cSc

Controls for Orbital Assembly of Large Space Structures

Mark Balas

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

Third Annual Symposium
November 21 & 22, 1991

Flexible Structure Control

PROF. MARK J. BALAS

Roger Davidson — PhD Completed 1990

Ali A. Gooyabadi

Ralph Quan — PhD Completed 1991

Brian Reisenauer

L. "Robbie" Robertson

Jim Mohl (Ball Aerospace)

Philip Good (Martin Marietta)

Loren Vredevoogd

Jose Galvez — PhD Completed 1991

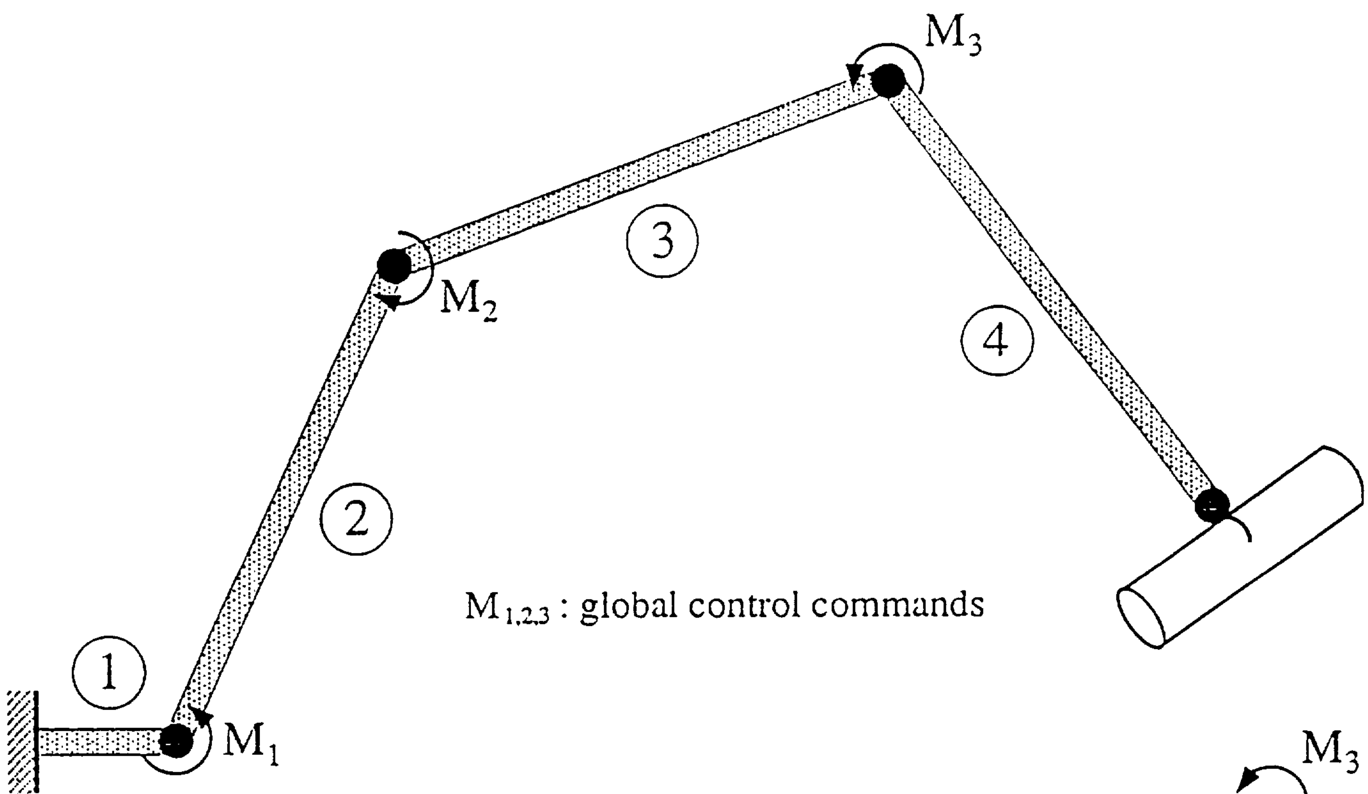
Shin-Ching Liang — PhD Completed 1991

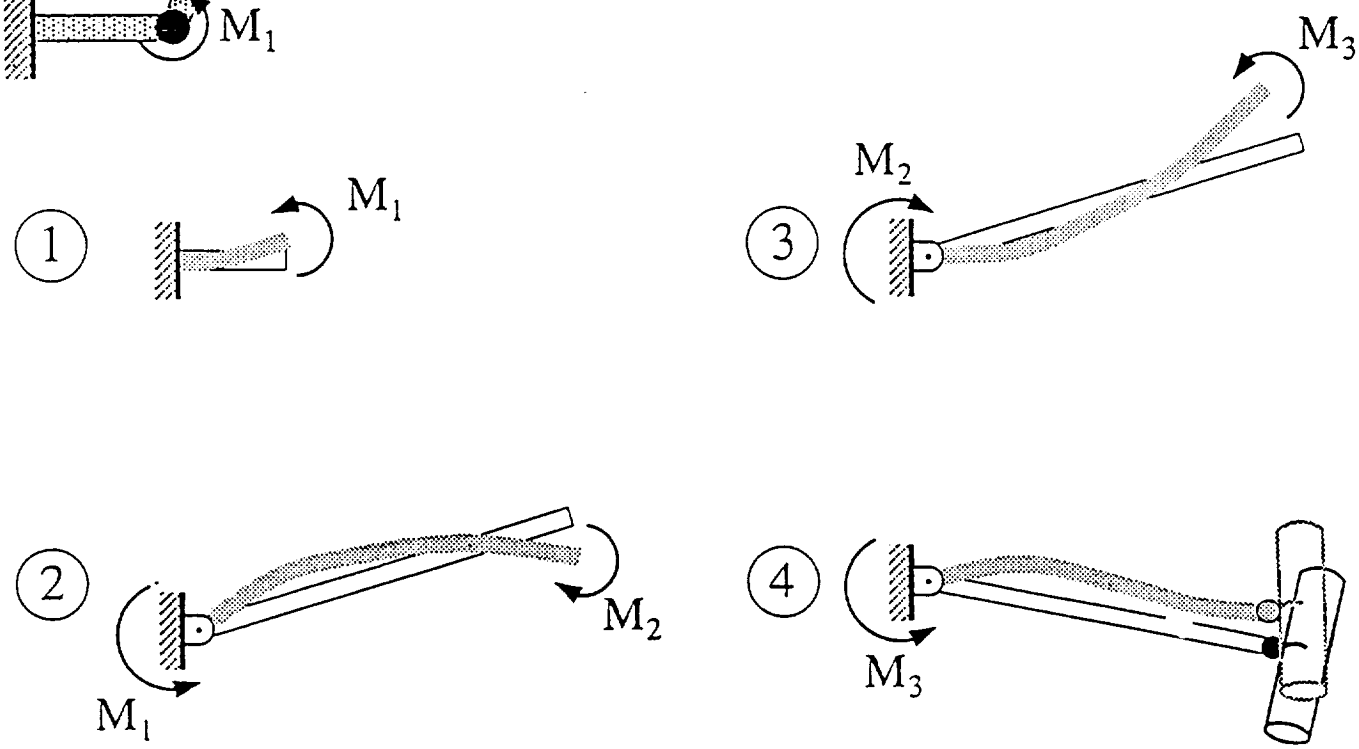
NASA Center for Space Construction
Univ. of Colorado, Boulder

Industrial affiliates

De-centralized Control for Flexible Multi-body Systems

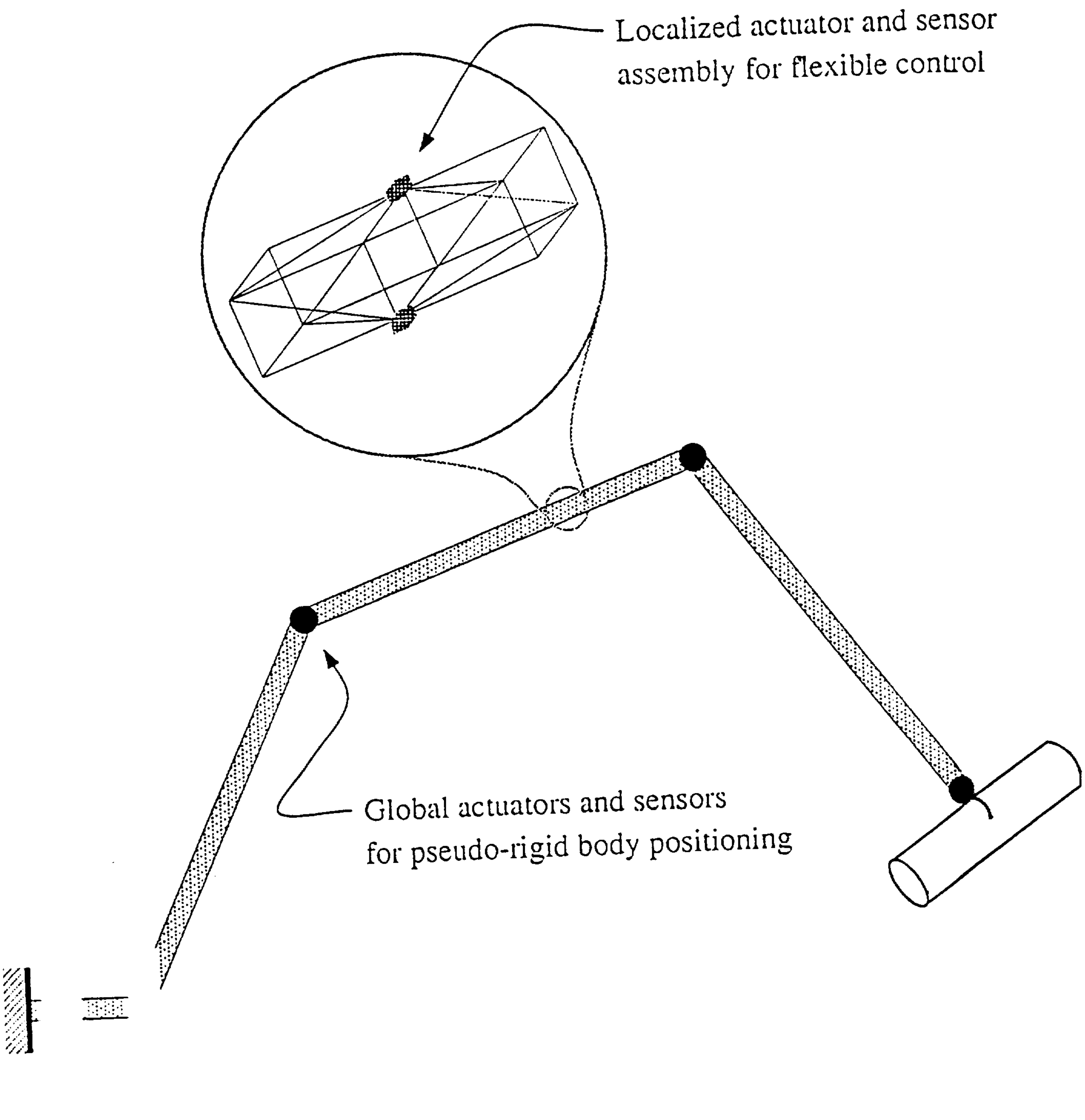
Flexible Sub-system Division



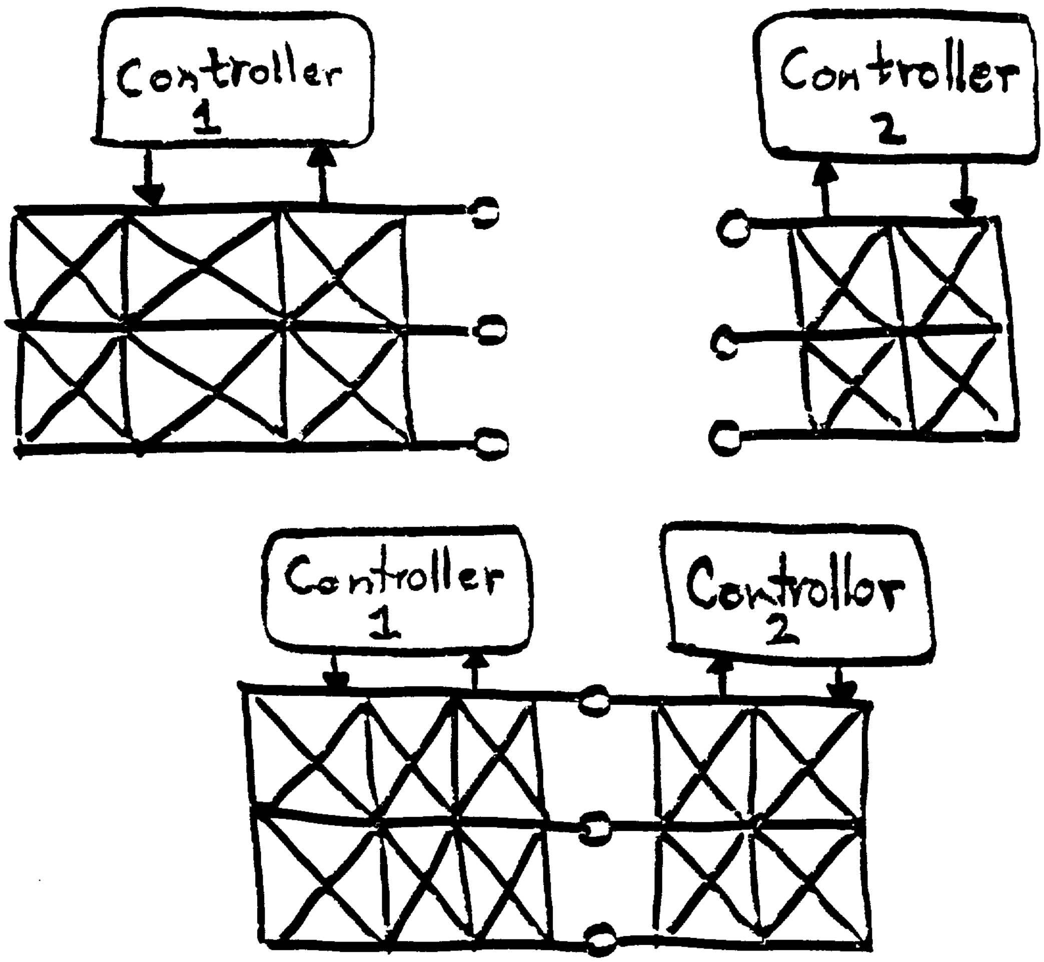


De-centralized Control for Flexible Multi-body Systems

Local and Global Control



L. (Robbie) Robertson

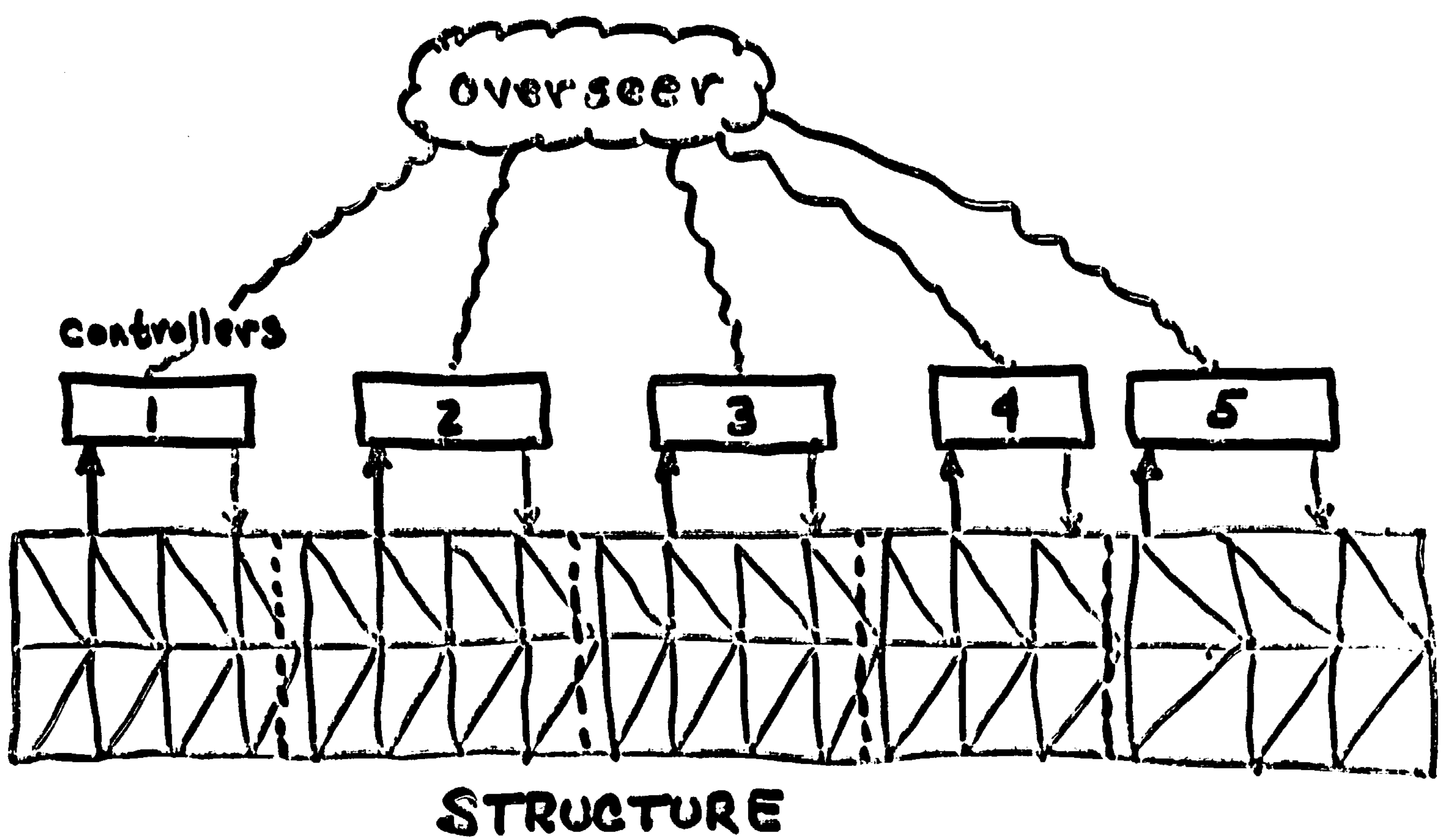


Control of Structures During Assembly

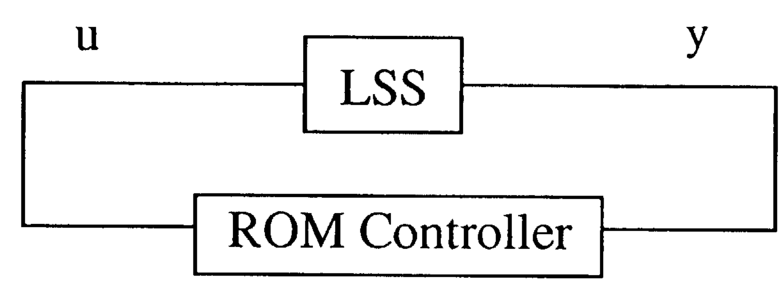
Normal (Planned) Assembly
Emergencies ($F^3 U$)

Docking & Berthing / Contact

Decentralized Control Using Structural Partitioning



Reduced-Order Model-Based Controller Design



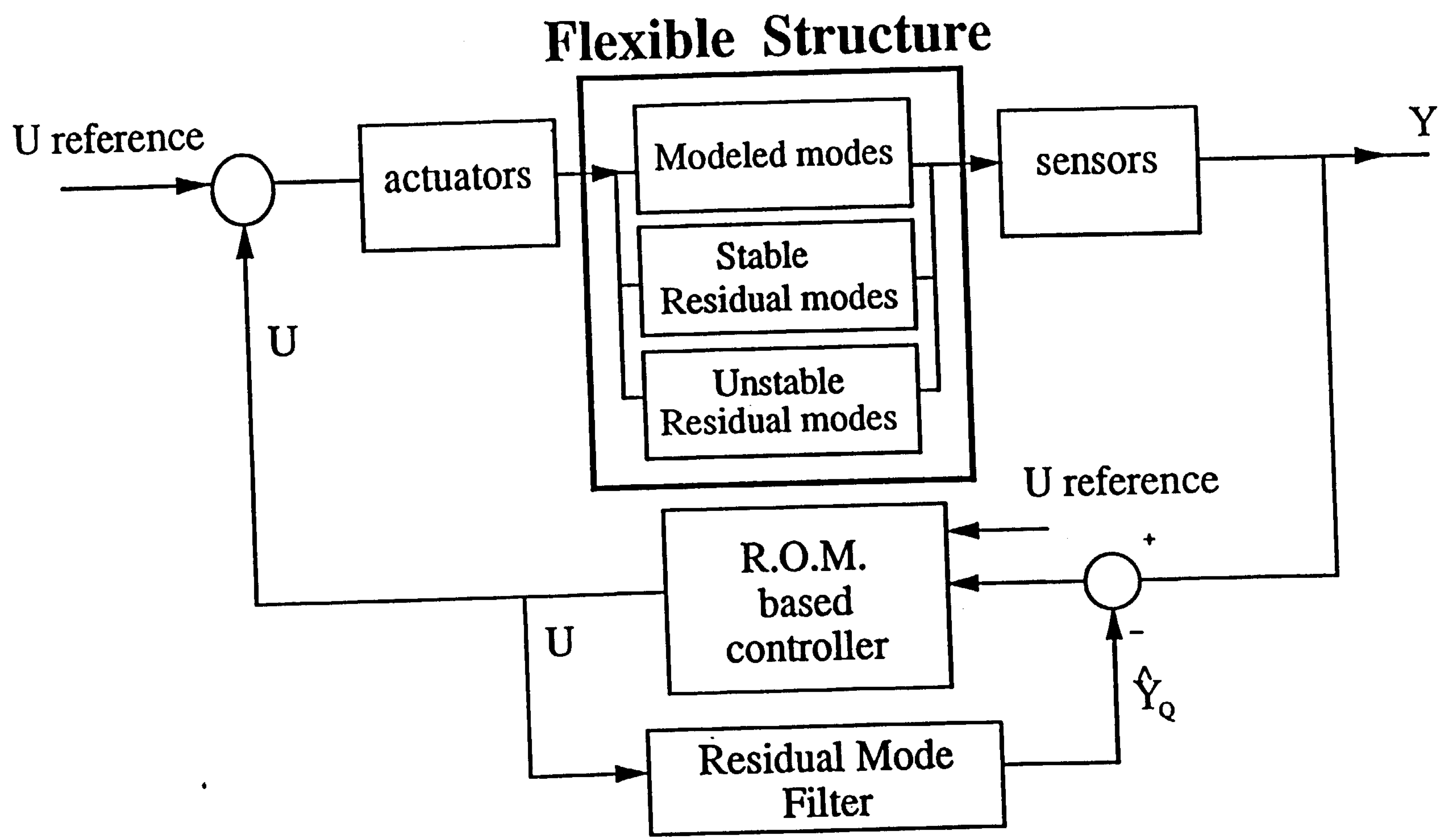
Closed Loop: $L_n = A_n + B_nG_n - K_nC_n$

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

OR

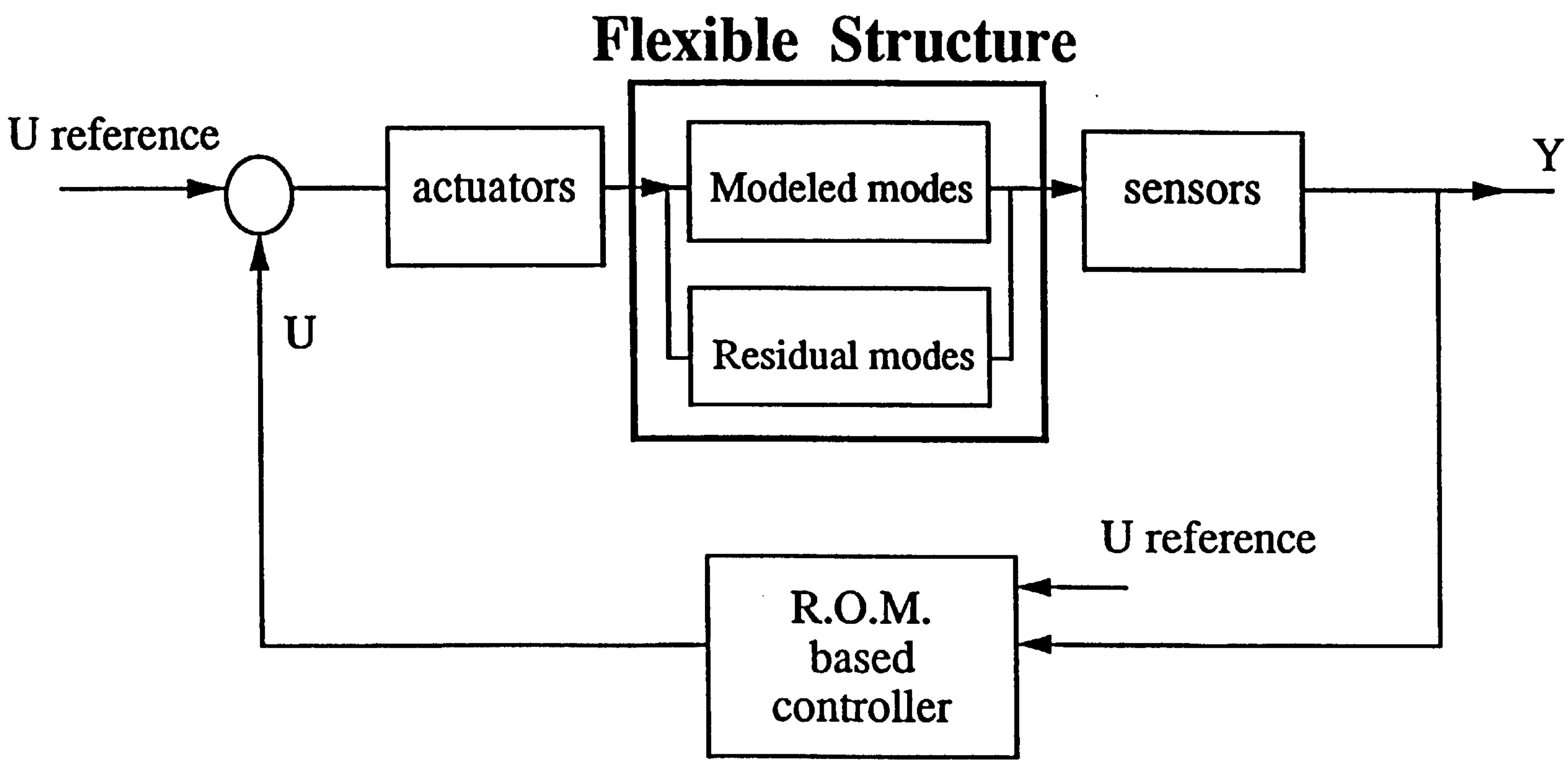
$$\begin{bmatrix} \dot{x}_n \\ \dot{e}_n \\ \dot{x}_r \end{bmatrix} = \begin{bmatrix} A_n + B_nG_n & B_nG_n & 0 \\ 0 & A_n + K_nC_n & K_nC_r \\ B_rG_n & B_rG_n & A_r \end{bmatrix} \begin{bmatrix} x_n \\ e_n \\ x_r \end{bmatrix}$$

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



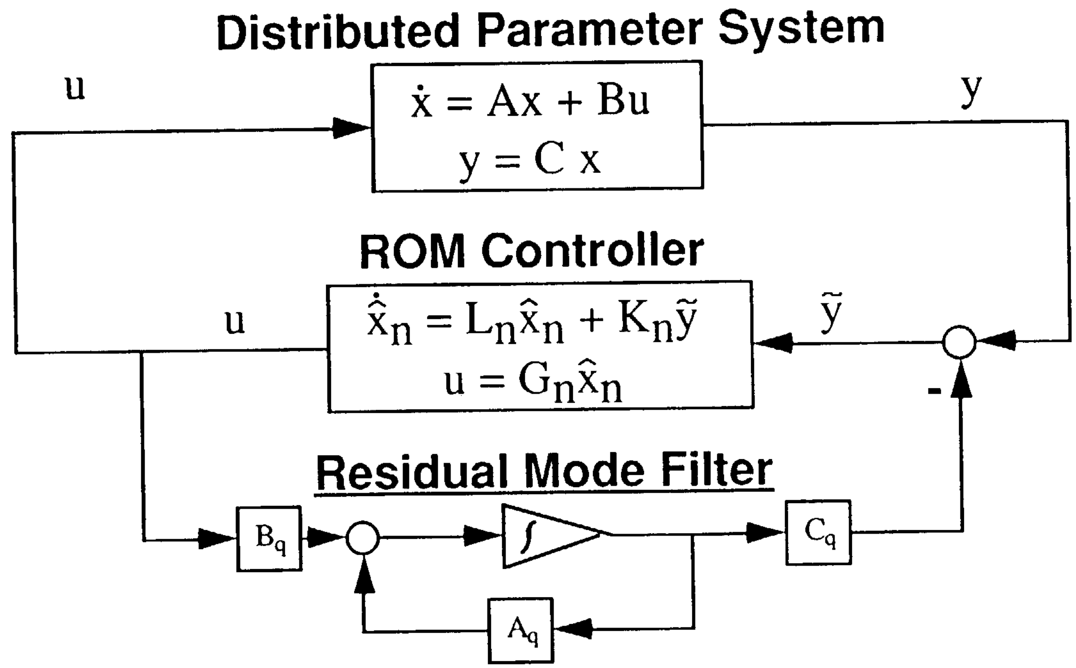
- **Develop a R.O.M. controller, designed for performance.**
- **Dimension of the controller << dimension of the structure.**

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



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

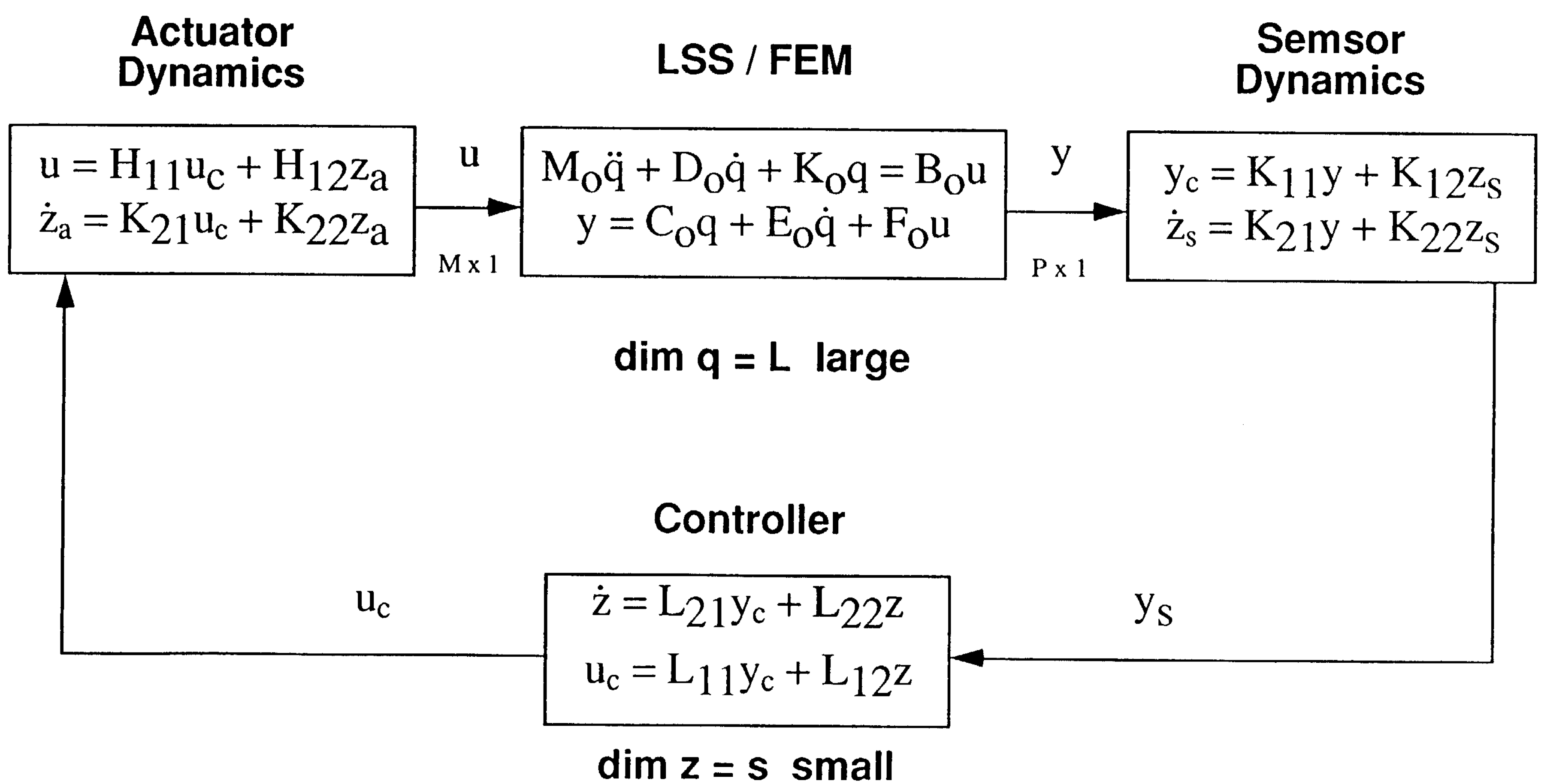
$\longleftarrow$ open-loop unstable modes
$\longleftarrow$ closed-loop unstable modes
$\longleftarrow$ unaffected residual modes (unmodelled dynamics)

DPS + Rom Controller $\longrightarrow$ unstable (q modes)

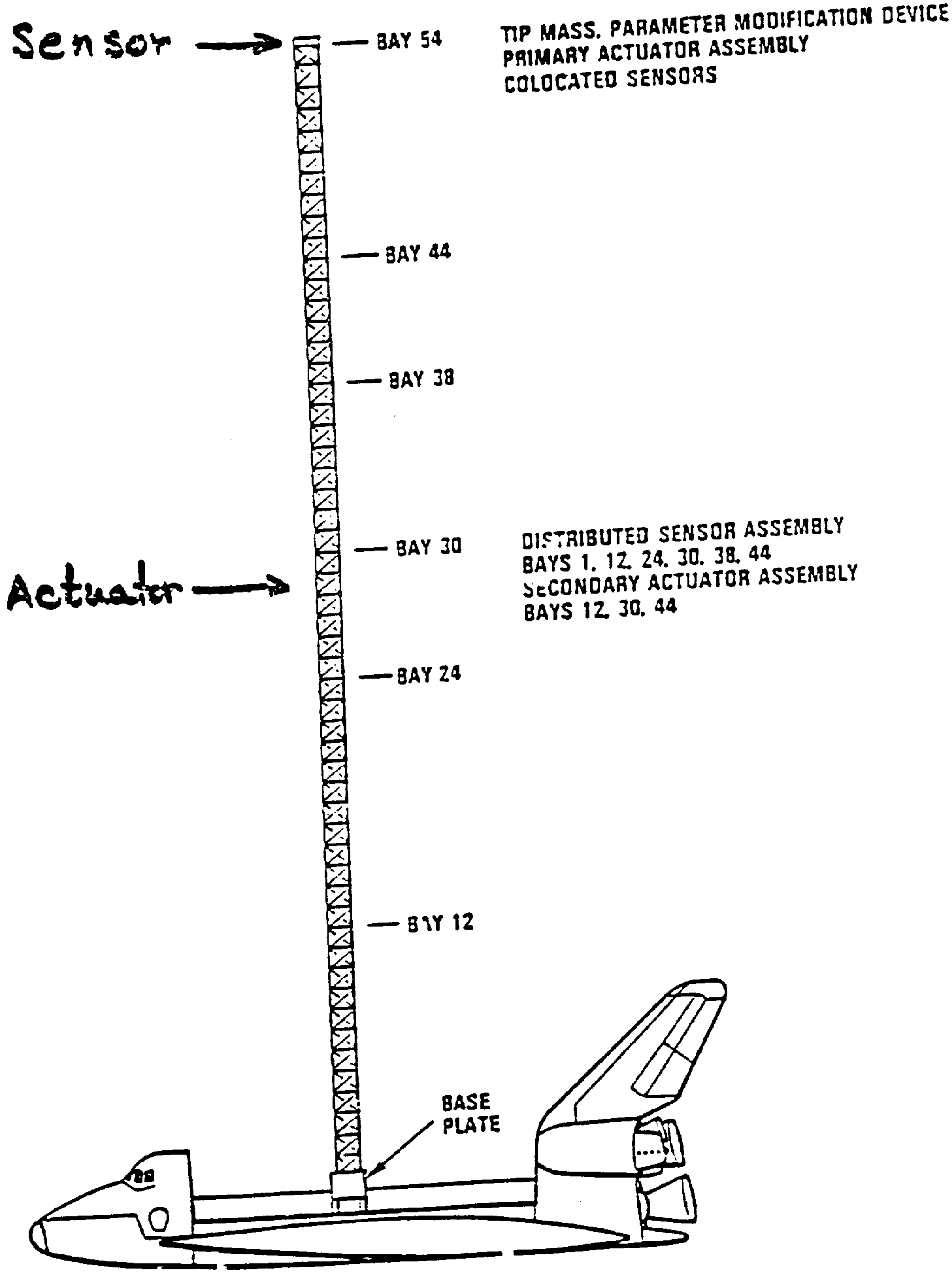
DPS + ROM Controller + RMF $\longrightarrow$ exponentially stable

LSS Active Control Simulation

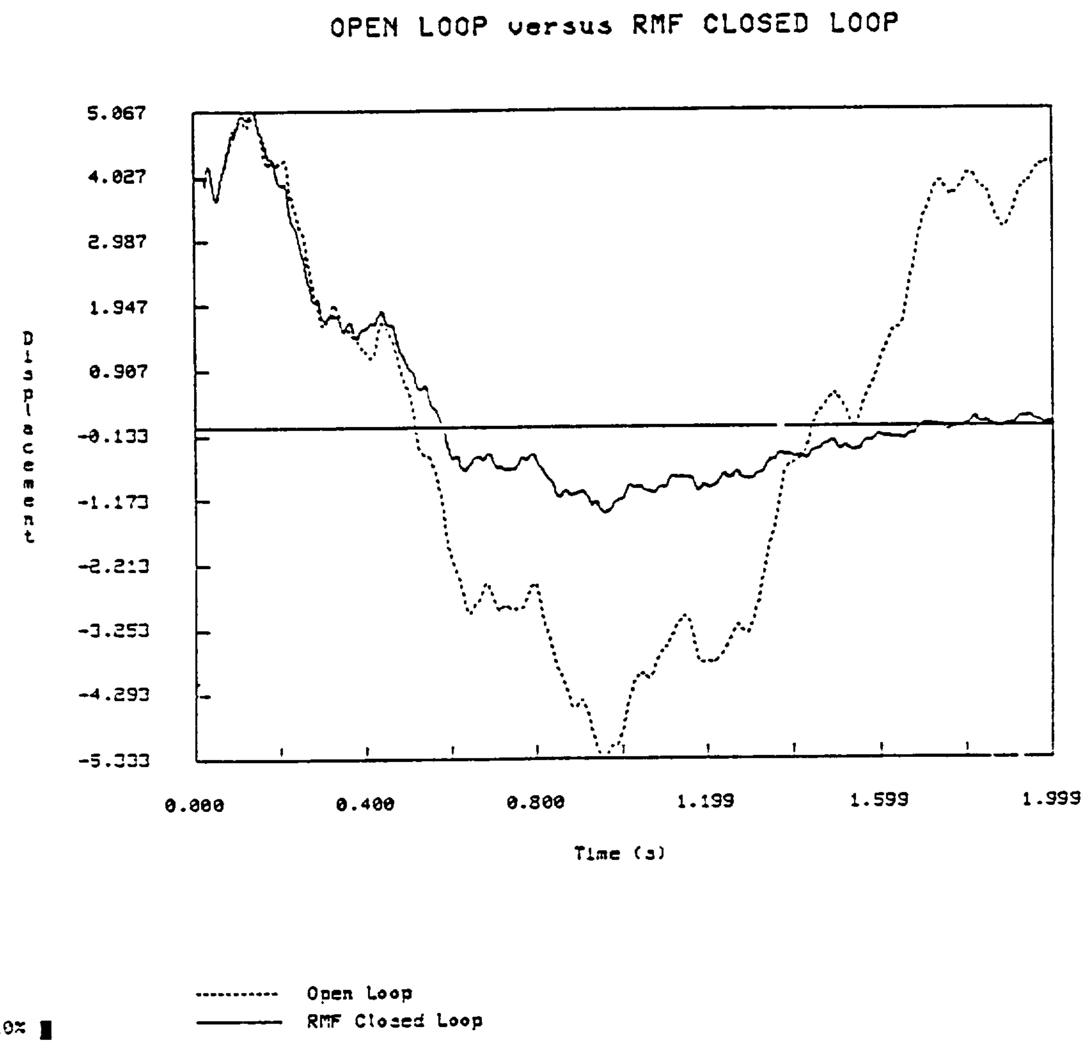
(Ralph Quan)



3-Dimensional Truss Beam



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



jupiter20%

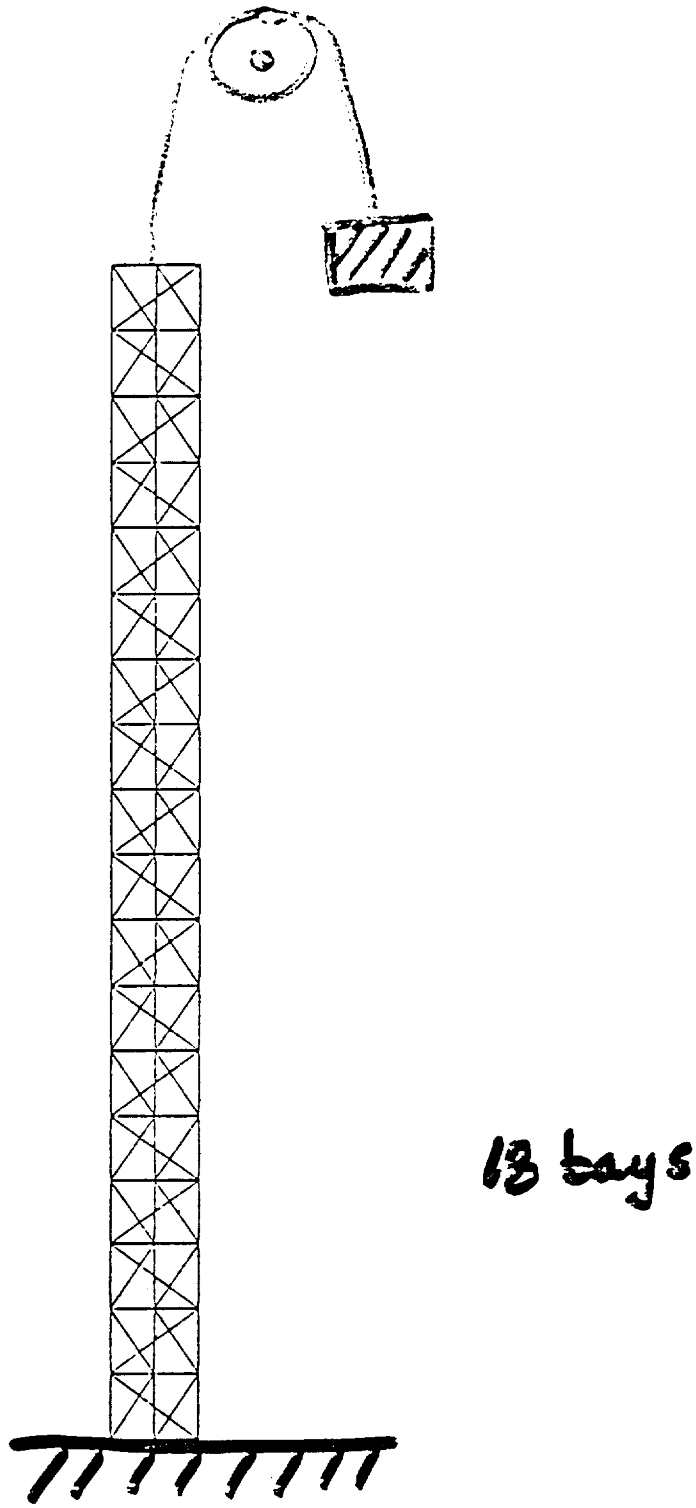


Figure 8.7 The Mini-Mast Truss

Langley

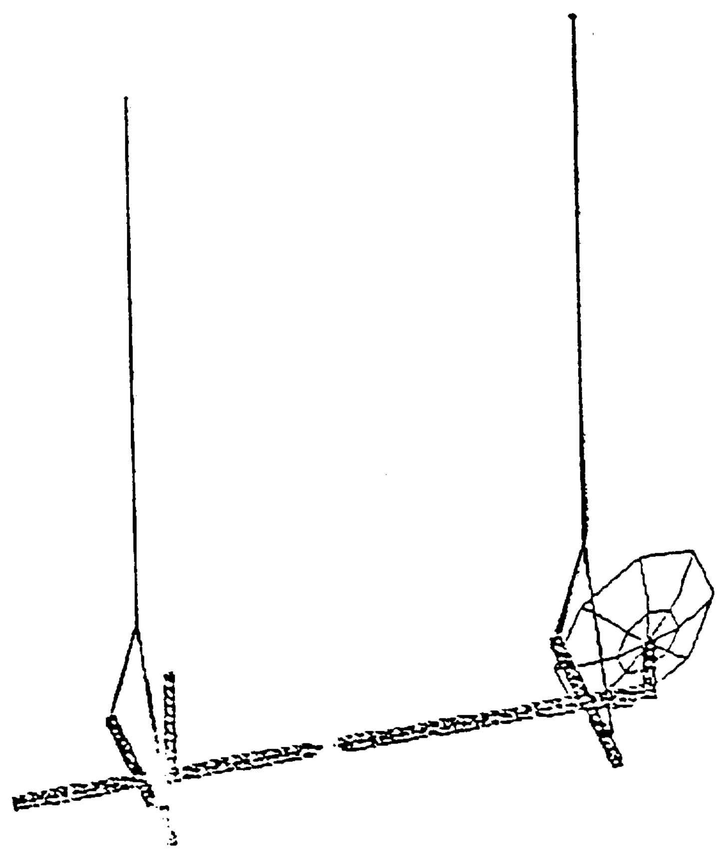
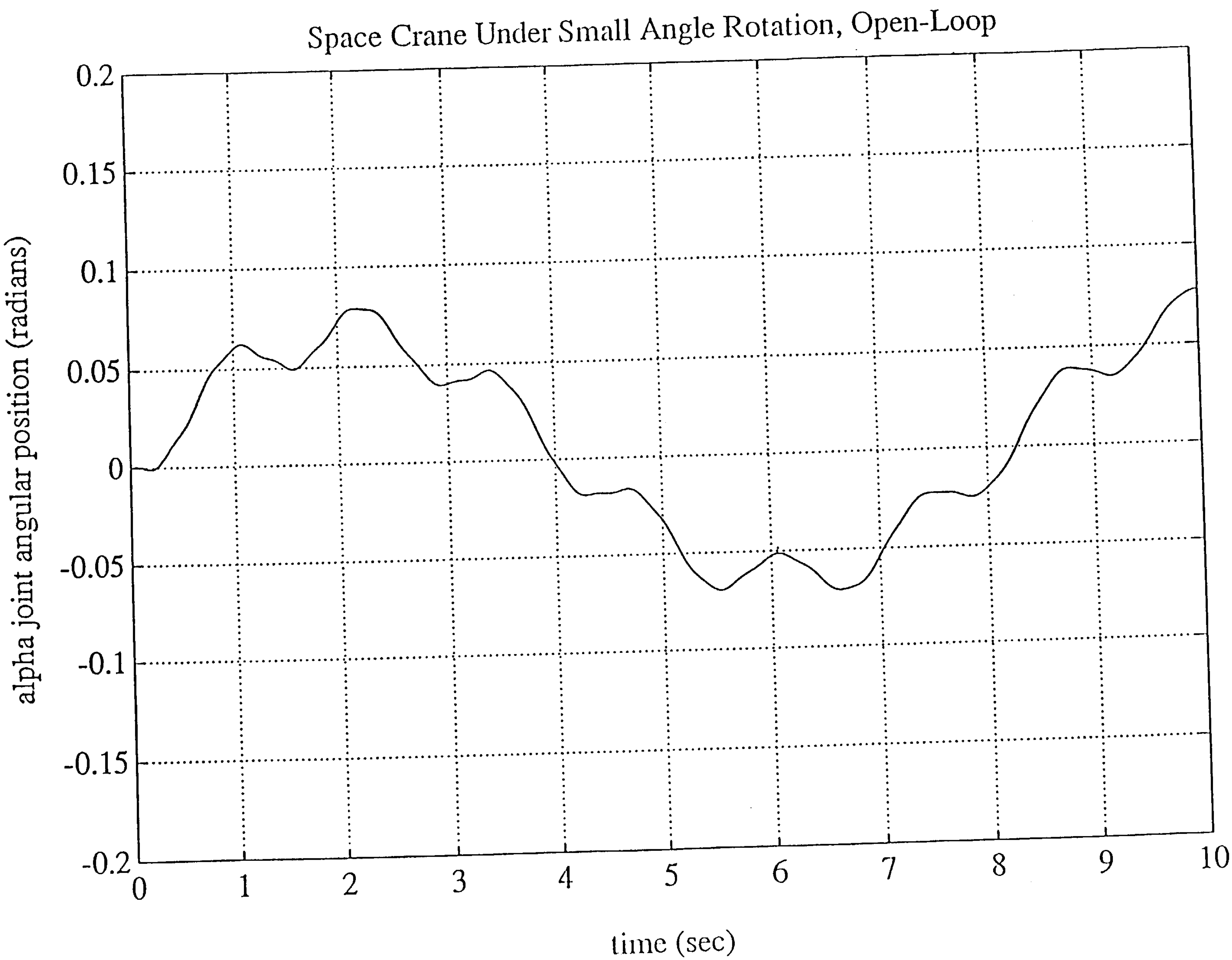
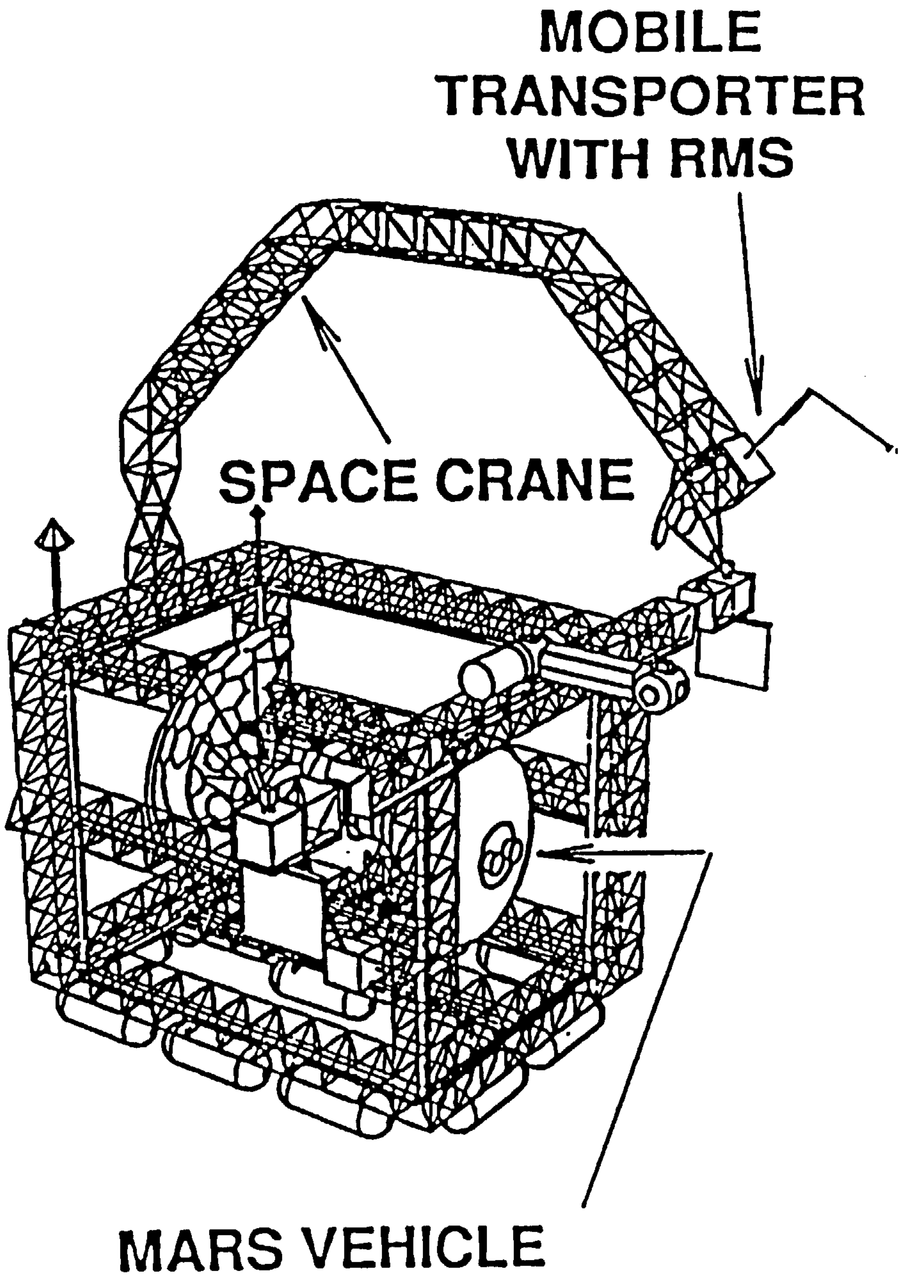
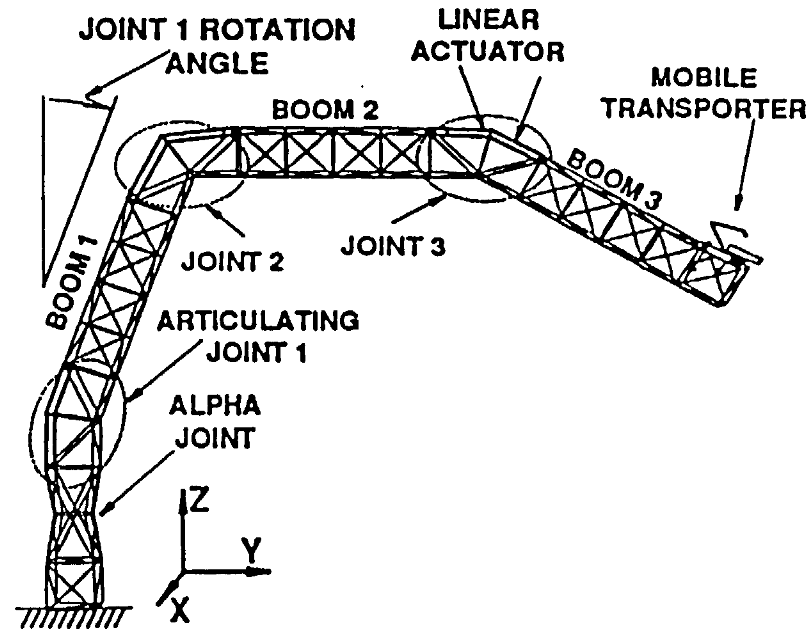
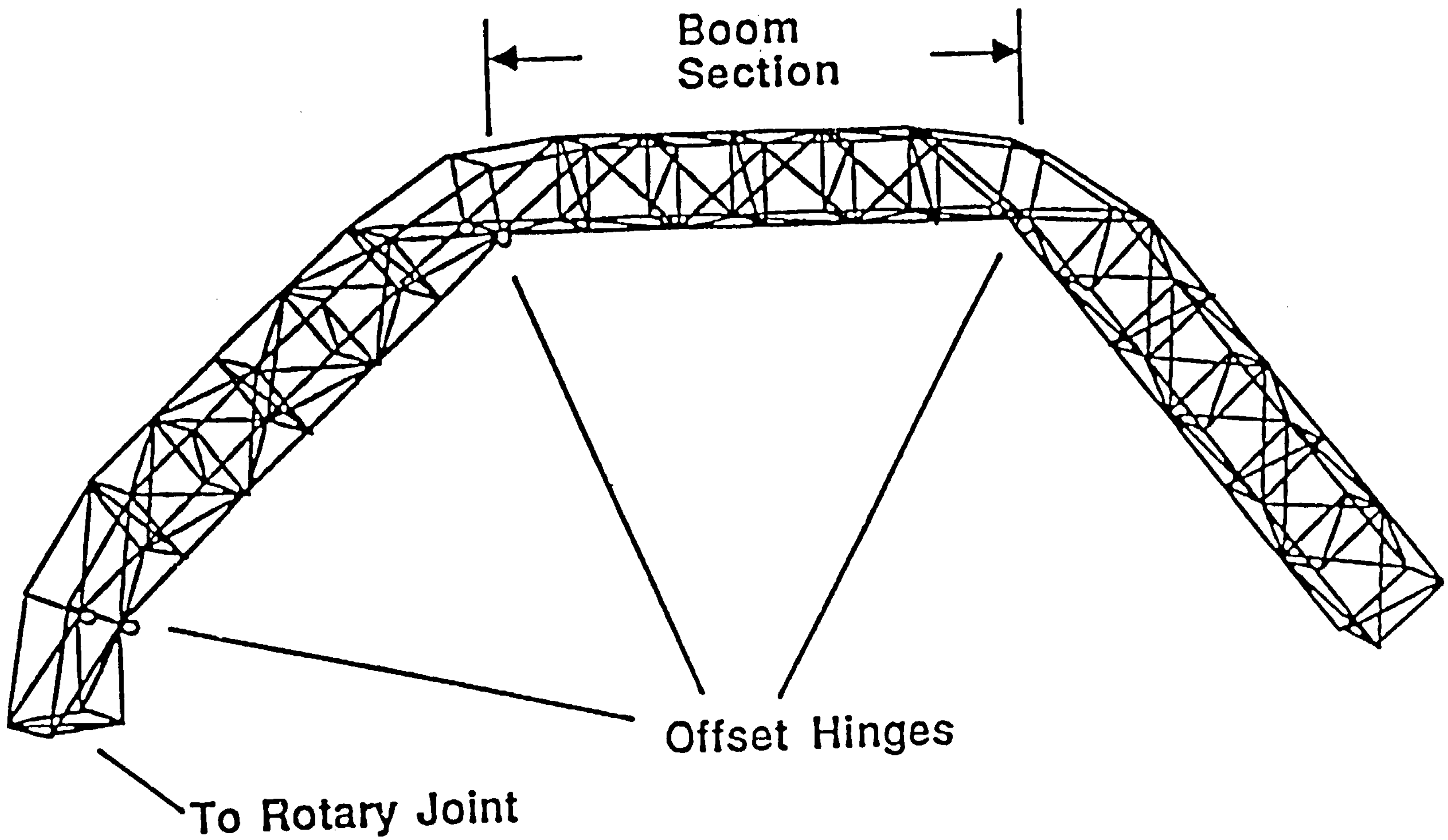


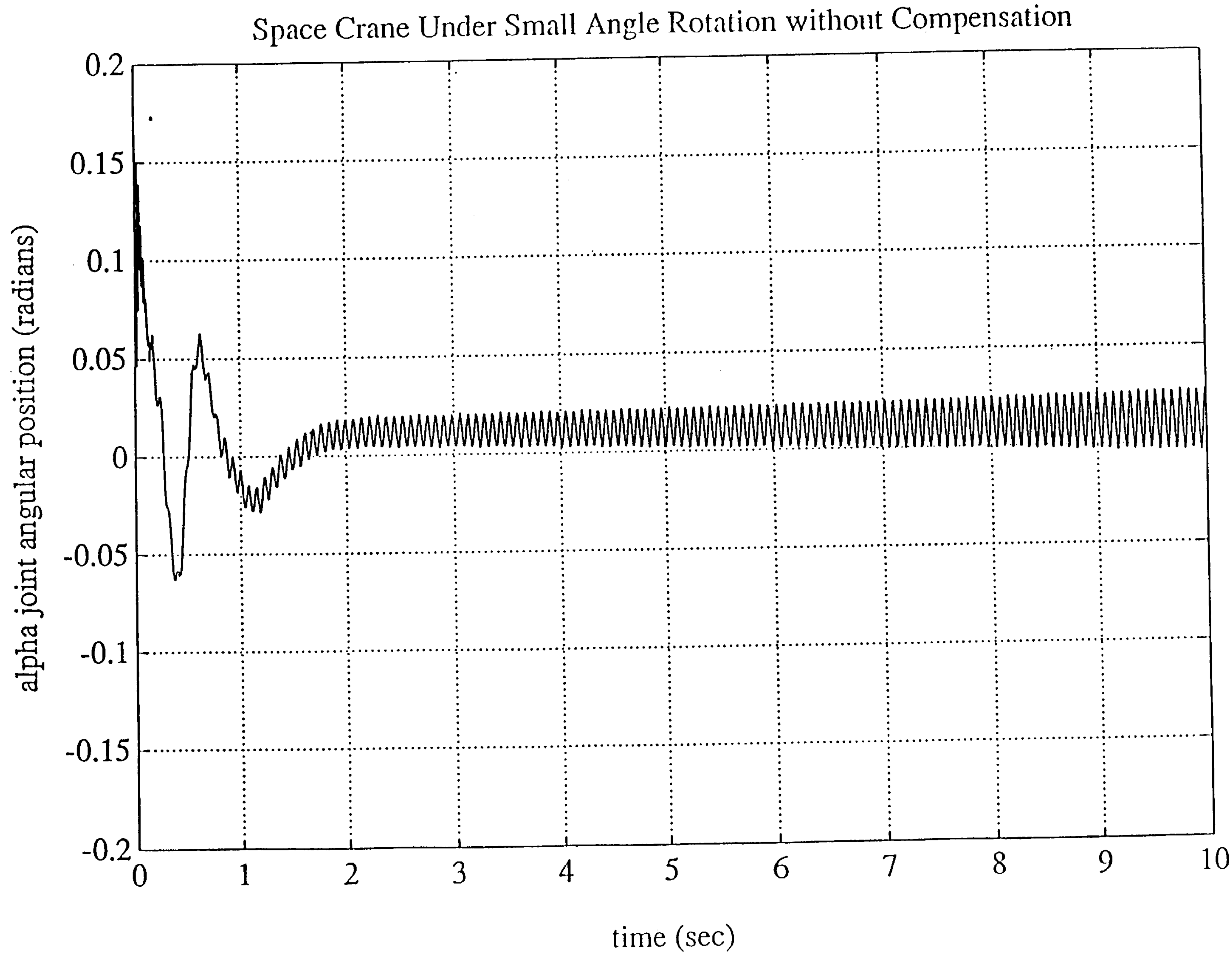
Figure 8.22 Phase [illegible]o Evolutionary Model


Space Crane Under Small Angle Rotation, Open-Loop
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)


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
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

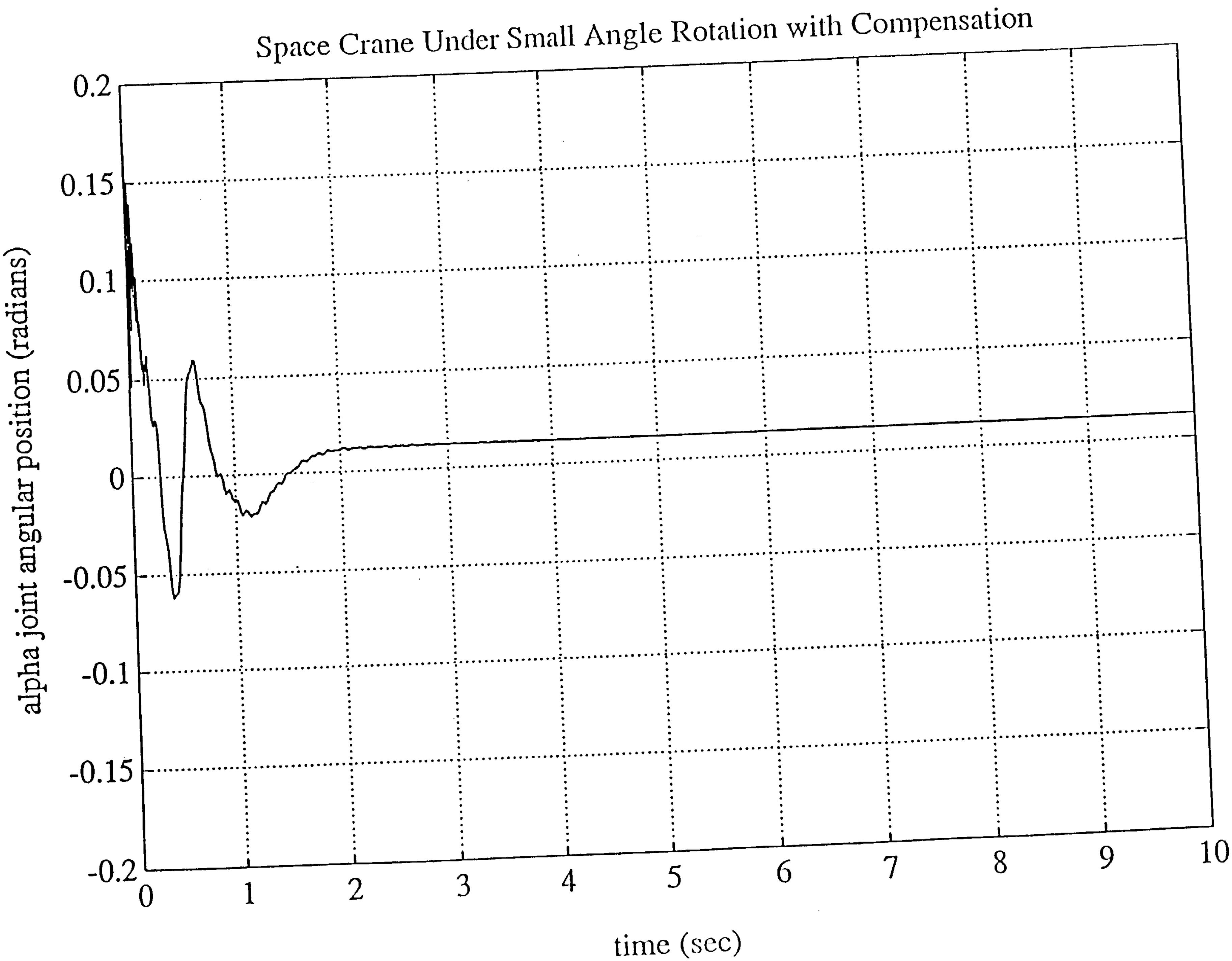

Space Crane Under Small Angle Rotation with Compensation
alpha joint angular position (radians)
time (sec)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
1
2
3
4
5
6
7
8
9
10

Figure 3 : Flexible Robot Manipulator at Martin Marietta

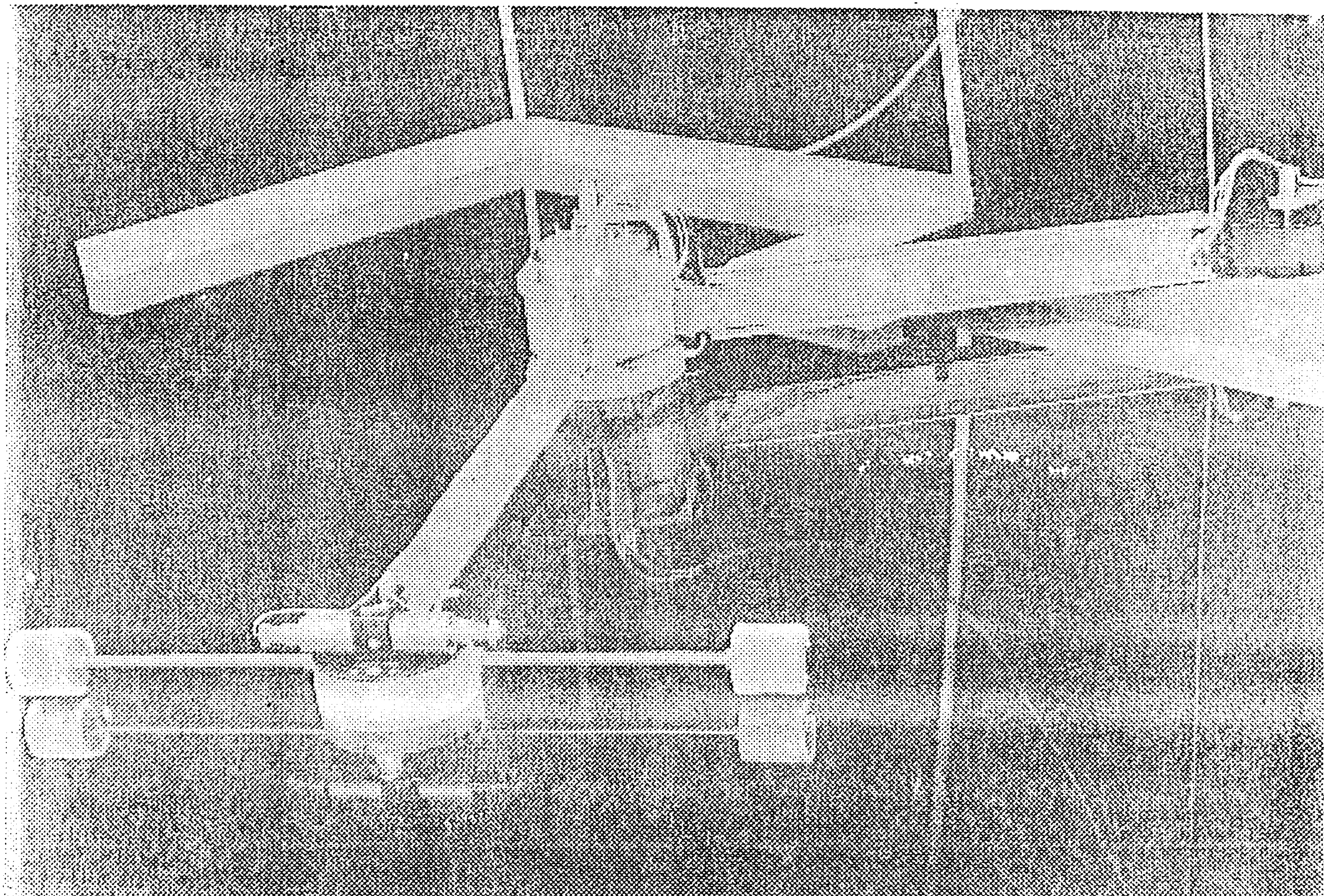


Figure 7 : Hub Position Without CSI Compensation

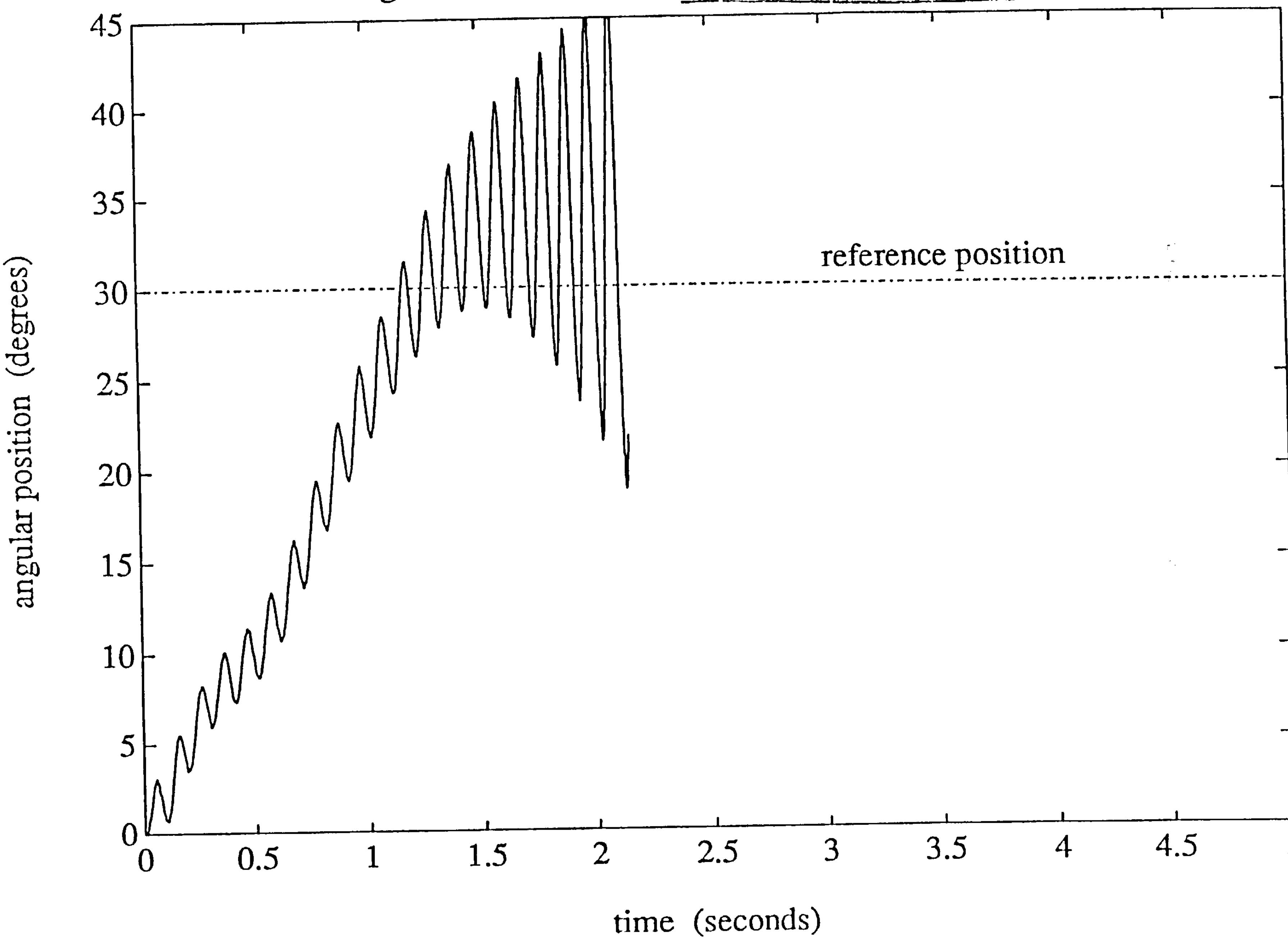
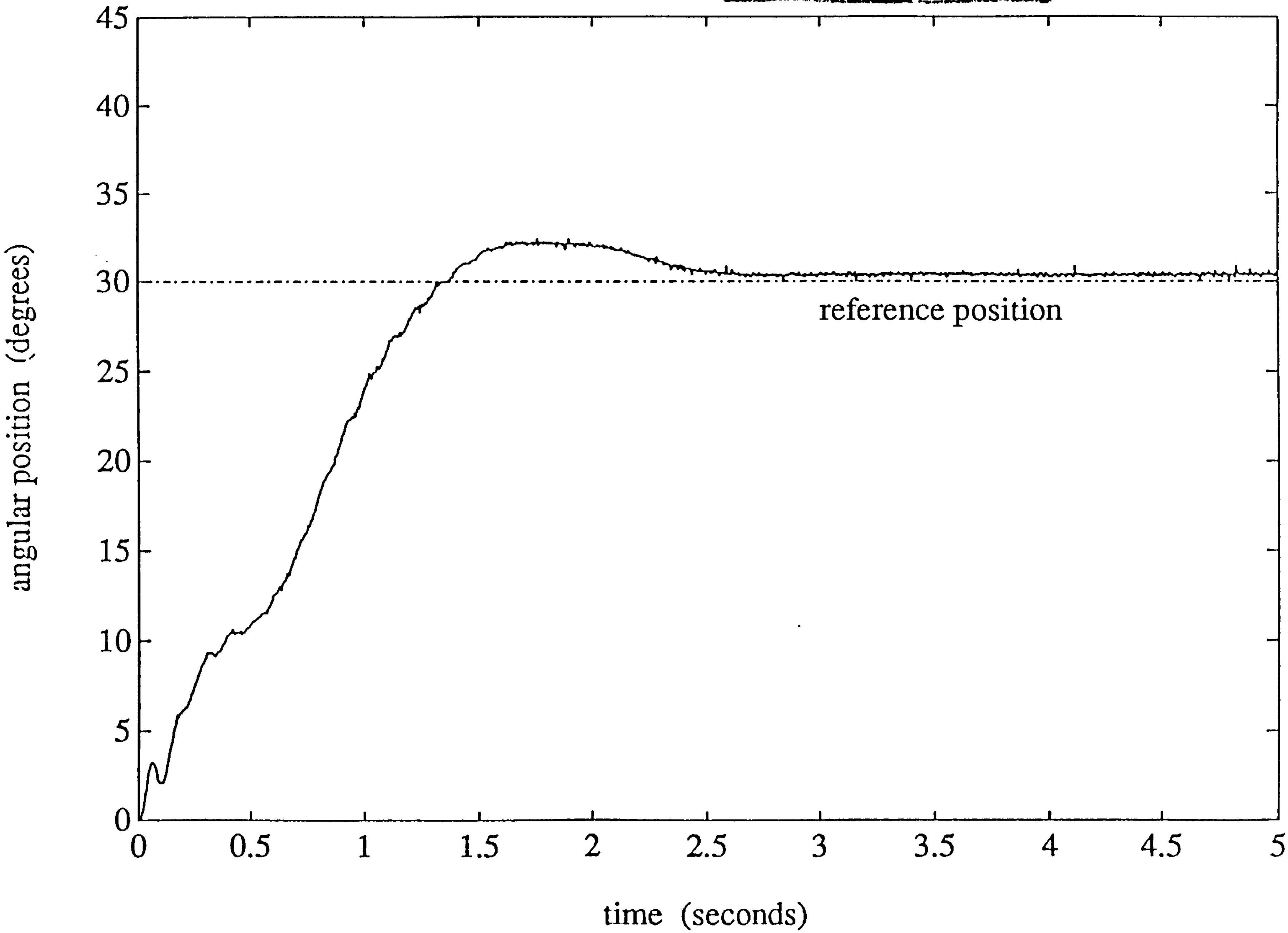


Figure 10 : Hub Position With CSI Compensation



Perturbation Analysis

Ali Gooyabadi
SPIE 1992

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

Asymptotic Eigenvalue Series:

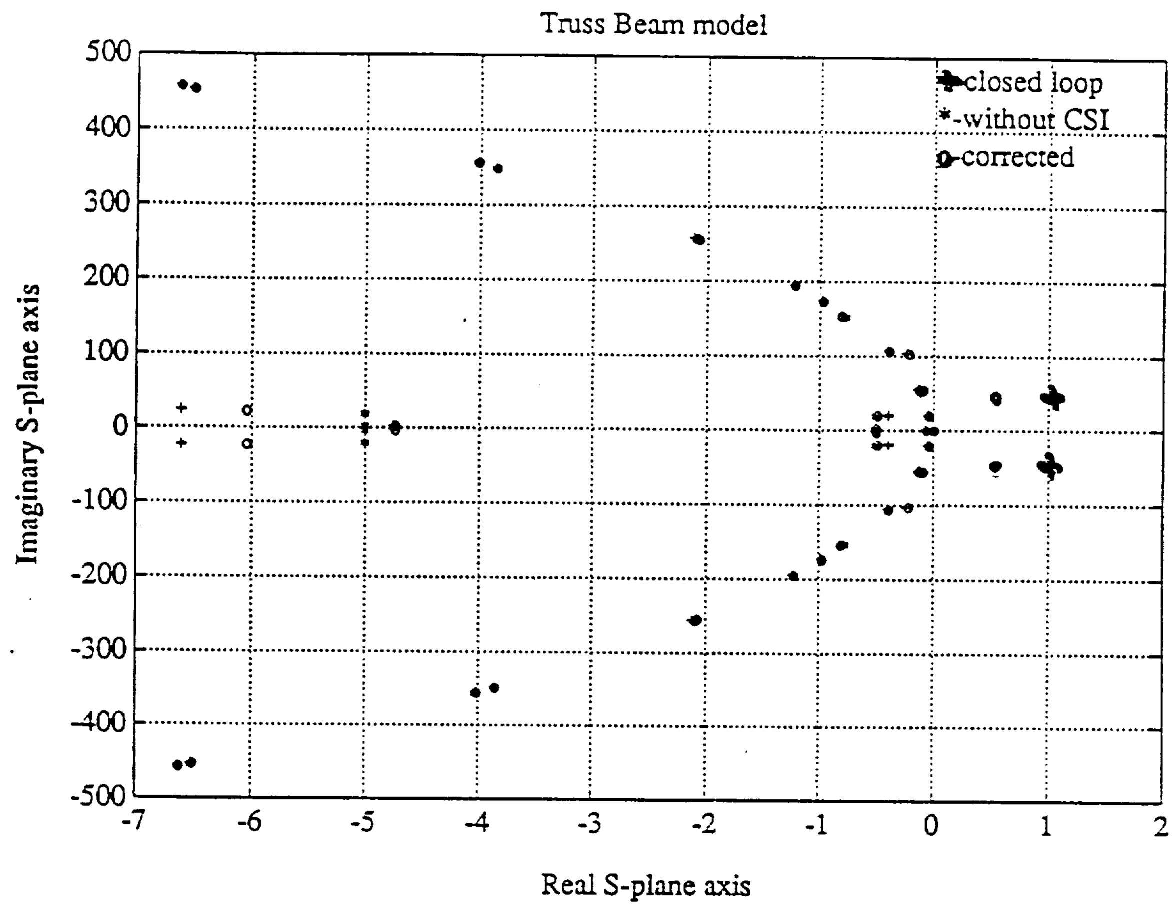
$$\hat{\lambda}_c(\epsilon) = \lambda_0 + \epsilon \lambda_1 + \epsilon^2 \lambda_2 + \cdots$$

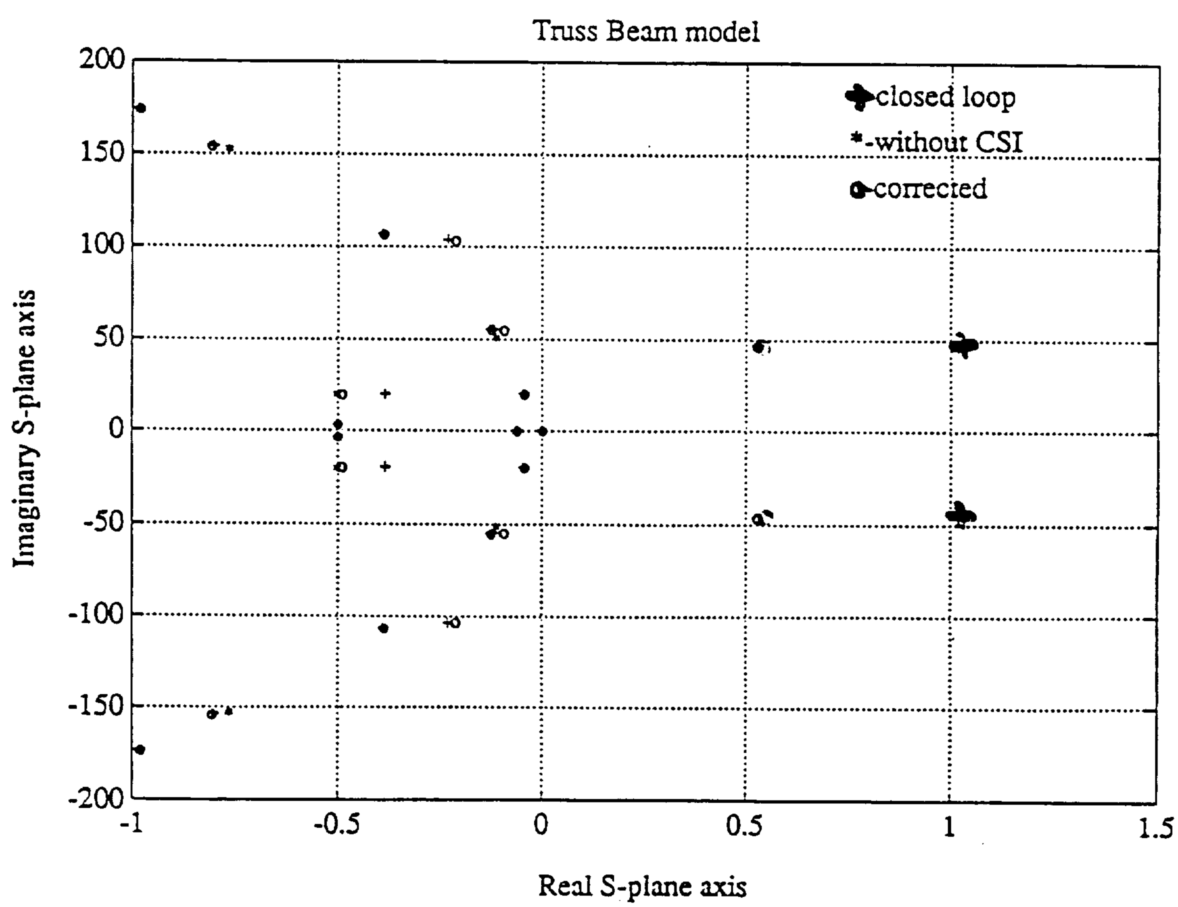
Closed-Loop (LSS + ROM Controller):

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

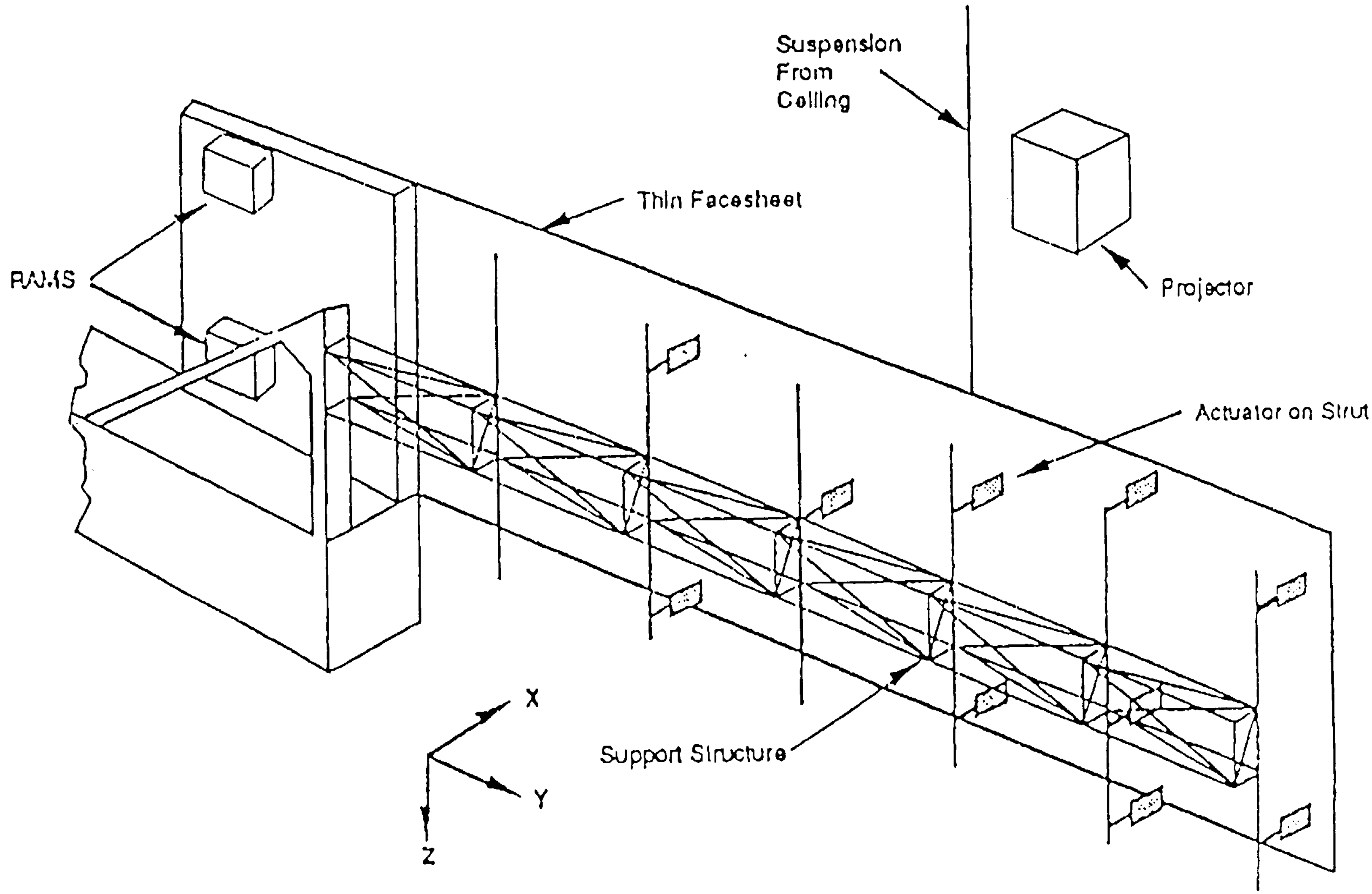
$$\therefore \ \hat{\lambda}_c(\epsilon) = \lambda_0 + \epsilon^2 \lambda_2$$

Note: $\lambda_1 = 0$ & $\lambda_3 = 0$

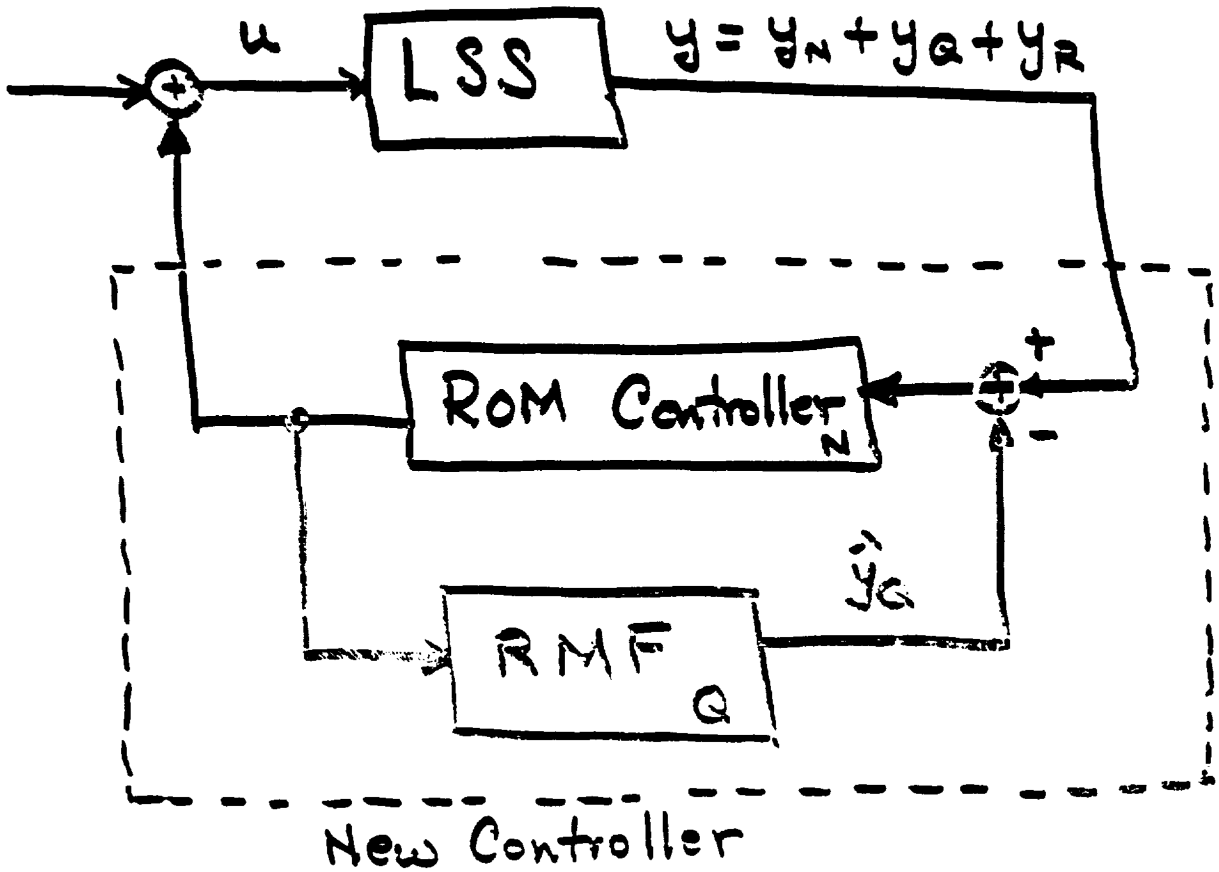

Truss Beam model
closed loop
*-without CSI
o-corrected
Imaginary S-plane axis
Real S-plane axis
500
400
300
200
100
0
-100
-200
-300
-400
-500
-7
-6
-5
-4
-3
-2
-1
0
1
2


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

Testbed Concept Has Thin Facesheet Controlled From Support Truss



A0236/594.003



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

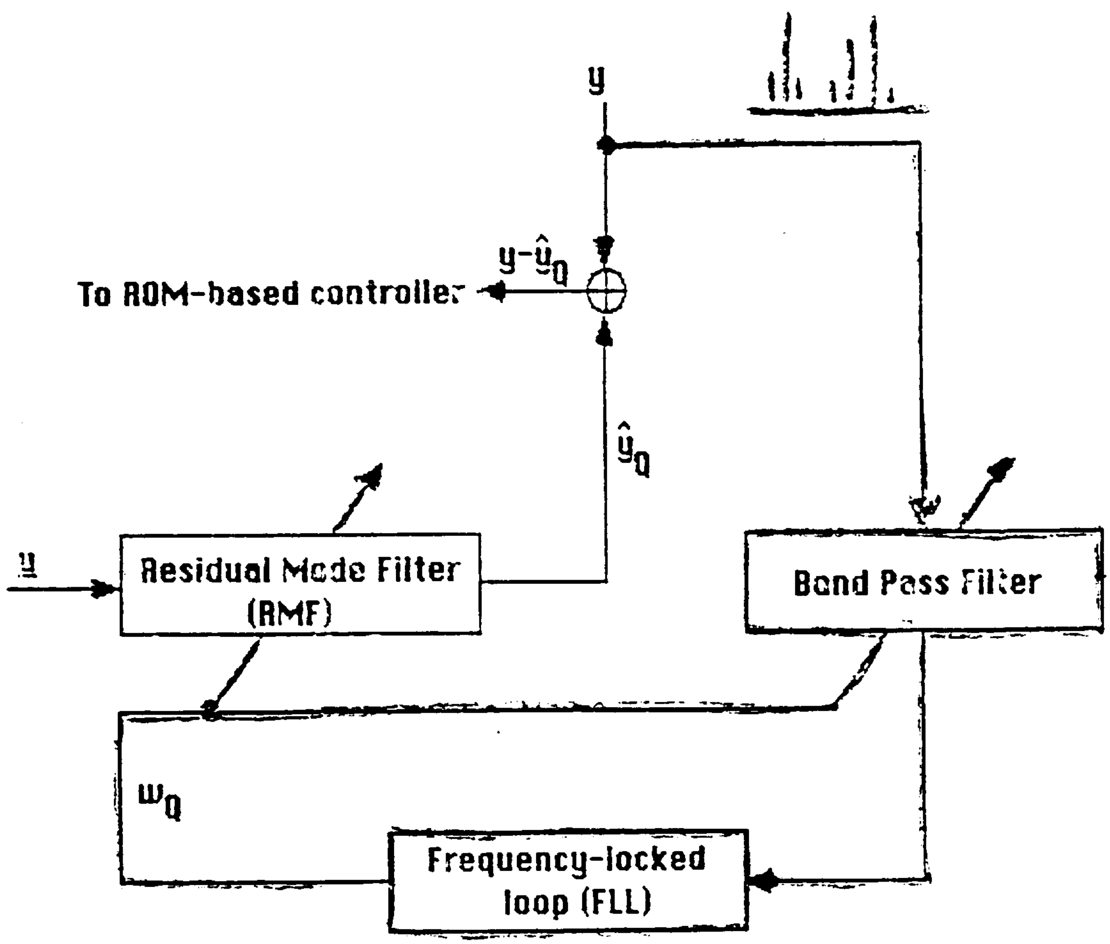


Figure 4. The adaptive, self-tuning RMF.

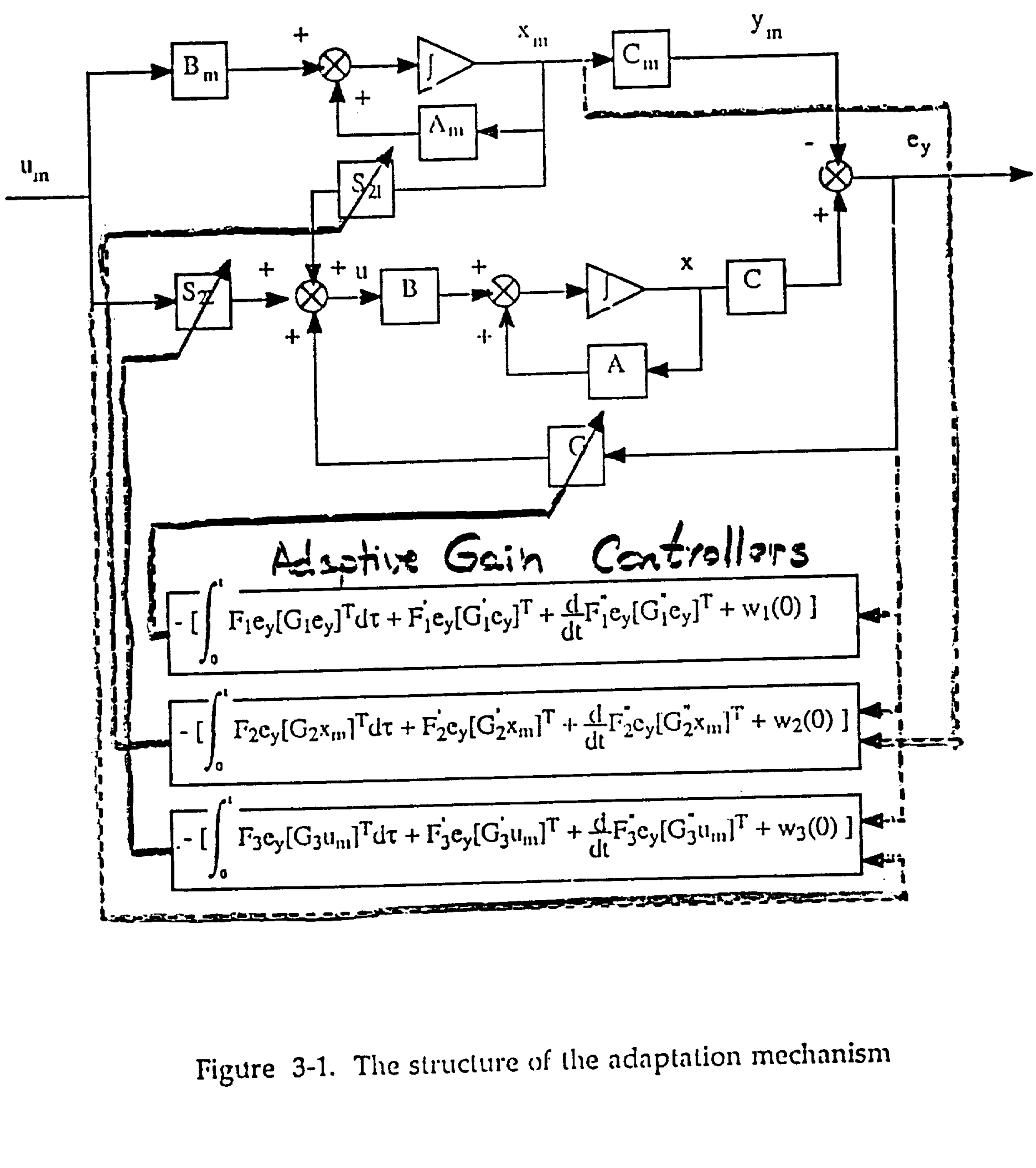
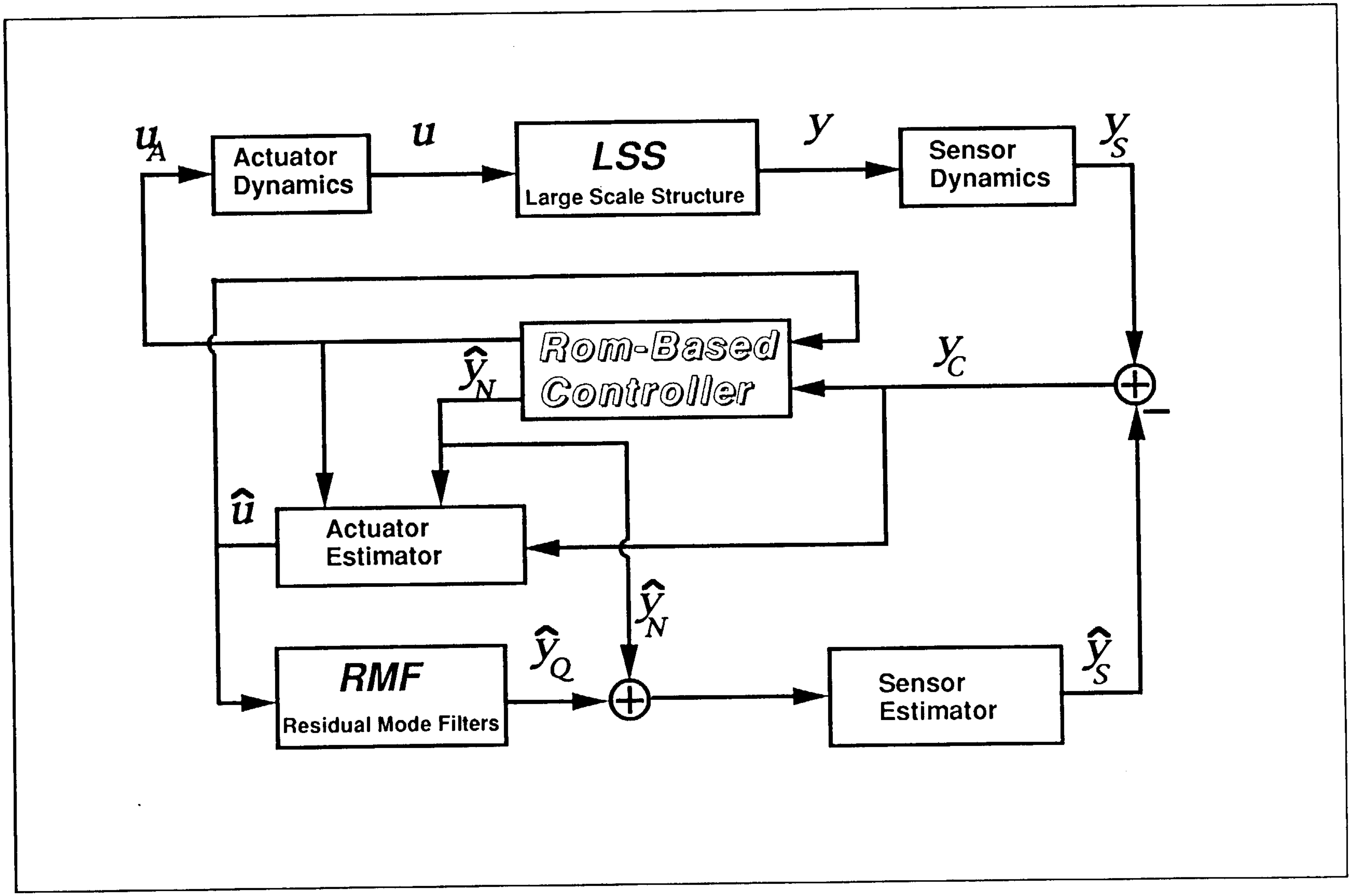
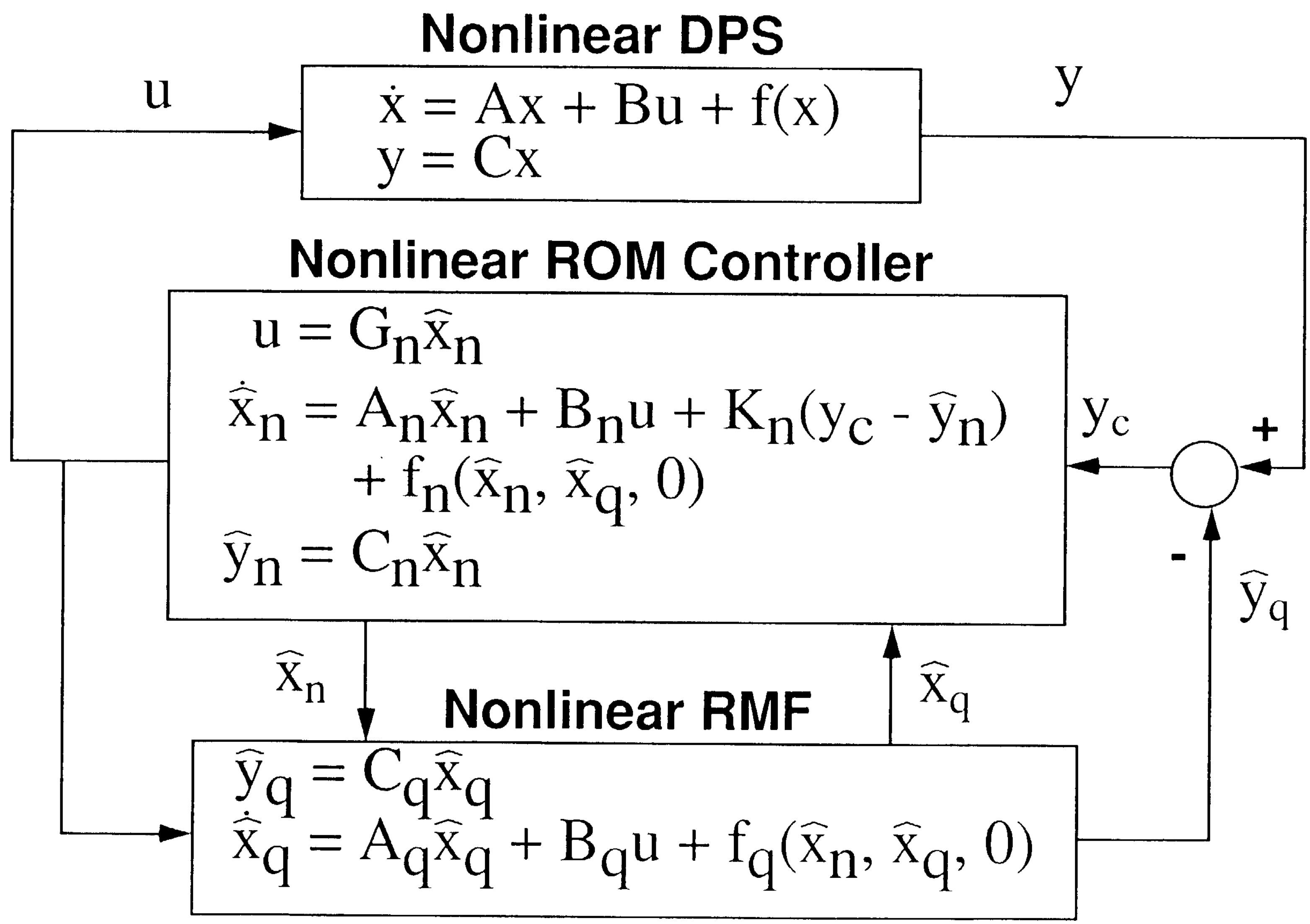


Figure 3-1. The structure of the adaptation mechanism

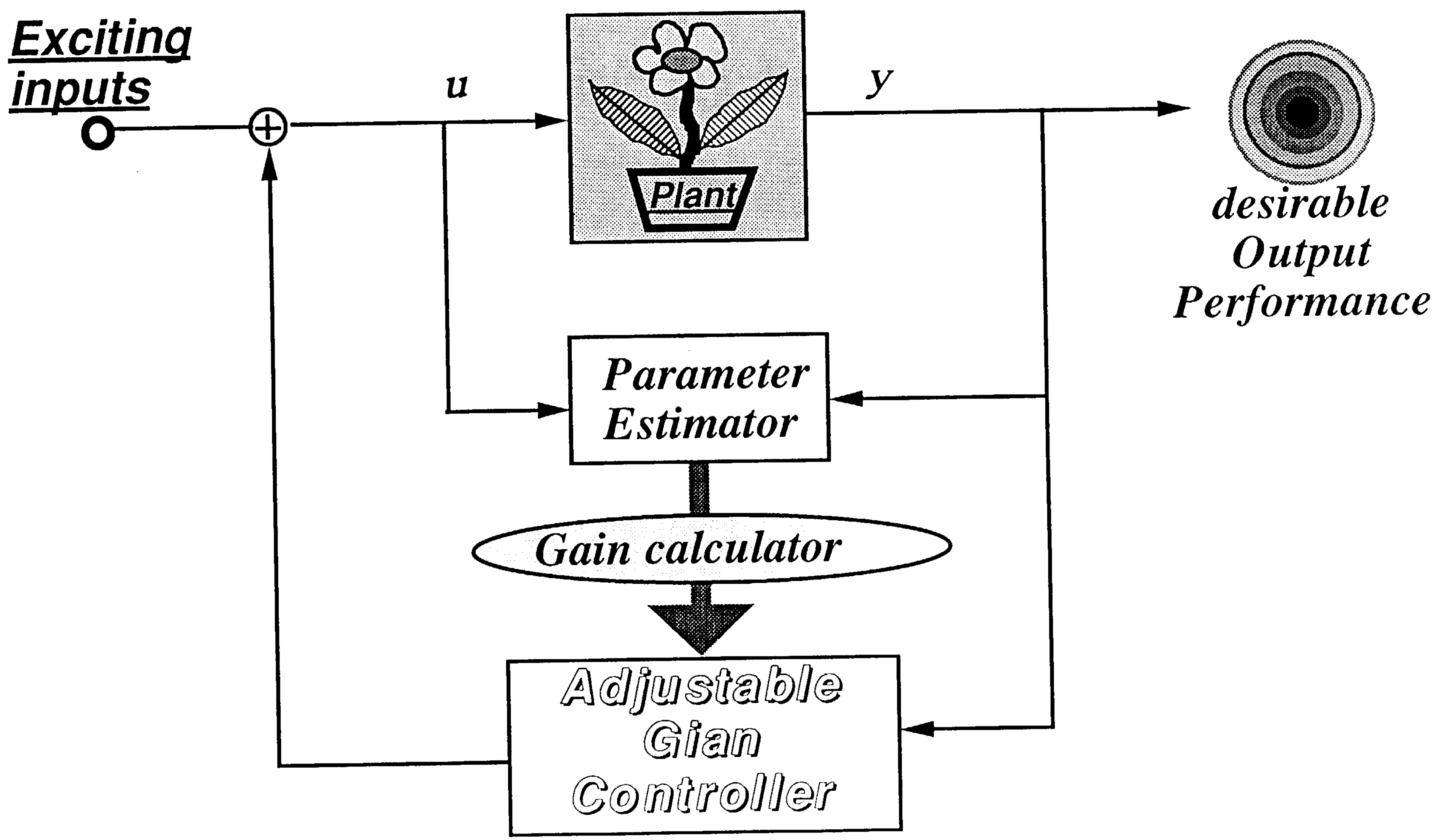
ROM/RMF with actuator/sensor dynamics



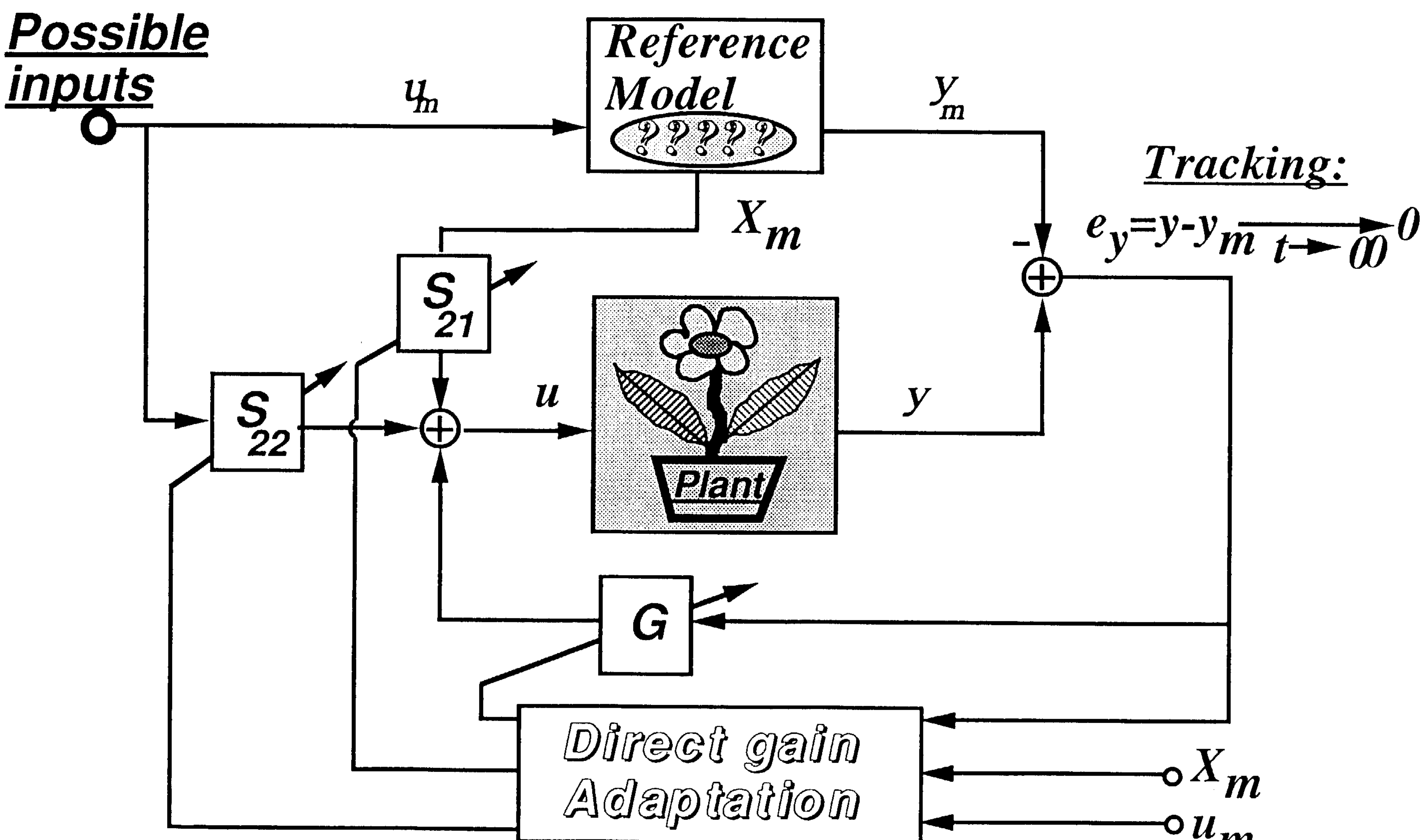
Modifications For Nonlinear ROM/RMF Control JMAA 1991

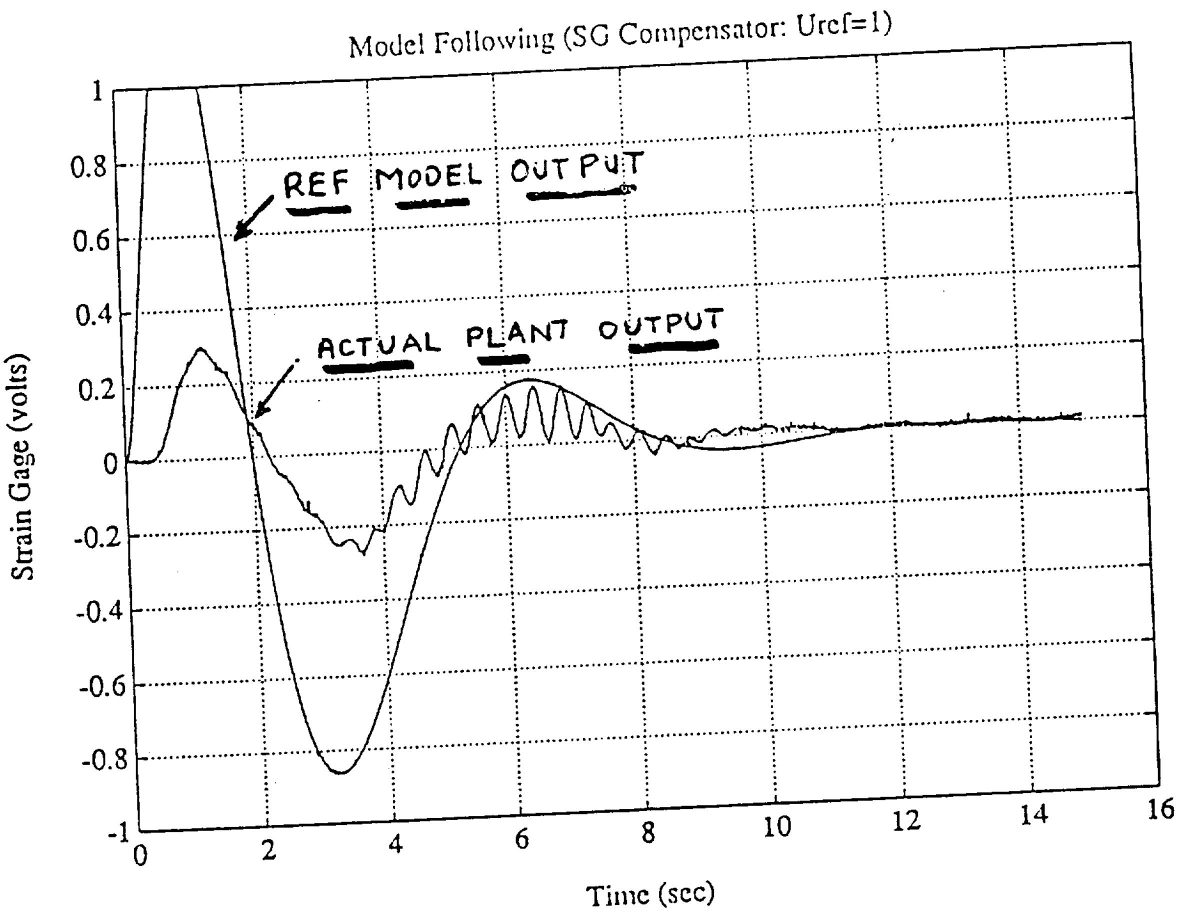


Indirect Adaptive Control



Direct Adaptive Control





Flexible Manipulator Experiments (SC Liang)

Hub Control - Strain Gauge Sensor

(Not Collocated)

Decentralized Controller Design

$\longrightarrow$ **Performance** $\longleftarrow$

Controller 1

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

Controller 2

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

y_1 u_1 y_2 u_2

Large Space Structure (LSS)

ROM :

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

RMF Compensation for Stable Control