N90-10123

OPTIMAL INTEGRAL CONTROLLER WITH SENSOR FAILURE ACCOMMODATION

By

Dr. T. Alberts
Old Dominion University
Norfolk, Virginia

and

Dr. T. Houlihan
The Jonathan Corporation
Norfolk, Virginia

ABSTRACT

An Optimal Integral Controller that readily accommodates Sensor Failure - without resorting to (Kalman) filter or observer generation - has been designed. The system is based on Navy-sponsored research for the control of high performance aircraft.

In conjunction with a NASA developed Numerical Optimization Code, the Integral Feedback Controller will provide optimal system response even in the case of incomplete state feedback. Hence, the need for costly replication of plant sensors is avoided since failure accommodation is effected by system software reconfiguration.

The control design has been applied to a particularly ill-behaved, third-order system. Dominant-root design in the classical sense produced an almost 100 percent overshoot for the third-order system response. An application of the newly-developed Optimal Integral Controller--assuming all state information available--produces a response with NO overshoot. A further application of the controller design--assuming a one-third sensor failure scenario--produced a slight overshoot response that still preserved the steady state time-point of the full-state feedback response.

The control design should have wide application in space systems. The design can be expanded to include gain scheduling that enhances system response to large-scale transients. For this latter instance, using the NASA optimization scheme, the guesswork normally required to determine feedback gains for large transients is eliminated.

Optimal Integral Control

With

Sensor Failure Accommodations

Dr. Thomas Alberts

Old Dominion University

Norfolk, Virginia

Dr. Thomas Houlihan

The Jonathan Corporation

Norfolk, Virginia

N A S A Workshop

Flexible System Control

12 July 1988

Optimal Integral Control Design

Introduction

Optimal Regulator

Augmented System

(Rates of Change of Input Signals)

Optimal Tracker

Optimal Integral

Control Design

Sensor Failure

Accommodation

Preliminary Results:

Third Order System

Introduction

Optimal Control Designs Compromised By:

Inaccessible States (Sensors)

Noisy Feed back Signals

OC Designs Resort To Use Of

Filter / Estimating Techniques

To Overcome These Obstacles

NAVY Research in 1970s

Leads to Alternative Approach

Optimal Regulator - Classic Design

Tradeoffs Between Accuracy of Control

And Energy Expenditure Reflected

In Weighting Matrices (Q and R)

Of Performance Index (J)

$$J = \int (X^T Q X + U^T R U)\, dt$$

Performance Index Formulation

Assumes <u>Unconstrained</u> Inputs.

In Reality, Inputs are Limited.

Futhermore, Rates of Change of

Input Signals Are Limited.

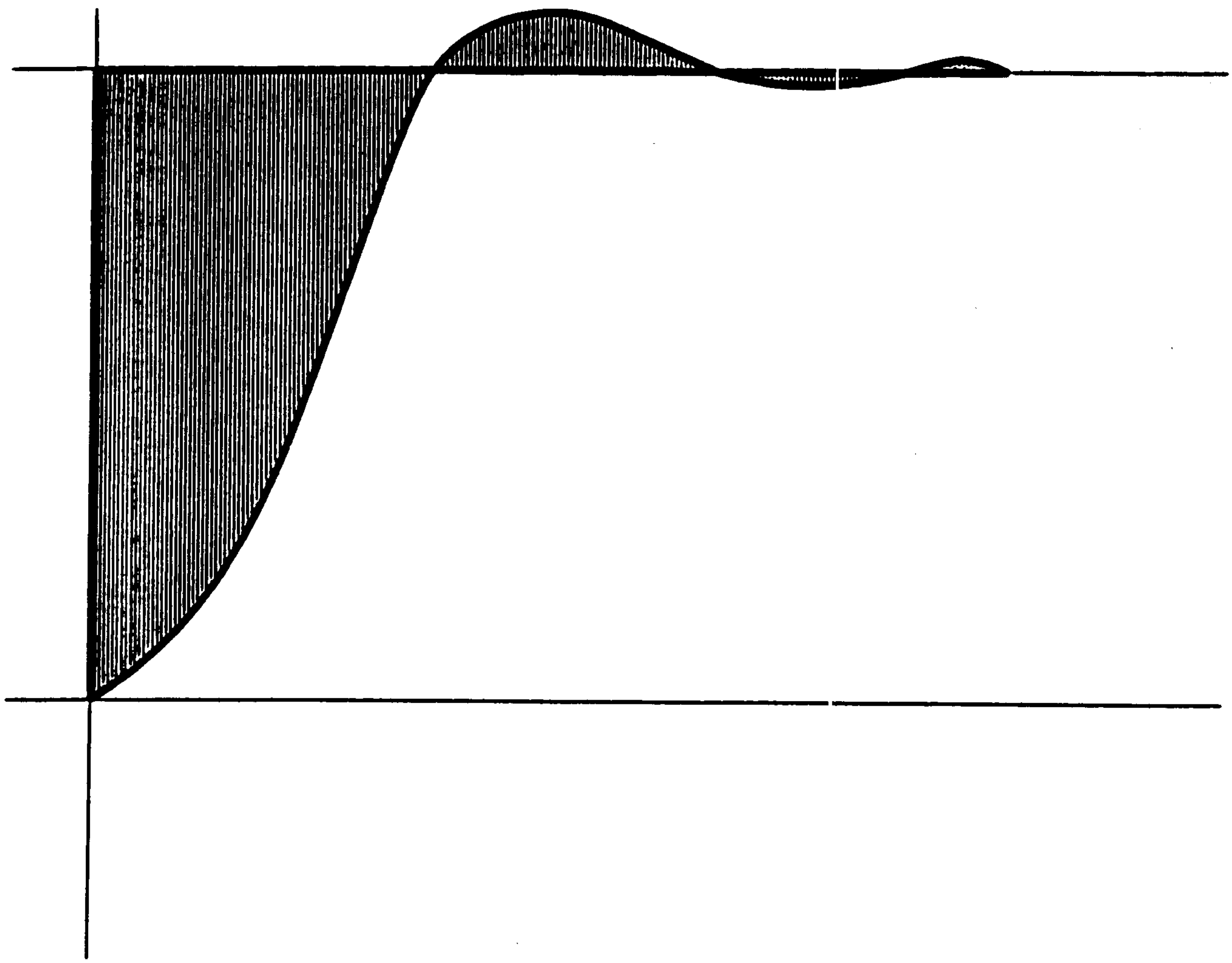

Figure 1. Typical System Response.

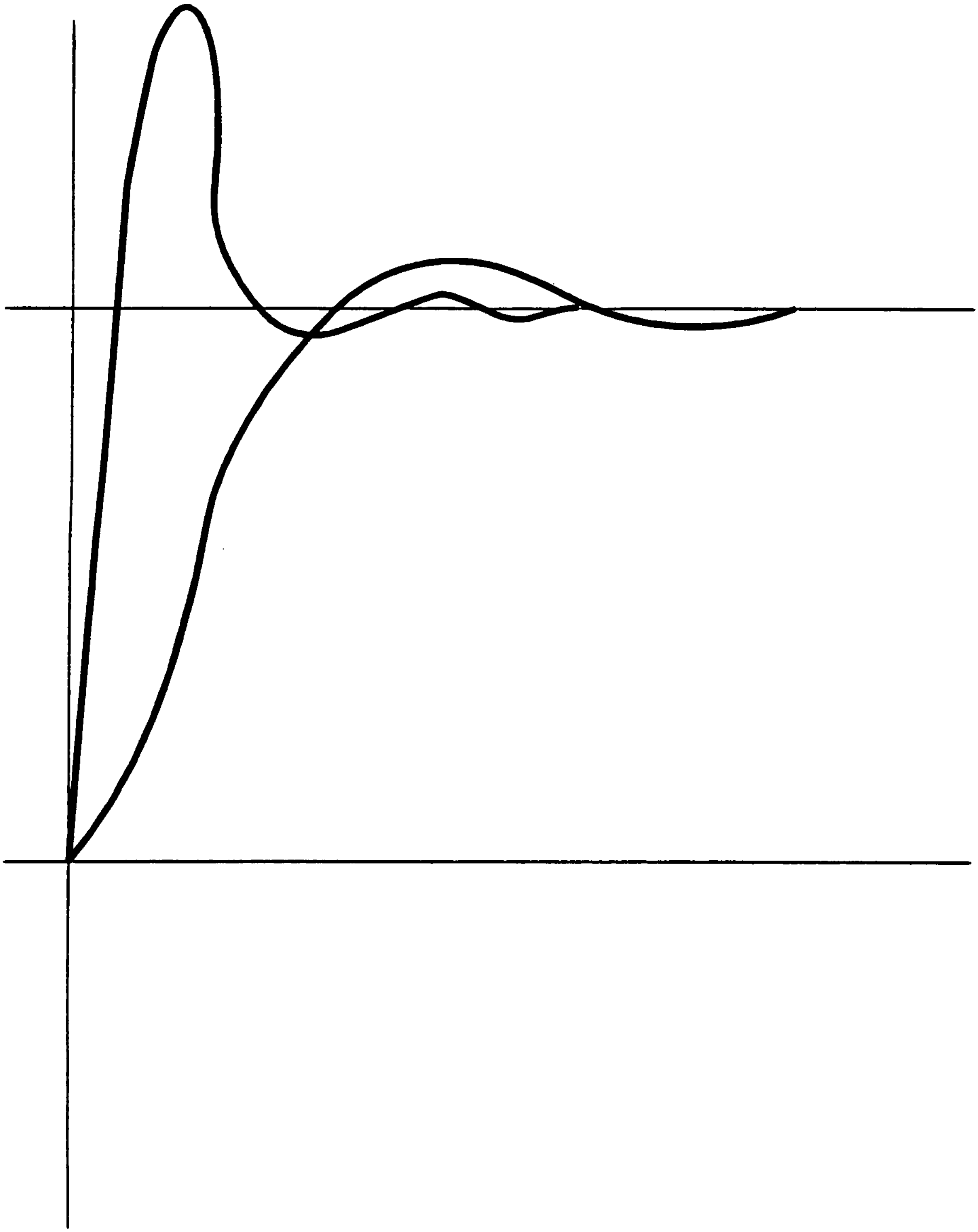

Figure 2. Comparative Optimal Responses.

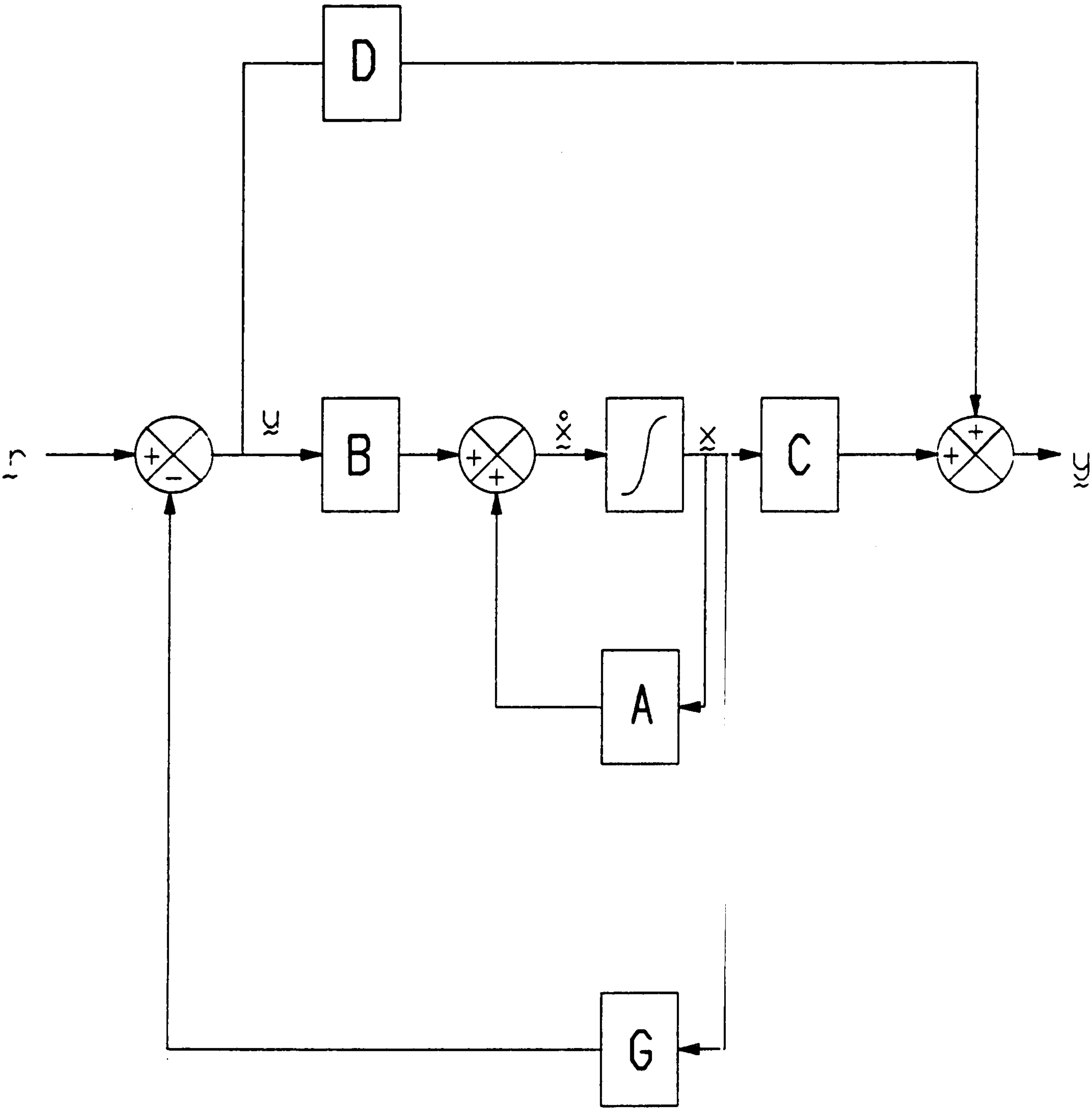

FIGURE 3. OPTIMAL REGULATOR SYSTEM

Augmented System:

Rates of Change of Input Signals

Can be Considered

New State Vector = Old State Vector
+
Input Signals

Optimal Regulator Solution of

Agumented System:

$U^* = -G^*X^* \qquad G^* = |G_1\ G_2|$

Gain Matrix (G^*) of Augmented

System Carries Information on System

States (X) and Inputs (U)!

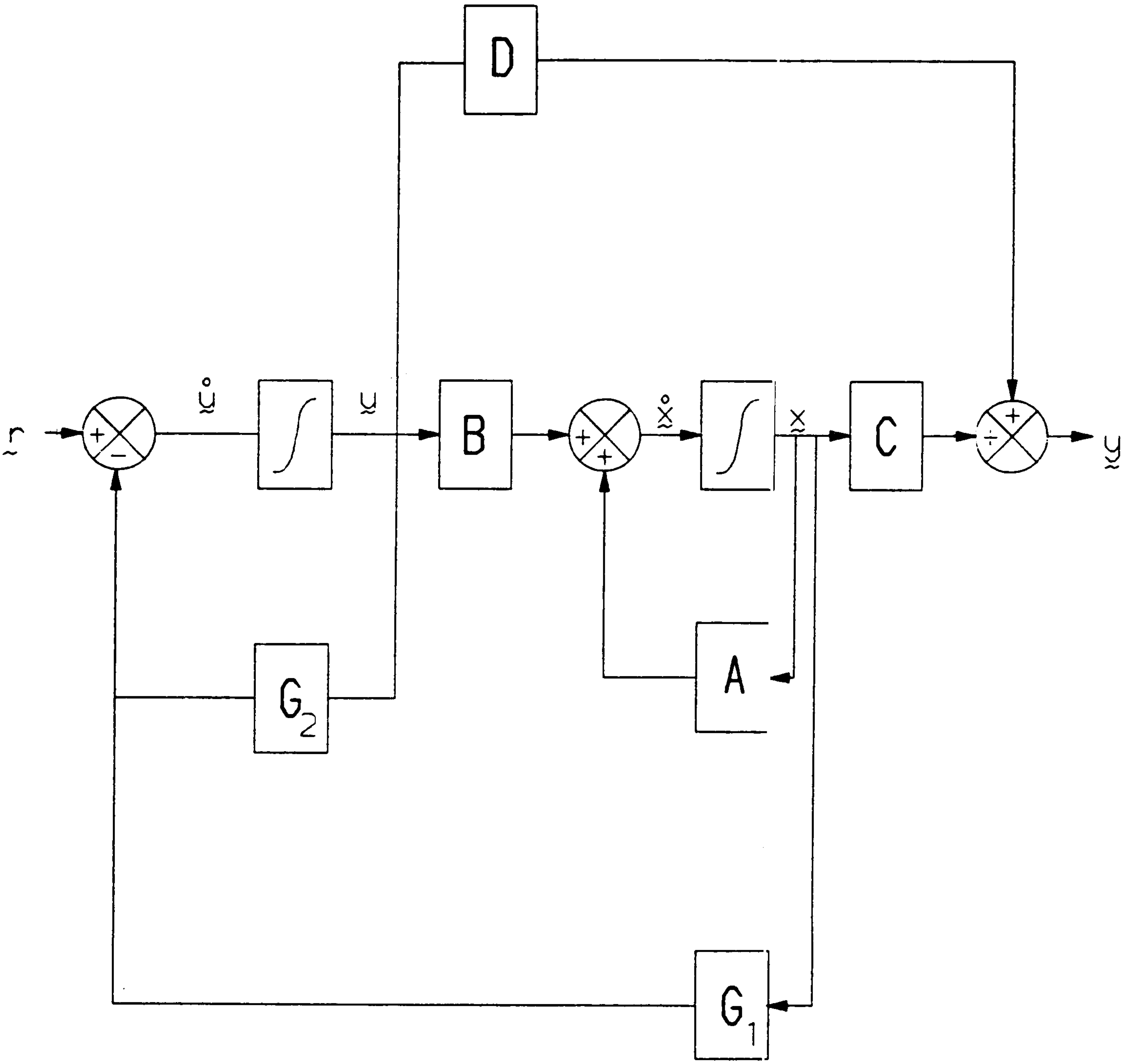

FIGURE 4. OPTIMAL REGULATOR-AUGMENTED SYSTEM

Optimal Tracker:

Add Gain Matrix (**M**) to

Select Command Inputs

NOTE: Tracker is NOT Integral Controller

Since Control Commands are NOT

Generated by Integral of Error

Between Desired Signals (**r**)

And Output Signals (**z**).

NOTE: Solution to Tracker Control

Configuration is KNOWN. It is

Solution of Augmented System.

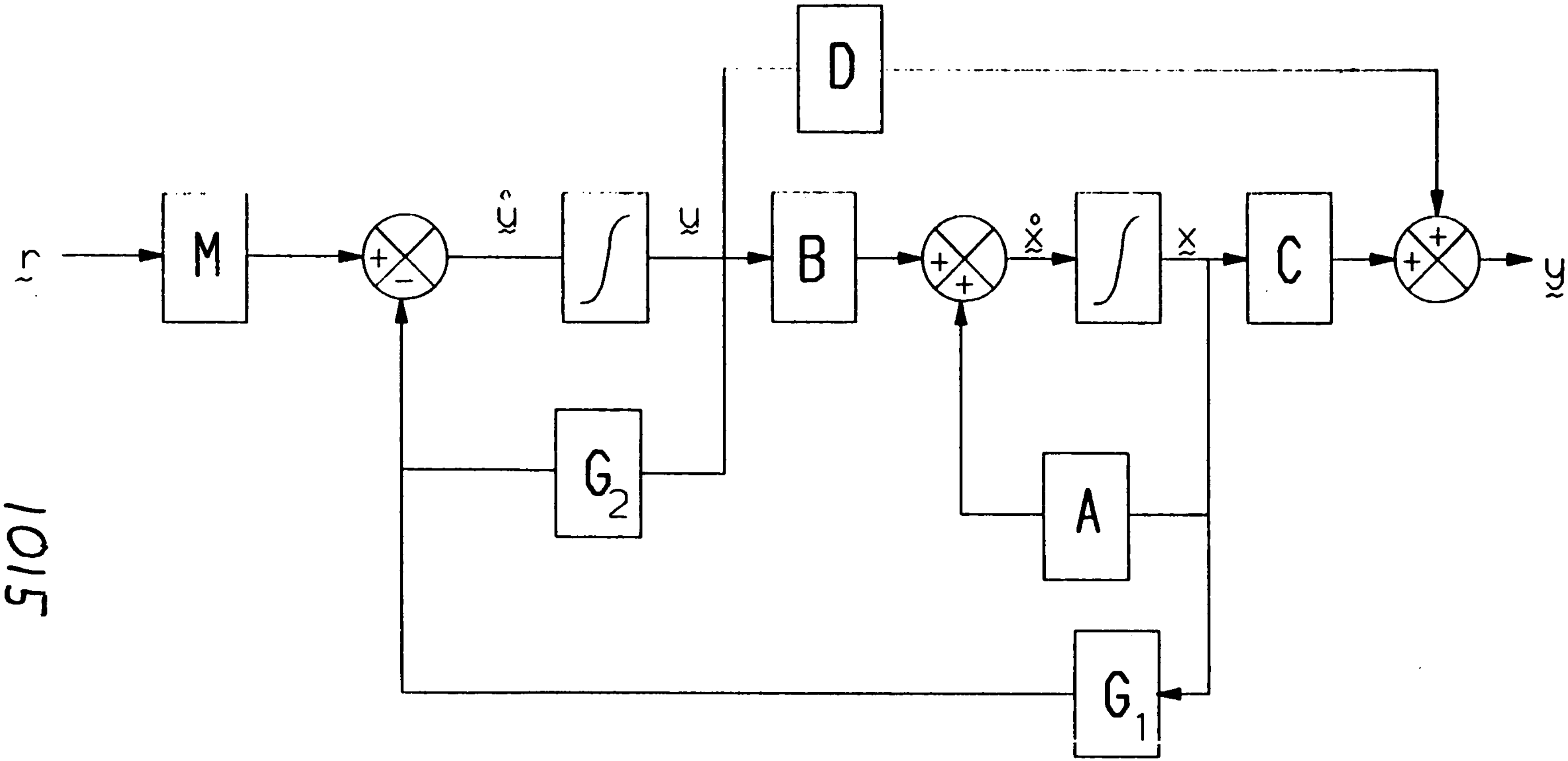

FIGURE 5. OPTIMAL TRACKING SYSTEM

Optimal Integral Control Design

Equality of Optimal Integral Control

Design and Optimal Tracker Design

Effected by Block Diagram Reduction

Techniques (Laplace Domain).

Results:

$$|L\ H| = |G_1\ G_2| \begin{vmatrix} A & B \\ EC & ED \end{vmatrix}^{-1}$$

Knowns:

A, B, C, D, E - Configuration Matrices

G_1, G_2 - Augmented System Solution

Thus:

L and **H** Matrices are Determinable

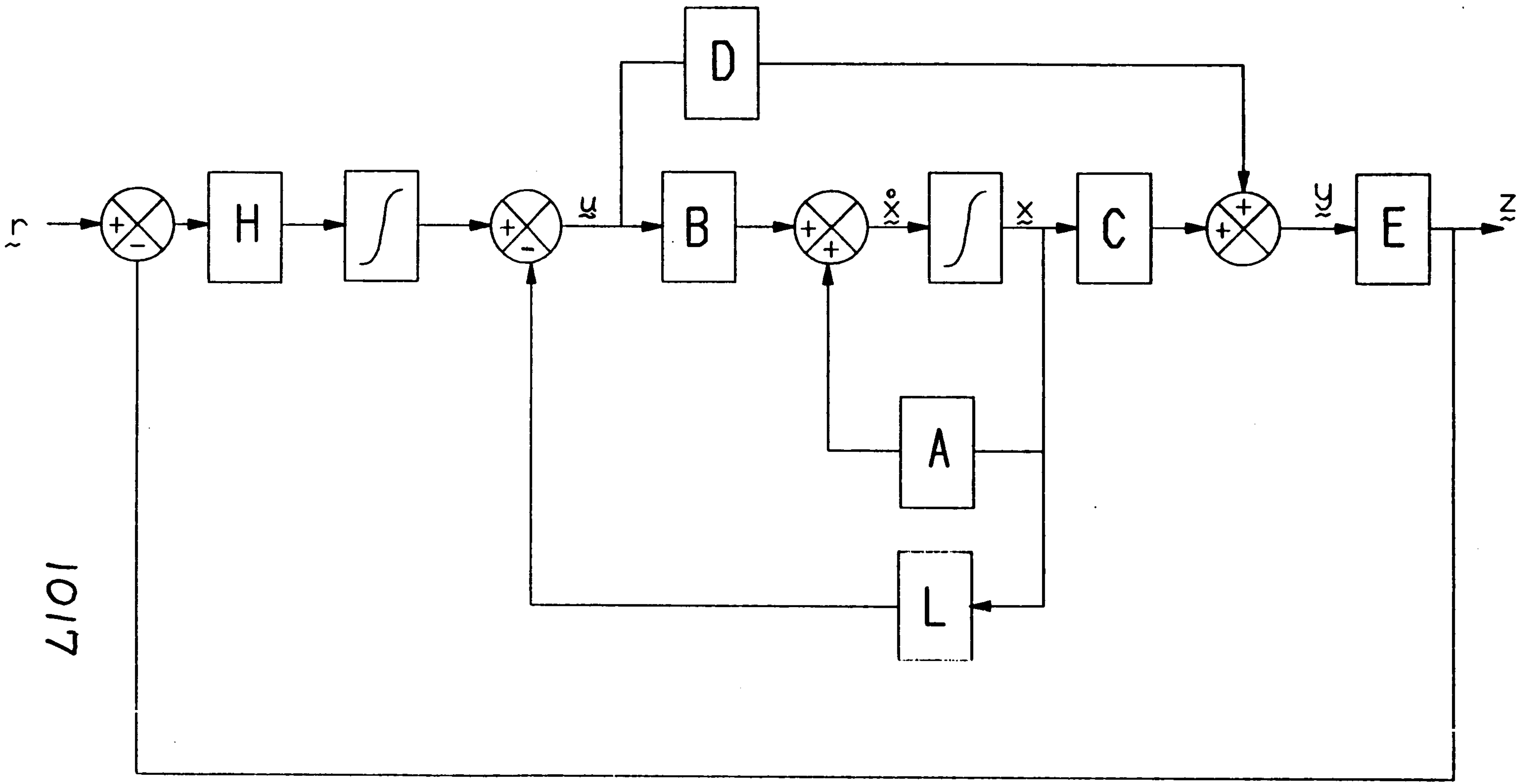

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FIGURE 6. OPTIMAL INTEGRAL TRACKING SYSTEM

Sensor Failure Accommodation

Matrices:

H = Error Gain Matrix
L = State Gain Matrix

If State Information Unavailable,

Corresponding Column Elements of L

Matrix Are Zeroed - Suboptimal Control!
From Before

$$|G_1 G_2| = |L_s H| \begin{vmatrix} A & B \\ EC & ED \end{vmatrix}$$

Hence, New Gain Matrix $|G_s| = |G_{1s} G_{2s}|$

Can be Determined to Effect Control

Preliminary Results are Encouraging

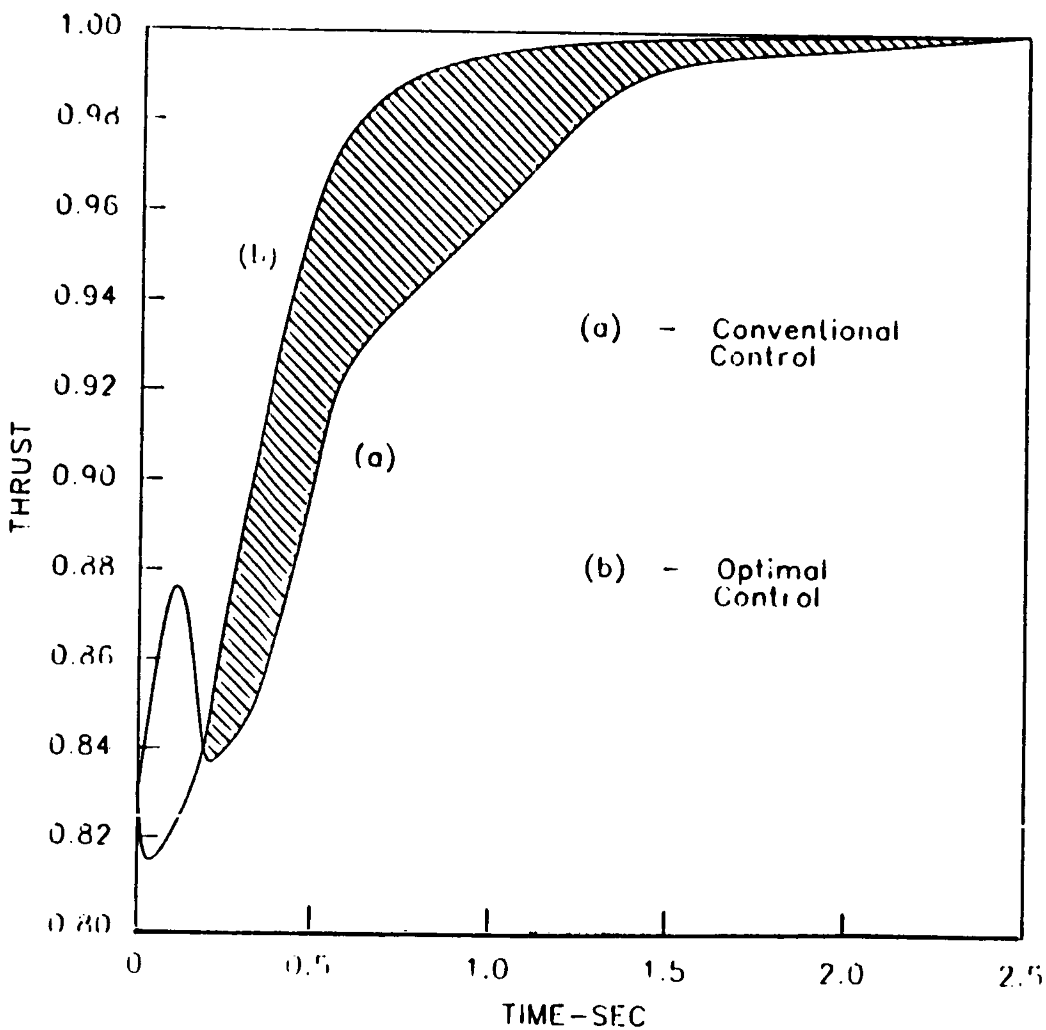

FIG. 7 F-100 THRUST CONTROL

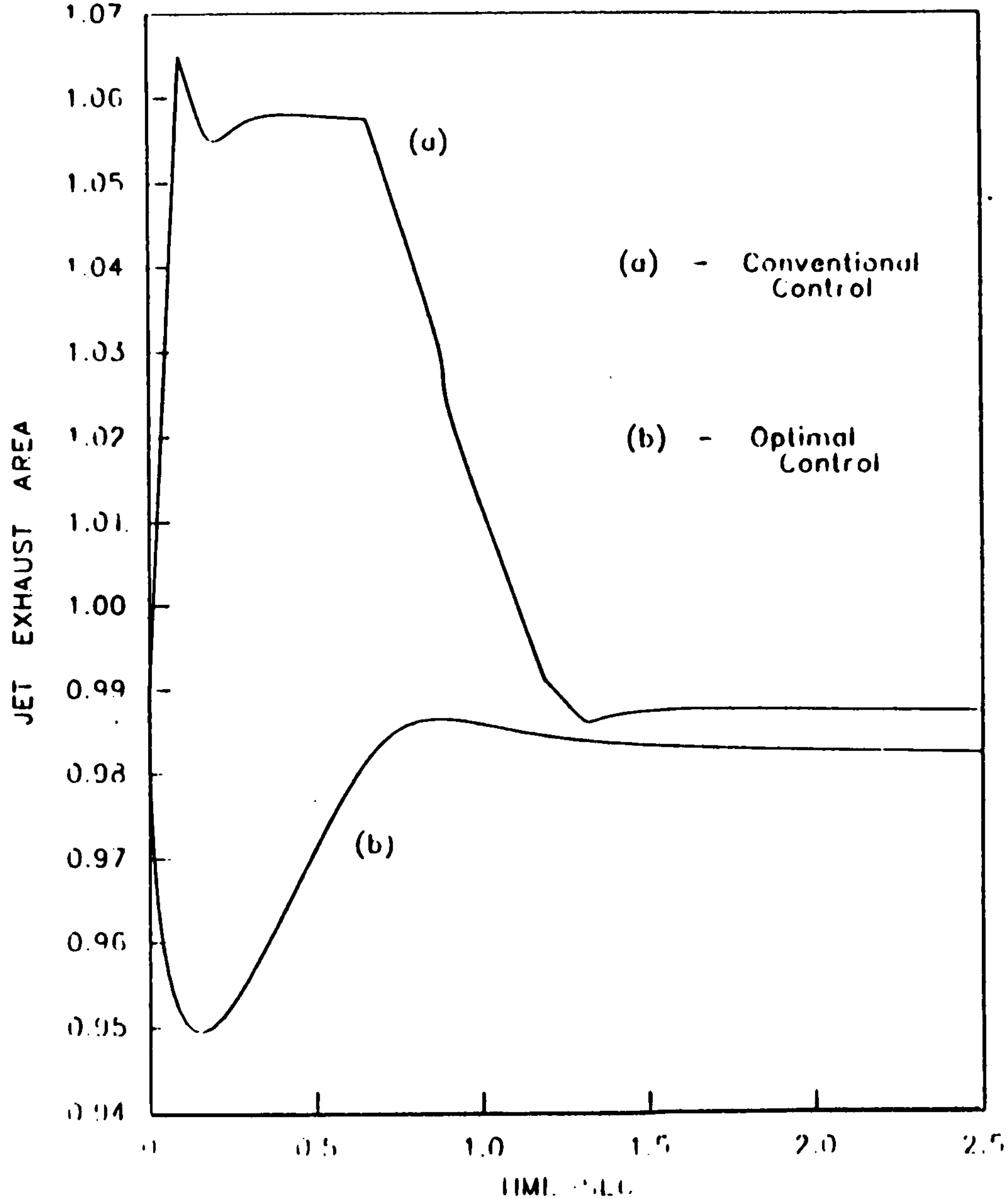

FIG. 8 F-100 AFTERBURNER CONTROL

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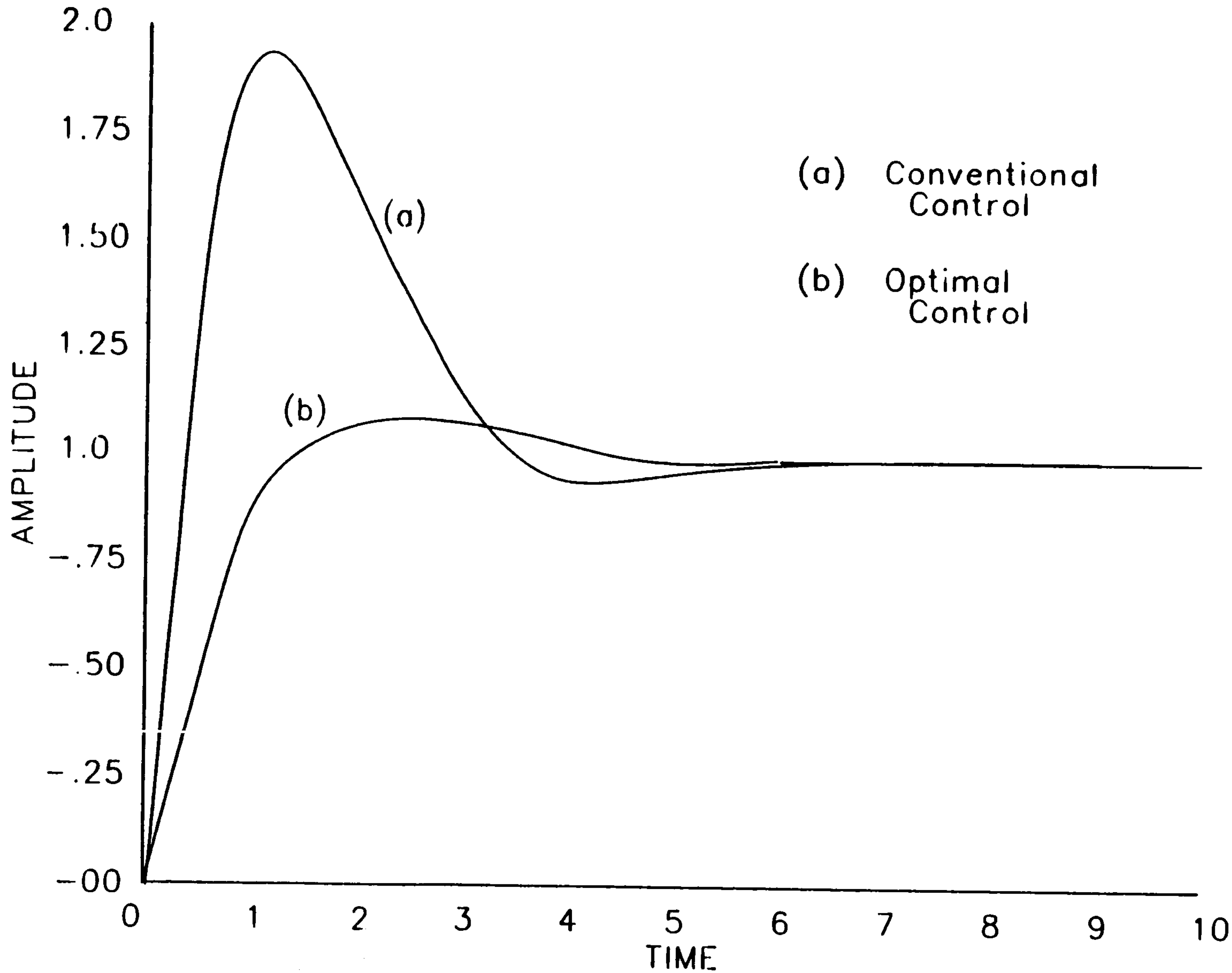

Fig.9. Third Order System Response Comparison

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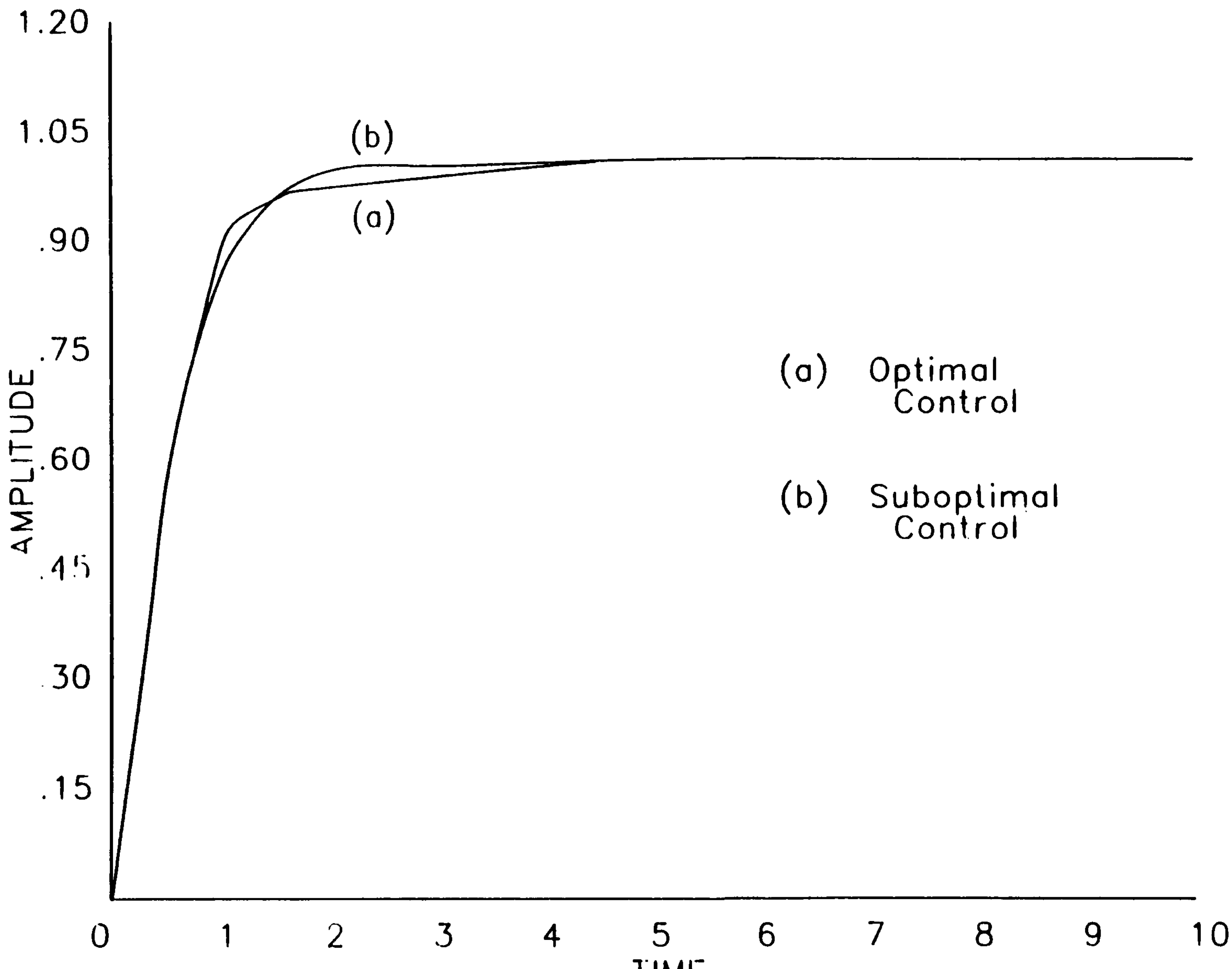

Fig.10. Third Order System Response Comparison

N A S A Workshop **July 1988**

Summary

Optimal Integral Control Design

Effected by a Combination of

Multivariable Control Analyses

Sensor Failure Accommodation

Accomplished Without Resort to

Supplemental Filter / Estimator Designs

Suboptimal Control Response

Effective for Ill-Behaved,

Third-Order Test Case

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Postscript to Computational Aspects...

Lawrence W. Taylor, Jr.
NASA Langley Research Center

What started as an effort to transcend various project and reasearch activities has become an official program..Computational Controls. The following charts describes that program at this early stage in its development. The next meeting on the subjects of the Computational Aspects Workshop will be the 3rd Annual Conference on Aerospace Computational Control. The conference will be held August 28-30, 1989 at Oxnard.

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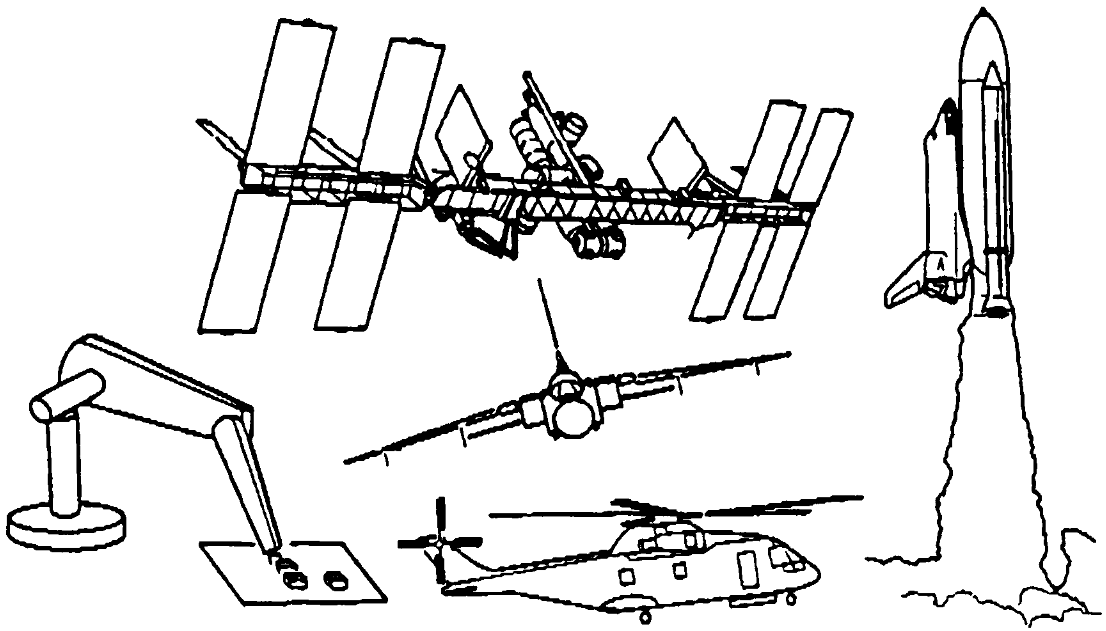
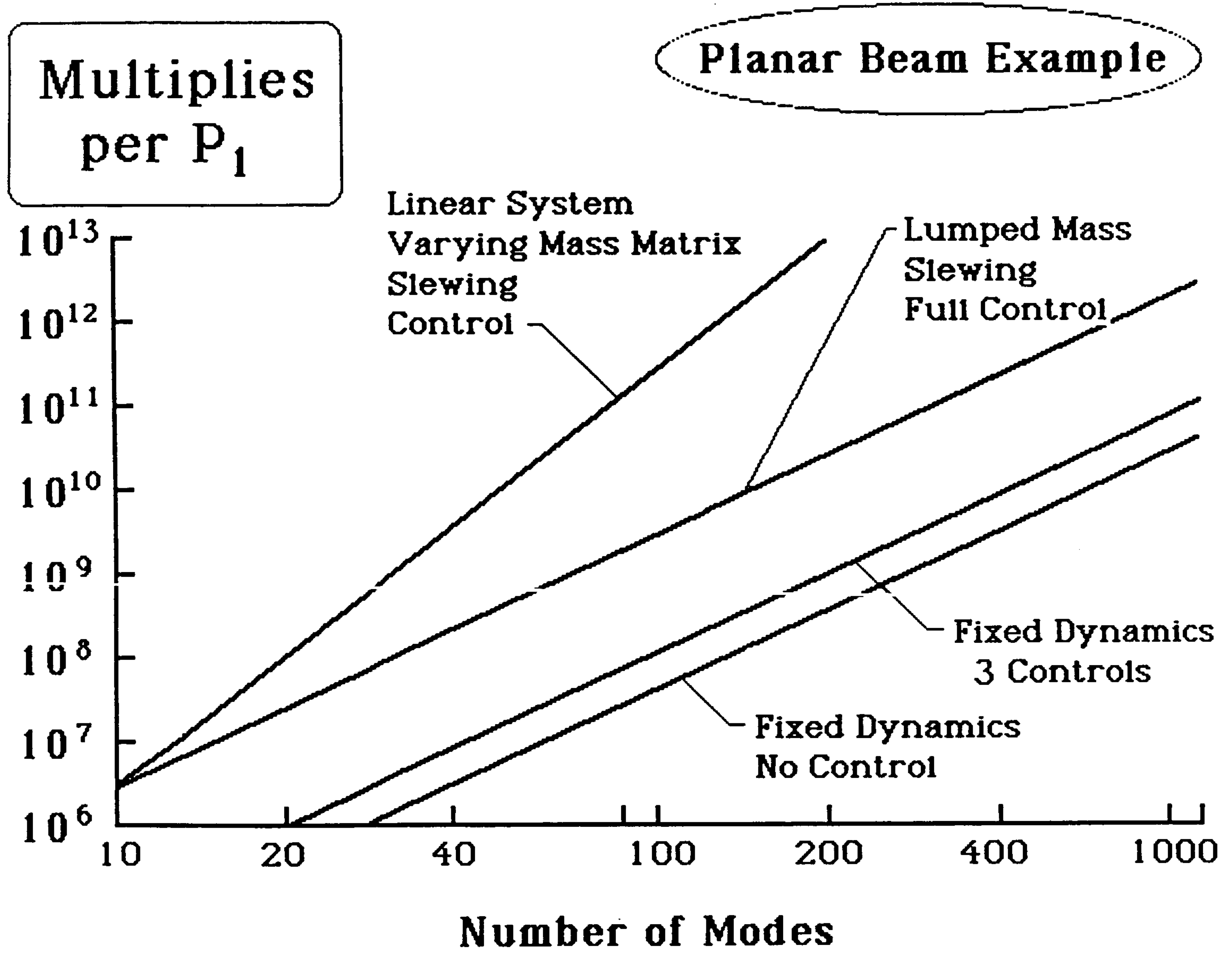
Computational Controls



Larry Taylor
NASA Langley Research Center

Computational Requirements



Computational Controls

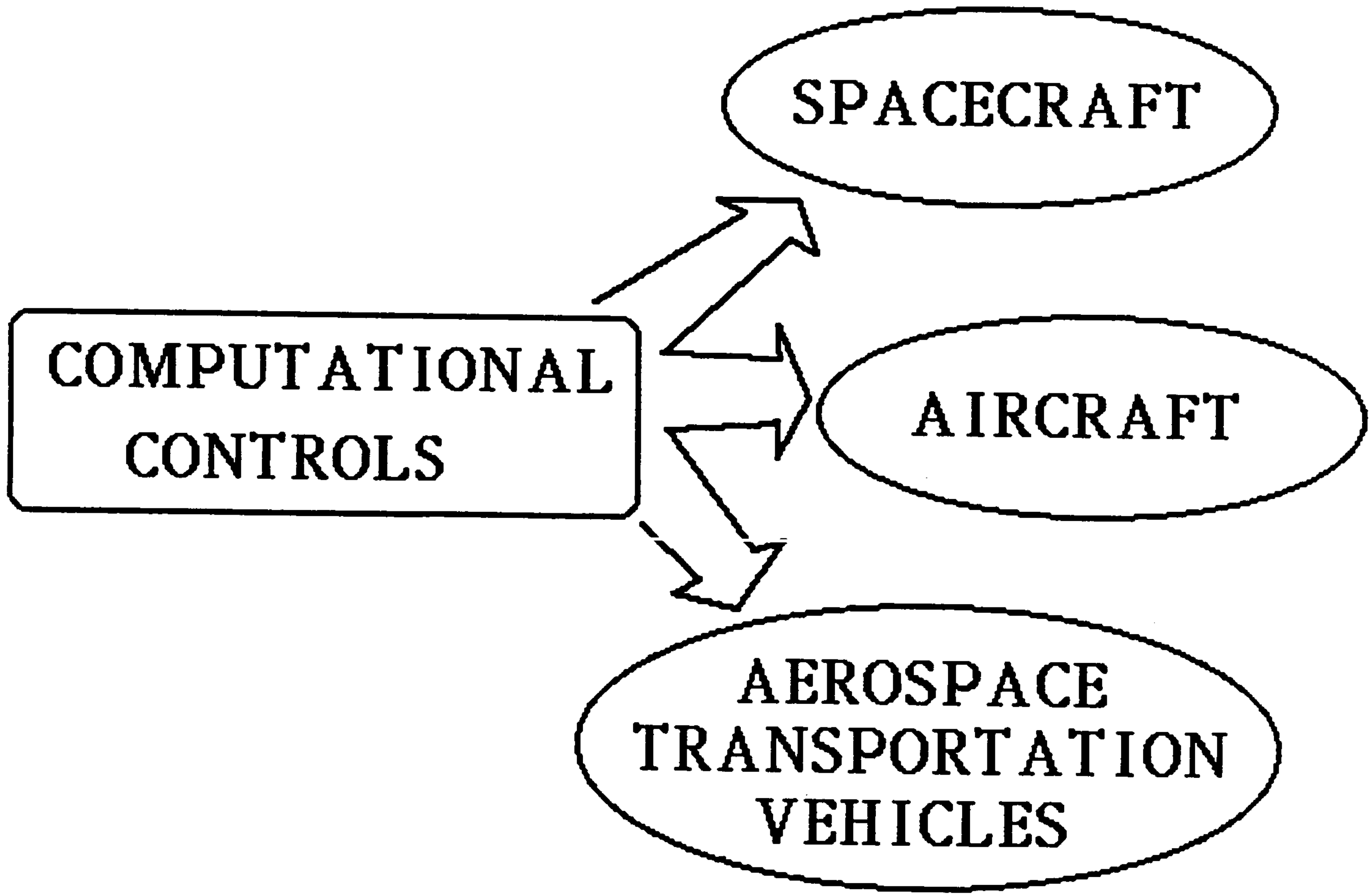
OBJECTIVE

"To Develop the NEW GENERATION

HIGH PERFORMANCE Aerospace

Modeling, Control, and Simulation Tools"

A THREE-PART PROGRAM



Computational Controls

Contacts:

Lee Holcomb - NASA HQ Code RC

John Dibattista - NASA HQ Code RC

Guy Man - JPL

Larry Taylor - LaRC

Harry Frisch - GSC

Henry Waites - MSFC

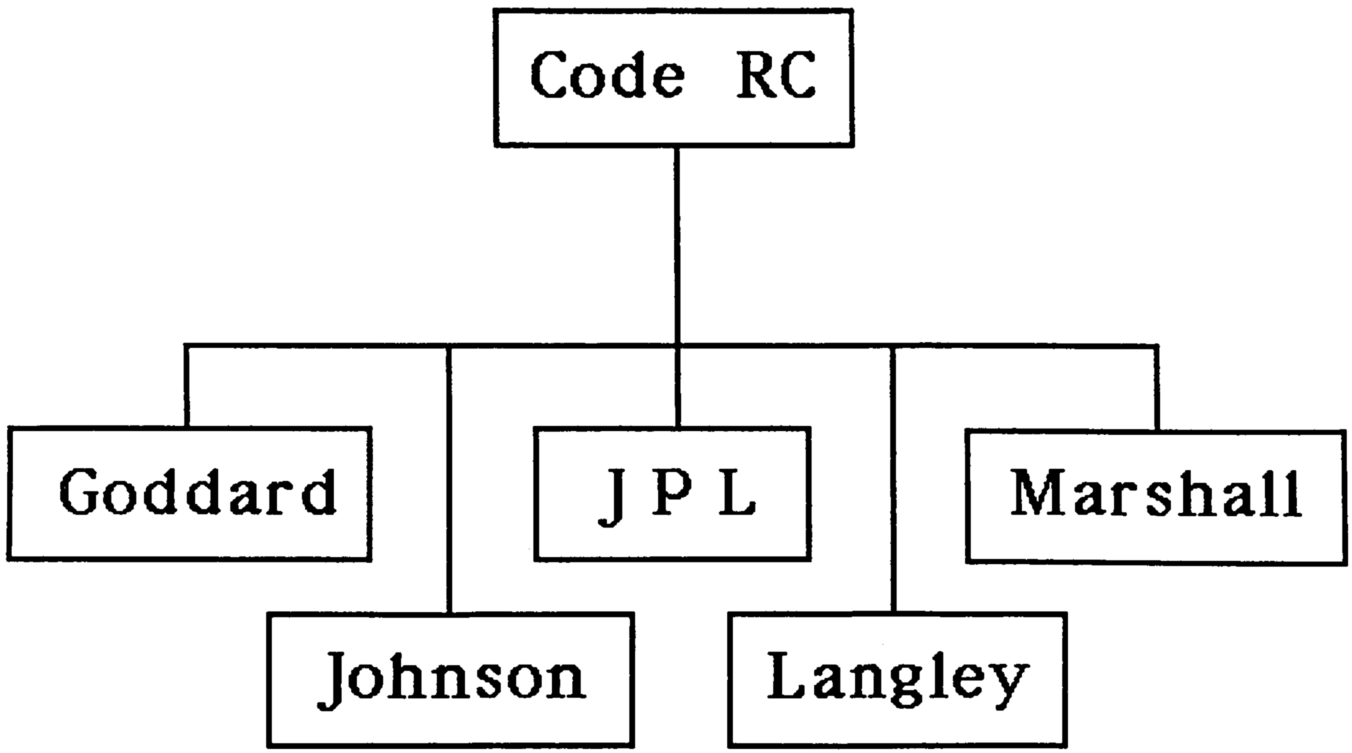
Ken Cox - JSC

JUSTIFICATION

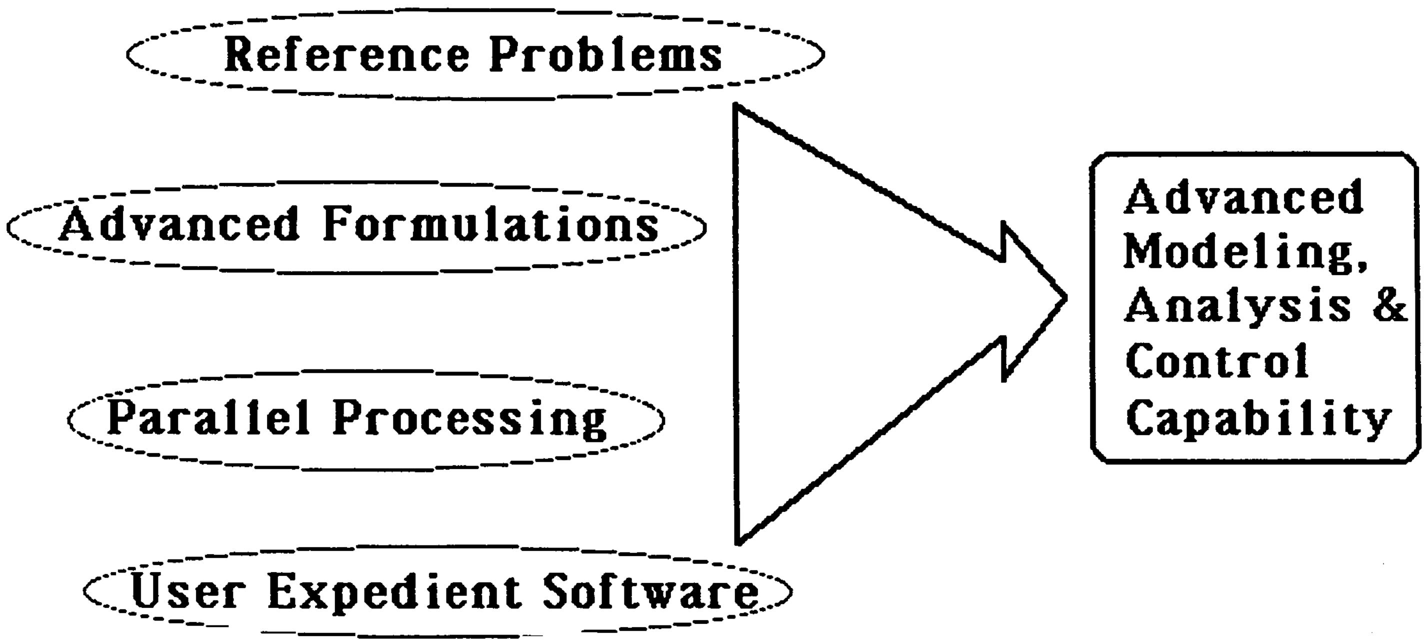
Current Practices in <u>Formulating</u>, <u>Modeling</u> and <u>Simulating</u> do not Meet today's needs.

- Hypersonic Cruise Vehicles
- Multi-Component Launch Vehicles
- Aeroassisted Orbital Transfer Vehicles

ORGANIZATION



APPROACH



Reference Problems
Advanced Formulations
Parallel Processing
User Expedient Software
Advanced Modeling, Analysis & Control Capability

Reference Problems

- Shuttle RMS
- Earth Orbiting Satellite
- Mini-MAST
- Pinhole Occulter
- Mariner Mark II
- Optical Interferometer
- Advanced Launch System
- F - 18 Fighter
- Trans-Atmospheric Vehicle

Advanced Formulations

- Order(n) Algorithms — LaRC
- Distributed Parameter Modeling — LaRC
- Mass Referenced Modeling — LaRC
- Composite Modeling — LaRC

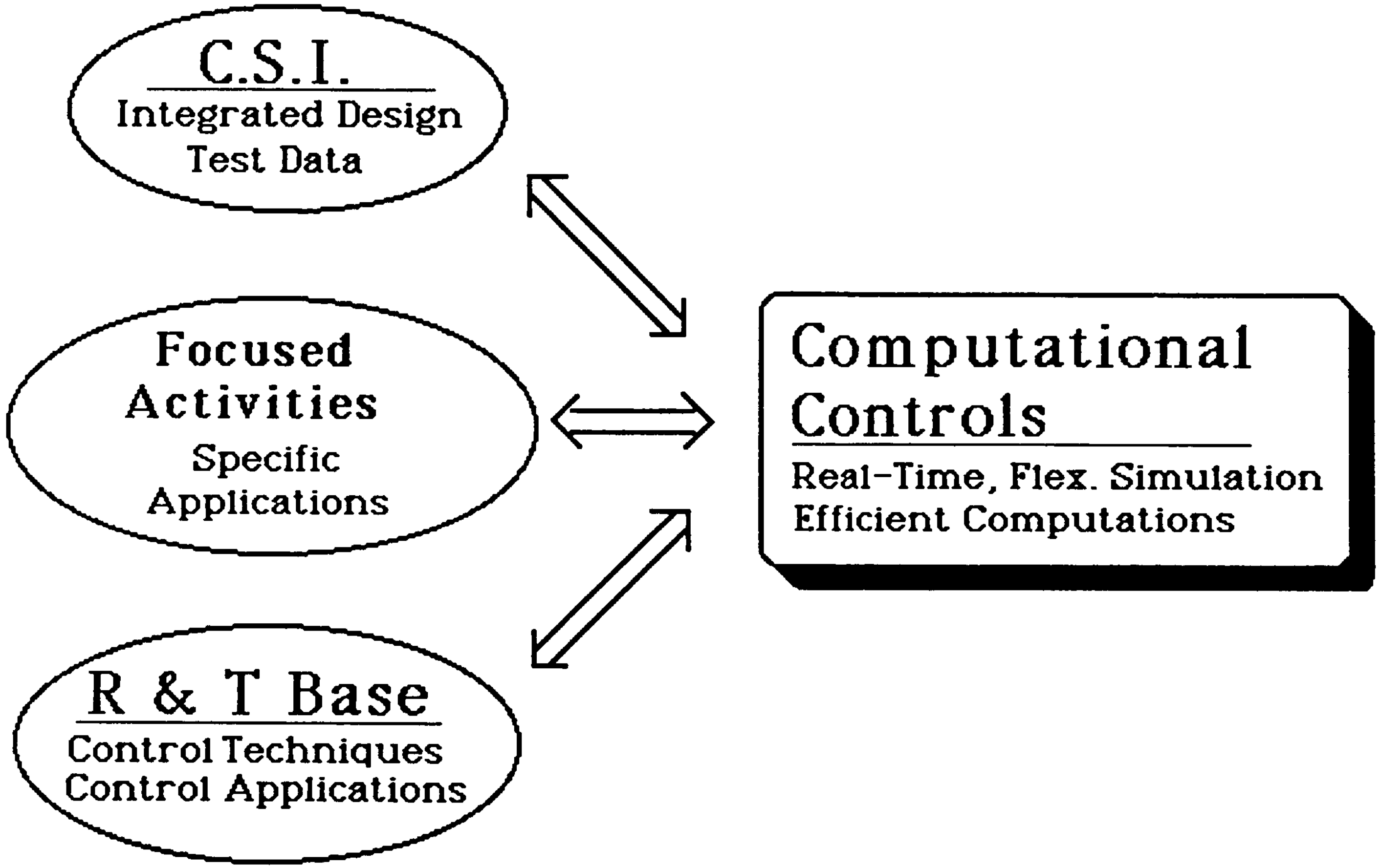
Parallel Processing

- Multiple Processors LaRC
- Array Processors LaRC
- Benchmarking LaRC

SOFTWARE

- Macintosh-Like User Environment
- Simultaneous Tasking
- Real-Time and Off-Line
- Modular (Particular Methods) LaRC
- Data Base Management
- Interactive Graphics

Related Activities

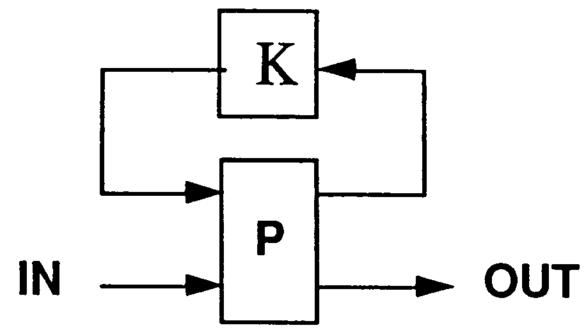


PROPOSED LARC AERO TASKS

1.1

DYNAMICS INTEGRATION AND ADVANCED CONTROL THEORY AND MODELING

- F-18 THRUST VECTORED HI- α VERSION
- TRANS-ATMOSPHERIC



1.4

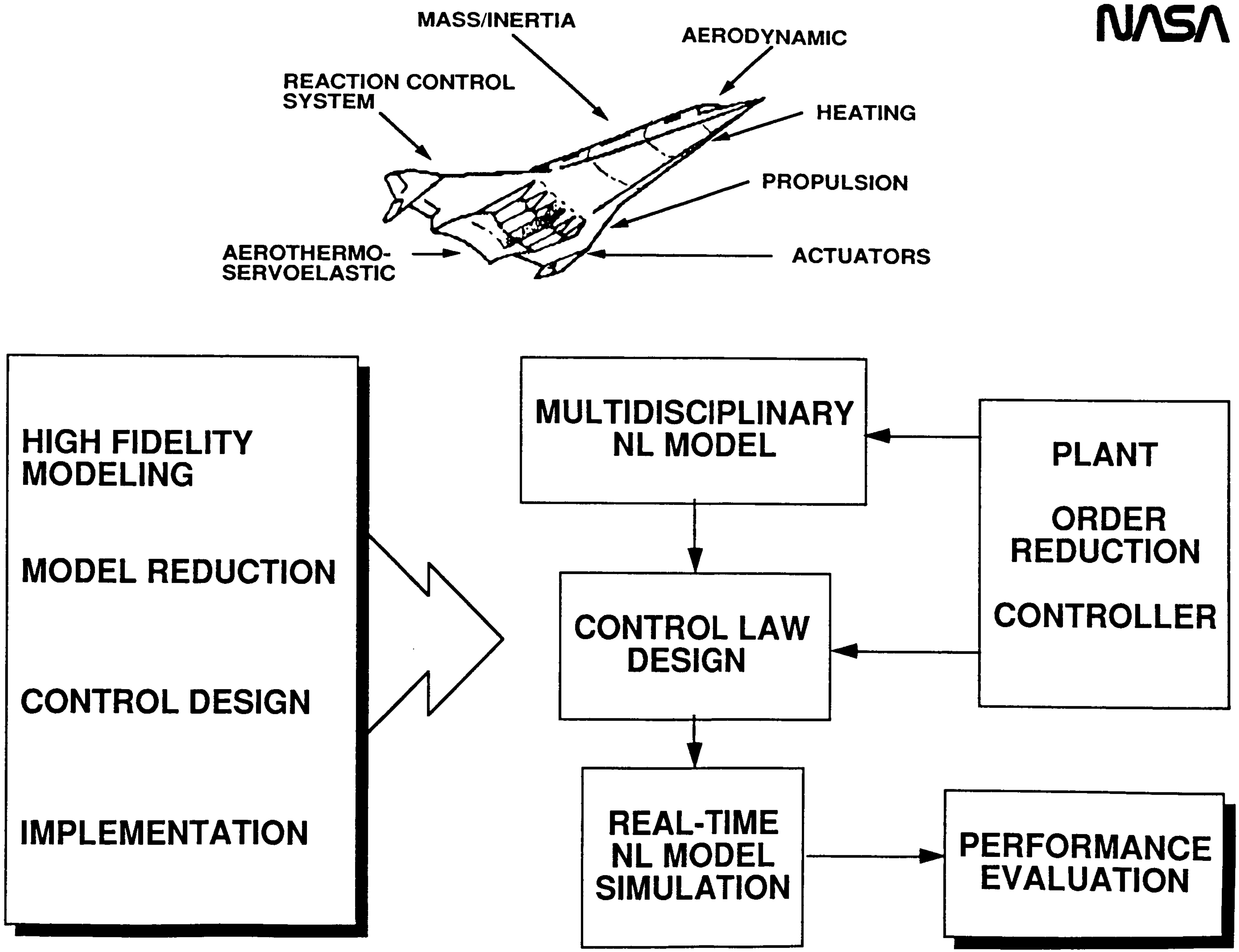
HIGH-ORDER, HIGH FIDELITY, NONLINEAR MATHEMATICAL MODELS OF HIGH PERFORMANCE AIRCRAFT

ADVANCED MODEL ORDER REDUCTION METHODS

ROBUST INTEGRATED CONTROL DESIGN METHODOLOGIES

1.5

RAPID CONTROLLER IMPLEMENTATION METHODOLOGIES


MASS/INERTIA
AERODYNAMIC
REACTION CONTROL SYSTEM
HEATING
PROPULSION
AEROTHERMO-SERVOELASTIC
ACTUATORS
HIGH FIDELITY MODELING
MODEL REDUCTION
CONTROL DESIGN
IMPLEMENTATION
MULTIDISCIPLINARY NL MODEL
PLANT
ORDER REDUCTION
CONTROLLER
CONTROL LAW DESIGN
REAL-TIME NL MODEL SIMULATION
PERFORMANCE EVALUATION

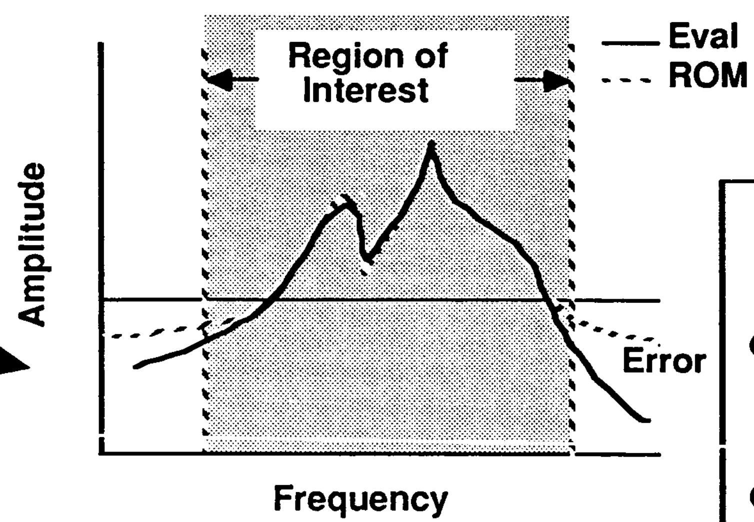
Plant Order Reduction for Controller Synthesis

Physical System

Evaluation Model

- High-Order
- Uncertain

Frequency Response



- Matches Evaluation Model in critical range
- Quantifiable errors outside region

Benefits

- Enhanced physical insight
- Error structured for robust control
- Reduced-order controllers

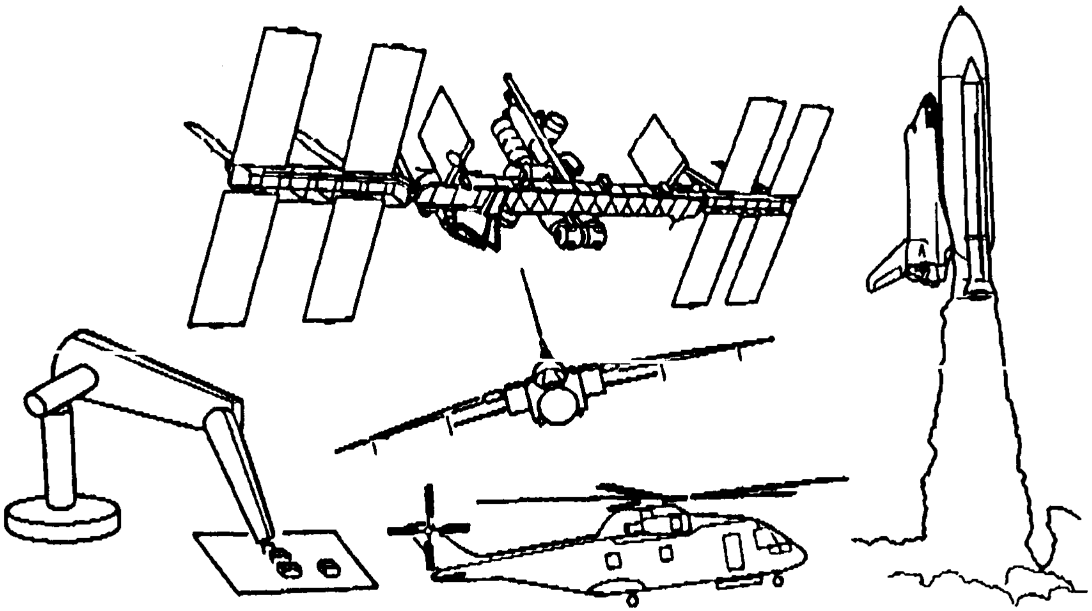
ACTIVITIES

- Advisory Committee /Quarterly
- Workshops /Annually
- Programmatic Status Repts /Quarterly
- Technical Reports /As Available

ANNOUNCEMENT & CALL FOR PAPERS

3rd Annual Conference on Aerospace Computational Control

Radisson Suite Hotel   August 28-30, 1989   Oxnard, California



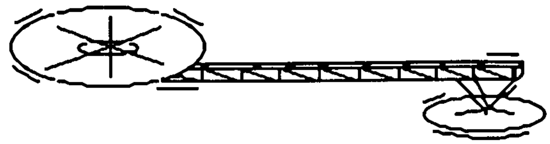
NASA

NSF

DoD

ANNOUNCEMENT of a CLASS on

TREETOPS*



* A Control System Simulation for Flexible and Articulating Structures

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WHEN: August 31, 1989(After Conference)

WHERE: 3rd Annual Conference on Aerospace Computational Control
Radisson Suite Hotel, Oxnard, CA

CONTENT:
- Overview
- Example Problems
- Hands-On Experience
- User's Manual

COST: No Charge for Class or Materials for Registered Conferees

CLASS REGISTRATION: Larry Taylor
NASA Langley
804-864-4040