GENERAL COMMENTS:

1. Only 2 students gave presentations during 1st day.
2. The 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 that 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 revealed 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.
November 21, 1991

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

November 22, 1991

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  
Meet at Main Lobby
CSC GOALS

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

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

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

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

---

In Orbit

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

---

On the Moon

- Extremely different and hostile construction environment
Orbital Structures and Systems

Space Station, Interplanetary Spacecraft, Earth Observation Satellite, Planetary Exploration Vehicle
Technical Challenges of Orbital Construction

1. Design:
   - Integrated process for structural design and construction methods

2. Analysis:
   - Construction dynamics and evolving structures
   - Systems trade-off models

3. Construction equipment:
   - Autonomous and telerobotic equipment
   - Supporting fixtures for construction

4. Mechanisms:
   - Joining devices and processes
   - Load absorption and stabilization devices

5. Experimentation:
   - Earth-based and space-based methods

6. Testing and Maintenance methods and facilities
CSC Orbital Construction Tasks

1. Design:
   - Expert systems for assembly sequence evaluation
   - 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 (Starr)
2. Indigenous material processing for structural elements (Rogers)
3. Lunar shelter design using indigenous materials (Happel)
4. Lunar crane system (Mikulas)
5. Robotic construction workers (Avery)
6. Lunar regolith penetration tools (Starr, 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.
<table>
<thead>
<tr>
<th>Existing Applicable Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truss Assembly Experiment in Buoyancy Tank</td>
</tr>
<tr>
<td>In-Space Shuttle-Based Deployment of Solar Panel and Truss</td>
</tr>
<tr>
<td>Den Hartog-Like Shock Isolation Elements</td>
</tr>
<tr>
<td>Contact/Impact Predictability via Simulation</td>
</tr>
<tr>
<td>High-Precision Flexible Multibody Simulation</td>
</tr>
<tr>
<td>Adaptive Elements for Localized Shock Mitigation</td>
</tr>
<tr>
<td>Fast Real-Time Control and Simulation</td>
</tr>
</tbody>
</table>
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

Straight Position

Intermediate Position

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

Starboard

Space Station Freedom
Librational Motion of a Space Shuttle

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

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.

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

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

m1 = 5 kg,  m2 = 2 Kg

1) v1 = 0.2 m/s,  v2 = -0.1 m/s
2) f1 = 0.01 N,  f2 = -0.008 N
3) v1 = 0.1 m/s,  v2 = -0.05 m/s,  f1 = 0.01 N,  f2 = -0.001 N
Contact Velocity of SRMS & Payload: X-axis

Contact Forces of SRMS & Payload: X-axis
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

3rd Summer Intern
Ph.D. Student

Third Annual Symposium
November 21 & 22, 1991
Dynamics and Control Problems of Joining Structures in Orbit

- structural vibrations
- multiple-point joining
- compliant contact
BASIC PROBLEMS

1. How will a payload controlled by active positioning devices interact dynamically with its environment?

2. How can closed-loop control be designed to achieve desired interactive dynamics?
Spring-and-Mass Models

1) 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

\[
\begin{bmatrix}
  x_m \\
  x_m \\
  x_L \\
  x_L
\end{bmatrix}
\begin{bmatrix}
  0 & 1 & 0 & 0 \\
  -K_s/M & -B_m/M & K_s/M & 0 \\
  0 & 0 & 0 & 1 \\
  -K_s/M_l & 0 & dK/M_l & -B_l/M_l
\end{bmatrix}
\begin{bmatrix}
  x_m \\
  x_m \\
  x_L \\
  x_L
\end{bmatrix}
+ \begin{bmatrix}
  0 & 0 \\
  -1/M & 0 \\
  0 & 0 \\
  0 & -1/M
\end{bmatrix}
\begin{bmatrix}
  f_m \\
  d
\end{bmatrix}
\]

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Inertia, $J_m$</td>
<td>0.0934</td>
<td>kg-m$^2$</td>
</tr>
<tr>
<td>(reflected to output side)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor Viscous Damping, $B_m$</td>
<td>3.4</td>
<td>N-m/(rad/s)</td>
</tr>
<tr>
<td>(reflected to output side)</td>
<td></td>
<td></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 Assemblies
of Large Space Structures

Mark Balas
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 ($F^3 U$)

Docking & Berthing / Contact
Decentralized Control
Using Structural Partitioning
Reduced-Order Model-Based Controller Design

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

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

or

\[
\begin{bmatrix}
  x_n \\
  e_n \\
  x_r
\end{bmatrix}
= 
\begin{bmatrix}
  A_n + B_n G_n & B_n G_n & 0 \\
  0 & A_n + K_n C_n & K_n C_r \\
  B_r G_n & B_r G_n & A_r
\end{bmatrix}
\begin{bmatrix}
  x_n \\
  e_n \\
  x_r
\end{bmatrix}
\]
ROM/RMF Control of Large Flexible Structures

Flexible Structure

- 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

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

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 \(\rightarrow\) unstable \(\text{(q modes)}\)
DPS + ROM Controller + RMF \(\rightarrow\) 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:
\[ M_0 \ddot{q} + D_0 \dot{q} + K_0 q = B_0 u \]
\[ y = C_0 q + E_0 \dot{q} + F_0 u \]

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 \( q \) = \( L \) large

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

dim \( z \) = \( s \) 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 12

BAY 24

BAY 30

BAY 44

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 8.7 The Mini-Mast Truss

13 bays
Figure 8.22 Phase o 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

(alpha Joint angular position (radians))

time (sec)
Perturbation Analysis

well known

Small Perturbation

Asymptotic Eigenvalue Series:

\[ \lambda_c(\epsilon) = \lambda_0 + \epsilon \lambda_1 + \epsilon^2 \lambda_2 + \cdots \]

Closed-Loop (LSS + ROM Controller):

\[
A_c(\epsilon) = \begin{bmatrix}
A_N & B_m G_m & O \\
K_m C_m & L_m & \epsilon K_m C_R \\
0 & \epsilon B_R G_m & A_R
\end{bmatrix}
\]

\[ \therefore \lambda_c(\epsilon) = \lambda_0 + \epsilon^2 \lambda_2 \]

Note: \( \lambda_1 = 0 \) and \( \lambda_3 = 0 \)
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 PMF.
Figure 3-1. The structure of the adaptation mechanism
ROM/RMF with actuator/sensor dynamics

- **Actuator Dynamics**
- **LSS** (Large Scale Structure)
- **Sensor Dynamics**
- **Rom-Based Controller**
- **Actuator Estimator**
- **RMF** (Residual Mode Filters)
- **Sensor Estimator**
Modifications For Nonlinear ROM/RMF Control  JMAA 1991

Nonlinear DPS
\[ \dot{x} = Ax + Bu + f(x) \]
\[ y = Cx \]

Nonlinear ROM Controller
\[ u = G_n \hat{x}_n \]
\[ \dot{\hat{x}}_n = A_n \hat{x}_n + B_n u + K_n (y_c - \hat{y}_n) \]
\[ + f_n(\hat{x}_n, \hat{x}_q, 0) \]
\[ \hat{y}_n = C_n \hat{x}_n \]

Nonlinear RMF
\[ \hat{y}_q = C_q \hat{x}_q \]
\[ \dot{\hat{x}}_q = A_q \hat{x}_q + B_q u + f_q(\hat{x}_n, \hat{x}_q, 0) \]
Indirect Adaptive Control

Exciting inputs

Plant

Parameter Estimator

Gain calculator

Adjustable Gain Controller

desirable Output Performance
Direct Adaptive Control

Reference Model

Possible inputs

Tracking:

$e_y = y - y_m$

$y_m$

$X_m$

$X_m$

Direct gain Adaptation

$G$

$S_{21}$

$S_{22}$
Flexible Manipulator Experiments (SC Liang)
Hub Control - Strain Gauge Sensor
(Not Collocated)
Decentralized Controller Design

Controller 1

\[ u_1 = K_1 y_1 + K_1 z_1 \]
\[ z_1 = L_1 z_2 + L_1 y_1 \]

Controller 2

\[ u_2 = K_2 y_2 + K_2 z_2 \]
\[ z_2 = L_2 z_2 + L_2 y_2 \]

Large Space Structure (LSS)

ROM:
\[ \dot{x}_n = A_n x_n + B_1 u_n + B_2 u_2 \]
\[ y_1 = C_1 x_n + \text{residuals} \]
\[ y_2 = C_2 x_n + \text{residuals} \]
RMF Compensation for Stable Control

Residual Mode Filter (RMF)

\[ \dot{x}_q = A_q \dot{x}_q + B_{1q} u_1 + B_{2q} u_2 \]
\[ \tilde{y}_{1q} = C_{1q} \dot{x}_q \]
\[ \tilde{y}_{2q} = C_{2q} \dot{x}_q \]

Controller 1 \( \alpha_1 \)

Controller 2 \( \alpha_2 \)

LSS

\[ \dot{x} = Ax + B_1 u_1 + B_2 u_2 \]
\[ y_1 = C_1 x \]
\[ y_2 = C_2 x \]
Structural Load Control During Construction

Martin Mikulas

Third Annual Symposium
November 21 & 22, 1991

A NASA Space Engineering Research Center at the University of Colorado
EXAMPLES OF HIGH TRANSIENT LOADINGS ON LARGE SPACE STRUCTURES

Docking Loads on Space Station

Shuttle Thruster Impingement on Solar Arrays

Side Loads From Tethers

Shuttle Accelerations Applied to Attached Beam
ENERGY ABSORBING/LOAD LIMITING STRUT RESEARCH OBJECTIVES

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

Develop analytical and design capability for energy absorbing struts

Develop several energy absorbing strut concepts (passive & active)

Experimentally demonstrate application of energy absorbing struts
SCOPE OF RESEARCH ON ENERGY ABSORBING STRUTS TO DATE

Rigid body analysis developed to scope problem

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.

Energy Absorbing Truss

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

Truss absorbed energy is:

\[ E = P \Delta \]

or

\[ E = P \frac{L}{H} \delta = 2P \delta \]

Truss strain energy is:

\[ \Pi = \frac{1}{2} P \Delta \]

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

Standard Truss

2P_L

2P_L

P

P

L

H
TEN BAY LONG RESILIENT TRUSS EXAMPLE

10 m

Energy Absorbing Strut

Buckling Critical Strut

a) Undeformed Truss

Pivots

b) Deformed Truss
STORED ENERGY CHARACTERISTICS OF ONE METER DEEP TRUSS.

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

b) Energy absorbed by resilient truss (2300 in-lb)
ENERGY ABSORBING POTENTIAL FOR 10-BAY 5-METER DEEP TRUSS

Load Limiting Strut

\[ \Delta = 1.7'' \]

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

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

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

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

Power to/from Motor

Motor

Ball Screw

Ball Nut

Thrust Bearing

Encoder

Coil Spring

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

Front View

Side View

Solar Array

Energy Absorbing Bay

Deformed Array

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

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

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

Applied Pressure Impulse

\[ p \]

\[ t \]

\[ t_p \]

Integration Yields:

\[ M_R - M_{\text{R}} = I \ddot{\theta} \]

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

or

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

\[ \delta = \frac{M_R t_p^2}{2I} H \left( \frac{M_R}{M_R - 1} \right) \]
SOLAR ARRAY PIECEWISE LINEAR RESPONSE

Angular Velocity

Angular Displacement

Applied Pressure

Time
### Solar Array Characteristics

<table>
<thead>
<tr>
<th>Array Beam (one bay)</th>
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<tbody>
<tr>
<td>Truss beam</td>
<td>315.78</td>
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<td>Canister</td>
<td>534.65</td>
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<tr>
<td>Array Blanket</td>
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<td><strong>Total</strong></td>
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<table>
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<tr>
<th>Longeron properties</th>
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</thead>
<tbody>
<tr>
<td>Area</td>
<td>$0.5 \times 5 = 2.5 \text{ in}^2$</td>
</tr>
<tr>
<td>$E$</td>
<td>$10^{6}$</td>
</tr>
<tr>
<td>$P_{crit}$</td>
<td>1250 lbs</td>
</tr>
</tbody>
</table>

Truss bending stiffness:

$$EI = 43 \times E \left( \text{theoretical} \right)$$

$$= 98 \text{ lb-in}^2 \text{(Tom Irvine)}$$
SOLAR ARRAY TIP DEFLECTION AND REQUIRED ACTUATOR STROKE

\[
\delta = \frac{M_a t_p^2 H}{2l} \left( \frac{M_0}{M_R} - 1 \right)
\]

Array input quantities

- \(t_p = .75\) 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
12 BAY ENERGY ABSORBING TEST BED

( Beam Length = 27.83' )

TOP VIEW

Energy Absorber
Pivot

Loading Cable
(178 lb)
2.92"

2300 lb steel weight
(36"x36"x6")

5000 lb Backstop

SIDE VIEW

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

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

Deflected Weight

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

Approximate Actuator Size

Thrust Bearing  Ball-Nut

MOTOR

\[ 2'' \]

\[ 75 \text{ lb} \]

\[ D = .2'' \]
NEW AERO-LAB WITH 12-BAY TEST BEAM

Overhead Door

Loading Cable

HIGH-BAY AREA

Loading Cable

Test Beam

Backstop

CONTROL ROOM

40 ft

20 ft
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
Progress Report
George W. Morgenthaler

PART I: DEFINITION AND SCOPE OF SPACE CONSTRUCTION

PART II: ORBITAL ASSEMBLY AND CONSTRUCTION

PART III: LUNAR BASE CONSTRUCTION

PART IV: MARS BASE CONSTRUCTION

(11/23/91)
"Constructability is defined as the optimum use of construction knowledge and expertise in the conceptual planning, detail engineering, procurement, and field operations phases to achieve the overall project objectives."

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

- Construction is Old; Construction Theory is young.

- The literature is filled with construction "war stories" and "Sea Bee" epics, but little quantitative analysis and optimization of construction.

- Strong parallels exist between Manufacturing and Construction:
  - Requirements are critical (confused requirements lead to waste)
  - Good design is critical; concurrent engineering requires iterations between Engineering and Manufacturing.
  - Material selection is critical (failure, weight, hazards)
  - Procurement (logistics) is critical
  - Manufacturing Engineering is critical
  - Inspection, QC, NDE are critical
  - Cost and schedule analysis is critical
  - A Systems Approach is required for success

- Analytical tools have been developed for terrestrial manufacturing and construction, but not for Space-based applications. (Synthesis tools do not as yet exist for either domain)

- We need to approach a Theory of Space Construction in the same way

  (Space construction is not as forgiving as manufacturing)
An Orbital Assembly Scenario

Phase I
Launch & Fairing Sep (~minutes)

Phase II
Rendezvous & Close Proximity OPS (~days)

Phase III
Final Closure & Soft Dock (~hours)

Phase IV
Hard Latch Assembly & Test (~months)

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

"deploy/unlatch"

existing

Vehicle

Deorbit?
## Center for Space Construction
**In-Space Construction Research (AY 1990-1991)**

<table>
<thead>
<tr>
<th>Introduction</th>
<th>DYCAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Theory of Space Construction</td>
<td>• Early Definition - U. Racheli</td>
</tr>
<tr>
<td>• A Systems Approach</td>
<td>• DYCAM 1.0 (IDEAS**2 + resource allocation) - H. Schroeder (Ph. D Thesis)</td>
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<tr>
<td>• Develop Construction Model Theory of CAE/Constructability Tools</td>
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<table>
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<tr>
<th>Logistics to LEO</th>
<th>Orbital Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Launch-on-time - GWM, K. Nii</td>
<td>• Problem Definition - S. Jolly, M. Loucks, GWM</td>
</tr>
<tr>
<td>(Compound Distribution)</td>
<td>• Simulation Model - M. D'Amara (Simulation + Monte Carlo)</td>
</tr>
<tr>
<td>• Vehicle Selection Model - GWM, A. Montoya</td>
<td>• Rendezvous + Docking - D. Mackison, K. Nii, D. Lawrence, GWM</td>
</tr>
<tr>
<td>• Simulation Models - K. Chan, K. Nii</td>
<td></td>
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<tr>
<td>• System Study: Need HLLV - GWM</td>
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<table>
<thead>
<tr>
<th>Interruptability</th>
<th>Logistics to SEI Destinations</th>
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<tbody>
<tr>
<td>• NASA Requests, Early Work</td>
<td>• Optimal Supply of GEOS - R. Coffey (Ph. D Thesis)</td>
</tr>
<tr>
<td>• The General Model - (Network Theory + Stability Matrices) J. Wade, H. Sato,</td>
<td>• Lunar/Mars Cyclers - C. Uphoff, M. Loucks</td>
</tr>
<tr>
<td>K. Chan (Ph. D Thesis)</td>
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<thead>
<tr>
<th>Joining, Test and NDE</th>
<th></th>
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<tbody>
<tr>
<td>• Joining - K. Nii, B. Nguyen</td>
<td></td>
</tr>
<tr>
<td>• Test and NDE - R. Nici</td>
<td></td>
</tr>
</tbody>
</table>
Center for Space Construction

On-Orbit Assembly

- Evaluation of Logistics Supply Needs
- Evaluation of Assembly Sites
- Evaluation of On-Orbit Assembly Operations
- Support Equipment Designs and Performances
- Evaluation of Space Transfer Vehicle Designs
A COST TRADE-OFF MODEL FOR ON-ORBIT ASSEMBLY LOGISTICS

George W. Morgenthalaler
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

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

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

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

Figure 3-5 Initial HLLV Cargo Delivery Manifests

* 38.5 T of TMI Topoff Required Per Tank
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)

20

15

10


5

0

Launch Vehicle Throw Weight (lbfm x 1000)

* REF ORBIT: 100 n.m., CIRC @ 20.5 deg

From Reference 10.
Figure 5

Shuttle C Performance

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 I. Vehicle Cost Performance (Thousands of 1990 dollars)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Cost (Millions)</th>
<th>Pounds to LEO</th>
<th>Kg to LEO</th>
<th>Cost/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>1391</td>
<td>635</td>
<td>44.33</td>
</tr>
<tr>
<td>Scout II</td>
<td>211</td>
<td>11841</td>
<td>5381</td>
<td>39.33</td>
</tr>
<tr>
<td>EPAC S-1</td>
<td>291</td>
<td>24991</td>
<td>11361</td>
<td>25.53</td>
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<td>EPAC S-II</td>
<td>431</td>
<td>56001</td>
<td>30001</td>
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<td>Delta II 6920</td>
<td>421</td>
<td>87001</td>
<td>3951</td>
<td>10.82</td>
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<td>Delta II 7920</td>
<td>711</td>
<td>110861</td>
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<td>14.09</td>
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<tr>
<td>Atlas 1</td>
<td>801</td>
<td>129801</td>
<td>59001</td>
<td>13.56</td>
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<tr>
<td>Atlas II</td>
<td>921</td>
<td>149161</td>
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<td>661</td>
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<td>EPAC S-4</td>
<td>751</td>
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<td>EPAC S-5</td>
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<td>Anshe IV</td>
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<td>Titan IV</td>
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<td>Shuttle C</td>
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<tr>
<td>Shuttle Z</td>
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<td>Titan IV/Cant</td>
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<tr>
<td>Saturn V</td>
<td>6001</td>
<td>3080001</td>
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<td>4.29</td>
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</table>

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

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

**Shuttle 2** this entry shows a reduction of the cost of the Shuttle "launch vehicle" by an estimate of the cost of the Orbiter, which is assumed to be replaced by a fairing. The amortized cost used was the $4.1 billion Orbiter cost divided by a 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)

- A: \( y = 0.34489 \times x^{0.57494} \) \( R = 0.90385 \)
- B: \( y = 0.37637 \times x^{0.56355} \) \( R = 0.92632 \)
- C: \( y = 0.43031 \times x^{0.54804} \) \( R = 0.91275 \)
- D: \( y = 0.53517 \times x^{0.52343} \) \( R = 0.84152 \)
Figure 8: Cost/kg vs. kg to LEO

- A: $y = 552.69 \cdot x^{(0.42735)}$, $R = 0.96416$
- B: $y = 597.65 \cdot x^{(0.4386)}$, $R = 0.97152$
- C: $y = 671.65 \cdot x^{(0.4365)}$, $R = 0.9739$
- D: $y = 817.41 \cdot x^{(0.47779)}$, $R = 0.97591$

R. 10^9 1990
Figure 9: "Useful" Volume vs. Payload

\[ y = m_0 + m_1x \]

- \( m_0 = 41.651644239 \)
- \( m_1 = 0.017549703449 \)
- \( r = 0.89255252554 \)
NUMBER OF PAYLOADS NEEDED

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

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

\[ N(w) = \text{Max} \{ N_L(w), N_V(w) \} \]

LAUNCH VEHICLE RELIABILITY

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

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

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,

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

\[
p^* = p_{\text{make launch window}} = p^N + C_i^{N+i-1} p^N q^i + C_i^{N+i-1} p^N q^2 + \ldots + C_i^{N+i-1} p^N q^i
\]

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

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

(15)

Connection Costs  Crew Transport Costs  Docking Costs  Facility Costs
+ (N(w)-1)(k)(C$C$) + (N(w) - 1)(C$S$ / P$S$) + (N(w)-1)C$D$ + \left\{1 + \left[\frac{N(w)}{15}\right]\right\}C$F$

(18) \quad C^*(w) = \{\text{Expected cost including probability of missing one launch window}\}
\quad = C(w) \left[ 1 + (1 - P^*)R \right],

where C(w) is found in (15).
Table V: Parameter Values Used with Equations (15) and (16) for Figure 14.

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<th>$N$ (LVL)</th>
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For Figure 14.

...
Figure 14: Total Expected Cost vs. LEO Payload Capability

$CH(w) =$ Expected Cost (Billions)

$w =$ LEO Payload Capability (lbs)

$SC$_1$ = $75 B

$SC$_2$ = $30 B
Expert Systems for Assembly Sequence Evaluation

Steve Jolly

Third Annual Symposium
November 21 & 22, 1991

A NASA Space Engineering Research Center at the University of Colorado
EXPERT SYSTEMS FOR ASSEMBLY SEQUENCE EVALUATION

PRESENTATION FOCUS:
- RESEARCH GOALS
- METHODOLOGIES
- RESULTS
- CONCLUSIONS & PLANS
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
Orbital support equipment: RCS, ACS, Power, Thermal, Comm., Structure support for launch

"deploy/unlatch"

existing

Phase I
Launch & Fairing Sep
(minutes)

Phase II
Rendezvous & Close Proximity
OPS (days)

Phase III
Final Closure & Soft Dock
(hours)

Phase IV
Hard Latch Assembly & Test
(months)

Vehicle

Deorbit?

Adaptable
- ACS
- Thermal
- Power
- Reboost

Connections
- structural
- electrical
- fluid

An Orbital Assembly Scenario

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SUBASSEMBLIES

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

A Beginning Taxonomy of Subassemblies:

Tanks
Partial Spacecraft
Complete Spacecraft
Structural

Crew
Avionics
Propulsion
Power
SUBASSEMBLY IDENTIFICATION SIMULATION MODEL

1. OOP Hierarchical Representation of Design

Input

S/C Conceptual Design (CAD) Like NTR

Distribution of Engineering Subsystems

2. Interface Estimation of all components using MBR

Imbedded

Hardware Attachment Methods Database

Heuristic Knowledge of H/W Interfaces

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

New Knowledge

4. Enumeration of all geometrically feasible sequences

5. Evaluation of Sequences using subjective measure(s)
ESTIMATING SUBASSEMBLY INTERFACES BY ENGINEERING FUNCTIONAL ALLOCATION USING MBR

A Mars Orbital Tank_detail Instance

Space Vehicle

A NASA Space Engineering Research Center at the University of Colorado
REPRESENTATIVE DATA BASE OF INTERFACE CONNECTIONS

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

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

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

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

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

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KS3 ALGORITHM: EXAMPLE

MTV = Highest topo Cl for Truss

Truss-Frame = Highest Cl

MTV = MTV

TB1 + ? =

TB2

MTV

ok

too Long

MTV

TB1
TB2
TB3
TB4
TB5
TB6

MTV

TB7

PVA1
PVA2

etc.

etc.

A NASA Space Engineering Research Center at the University of Colorado

12 SDJ_10-26-91
KS3: Flight Manifest Results

- Two New Aggregates Created
- True Synthesis

Subassembly mass = 68.59 metric tons
Mass efficiency = 69.76%
Volumetric efficiency = 26%

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

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

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

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

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

A NASA Space Engineering Research Center at the University of Colorado
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
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

A NASA Space Engineering Research Center at the University of Colorado
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

A NASA Space Engineering Research Center at the University of Colorado
MRS-Lade Prediction for Unconfined Tension From Calibration at Ultra-Low Stress Levels
TYPICAL RANGES OF ENGINEERING PROPERTIES FOR DRY TERRESTRIAL COHESIONLESS SOILS AND LUNAR REGOLITH (REAL AND SIMULATED)

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<td>Bearing Capacity of a 0.10 m by 0.10 m Footing on Level Ground ($q_f$, $\text{KN/m}^2$)</td>
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<td>Modulus of Subgrade Reaction (est.) ($k_s$, $\text{MN/m}^3$)</td>
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- ADVANTAGES
  - Increased Strength
  - Increased Stiffness
  - Subsurface Homogeneity

- DISADVANTAGES
  - Electrostatic Attraction To All Non-Geologic Matter
  - Difficult To Excavate
MODEL

Lunar Prototype II.I.M. Dimensions

SLOPE ANGLE   VOLUME [m^3]

30°   1,245
55°   705
90°   690

ρ = 1.90 g/cm³

ρ = 2.17 g/cm³

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Comparison of Conventional Slope Stability Solutions To Centrifuge model
LAMINAR CONTAINER TO SIMULATE FREE FIELD MOTION
PHYSICAL PROPERTIES OF LUNAR REGOLITH

APOLLO 15 CORE TUBE SITES


A NASA Space Engineering Research Center at the University of Colorado
LUNAR CRANE CAN PROVIDE EXCAVATING CAPABILITY USING A VIBRATING EXCAVATOR

(After Martin Mikulas)
Static Vs. Vibration Assisted Penetration

Penetrator Resistance

Penetrator Displacement

Static

5 & 120 Hz

10 & 40 Hz

20-30 Hz
RESPONSE OF 6 IN. STEEL PENETRATOR
Power Input - 6" Steel Tip Rod

Power (Watt)

Frequency (Hz)
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 Vib)
- 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
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.

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<th>Why</th>
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<td>Pay-load weight savings</td>
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<td>Long term manned presence in space</td>
<td>Significant infrastructure</td>
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</table>
Comparison of Various Lunar Structures

- **SFF**: Space Station Freedom Module
- **HLLV**: Heavy Lift Launch Vehicle Module
- **PREFAB**: Deplorable Module
- **INFLAT**: Inflatable Sphere
- **CAST**: Cast Regolith Structure

A NASA Space Engineering Research Center at the University of Colorado
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 (Khalili SCIA). *Materials do not have good mechanical properties.*

- **Solar power fused regolith** for large layered slabs (Clifton). *Solar power is not sufficient to melt large quantities of regolith in reasonable lengths of time.*

- **Sintered and hot pressed regolith** for bricks, plates, columns (Simonds, NASA LSI; Meek, UT; Vaniman, LANL; Sullivan, Battelle). *Small structural components. Not suited to tensile (pressurized) loading conditions or automated construction.*

- **Concrete**: traditional steel reinforced concrete structure using columns, beams, and slabs (Lin, CTL). *Lack of water.*

- **Iron and Steel**, high quality construction materials (UA). *Complex processing methods with high energy requirements.*

- **Cast basalt**: liquified regolith cast into large slab forms (Capps and Wise, Boeing; Binder, Lockheed)
Guidelines for Material Processing Method

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

- Material processing method is intended for far-term lunar base. A certain level of infrastructure must be in place.

- Power source of 100 kW is available (SP-100 nuclear reactor). This places tight constraints on processing time and structural component size.

- Earth moving equipment is available. All scenarios include plans for regolith shielding which requires earth moving.

- Lunar crane with 10 ton capacity is available. Near-term lunar base construction is likely to require lunar crane.
Cast Lunar Regolith

- **Raw materials**: regolith is abundant over the lunar surface. Chemical composition of regolith is very similar to terrestrial basalts.

- **Terrestrial cast basalt** processing methods are moderately well established. Cast basalt has good mechanical properties and can be formed into complex geometries.

- **Proposed cast regolith** process is a simplification of terrestrial cast basalt suited to the lunar environment. Beneficiation, 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
- power
  100 kW
- collect volatiles
- form
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.
# Mechanical Properties of Cast Basalt

<table>
<thead>
<tr>
<th></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 liquefication, 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

A NASA Space Engineering Research Center at the University of Colorado
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
*Vanderbilt, M.D., Criswell, M.E., Sadeh, W.T.; C.S.U.; 1988

(a) Cutaway of Structure

(b) Section Through Interior

Figure 2. Cutaway and Section of Structure

- Membrane
- Arch radius (17.3 ft)
- Rigid arch
- Column

Inflated Shape

Deflated Shape

Figure 3. Arched Membrane System

- Rigid arch
- Membrane
- Regolith

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

CROSS SECTION OF ASSEMBLY FACILITY

- SUPPORT TRUSS (5M CENTERS)
- O.B. BAR INTERNAL PRESSURE
- TIE CABLE
- REGOLITH BALLAST
- GEOFABRIC FLOOR SURFACE
- GEOFABRIC MEMBRANE
- REGOLITH SHIELDING
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

- 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:  $f_t = 34.5$ MPa (5,000 psi);

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

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

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

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

    Melting point:  $1300^\circ$C
8. **Design Variables:**

* Shelter sizing;
  
  large enough to contain Space Station Freedom modules

* Loading conditions;
  
  Internal pressure=10 psi (0.069 MPa)
  
  Regolith shielding depth= 15 ft (4.5m)

* Constraints imposed by cast basalt;
  
  Brittle:

  Low tensile stresses

  Compression should dominate structure

  Post-tensioning

  Material hardness

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

  Determined by casting process

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

* Minimize use of imported materials;

  Minimize tensile reinforcement

* Self-equilibrating structure;

  Tensile loads self-contained

  No arches, vaults, or domes

* Minimize excavation
9. **Design One, Cylindrical Segments:**

**Dimensions:**
- Diameter = 23 ft (7m)
- Wall thickness = 3 in. (7.6 cm)
- Total length = 60 ft (18.3m), forty segments
- Segment length = 1.5 ft. (46 cm)
- Floor thickness = 8 in. (20 cm)
- Leg width = 15 in. (38 cm)
- Segment mass = 2200 lunar lbs (6000 kg)

**Design Features:**

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

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

18m (60')
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
Configuration Optimization of Space Structures

Carlos Felippa
Luis A. Crivelli
David Vandenbelt

Third Annual Symposium
November 21 & 22, 1991
Objective

✓ Develop a Computer Aid for the Conceptual/Initial Design of Aerospace Structures, allowing configuration and shape to be a priori Design Variables.
Approach

KIKUCHI'S HOMOGENIZATION METHOD:
A "DESIGN DOMAIN BLOCK," FILLED INITIALLY WITH
"SCULPTED" HOMOGENIZED FINITE ELEMENTS, IS GRADUALLY
CONTROLLED 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

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

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

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

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

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

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

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

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

✓ **Volume Inequality Constraint**

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

✓ **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

\[ L = \Pi - \lambda_V C_\perp + \sigma_V C^2_\perp \]

where

\[ \lambda_V = \text{Lagrangian multiplier estimate} \]
\[ \sigma_V = \text{penalty weight} \]

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

✓ Objective Function Gradients
\[
\frac{\partial p^Tv}{\partial a^e} = -v^T \frac{\partial K}{\partial a^e} v
\]
\[
\frac{\partial p^Tv}{\partial b^e} = -v^T \frac{\partial K}{\partial b^e} v
\]

✓ Stifness (Discrete Equilibrium) Constraints
\[
\frac{\partial v}{\partial a^e} = -K^{-1} \frac{\partial K}{\partial a^e} v
\]
\[
\frac{\partial v}{\partial b^e} = -K^{-1} \frac{\partial K}{\partial b^e} v
\]
\( \triangleright \text{Stiffness Variations} \)

\(\sqrt{\text{For Element Stiffness}}\)

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

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

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

\(\sqrt{\text{For Global Stiffness}}\)

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

First Variation

\[ \delta \Pi = -v^T \delta K v \equiv - \int_A e^T \delta \epsilon e dA = 0 \]

Second Variation

\[ \delta^2 \Pi \approx 2 \int_A \delta e^T \delta \epsilon e dA - \int_A e^T \delta^2 \epsilon e dA \]
Schematics of the Optimization Program.
Progress

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

\[ V_{ref} = 50 \]
\[ E = 10,000 \]
\[ v = 0 \]
\[ R = 1 \]

2x2 mesh over D.D.
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
Jane Pavlich
Wayne Jermstad

Mike Matthews
Gary Snyder
Chris Steffen

Faculty

Jim Avery, Renjeng Su

Staff

Walter Lund
Objectives

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

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

Coordination is required between these independent systems.

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

Goal is "plug and play" modularity.
Advantages of Modularity

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

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

Individual systems are less complex; each can be dedicated to a separate sub-task.
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 ± 2 cm in two dimensions
- Derived from GPS technology
- Currently only ± 5 cm available
IR TROP System Design

- Pseudo Random Noise Generator (PRN)
  - Multi-channel Wideband Mixer
    - Power Amplification
  - 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
Testbed Layout

Infrared beacons

IR receivers

Robot
Centralized Control
Modularized Control

Messages contain requests and information.

Messages passed between arbitrary number of objects.

Control algorithms distributed.
Lunar Surface Structural Concepts

and Construction Studies

Martin Mikulas

Third Annual Symposium
November 21 & 22, 1991
# 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></td>
</tr>
<tr>
<td>- Deployable Tower</td>
<td>Automatically Deployable Towers and Beam Type Structures With Minimal Deployment Equipment</td>
</tr>
<tr>
<td>- Lunar Module Unloading Device</td>
<td>Capability For Self Off-Loading of Modules &amp; Equipment</td>
</tr>
<tr>
<td>- Deployable Solar Concentrator</td>
<td>Automatically Deployable Reflector With Minimal Deployment Equipment</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>Three Cables</th>
<th>Single Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 DOF</td>
<td>3 DOF</td>
<td>1 DOF</td>
</tr>
<tr>
<td></td>
<td>Structurally Stiff</td>
<td>Structurally Stiff</td>
<td>Structurally Stiff</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stiffened by Triangulated Cables</td>
<td></td>
</tr>
</tbody>
</table>
NIST SIX-CABLE SUSPENSION CRANE

Cable Geometry

- Controlled Trolley Motion
- Modified Bridge Crane Trolley
- Wirerope
- Platform
- Load

Cable Drive System

James S. Albus
1/15/85
NUMERICAL EXAMPLE OF NATURAL FREQUENCY

A Symmetric Model

A Swinging Pendulum

\[ F = \sqrt{\left(\frac{\ell_h}{h-\ell_h}\right) \left[\ell_h h + \frac{\ell_a^2}{4}\right] + \ell_e h} \]

\[ F_{\text{pendulum}} = \frac{1}{2\pi} \sqrt{\frac{g}{h}} \]
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
CMG CONTROL SIMULATION RESULTS

- X-coordinate of point H (in)
  - CMG Control
  - No Control

- 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

(a) Framework Angular Angle

(b) Framework Angular Velocity

(c) Module Angular Angle

(d) Module Angular Velocity

(e) Control Force Along EF

(f) Initial EF = 100 in

---

Cable #1 & #3

Structural Framework

Screw-Drive Actuator

Module

Y-axis

l_a

X-axis

l_d

l_c

l_b

\( \alpha \)

\( \beta \)

\( \beta_0 \)

\( \psi \)

P

G c.g.

\( l_e \)

\( l_0 \)

(initial)
SLEWING SIMULATION RESULTS

- X-Y Plot of Point H on End-Effector
  - Y-Coord. of H (in)
  - X-Coord. of H (in)

- 60 deg. Maneuver

- Angles of Boom (deg) vs. Time (sec)

- Control Moment of Boom (lb-in) vs. Time (sec)

- Angles of End-Effector vs. Time (sec)

- Angles of Module vs. Time (sec)
ONE-SIXTH SCALE LUNAR CRANE TEST-BED USING G.E. ROBOT FOR GLOBAL MANIPULATION.
BASIC DEPLOYABLE TRUSS APPROACHES

Warren Truss

Sequentially Deployable Truss

Synchronizing Bar

Synchronously Deployable Truss

Standard Sequential Packaging
COMPARISON OF ELEVATOR PLATFORMS

Bi-Pantograph

Pantograph
BI-PANTOGRAPH VS PANTOGRAPH STIFFNESS

\[ \frac{EI}{L}, \text{in-lb} \]

\[ \text{Theta, Degrees} \]
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

Unloading Winch

Self-Positioning Regolith Auger

Lowering Cable

Module Rotation Arm

Module Rotation Pivot

65'

63'

25'

19'

47.5'

38'

13'
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
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

- Shuttle Dynamic Envelope
- Deployment Arm

Dimensions:
- 0.384 m
- 1.15 m
- 3" (0.762 m)
- 3.616 m
FOCAL POINT AND THICKNESS PACKAGING CONSIDERATIONS

(3 Ring, 20 m D eff)

Cargo Bay Representation

Panel Thickness, in

Reflector Volume

Cargo Bay Volume

Top View

Side View

21.9 m

3.6 m

f/D

1.5

2.5

3.5

∞
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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