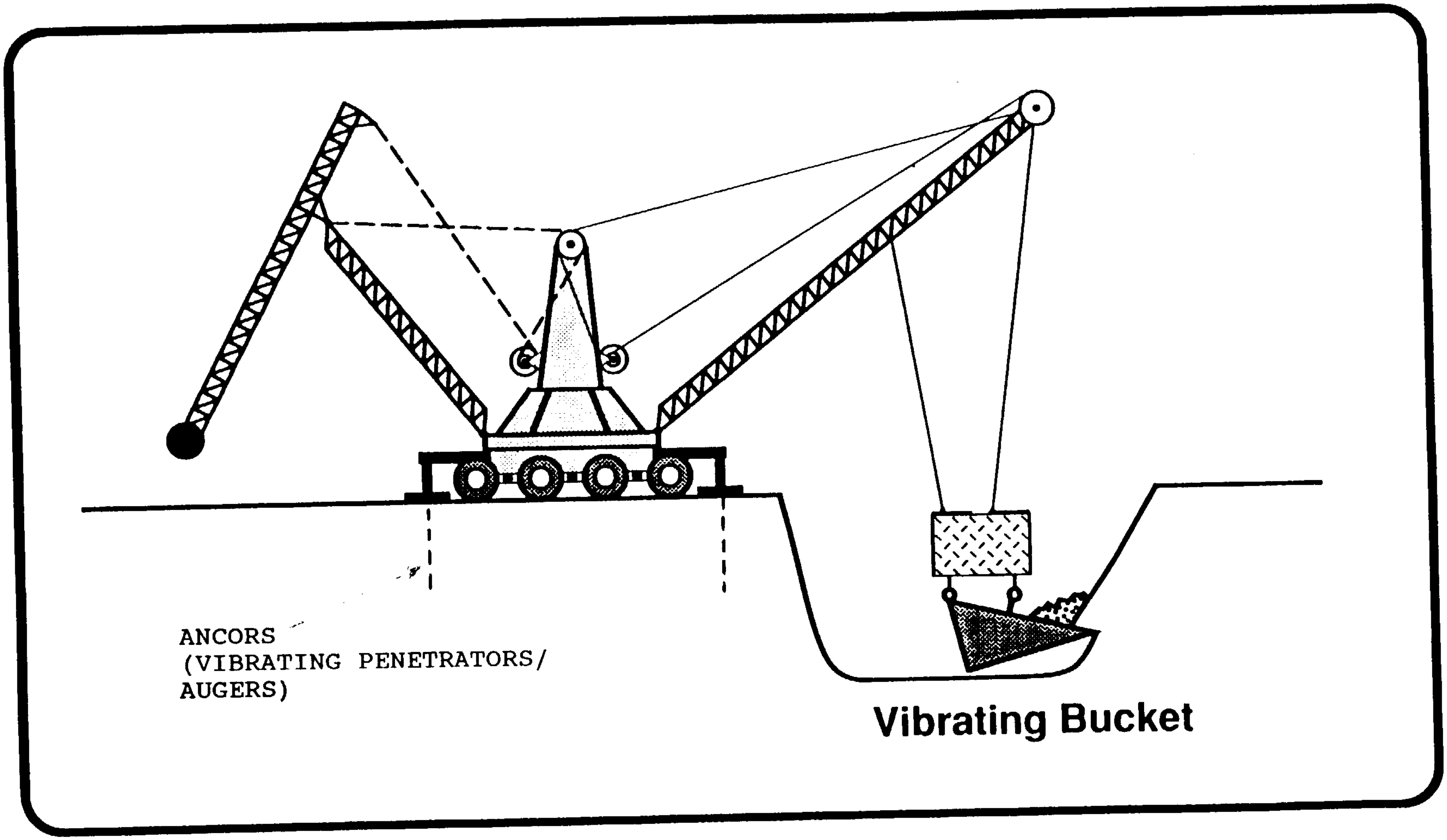
(Mitchell et al., Proc. 3'd Lunar Sci. Conf., 1972)



(5 TESTS AT DIFFERENT INTENSITIES)

LUNAR CRANE CAN PROVIDE EXCAVATING CAPABILITY USING A VIBRATING EXCAVATOR

(After Martin Mikulas)



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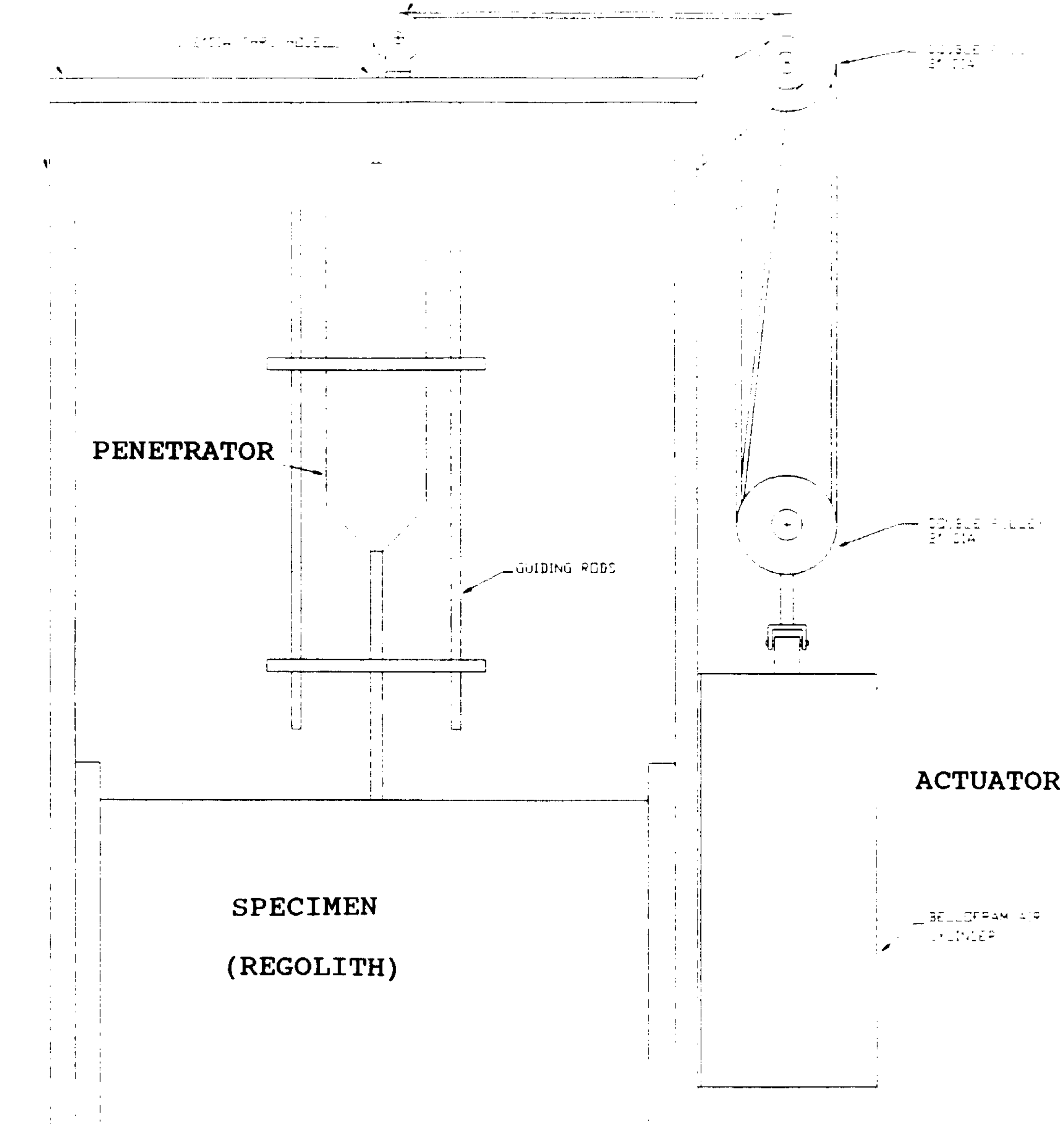
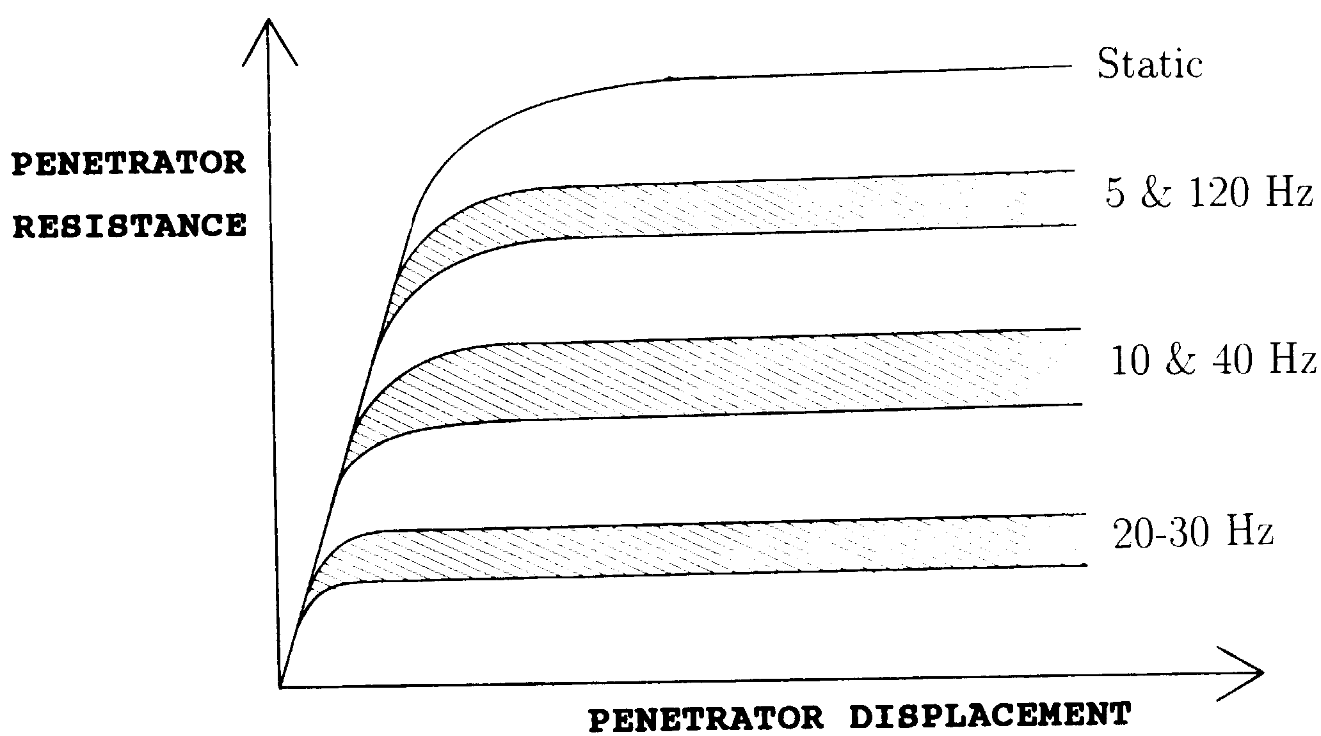
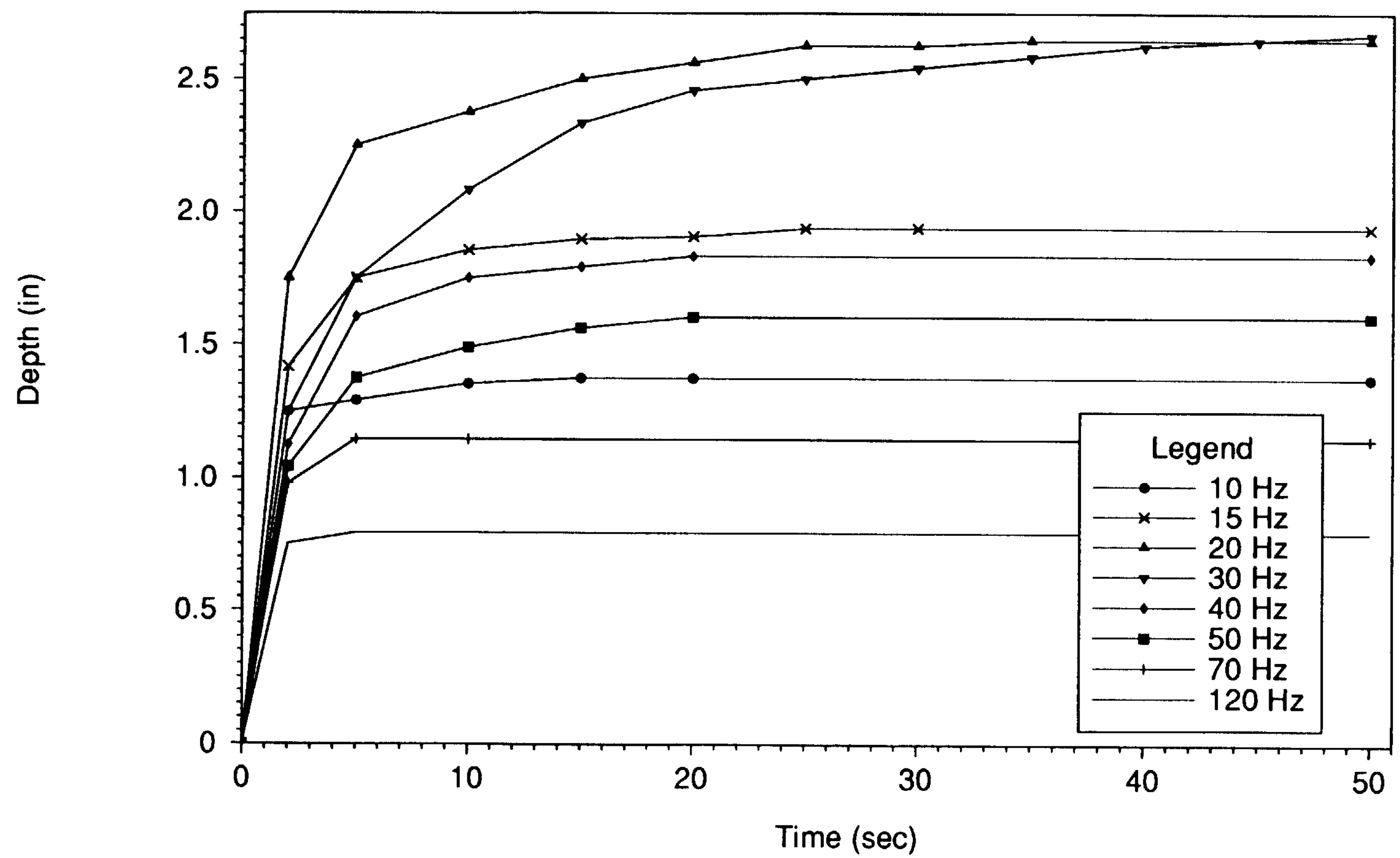
CENTRIFUGE MODELING OF PENETRATOR PERFORMANCE



Static Vs. Vibration Assisted Penetration



Average Depth - 6" Steel Tip Rod



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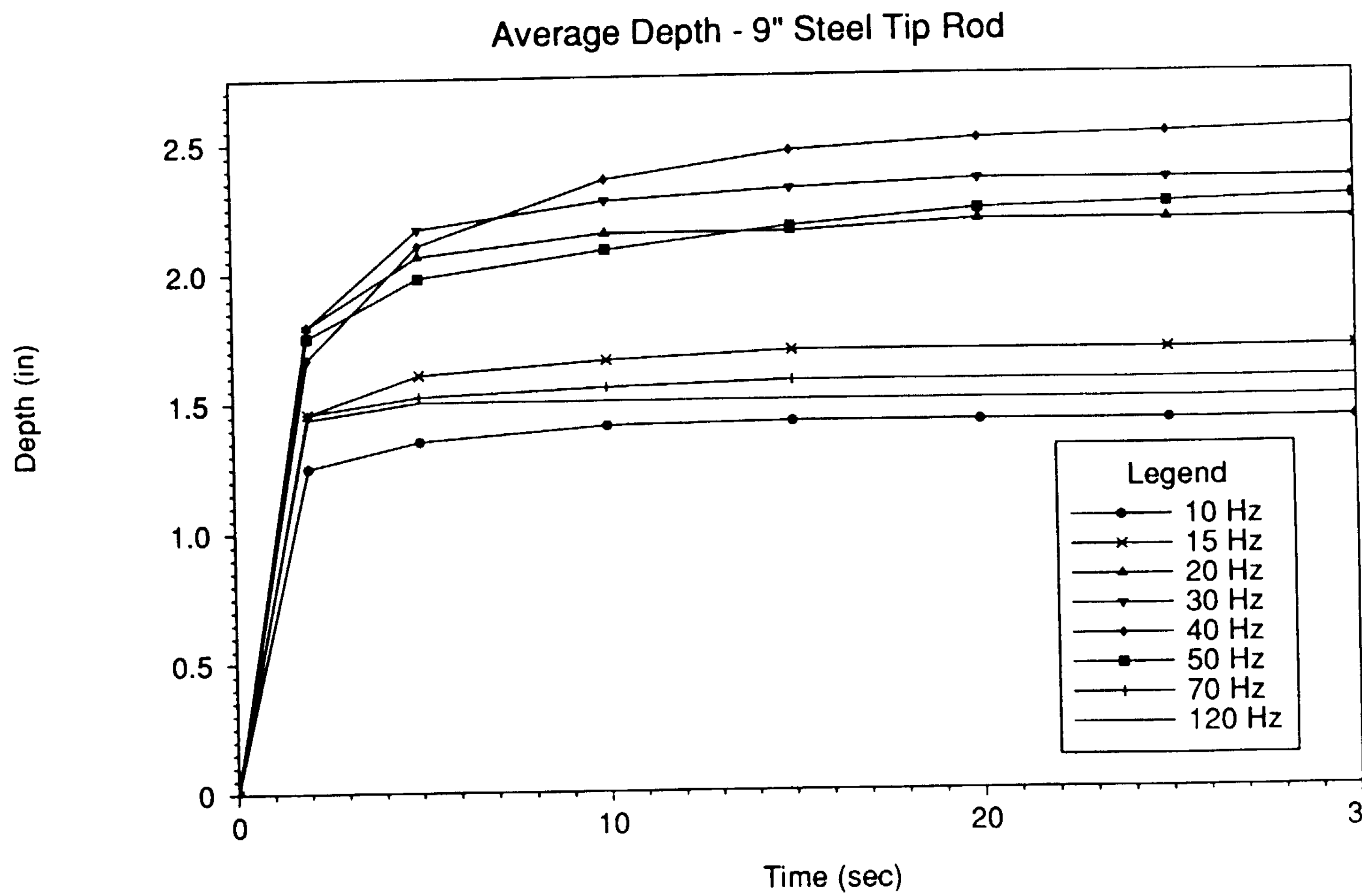
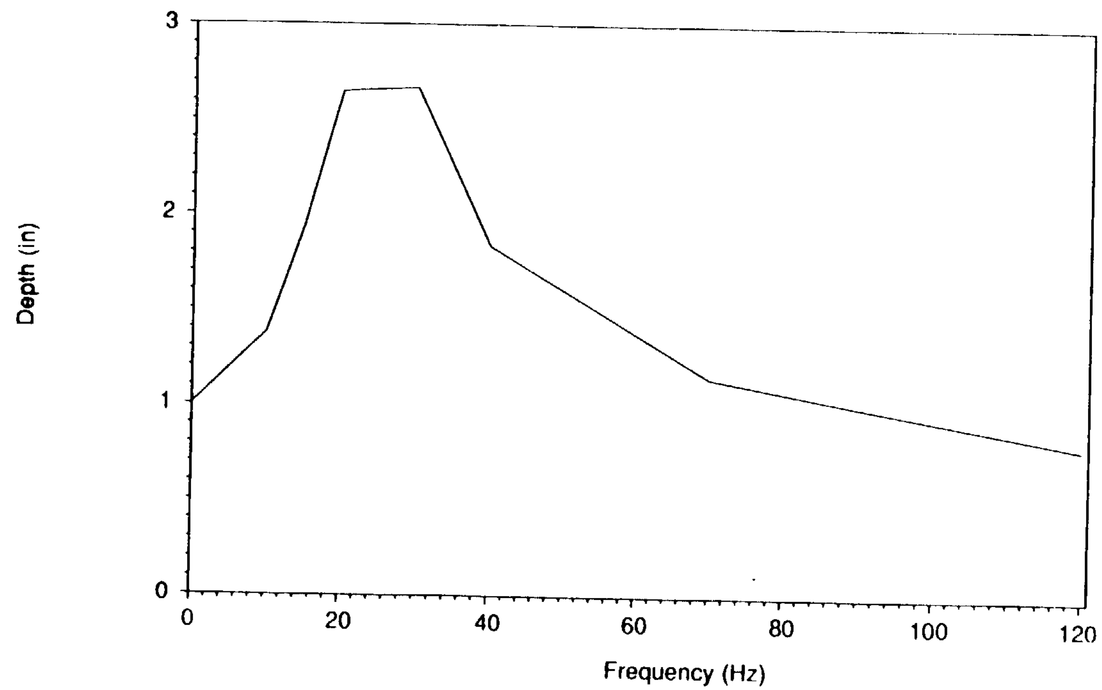

Average Depth - 9" Steel Tip Rod
Depth (in)
0
0.5
1.0
1.5
2.0
2.5
0
10
20
30
Time (sec)
Legend
10 Hz
15 Hz
20 Hz
30 Hz
40 Hz
50 Hz
70 Hz
120 Hz

RESPONSE OF 6 IN. STEEL PENETRATOR



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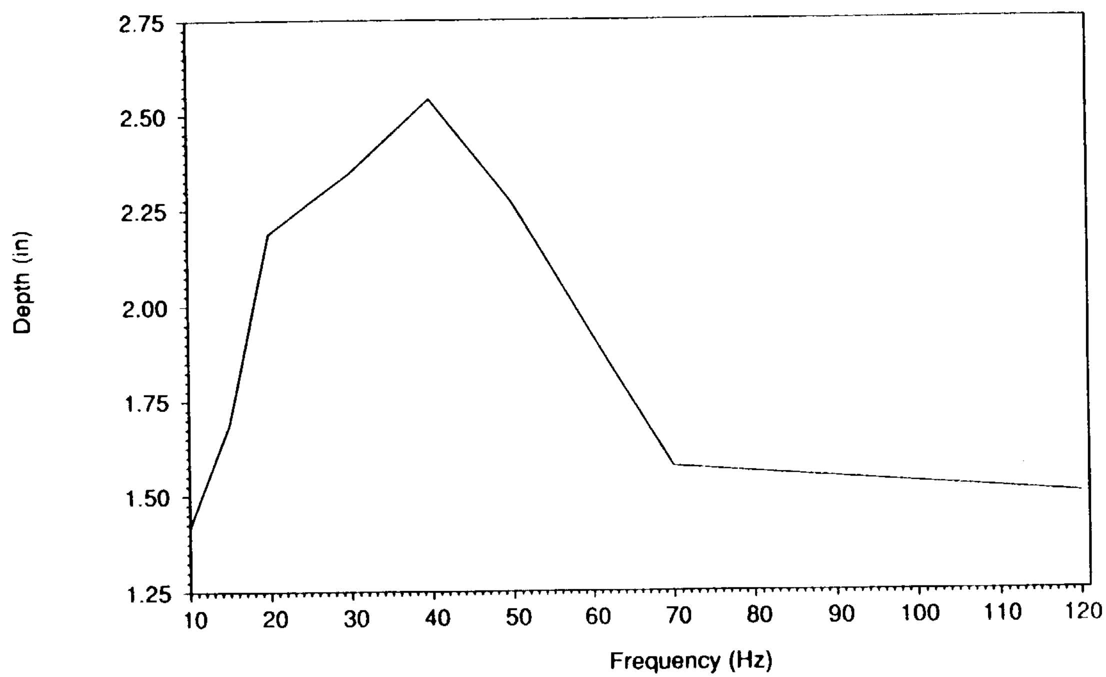
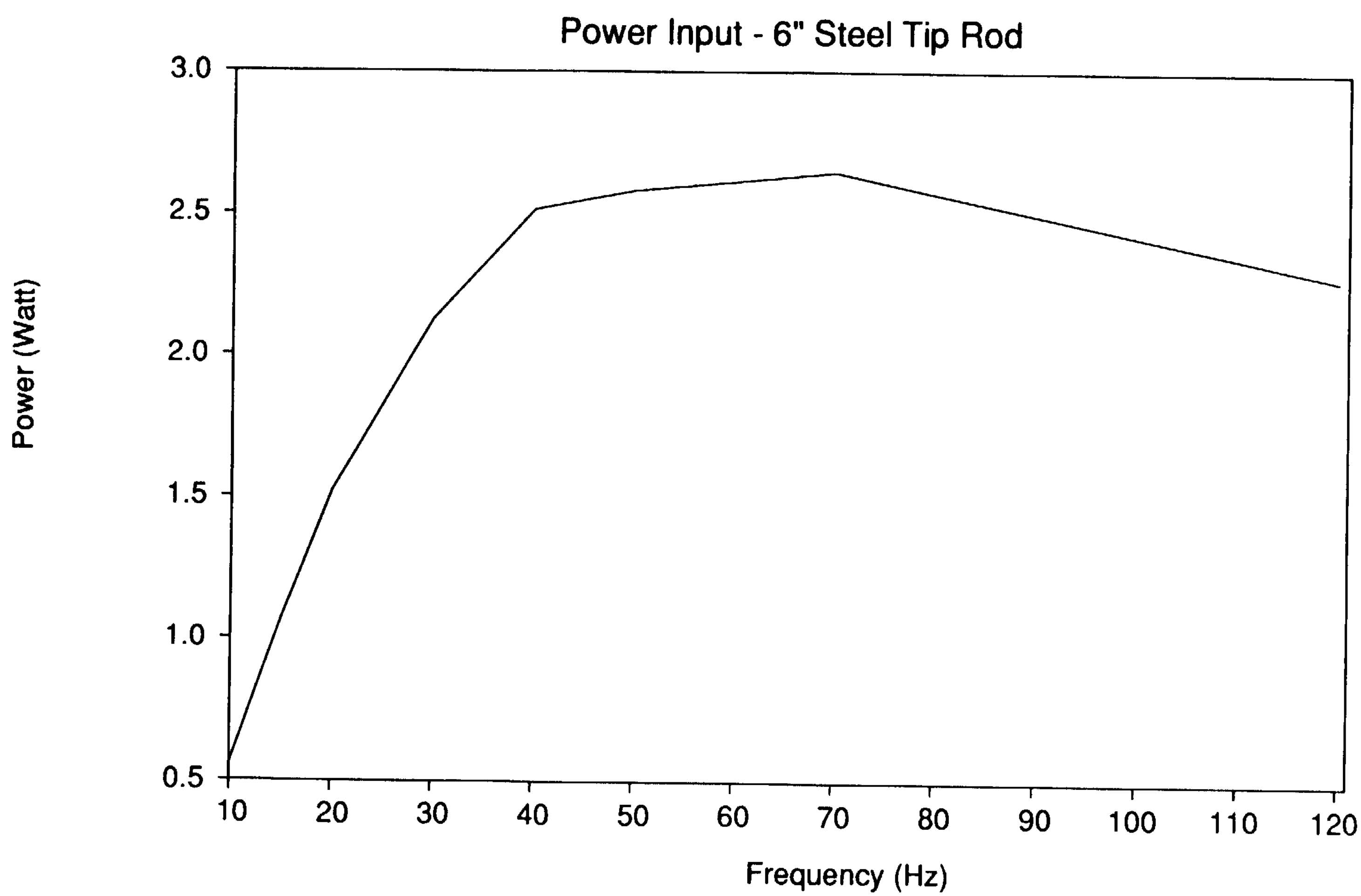
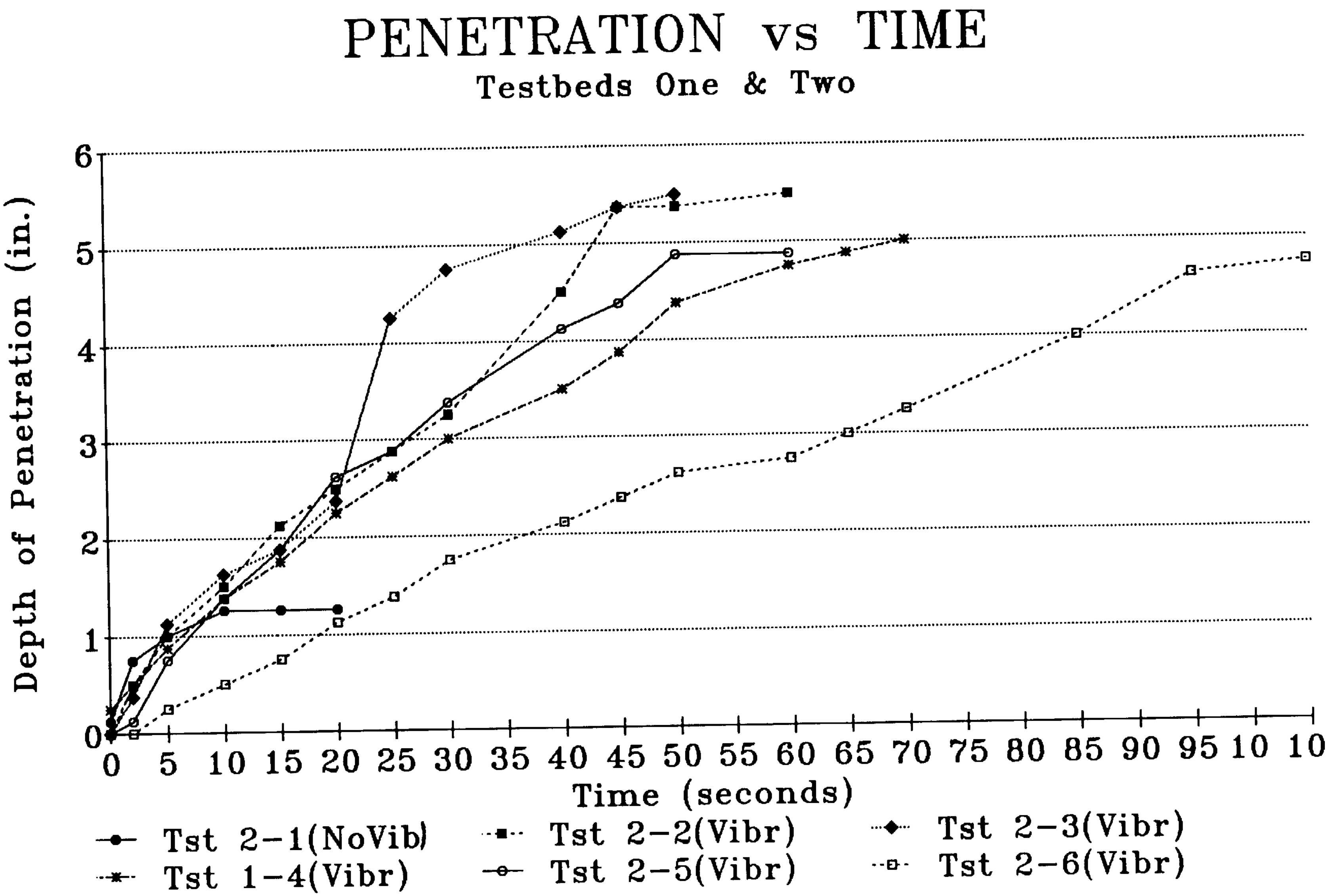
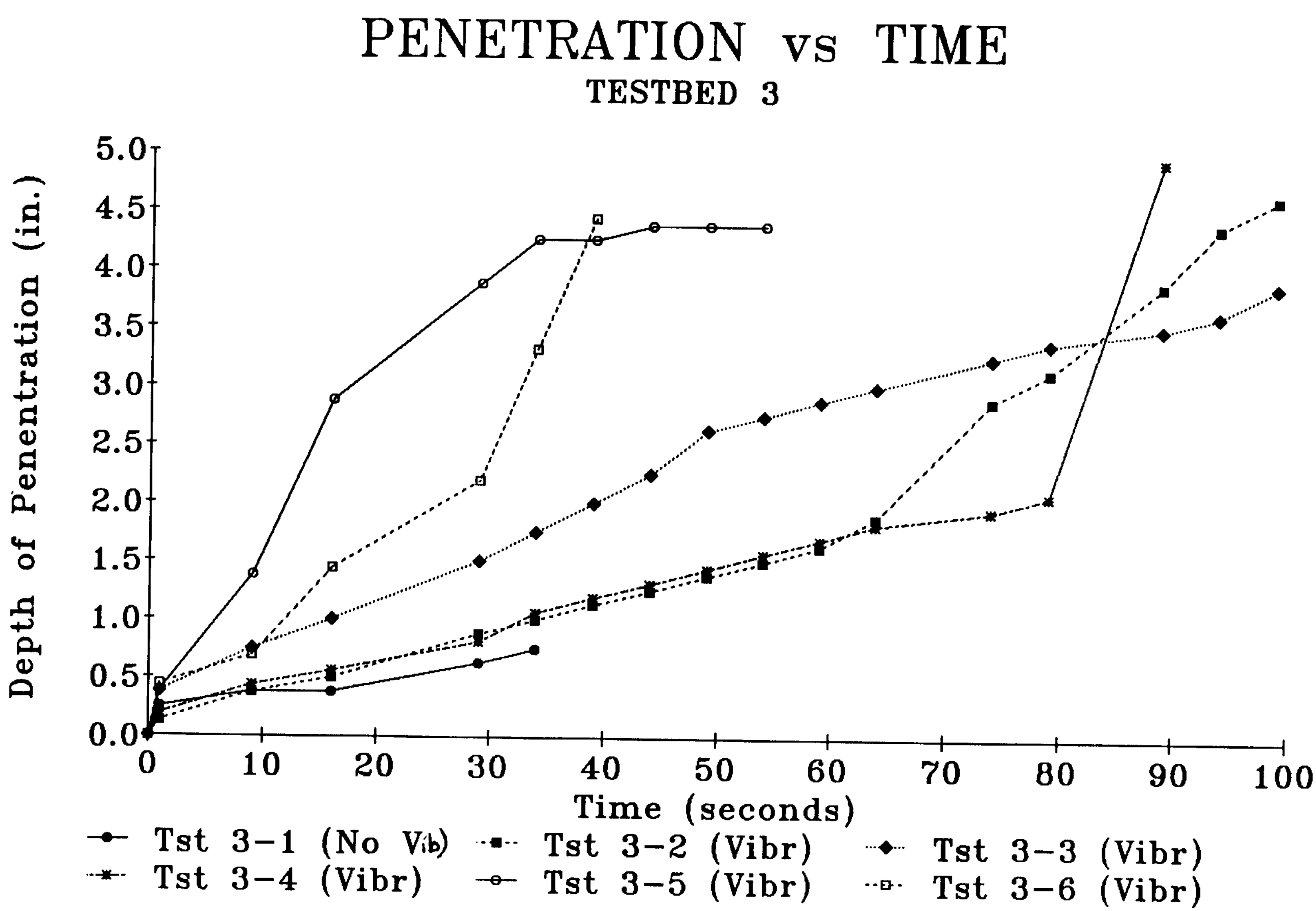
RESPONSE OF 9 IN. STEEL PENETRATOR




Power Input - 6" Steel Tip Rod
Power (Watt)
3.0
2.5
2.0
1.5
1.0
0.5
10
20
30
40
50
60
70
80
90
100
110
120
Frequency (Hz)


PENETRATION vs TIME
Testbeds One & Two
Depth of Penetration (in.)
0
1
2
3
4
5
6
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 10 10
Time (seconds)
Tst 2-1(NoVib)
Tst 2-2(Vibr)
Tst 2-3(Vibr)
Tst 1-4(Vibr)
Tst 2-5(Vibr)
Tst 2-6(Vibr)


PENETRATION vs TIME
TESTBED 3
Depth of Penentration (in.)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
60
70
80
90
100
Time (seconds)
Tst 3-1 (No Vib)
Tst 3-2 (Vibr)
Tst 3-3 (Vibr)
Tst 3-4 (Vibr)
Tst 3-5 (Vibr)
Tst 3-6 (Vibr)

N93-26413

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Indigenous Lunar Construction Materials

Wayne Rogers
Stein Sture

Third Annual Symposium
November 21 & 22, 1991

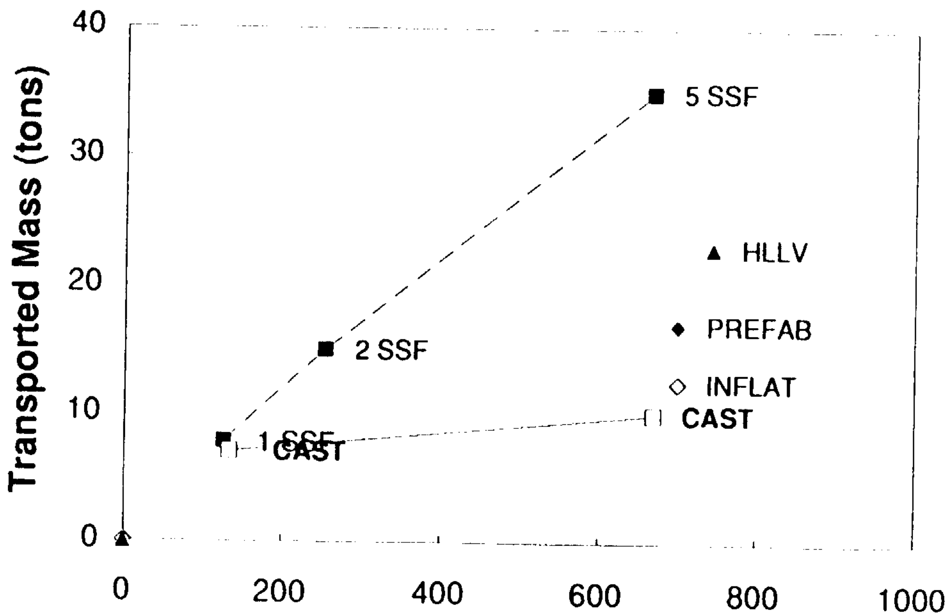
Motivation

The utilization of local resources for the construction and operation of a lunar base can significantly reduce the costs of transporting materials and supplies from Earth.

- Primary examples of utilization of lunar resources: radiation shielding, oxygen extraction, water production, helium-3 mining.
- **Construction materials** are excellent candidates for utilization of local resources: they are relatively simple, heavy, and available. Raw materials may be by-product of other operations such as oxygen extraction.

Why	Why not
Pay-load weight savings	Unfamiliar technologies
Long term manned presence in space	Significant infrastructure

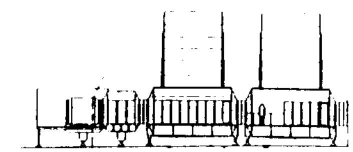
Comparison of Various Lunar Structures



SFF

Space Station

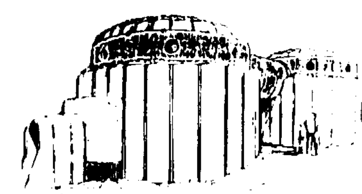
Freedom Module



HLLV

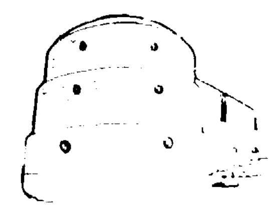
Heavy Lift Launch

Vehicle Module



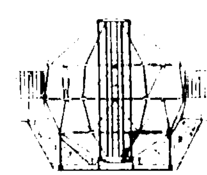
PREFAB

Deployable Module



INFLAT

Inflatable Sphere



CAST Cast Regolith Structure

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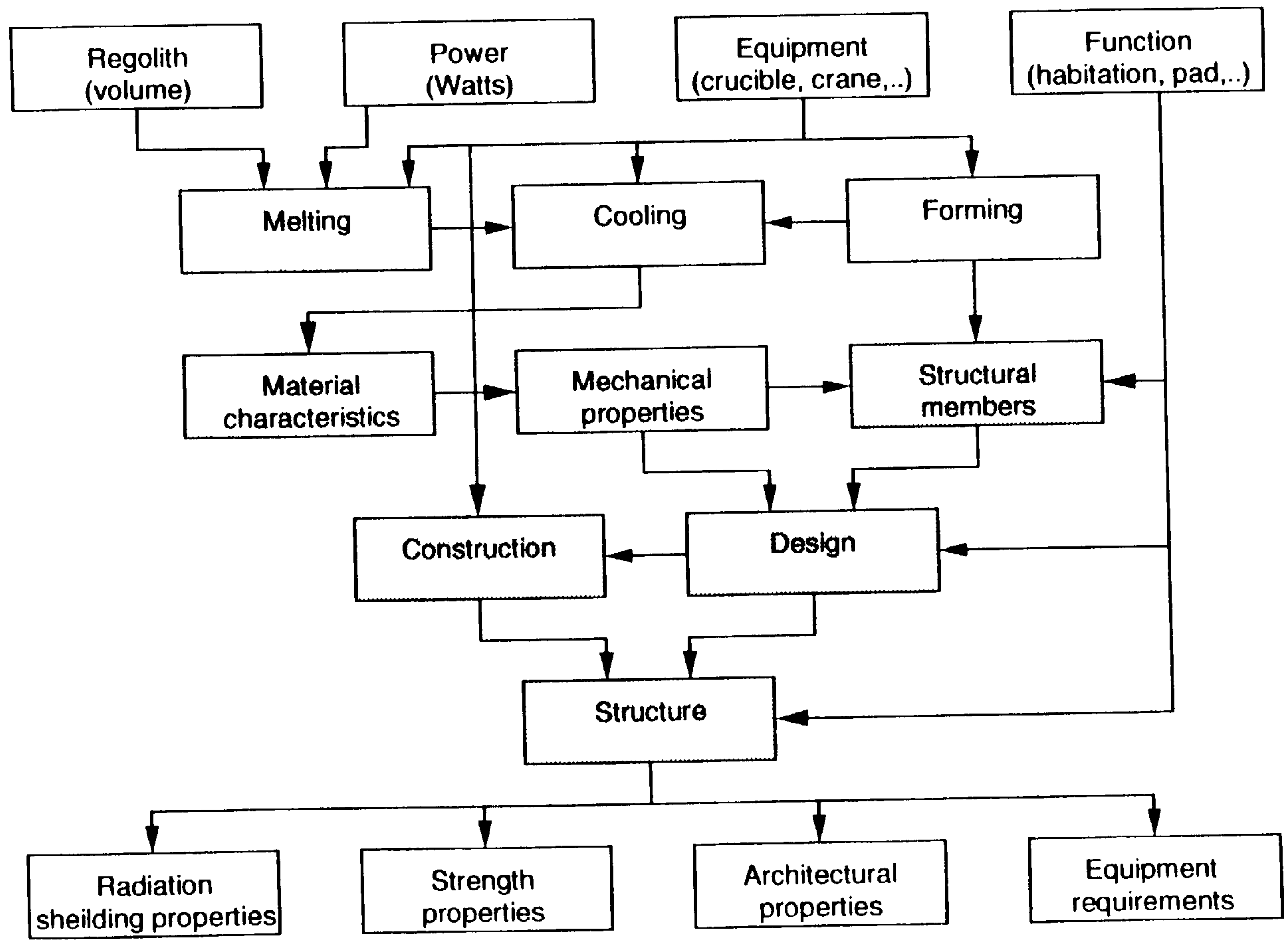
Processing - material - construction - structure relationships



Objectives

- Investigate the *feasibility* of the the use of local lunar resources for construction of a lunar base structure.
- Develop a material processing method and integrate the method with design and construction of a pressurized habitation structure.
- Estimate specifications of the support equipment necessary for material processing and construction.
- Provide parameters for systems models of lunar base constructions, supply and operations.

Indigenous Lunar Construction Materials

- **Minimally processed materials**: lunar rocks, regolith mortar, compressed regolith, free flowing molten regolith, for domes, roads, and landing pads (Khalili SCIA). *Materials do not have good mechanical properties.*
- **Solar power fused regolith** for large layered slabs (Clifton). *Solar power is not sufficient to melt large quantities of regolith in reasonable lengths of time.*
- **Sintered and hot pressed regolith** for bricks, plates, columns (Simonds, NASA LSI; Meek, UT; Vaniman, LANL; Sullivan, Battelle). *Small structural components. Not suited to tensile (pressurized) loading conditions or automated construction.*
- **Concrete**: traditional steel reinforced concrete structure using columns, beams, and slabs (Lin, CTL). *Lack of water.*
- **Iron and Steel**, high quality construction materials (UA). *Complex processing methods with high energy requirements.*
- **Cast basalt:** liquified regolith cast into large slab forms (Capps and Wise, Boeing; Binder, Lockheed)

Guidelines for Material Processing Method

- Material processing method should be applicable to a variety of structural element geometries and sizes.
- Processing method should produce a material with good, consistent mechanical properties.
- Amount of material processing-specific support equipment should be minimized.
- Material processing method should be integrated with structural design and construction operations.
- Processing and construction steps should be simple in order to accommodate robotic automation.

Assumptions

- Material processing method is intended for **far-term lunar base**. *A certain level of infrastructure must be in place.*
- **Power source** of 100 kW is available (SP-100 nuclear reactor). *This places tight constraints on processing time and structural component size.*
- **Earth moving equipment** is available. *All scenarios include plans for regolith shielding which requires earth moving.*
- **Lunar crane** with 10 ton capacity is available. *Near-term lunar base construction is likely to require lunar crane.*

Cast Lunar Regolith

- **Raw materials**: regolith is abundant over the lunar surface. Chemical composition of regolith is very similar to terrestrial basalts.
- **Terrestrial cast basalt** processing methods are moderately well established. Cast basalt has good mechanical properties and can be formed into complex geometries.
- **Proposed cast regolith** process is a simplification of terrestrial cast basalt suited to the lunar environment. Benificiation, grinding, homogenization steps are unnecessary. High vacuum and low gravity pose no unusual problems.
- Material processing may be integrated with oxygen production.

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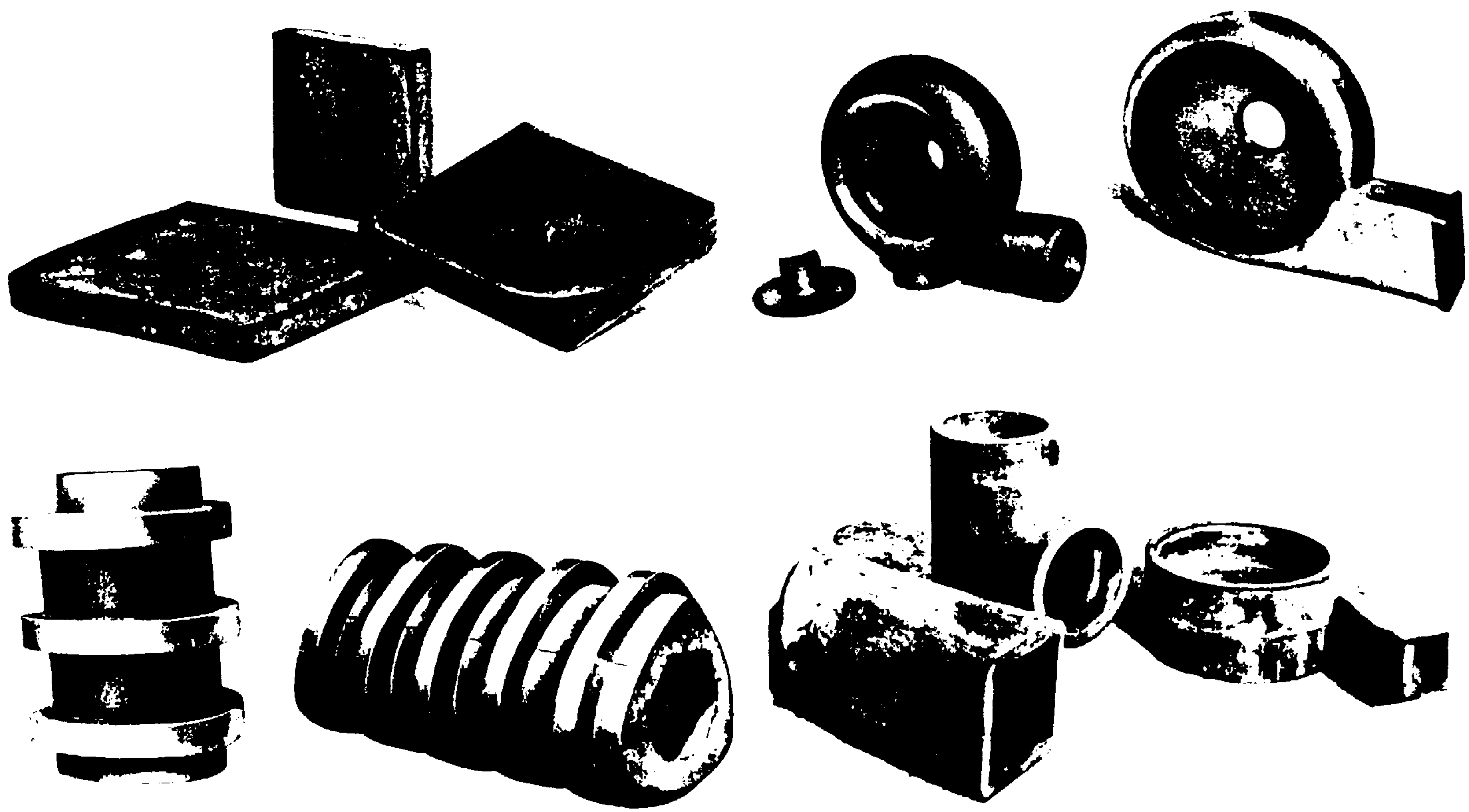
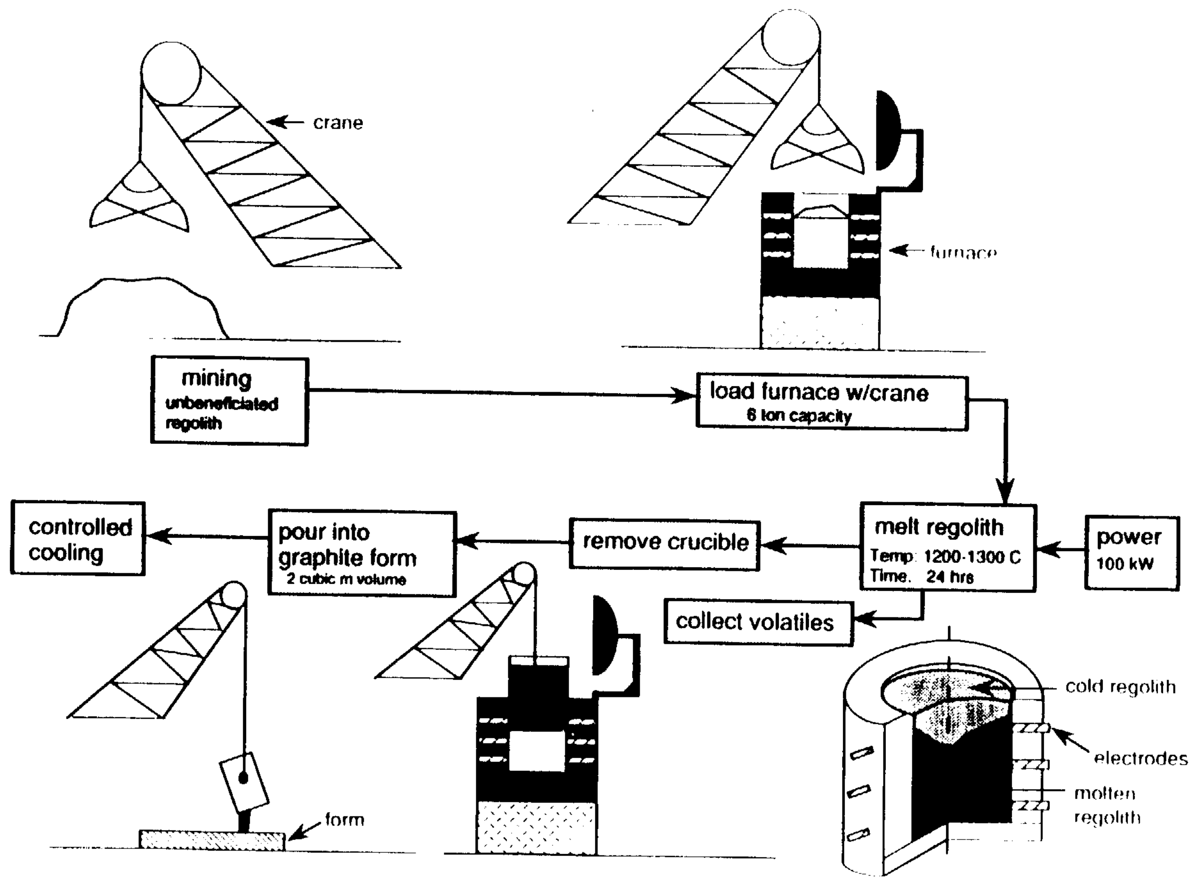
Examples of Cast Basalt Components



Cast Regolith Process



Processing Equipment

- **Furnace**: batch operation, electrical resistance, 1300°C capability, 90% efficiency, 3 ton weight, enclosed heating chamber for recovery of volatiles (hydrogen, nitrogen,...). At 100 kW, melting cycle lasts 24 hrs for 6 ton regolith capacity.
- **Ladle**: heating chamber of furnace is removable to act as a ladle for the transfer of molten regolith to casting forms.
- **Casting forms**: reinforced graphite panels, 1500°C capability, 0.5 ton weight. Reflective surfaces reduce radiative heat transfer for controlled cooling and recrystalization over a 24 hr period.

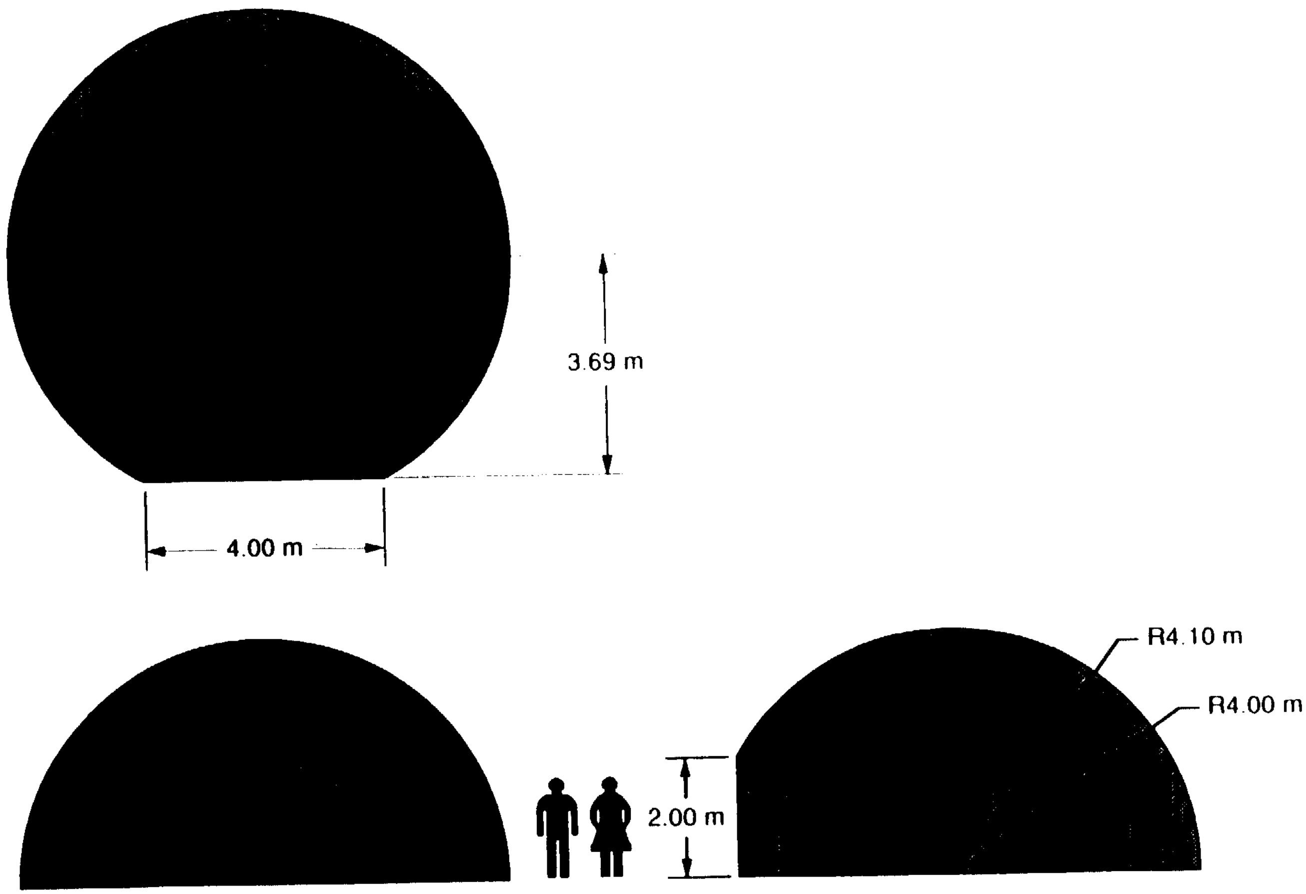
Mechanical Properties of Cast Basalt

	Cast Regolith	Concrete	Cast Iron	Aluminum
Density (g/cc)	2.9	2.4	7.1	2.8
Elastic Modulus (GPa)	110	21	160	70
Tensile Strength (MPa)	>35	7	125	100*
Fracture Tough. ($MPa\sqrt{m}$)	2	2	15	25
Thermal Expan. ($x10^{-6}/°C$)	7.8	13	11	22
Melting Point (°C)	1200	-	1400	600

* yield

Material Properties and Structural Design

- **Brittle material**. Design must minimize tensile and bending stresses and stress concentrations. Compression loading is ideal but unrealistic for pressurized structure.
- **Joining** introduces stress concentrations so the minimum number of structural components should be used. The maximum size of a structural element is dictated by the capacity of the batch furnace, casting capabilities, and constructibility.
- **Net shape forming** is necessary because cutting is very difficult.
- Large factors of safety must be avoided to reduce mass of structure and time required for material processing.
- Earth-based structural elements are necessary for joining, reinforcement, and air-locks. Design should minimize these.


3.69 m
4.00 m
R4.10 m
R4.00 m
2.00 m

Future Work

- **Material processing demonstration**. Demonstrate liquification, casting characteristics, viscosity, cooling and recrystalization, environmental effects.
- **Material property evaluation**: density, elastic moduli, fracture toughness, statistical measures of strength.
- **Structural design**. Develop a point estimate of a pressurized lunar habitation structure based on cast regolith.
- **Construction methods**. Establish integrated material processing and construction steps. Investigate potential for robotic automation.
- **Scale structural testing**. Validate design models and demonstrate structural reliability of point design.

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Design Concepts for Pressurized Lunar Shelters Utilizing Indigenous Materials

John Happel
Kaspar Willam
Benson Shing

Concept 1
- Cast basalt cylindrical segments; held together w/ long tensile cables.
- No end closures, ingress, egress, windows, etc.
- Requires clamps/jacks to final assembly.

Option 2
- arch slabs
- 4-sided w/ tension strands.

Notes - not much has been done here. Most of the work is in the future.
- should consider tunneling & excavation.
- should develop tool (KC Park)

Third Annual Symposium
November 21 & 22, 1991

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Structural Design Concepts for Pressurized Lunar Shelters Utilizing Indigenous Materials:

John Amin Happel, Kaspar Willam, Benson Shing

1. Design Objective:

Pressurized shelter built of indigenous lunar materials

2. Scope:

a.) Structural Design w/ Lunar Conditions

b.) Review of Previous Concepts

c.) Selection of Indigenous Material

d.) Design Variables

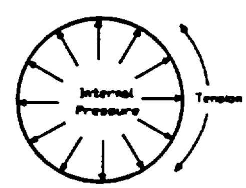
e.) Design 1: Cylindrical Segments

f.) Design 2: Arch-Slabs with Post-Tensioned Ring Girders

3. Lunar Conditions Which Impact Design:

Primary Factors:

* High Vaccuum;



Pressure vessels

Tension loads

Primary design load

1 atm. pressure = 1440 psf load, terrestrial loads ≈ 150 psf

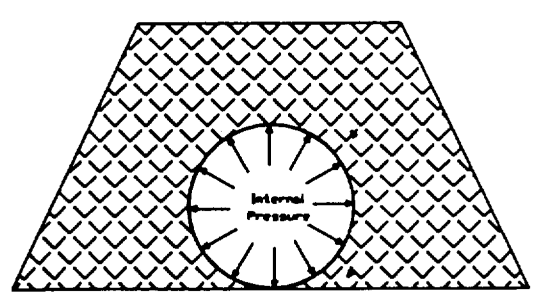
100 ft. (30.5m) of regolith to balance pressure load

* High Radiation;

Radiation shielding required

15 ft. (4.5m) regolith (or more?)

Regolith excavation

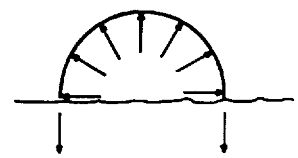


* Poor Soil Conditions for Anchoring Foundations;

  Regolith depth > 16ft (5m) most locations

  Tension anchors difficult

  "floating" structures



* Very Remote Site;

  Setup & resupply expensive

  Indigenous materials permit rapid expansion

  Safety

  Speed & Simplicity

Secondary Factors:

Meteoroids (impact damage)

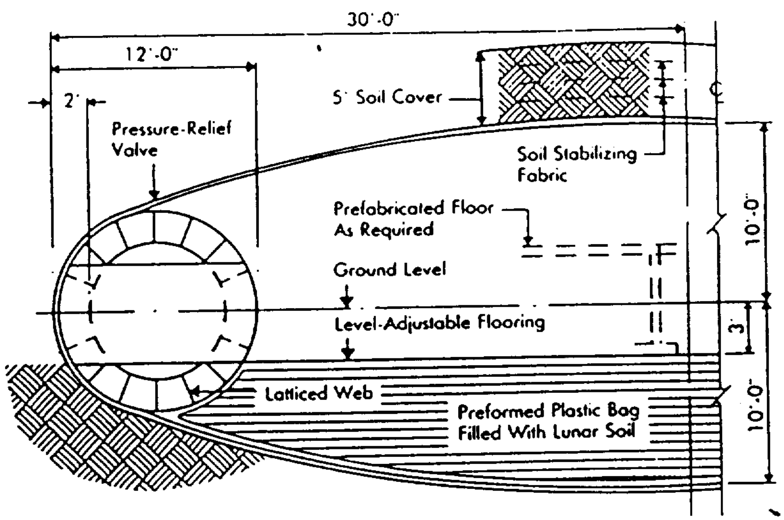
Low Gravity (construction)

Long Days and Nights (construction)

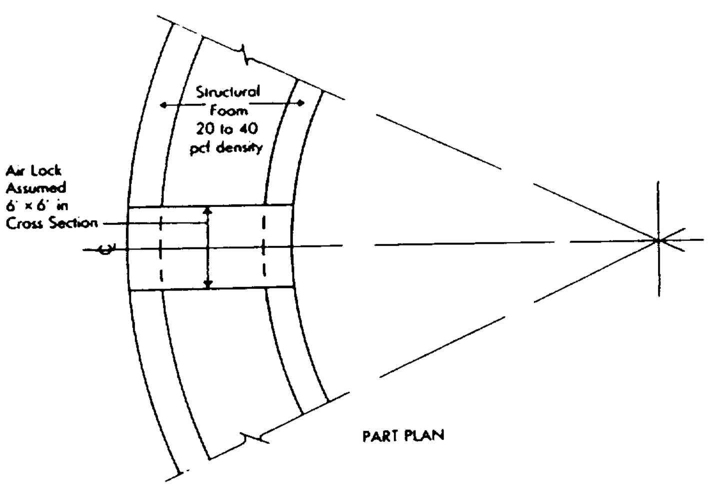
Extreme Temperatures (sealants)

4. Review of Previously Proposed Concepts:

*Chow, P.Y., Lin, T.Y. ; T.Y. Lin Assoc.; 1989



CROSS SECTION



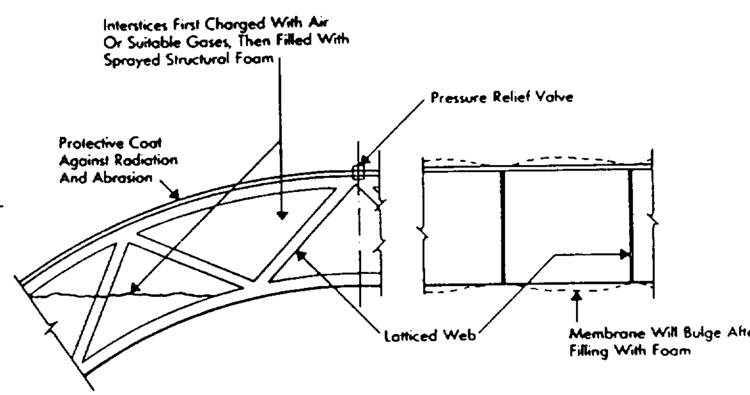
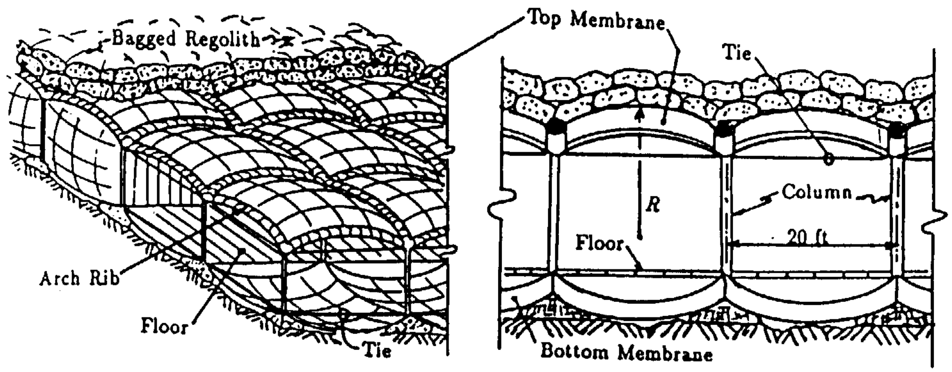


FIG. 3. Wall Construction and Latticed Web Details

FIG. 1. Pressurized Self-Supporting Membrane Structure (PSSMS)

*Vanderbilt, M.D., Criswell, M.E., Sadeh, W.T.; C.S.U.; 1988



(a) Cutaway of Structure

(b) Section Through Interior

Figure 2. Cutaway and Section of Structure

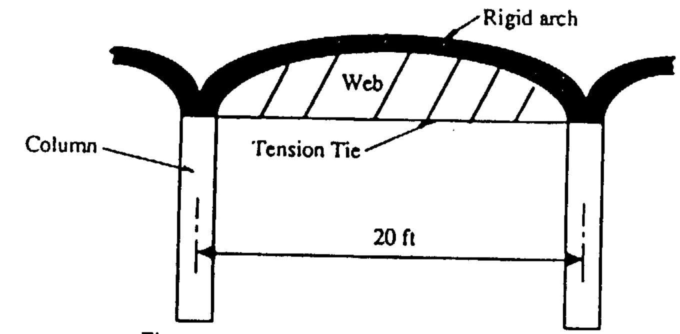
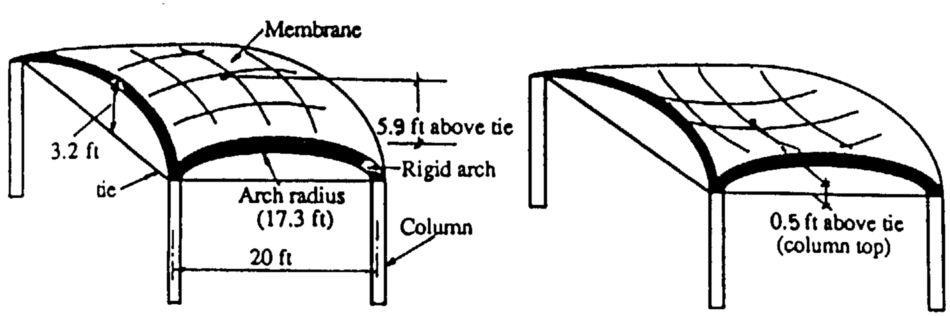


Figure 5. Arch Rib System with Web



Inflated Shape

Deflated Shape

Figure 3. Arched Membrane System

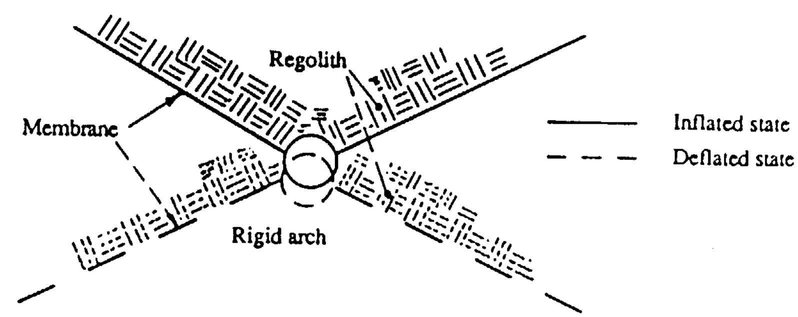


Figure 4. Cross Section of Arch Rib

*Yin, P.K., NASA 90 Day Study; 1990

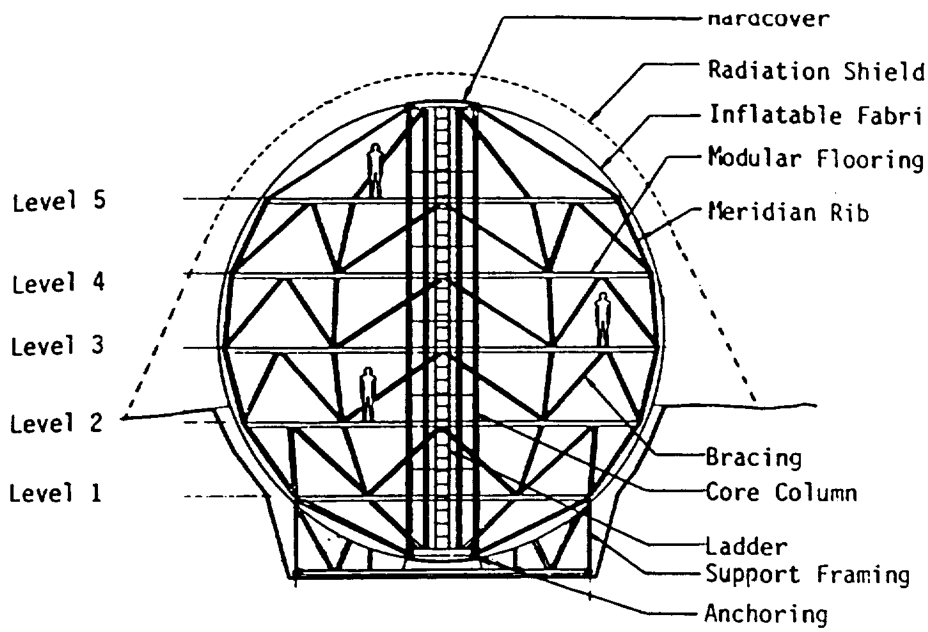


Figure 1. - Elevation

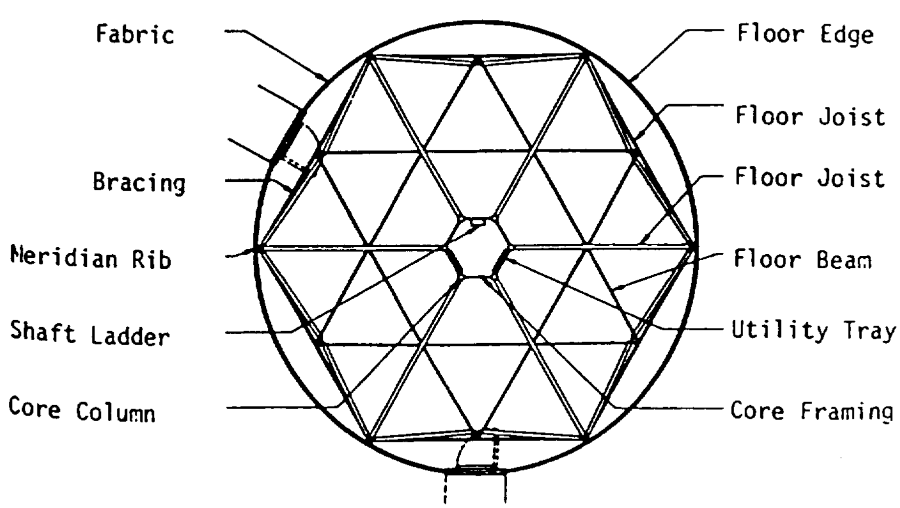
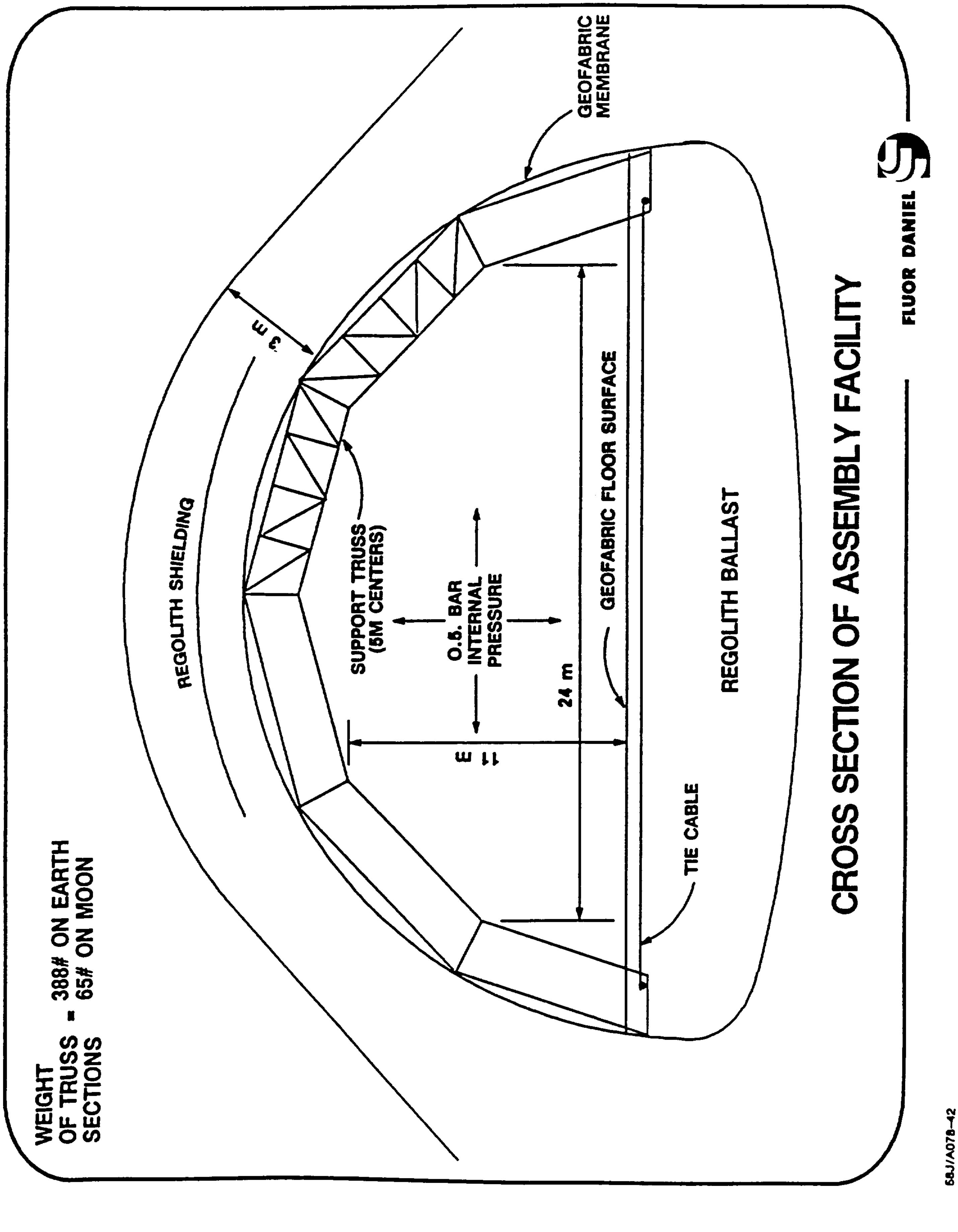


Figure 2. - Typical Framing Plan

*Richter, P.J., Drake, R.M.; Fluor Daniels; 1990



5. **Rationale for Indigenous Materials:**

* Large structures need large quantities of materials

* Permits rapid growth and expansion of activities;

  Reduces shipping costs

  Reduces time

* Ship high tech equipment not structural mass

6. **Indigenous Material Choices:**

* Fused and Sintered Regolith, Bricks and Blocks;

  Easy to manufacture

  Low strength, highly heterogenous material properties

* Lunar Glasses and Glass-Glass Composites;

  High strength

  Very promising still experimental

* Lunar Concrete;

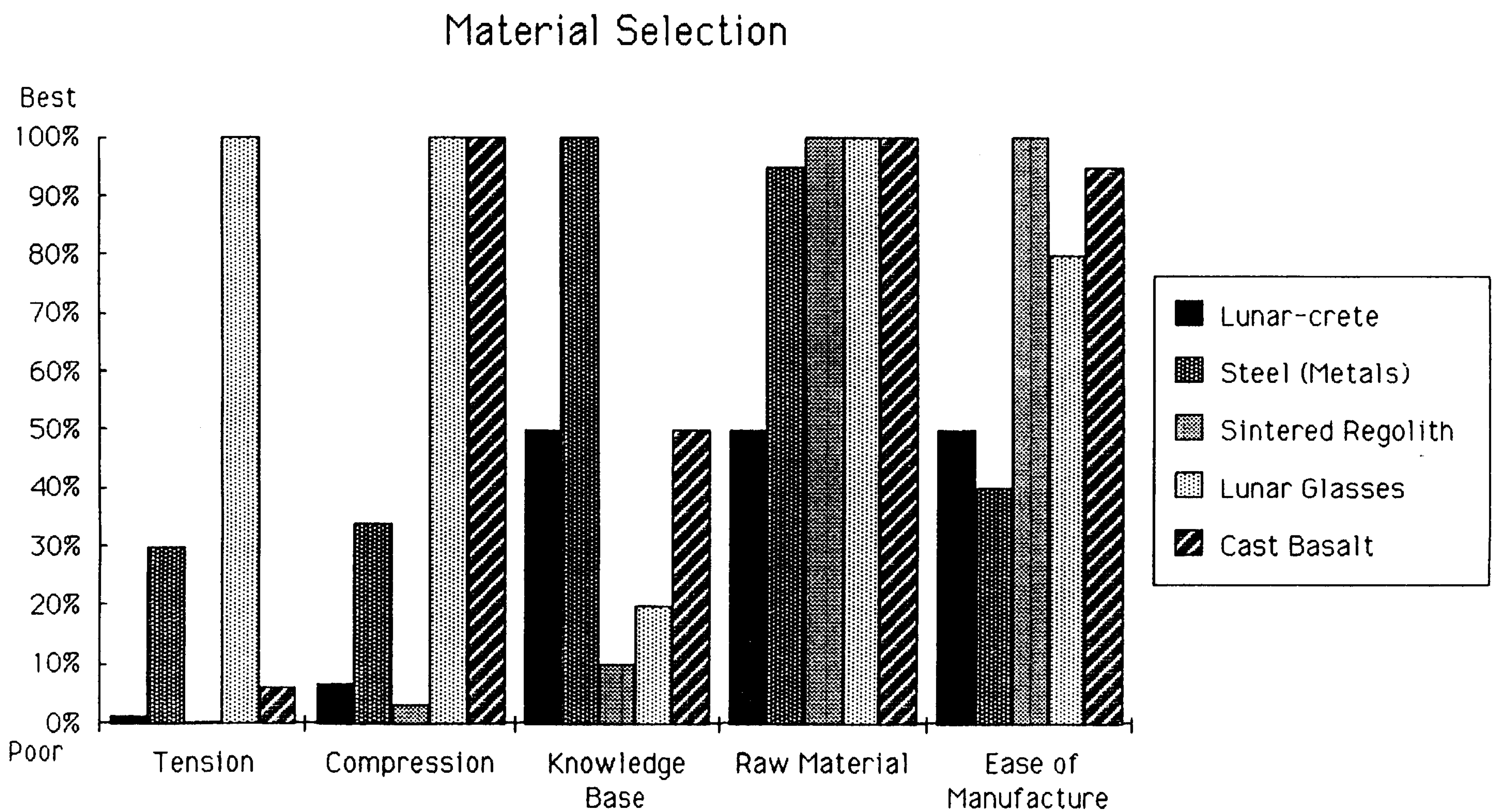
  Raw materials for aggregrate and cement available

  Mechanical properties well understood

* Steel and other Structural Metals;

  Excellent mechanical properties

  Complicated, multi-step manufacturing process


Material Selection
Best
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Poor
Tension
Compression
Knowledge Base
Raw Material
Ease of Manufacture
Lunar-crete
Steel (Metals)
Sintered Regolith
Lunar Glasses
Cast Basalt

* Cast Basalt;

  One step manufacturing process

  Good mechanical strength properties

  <u>Selected as primary construction material</u>

7. **Cast Basalt Properties:**

Tensile strength: f_t= 34.5 MPa (5,000 psi);

Compressive strength: f_c=538 MPa (78,000 psi);

Modulus of elasticity: E=100 GPa (14E6 psi);

Fracture toughness: Kc= 2 MPa$\sqrt{m}$, +/- 50%

Mass density: 3 g/cm^3 (specific lunar weight= 31.2 lunar lb/ft^3).

Melting point: 1300°C

8. **Design Variables:**

* Shelter sizing;

  large enough to contain Space Station Freedom modules

* Loading conditions;

  Internal pressure=10 psi (0.069 MPa)

  Regolith shielding depth= 15 ft (4.5m)

* Constraints imposed by cast basalt;

  Brittle:

  - Low tensile stresses
  - Compression should dominate structure
  - Post-tensioning

  Material hardness

  Maximum volume of single component= 70.6 ft^3 (2 m^3)

  - Determined by casting process

* Maximum moveable weight= 1,670 lunar lbs (44.5 kN)

* Minimize use of imported materials;

  Minimize tensile reinforcement

* Self-equilibrating structure;

  Tensile loads self-contained

  No arches, vaults, or domes

* Minimize excavation

9. Design One, Cylindrical Segments:

Dimensions:

Diameter= 23 ft (7m)

Wall thickness=3 in. (7.6 cm)

Total length= 60 ft (18.3m), forty segments

Segment length= 1.5 ft. (46 cm)

Floor thickness= 8 in. (20 cm)

Leg width= 15 in. (38 cm)

Segment mass ≈ 2200 lunar lbs (6000 kg)

Design Features:

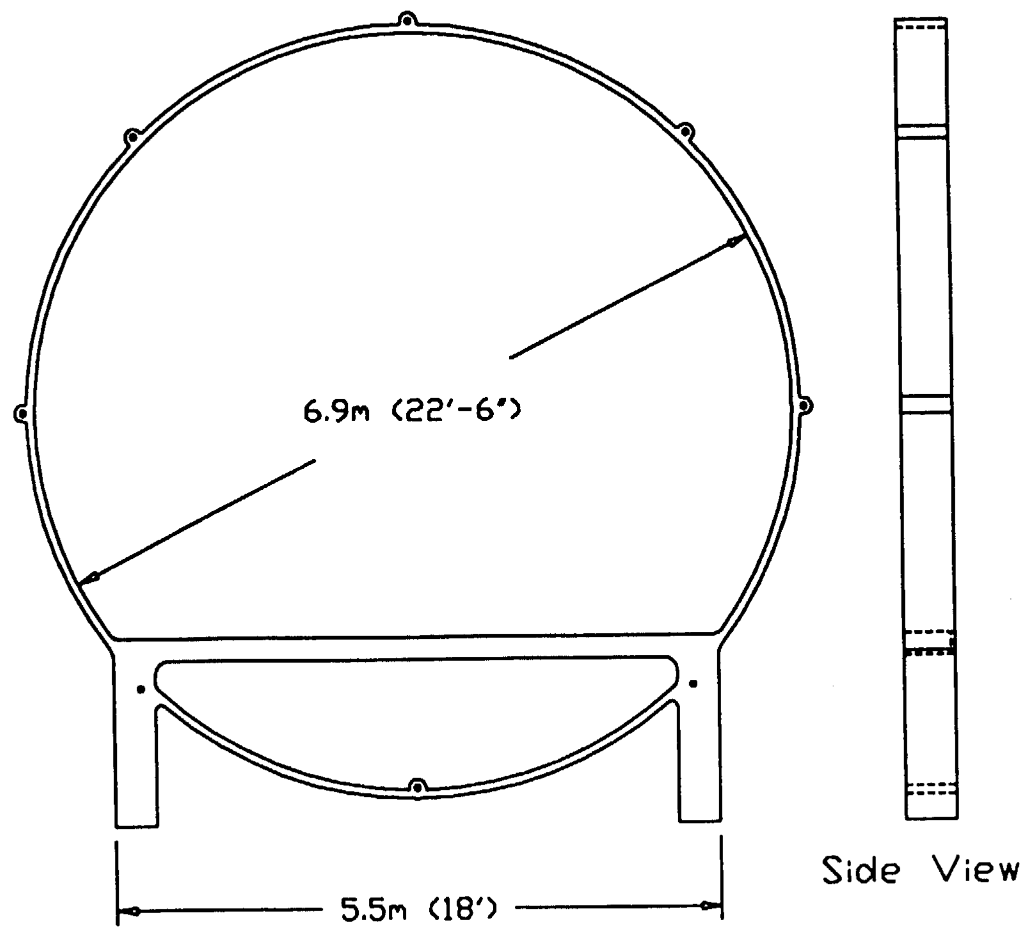
*Positive;

- Pre-cast floor
  - Passage for utilities
- Rapid assembly
- Readily expandable
- Only three components
- Minimal use of reinforcing
- Efficient

*Negative;

- Feasibility of casting basalt into large structural elements
  - a.) under lunar conditions
  - b.) mold design
- Uncertain crack and notch sensitivity of cast basalt

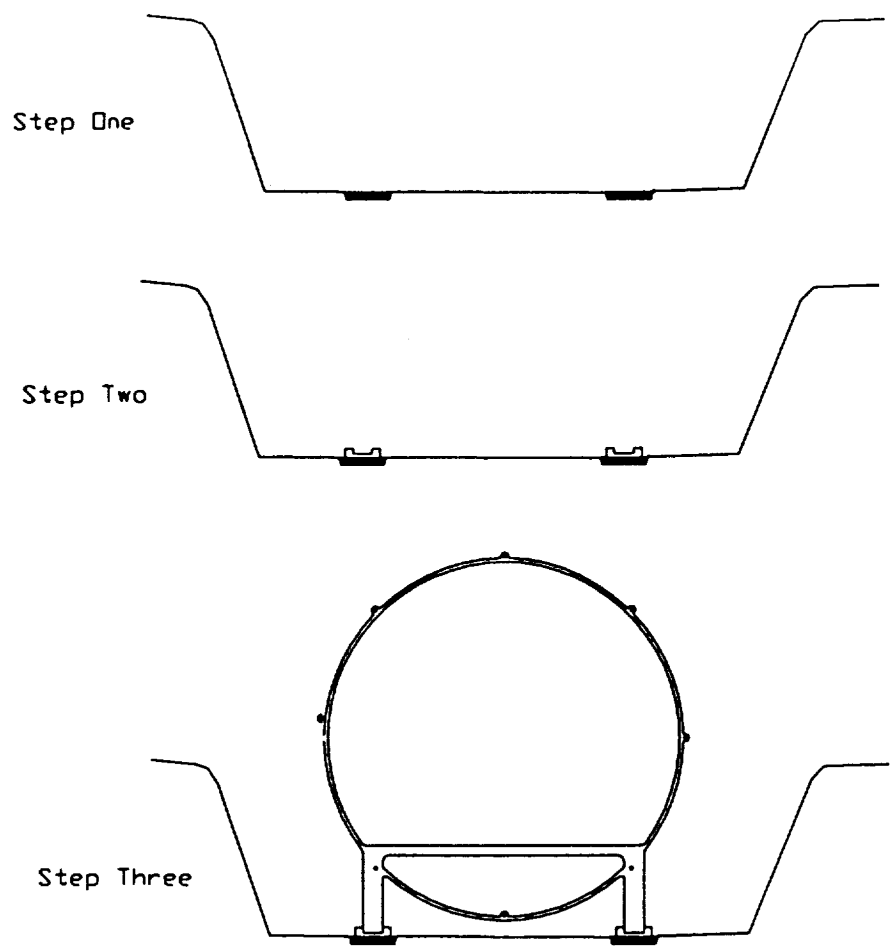
CAST CYLINDRICAL SEGMENT



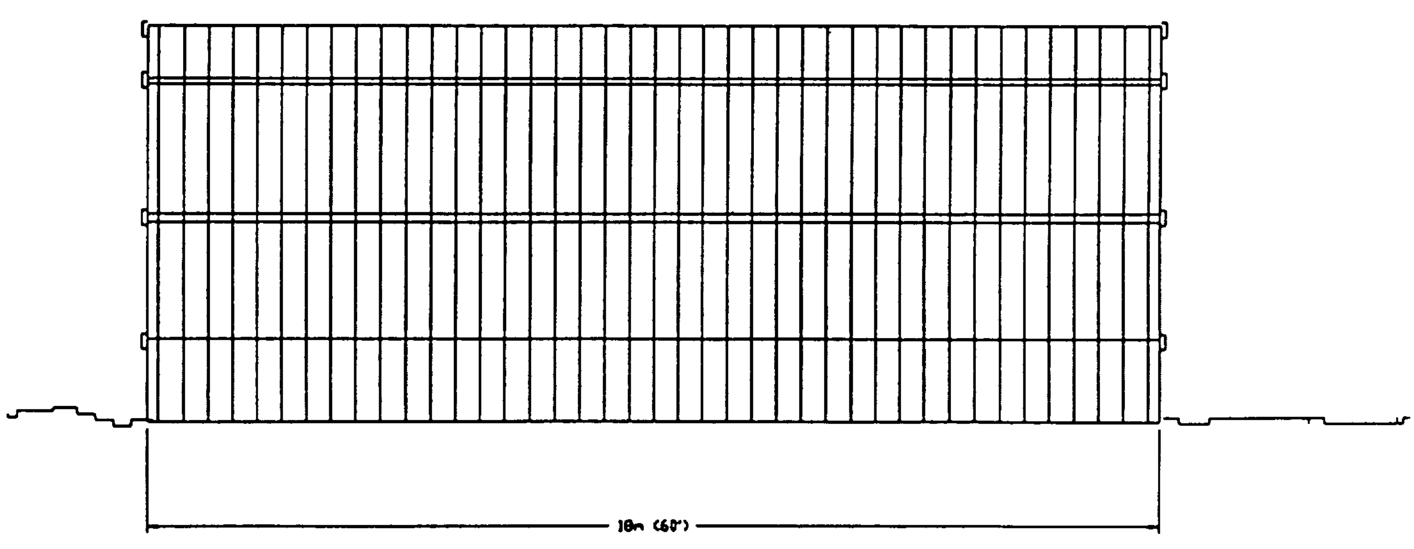
Construction Sequence:

1. Cast 40 segments, 2 end caps
2. Smooth site, area= 33 x 60 ft (10 x 18m)

   or excavate a flat-bottomed trench, depth ≈ 6.5 ft. (2m)
3. Place two long guide-rail beams
   - a.) cast in segments
   - b.) cast in place
4. Align rail sections and bolted together
5. Place first cylindrical segment
   - a.) Insert eight tendons into ducts
   - b.) Install the gasket material
6. Place following segment on rails
   - a.) advance tendons through the current segment
   - b.) repeat steps 5 & 6 until the last segment is in place
7. Install end caps
8. Post-tension tendons to pull entire structure tightly together
9. Pressurize structure
10. Bury the structure
11. Fit out interior with partitions and utilities



Assembled Base



10. **Design Two, Arch-Slabs with Post-Tensioned Ring Girders**

Dimensions:

* Overall Dimensions;

Height= 18 ft (5.5m), Width = 23 ft (18m)

Length= 60 ft.(18m)

*Slab Dimensions;

Span= 76 in (193 cm), Edge thickness≈ 10 in (25 cm)

Center thickness≈ 3 in (7.6 cm)

*Girder Dimensions;

Span= 25 ft (7.6m), Width= 7 in (17.8 cm)

Center depth= 36 in (91.5 cm), End depths= 12 in (30.5 cm)

Design Features:

*Positive;

Compression dominated

Inherently safe design

Crack growth limited

Components utilize simpler molds

Orthogonal expansion

All surfaces flat

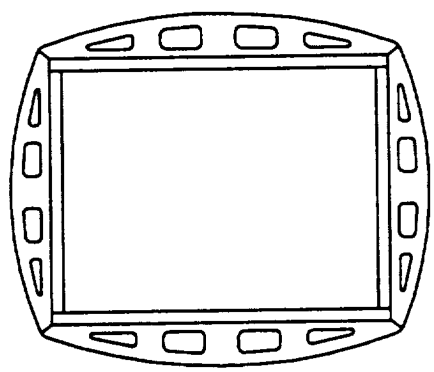
*Negative;

Greater number of cast pieces

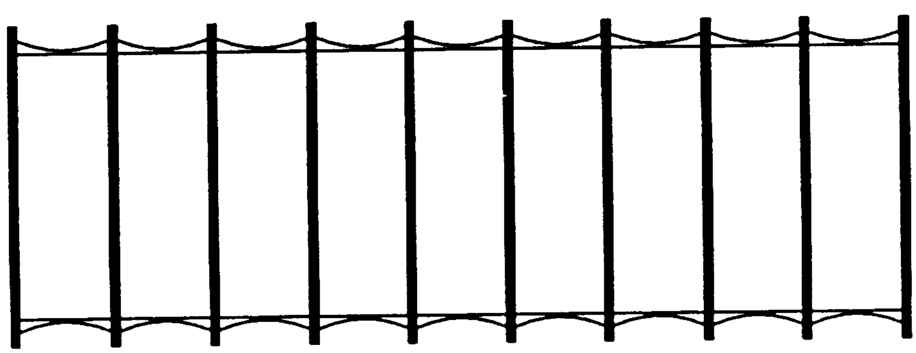
More complicated construction sequence

Much more reinforcement material needed

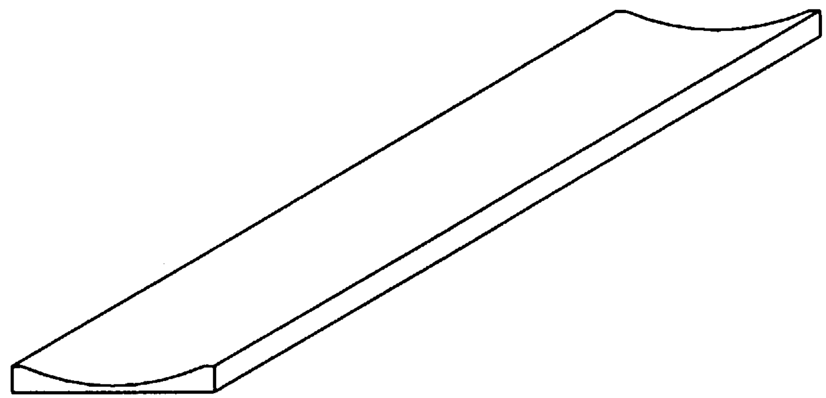
Archslabs With Post-Tensioned Ring Girders



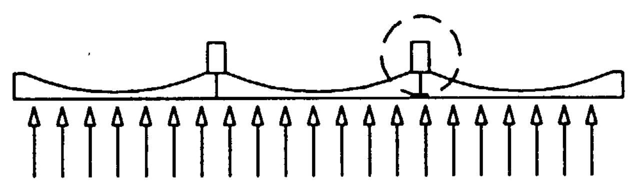
End View

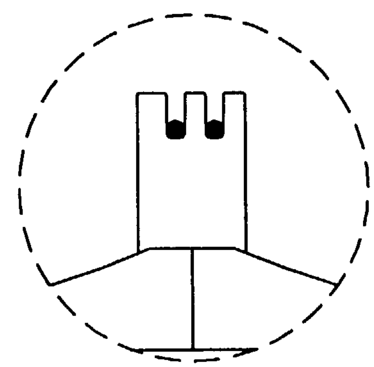


Side View



Archslab Component





Girder-Slab Joint

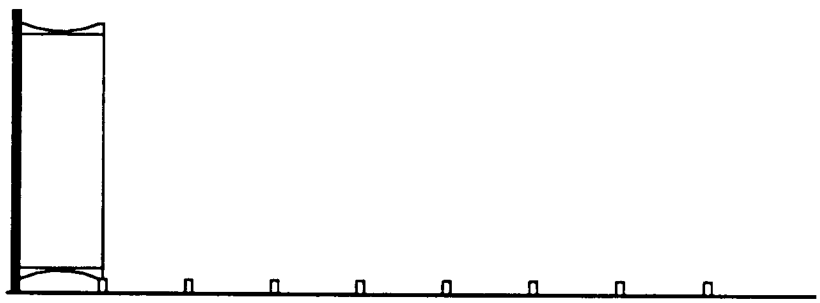
Construction Sequence:

1. Cast; 36 arch-slabs, 40 girders, 2 end caps
2. Level site
3. Place first 2 floor girders
   a.)lay tendons beneath,
   b.)set slab between them
   c.) repeat nine times
4. Place end cap in position and brace
5. Install 2 opposing wall slabs,
   a.) set ceiling slab on top
6. Install first complete ring girder set
   a.) wrap tendons around girder set
   b.) post-tension first two tendons
7. Repeat steps (5.) and (6.) nine times
8. Install final end cap
9. Install and post-tension longitudinal tendons
10. Pressurize
11. Bury
12. Fit out interior

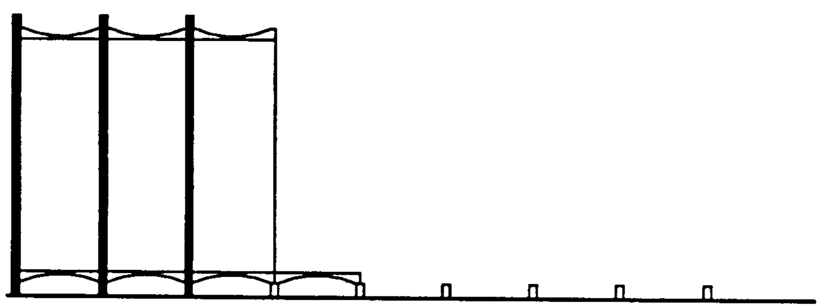
Construction Sequence

Steps 1 to 3

Steps 4 to 6



Step 7 (etc.)



11. Future Research:

* Mechanical properties of cast basalt;
  - a.) fracture toughness & notch sensitivity
  - b.) distribution of tensile strength values

* Feasibility of casting basalt into large structural elements

* Gasket material and design

* Additional design(s) under consideration;
  - a.) evaluate three designs
  - b.) select one for detailed design and testing

* Develop FE predictive model for full stress analysis of final concept

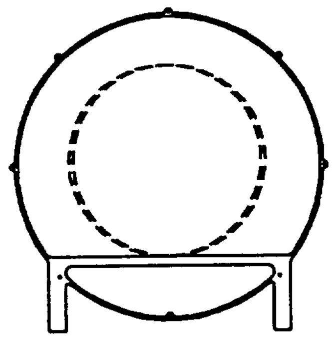
* Build and test 1/6 scale model in laboratory utilizing cast basalt or simulant materials

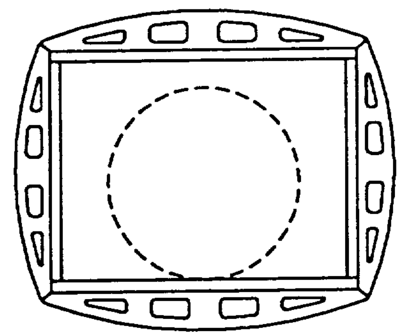
12. Conclusions:

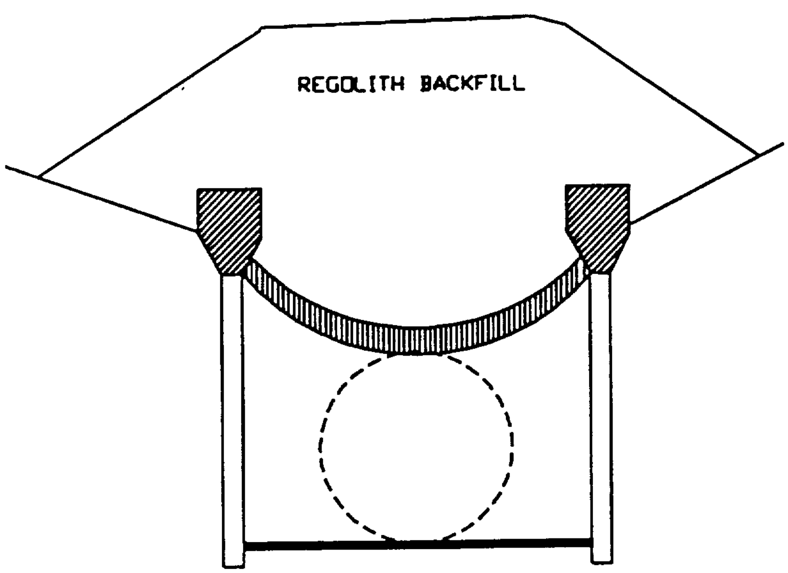
1.) Cast basalt selected

2.) Several designs are feasible

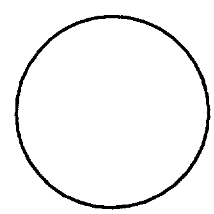
3.) Additional research needed







INVERTED COMPRESSION ARCH



Space Station Freedom
Module Cross Section

⇒ Develop tools

N93-26415

cSc

Configuration Optimization of Space Structures

Carlos Felippa
Luis A. Crivelli
David Vandenbelt

N.B. In my opinion this activity should be funded outside of CSC, as a separate grant from the M&S program.

Third Annual Symposium
November 21 & 22, 1991

▷ Objective

√ DEVELOP A COMPUTER AID FOR THE CONCEPTUAL/INITIAL DESIGN OF AEROSPACE STRUCTURES, ALLOWING CONFIGURATION AND SHAPE TO BE *a priori* DESIGN VARIABLES.

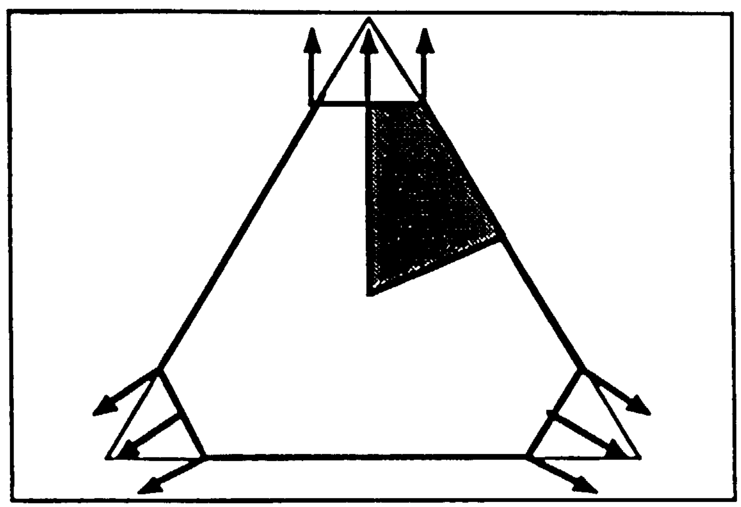
▷ Approach

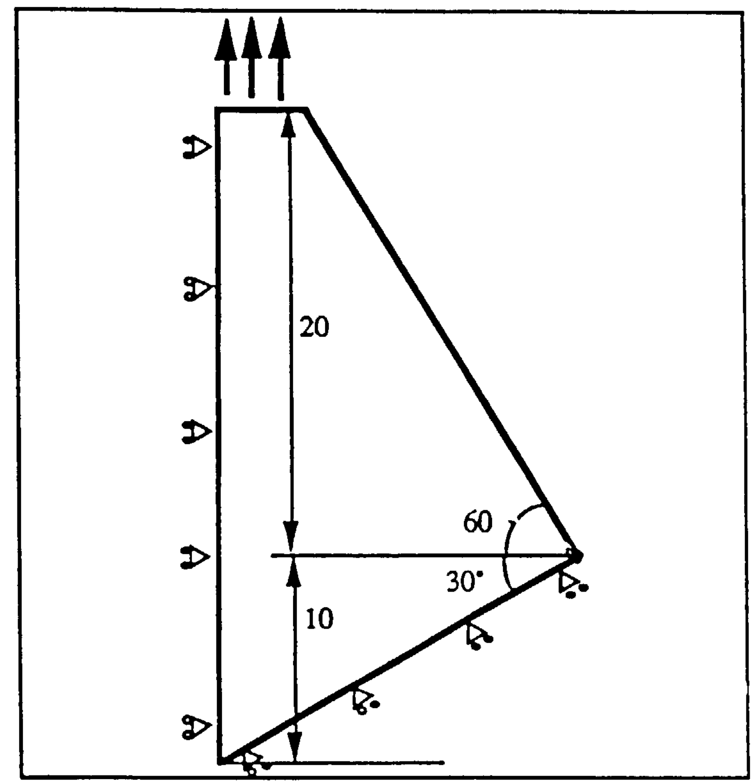
√ Kikuchi's Homogenization Method:

A "Design Domain Block," Filled Initially with Homogenized Finite Elements, is Gradually "Sculpted" into an Optimal Structure under Control of an Optimization Driver.

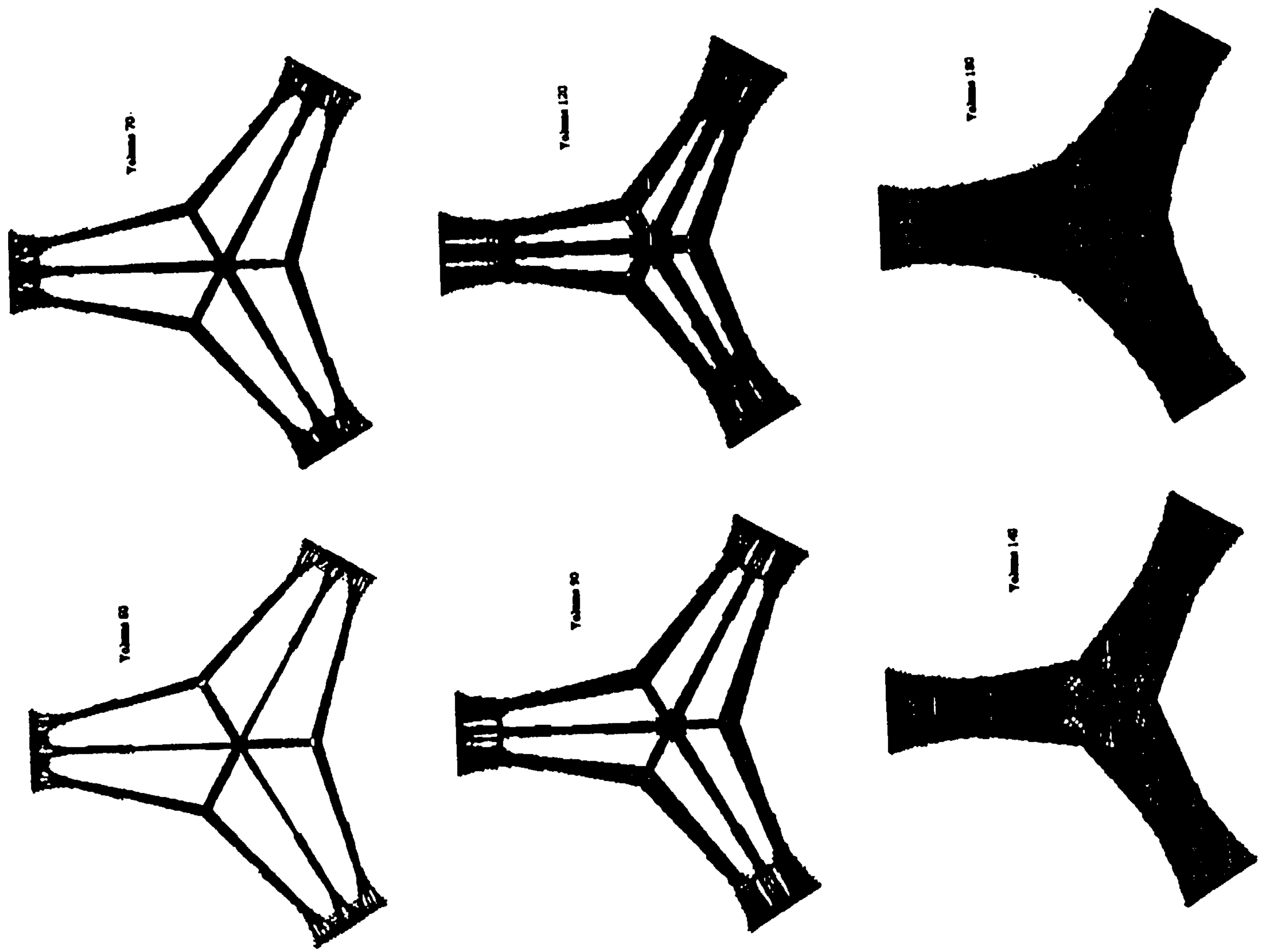
√ A *Sequence* of such Structures may be Obtained. This can Help the Conceptual Designer.

▷ Example: A Classical Shape Design Problem

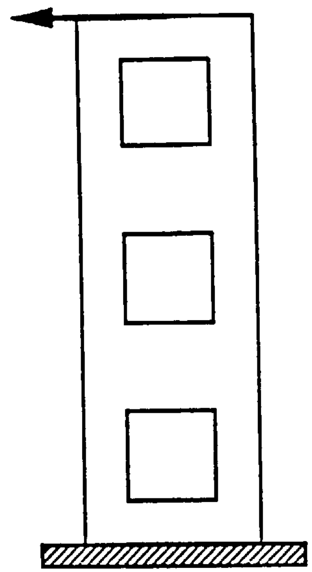


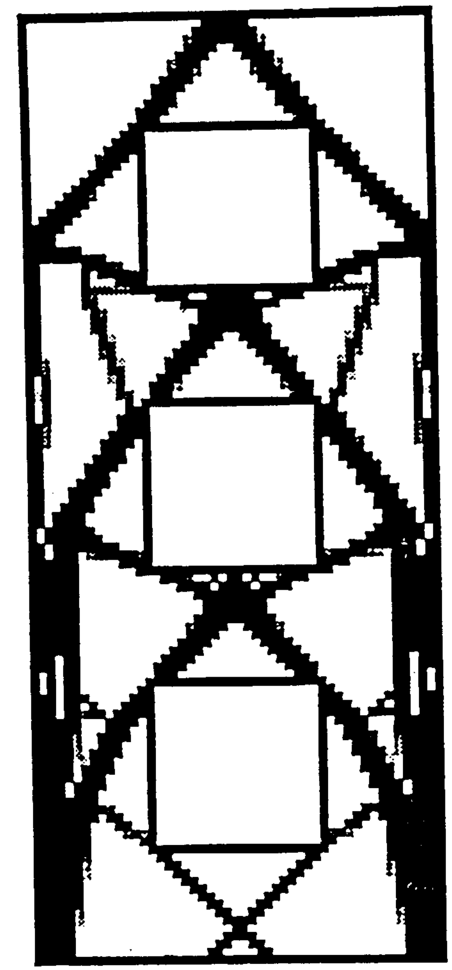


▹ Example (continued)



▷ Design Domain May Contain Predetermined Holes:

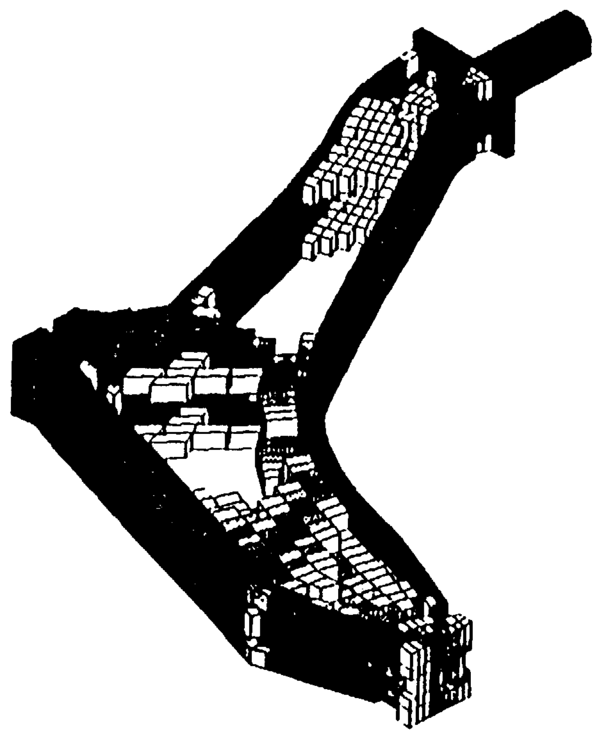


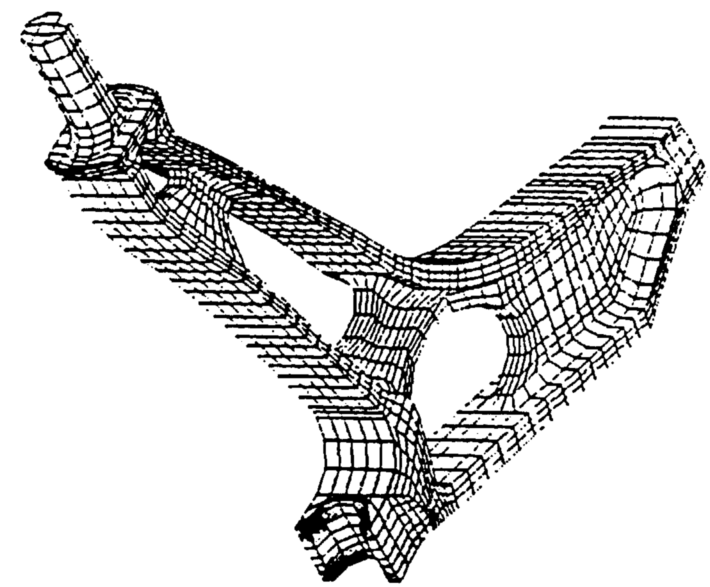


▷ Homogenization Method Steps

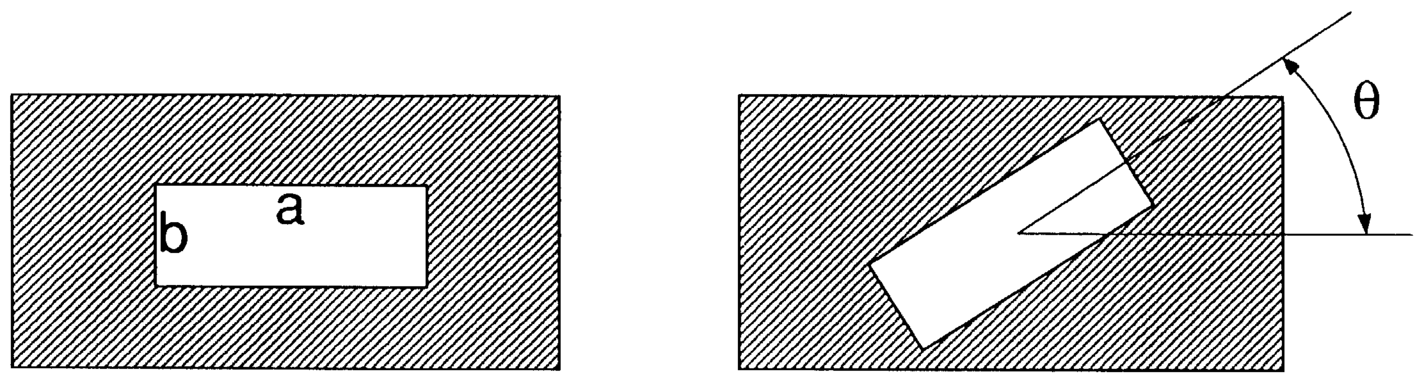
- √ Set up a Design Domain.
- √ Fill it with Homogenized Finite Elements.
- √ Define Loads and Support Conditions.
- √ Minimize an Objective Function (e.g. Compliance) under Maximum-Volume Constraint.
- √ Changing Maximum Volume Yields a Sequence of Designs.
- √ If Satisfied with a Design, Body-Fit-Remesh it, and Proceed with Standard Finite Element Analysis.

▷ Example: 3D Mechanical Component Design





▹ Element-Level Design Variables: MicroHole Dimensions



In two dimensions: a, b, θ in each element (3)

In three dimensions: a, b, c, θ_1, θ_2, θ_3 in each element (6)

100×100 2D mesh: 30,000 Design Variables

$30 \times 30 \times 30$ 3D mesh: 162,000 Design Variables

▹ Taking Advantage of Design-Variable Locality Essential

▷ Forming a Homogenized Finite Element

$$\mathbf{K}^e = \int_A h\mathbf{B}^T\mathbf{C}_H\mathbf{B}\,dA$$

$\mathbf{C}_H = \mathbf{C}_H(a, b, \theta)$ *homogenized* material response matrix

$\mathbf{C} = \mathbf{C}_H(0, 0, 0)$ full element; no microhole

$\mathbf{C} = \mathbf{C}_H(1, 1, \theta) = \mathbf{0}$ void; microhole fills element

▹ 2-D Optimization Problem

- √ OBJECTIVE FUNCTION (COMPLIANCE ≡ INVERSE STIFFNESS)

$$\Pi(\mathbf{a},\mathbf{b},\boldsymbol{\theta}) = \mathbf{p}^T\mathbf{v}$$

- √ STIFFNESS RELATION (DISCRETE FE EQUATION)

$$\mathbf{v}(\mathbf{a},\mathbf{b},\boldsymbol{\theta}) = \mathbf{K}^{-1}(\mathbf{a},\mathbf{b},\boldsymbol{\theta})\,\mathbf{p}, \qquad \mathbf{K} = \sum_e \mathbf{L}^{eT}\mathbf{K}^e(a^e,b^e,\theta^e)\mathbf{L}^e$$

- √ VOLUME INEQUALITY CONSTRAINT

$$V(\mathbf{a},\mathbf{b}) \le V_T = \kappa V_{domain}, \qquad 0 < \kappa \le 1$$

- √ MICROHOLE CONSTRAINTS

$$0 \le a^e \le 1, \qquad 0 \le b^e \le 1, \qquad -45^\circ \le \theta^e \le 45^\circ, \qquad e = 1,\dots N_e$$

▹ Treatment of Volume Inequality Constraint

√ Augmented Lagrangian Formulation

$$L = \Pi - \lambda_V C_- + \sigma_V C_-^2$$

where

$$\lambda_V = \text{Lagrangian multiplier estimate}$$

$$\sigma_V = \text{penalty weight}$$

$$C_- = \begin{cases} V_T - V, & \text{if } V_T < V; \\ 0, & \text{otherwise.} \end{cases}$$

▹ Algorithm for the Volume Inequality Constraint

i) Set $\lambda_V^{(1)} = \lambda_V^0$, $\sigma_V^{(1)} = \sigma_V^0$, $k = 1$

ii) Minimize $\Pi(\mathbf{a}, \mathbf{b}, \boldsymbol{\theta}, \lambda_V^{(k)}, \sigma_V^{(k)})$ keeping λ_V and σ_V fixed, with $(\mathbf{a},\mathbf{b},\boldsymbol{\theta})$ subjected to limit constraints.

iii) Compute $C = C^{(k)} = V_T - V(\mathbf{a}, \mathbf{b}, \boldsymbol{\theta})$.
If $C < 0$ and $|C| > \frac{1}{4}|C^{(k-1)}|$ set $\sigma_V = 10\sigma_V$ and go to ii)

iv) else set

$$k = k + 1$$
$$\lambda_V^{(k)} = \lambda_V^{(k-1)} - \sigma_V C$$

If $C < 0$ go to ii) else done

▷ Object Function Derivatives: Taking Advantage of Design Locality

√ Objective Function Gradients

$$\frac{\partial \mathbf{p}^T \mathbf{v}}{\partial a^e} = -\mathbf{v}^T \frac{\partial \mathbf{K}}{\partial a^e} \mathbf{v}$$

$$\frac{\partial \mathbf{p}^T \mathbf{v}}{\partial b^e} = -\mathbf{v}^T \frac{\partial \mathbf{K}}{\partial b^e} \mathbf{v}$$

√ Stifness (Discrete Equilibrium) Constraints

$$\frac{\partial \mathbf{v}}{\partial a^e} = -\mathbf{K}^{-1} \frac{\partial \mathbf{K}}{\partial a^e} \mathbf{v}$$

$$\frac{\partial \mathbf{v}}{\partial b^e} = -\mathbf{K}^{-1} \frac{\partial \mathbf{K}}{\partial b^e} \mathbf{v}$$

▹ Stiffness Variations

√ For Element Stiffness

$$\mathbf{K}^e = \int_{V^e} \mathbf{B}^T \mathbf{C}(a^e, b^e, \theta^e) \mathbf{B} \, dV^e$$

$$\frac{\partial \mathbf{K}^e}{\partial a^e} = \int_{V^e} \mathbf{B}^T \frac{\partial \mathbf{C}(a^e, b^e, \theta^e)}{\partial a^e} \mathbf{B} \, dV^e$$

$$\frac{\partial \mathbf{K}^e}{\partial b^e} = \int_{V^e} \mathbf{B}^T \frac{\partial \mathbf{C}(a^e, b^e, \theta^e)}{\partial b^e} \mathbf{B} \, dV^e$$

√ For Global Stiffness

$$\frac{\partial \mathbf{K}}{\partial a^e} = \mathbf{L}^{eT} \frac{\partial \mathbf{K}^e}{\partial a^e} \mathbf{L}^e \qquad \frac{\partial \mathbf{K}}{\partial a^e} = \mathbf{L}^{eT} \frac{\partial \mathbf{K}^e}{\partial a^e} \mathbf{L}^e$$

▹ Variations of the Potential

√ Potential

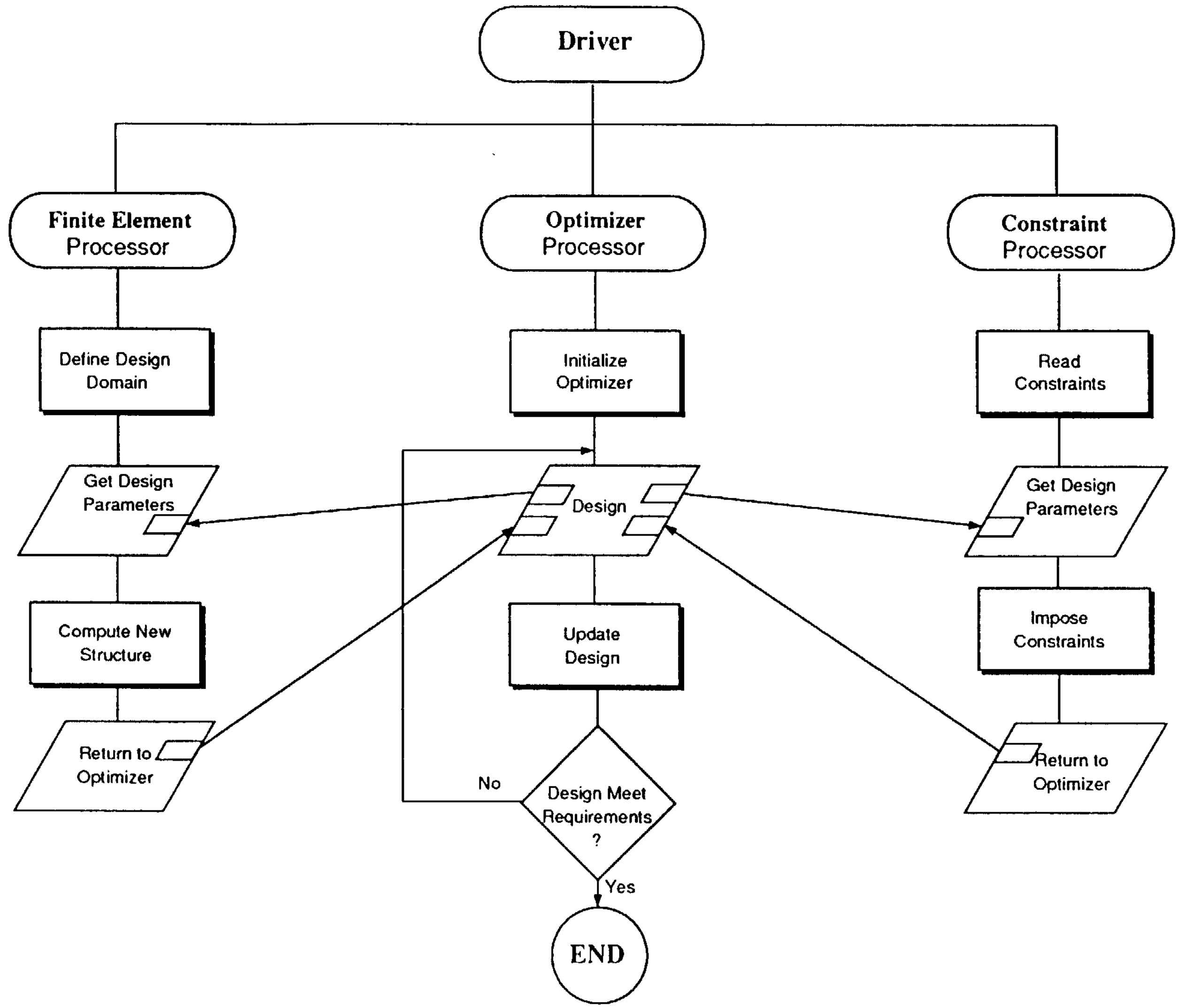
$$\Pi = \mathbf{v}^T \mathbf{K} \mathbf{v}$$

√ First Variation

$$\delta\Pi = -\mathbf{v}^T \delta\mathbf{K}\mathbf{v} \equiv -\int_A \epsilon^T \delta\mathbf{C}\epsilon \, dA = 0$$

√ Second Variation

$$\delta^2\Pi \simeq 2\int_A \epsilon\delta\mathbf{C}\mathbf{C}^{-1}\delta\mathbf{C}\epsilon \, dA - \int_A \epsilon^T \delta^2\mathbf{C}\epsilon \, dA$$



Schematics of the Optimization Program.

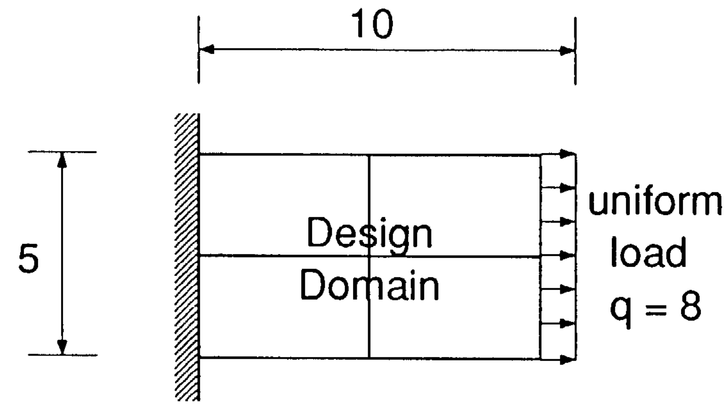
▹ Progress

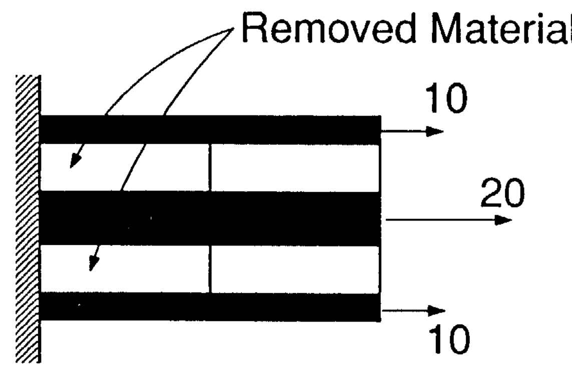
- √ Simple C_H developed and implemented.
- √ Homogenized F.E. Model of Design implemented.
- √ Optimization method:
  - √ Simulating Annealing: did not work.
  - √ Augmented Lagrangian with Conjugate Gradient:

    works for simple problems (next slide)
  - √ Augmented Lagrangian with Newton/Projected Gradient:

    implemented; under testing.

▷ Validation Problem (First Successful Solution)





$V_{ref} = 50$
$E = 10{,}000$
$\nu = 0$
$R = 1$

2x2 mesh over D.D.

Solution for 50% volume reduction
Target volume $V = \frac{1}{2} V_{ref} = 25$
Computed solution agrees with analytical solution from Lagrangian function
Minimization Method: AL + CG + CPT
189 object function evaluations

▷ Computational Issues

- √ Coping with Large Number of Design Variables (10^2–10^6): Adaptive Hierarchical Optimization, Domain Decomposition, "Hole Dropping"
- √ Handling Design-Following Loads.
- √ Handling Different Materials over Design Domain.
- √ Parallel Computations.

▷ Research Issues

- ✓ Different Optimality Criteria:

  Concurrent Object Functions Over Domain
  (e.g. Multiple Load Cases)

  Different Object Functions over Subdomains
  (e.g. Maximum Energy Absortion on one,
  Minimum Compliance on Another)

- ✓ Tension/compression Design — Cables, Brittle Materials.

- ✓ Anisotropic Design — Composites.

- ✓ Vibration/Stability Constraints.

Telerobotic Rovers for Extraterrestrial Construction

Jim Avery

Why are we doing this under CSC?

Third Annual Symposium
November 21 & 22, 1991

N93-26416

Telerobotic Rovers for Extraterrestrial Construction

Students

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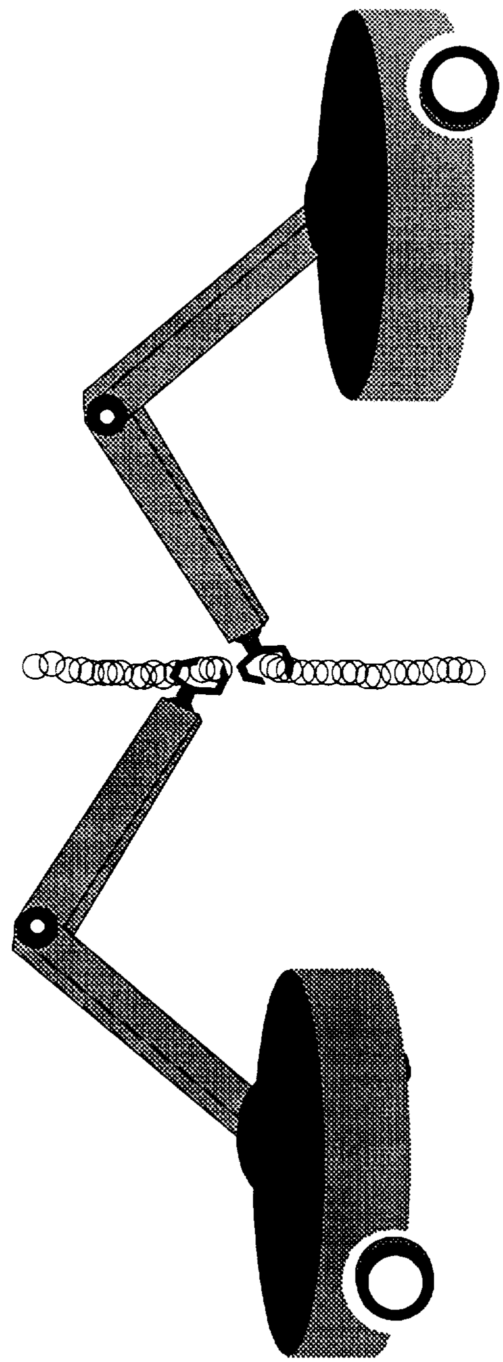
Jane Pavlich
Wayne Jermstad
Mike Matthews
Gary Snyder
Chris Steffen

Faculty

Jim Avery, Renjeng Su

Staff

Walter Lund



Objectives

- Design Small Modular Robots
- Test Robotic Cooperation and Tele-operation
- Develop Modular Control Software
- Develop Inter-module Communication Network
- Develop High Accuracy Positioning System
- Explore Distributed Algorithms for Coordination

Fundamental Concepts

Modularity implies that "robots" are temporary aggregates of independent systems

Coordination is required between these independent systems

More information passes between closely coupled modules (inside a "robot") than between robots

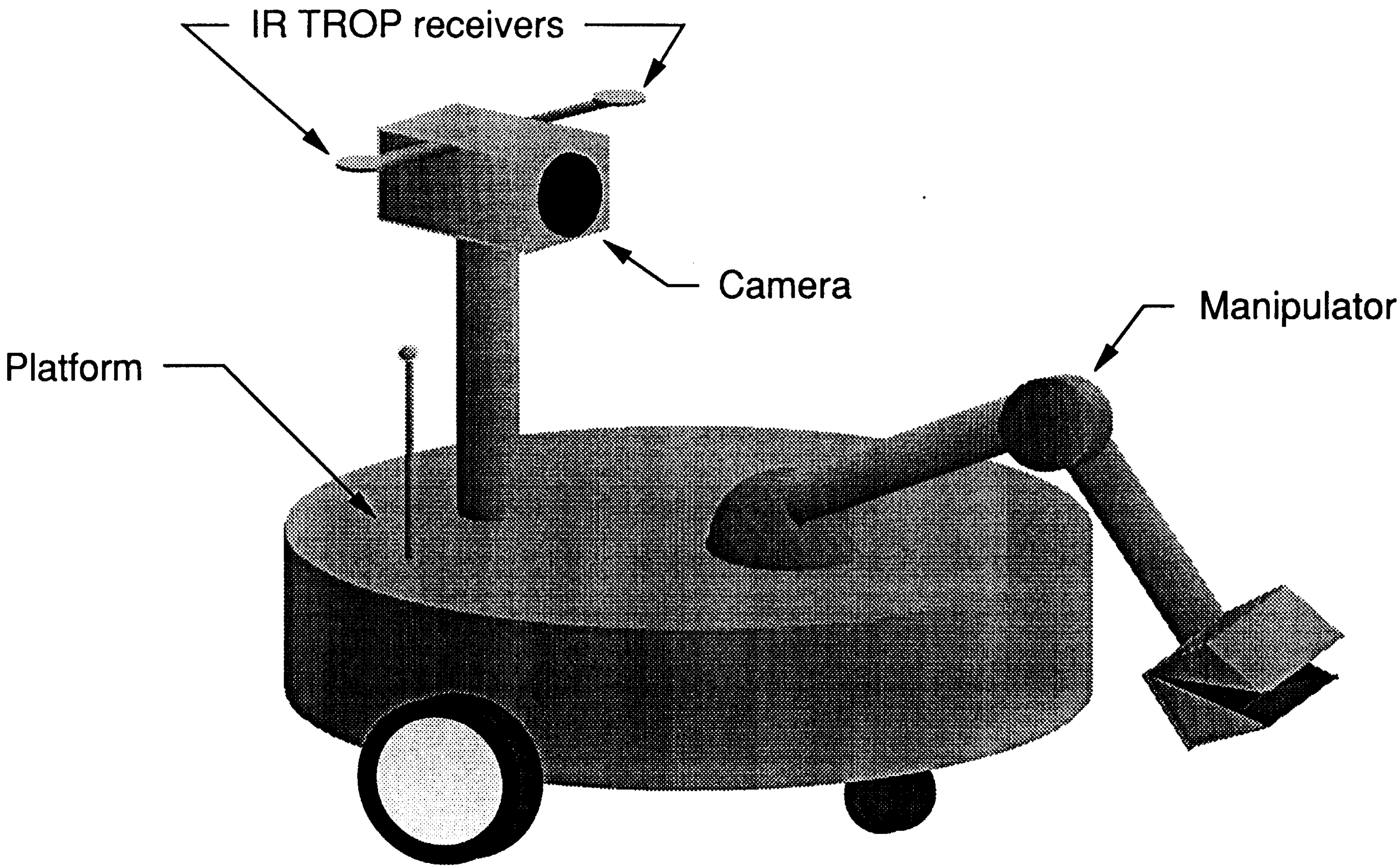
Goal is "plug and play" modularity

Advantages of Modularity

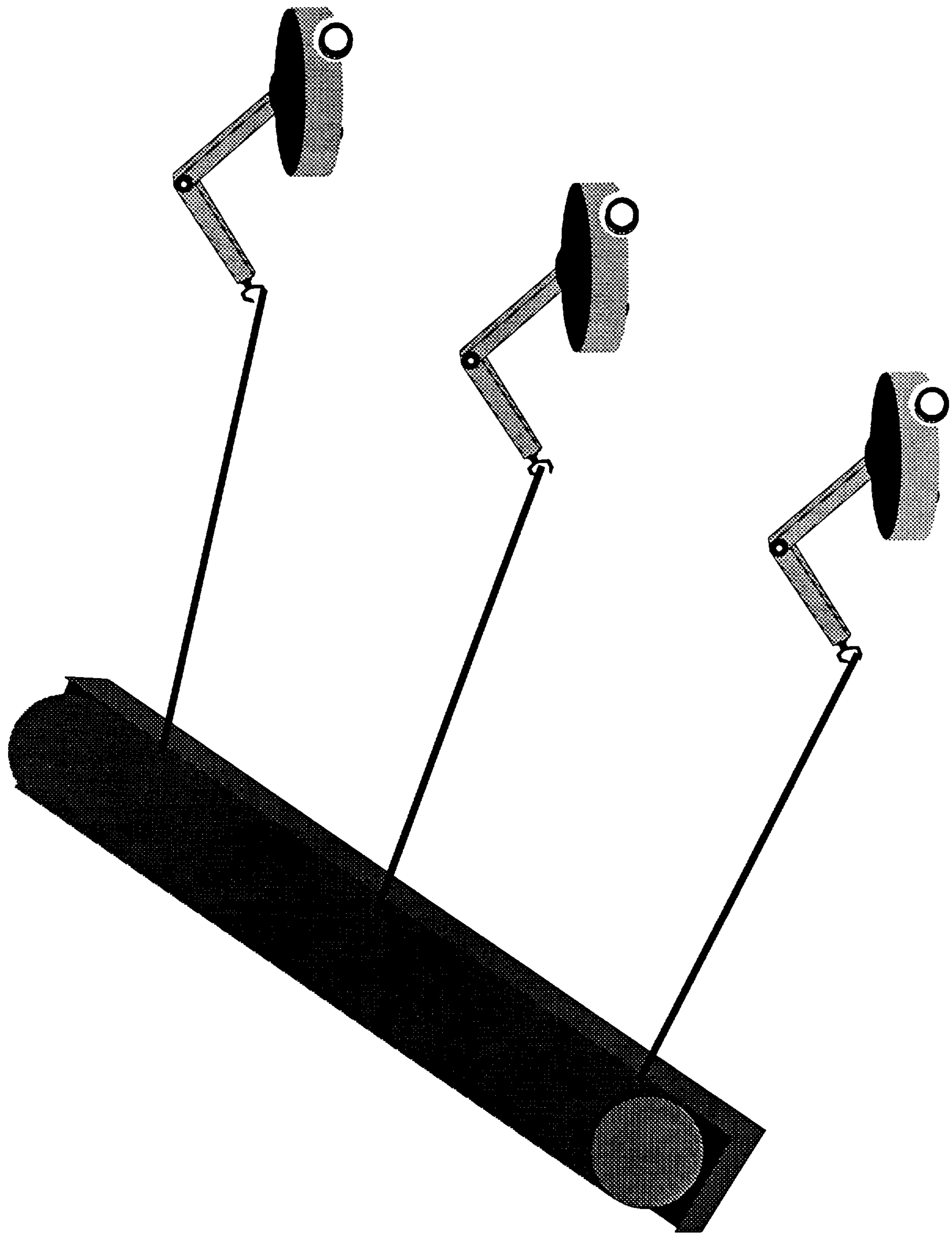
Small, multi-purpose devices are easier to transport, maintain, and configure.

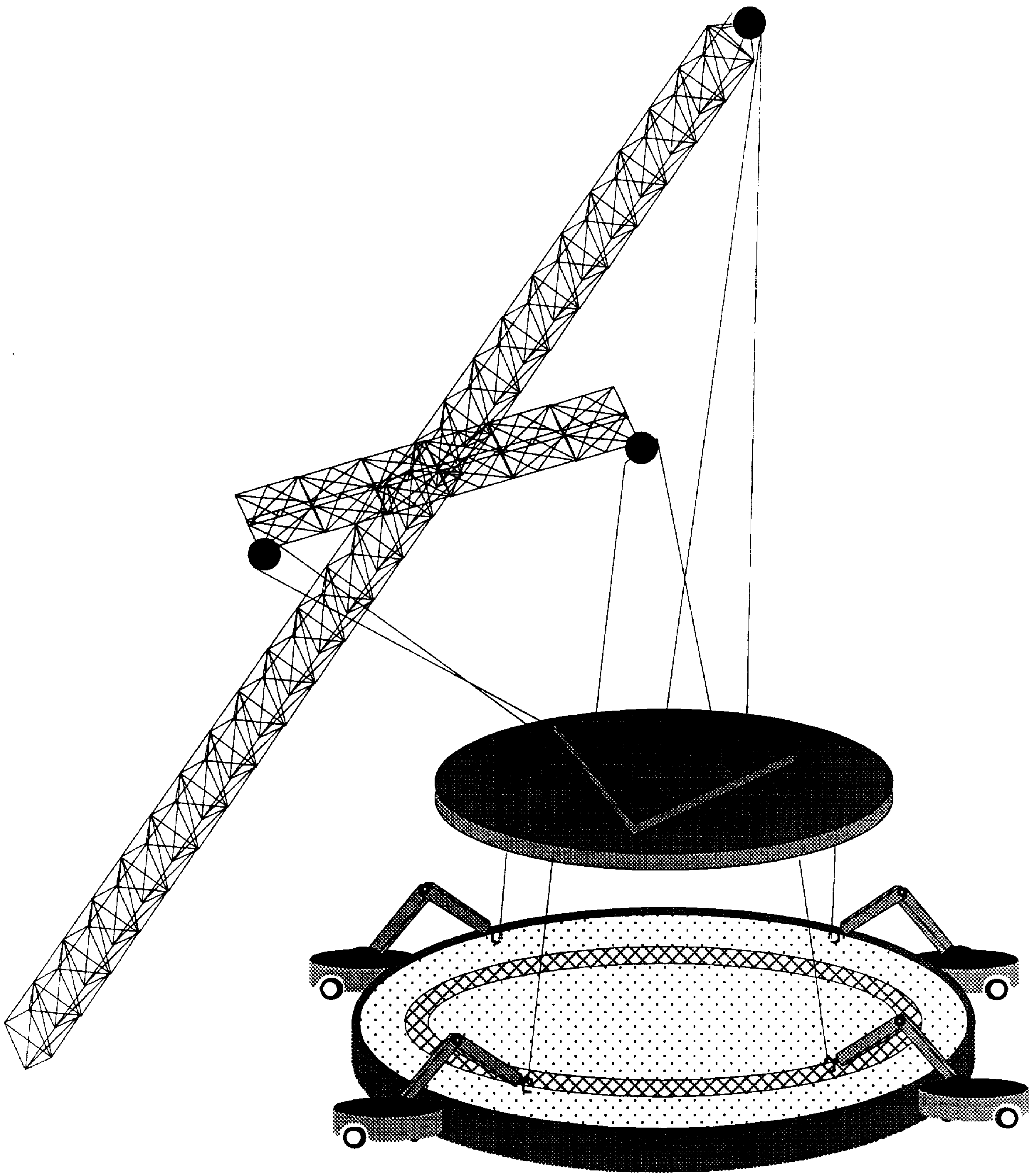
No large single-point failure mechanisms as with special purpose systems.

Individual systems are less complex; each can be dedicated to a separate sub-task.



Modular Robot





Robot Design

Three (nearly) identical robots under construction:

- 80 lb payload
- Attachment point for manipulator
- Battery powered
- Speed 1 ft/s
- Card cage for electronics

Motor Control System

- DC motors driven by HP motor control chip
- Control chip programmed by 8088-based microcomputer
- System being tuned to match motor characteristics
- Capable of path following
- Processor knows possible performance envelope

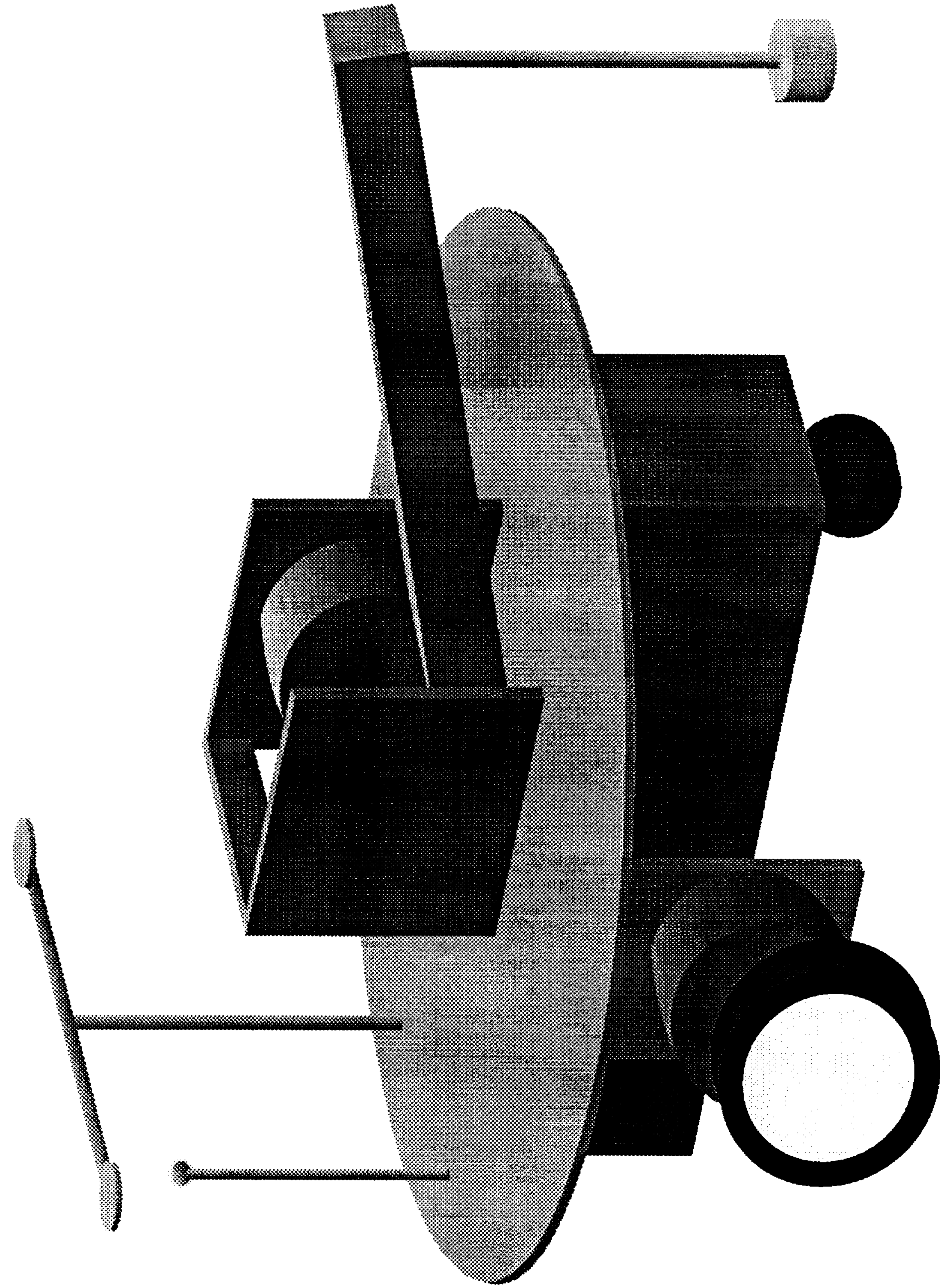
Simple Manipulator

First manipulator designed to test coordinated movement of robot

One degree of freedom

Simple to build, shares most components with rover base

More complex units under consideration



4 Degree of Freedom Manipulator

New design utilizing ball joint

Plug and play replacement for simple manipulator

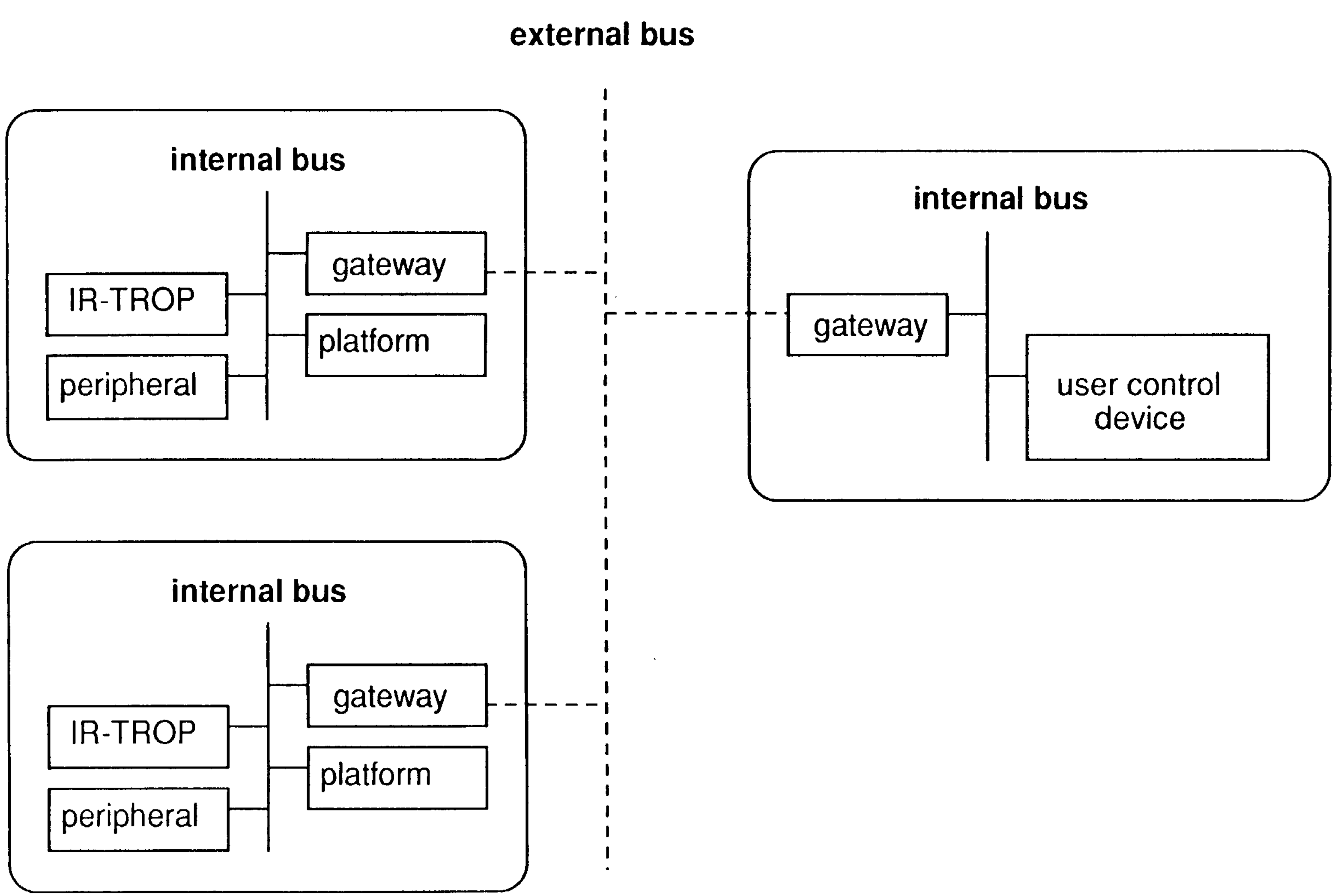
Kinematics and control theory under investigation

Inter-Module Communication

We are designing a hierarchical communication system for the test-bed:

- Physically connected units communicate over a twisted pair ethernet
- Separated units communicate over radio frequency local area network (RF LAN)
- Bus managers act as gateways between systems
- Operators communicate with rovers over RF LAN

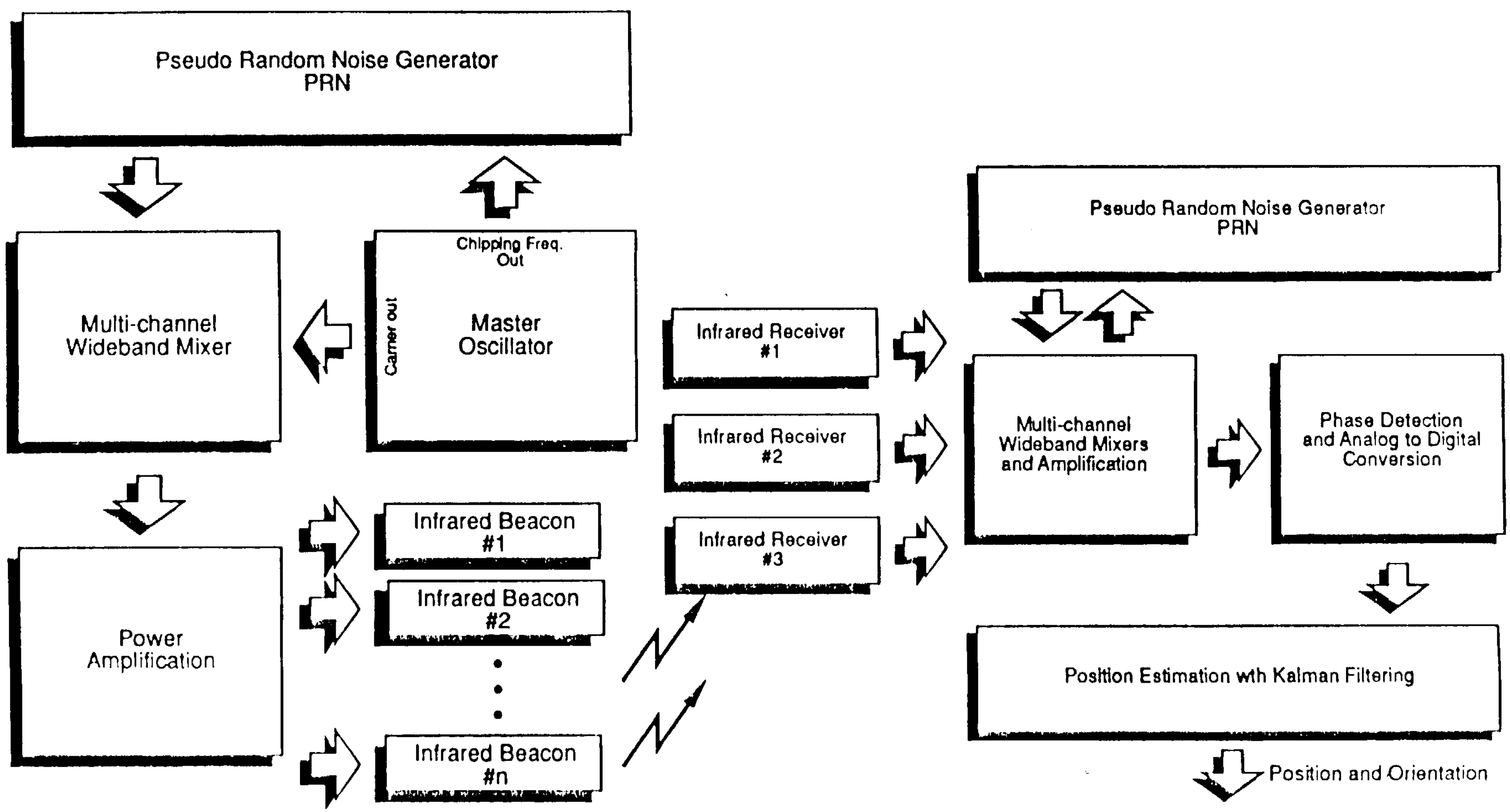
Network Layout



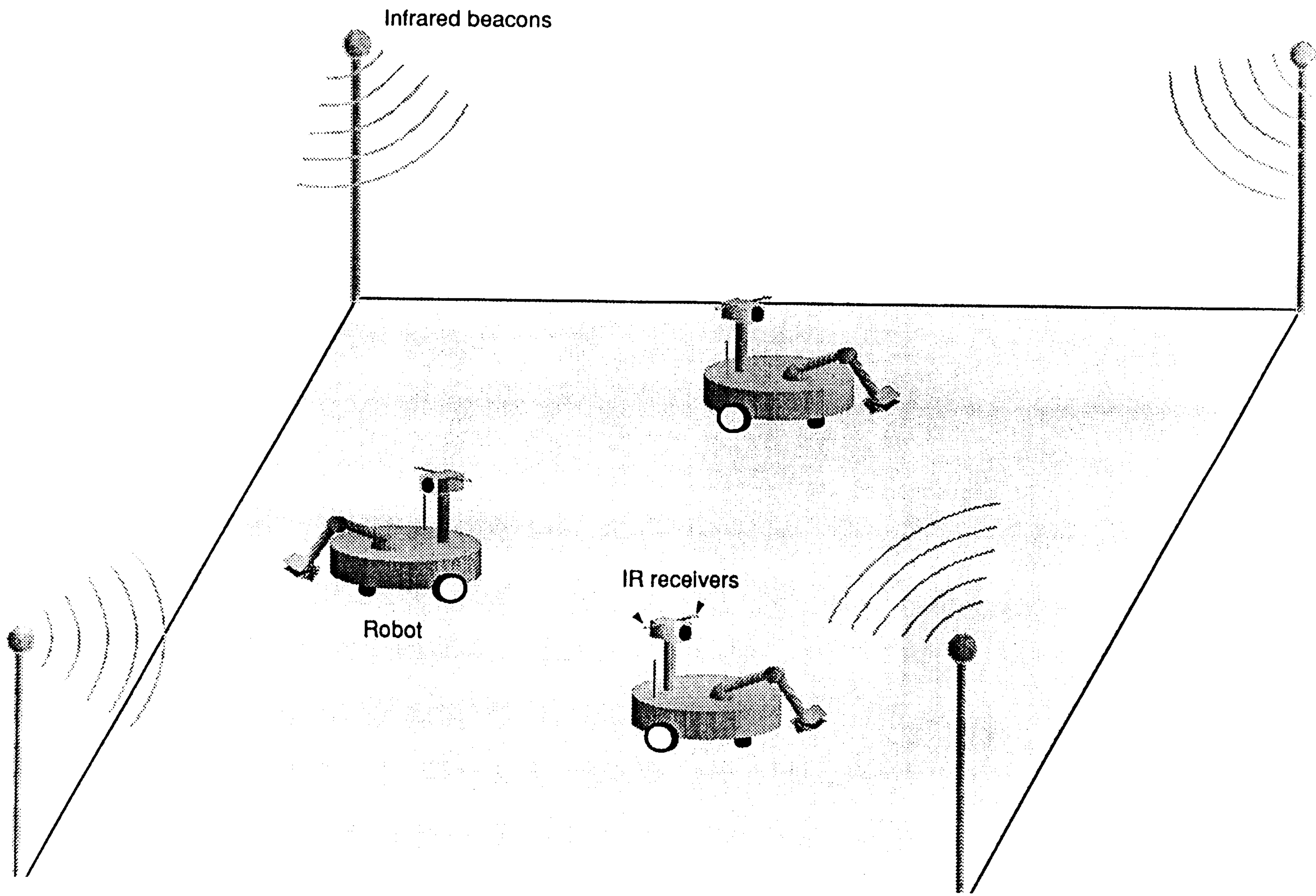
Positioning System: IR-TROP

- Goal to provide position sensing to $\pm$ 2 cm in two dimensions
- Derived from GPS technology
- Currently only $\pm$ 5 cm available

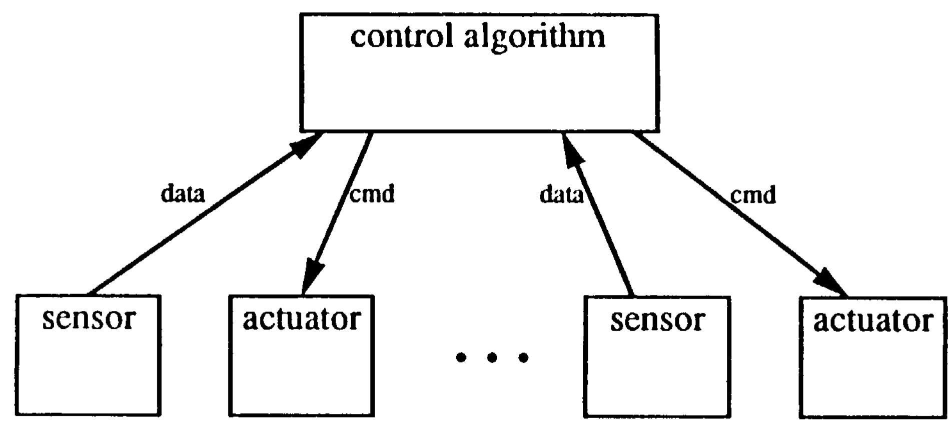
IR TROP System Design



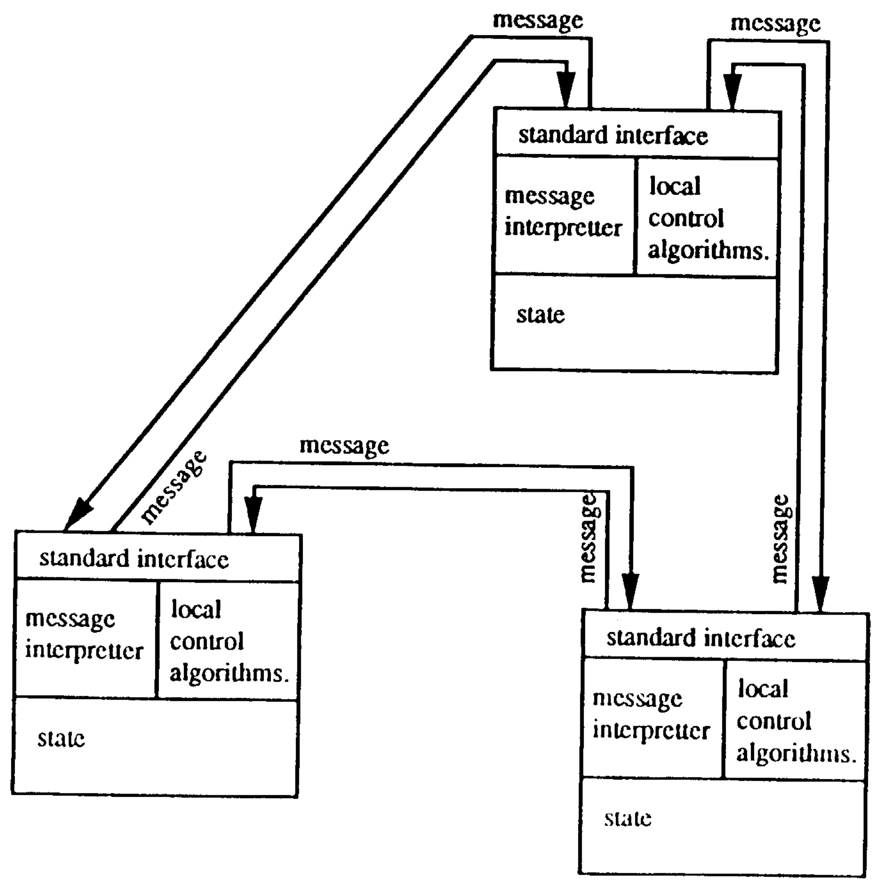
Testbed Layout



Centralized Control



Modularized Control



Messages contain requests and information

Messages passed between arbitrary number of objects

Control algorithms distributed

N93-26417

Lunar Surface Structural Concepts and Construction Studies

Martin Mikulas

Third Annual Symposium
November 21 & 22, 1991

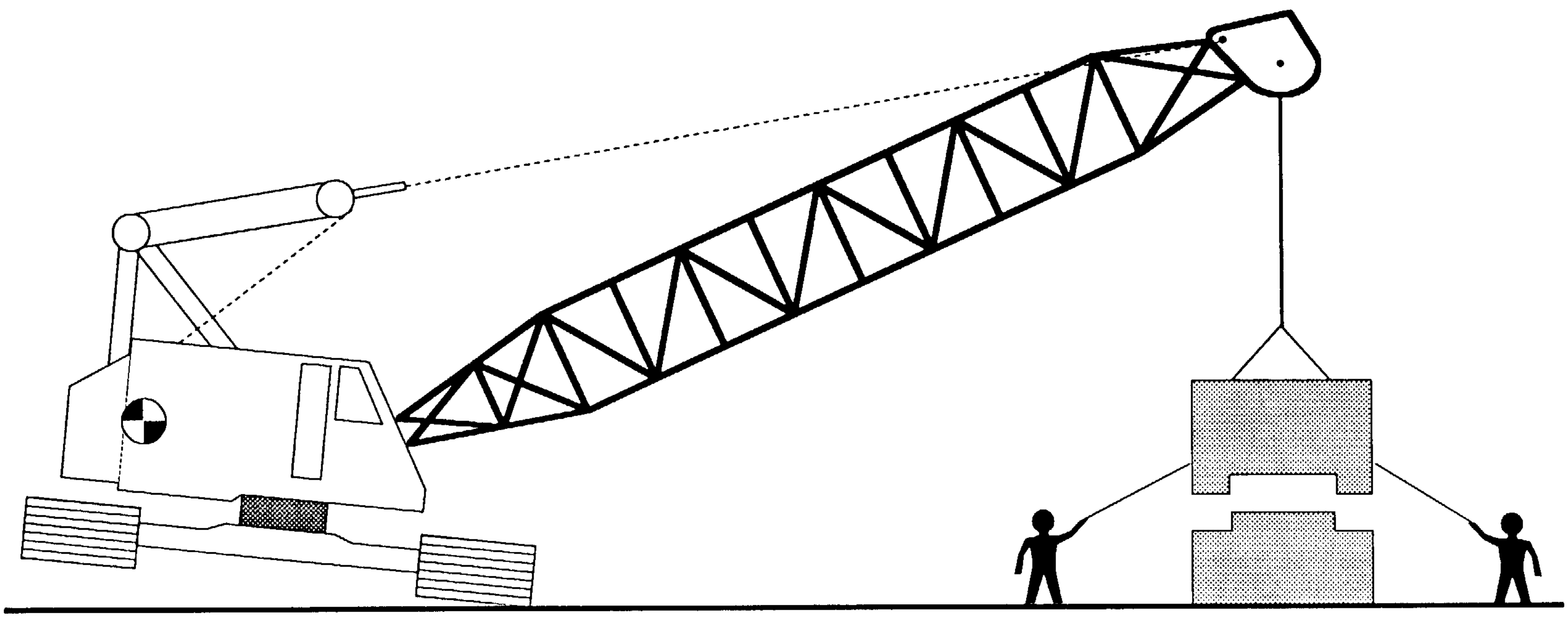
LUNAR SURFACE STRUCTURES CONSTRUCTION RESEARCH AREAS

RESEARCH AREA	OBJECTIVE
- Multiple Cable Crane - Articulating Arm Crane	Remote and/or Precision Positioning Capability For Lunar Construction
- Deployable Tower	Automatically Deployable Towers and Beam Type Structures With Minimal Deployment Equipment
- Lunar Module Unloading Device	Capability For Self Off-Loading of Modules & Equipment
- Deployable Solar Concentrator	Automatically Deployable Reflector With Minimal Deployment Equipment

LUNAR CRANE RELATED DISCIPLINES

- o Remote control and/or autonomous precision construction operations
- o Multibody dynamics analysis and control of large flexible systems
- o Analysis and control of cable structures
- o Quantification of control actuator concepts for large flexible systems
- o Design of large complex flexible sytems
- o System identification of nolinear systems

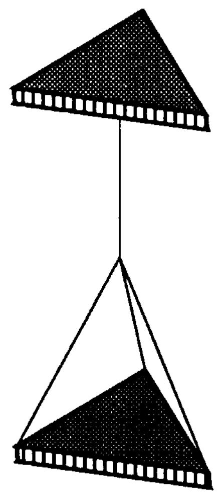
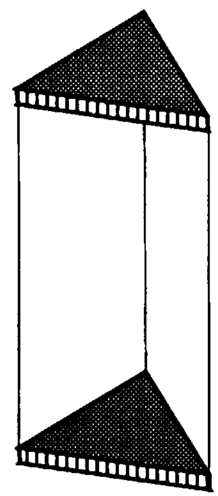
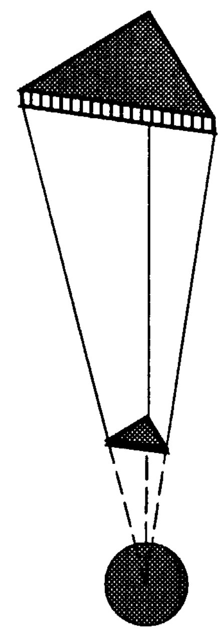
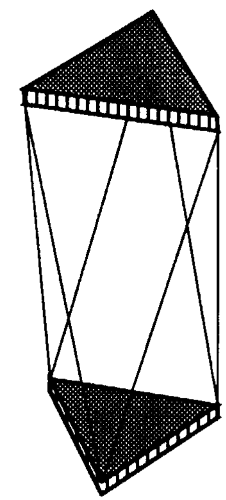
TYPICAL MOBILE CRANE HAS TWO MAJOR SHORTCOMINGS FOR LUNAR BASE APPLICATION



1) Very large mass required to resist tipping

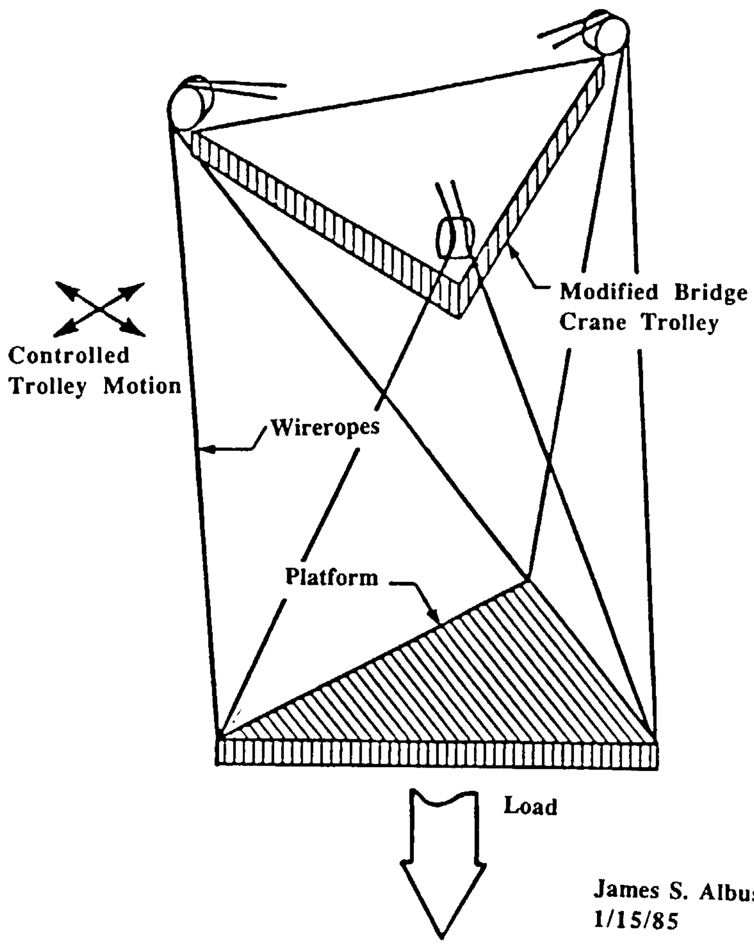
2) Human guidance required for accurate positioning

CANDIDATE CRANE CABLE SUSPENSION SYSTEMS

			
Single Cable	Three Cables	Three Cables	Six Cables
1 DOF Structurally Stiff	3 DOF Structurally Stiff	3 DOF Structurally Stiff 3 DOF Stiffened by Triangulated Cables	6 DOF Structurally Stiff

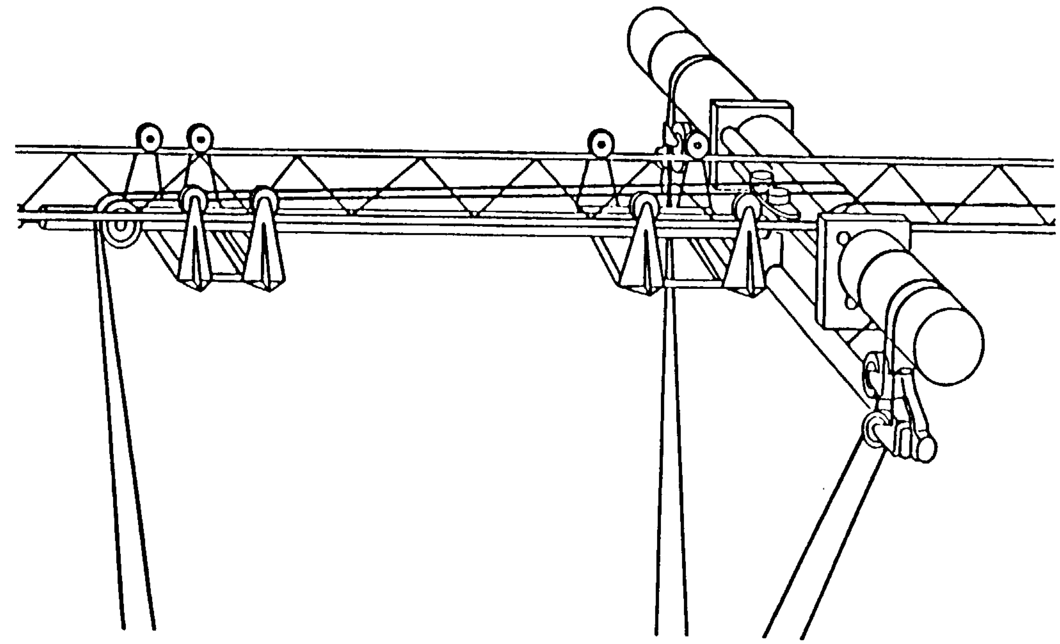
NIST SIX-CABLE SUSPENSION CRANE

Cable Geometry



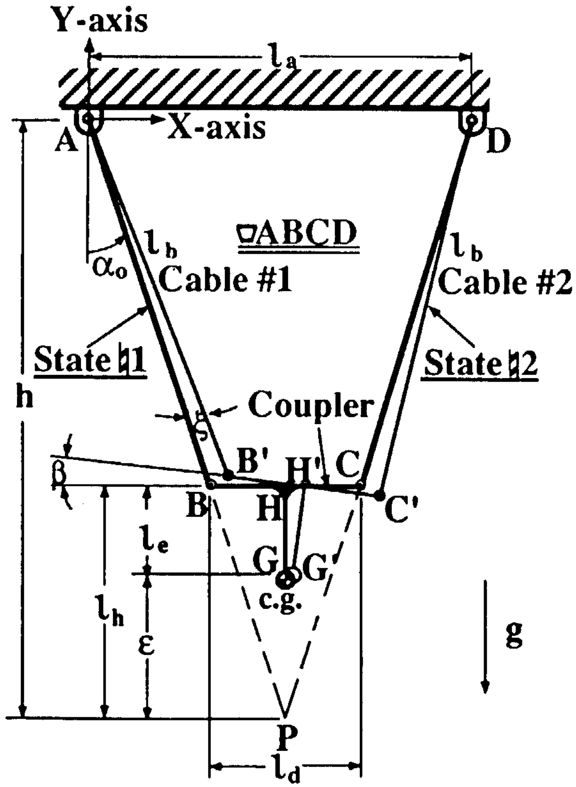
James S. Albus
1/15/85

Cable Drive System

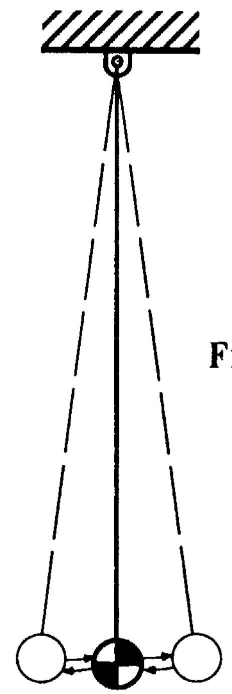


NUMERICAL EXAMPLE OF NATURAL FREQUENCY

A Symmetric Model

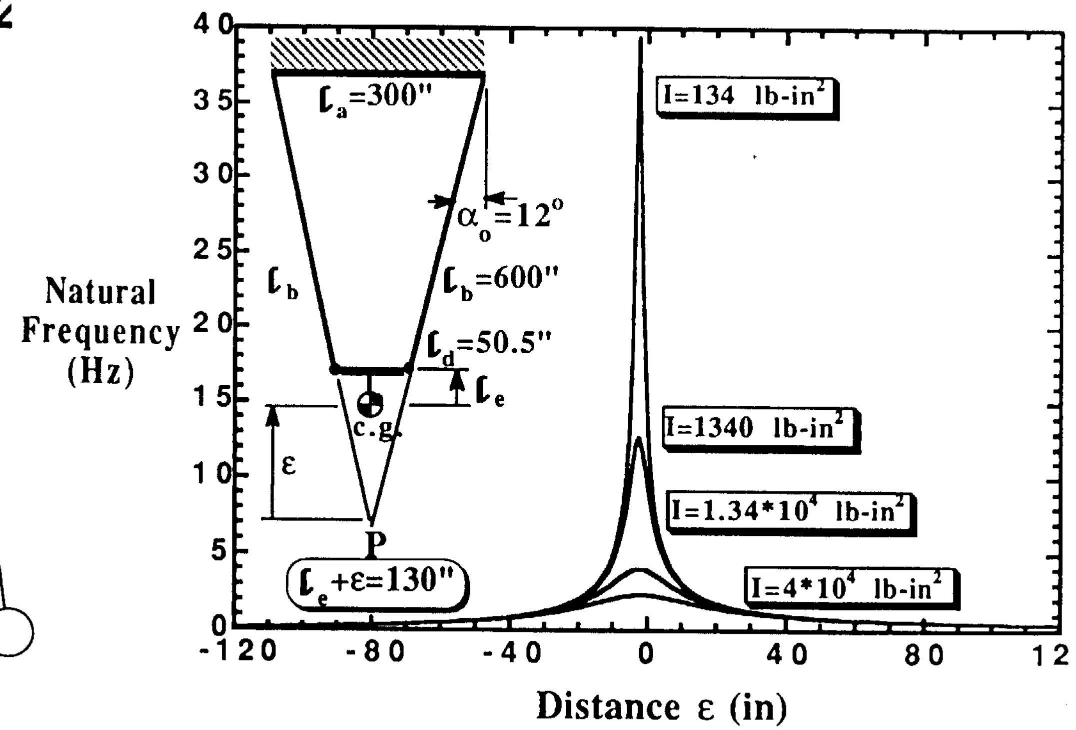


A Swinging Pendulum

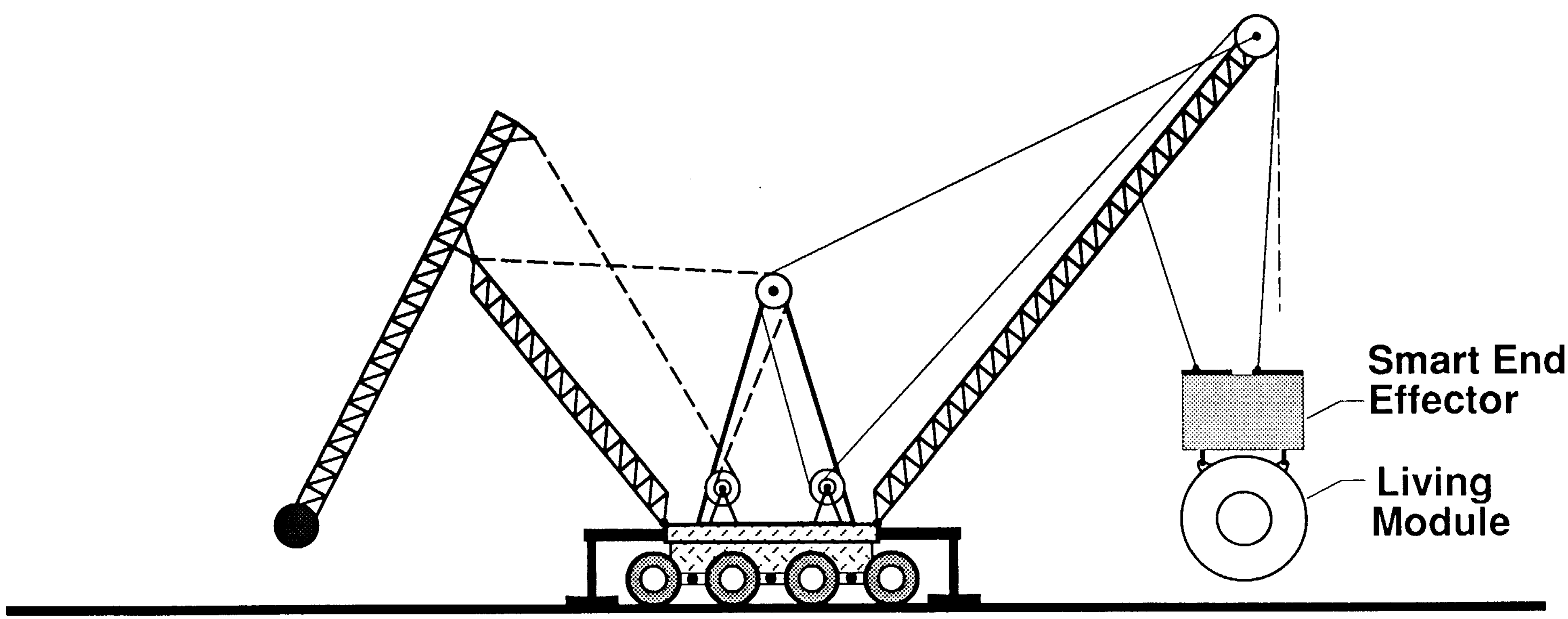


$$\mathcal{F} = \sqrt{\frac{\left(\frac{\ell_h}{h-\ell_h}\right)\left[\ell_h h + \frac{\ell_a^2}{4}\right] + \ell_e h}{\varepsilon^2 + \rho^2}}\mathcal{F}_{pendulum}$$

$$\mathcal{F}_{pendulum} = \frac{1}{2\pi}\sqrt{\frac{g}{h}},$$



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



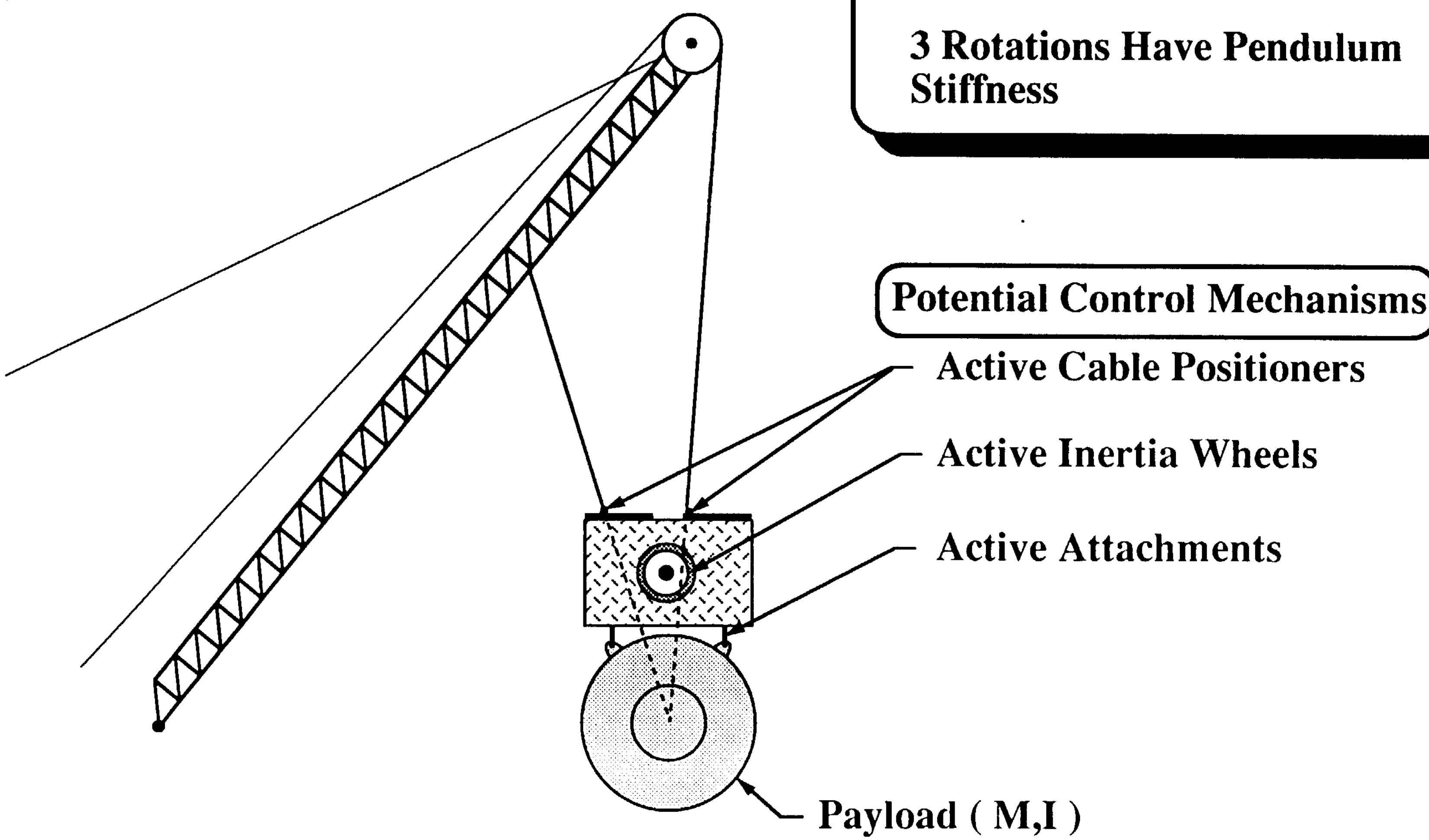
1) Active Counter Weight to Reduce Overturning Moment

2) Multiple Payload Suspension Cables to Provide Stable Precision Positioning

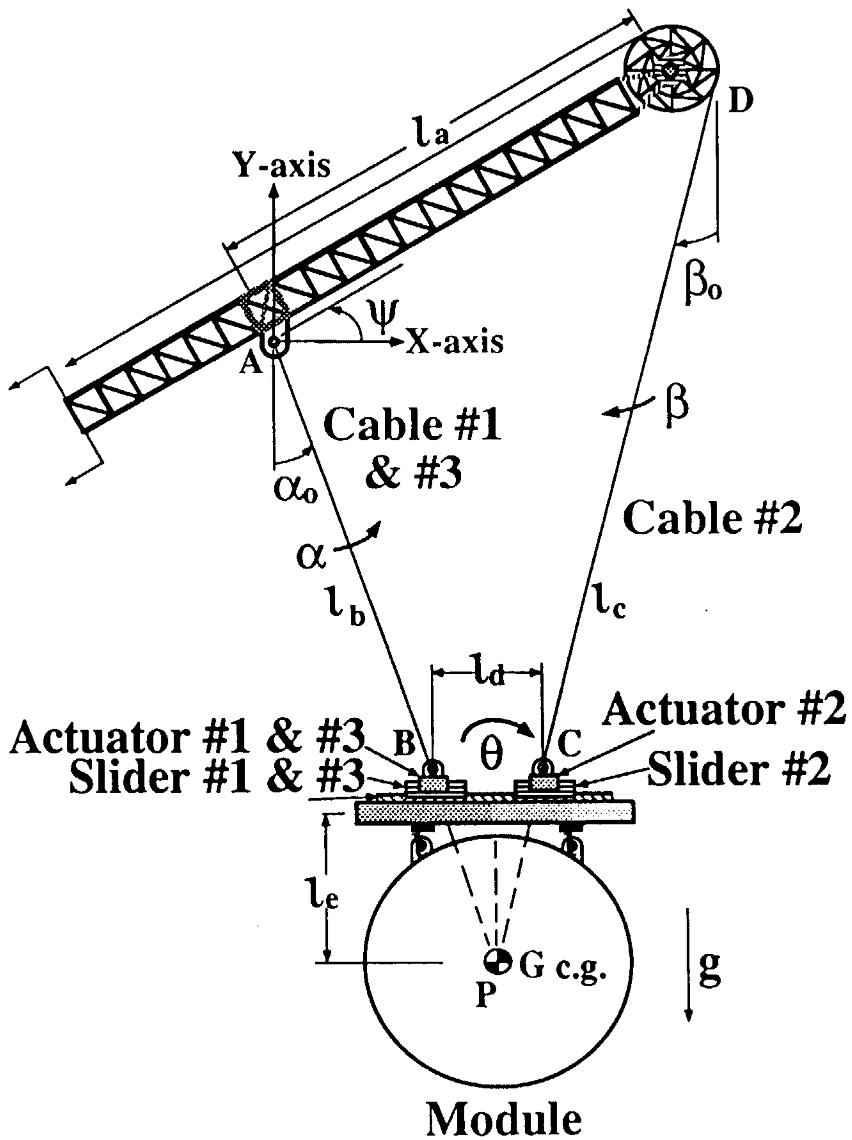
LUNAR CRANE PENDULUM MECHANICS

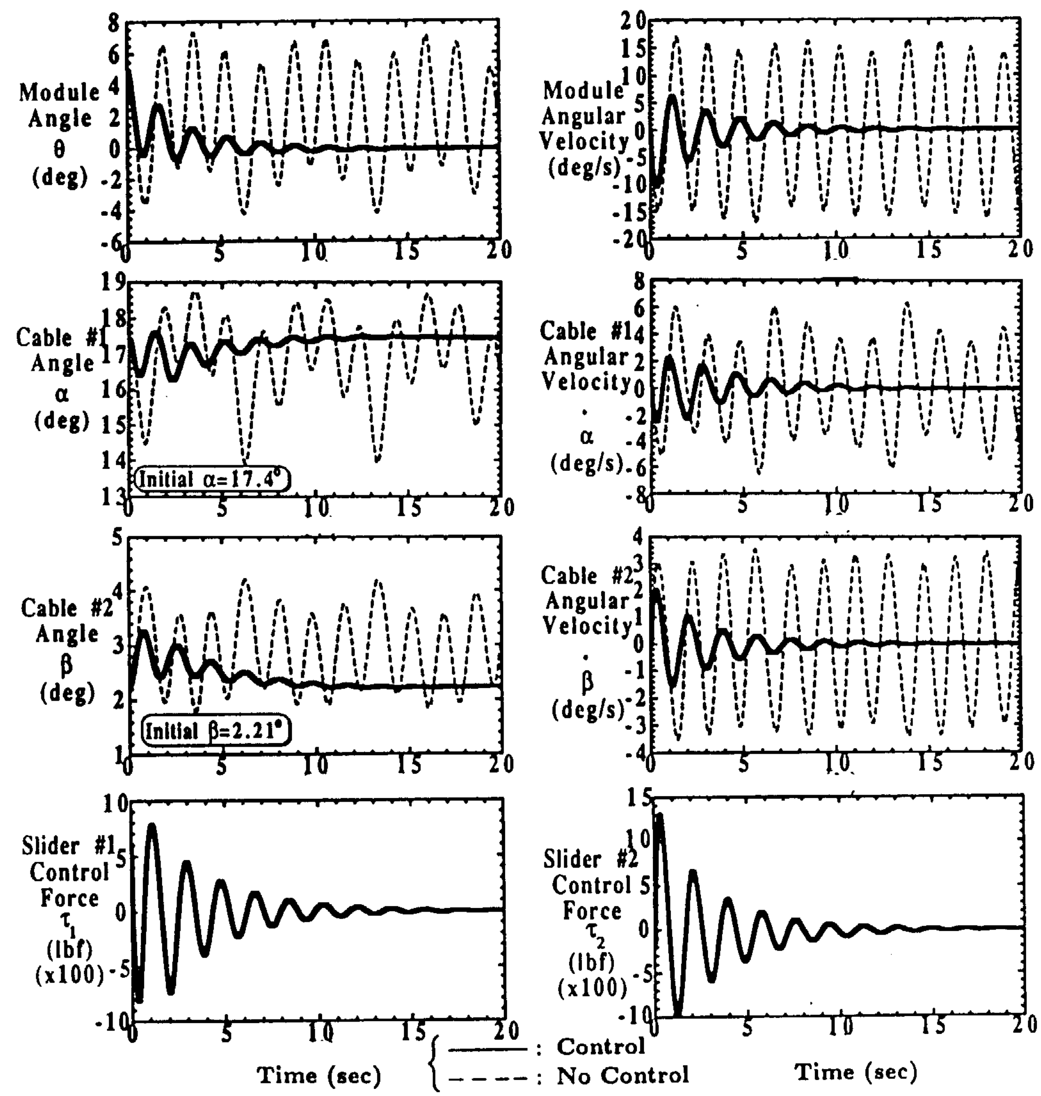
3 Translations Have Structural Stiffness

3 Rotations Have Pendulum Stiffness

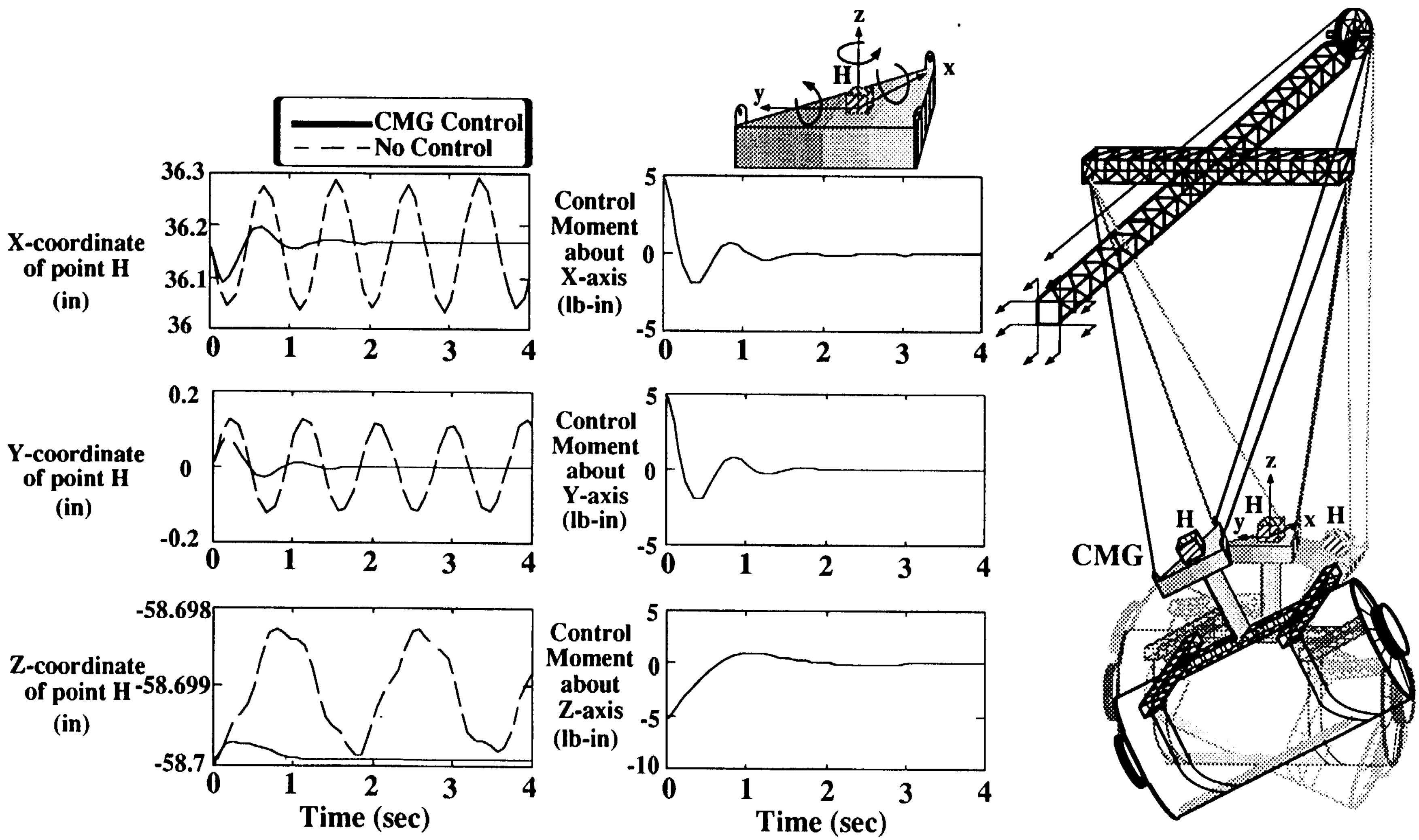


SIMULATION RESULTS (II)

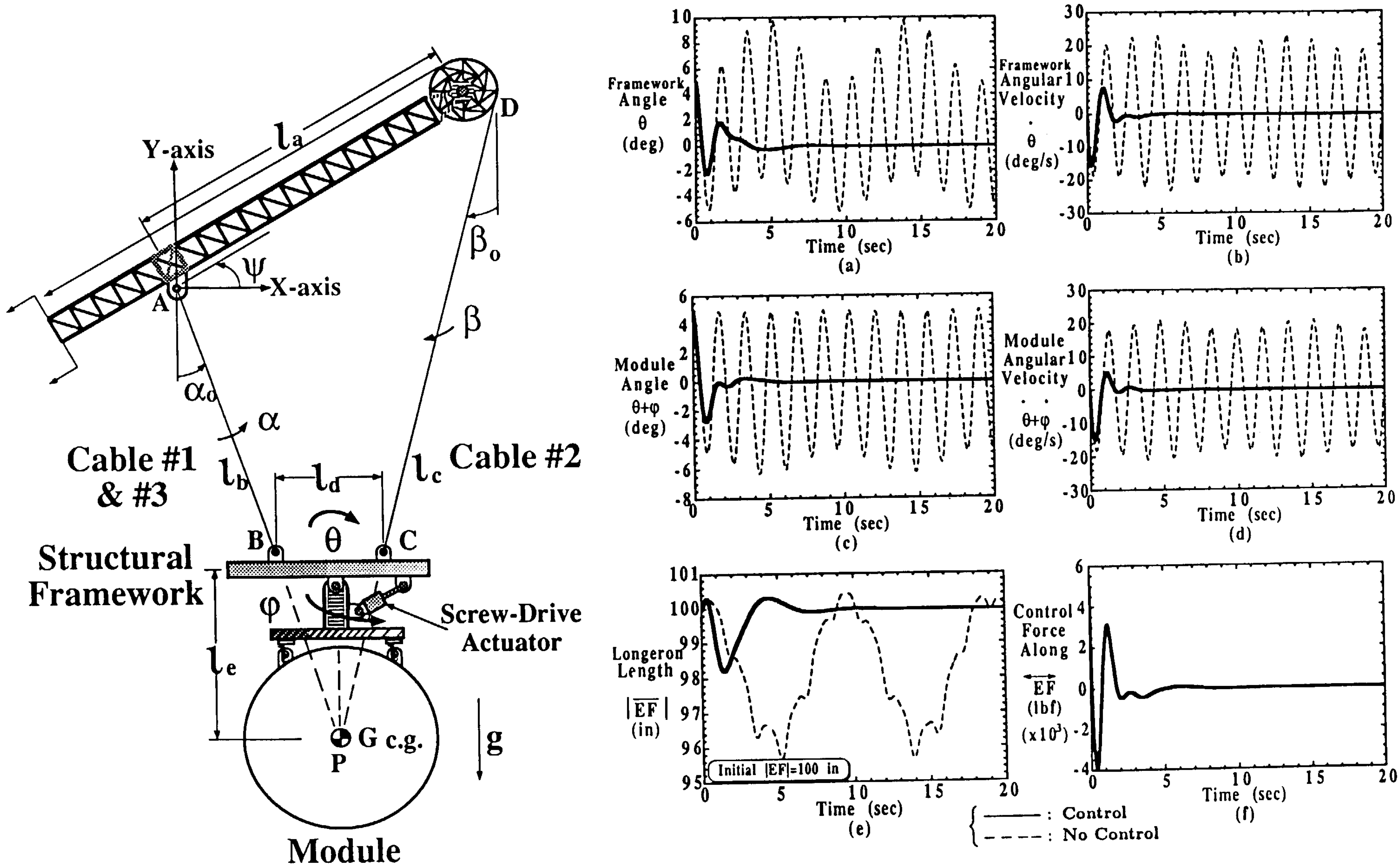




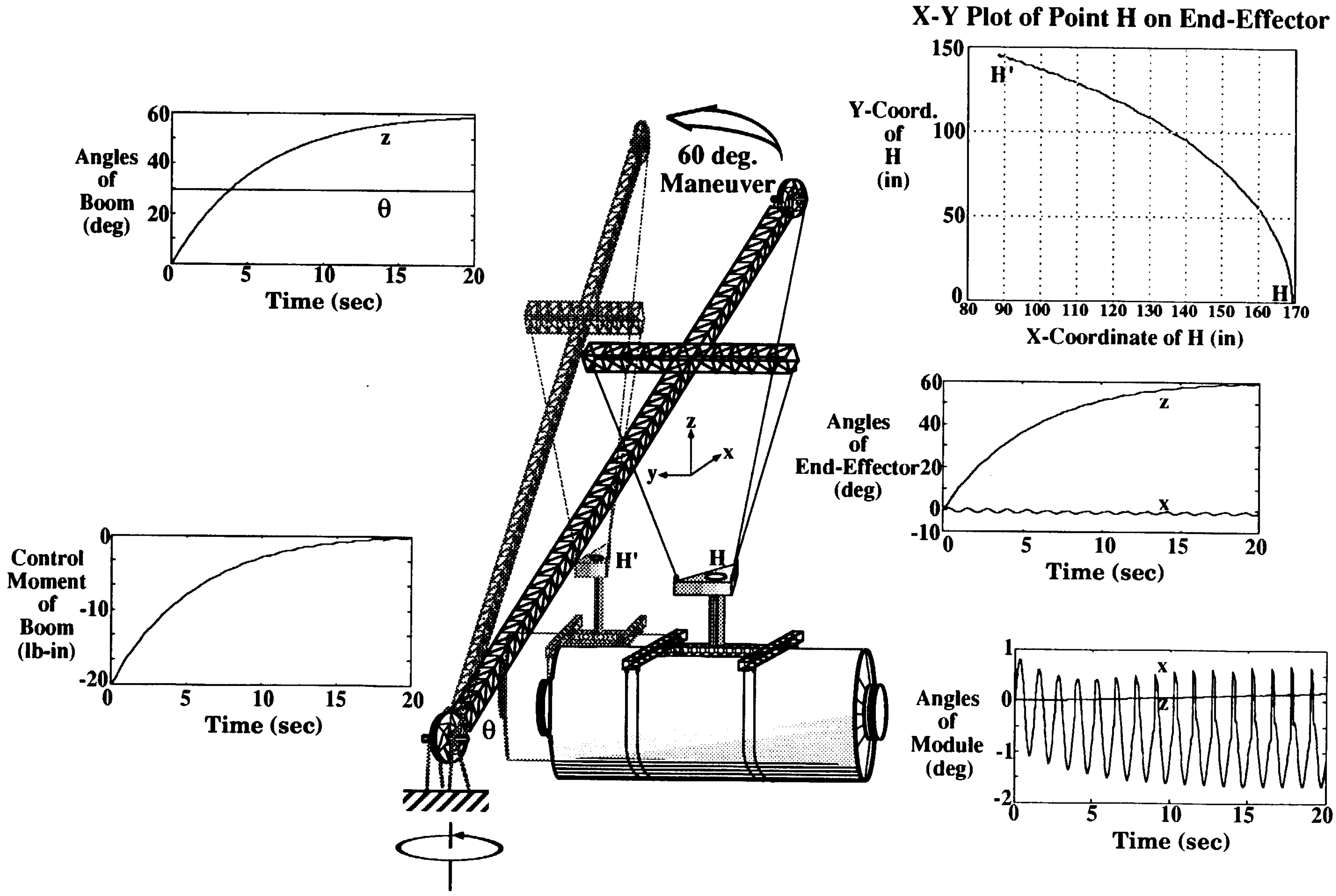
CMG CONTROL SIMULATION RESULTS



SIMULATION RESULTS
(I)

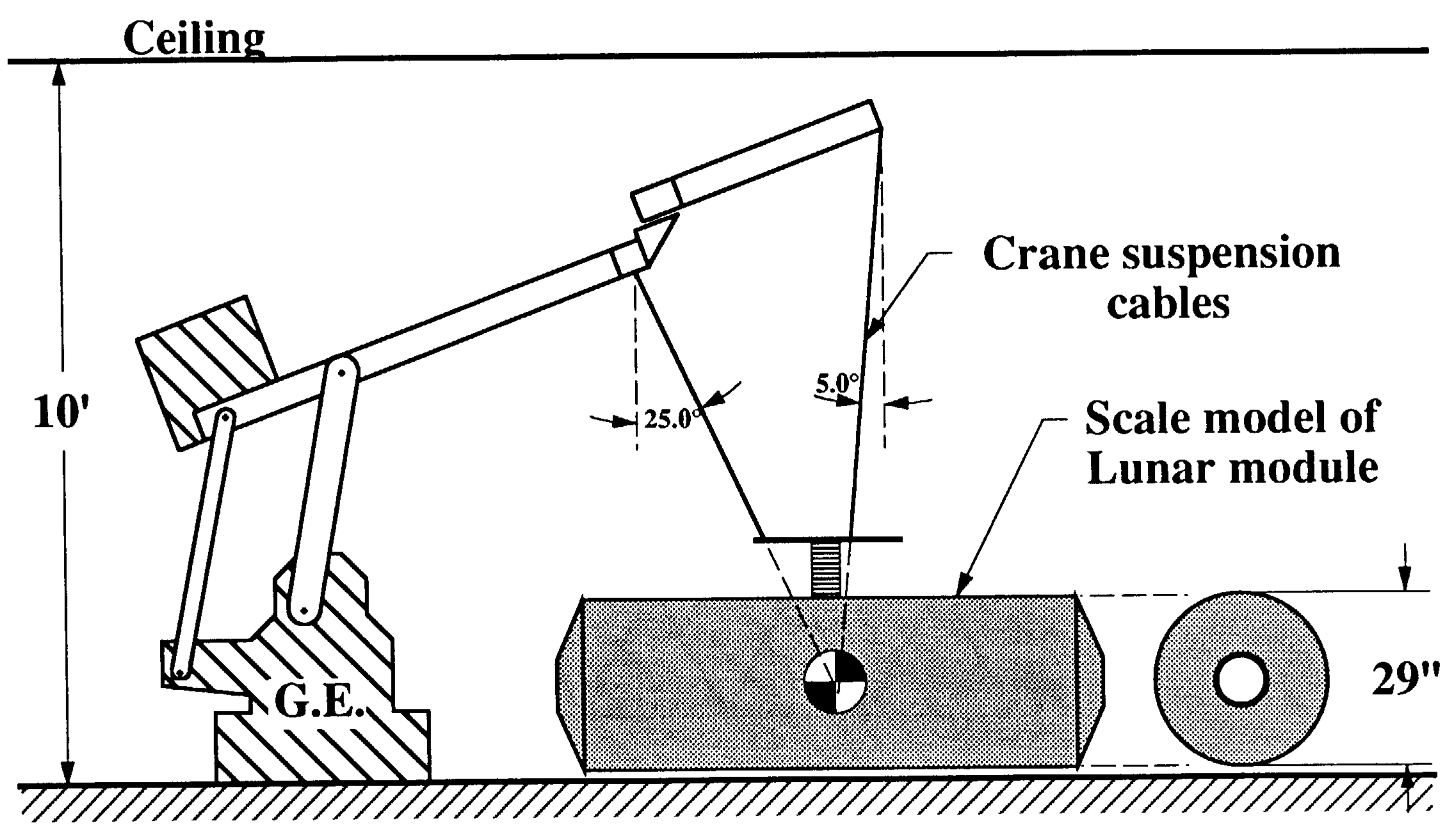


SLEWING SIMULATION RESULTS

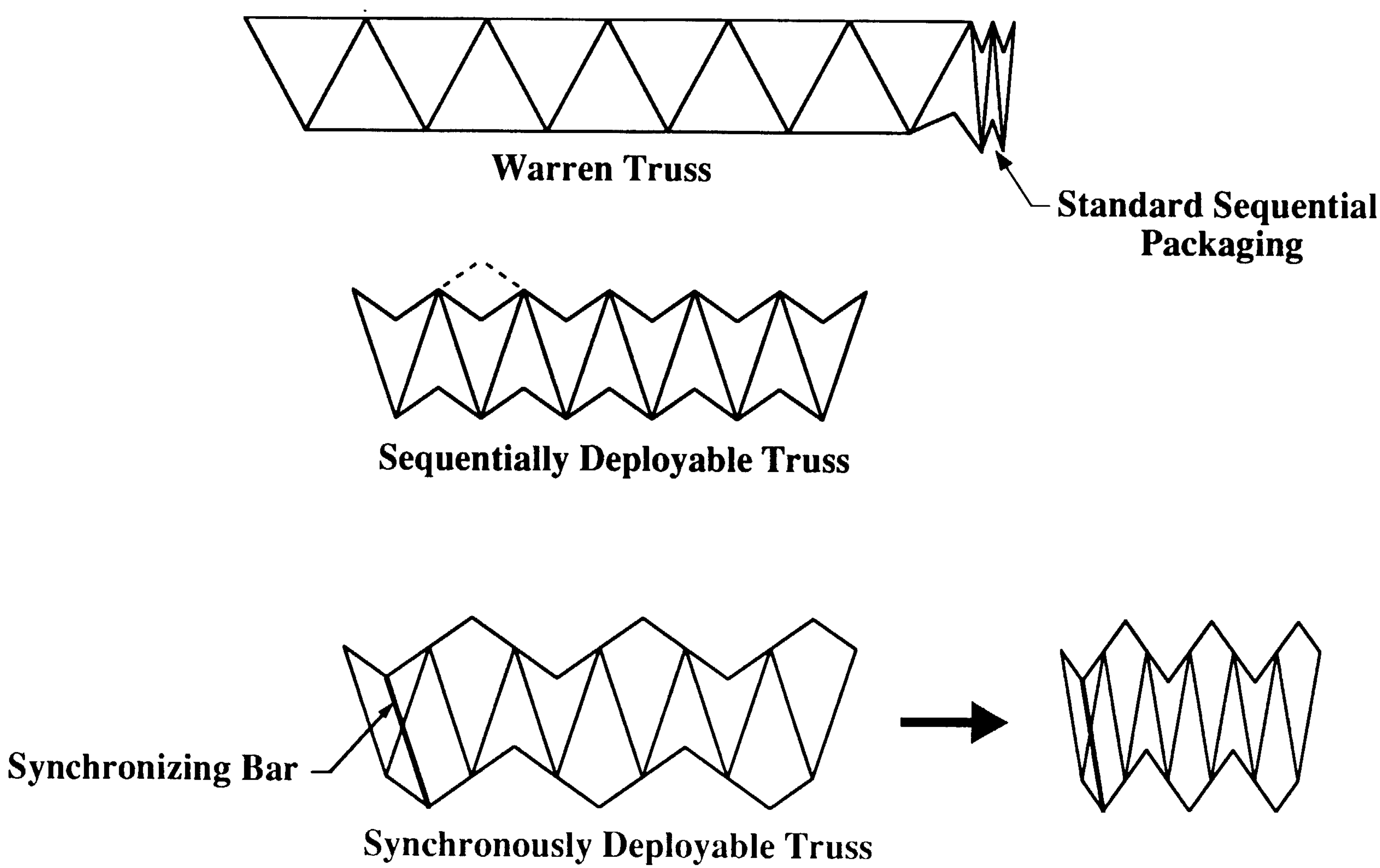


C-4

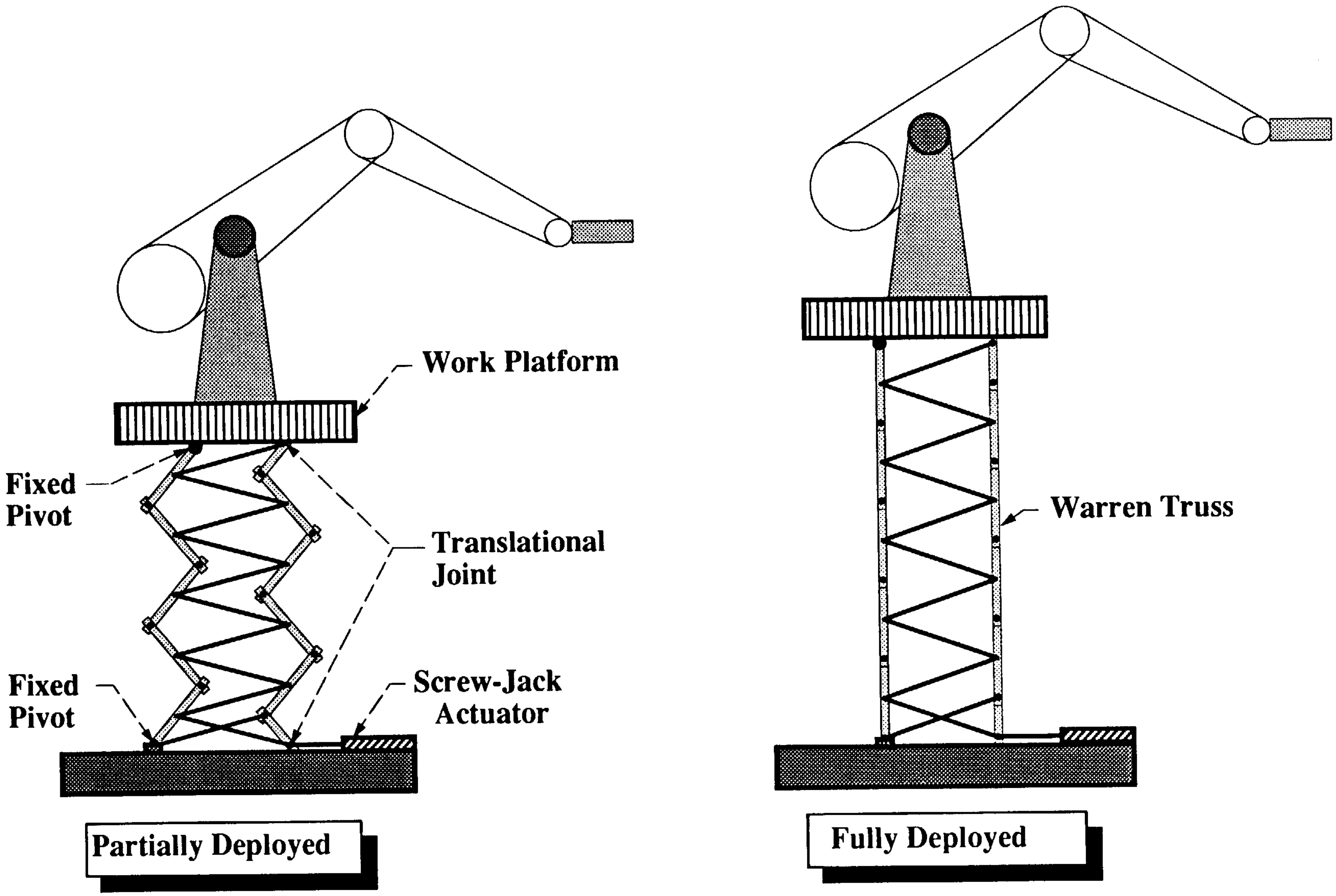
ONE-SIXTH SCALE LUNAR CRANE TEST-BED USING G.E. ROBOT FOR GLOBAL MANIPULATION.



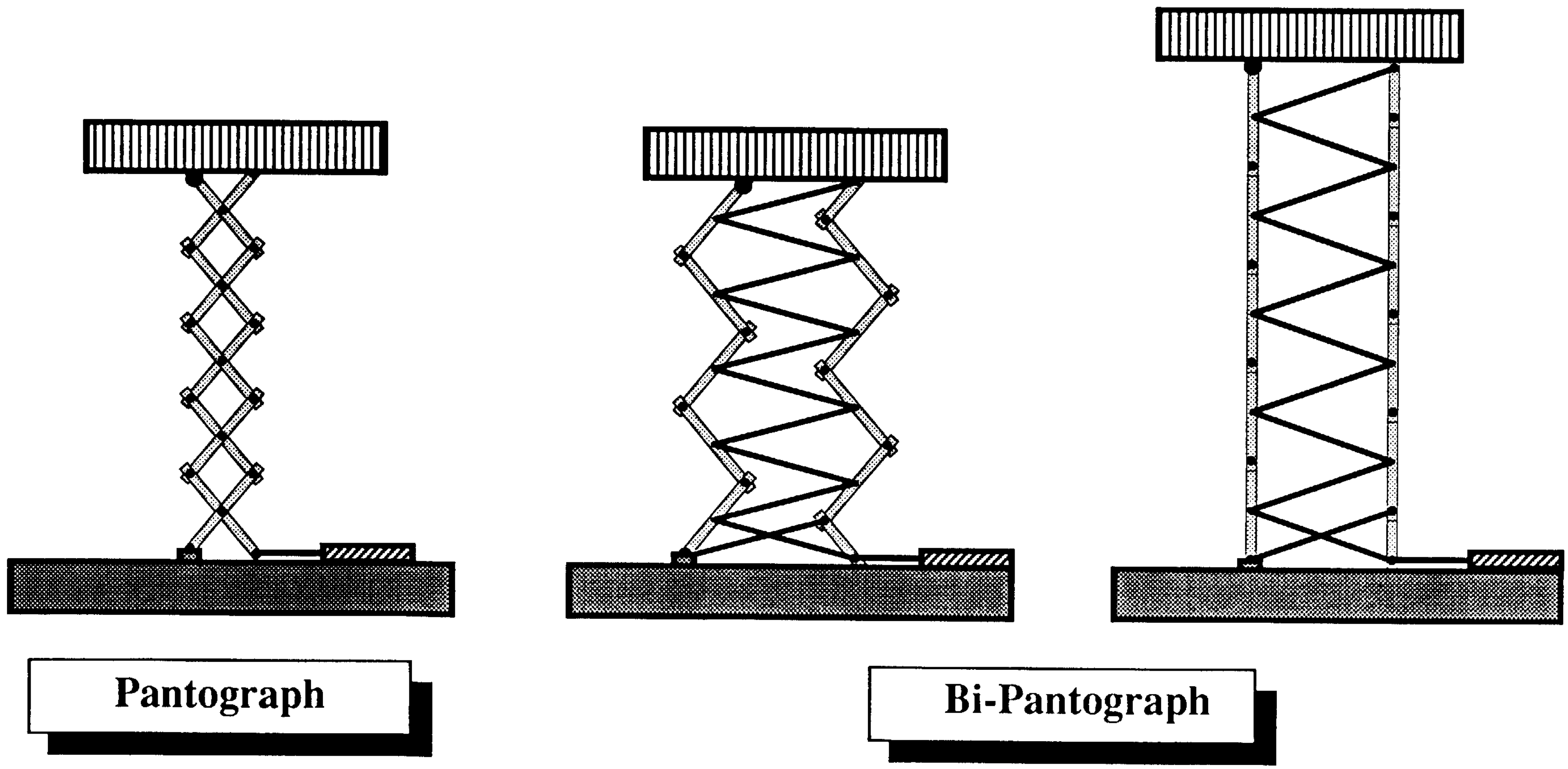
BASIC DEPLOYABLE TRUSS APPROACHES



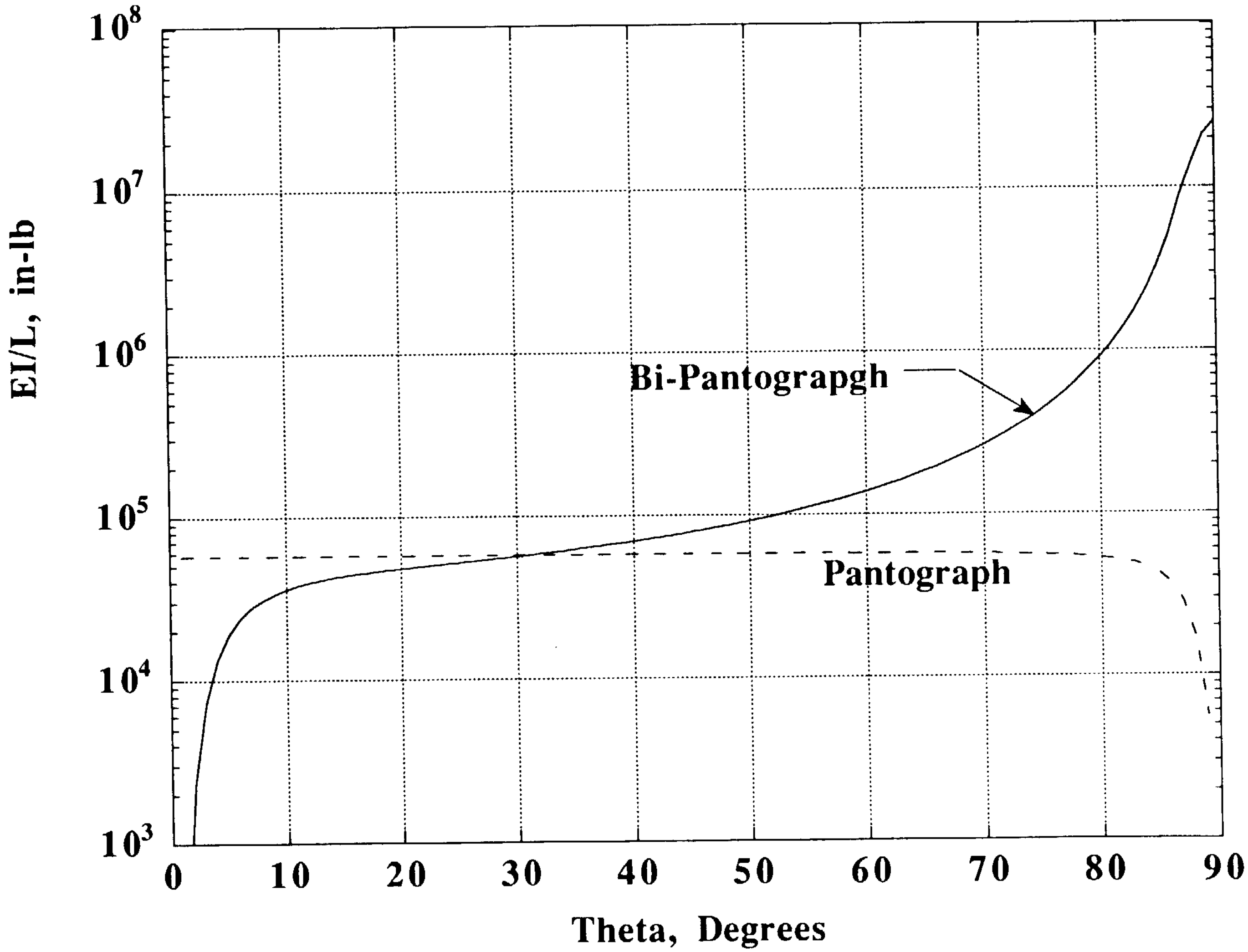
BI-PANTOGRAPH ELEVATOR PLATFORM



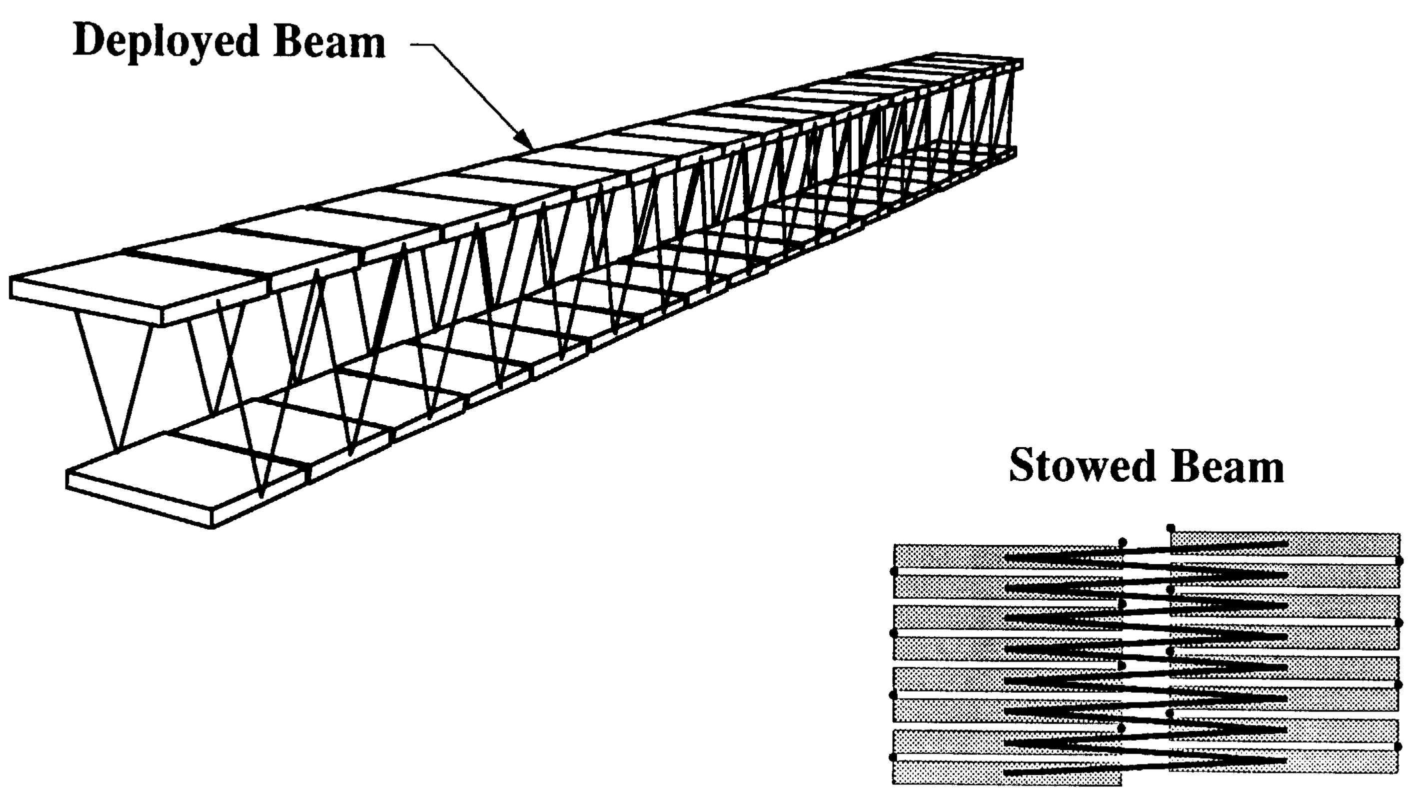
COMPARISON OF ELEVATOR PLATFORMS



BI-PANTOGRAPH VS PANTOGRAPH STIFFNESS

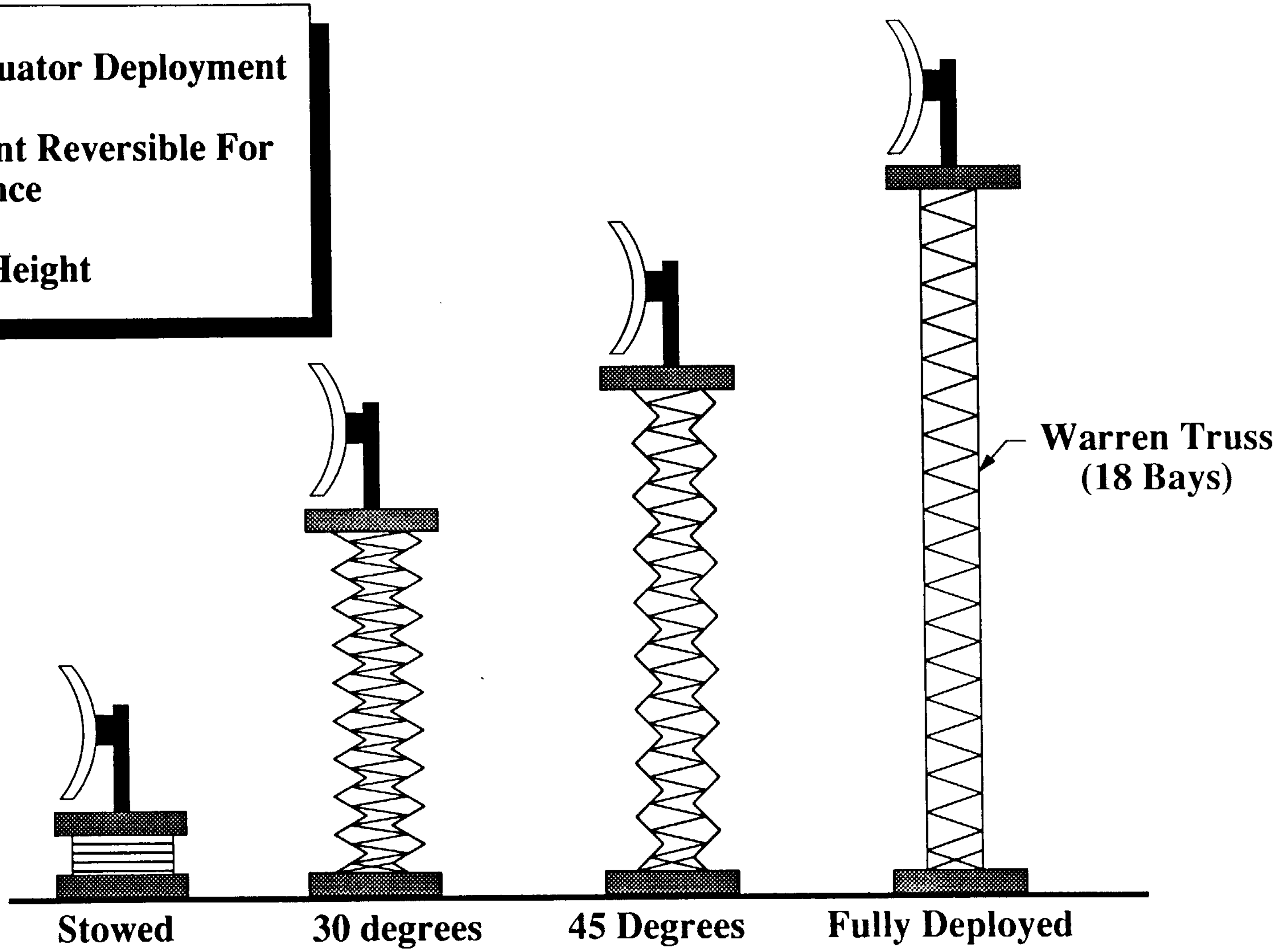


PERSPECTIVE OF BI-PANTOGRAPH BEAM

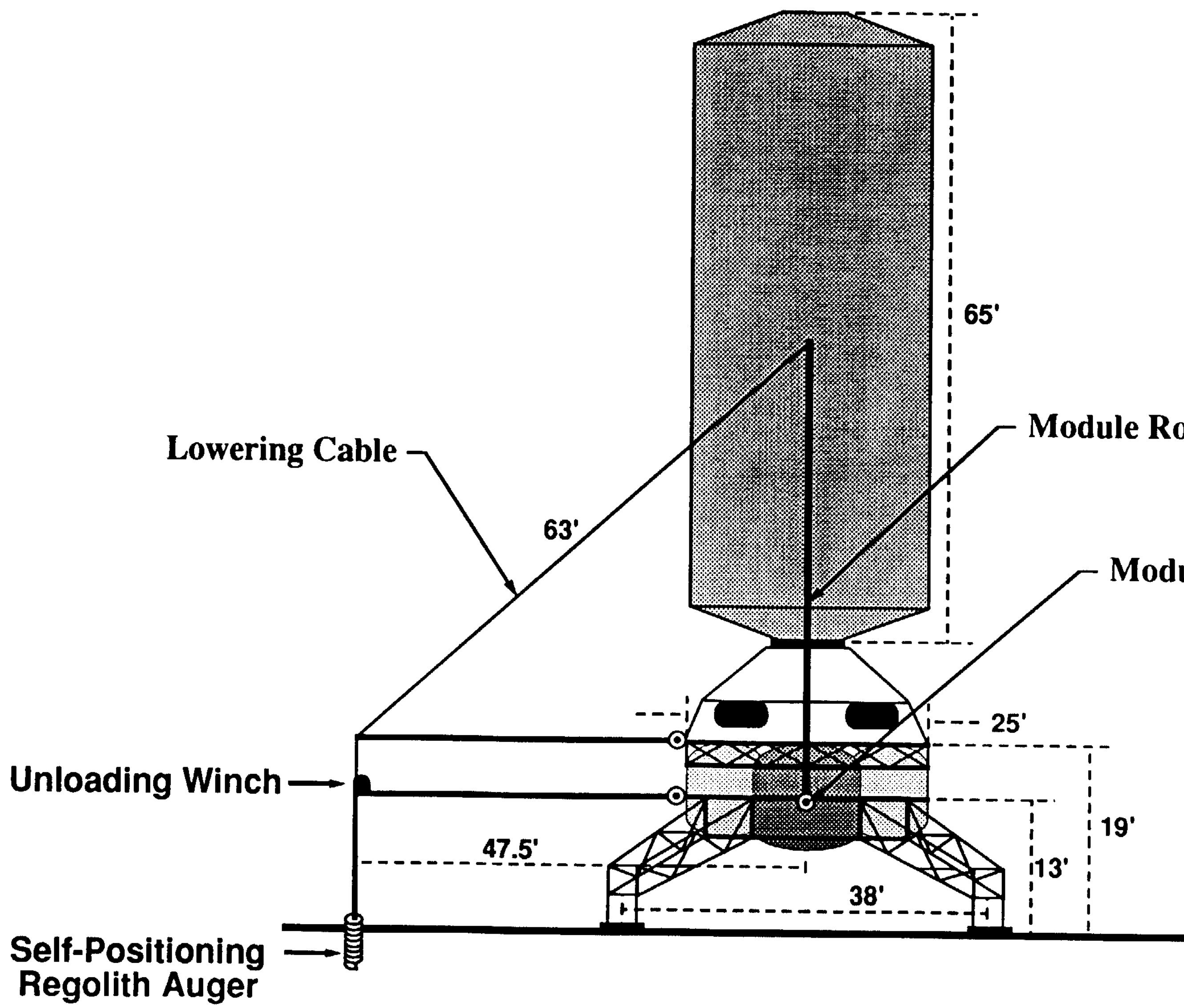


BI-PANTOGRAPH SYNCHRONOUSLY DEPLOYABLE TOWER/BEAM

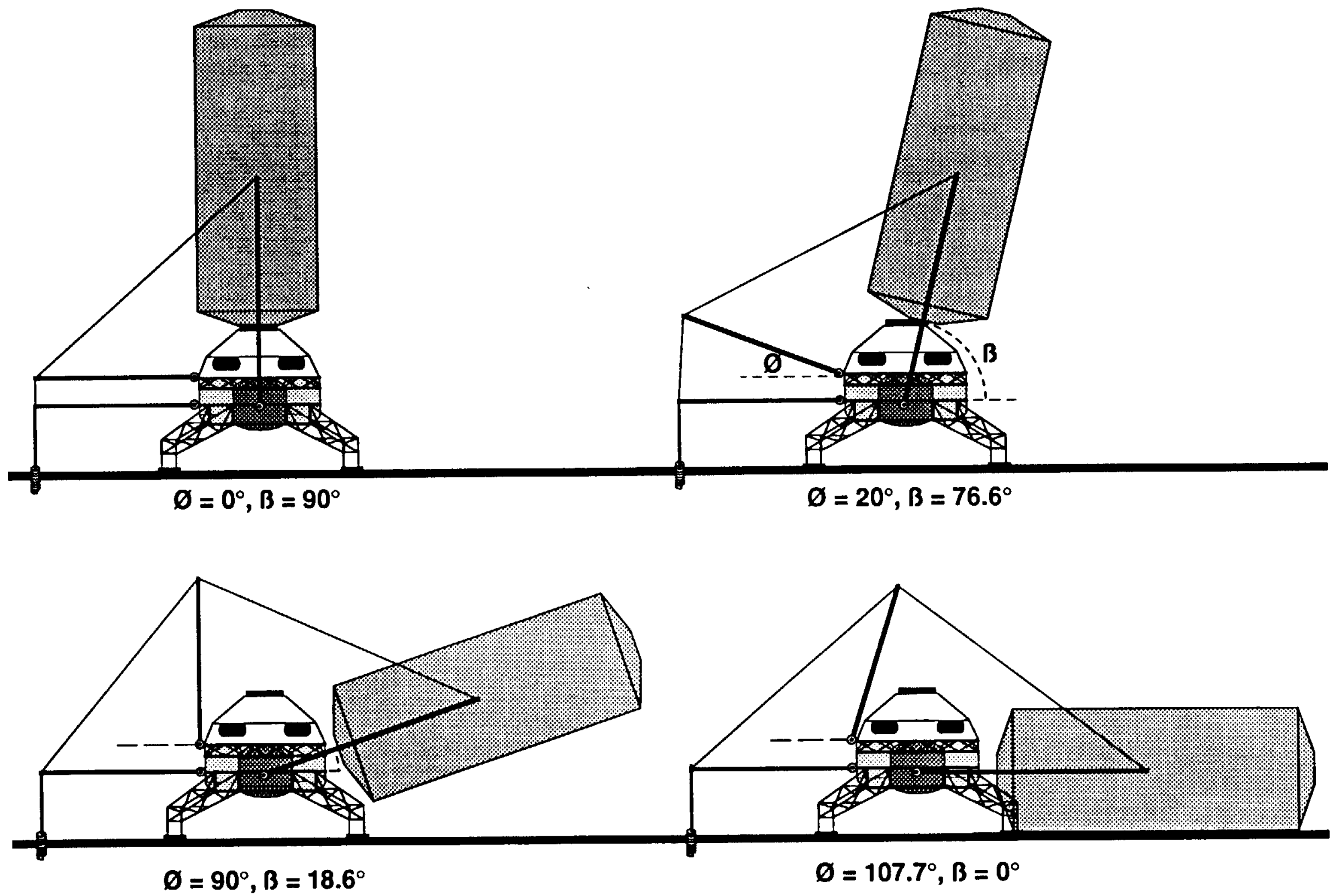
- Single Actuator Deployment
- Deployment Reversible For Maintenance
- Variable Height



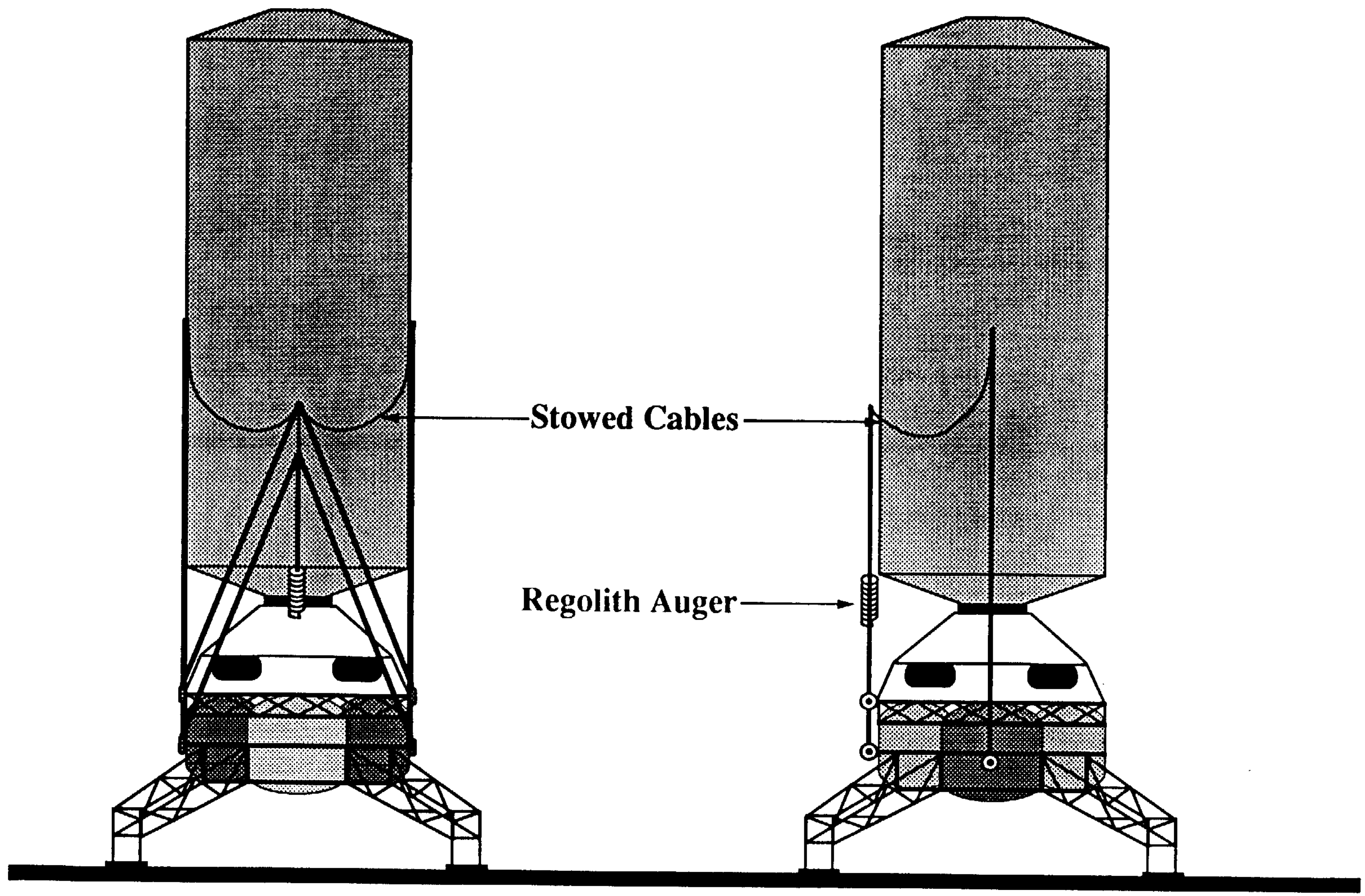
LUNAR MODULE OFF-LOADING CONCEPT



LUNAR MODULE OFF-LOADER CONCEPT DURING VARIOUS PHASES OF OPERATION



MODULE OFF-LOADER CONCEPT PACKAGED
(REAR & SIDE VIEWS)



STARBURST DEPLOYABLE PRECISION REFLECTOR

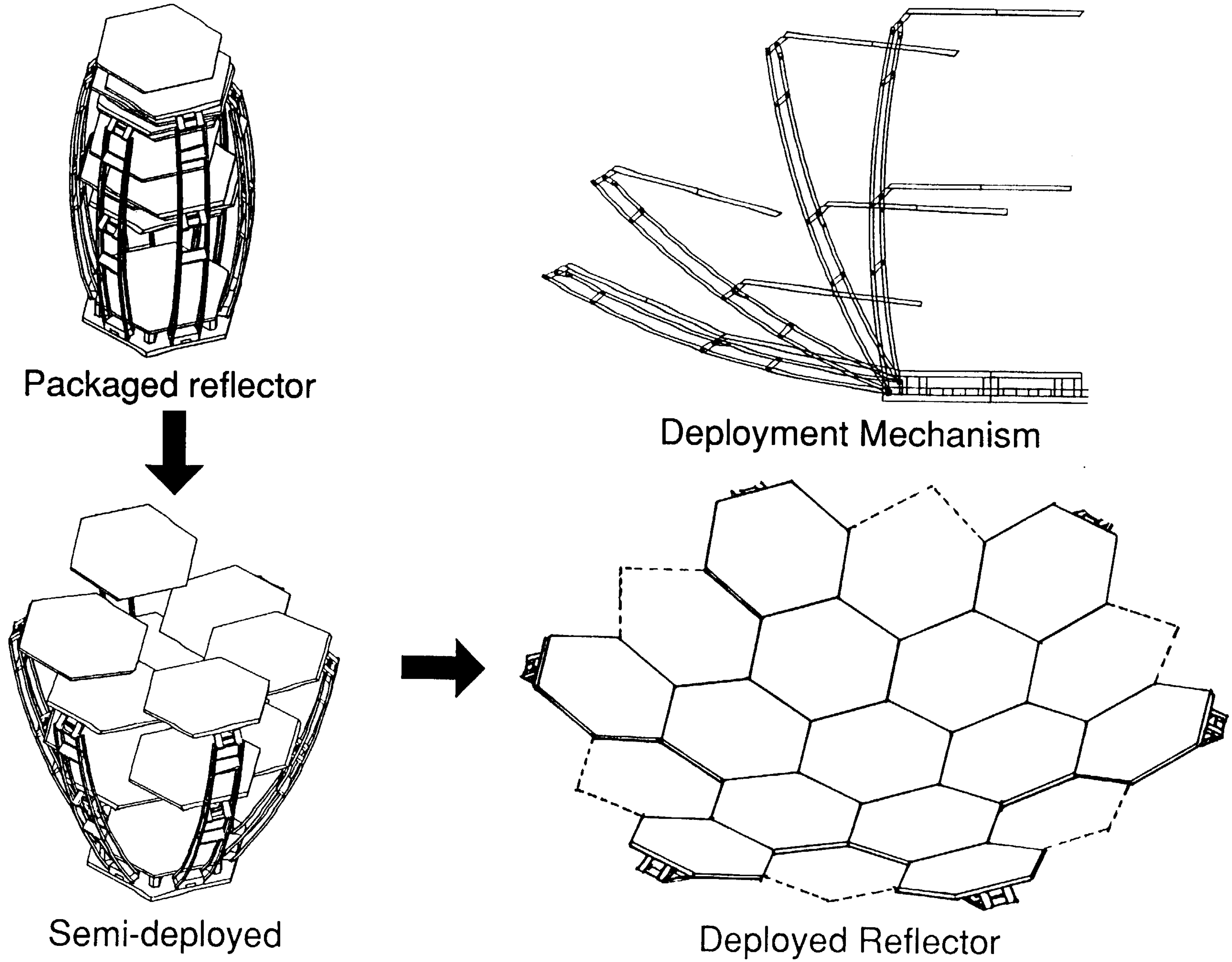
Features

- Maximum packaging efficiency for reflector panels
- Simple one-degree-of-freedom deployment of reflector arms
- Permits integrated reflector system

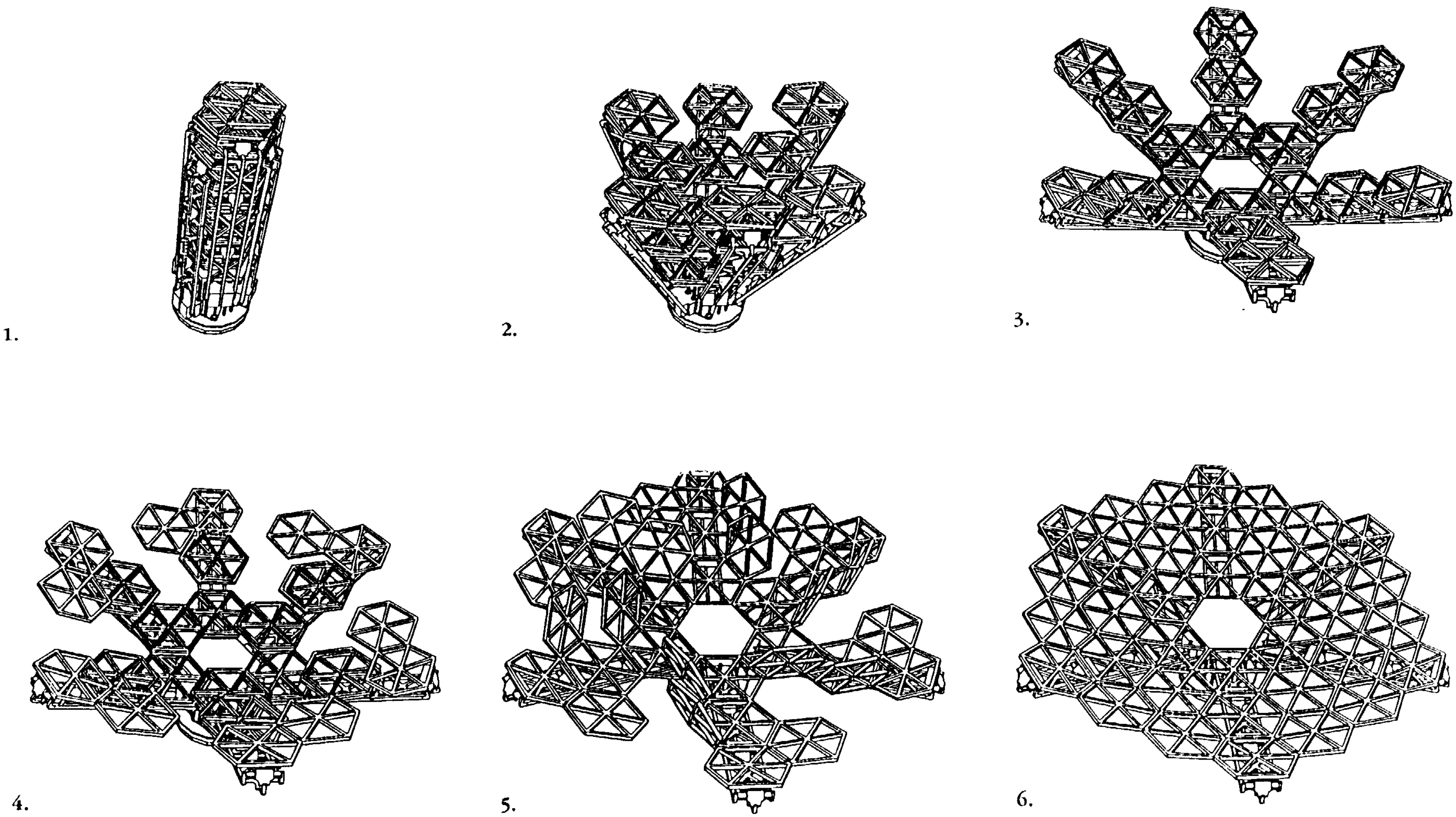
Applications

- LDR-type telescopes
- Microwave radiometers
- Solar concentrators

"STAR BURST" CONCEPT HAS POTENTIAL FOR DEPLOYING 20 METER DIAMETER PRECISION DEFLECTOR

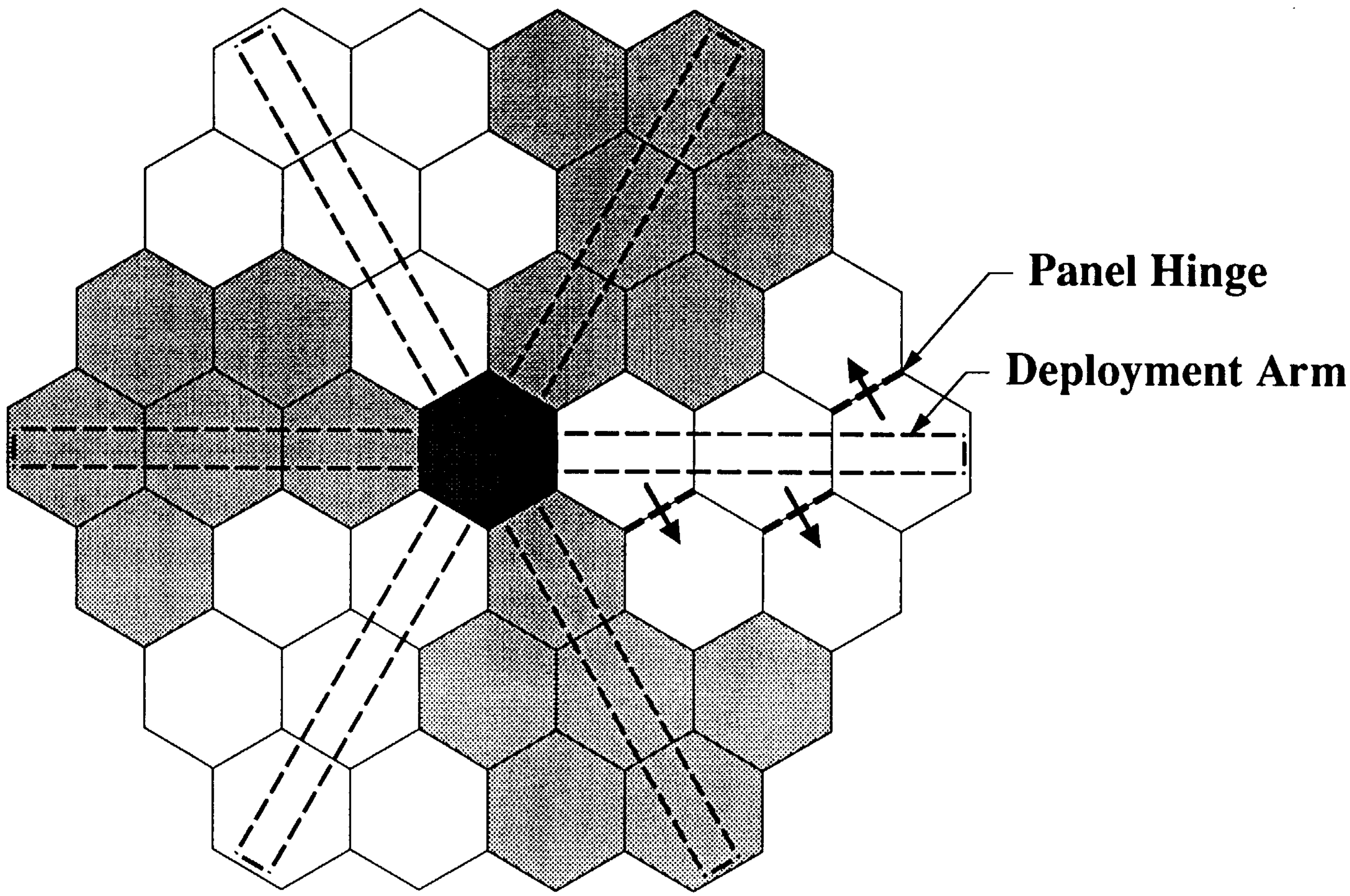


STARBURST DEPLOYABLE PRECISION REFLECTOR

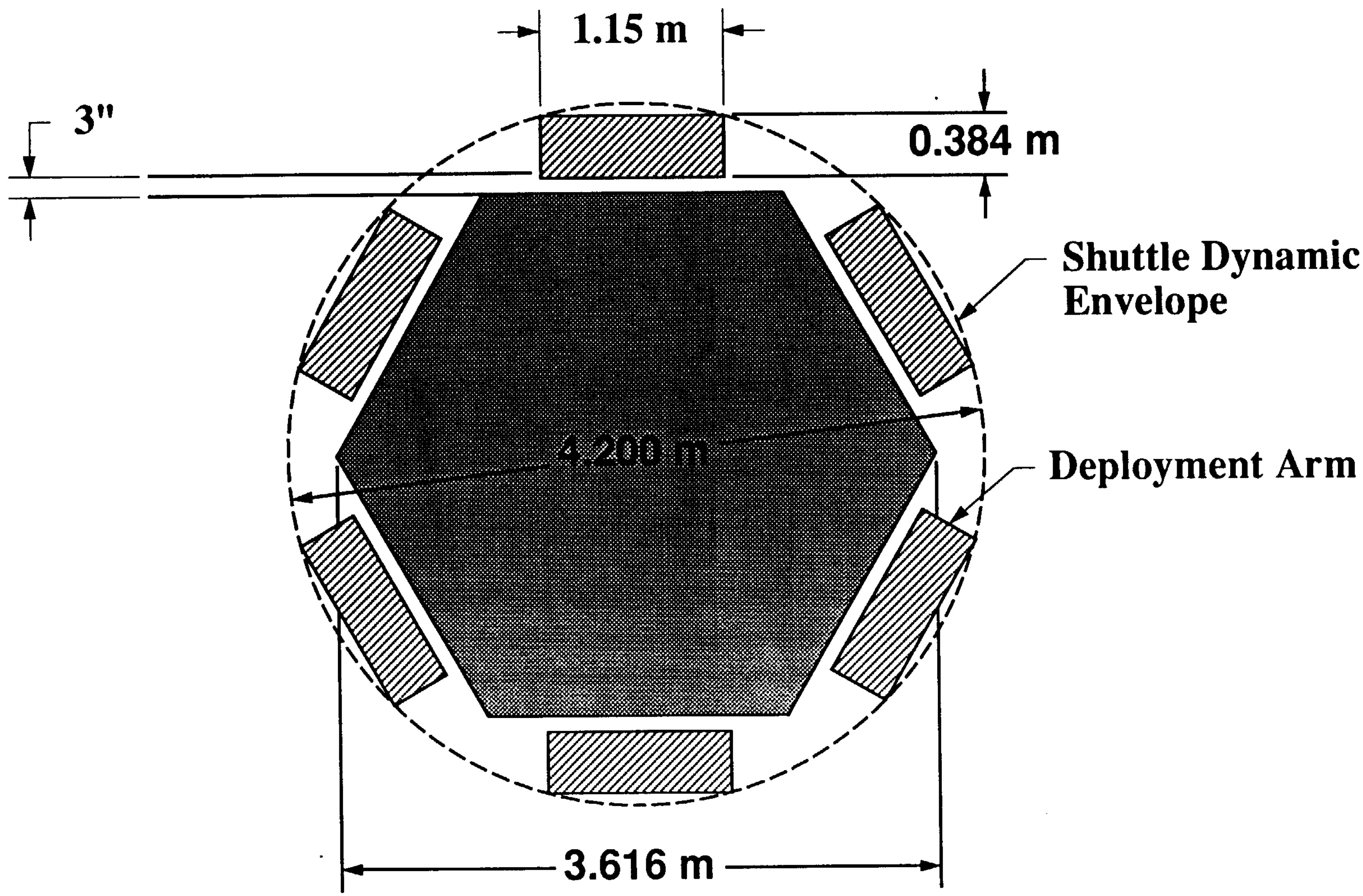


3 RING REFLECTOR DEPLOYMENT SCHEME

- 37 Panels Total
- 6 Deployment Arms
- 6 Panels Per Deployment Arm

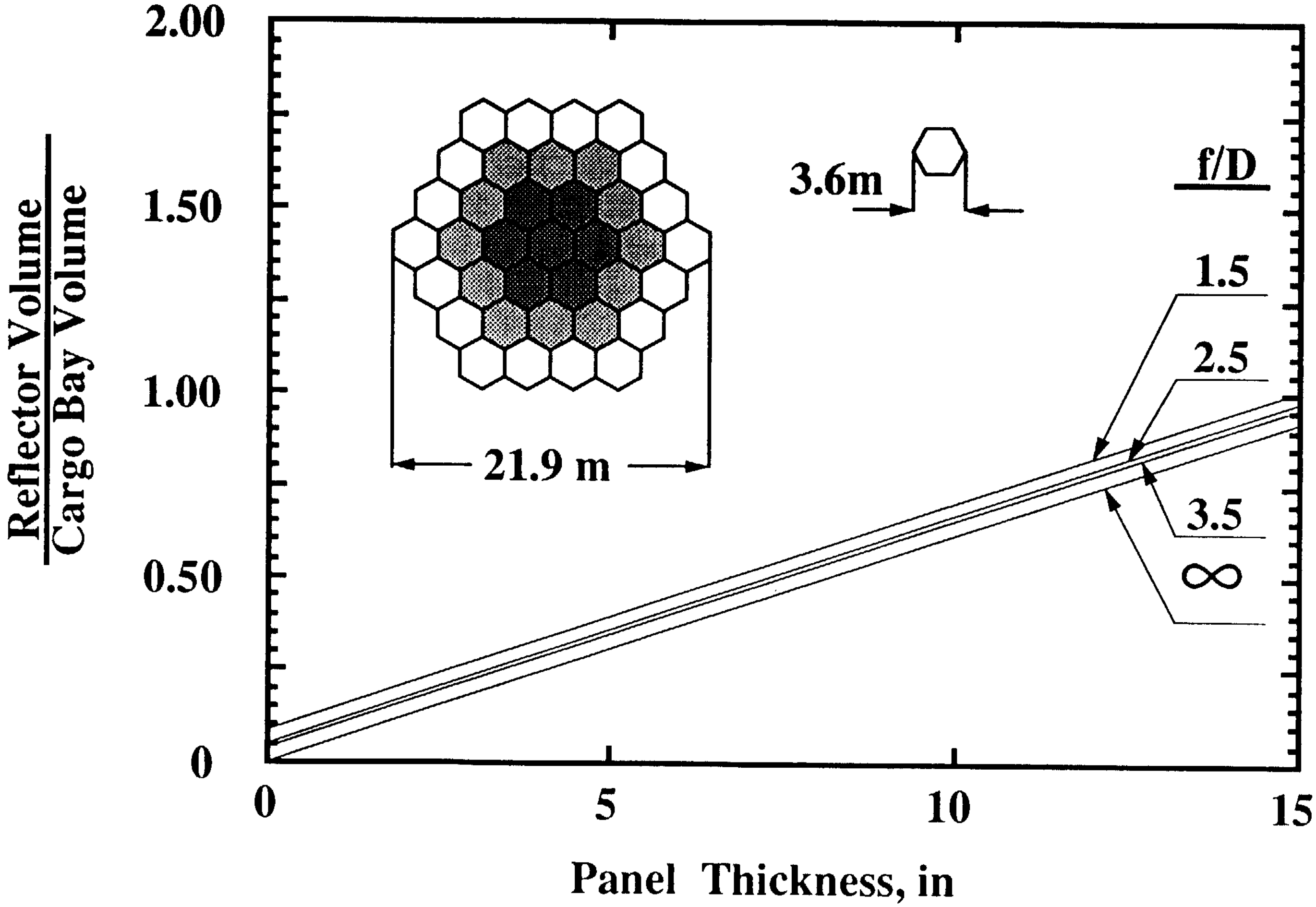


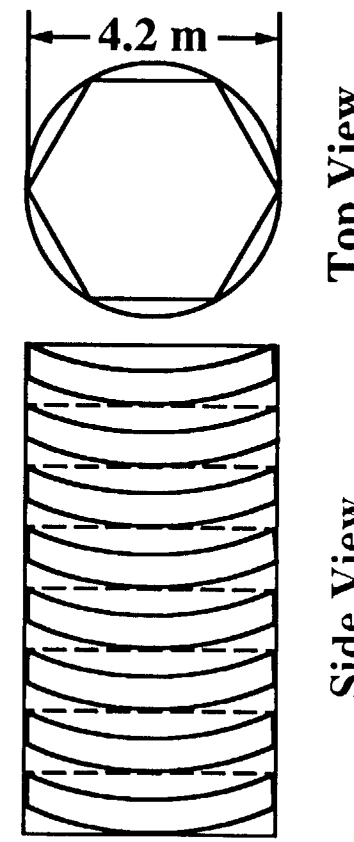
CROSS-SECTION OF PACKAGED STARBURST REFLECTOR



FOCAL POINT AND THICKNESS PACKAGING CONSIDERTIONS

(3 Ring, 20 m D eff)





STARBURST COMMENTS

Low level of effort to date (Primarily a concept feasibility study)

Has potential for deploying 20 meter class reflectors from Shuttle-size cargo bay

Two basic deployment concepts
- o Synchronized mechanism
- o Distributed actuators

Further work needed
- o Detailed packaging study for both concepts
- o Deployment simulation for both concepts
- o Build demonstration model
- o Deployable support structure concept study
- o Dynamic & accuracy active control operation simulation studies

Center for Space Construction
Third Annual Symposium
November 21, 22, 1991

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