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p. 36

cSc

Controls for Orbital Assembly of Large Space Structures

Mark Balas

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

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

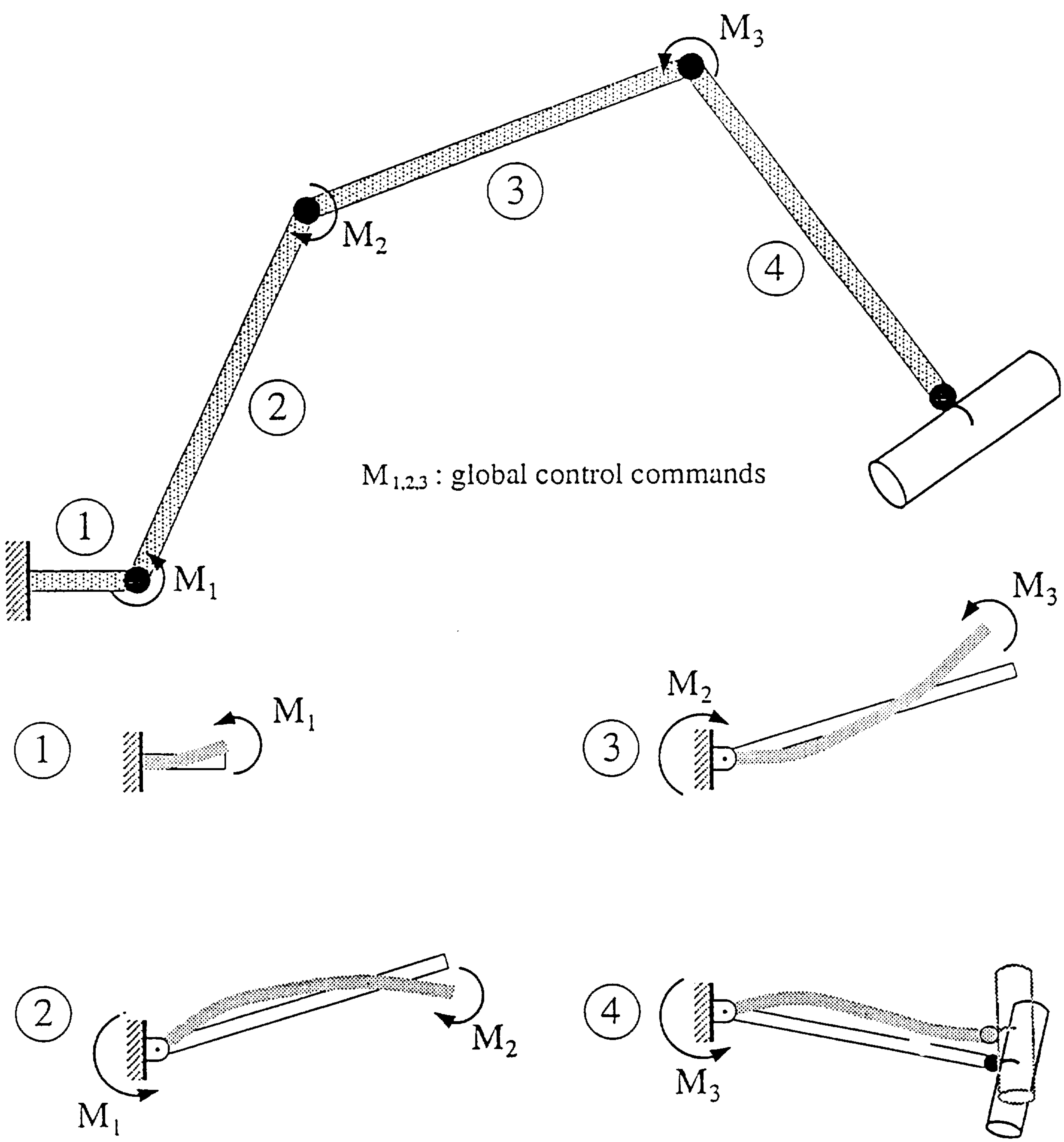
Shin-Ching Liang PhD Completed 1991

NASA Center for Space Construction
Univ. of Colorado, Boulder

Industrial affiliates

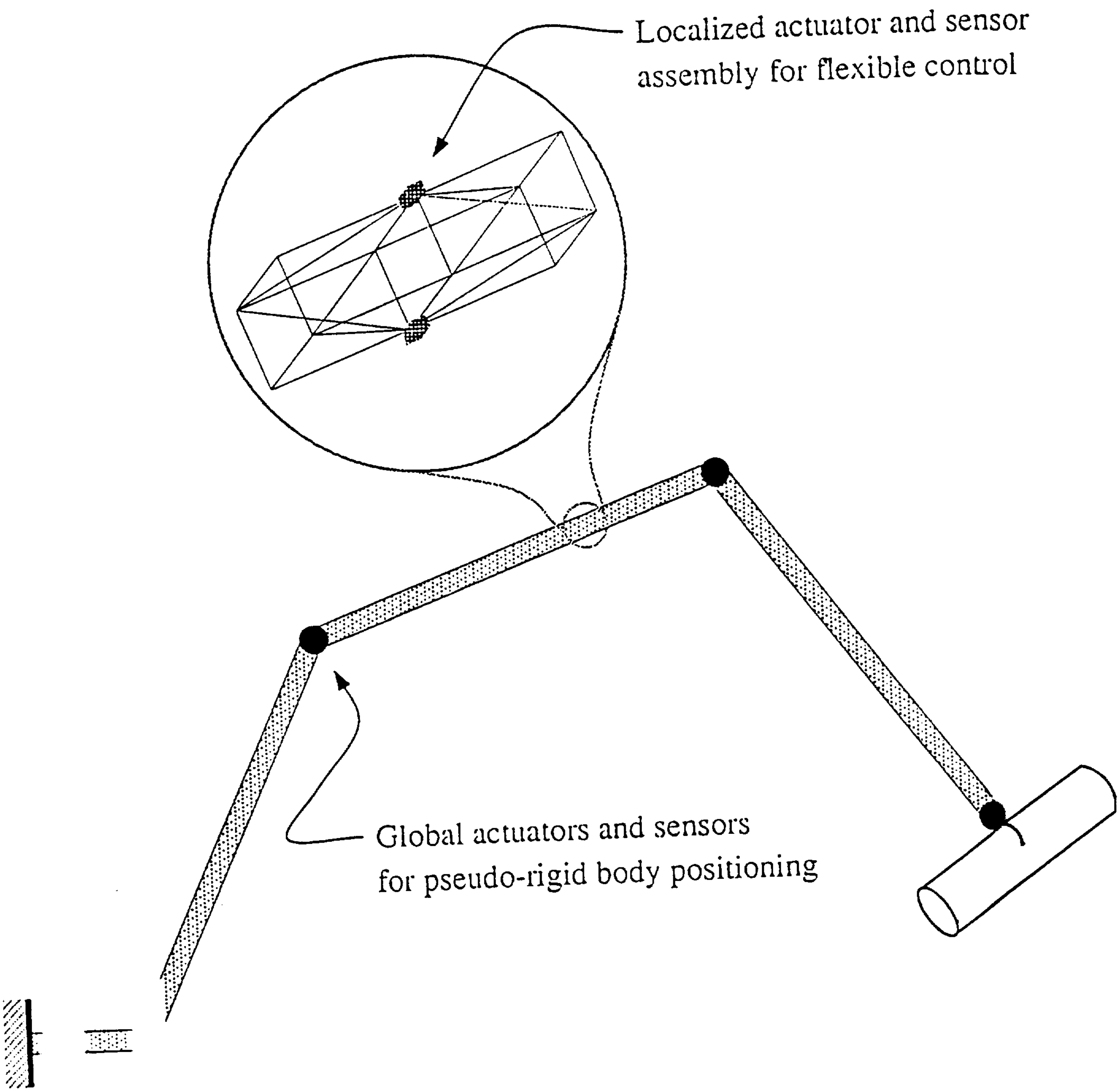
De-centralized Control for Flexible Multi-body Systems

Flexible Sub-system Division

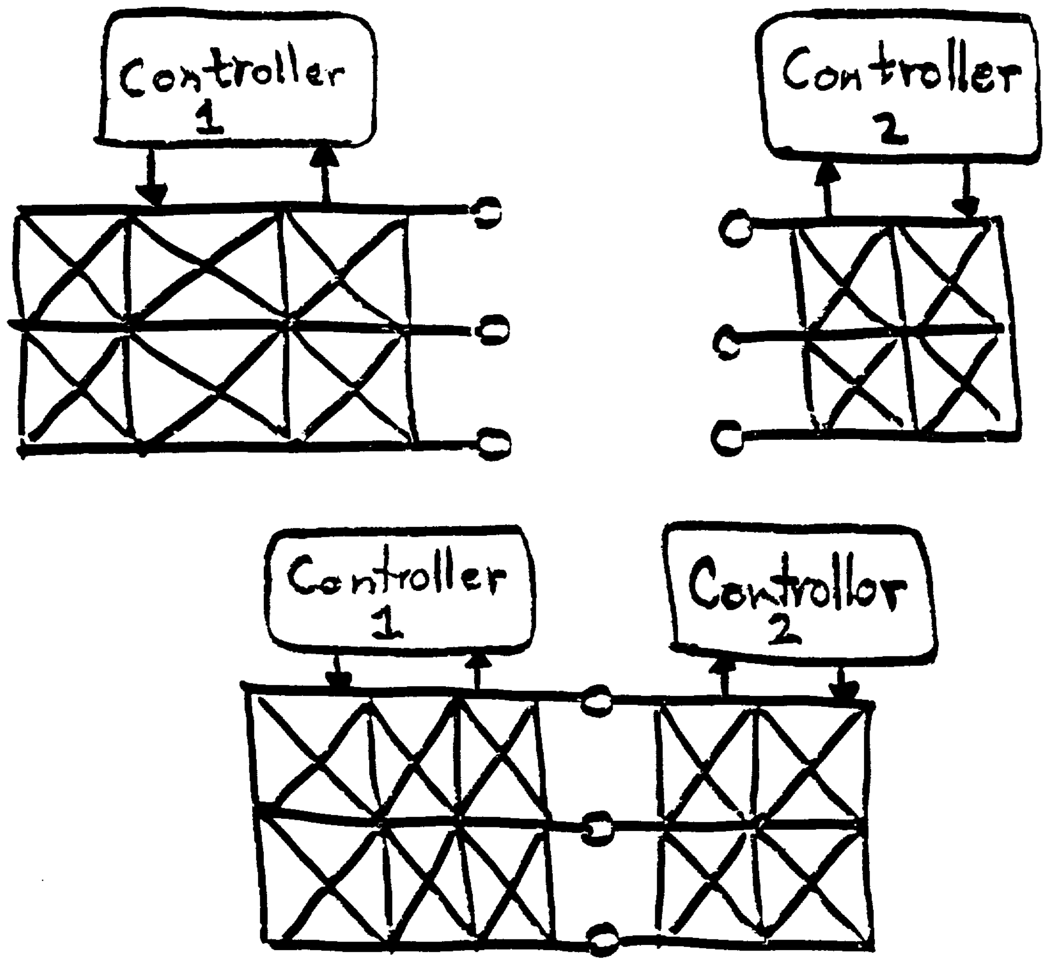


De-centralized Control for Flexible Multi-body Systems

Local and Global Control



L. (Robbie) Robertson

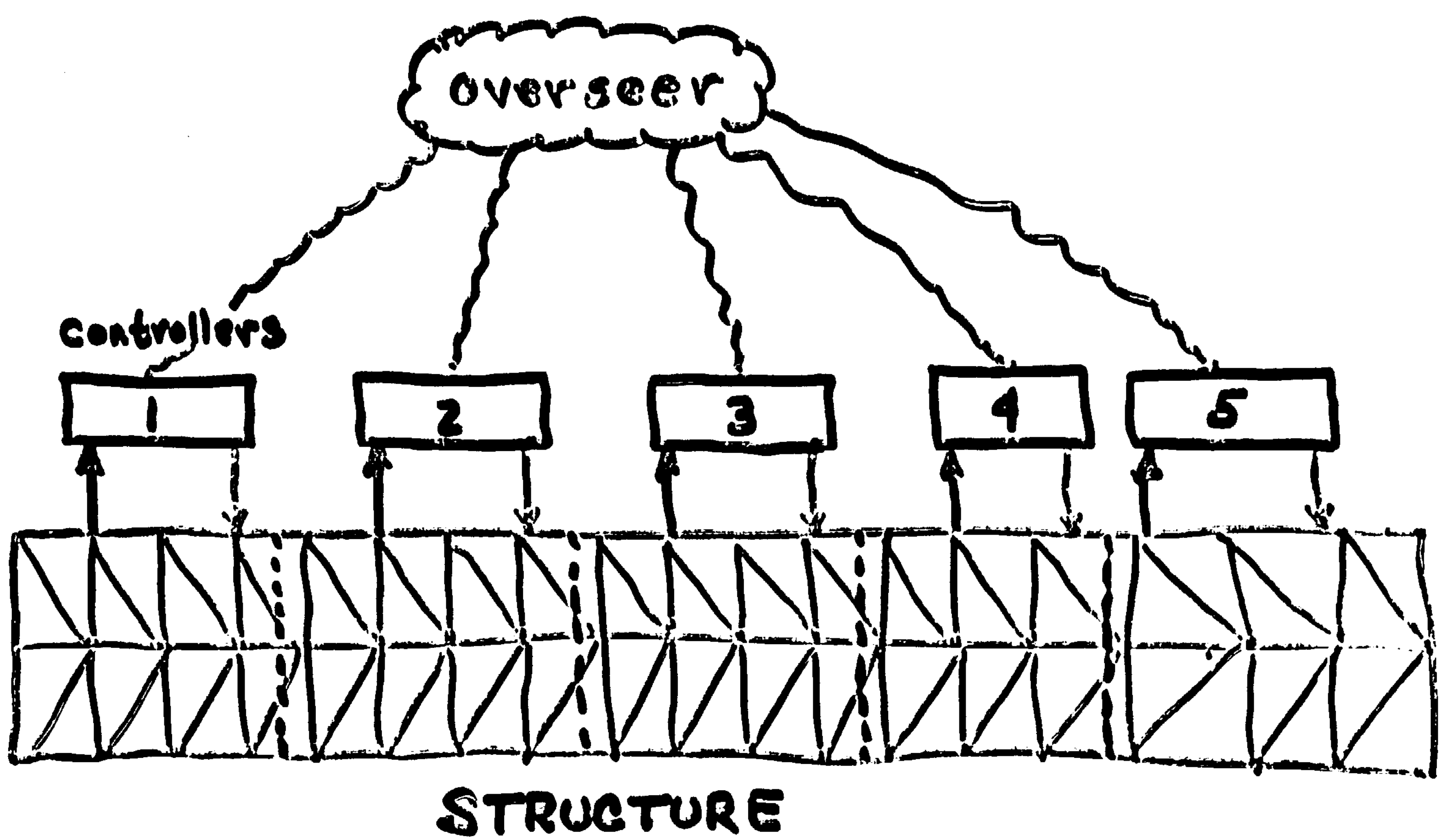


Control of Structures During Assembly

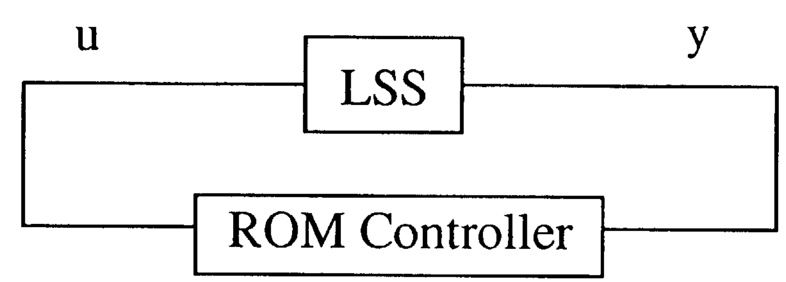
Normal (Planned) Assembly
Emergencies (F^3U)

Docking & Berthing / Contact

Decentralized Control
Using Structural Partitioning



Reduced-Order Model-Based Controller Design



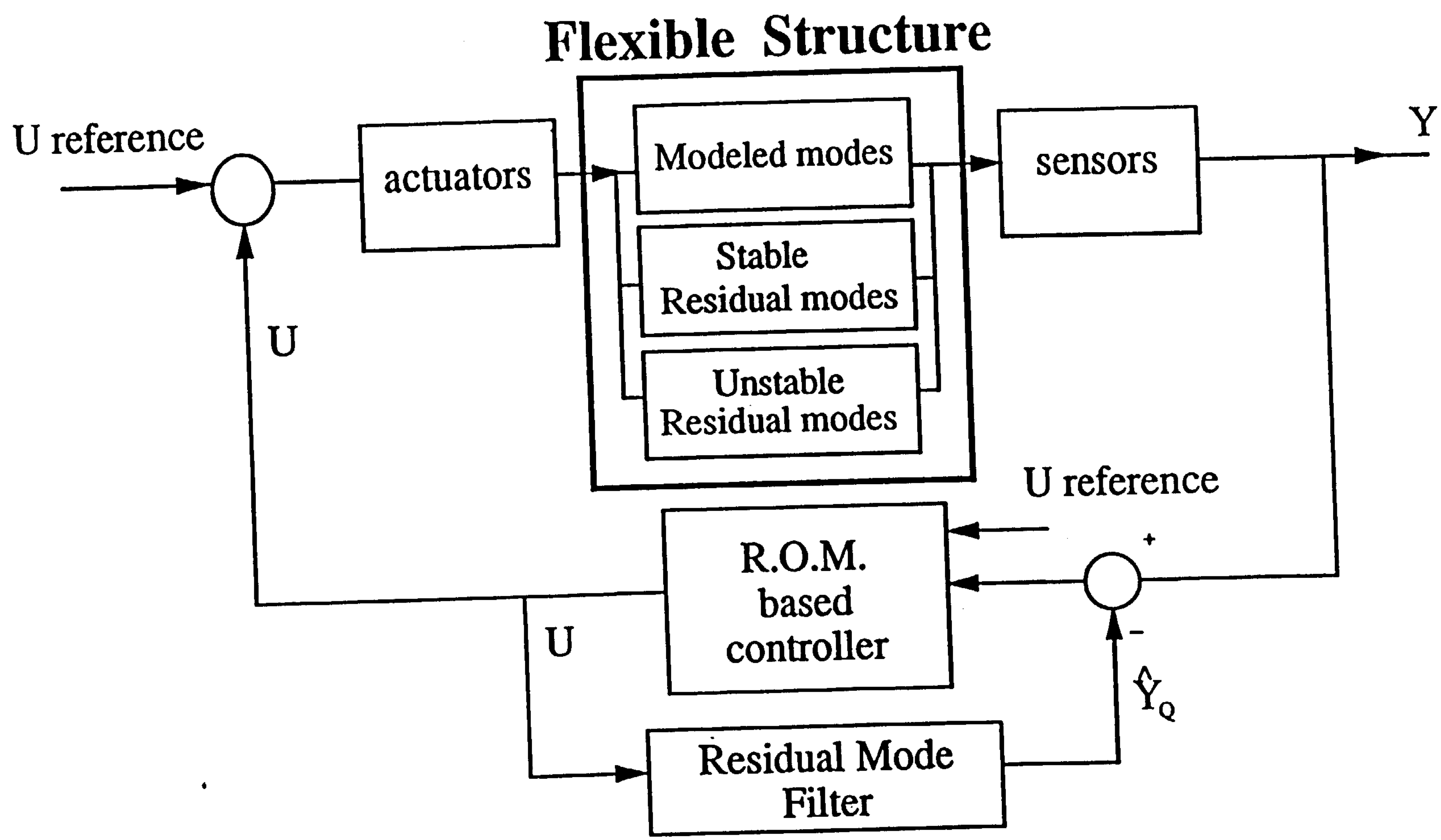
Closed Loop: $L_n = A_n + B_nG_n - K_nC_n$

$$\begin{bmatrix} \dot{x}_n \\ \dot{\hat{x}}_n \\ \dot{x}_r \end{bmatrix} \quad \underbrace{\begin{bmatrix} A_n & B_nG_n & 0 \\ K_nC_n & L_n & K_nC_r \\ 0 & B_rG_n & A_r \end{bmatrix}}_{A_c} \begin{bmatrix} x_n \\ \hat{x}_n \\ x_r \end{bmatrix}$$

OR

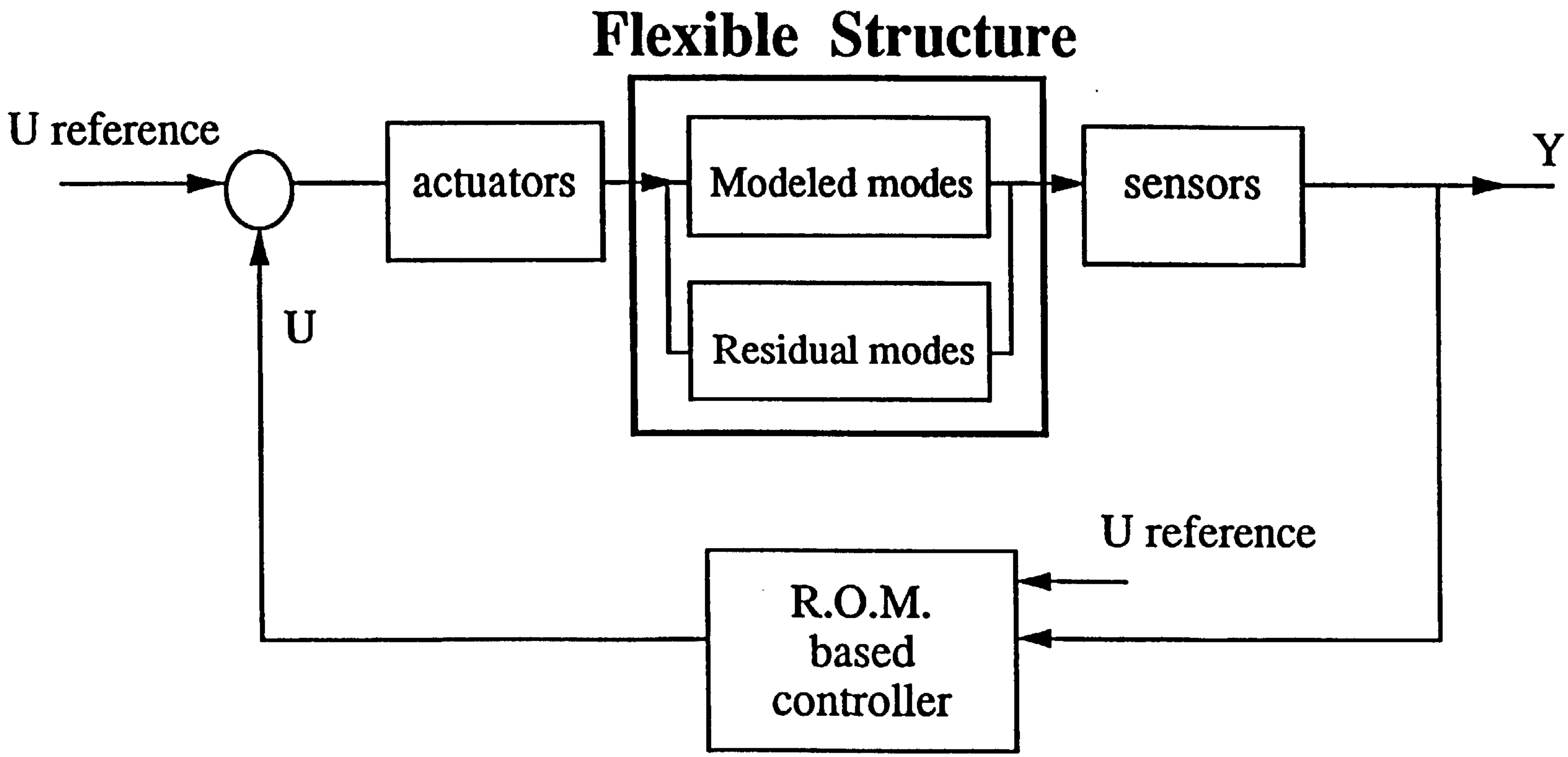
$$\begin{bmatrix} \dot{x}_n \\ \dot{e}_n \\ \dot{x}_r \end{bmatrix} = \begin{bmatrix} A_n + B_nG_n & B_nG_n & 0 \\ 0 & A_n + K_nC_n & K_nC_r \\ B_rG_n & B_rG_n & A_r \end{bmatrix} \begin{bmatrix} x_n \\ e_n \\ x_r \end{bmatrix}$$

ROM/RMF Control of Large Flexible Structures



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

ROM-based Control of Large Flexible Structures



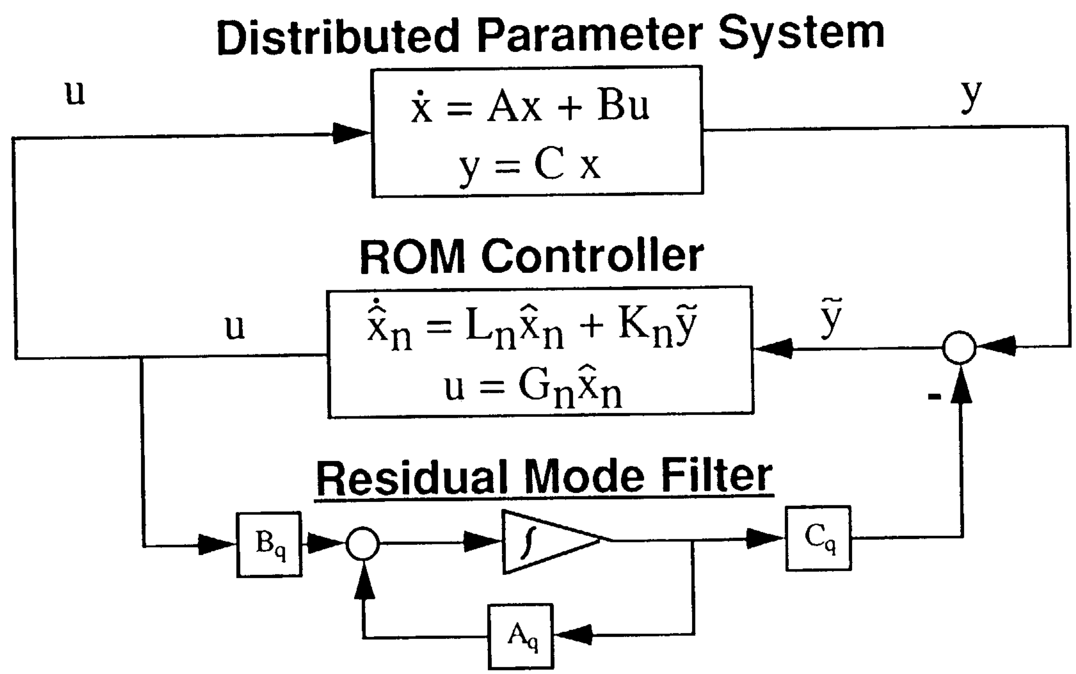
- **Develop a R.O.M. controller, designed for performance.**
- **Dimension of the controller << dimension of the structure.**

BUT

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

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

Balas: JMAA 1988



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

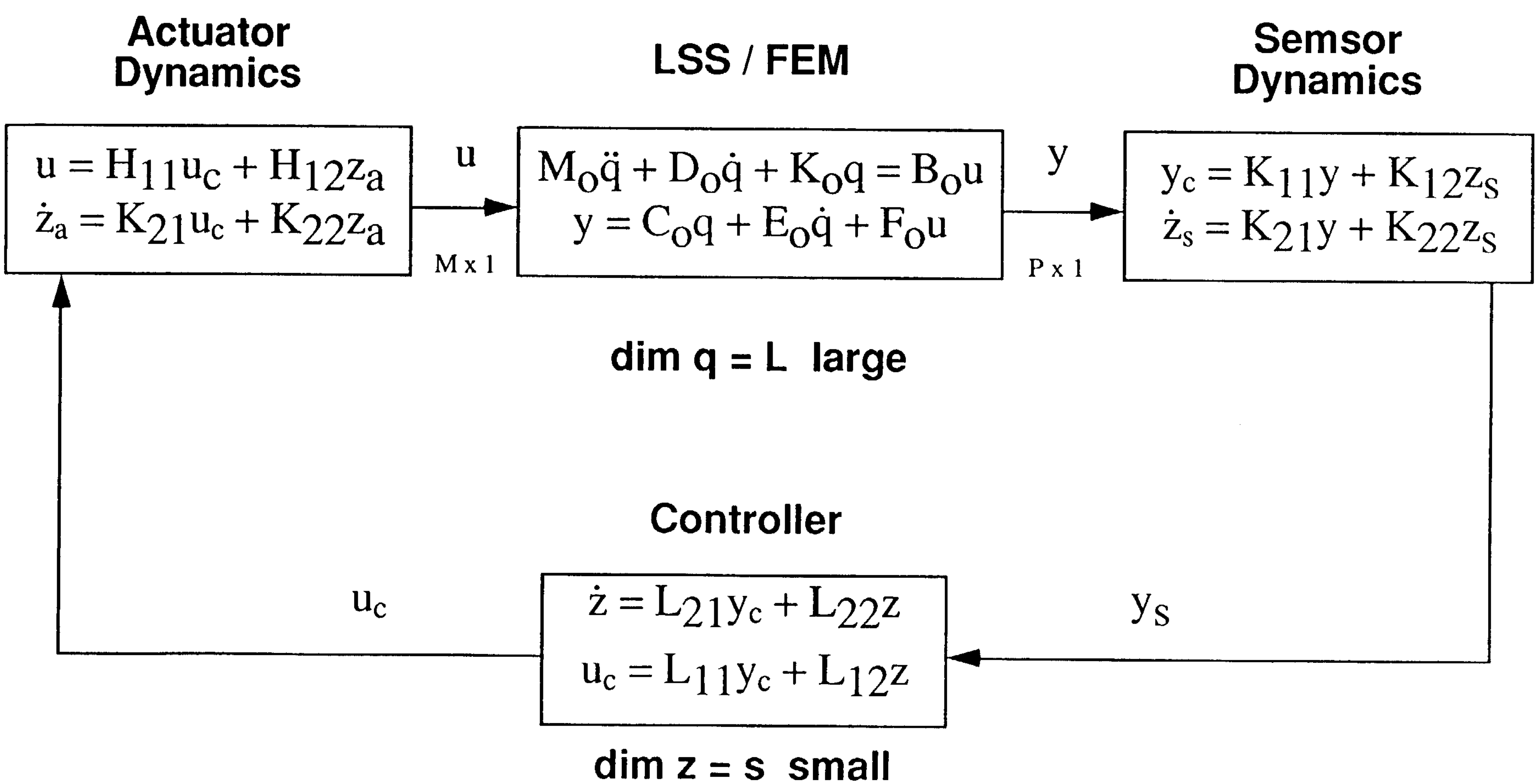
- A_n ← **open-loop unstable modes**
- A_q ← **closed-loop unstable modes**
- A_r ← **unaffected residual modes** (unmodelled dynamics)

DPS + Rom Controller → unstable (q modes)

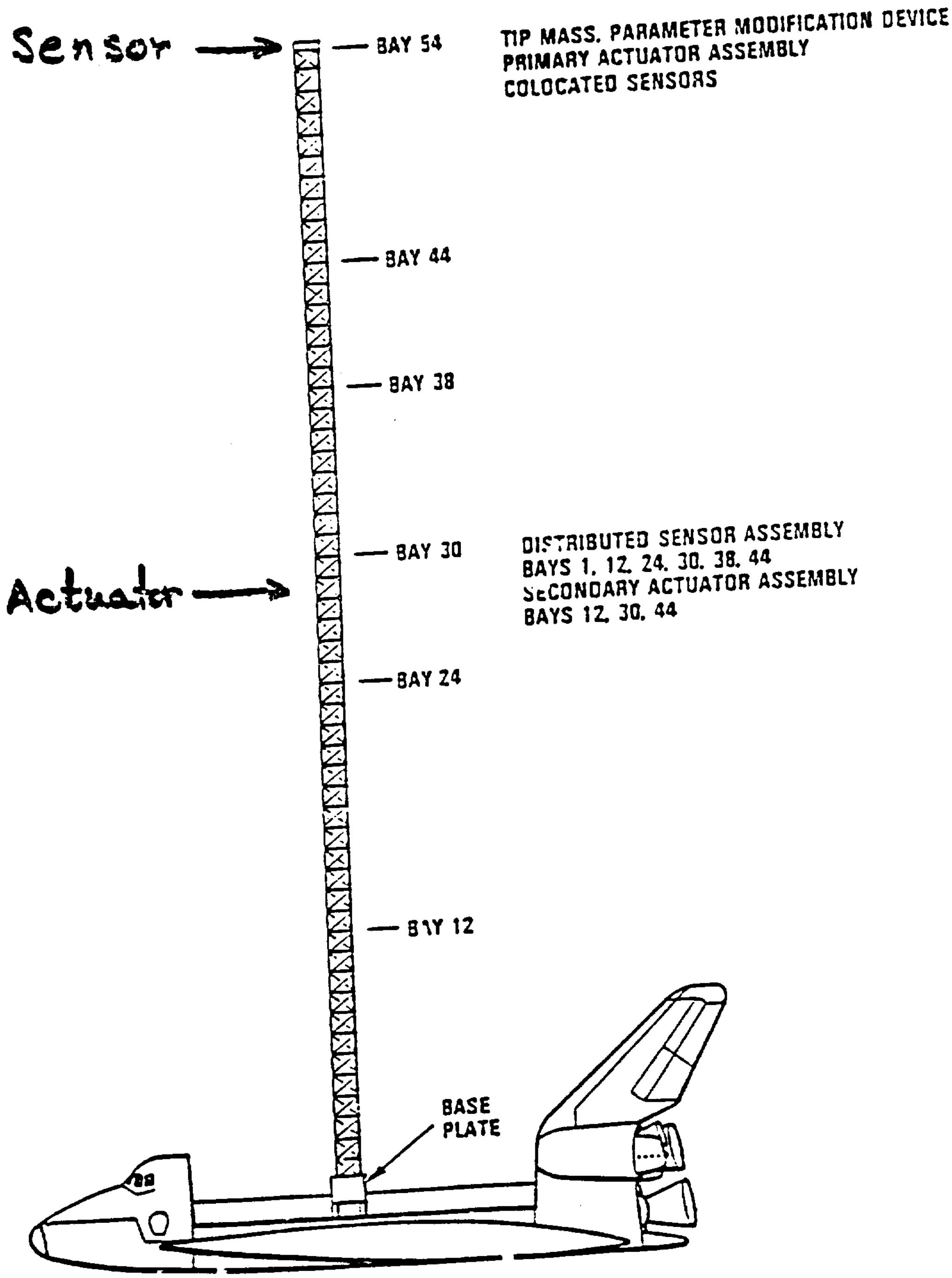
DPS + ROM Controller + RMF → exponentially stable

LSS Active Control Simulation

(Ralph Quan)

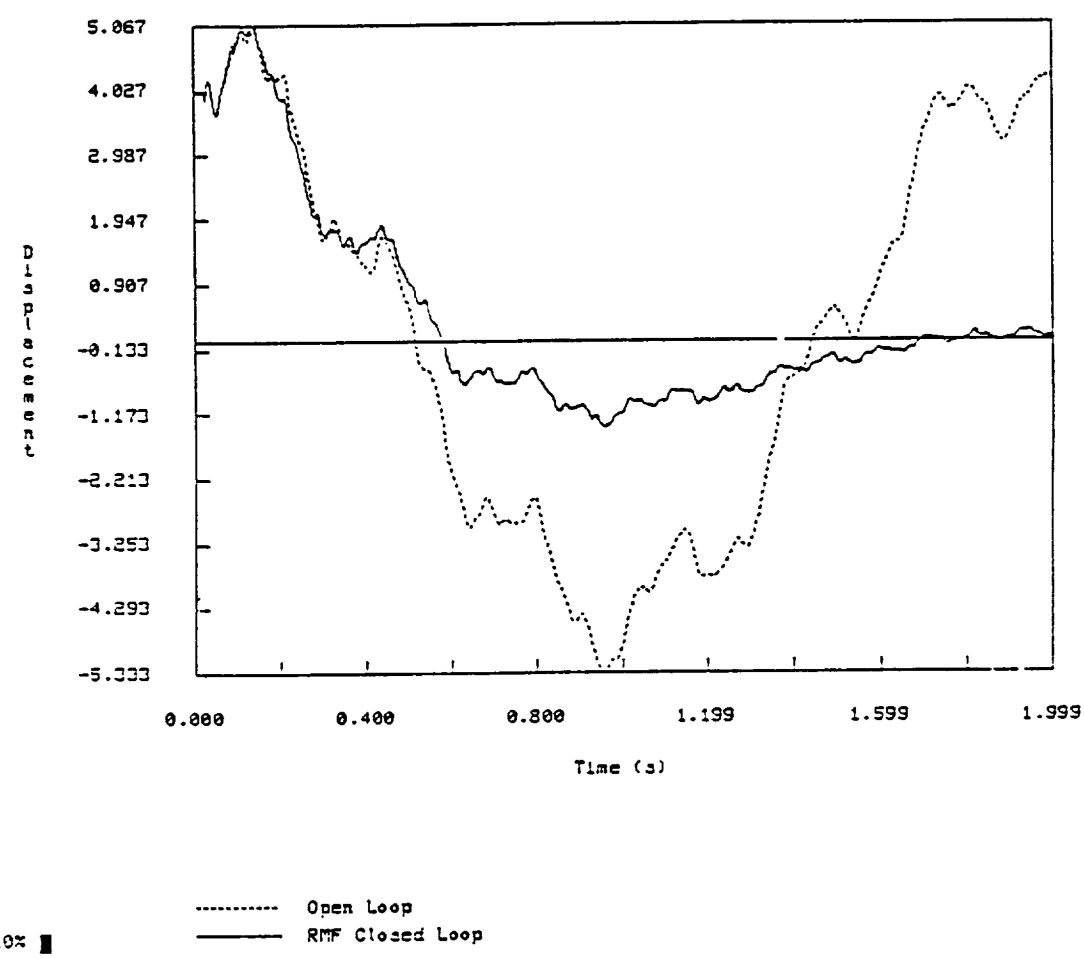


3-Dimensional Truss Beam



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

OPEN LOOP versus RMF CLOSED LOOP



jupiter20%

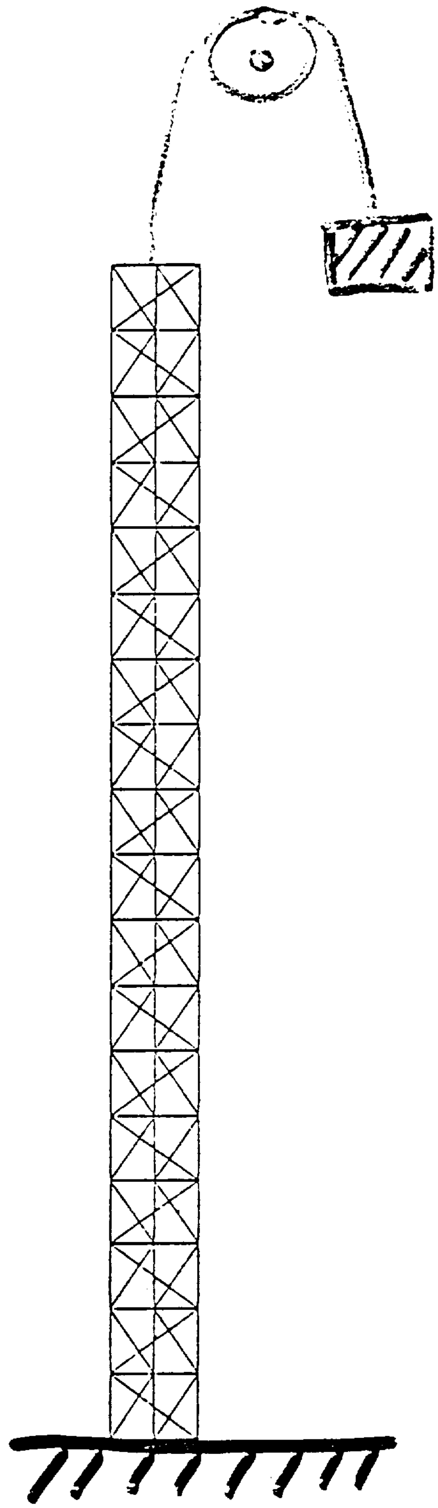


Figure 8.7 The Mini-Mast Truss

Langley

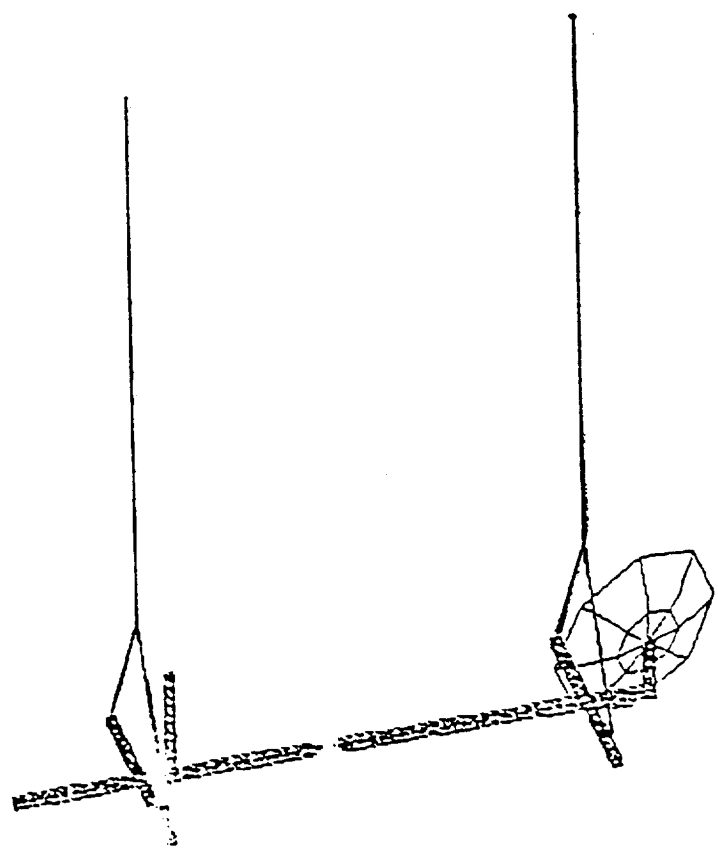
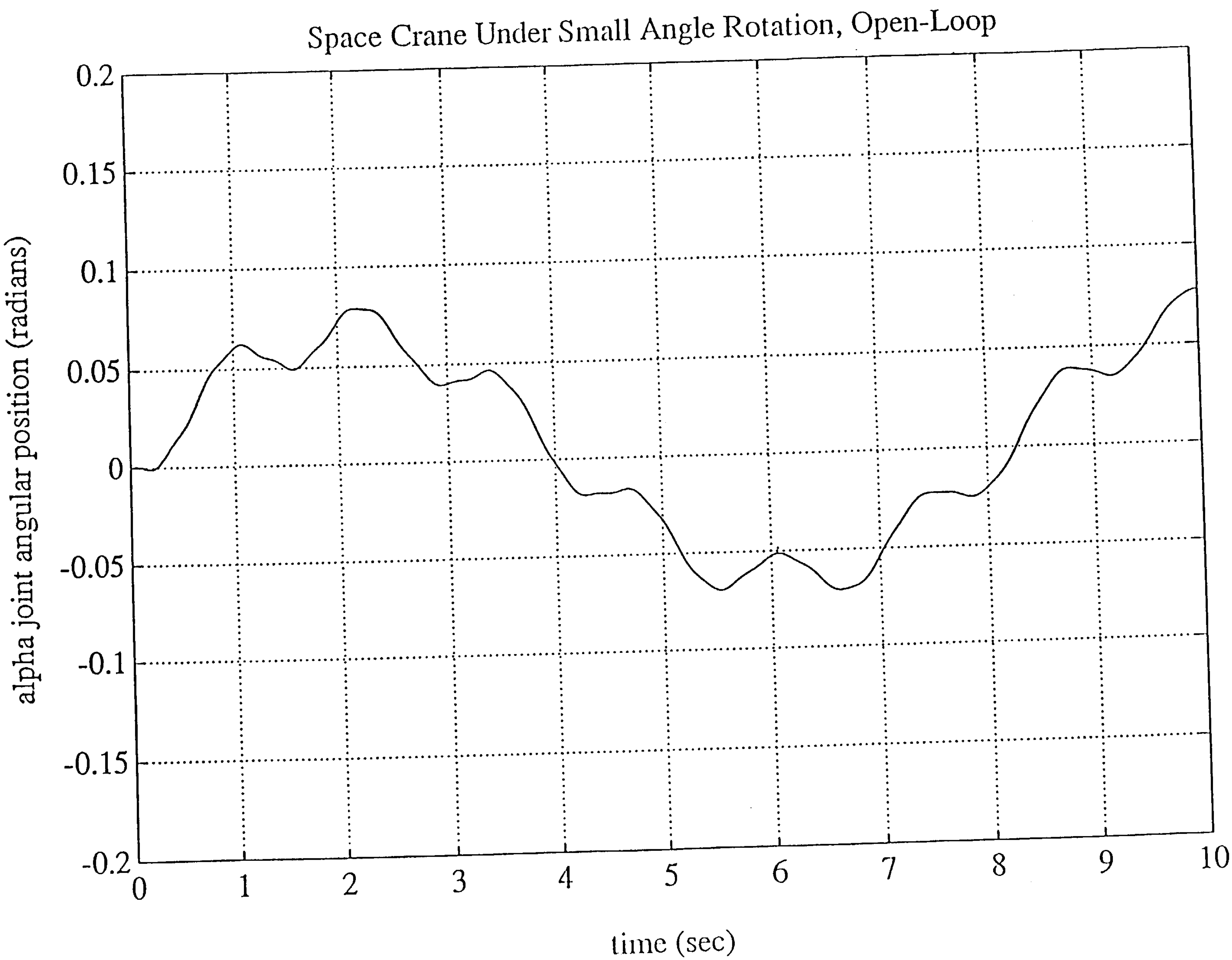
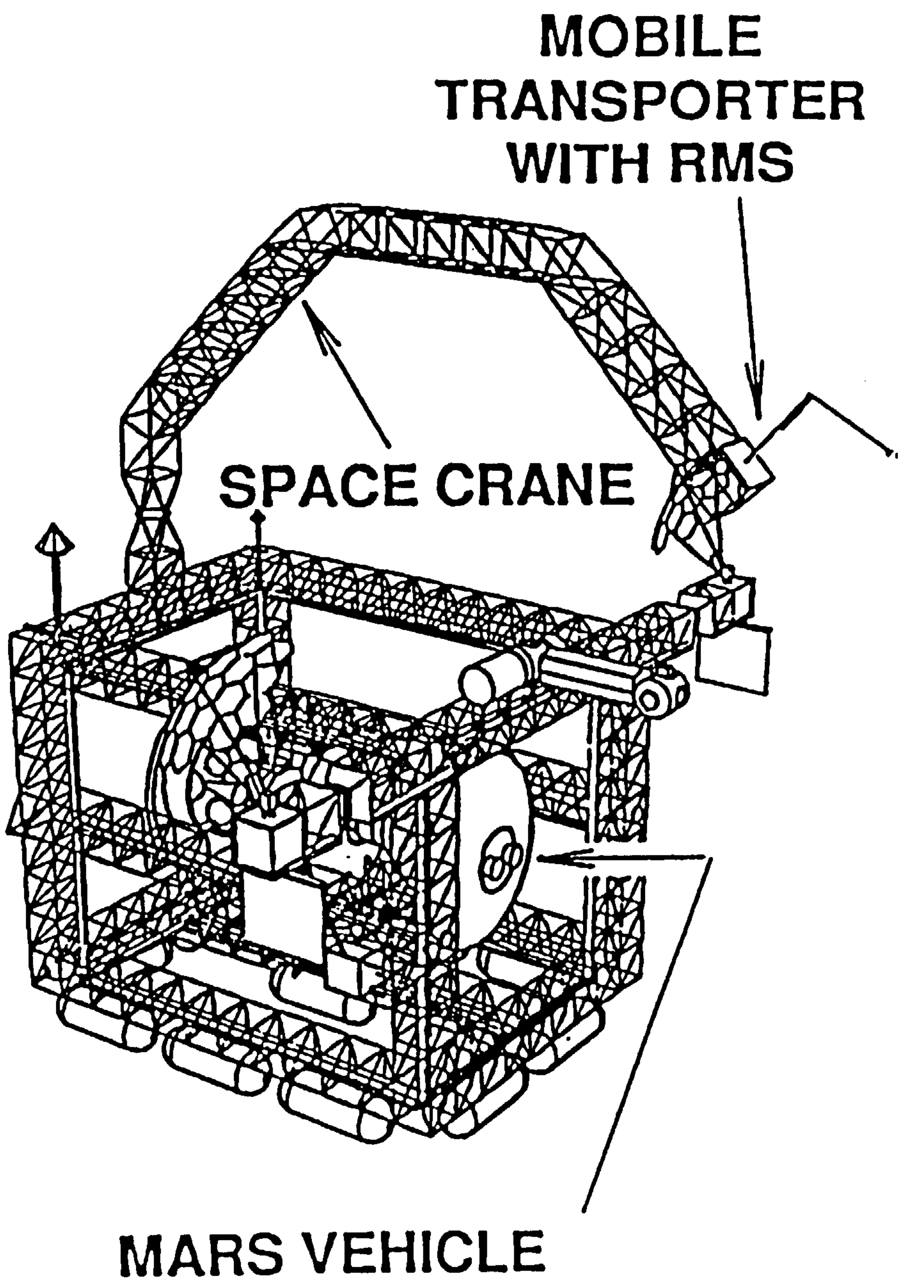
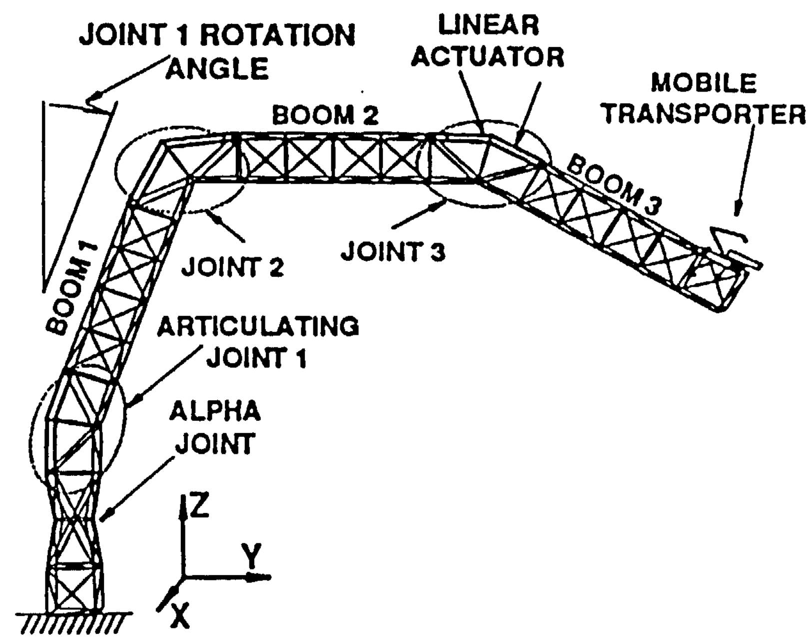


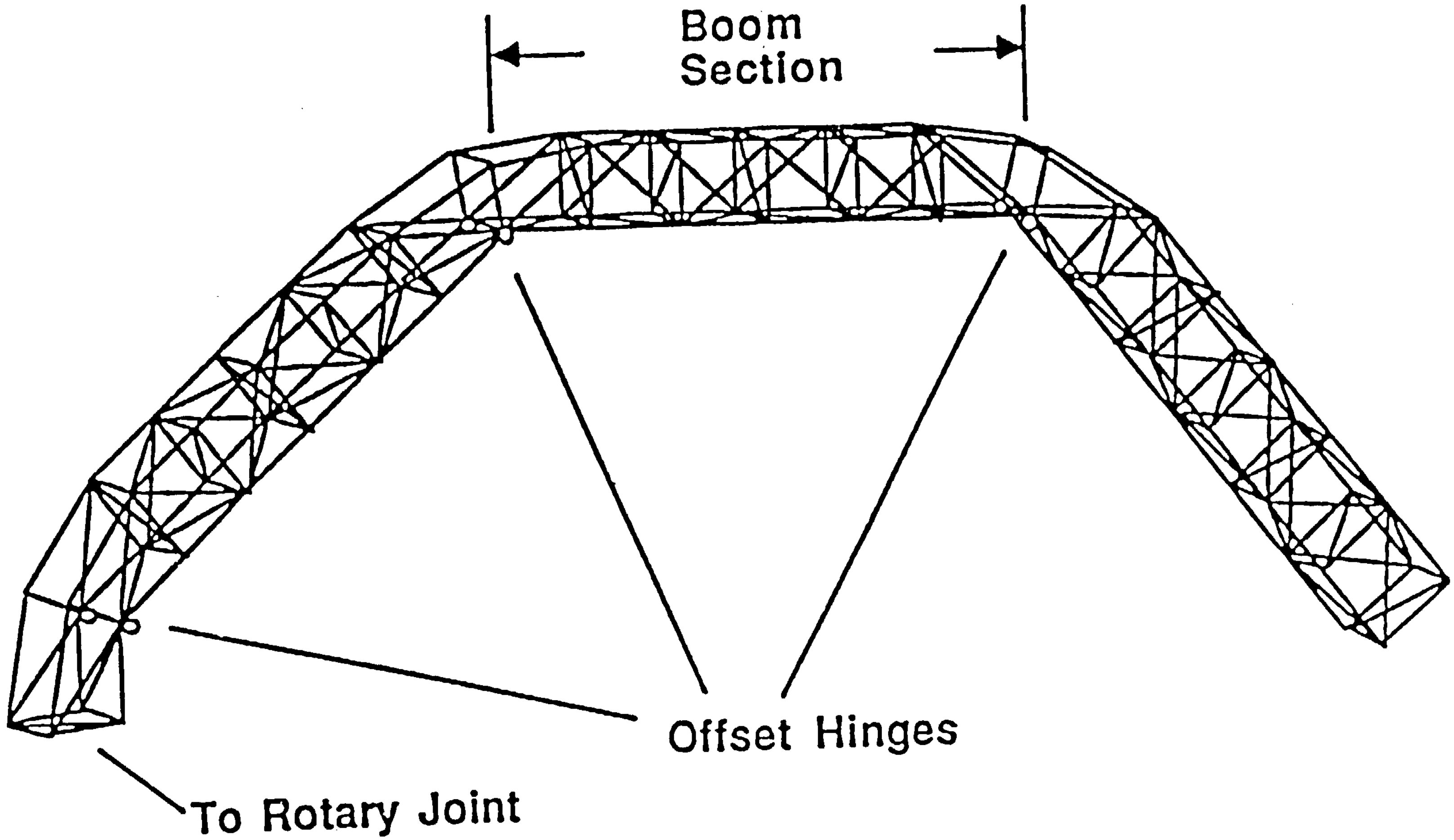
Figure 8.22 Phase o Evolutionary Model

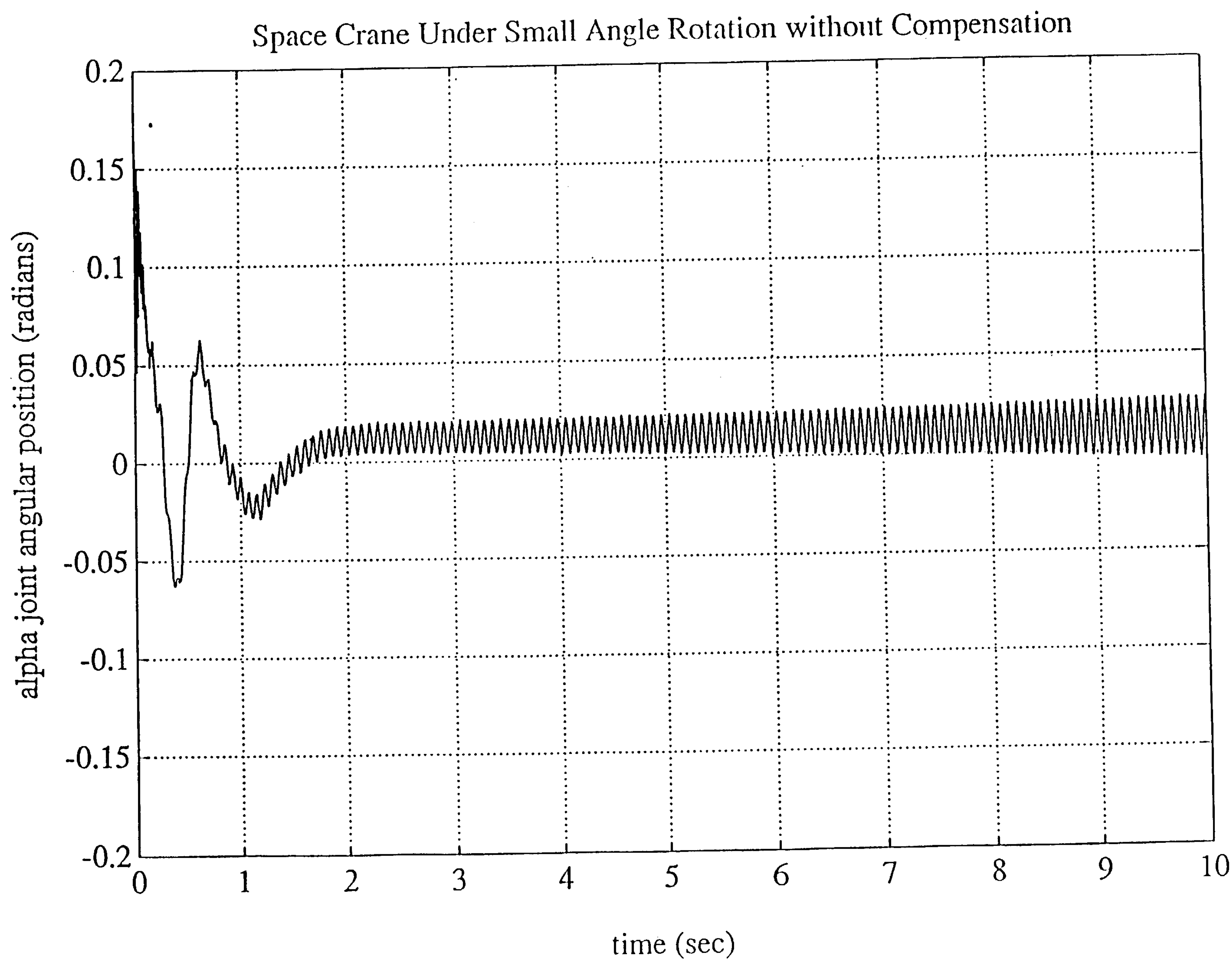


Space Crane Under Small Angle Rotation, Open-Loop
alpha joint angular position (radians)
time (sec)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
1
2
3
4
5
6
7
8
9
10


MOBILE
TRANSPORTER
WITH RMS
SPACE CRANE
MARS VEHICLE


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


Boom
Section
Offset Hinges
To Rotary Joint


Space Crane Under Small Angle Rotation without Compensation
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
alpha joint angular position (radians)
0
1
2
3
4
5
6
7
8
9
10
time (sec)

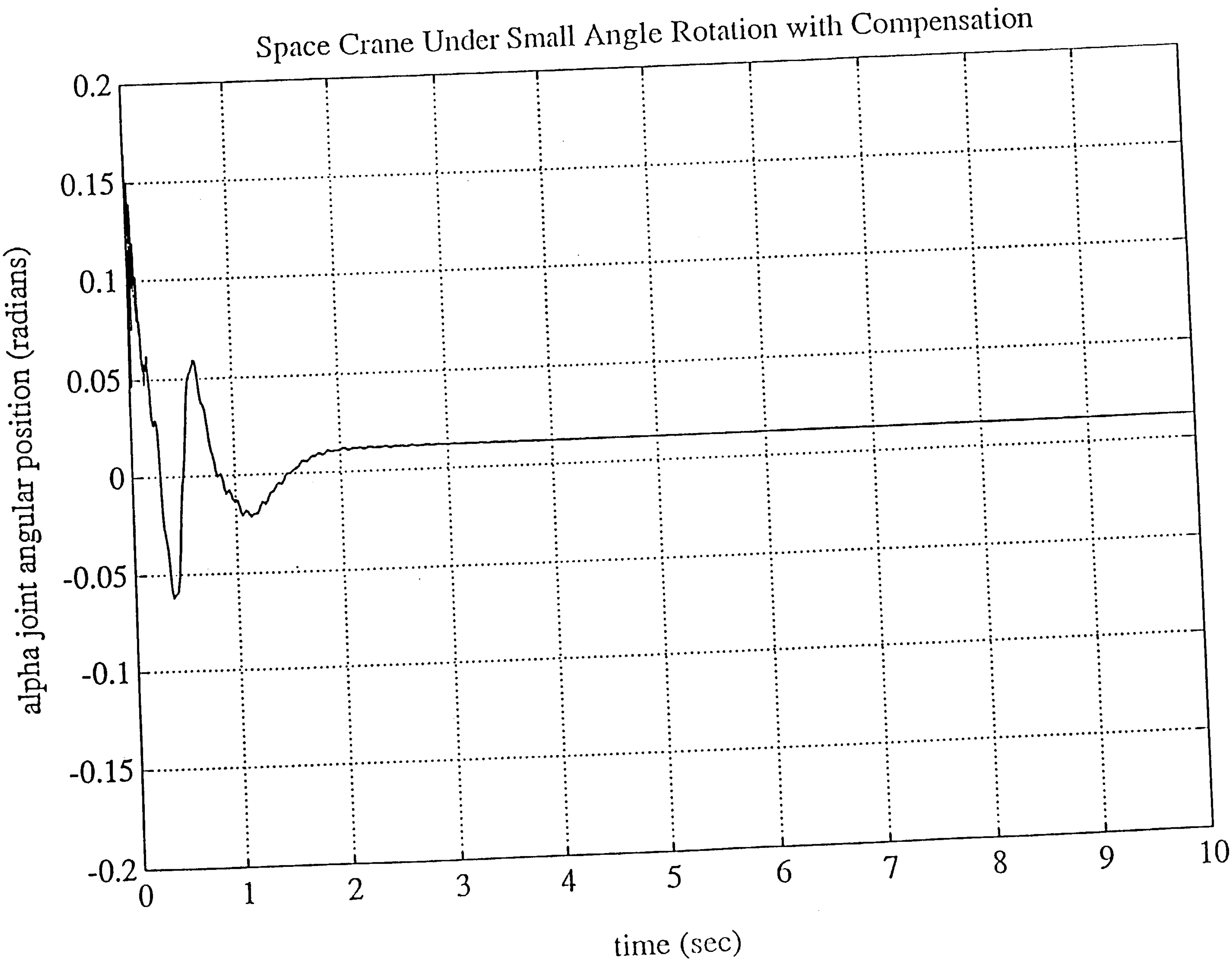

Space Crane Under Small Angle Rotation with Compensation
alpha joint angular position (radians)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
1
2
3
4
5
6
7
8
9
10
time (sec)

Figure 3 : Flexible Robot Manipulator at Martin Marietta

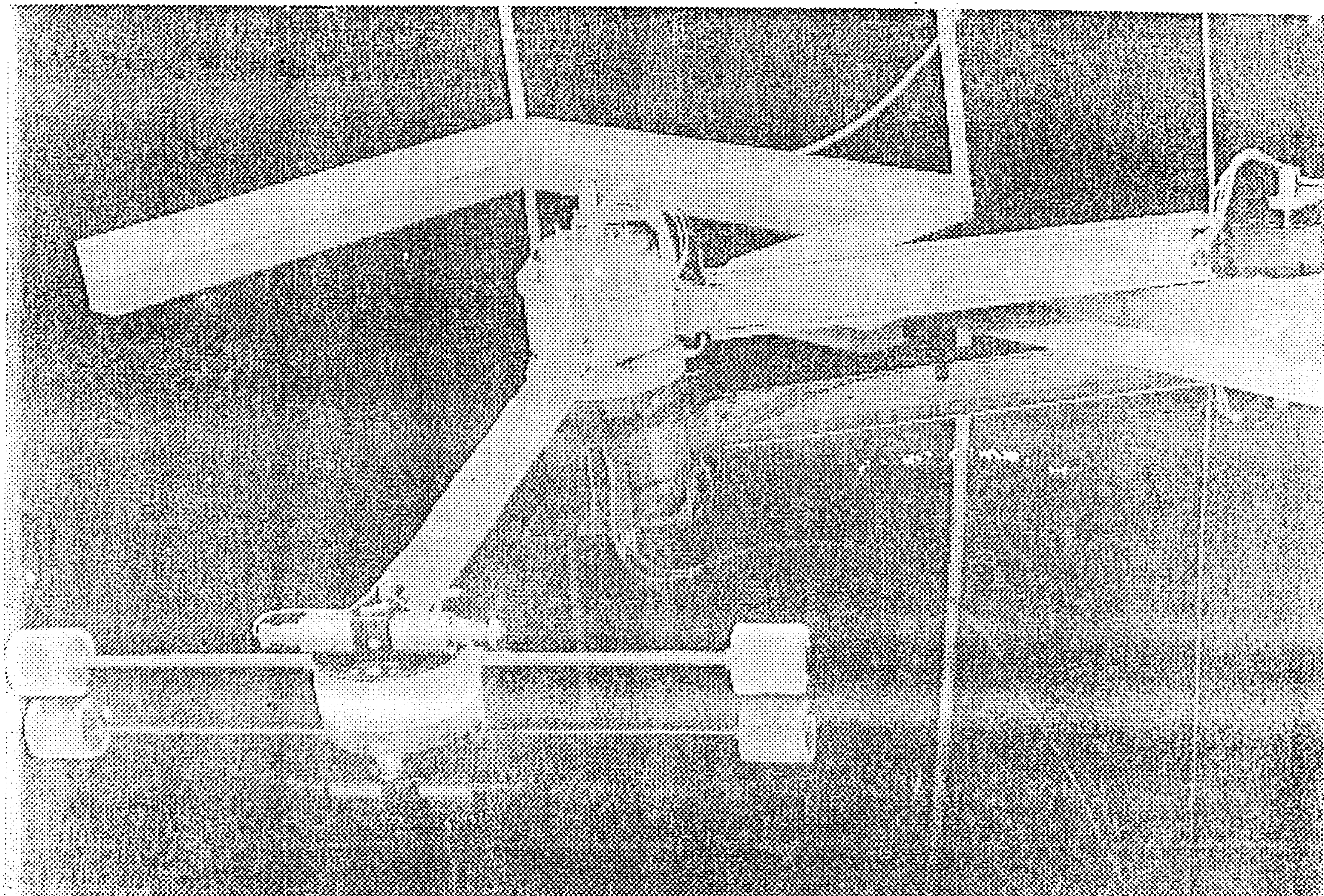


Figure 7 : Hub Position Without CSI Compensation

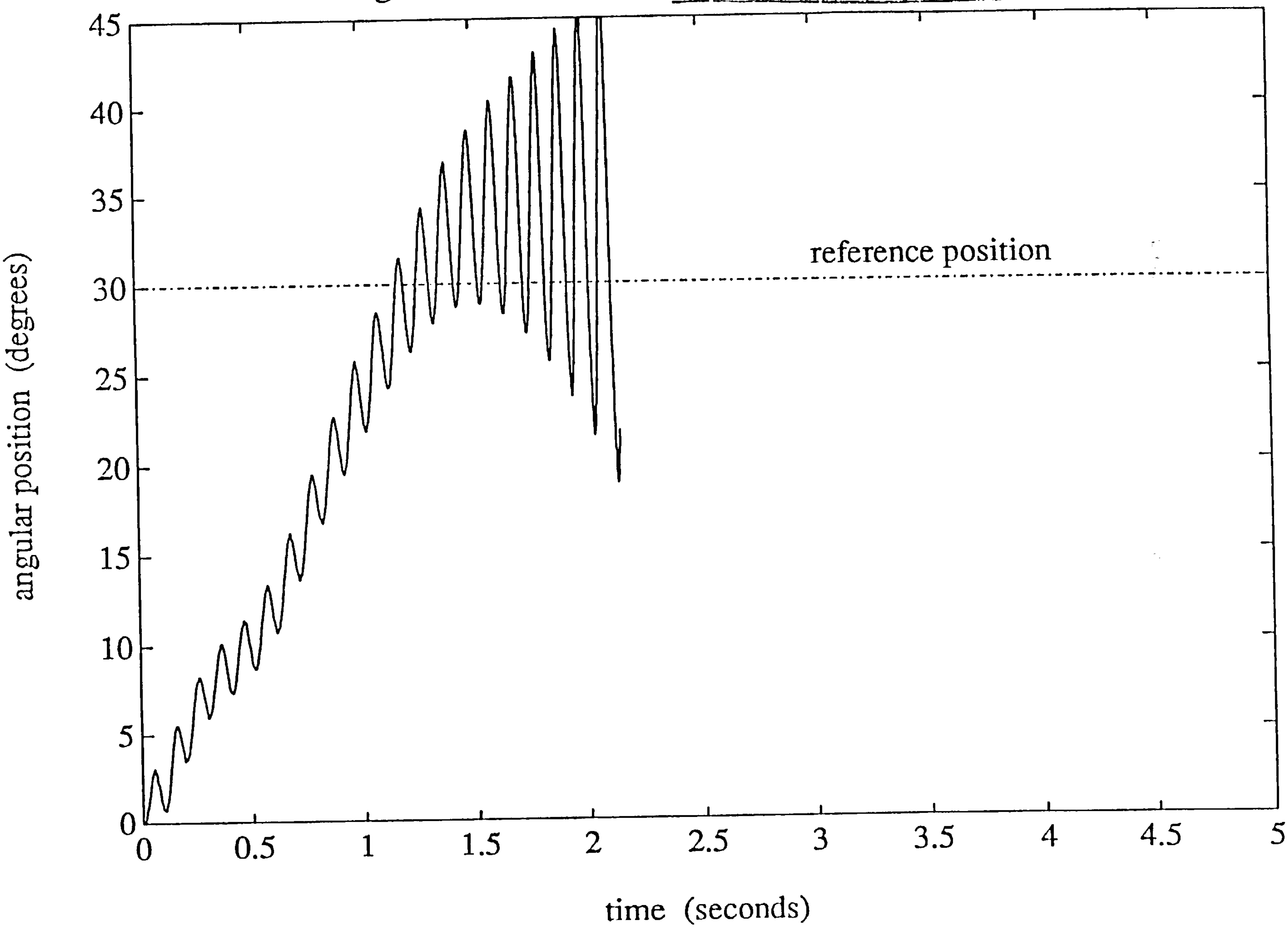
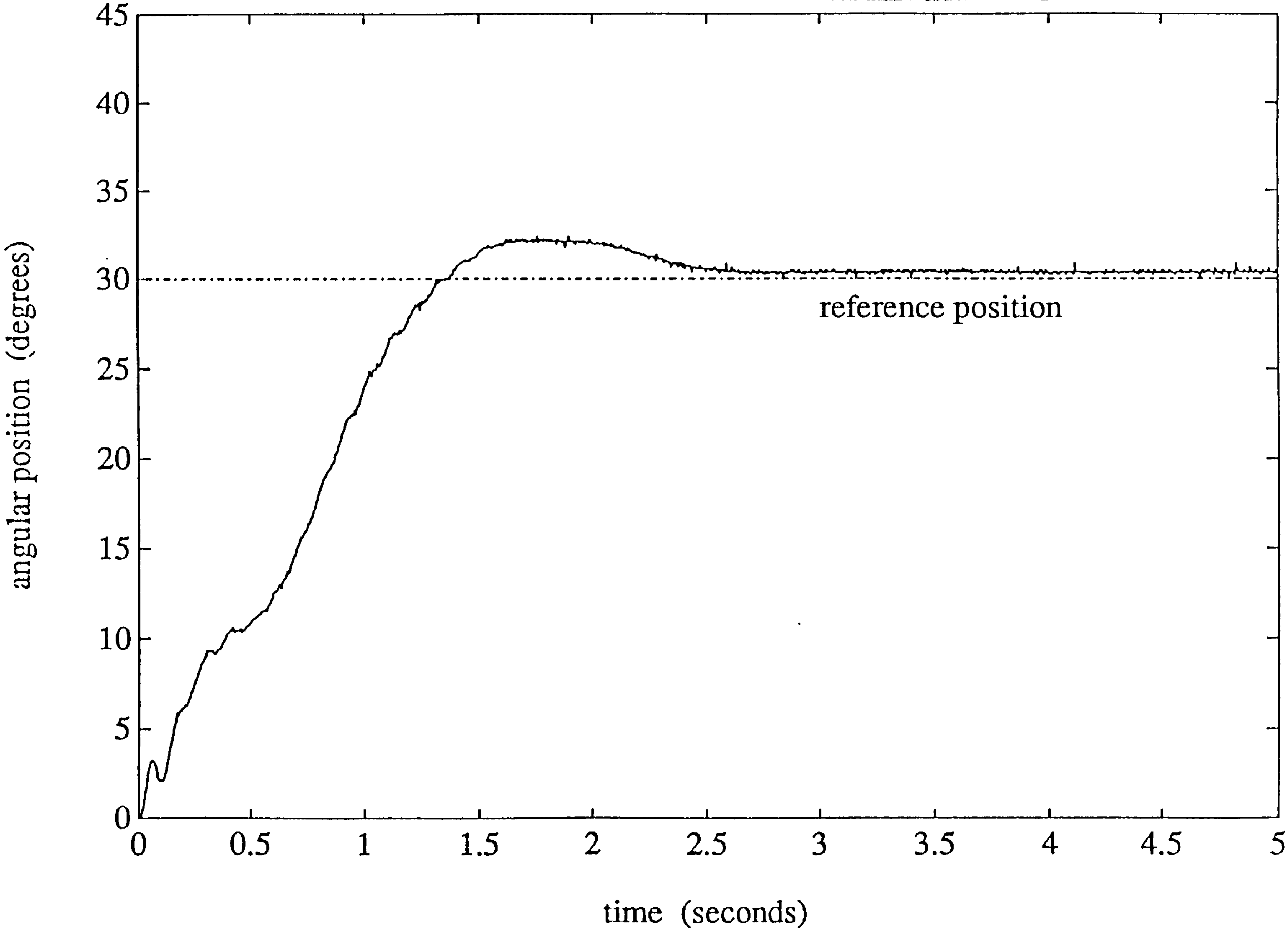


Figure 10 : Hub Position With CSI Compensation



Perturbation Analysis

Ali Gooyabadi
SPIE 1992

well known — Small Perturbation

$$A_c(\epsilon) = A_0 + \epsilon \Delta A$$

Asymptotic Eigenvalue Series:

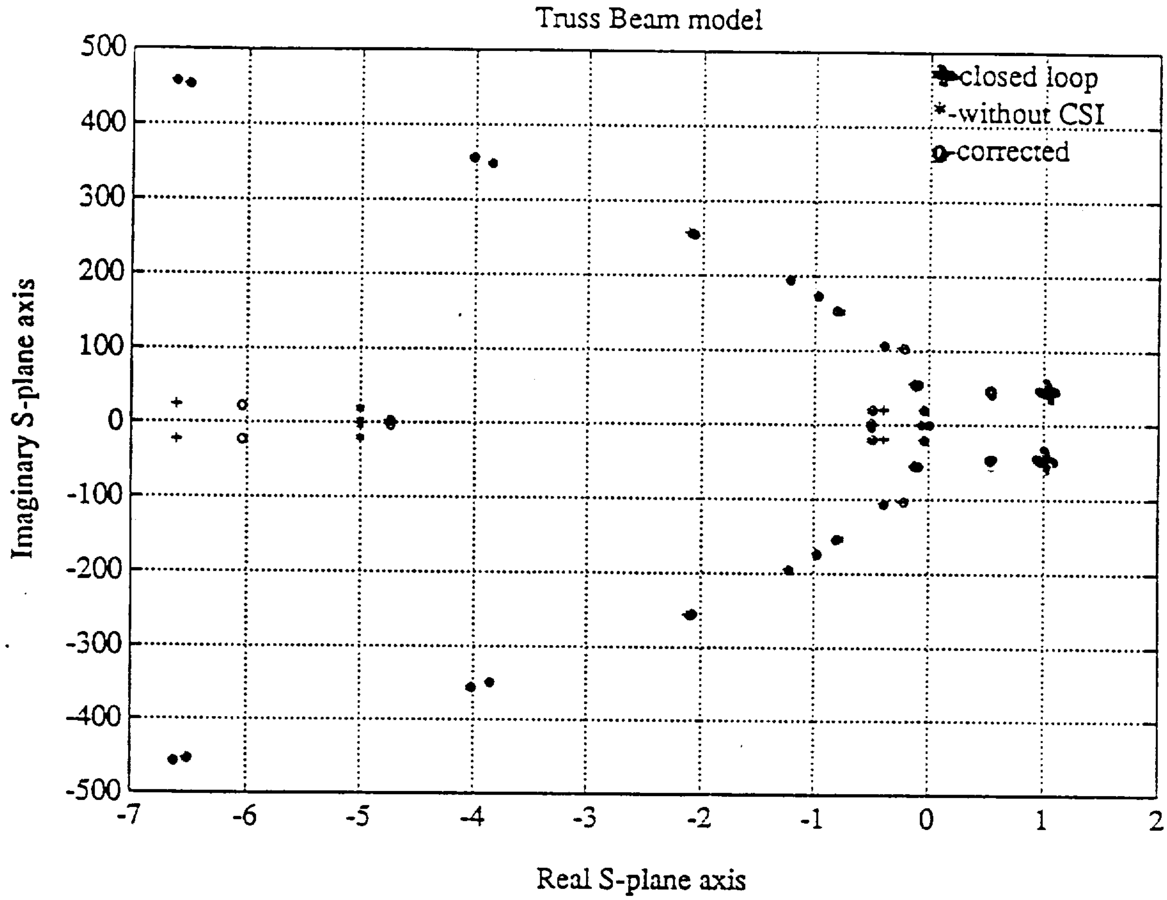
$$\hat{\lambda}_c(\epsilon) = \lambda_0 + \epsilon \lambda_1 + \epsilon^2 \lambda_2 + \cdots$$

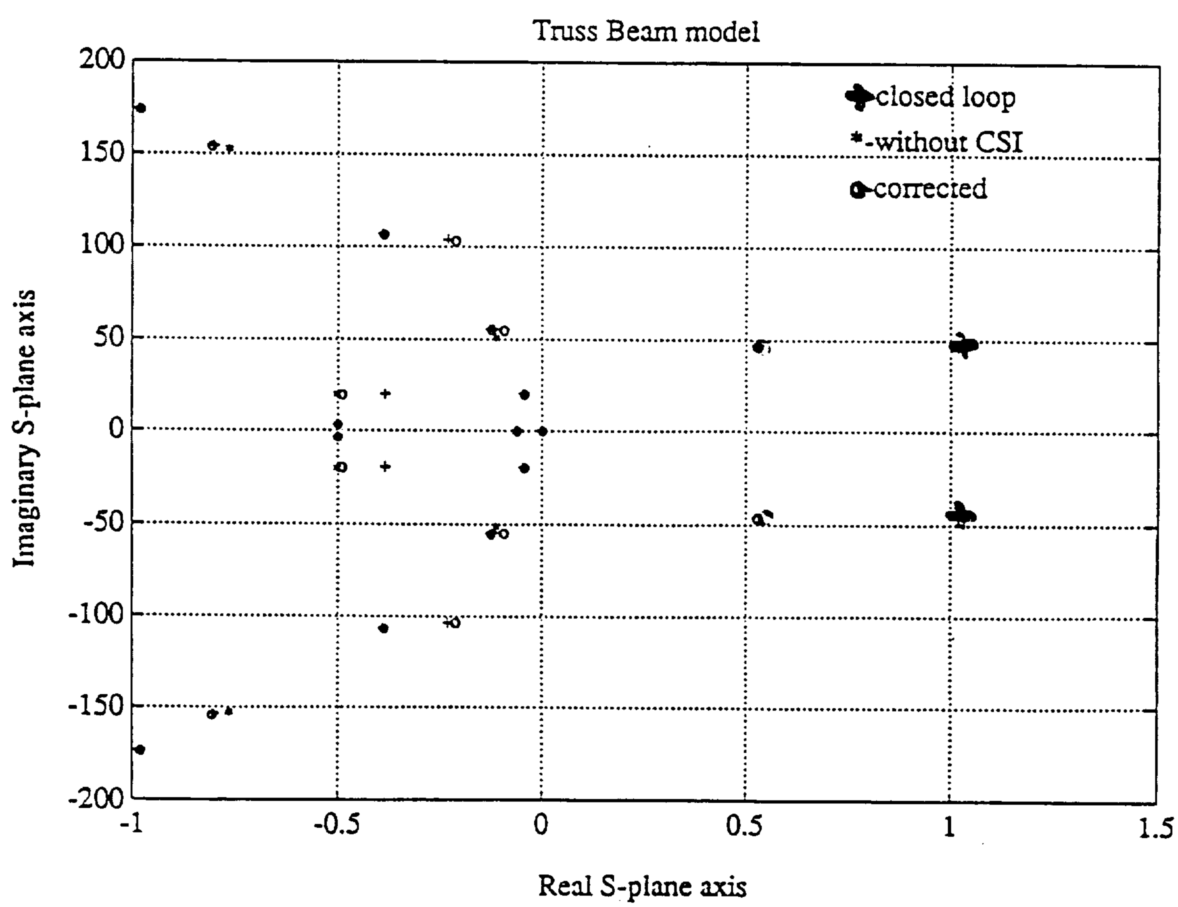
Closed-Loop (LSS + ROM Controller):

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

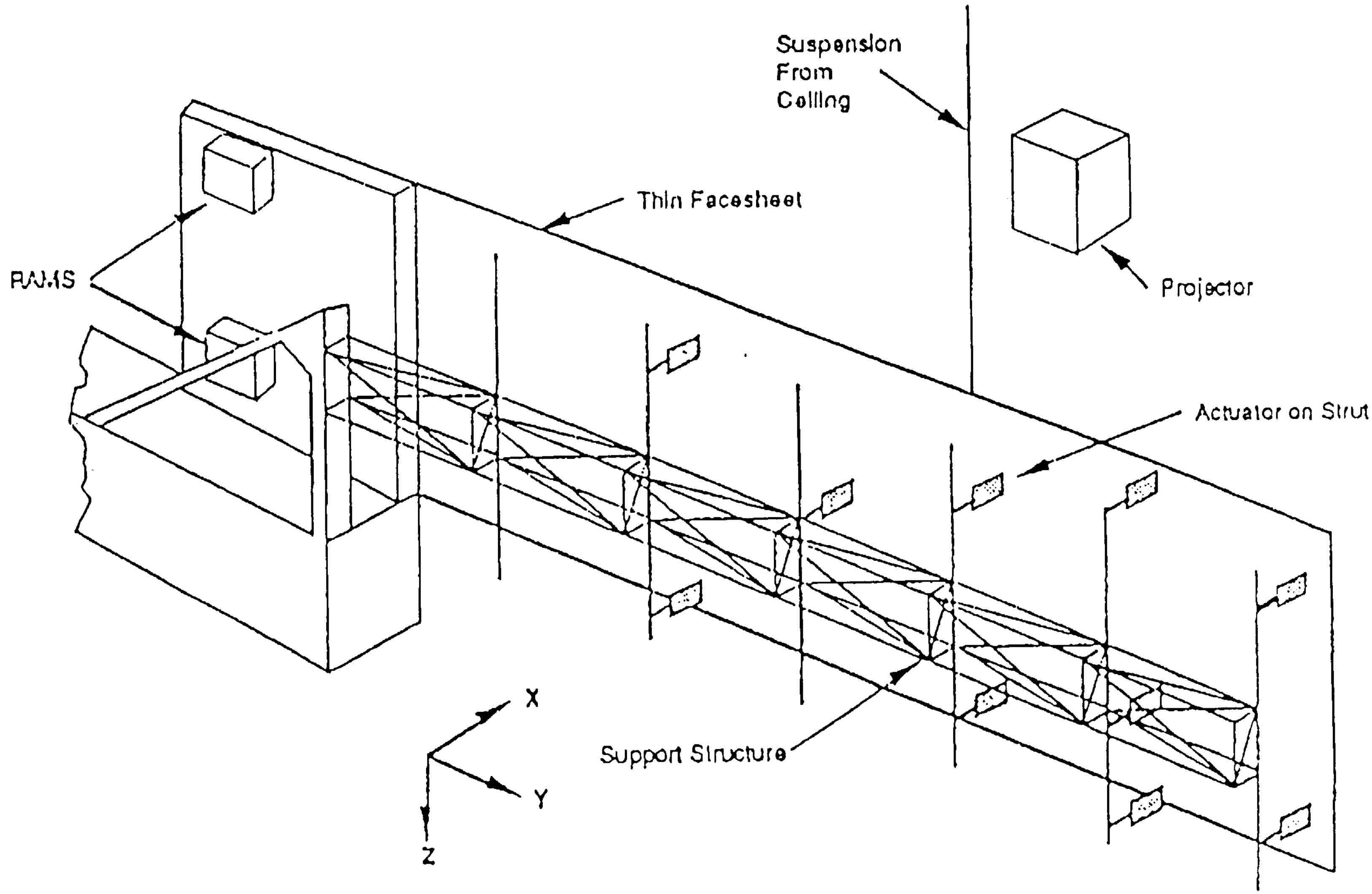
$$\therefore \quad \hat{\lambda}_c(\epsilon) = \lambda_0 + \epsilon^2 \lambda_2$$

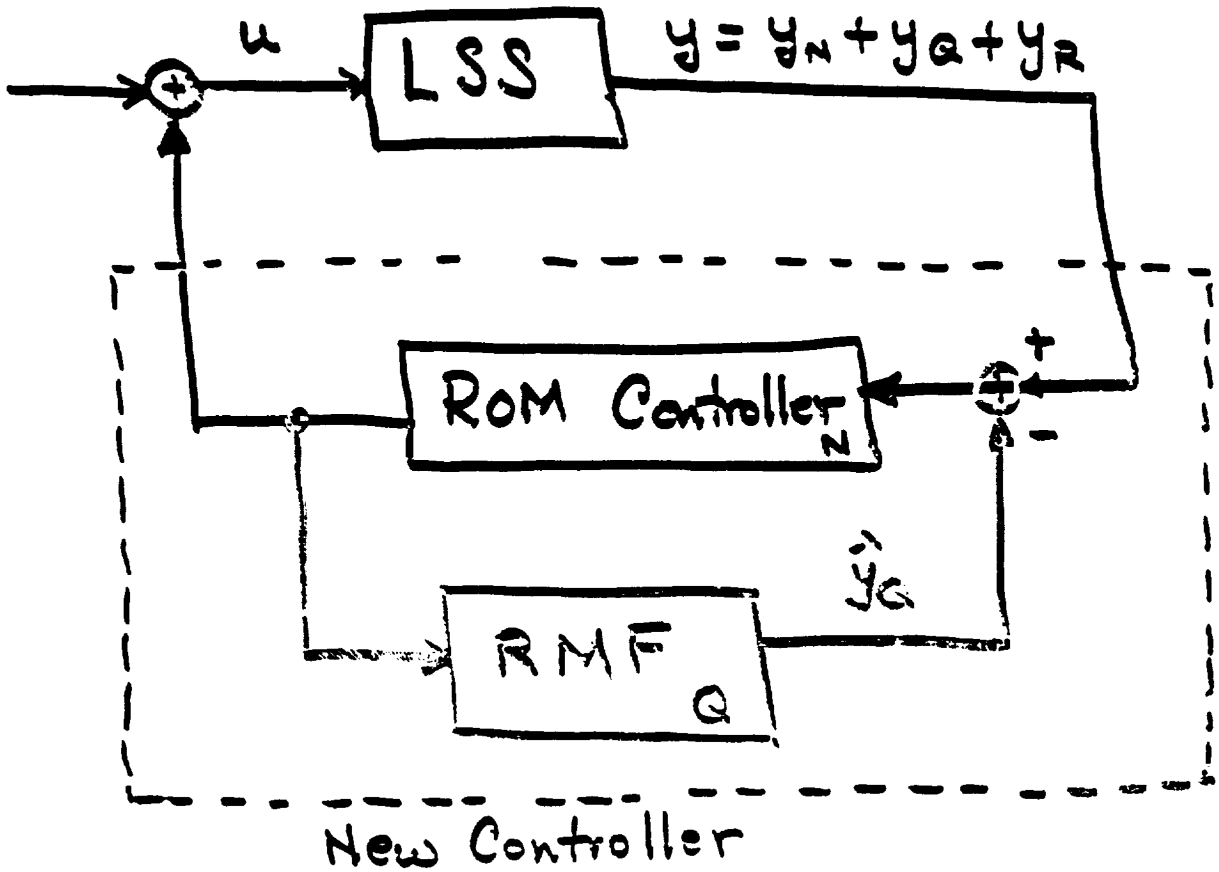
<u>Note:</u> $\lambda_1 = 0$ & $\lambda_3 = 0$


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


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

Testbed Concept Has Thin Facesheet Controlled From Support Truss





Good Stuff:

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

Difficulties:

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

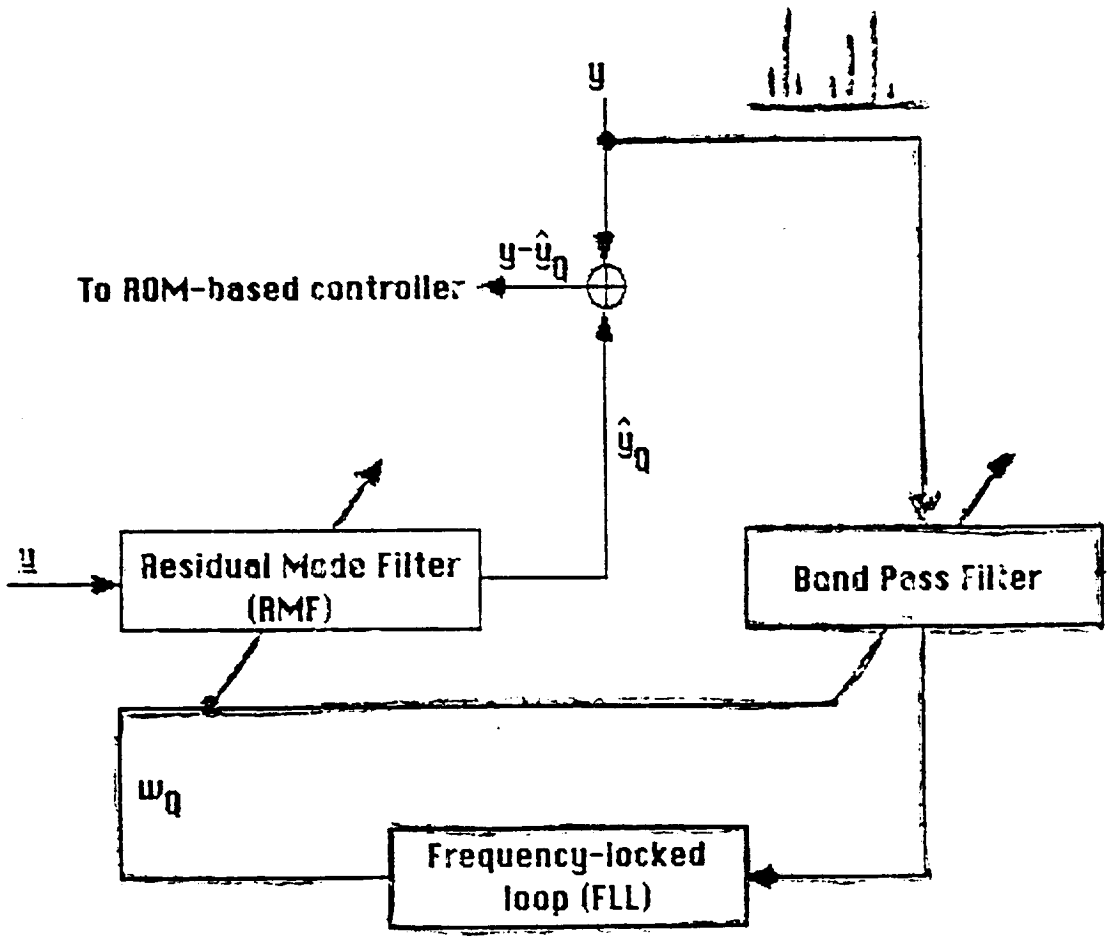


Figure 4. The adaptive, self-tuning RMF.

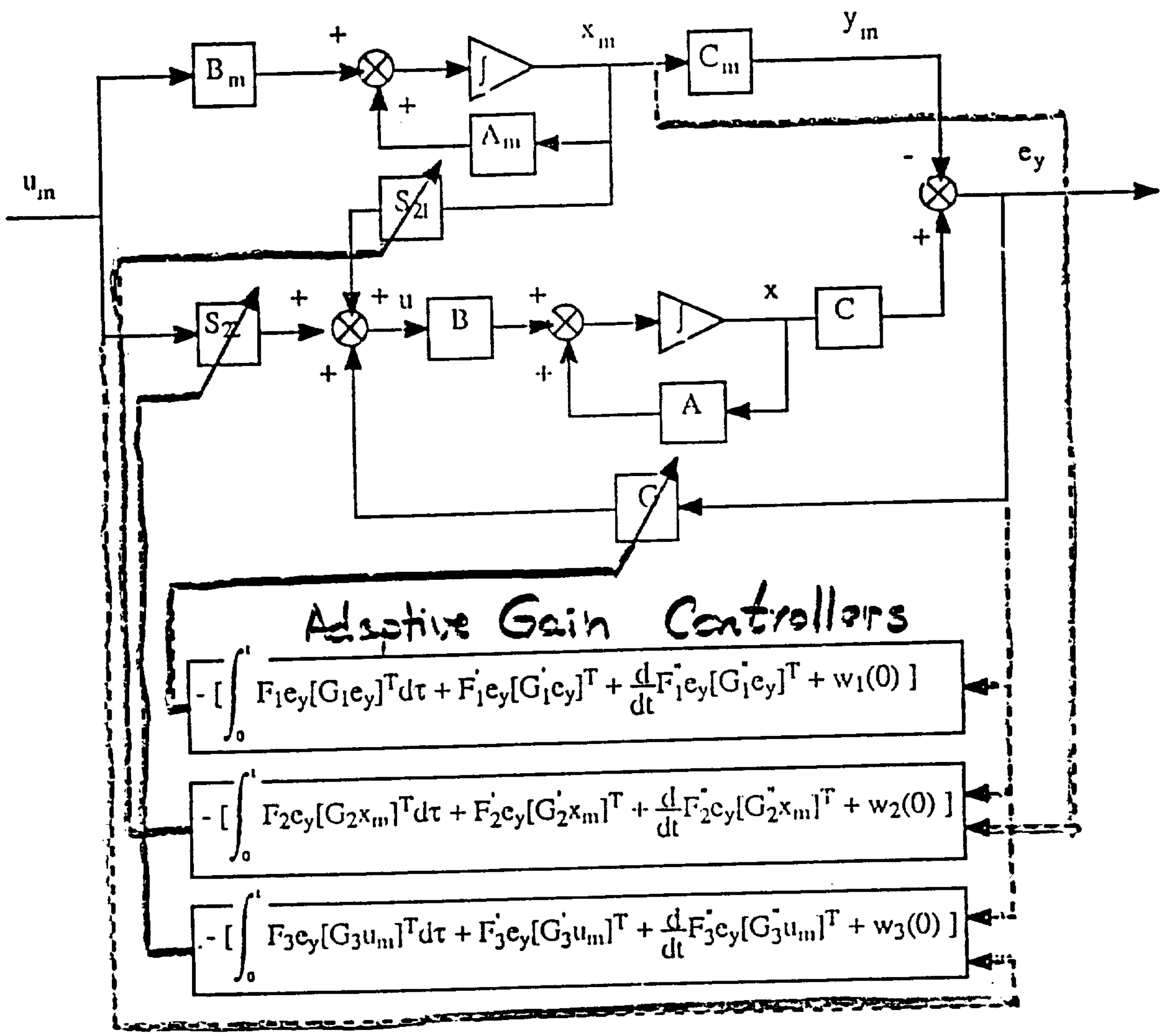
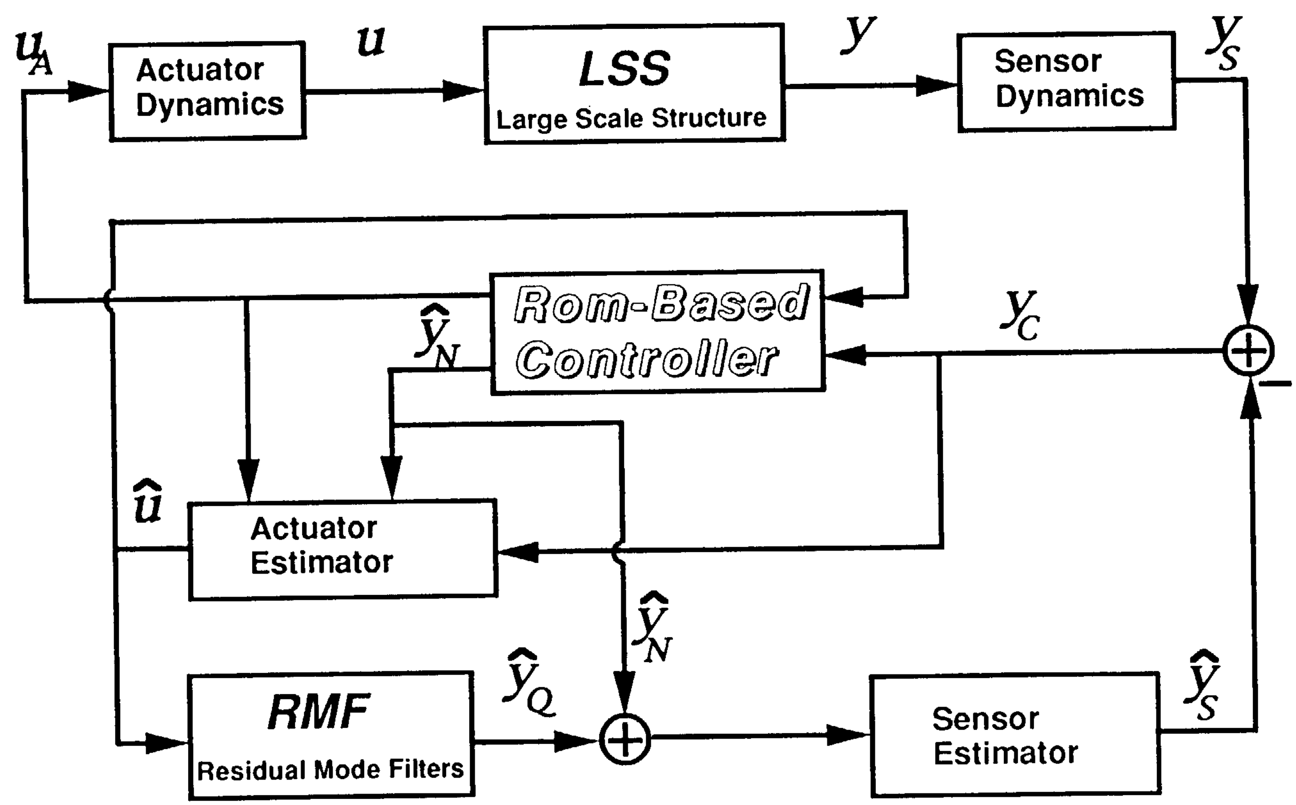
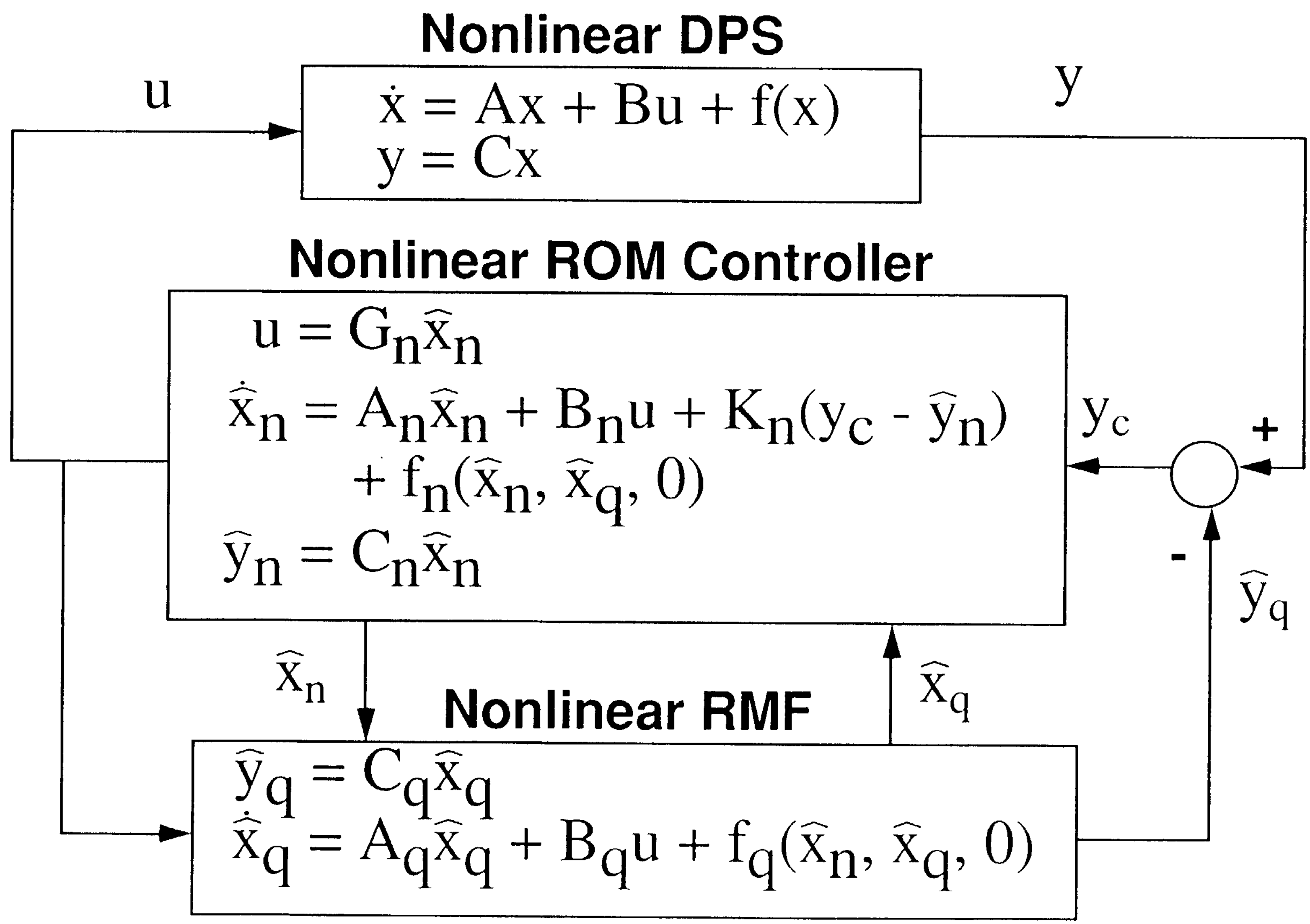


Figure 3-1. The structure of the adaptation mechanism

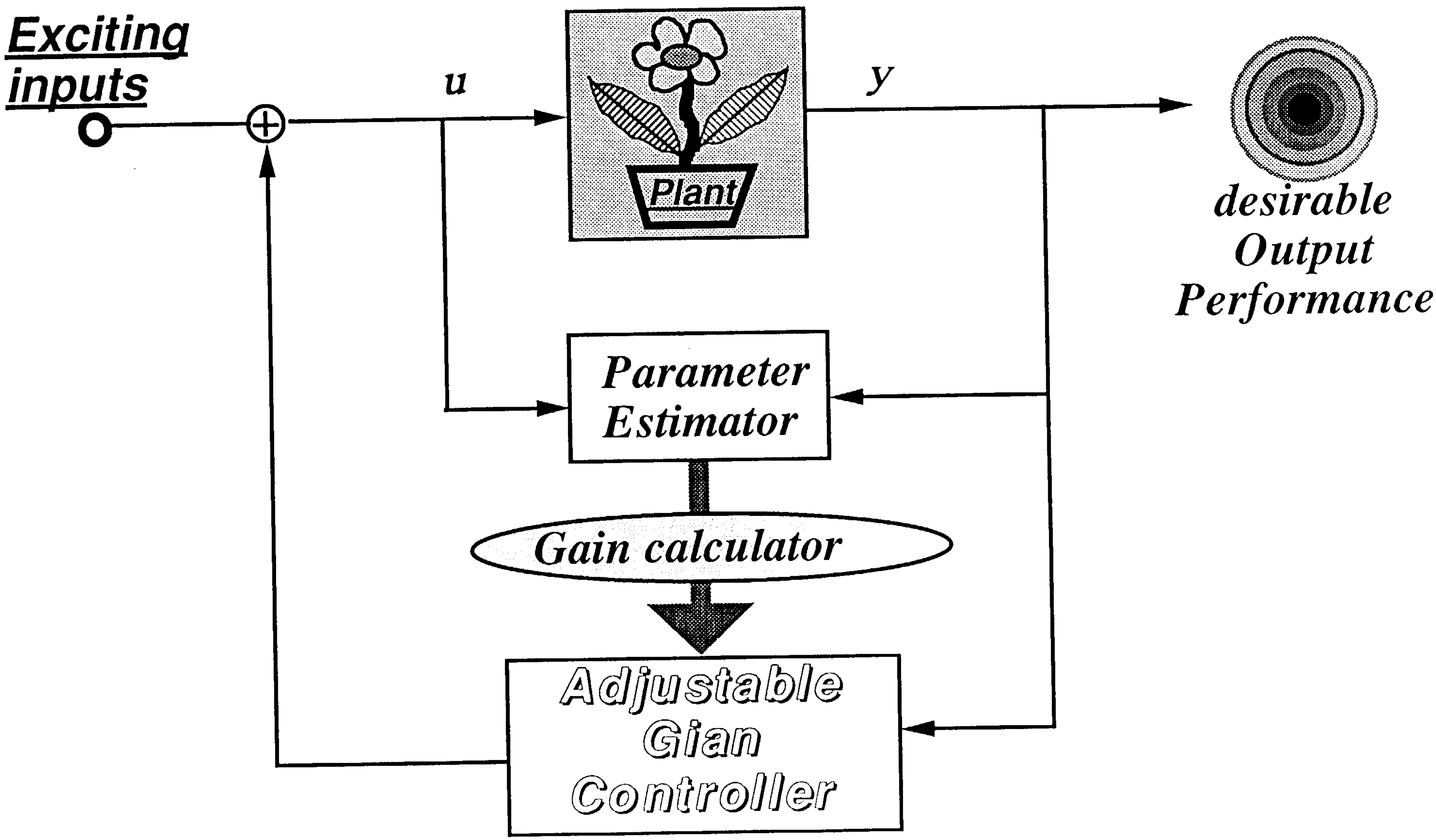
ROM/RMF with actuator/sensor dynamics



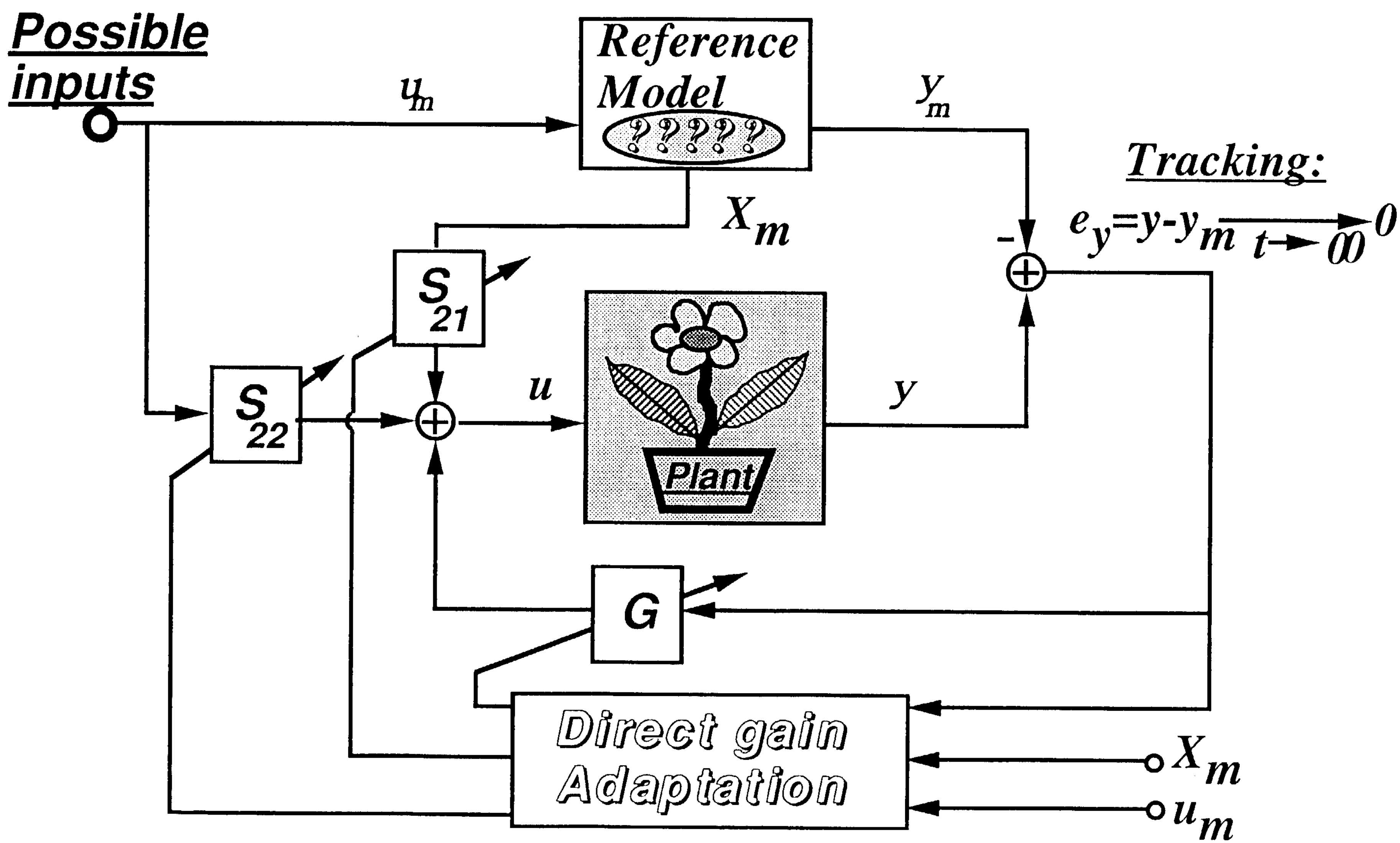
Modifications For Nonlinear ROM/RMF Control JMAA 1991

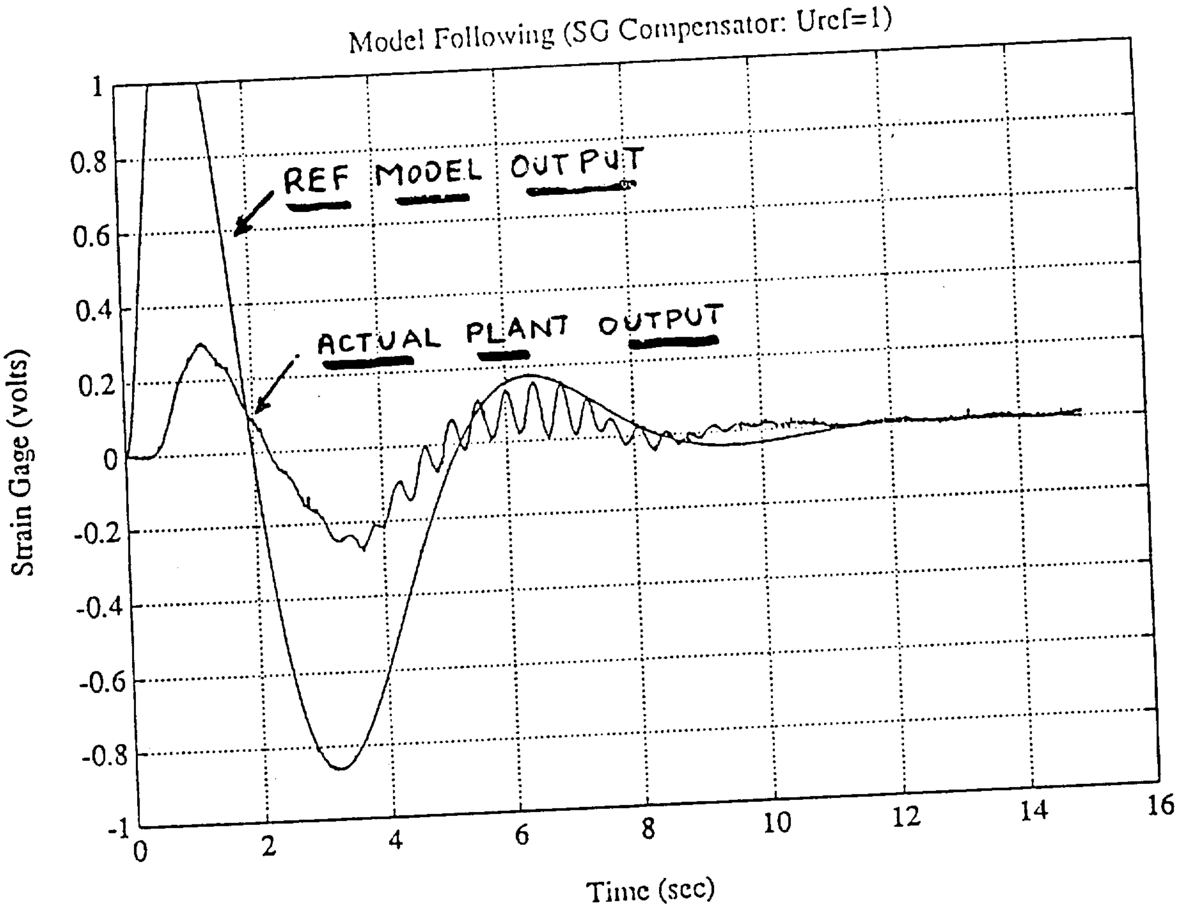


Indirect Adaptive Control



Direct Adaptive Control





Flexible Manipulator Experiments (SC Liang)

Hub Control - Strain Gauge Sensor
(Not Collocated)

Decentralized Controller Design

→ **Performance** ←

Controller 1

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

y_1 (↑) u_1 (↓)

Controller 2

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

y_2 (↑) u_2 (↓)

Large Space Structure (LSS)

ROM :

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

RMF Compensation for Stable Control