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 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 much interdisciplinary activity.
     Each prof. simply doing their own thing.
   - Goal 2 - educate students in vision and tech skills: No direct evidence in symposium
     that reveals CSC doing anything out of the ordinary here.

November 21 - 22, 1991
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
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

<table>
<thead>
<tr>
<th>In Orbit</th>
<th>On the Moon</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Large volume and mass</td>
<td>• Extremely different and hostile</td>
</tr>
<tr>
<td>• Free flying in reduced-gravity</td>
<td>construction environment</td>
</tr>
<tr>
<td>environment</td>
<td></td>
</tr>
<tr>
<td>• Fragility</td>
<td></td>
</tr>
</tbody>
</table>
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
   - Control for evolving structures during construction

2. Analysis:
   - Multi-body dynamics simulation capability
   - Component mode synthesis methods

3. Construction equipment:
   - Space crane control
   - Robotic positioning and attachment of structural payloads

4. Mechanisms:
   - Passive/active load control mechanisms
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
2. Structural designs using indigenous materials
3. Construction equipment with increased efficiency, teleoperation capabilities, flexibility, and reliability
4. Rigorous analysis of performance and energy consumption for construction equipment
5. Systems analysis
CSC Lunar Construction Tasks

1. Lunar regolith condition and structures (Stuart)
2. Indigenous material processing for structural elements (Rogers)
3. Lunar shelter design using indigenous materials (Hopper)
4. Lunar crane system (Mikulcs)
5. Robotic construction workers (Avern)
6. Lunar regolith penetration tools (Stuart, Barnes)
7. Systems analysis of construction equipment and structural concepts
Space Construction: A New Engineering 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
Dynamics of On-Orbit Construction Process

K.C. Park

Third Annual Symposium
November 21 & 22, 1991

A NASA Space Engineering Research Center at the University of Colorado
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 critically dictated 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.

Frequency Variations During Maneuvering of SRMS

SRMS Configuration

Straight Position

Intermediate Position

Question: How effective can linear control strategies be for changing frequencies and mode shapes?
SPACE STATION FREEDOM ASSEMBLY SEQUENCE

First Element Launch 1995

Man Tended Capability 1996

Permanently Manned 1999

---Space Station Freedom---

McDonnell Douglas • GE • Honeywell • IBM • Lockheed
THE SEGMENTS

Starboard

S4, S3
(45ft)

S2 (23ft)

S1 (43ft)

M1 (45ft)

P1 (23ft)

P2 (45ft)

P3, P4
(45ft)

Port

—Space Station Freedom—

McDonnell Douglas • GE • Honeywell • IBM • Lockheed
Librational Motion of a Space Shuttle

- 100 minutes circular orbit
- \((I_{zx} - I_{zz})/I_{yy} = 1\)
- 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

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

![Graph of librational response of a Space Shuttle](image-url)

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

![Graph of librational response of a Space Shuttle](image-url)

**Fig. 4** Librational Response of a Space Shuttle Under Small Disturbances
Pitching Angle = Rolling Angle = Yawing Angle = 25 degrees
Maneuvering of Shuttle Remote Maneuvering Systems (SRMS)

Properties of SRMS:
- Weight = 410 Kg
- Length = 15 m
- Cross Section Area = 0.0022 m²
- Young's Module = 1.27 X 10¹¹ Pa
- Shear Module = 3.18 X 10¹⁰ Pa
- Density = 1.2 X 10⁴ Kg/m³
- Tip Maneuvering Speed (without payload) = 0.6 m/s
CONTACT/IMPACT OF 2 RIGID BALLS

\[ m_1 = 5 \text{ kg}, \quad m_2 = 2 \text{ Kg} \]

1) \( v_1 = 0.2 \text{ m/s}, \quad v_2 = -0.1 \text{ m/s} \)
2) \( f_1 = 0.01 \text{ N}, \quad f_2 = -0.008 \text{ N} \)
3) \( v_1 = 0.1 \text{ m/s}, \quad v_2 = -0.05 \text{ m/s}, \quad f_1 = 0.01 \text{ N}, \quad f_2 = -0.001 \text{ N} \)
Tip Trajectory of Rigid & Flexible SRMS

Displacements, m

Time, sec

Velocities, m/s & rad/s

Time, sec
Contact Velocity of SRMS & Payload: X-axis

Velocity, m/s

Time, sec

Contact Forces of SRMS & Payload: X-axis

Forces, Newton

Time, sec
Contact Velocity of SRMS & Payload: Z-axis

Contact Forces of SRMS & Payload: Z-axis
Interaction Dynamics and Control for Orbital Assembly

Renjeng Su
Jim Chapel

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

MM. 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

assembly fixture
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)

Control Force

2)

Control Force
Admittance model of the manipulator.

\[ \int_{t_0}^{T} F_m(t)V_m(t)dt \geq 0 \]
Condition for manipulator passivity

Impedance model of the environment.

\[ \int_{t_0}^{T} F_e(t)V_e(t)dt \geq 0 \]
Condition for environmental passivity

Model of manipulator coupled to environment.
A Simple Example

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

Feedback controls:
1. simple PD control
2. Torque loop
3. Impedance shaping
Removal/insertion of a misaligned module.
Model of a "typical" actuator.

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

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, $K_p=116$, $K_v=12.5$)
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 $H_\infty$ minimization problem.
Achieved (solid line) and target (dashed line) admittance responses for example $H_\infty$ design using $K_f(s)$. 
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.
Controls for Orbital Assembly of Large Space Structures

Mark Balas

Third Annual Symposium
November 21 & 22, 1991

A NASA Space Engineering Research Center at the University of Colorado
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

$M_{1,2,3}$ : global control commands
De-centralized Control for Flexible Multi-body Systems

Local and Global Control

Localized actuator and sensor assembly for flexible control

Global actuators and sensors for pseudo-rigid body positioning
Control of Structures During Assembly

Normal (Planned) Assembly
Emergencies ($F^3O$)

Docking & Berthing / Contact
Decentralized Control
Using Structural Partitioning

[Diagram showing an overseer connected to controllers labeled 1 to 5, which are connected to a large structure]
Reduced-Order Model-Based Controller Design

Closed Loop: \( L_n = A_n + B_n G_n - K_n C_n \)

\[
\begin{bmatrix}
\dot{x}_n \\
\dot{\hat{x}}_n \\
x_r
\end{bmatrix}
= \begin{bmatrix}
A_n & B_n G_n & 0 \\
K_n C_n & L_n & K_n C_r \\
0 & B_r G_n & A_r
\end{bmatrix}
\begin{bmatrix}
x_n \\
\hat{x}_n \\
x_r
\end{bmatrix}
\]

OR

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

Flexible Structure

- 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

Distributed Parameter System

\[
\dot{x} = Ax + Bu \\
y = Cx
\]

ROM Controller

\[
\hat{x}_n = L_n\hat{x}_n + K_n\tilde{y} \\
u = G_n\hat{x}_n
\]

Residual Mode Filter

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

open-loop unstable modes
closed-loop unstable modes
unaffected residual modes (unmodelled dynamics)

DPS + Rom Controller \(\longrightarrow\) unstable (q modes)
DPS + ROM Controller + RMF \(\longrightarrow\) exponentially stable
LSS Active Control Simulation
(Ralph Quan)

Actuator Dynamics
\[ u = H_{11}u_c + H_{12}z_a \]
\[ \dot{z}_a = K_{21}u_c + K_{22}z_a \]

LSS / FEM
\[ M_0\ddot{q} + D_0\dot{q} + K_0q = B_0u \]
\[ y = C_0q + E_0\dot{q} + F_0u \]

Sensor Dynamics
\[ y_c = K_{11}y + K_{12}z_s \]
\[ \dot{z}_s = K_{21}y + K_{22}z_s \]

Controller
\[ \dot{z} = L_{21}y_c + L_{22}z \]
\[ u_c = L_{11}y_c + L_{12}z \]

\[ \dim q = L \text{ large} \]
\[ \dim z = s \text{ small} \]
3-Dimensional Truss Beam

Sensor → BAY 54
              TIP MASS, PARAMETER MODIFICATION DEVICE
              PRIMARY ACTUATOR ASSEMBLY
              COLOCATED SENSORS

BAY 44

BAY 38

BAY 30

DISTRIBUTED SENSOR ASSEMBLY
BAYS 1, 12, 24, 30, 38, 44
SECONDARY ACTUATOR ASSEMBLY
BAYS 12, 30, 44

Actuator →

BAY 24

BAY 12

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

OPEN LOOP versus RMF CLOSED LOOP

Time (s)

Open Loop
RMF Closed Loop
Figure S.7  The Mini-Mast Truss

Longley
Figure 8.22 Phase Evolutionary Model
Space Crane Under Small Angle Rotation, Open-Loop

alpha joint angular position (radians)

time (sec)
Space Crane Under Small Angle Rotation without Compensation

Time (sec)

Alpha Joint Angular Position (radians)
Figure 7: Hub Position Without CSI Compensation

- Angular position (degrees)
- Time (seconds)

Reference position
Figure 10: Hub Position With CSI Compensation

Angular position (degrees)

Time (seconds)
Perturbation Analysis

well known

\[ A_c(\varepsilon) = A_0 + \varepsilon \Delta A \] Small Perturbation

Asymptotic Eigenvalue Series:

\[ \hat{\lambda}_c(\varepsilon) = \lambda_0 + \varepsilon \lambda_1 + \varepsilon^2 \lambda_2 + \ldots \]

Closed-Loop (LSS + ROM Controller):

\[ A_c(\varepsilon) = \begin{bmatrix} A_H & B_H G_m & 0 \\ K_m C_m & L_m & \varepsilon K_mC_R \\ 0 & \varepsilon B_R G_m & A_R \end{bmatrix} \]

\[ \therefore \hat{\lambda}_c(\varepsilon) = \lambda_0 + \varepsilon^2 \lambda_2 \]

Note: \( \lambda_1 = 0 \) \& \( \lambda_3 = 0 \)
Testbed Concept Has Thin Facesheet Controlled From Support Truss
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

Nonlinear DPS

\[
\begin{align*}
\dot{x} &= Ax + Bu + f(x) \\
y &= Cx
\end{align*}
\]

Nonlinear ROM Controller

\[
\begin{align*}
u &= G_n \ddot{x}_n \\
\dot{x}_n &= A_n \ddot{x}_n + B_n u + K_n(y_c - \ddot{y}_n) \\
&\quad + f_n(\ddot{x}_n, \ddot{x}_q, 0) \\
\ddot{y}_n &= C_n \ddot{x}_n
\end{align*}
\]

Nonlinear RMF

\[
\begin{align*}
\ddot{y}_q &= C_q \ddot{x}_q \\
\dot{x}_q &= A_q \ddot{x}_q + B_q u + f_q(\ddot{x}_n, \ddot{x}_q, 0)
\end{align*}
\]
Indirect Adaptive Control

Desirable Output Performance

Plant

Parameter Estimator

Gain calculator

Adjustable Gain Controller

Exciting inputs

u

y
Direct Adaptive Control

Possible inputs

Reference Model

Tracking:

\[ e_y = y - y_m \]

Direct gain Adaptation

Possible inputs

\[ u \]

\[ X_m \]

\[ u_m \]
Model Following (SG Compensator: Uref=1)

Flexible Manipulator Experiments (SC Liang)

Hub Control - Strain Gauge Sensor
(Not Collocated)
Decentralized Controller Design

Controller 1

\[ u_1 = K_1^0 y_1 + K_1^1 z_1 \]
\[ \dot{z}_1 = L_1^0 z_1 + L_1^1 y_1 \]

Controller 2

\[ u_2 = K_2^0 y_2 + K_2^1 z_2 \]
\[ \dot{z}_2 = L_2^0 z_2 + L_2^1 y_2 \]

Large Space Structure (LSS)

\[ \dot{x}_n = A_n x_n + B_1 u_n + B_2 u_2 \]
\[ y_1 = C_1 x_n + \text{residuals} \]
\[ y_2 = C_2 x_n + \text{residuals} \]

Performance
RMF Compensation for Stable Control

Residual Mode Filter (RMF)

\[ \dot{x}_q = A_q \dot{x}_q + B_1 q u_1 + B_2 q u_2 \]
\[ \tilde{y}_1 q = C_1 q \dot{x}_q \]
\[ \tilde{y}_2 q = C_2 q \dot{x}_q \]

Controller 1

\[ \alpha_1 \]

\[ y_1 \]
\[ u_1 \]

LSS

\[ x = Ax + B_1 u_1 + B_2 u_2 \]
\[ y_1 = C_1 x \]
\[ y_2 = C_2 x \]

Controller 2

\[ \alpha_2 \]

\[ u_2 \]
\[ \tilde{y}_2 q \]
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

Tip Mass

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

Initial contacts made with LeRC to understand solar array problem

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

Cooperative agreement made with Honeywell to co-develop an energy absorber
ENERGY CHARACTERISTICS OF CANTILEVERED TRUSSES WITH A TIP LOAD.

Standard Truss

\[ 2P_LH = PL \Rightarrow P_L = \frac{PL}{2H} \]

Truss strain energy is:
\[ \Pi = \frac{1}{2} P\Delta \]

Where
\[ \Delta = \frac{PL^3}{3EI} \]

Energy Absorbing Truss

\[ \frac{\delta}{H} = \frac{\Delta}{L} \Rightarrow \Delta = \frac{L}{H}\delta \]

Truss absorbed energy is:
\[ E = P\Delta \]

or
\[ E = P\frac{L}{H}\delta = 2P_L\delta \]
TEN BAY LONG RESILIENT TRUSS EXAMPLE

Energy Absorbing Strut

Buckling Critical Strut

Pivots

10 m

1 m

\( P \)

\( \Delta \)
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

Load Limiting Strut

\[ P = \frac{2P_L H}{L} = 260 \text{ lbs} \]

\[ \Delta = 1.7'' \]

\[ P_{\text{buckling}} = 1300 \text{ lbs} \]

\[ E = \frac{1}{2} P \Delta = \frac{1}{2} \times 260 \times 1.7 = 220 \text{ in-lb} \]

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

\[ E = 2P_L \delta = 2 \times 500 \times 4 = 4000 \text{ in-lb} \]

\[ \Delta = 10 \delta = 40'' \]

\[ \frac{\Delta}{H} = \frac{40}{196} = .2 \]
SCHEMATIC OF ENERGY ABSORBING STRUT

- Spring with pretension
- Brake System
- Cylindrical Tube
- Relaxed Position
- Extended Position
LINEAR LOAD AND MOTION CONTROL ACTUATOR

( Energy Absorbing Strut )

Control Computer

Motor

Power to/from

Ball Screw

Ball Nut

Coil Spring

Thrust Bearing

Encoder

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

Front View

Side View

Energy Absorbing Bay

Applied Pressure Impulse

\[ p \]

\[ t_p \]

\[ p \]

Deformed Array

\[ \theta \]

\[ M_{\text{Dynamic}} = I \ddot{\theta} \]

\[ M_{\text{Applied}} = pbL \left( \frac{L}{2} \right) \]

\[ M_{\text{Resisting}} = 2P_LH \]

(1) \[ M_R - M_R = I \ddot{\theta} \]

Integration Yields:

(2) \[ \theta = \frac{M_{\text{App}} t_p^2}{2I} \left( \frac{M_{\text{App}}}{M_R} - 1 \right) \]

or

(3) \[ \delta = \frac{M_{\text{App}} t_p^2}{2I} H \left( \frac{M_{\text{App}}}{M_R} - 1 \right) \]
SOLAR ARRAY CHARACTERISTICS

Array Weight, lbs

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip</td>
<td>31</td>
</tr>
<tr>
<td>Truss beam</td>
<td>315.78</td>
</tr>
<tr>
<td>Canister</td>
<td>534.65</td>
</tr>
<tr>
<td>Array Blanket</td>
<td>1246.57</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2128</strong></td>
</tr>
</tbody>
</table>

Array Beam (one bay)

Longeron properties

Area = 0.5 x 0.5 = 0.25 in²
E = 10e6
Pcrit = 1250 lbs

Truss bending stiffness

EI = 0.43 x EI(theoretical)
   = 98 lb-in² (Tom Irvine)
SOLAR ARRAY TIP DEFLECTION AND REQUIRED ACTUATOR STROKE

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

---

**Array input quantities**

- \( t_p = .75 \text{ sec} \)
- Plume pressure = .0002 psi
- Total load on array = 104 lbs
- Assumed actuator preload = 300lb

---

**Tip displacement**

- Rigid body - 31"
- Finite Element - 98"; Actuator stroke = 2.1"
SOLAR ARRAY RESPONSE FROM FINITE ELEMENT ANALYSIS

Shuttle Plume Loads
12 BAY ENERGY ABSORBING TEST BED

(Beam Length = 27.83')

TOP VIEW

- Energy Absorber
- Pivot
- Loading Cable (178 lb)
- 2300 lb steel weight (36"x36"x6")
- 2.92"

SIDE VIEW

- 5000 lb Backstop
- Air Bearing

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

Max. Absorber Load = 75 lb

\[ V = 3.9 \text{ ft/min} \]

\[ V = 46.6 \text{ ft/min} \]

\[ \text{Horsepower} = \frac{(F \times V)}{33,000} = \frac{(75 \times 3.9)}{33,000} = 0.0088 \]

Deflected Weight

Approximate Actuator Size

Thrust Bearing

Ball-Nut

MOTOR

75 lb

D = .2"
NEW AERO-LAB WITH 12-BAY TEST BEAM

Loading Cable

40 ft

Overhead Door

20 ft

HIGH-BAY AREA

Backstop

Loading Cable

Test Beam

CONTROL ROOM
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.
Systems Engineering Studies of On-Orbit Assembly Operations

George W. Morgenthaler

Third Annual Symposium November 21 & 22, 1991

cSc
The Theory of Space Construction

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)

Center for Space Construction

Progress Report

George W. Morgenthaler
"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
Center for Space Construction

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

ET Orbital Habitats
TBD

Lunar Base
Jim Stuart
Lunar Workshops
LLNL (Janet Gleave)
Dalton Point

ET Surface Construction

ET In-situ Resources

ET Surface Vehicles

ET Launch Vehicles

Century XXI DoDE
Extra Funding
USAF
SMART
Industrial Associates
NSCORT

Space Transfer Vehicle Habitat

Randy Colley

L M

Earth Orbital Habitats

Launch Vehicles to LEO

Launch-On-Time Vehicle Selection

NSCORT

EVA

Interruptibility
DYCAM 1.0
DYCAM 2.0
Simulation

Earth Surface Facilities

Analog

Focus

Orbital support equipment: RCS, ACS, Power, Thermal, Comm., Structure support for launch

"deploy/unlatch"

existing

Phase II
Rendezvous & Close Proximity OPS ("days")

Phase III
Final Closure & Soft Dock ("hours")

Phase I
Launch & Fairing Sep ("minutes")

Phase IV
Hard Latch Assembly & Test ("months")

An Orbital Assembly Scenario

Vehicle

Deorbit?
## 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

#### 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
Center for Space Construction

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

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

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

- Need HLLV Vehicle Requirements Model
Figure 2-1 Reference Boeing NTR Vehicle

HLLV Config: 5
Fairing: ECA
Payload Mass: 62 T
(Cargo Frame Mass: 14.3 T)

HLLV Config: 5
Fairing: ECA
Payload Mass: 116.5 T
(Cargo Frame Mass: 15.2 T)

HLLV Config: 6
Fairing: LMCA
Payload Mass: 145 T
(Cargo Frame Mass: 18.9 T)

HLLV Config: 1
Fairing: NCA
Payload Mass: 102 T
(Cargo Frame Mass: 13.3 T)

HLLV Config: 5
Fairing: ECA
Payload Mass: 93.5 T
(Cargo Frame Mass: 26.7 T)

Titan IV Configuration
Payload Mass: 19.9 T
(Cargo Frame Mass: 5.7 T)

* 38.5 T of TMI Topoff Required Per Tank

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

COST PER POUND TO ORBIT* ($K/lbm)

LAUNCH VEHICLE THROW WEIGHT (lbm x 1000)

* REF ORBIT: 100 n.mi. CIRC @ 20.5 deg

From Reference 10.
Figure 5

Shuttle C Performance

Shuttle Derived Launch Vehicles

Figure 6

Performance of Shuttle Derived Launch Vehicles

From Reference 10.
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.
Table 1. Vehicle Cost Performance (Thousands of 1990 dollars)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>iCost (Millions)</th>
<th>Pounds to LEO</th>
<th>Kg to LEO</th>
<th>iCost/Kg (thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scout I</td>
<td>171</td>
<td>5741</td>
<td>2611</td>
<td>65.13</td>
</tr>
<tr>
<td>Conestoga</td>
<td>231</td>
<td>13971</td>
<td>6351</td>
<td>44.09</td>
</tr>
<tr>
<td>Scout II</td>
<td>211</td>
<td>11341</td>
<td>5381</td>
<td>39.03</td>
</tr>
<tr>
<td>EPAC S-I</td>
<td>291</td>
<td>24991</td>
<td>11361</td>
<td>25.53</td>
</tr>
<tr>
<td>EPAC S-II</td>
<td>451</td>
<td>56001</td>
<td>30001</td>
<td>14.33</td>
</tr>
<tr>
<td>Delta II 6920</td>
<td>421</td>
<td>87001</td>
<td>39551</td>
<td>10.52</td>
</tr>
<tr>
<td>Delta II 7920</td>
<td>71</td>
<td>110861</td>
<td>50391</td>
<td>14.09</td>
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<tr>
<td>Atlas I</td>
<td>801</td>
<td>129801</td>
<td>59001</td>
<td>13.56</td>
</tr>
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<td>149161</td>
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<tr>
<td>Ande IV</td>
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<tr>
<td>Titan III</td>
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<tr>
<td>Shuttle Z</td>
<td>3431</td>
<td>2500001</td>
<td>1136361</td>
<td>3.02</td>
</tr>
<tr>
<td>Titan IV/Cant</td>
<td>2761</td>
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<td>309091</td>
<td>8.93</td>
</tr>
<tr>
<td>Saturn V</td>
<td>601</td>
<td>3080001</td>
<td>1400001</td>
<td>4.29</td>
</tr>
</tbody>
</table>

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 25 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)

\[ y = 0.34489 \times x^{(0.57494)} \quad R^2 = 0.90385 \]

\[ y = 0.37637 \times x^{(0.56355)} \quad R^2 = 0.92632 \]

\[ y = 0.43031 \times x^{(0.54804)} \quad R^2 = 0.91275 \]

\[ y = 0.53517 \times x^{(0.52343)} \quad R^2 = 0.84152 \]
Figure 8: Cost/kg vs. kg to LEO

- A: $y = 552.69 \cdot x^{(-0.42735)} R = 0.96416$
- B: $y = 597 \cdot x^{(-0.4386)} R = 0.97152$
- C: $y = 671.65 \cdot x^{(-0.45365)} R = 0.9739$
- D: $y = 817.41 \cdot x^{(-0.47799)} R = 0.97591$
Figure 9: "Useful" Volume vs. Payload

\[ y = m_0 + m_1x \]

- \[ m_0: -41.65 \times 10^4 \]
- \[ m_1: 0.0175 \times 10^4 \]
- \[ r^2: 0.8925 \times 10^2 \]

P/L to 200 km. (in kg.)

Volume (m³)
NUMBER OF PAYLOADS NEEDED

\[ NL(w) = \left[ \frac{W_o}{w} \right] + \frac{1}{2} \left( 1 + \text{sgn} \left( \frac{W_o}{w} - \left[ \frac{W_o}{w} \right] \right) \right) \text{sgn} \left( \frac{W_o}{w} - \left[ \frac{W_o}{w} \right] \right) \]

\[ NV(w) = \left[ \frac{V_o}{V_H(w)} \right] + \frac{1}{2} \left( 1 + \text{sgn} \left( \frac{V_o}{V_H(w)} - \left[ \frac{V_o}{V_H(w)} \right] \right) \right) \times \text{sgn} \left( \frac{V_o}{V_H(w)} - \left[ \frac{V_o}{V_H(w)} \right] \right) \]

\[ N(w) = \max \{ NL(w), NV(w) \} \]

LAUNCH VEHICLE RELIABILITY

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

\[ P_n(n-h) = \sum_{j=0}^{h} \frac{(n!)}{(n-j)!j!} p^n q^j (1-r)^j \]

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

\[ q = qr + q(1-r), \]

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

Hence,

\[ P_n(n) = p^n q^0 (1-r)^0 = p^n \]
\[ P_n(n-1) = np^{n-1} q(1-r) + p^n \]
\[ P_n(n-2) = \frac{(n(n-1)/2)p^{n-2} q^2 (1-r)^2 + np^{n-1} q(1-r) + p^n}. \]
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,

\[
p^* = p^{\text{make launch window}} = p^N + C_i^j p^N q^i + C_i^{N+1} p^N q^{i+1} + \ldots + C_i^{N+i-1} p^N q^i
\]

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 \( N \)th 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

\[
C(w) = \text{[Expected Cost]} = \frac{N(w)C_H(w)}{P_H(w)} + \frac{(SC)_S + (SC)_F}{N(w)} \left\{ \frac{N(w)}{P_H(w)} - N(w) \right\}
\]

(15)

\[
C^*(w) = \text{[Expected cost including probability of missing one launch window]}
\]

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

where \(C(w)\) is found in (15).
Table V: Parameter Values Used with Equations (15) and (18) for Figure 14.

<table>
<thead>
<tr>
<th>IILV Payload (lbs)</th>
<th>h</th>
<th>N[w]</th>
<th># Cluster</th>
<th>P[h(w)]</th>
<th>k</th>
<th>C%</th>
<th>Ps</th>
<th>Cs ($10^6$)</th>
<th>CSD ($10^6$)</th>
<th>FH[w] ($10^6$)</th>
<th># Bases</th>
<th>F*</th>
<th>r</th>
<th>C*[w] calc ($10^6$)</th>
<th>CH[w] list ($10^6$)</th>
<th>C*[list] ($10^6$)</th>
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<tr>
<td>$75 BILION CASE$</td>
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<td>2</td>
<td>36</td>
<td>0.82</td>
<td>100</td>
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<td>0</td>
<td>170</td>
<td>10</td>
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<td>2</td>
<td>18</td>
<td>0.91</td>
<td>100</td>
<td>0</td>
<td>170</td>
<td>10</td>
<td>2</td>
<td>1</td>
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<td>3</td>
<td>14</td>
<td>0.93</td>
<td>100</td>
<td>0</td>
<td>170</td>
<td>10</td>
<td>2</td>
<td>1</td>
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<td></td>
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<tr>
<td>440000</td>
<td>2</td>
<td>4</td>
<td>10</td>
<td>0.95</td>
<td>100</td>
<td>0</td>
<td>170</td>
<td>10</td>
<td>2</td>
<td>1</td>
<td>.9825</td>
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<td>0</td>
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<td>170</td>
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<td>100</td>
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<td>10</td>
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<td>6800 Titan IV/cent</td>
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<td>30</td>
<td>0.98</td>
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<td>10</td>
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<td>100</td>
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<td>0</td>
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<td>10</td>
<td>2</td>
<td>4</td>
<td>.8220</td>
<td>0.5</td>
<td>109</td>
<td>185</td>
<td>112.2</td>
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<tr>
<td>32432 Titan III</td>
<td>50</td>
<td>1</td>
<td>30</td>
<td>0.98</td>
<td>100</td>
<td>0</td>
<td>170</td>
<td>10</td>
<td>2</td>
<td>4</td>
<td>.8220</td>
<td>0.5</td>
<td>109</td>
<td>185</td>
<td>112.2</td>
<td></td>
</tr>
</tbody>
</table>

| $30 BILION CASE$  | 1 | 2   | 36       | 0.82   | 100| 0  | 0  | 0          | 0           | 2            | 1        | .9676 | 0.5 | 96.3            |                  |                |
| 1620000           | 2 | 1   | 36       | 0.91   | 100| 0  | 170| 10         | 2            | 1            | .9771  | 0.5 | 87.2            |                  |                |
| 810000            | 2 | 2   | 18       | 0.91   | 100| 0  | 170| 10         | 2            | 1            | .9733  | 0.5 | 86.1            |                  |                |
| 550000            | 2 | 3   | 14       | 0.93   | 100| 0  | 170| 10         | 2            | 1            | .9774  | 0.5 | 84.7            |                  |                |
| 440000            | 2 | 4   | 10       | 0.95   | 100| 0  | 170| 10         | 2            | 1            | .9825  | 0.5 | 82.9            |                  |                |
| 330000            | 2 | 5   | 6        | 0.97   | 100| 0  | 170| 10         | 2            | 1            | .9869  | 0.5 | 83.4            |                  |                |
| 220000            | 2 | 6   | 5        | 0.98   | 100| 0  | 170| 10         | 2            | 1            | .9911  | 0.5 | 84.7            |                  |                |
| 110000            | 2 | 7   | 5        | 1.00   | 100| 0  | 170| 10         | 2            | 1            | .9811  | 0.5 | 83.4            |                  |                |
| 6800 Titan IV/cent| 24| 1   | 30       | 0.98   | 100| 0  | 170| 10         | 2            | 3            | .8723  | 0.5 | 93.9            | 276             | 95.8           |
| 55000 Shuttle     | 15| 1   | 30       | 0.98   | 100| 0  | 170| 10         | 2            | 3            | .8220  | 0.5 | 102.3           | 270             | 107            |
| 4600 Titan IV     | 15| 1   | 30       | 0.98   | 100| 0  | 170| 10         | 2            | 4            | .8220  | 0.5 | 109             | 185             | 112.2          |
| 32432 Titan III   | 50| 1   | 30       | 0.98   | 100| 0  | 170| 10         | 2            | 4            | .8220  | 0.5 | 109             | 185             | 112.2          |
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
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
cSc

Orbital support equipment:
RCS, ACS, Power, Thermal, Comm., Structure support for launch

"deploy/unlatch"

existing

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

Vehicle

Deorbit?

Adaptable
- ACS
- Thermal
- Power
- Reboost

Connections
- structural
- electrical
- fluid

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3 SDJ_10-26-91
SUBASSEMBLIES

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

A Beginning Taxonomy of Subassemblies:

<table>
<thead>
<tr>
<th>Tanks</th>
<th>Crew</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial Spacecraft</td>
<td>Avionics</td>
</tr>
<tr>
<td>Complete Spacecraft</td>
<td>Propulsion</td>
</tr>
<tr>
<td>Structural</td>
<td>Power</td>
</tr>
</tbody>
</table>
ESTIMATING SUBASSEMBLY INTERFACES BY ENGINEERING FUNCTIONAL ALLOCATION USING MBR

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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

Inspection/Verification 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
VEHICLE DECOMPOSITION MODEL

Solution Blackboard

Stage 1

"Separable" rules
f (PFA, LTAA, and
separable rules)

"Hazard" rules
f (PFA, LTAA, and
hazard rules)

Connection-Index
Rules
f (PFA, LTAA, and
index rules)

Rendezvous & Dock
Rules
f (PFA, LTAA, and R&D
rules)

Controller/Scheduler
- Heuristics?
- Fuzzy reasoning?
- Algorithmic?

KS Common
filters and
knowledge:

Packing
Feasibility
Algorithm
(PFA)

Launch
Thrust
Axis
Algorithm
(LTAA)

NTMTV
Internal
Vehicle
Model

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CONNECTION INTERFACE ESTIMATION MODEL RESULTS

Connection Category
Mars Vehicle Interface Estimation Results, Model vs. CSC study
Total Connections (10 Subassemblies, Boeing NTR-2016) = 379
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

Truss-Frame = Highest Cl

MTV = Highest topo Cl for Truss

MTV

TB1

TB2

OK

Too Long

MTV

TB1

TB2

TB3

TB4

TB5

TB6

MTV

TB7

PVA1

PVA2

etc.

etc.

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KS3: Flight Manifest Results

- Two New Aggregates Created
- True Synthesis

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)

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

1. OOP
Hierarchical Representation of Design

2. Interface Estimation
of all components using MBR

3. Identification/ Formation
of Orbital Subassemblies
and manifests using BB

4. Enumeration of all geometrically feasible sequences

5. Evaluation of Sequences using subjective measure(s)

- 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 perturbation analyses of inputs, and introduction of other orbital assembly designs
LUNAR CONSTRUCTION
Lunar Regolith and Structure Mechanics

Stein Sture

Third Annual Symposium
November 21 & 22, 1991
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

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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

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In Situ Density, $\rho$ (g/cm$^3$)

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

Friction Angle, $\phi$ (degrees)

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

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CTC Experimental Results and Predictions For "High" Confining Stress Levels (Dense)
CTC Experimental Results and Predictions For "low" Confining Stress Levels (Dense)
MRS-Lade Prediction for Unconfined Compression Test From Calibration at Ultra-Low Stress Levels
TENSILE STRENGTH EXPERIMENT

Paper Membrane

Aluminium Mold

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

ULTIMATE STRENGTH ENVELOPE FOR MLS-1
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

<table>
<thead>
<tr>
<th>Property</th>
<th>Terrestrial Soils</th>
<th>Lunar Regolith and MLS</th>
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<td>Friction Angle ($\phi, ^o$)</td>
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<td>44-66</td>
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<tr>
<td>Cohesion/Adhesion ($c, \frac{kN}{m^2}$)</td>
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<td>0.05-4.50</td>
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<tr>
<td>Specific Mass of Solids ($\rho_s, \frac{g}{cm^3}$)</td>
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<td>3.1</td>
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<tr>
<td>Mass Density of Particulate Void-Solids Composite ($\rho, \frac{g}{cm^3}$)</td>
<td>1.4-1.9</td>
<td>1.8-2.2</td>
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<tr>
<td>Unit Weight ($\gamma, \frac{kN}{m^3}$)</td>
<td>14.19</td>
<td>2.9-3.6</td>
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<td>Bearing Capacity of a 0.10 m by 0.10 m Footing on Level Ground ($q_f, \frac{kN}{m^2}$)</td>
<td>8.45</td>
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<td>Modulus of Subgrade Reaction (est.) ($k_s, \frac{MN}{m^3}$)</td>
<td>0.5-15</td>
<td>1-10^4</td>
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</table>

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MODEL

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

Lunar Prototype II.H.M. Dimensions

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A NASA Space Engineering Research Center at the University of Colorado
Comparison of Conventional Slope Stability Solutions To Centrifuge model
DENSITY OF LUNAR REGOLITH

LAMINAR CONTAINER TO SIMULATE FREE FIELD MOTION

1 side support
2 end stopper
3 base plate
4 laminar plate

BEFORE SHAKING

DURING SHAKING

Direction of shaking

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PHYSICAL PROPERTIES OF LUNAR REGOLITH

APOLLO 15 CORE TUBE SITES


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LUNAR CRANE CAN PROVIDE EXCAVATING CAPABILITY USING A VIBRATING EXCAVATOR

(After Martin Mikulas)
CENTRIFUGE MODELING OF PENETRATOR PERFORMANCE

SPECIMEN
( REGOLITH )

PENETRATOR

ACTUATOR

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Static Vs. Vibration Assisted Penetration

**PENETRATOR RESISTANCE**

- Static
- 5 & 120 Hz
- 10 & 40 Hz
- 20-30 Hz

**PENETRATOR DISPLACEMENT**

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Average Depth - 6" Steel Tip Rod

Legend

- 10 Hz
- 15 Hz
- 20 Hz
- 30 Hz
- 40 Hz
- 50 Hz
- 70 Hz
- 120 Hz

Depth (m)

Time (sec)

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RESPONSE OF 6 IN. STEEL PENETRATOR

Depth (in)

Frequency (Hz)
RESPONSE OF 9 IN. STEEL PENETRATOR

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PENETRATION vs TIME
Testbeds One & Two

Depth of Penetration (in.)

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 Penetration (in.)

Time (seconds)

- Tst 3-1 (No Vibr)
- Tst 3-2 (Vibr)
- Tst 3-3 (Vibr)
- Tst 3-4 (Vibr)
- Tst 3-5 (Vibr)
- Tst 3-6 (Vibr)
Indigenous Lunar Construction Materials

Wayne Rogers
Stein Sture

Third Annual Symposium
November 21 & 22, 1991

cSc

A NASA Space Engineering Research Center at the University of Colorado
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.

<table>
<thead>
<tr>
<th>Why</th>
<th>Why not</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pay-load weight savings</td>
<td>Unfamiliar technologies</td>
</tr>
<tr>
<td>Long term manned presence in space</td>
<td>Significant infrastructure</td>
</tr>
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</table>
Comparison of Various Lunar Structures

![Graph comparing transported mass vs. enclosed pressurized volume for various lunar structures: SFF (Space Station Freedom Module), HLLV (Heavy Lift Launch Vehicle Module), PREFAB (Deployable Module), INFLAT (Inflatable Sphere), and CAST (Cast Regolith Structure).]

SFF
Space Station Freedom Module
HLLV
Heavy Lift Launch Vehicle Module
PREFAB
Deployable Module
INFLAT
Inflatable Sphere
CAST
Cast Regolith Structure
Processing - material - construction - structure relationships

- Regolith (volume)
- Power (Watts)
- Equipment (crucible, crane,..)
- Function (habitation, pad,..)

- Melting
- Cooling
- Forming
- Mechanical properties
- Structural members
- Construction
- Design
- Structure

- Radiation shielding properties
- Strength properties
- Architectural properties
- Equipment requirements

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Objectives

- Investigate the *feasibility* of 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 (Khalilli 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. Benification, grinding, homogenization steps are unnecessary. High vacuum and low gravity pose no unusual problems.

- Material processing may be integrated with oxygen production.
Examples of Cast Basalt Components
Cast Regolith Process

- Crane
- Mining: Unbeneficiated regolith
- Load furnace w/crane: 6 ton capacity
- Controlled cooling
- Pour into graphite form: 2 cubic m volume
- Remove crucible
- Melt regolith: Temp 1200-1300°C, Time 24 hrs
- Collect volatiles
- Form
- Cold regolith
- Electrodes
- Motion regolith

A NASA Space Engineering Research Center at the University of Colorado
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 recrystallization over a 24 hr period.

A NASA Space Engineering Research Center at the University of Colorado
### Mechanical Properties of Cast Basalt

<table>
<thead>
<tr>
<th>Property</th>
<th>Cast Regolith</th>
<th>Concrete</th>
<th>Cast Iron</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cc)</td>
<td>2.9</td>
<td>2.4</td>
<td>7.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Elastic Modulus (GPa)</td>
<td>110</td>
<td>21</td>
<td>160</td>
<td>70</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>&gt;35</td>
<td>7</td>
<td>125</td>
<td>100*</td>
</tr>
<tr>
<td>Fracture Tough. (MPa√m)</td>
<td>2</td>
<td>2</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Thermal Expan. (x10^-6/°C)</td>
<td>7.8</td>
<td>13</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>1200</td>
<td>-</td>
<td>1400</td>
<td>600</td>
</tr>
</tbody>
</table>

* 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.
Future Work

- **Material processing demonstration.** Demonstrate liquefaction, casting characteristics, viscosity, cooling and recrystallization, 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.
Design Concepts
for Pressurized Lunar Shelters
Utilizing Indigenous Materials

John Happel
Kaspar Willam
Benson Shing

Third Annual Symposium
November 21 & 22, 1991
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 Vacuum;
     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:


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

FIG. 3. Wall Construction and Latticed Web Details
Figure 2. Cutaway and Section of Structure

Figure 3. Arched Membrane System

Figure 4. Cross Section of Arch Rib

Figure 5. Arch Rib System with Web
Figure 1. - Elevation

Figure 2. - Typical Framing Plan
WEIGHT OF TRUSS SECTIONS
- 388# ON EARTH
- 65# ON MOON

REGOLITH SHIELDING

SUPPORT TRUSS (5M CENTERS)

O.B. BAR INTERNAL PRESSURE

11 m

24 m

GEOFABRIC FLOOR SURFACE

TIE CABLE

REGOLITH BALLAST

CROSS SECTION OF ASSEMBLY FACILITY

FLUOR DANIEL
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 aggregate and cement available
  
  Mechanical properties well understood

* Steel and other Structural Metals;
  
  Excellent mechanical properties
  
  Complicated, multi-step manufacturing process
Material Selection

- Tension
- Compression
- Knowledge Base
- Raw Material
- Ease of Manufacture

Legend:
- Lunar-crete
- Steel (Metals)
- Sintered Regolith
- Lunar Glasses
- Cast Basalt
* Cast Basalt;
  One step manufacturing process
  Good mechanical strength properties
  **Selected as primary construction material**

7. **Cast Basalt Properties:**

Tensile strength: $f_t = 34.5 \text{ MPa (5,000 psi)}$;

Compressive strength: $f_c = 538 \text{ MPa (78,000 psi)}$;

Modulus of elasticity: $E = 100 \text{ GPa (14E6 psi)}$;

Fracture toughness: $K_c = 2 \text{ MPa} \sqrt{\text{m}}, +/– 50\%$

Mass density: $3 \text{ g/cm}^3$ (specific lunar weight = 31.2 lunar lb/ft³).

Melting point: $1300^\circ\text{C}$
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 ft³ (2 m³)
    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

6.9m (22'6"

5.5m (18"

Side View
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
Step One

Step Two

Step Three

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


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
REGOLITH BACKFILL

INVERTED COMPRESSION ARCH

Space Station Freedom Module Cross Section
Configuration Optimization of Space Structures

Carlos Felippa
Luis A. Crivelli
David Vandenbelt

Third Annual Symposium
November 21 & 22, 1991

A NASA Space Engineering Research Center at the University of Colorado
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
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: $a, b, \theta$ in each element (3)
In three dimensions: $a, b, c, \theta_1, \theta_2, \theta_3$ in each element (6)

100 x 100 2D mesh: 30,000 Design Variables
30 x 30 x 30 3D mesh: 162,000 Design Variables

Taking Advantage of Design-Variable Locality Essential
Forming a Homogenized Finite Element

\[ K^e = \int_A hB^T C_H B \, dA \]

\[ C_H = C_H(a, b, \theta) \quad \text{homogenized material response matrix} \]

\[ C = C_H(0, 0, 0) \quad \text{full element; no microhole} \]

\[ C = C_H(1, 1, \theta) = 0 \quad \text{void; microhole fills element} \]
2-D Optimization Problem

- **Objective Function (Compliance ≡ Inverse Stiffness)**

\[ \Pi(a, b, \theta) = p^T v \]

- **Stiffness Relation (Discrete FE Equation)**

\[ v(a, b, \theta) = K^{-1}(a, b, \theta) p, \quad K = \sum_{e} L^e K^e(a^e, b^e, \theta^e) L^e \]

- **Volume Inequality Constraint**

\[ V(a, b) \leq V_T = \kappa V_{domain}, \quad 0 < \kappa \leq 1 \]

- **Microhole Constraints**

\[ 0 \leq a^e \leq 1, \quad 0 \leq b^e \leq 1, \quad -45^\circ \leq \theta^e \leq 45^\circ, \quad e = 1, \ldots, N_e \]
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 $\Pi(a, b, \theta, \lambda_V^{(k)}, \sigma_V^{(k)})$ keeping $\lambda_V$ and $\sigma_V$ fixed, with $(a, b, \theta)$ subjected to limit constraints.

iii) Compute $C = C^{(k)} = V_T - V(a, b, \theta)$.
   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

\[ \frac{\partial p^T v}{\partial a^e} = -v^T \frac{\partial K}{\partial a^e} v \]

\[ \frac{\partial p^T v}{\partial b^e} = -v^T \frac{\partial K}{\partial b^e} v \]

Stiffness (Discrete Equilibrium) Constraints

\[ \frac{\partial v}{\partial a^e} = -K^{-1} \frac{\partial K}{\partial a^e} v \]

\[ \frac{\partial v}{\partial b^e} = -K^{-1} \frac{\partial K}{\partial b^e} v \]
Stiffness Variations

✓ For Element Stiffness

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

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

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

✓ For Global Stiffness

\[ \frac{\partial K}{\partial a^e} = L^e T \frac{\partial K^e}{\partial a^e} L^e \]

\[ \frac{\partial K}{\partial a^c} = L^e T \frac{\partial K^c}{\partial a^c} L^e \]
Variations of the Potential

\[ \Pi = \mathbf{v}^T \mathbf{K} \mathbf{v} \]

First Variation

\[ \delta \Pi = -\mathbf{v}^T \delta \mathbf{K} \mathbf{v} \equiv - \int_{A} \mathbf{\epsilon}^T \delta \mathbf{\epsilon} \, dA = 0 \]

Second Variation

\[ \delta^2 \Pi \approx 2 \int_{A} \mathbf{\epsilon} \delta \mathbf{C} \mathbf{C}^{-1} \delta \mathbf{\epsilon} \, dA - \int_{A} \mathbf{\epsilon}^T \delta^2 \mathbf{\epsilon} \, dA \]
Schematics of the Optimization Program.
Progress

- Simple C_{II} 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)

Design Domain

uniform load
q = 8

5

10

V_{ref} = 50
E = 10,000
v = 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 Absorption 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

Third Annual Symposium
November 21 & 22, 1991
Telerobotic Rovers for Extraterrestrial Construction

Students
Chris Grasso          Mike Matthews
Jane Pavlich          Gary Snyder
Wayne Jermstad       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.
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
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

- Pseudo Random Noise Generator (PRN)
  - Multi-channel Wideband Mixer
    - Chipping Freq. Out
      - Master Oscillator
        - Infrared Receiver #1
        - Infrared Receiver #2
        - Infrared Receiver #3
          - Multi-channel Wideband Mixers and Amplification
            - Phase Detection and Analog to Digital Conversion
              - Position Estimation with Kalman Filtering
                - Position and Orientation
  - Power Amplification
    - Infrared Beacon #1
    - Infrared Beacon #2
    - Infrared Beacon #3
      - Infrared Beacon #n
Testbed Layout

Infrared beacons

Robot

IR receivers
Centralized Control
Modularized Control

Messages contain requests and information

Messages passed between arbitrary number of objects

Control algorithms distributed
# LUNAR SURFACE STRUCTURES CONSTRUCTION

## RESEARCH AREAS

<table>
<thead>
<tr>
<th>RESEARCH AREA</th>
<th>OBJECTIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Multiple Cable Crane</td>
<td>Remote and/or Precision Positioning Capability For Lunar Construction</td>
</tr>
<tr>
<td>- Articulating Arm Crane</td>
<td>Automatically Deployable Towers and Beam Type Structures With Minimal Deployment Equipment</td>
</tr>
<tr>
<td>- Deployable Tower</td>
<td>Capability For Self Off-Loading of Modules &amp; Equipment</td>
</tr>
<tr>
<td>- Lunar Module Unloading Device</td>
<td>Automatically Deployable Reflector With Minimal Deployment Equipment</td>
</tr>
<tr>
<td>- Deployable Solar Concentrator</td>
<td></td>
</tr>
</tbody>
</table>
LUNAR CRANE RELATED DISCIPLINES

- Remote control and/or autonomous precision construction operations
- Multibody dynamics analysis and control of large flexible systems
- Analysis and control of cable structures
- Quantification of control actuator concepts for large flexible systems
- Design of large complex flexible systems
- System identification of nonlinear 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
<table>
<thead>
<tr>
<th>Candidate Crane Cable Suspension Systems</th>
<th>Six Cables</th>
<th>6 DOF</th>
<th>Structurally Stiff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three Cables</td>
<td>3 DOF</td>
<td>3 DOF</td>
<td>Structurally Stiff</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Stiffened by Triangulated Cables</td>
</tr>
<tr>
<td>Single Cable</td>
<td>1 DOF</td>
<td></td>
<td>Structurally Stiff</td>
</tr>
</tbody>
</table>
NUMERICAL EXAMPLE OF NATURAL FREQUENCY

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

\[ \mathcal{F}_{\text{pendulum}} = \frac{1}{2\pi} \sqrt{\frac{g}{h}} \]
COUNTER-BALANCED ACTIVELY-CONTROLLED LUNAR CRANE INCORPORATES TWO NEW FEATURES FOR IMPROVED PERFORMANCE

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

Potential Control Mechanisms
- Active Cable Positioners
- Active Inertia Wheels
- Active Attachments

Payload (M,I)
SIMULATION RESULTS

(II)
CMG CONTROL SIMULATION RESULTS

X-coordinate of point H (in)

Y-coordinate of point H (in)

Z-coordinate of point H (in)

Control Moment about X-axis (lb-in)

Control Moment about Y-axis (lb-in)

Control Moment about Z-axis (lb-in)

Time (sec)
SIMULATION RESULTS

(I)

Cable #1 & #3
Structural Framework

Module
SLEWING SIMULATION RESULTS
ONE-SIXTH SCALE LUNAR CRANE TEST-BED USING G.E. ROBOT FOR GLOBAL MANIPULATION.
BASIC DEPLOYABLE TRUSS APPROACHES

Warren Truss

Standard Sequential Packaging

Sequentially Deployable Truss

Synchronizing Bar

Synchronously Deployable Truss
COMPARISON OF ELEVATOR PLATFORMS

Pantograph

Bi-Pantograph
BI-PANTOGRAPH VS PANTOGRAPH STIFFNESS

![Graph showing the comparison between Bi-Pantograph and Pantograph stiffness as a function of theta, degrees. The y-axis represents EI/L in-lb on a logarithmic scale, ranging from 10^3 to 10^8. The x-axis represents theta, degrees, ranging from 0 to 90.}]
PERSPECTIVE OF BI-PANTOGRAPH BEAM

Deployed Beam

Stowed Beam
BI-PANTOGRAPH SYNCHRONOUSLY DEPLOYABLE TOWER/BEAM

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

Stowed 30 degrees 45 Degrees Fully Deployed

Warren Truss (18 Bays)
LUNAR MODULE OFF-LOADING CONCEPT

Lowering Cable

Module Rotation Arm

Module Rotation Pivot

Unloading Winch

Self-Positioning Regolith Auger
LUNAR MODULE OFF-LOADER CONCEPT DURING VARIOUS PHASES OF OPERATION

\[ \Theta = 0^\circ, \beta = 90^\circ \]

\[ \Theta = 20^\circ, \beta = 76.6^\circ \]

\[ \Theta = 90^\circ, \beta = 18.6^\circ \]

\[ \Theta = 107.7^\circ, \beta = 0^\circ \]
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

Packaged reflector

Deployment Mechanism

Semi-deployed

Deployed Reflector
STARBURST DEPLOYABLE PRECISION REFLECTOR

1. 
2. 
3. 
4. 
5. 
6.
3 RING REFLECTOR DEPLOYMENT SCHEME

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

Panel Hinge
Deployment Arm
CROSS-SECTION OF PACKAGED STARBURST REFLECTOR
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
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