Automation and Robotics for Space-Based Systems—1991

Edited by
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NASA Langley Research Center
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MAY 1992
Automation and Robotics
for Space-Based Systems - 1991

Preface

A NASA Langley workshop on Automation and Robotics for Space-Based Systems was held on December 10, 1991, from 8:30 a.m. to 4:00 p.m. This conference proceedings document presents the overhead slides from each speaker at this event. The purpose of this in-house workshop was to assess the state-of-the-art of automation and robotics for space operations from a Langley Research Center perspective and to identify areas of opportunity for future research. The workshop was sponsored by the Guidance, Navigation, and Control Technical Committee, chaired by Dr. Raymond C. Montgomery.

Nineteen talks were given, reflecting a high level of interest in the field of automation and robotics at NASA Langley. Over half of the presentations came from the Automation Technology Branch, covering telerobotic control, EVA and IVA telerobotics, hand controllers for teleoperation, sensors, neural networks, and automated structural assembly, all applied to space telerobotic missions. Other talks covered RMS active damping augmentation, space crane work, modeling, simulation, and control of large, flexible space manipulators, and virtual passive controller designs for space robots.

The 1991 NASA Langley Workshop on Automation and Robotics for Space-Based Systems provided a good overview of current effort in this field at NASA Langley. The workshop served to open or renew lines of communication between various researchers working in diverse areas of automation and robotics. This document summarizes the talks of this workshop using the presentation overheads.

Robert L. Williams II
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Summary of Compliant and Multi-Arm Control at Langley Research Center

by

Fenton W. Harrison
Single Arm System

Single Arm Philosophy

a. Axis Systems
b. Control Systems
c. Results
Single Arm Axis System

MRF - Moving Reference Frame

CRF - Control Reference Frame

Wrist

Base

World axis system
Single Arm Control Systems

1. Manual Control
2. Position control
3. Vision control
4. Force control
Single Arm Hand Controller Axis System

Desired Velocity

MRF - Moving Reference Frame

CRF - Control Reference Frame

Wrist

Base

World axis system
ISRL HAND CONTROL FLOW DIAGRAM

Fixed Scalar gain
Foot pedal gain

\[ \dot{x} \]

\[ \dot{x}_r \]

\[ M_{2W} \]
\[ \text{(S)} \]

\[ \dot{x}_{r\text{ in}_B} \]

\[ J^{-1} \]

\[ \theta_0 \]

Insure Local Smoothness

\[ \tilde{\theta}_0 \]

PID

Forward Kinematics

CALC

Wr2B

\[ W_2B \]
\[ B_2W \]

D - H Params

STORE

ARM PLANT

\[ \theta \]

\[ \text{sensor} \]
Single Arm Position Axis System

$E = R \cdot C$

CRF - Control Reference Frame

World axis system
Single Arm Vision Axis System

\[ E = R - C \]
Single Arm Force Axis System

Base

Wrist

MRF

R

C

Desired Force

E = R - C

World axis system
Multi Arm System

Multi Arm Philosophy

a. Axis Systems
b. Control Systems
c. Results
Multi Arm Axis System

Robot(n)

Robot(2)

Robot(1)

MRF

CRF
SUMMARY

Velocity Control
- Natural for operator input.
- Summing of sensor input.

Single Arm Philosophy
- Uses of sensors to correct for errors.
- Precise calibration is eliminated.

Multi Arm Philosophy
- Use many independent single arm systems to make one multi arm system.

Use of MRF and CRF
- Decouples operator from the manipulators.
- Take advantage of symmetry of task.
- To control compounded manipulators.
- Tracking of objects.

Use of optimal load distribution.
EVA ROBOTICS FOR SPACE STATION FREEDOM

Dextrous Manipulator Development (DEMAND)

Bob Williams
Automation Technology Branch
Dexterous Manipulator Development

(DeManD)

Automation Technology Branch
NASA Langley Research Center
October 1991
The Problem

- Current Space Station Maintenance demand exceeds capability.

- Increasing interest in utilizing telerobotics but limited confidence.

- Canadian SPDM would have to do the work.
Projected EVA Backlog

Backlog
(6 Hr Missions)

1995
1996
1997
1998
1999

1 2 3 4 5 6 7 8 9 10 11

1 2 3 4 5 6 7

FEL
MTC
Utilization Flights
Manned Base Flights
Objective

Evaluate and enhance Special Purpose Dexterous Manipulator (SPDM) utilization in realistic Space Station Freedom tasks.
Approach

- Identify opportunities to enhance SPDM operations for Space Station Freedom (SSF).
- Construct a functionally equivalent segment of SSF including SPDM.
- Apply and enhance technology to accomplish SPDM tasks.
- Demonstrate SPDM operations in a realistic environment.
Potential SPDM Tasks

- Inspection
- ORU Change Out
- Work Site Setup
- Repair

CURRENTLY PROJECTED SPDM TASKS DO NOT USE THE SPDM'S FULL CAPABILITY!
Dexterous Manipulator Development Laboratory - FY92
Apply and Enhance Technology

- Rate Control
- Position Control
- Hand Controllers
- Simultaneous Shared Control
- Degree-of-Automation
- Multiple Arm Control
- Computer Hardware, Software, Communications
Apply and Enhance Technology (con't)

- Force Accommodation
- Force Reflection
- Vision Control
- Laser Ranging Control
- Redundancy, Hyper-Redundancy
- Dynamics
- Disturbance Compensation
Program Goals

- Determine reliable and efficient strategies for use of SPDM
- Offer suggestions for SPDM development and usage based on hard operational data
- Develop techniques for non-standard uses of SPDM such as
  - Inspection
  - Maintenance of robot unfriendly components
  - Emergency repairs
- Provide an open resource to test innovative ideas in a realistic environment
Summary

- Space Station Office has identified robotics as a desired approach for reducing EVA backlog.
- Telerobotic worksite setup has high potential for EVA savings.
- SSF repair is not anticipated, but capability should be available
- Program will add to existing technology base and give confidence to potential robot users.
Footnote

- FTS Hardware

- Electromagnetic "Glue Gun"
IVA Robotics for Space Station Freedom

Sharon Monica Jones
Automation Technology Branch

December 10, 1991
Objective

To increase the scientific productivity of Space Station Freedom (Spacelab) during the man-tended phase and beyond
Space Station Freedom

Background

- Volume decreased
- Communication capability decreased
- Limited crew visits
- Man-tended phase begins in 1996
- Will last approximately 3 years
Man-Tended Phase
U.S. Lab Module Volume

- Core Structure: Original 44, Restructure 24
- System Racks: Original 16, Restructure 9
- User Racks: Original 28, Restructure 15

Source: LaRC SSFO
IVA Robotics

Goals

- Increase scientific productivity
  - more and/or extended experiments
  - less microgravity disturbance
  - in situ monitoring and inspection
  - more efficient rack support utilization

- Maintain U.S. space telerobotics capability
IVA Robotics
ATB Program Purpose

Demonstrate an increase in the productivity of Space Station Freedom experiments through the application of automation technology in a realistic environment
IVA Robotics

Approach

- Obtain background information
- Construct full scale laboratory module mockup
- Install telerobotic system in mockup
- Develop functional experiment hardware
- Define space IVA telerobotic criteria
Experiment
Protein Crystal Growth

PCG Flight Hardware
## Candidate Mockup Demonstrations

<table>
<thead>
<tr>
<th>DEMO NO.</th>
<th>TASK</th>
<th>SEMICONDUCTOR MATERIALS SOLIDIFICATION</th>
<th>PROTEIN CRYSTAL GROWTH</th>
<th>FLUID PHYSICS</th>
<th>COMBUSTION RESEARCH</th>
<th>FLOAT ZONE CRYSTAL GROWTH</th>
<th>GAS GRAIN SIMULATION</th>
<th>GRAVITATIONAL BIOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SAMPLE CHANGEOUT</td>
<td>DEMO 2</td>
<td>DEMO 1</td>
<td>DEMO 3</td>
<td>DEMO 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>INSPECTION</td>
<td>DEMO 2</td>
<td>DEMO 2</td>
<td></td>
<td>DEMO 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>WASTE GAS DISPOSAL</td>
<td>DEMO 2</td>
<td></td>
<td></td>
<td></td>
<td>DEMO 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>DATA REMOVAL AND STORAGE</td>
<td>DEMO 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>UTILITY HOOK-UPS</td>
<td>DEMO 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>ANIMAL AND PLANT CARE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DEMO 4</td>
<td>DEMO 4</td>
</tr>
</tbody>
</table>
IVA Robotics
IVA Team Members

- L. Keith Barker
- Walter Hankins
- Sharon Monica Jones
- Randy Mixon
- A. Terry Morris
- Kelli Willshire
HAND CONTROLLER STUDY
OF FORCE AND CONTROL MODE

1991 NASA Langley Workshop on Automation and
Robotics for Space-Based Systems

Information Systems Division
Automation and Technology Branch
A. Terry Morris

December 10, 1991
HAND CONTROLLER STUDY
OF FORCE AND CONTROL MODE

O OBJECTIVES

- COMPARE AND EVALUATE UTILITY AND EFFECTIVENESS OF VARIOUS
  INPUT CONTROL DEVICES, E.G., HAND CONTROLLERS, WITH RESPECT TO
  THE RELATIVE IMPORTANCE OF FORCE AND OPERATIONAL CONTROL MODE
  (E.G., RATE OR POSITION) FOR SPACE STATION RELATED TASKS.

O APPROACH

- STUDIES WERE DONE WITH TWO DIFFERENT MANIPULATOR
  SYSTEMS

  INTELLIGENT RESEARCH SYSTEMS LAB (ISRL) WITH A PUMA ROBOT
  AND THE TELEROBOTIC SYSTEMS RESEARCH LABORATORY (TSRL) WITH
  THE LABORATORY TELEROBOTIC MANIPULATOR (LTM), A MASTER SLAVE
  SYSTEM

- THREE STUDIES WERE PERFORMED: ONE PILOT STUDY IN ISRL,
  ONE FULL STUDY IN ISRL, AND ONE FULL STUDY IN TSRL
METHOD

O SUBJECTS
- UNDERGRADUATE ENGINEERING/SCIENCE STUDENTS, AGES 18-29 YEARS, EIGHT IN ISRL, AND EIGHT IN TSRL. AND FOUR OTHER SUBJECTS FOR ISRL PILOT STUDY PRACTICED TO PREDETERMINED LEVELS OF PERFORMANCE

O INDEPENDENT VARIABLES
- UP TO FOUR TYPES OF FORCE INFORMATION: NONE, REFLECTION, ACCOMMODATION, REFLECTION PLUS ACCOMMODATION
- THREE HAND CONTROLLERS: KRAFT, HONEYWELL, TWO 3 DOFS
- THREE TASKS: STRUT INSERTION, THERMAL BLANKET, DUAL-PEG-IN-HOLE
- TWO CONTROL MODES: RATE AND POSITION

O DEPENDENT VARIABLES
- TASK AND SUB TASK COMPLETION TIMES, FORCES EXERTED, SUBJECTIVE ASSESSMENTS

O DATA COLLECTION
- DEPENDENT VARIABLE DATA COLLECTED AUTOMATICALLY BY THE SYSTEM.
- VIDEO AND AUDIO RECORDING.
## ISRL Experimental Design - Pilot Exp

<table>
<thead>
<tr>
<th></th>
<th>HONEYWELL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TASK</td>
<td>1 2 3</td>
</tr>
<tr>
<td>FORCE</td>
<td>0.1 0.1 0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HAND CNTRL</th>
<th>FORCE</th>
<th>SUBJS</th>
</tr>
</thead>
<tbody>
<tr>
<td>KRAFT 1 2 3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Do all tasks (in randomized order) within each hand controller, counter balance for force and not force.

Total of 12 conditions per subject, three trials each.
ISRL EXPERIMENTAL DESIGN

<table>
<thead>
<tr>
<th>(3) HAND CNTRL</th>
<th>NON - FORCE REFLECTING</th>
<th>FORCE REFLECTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4) FORCE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUBJS TRIALS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 1-3</td>
<td>0, 1</td>
<td>0, 1, 2, 3, 3</td>
</tr>
<tr>
<td>. . .</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 1-3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Counter balance for force conditions
Total of 10 conditions per subject, three trials each.
Levels of force are: none (0), force accommodation (1),
force reflection with accommodation (2),
modified force reflection with accommodation (3)
## TSRL FINAL EXPERIMENTAL DESIGN

<table>
<thead>
<tr>
<th>(2) TASK</th>
<th>1 (peg)</th>
<th>2 (blanket)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) FORCE</td>
<td>0,1</td>
<td>0,1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GENDER</th>
<th>SUBJS</th>
<th>TRIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1-3</td>
</tr>
<tr>
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<td>2</td>
<td>1-3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1-3</td>
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<tr>
<td></td>
<td>4</td>
<td>1-3</td>
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<td>2</td>
<td>5</td>
<td>1-3</td>
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<td>6</td>
<td>1-3</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1-3</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1-3</td>
</tr>
</tbody>
</table>

One-half subjects practice with force reflection, and one-half practice without it. Test with opposite conditions. Do both tasks (in randomized order), counter balance for force and not force. Total of 4 conditions per subject, three trials each. (8 subjects) Force: 0 = no force reflection, 1 = force reflection
(a) Thermal blanket task

(b) Dual peg task

SIGNIFICANT PRACTICE BY TASK BY SUBTASK INTERACTION IN TSRL
# Factor Analysis Summary of Results

Top Three out of Seven Principal Components (Linear Composites) for Each Condition and Percent of Variance Explained by Them

<table>
<thead>
<tr>
<th>Component 1</th>
<th>Blanket, No Force</th>
<th>Blanket, Force</th>
<th>Dual-Peg, No Force</th>
<th>Dual-Peg, Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC Char</td>
<td>Demands &amp; Time</td>
<td>Frustration, Task Load</td>
<td>Overall Condit, and Task Load</td>
</tr>
<tr>
<td></td>
<td>(22.9%)</td>
<td>(22.775 %)</td>
<td>(24.896 %)</td>
<td>(20.202 %)</td>
</tr>
<tr>
<td>Component 2</td>
<td>Task Rank/Load</td>
<td>HC Char</td>
<td>Rank</td>
<td>Temp Demand &amp; Effort (Phys)</td>
</tr>
<tr>
<td></td>
<td>(20.826)</td>
<td>(18.979)</td>
<td>(15.269)</td>
<td>(Neg) (20.167)</td>
</tr>
<tr>
<td>Component 3</td>
<td>Handsize</td>
<td>Handsize</td>
<td>Performance by Handsize</td>
<td>Handsize by Performance</td>
</tr>
<tr>
<td></td>
<td>(17.601)</td>
<td>(15.823)</td>
<td>(14.477)</td>
<td>(19.271)</td>
</tr>
<tr>
<td>Cumulative Percent Variance</td>
<td>61.327</td>
<td>57.577</td>
<td>54.637</td>
<td>59.64</td>
</tr>
</tbody>
</table>
SUMMARY AND CONCLUSIONS

O TSRL STUDY

THERE WAS NO DIFFERENCE BETWEEN FORCE REFLECTION AND NO FORCE FOR THE TASK TIME DATA

HOWEVER, SUBJECTIVELY MORE PARTS OF THE BODY WERE IDENTIFIED AS EXPERIENCING DISCOMFORT AND THE FORCE REFLECTION CONDITIONS HAD SOMEWHAT MORE SUBJECTIVE TASK LOAD DEMANDS

FEMALES PERFORMED THE THERMAL BLANKET TASK MORE QUICKLY THAN MALES EVEN THOUGH GENDER WAS NOT CORRELATED WITH QUESTIONS ABOUT COORDINATED MOVEMENTS

THERE WAS LITTLE RELATIONSHIP BETWEEN AVERAGE TASK TIMES AND MENTAL WORKLOAD RATINGs OR TOTAL TASK LOAD INDEX MEASURES

THE KRAFT CONTROLLER WAS SIGNIFICANTLY MORE ACCEPTABLE FOR PERFORMING THE THERMAL BLANKET TASK THAN THE DUAL PEG TASK IN THE AREAS OF TRANSLATION, SINGLE AXIS MOVEMENTS, FINE MOVEMENT, AND GRIP ACCEPTABILITY.

O CONCLUSIONS

RESULTS FROM THE TSRL STUDY AGREE WITH JSC STUDY IN THAT NO DIFFERENCE WAS FOUND BETWEEN FORCE REFLECTION AND NO FORCE FOR TASK TIME DATA

HOWEVER, GENDER DIFFERENCE HAS NOT BEEN PREVIOUSLY REPORTED AND IS AN AREA FOR FUTURE INVESTIGATION

RESULTS FROM TSRL AND ISRL STUDIES WILL BE AVAILABLE FOR THE SPACE STATION PROGRAM TO USE IN MAKING DECISIONS AND DESIGNING FOR SPACE TELEROBOTS
RESULTS OF TELEROBOTIC HAND CONTROLLER STUDY
USING FORCE INFORMATION AND RATE CONTROL

Kelli F. Willshire, F. Wallace Harrison, and Edward F. Hogge
Automation Technology Branch
Ext. 41965 December 1991
RTOP 595-11-22-01
Code RC WBS 43

Research Objective
To evaluate the operator task performance and subjective workload of kinesthetic force feedback and/or local force accommodation as used with three different input control devices (e.g., hand controllers) operating in rate control mode for a Space Station Freedom related task.

Approach
Two studies were performed in the Intelligent Systems Research Laboratory with PUMA robots remotely operated under rate control using only video camera views without any direct vision. The first, a pilot study, consisted of four inexperienced subjects performing three tasks with two hand controllers, both with and without kinesthetic force feedback, e.g., force reflection. The results were used to select the dual-peg-in-hole task for the second study. For that study, eight new subjects performed the dual-peg task using three hand controllers without any force assistance, with local force accommodation, force reflection combined with local accommodation, and a modified force reflection with local accommodation.

Accomplishments
All testing has been completed, and the data (except energy) has been reduced. Statistical analysis has been started. Preliminary analysis indicates that there may be a difference between the force conditions for one of the hand controllers (e.g., Honeywell six degree-of-freedom). For that hand controller, the condition of force reflection combined with local force accommodation had the longest average task completion time. Further analyses will more closely investigate these differences as well as their relationship to subjective workload measures.

Significance
Few studies have investigated the effect of combining force reflection with local force accommodation in a rate control mode. The Space Station Freedom Program is interested in such results and may use this information in deciding upon telerobotic options for the Space Station.

Future
Further analysis will test the significance of these and other results and their implications for telerobot design.
(a) ISRL pilot study mean task times.

(b) ISRL second experiment mean times for dual-peg task.

ISRL HAND CONTROLLER STUDY MEAN TIMES ACROSS TRIALS
Coherent Laser RADAR Vision System and Taskspace Identification

Hal Aldridge

NASA Langley Workshop on Automation and Robotics for Space-Based Systems
December 10, 1991
Why Laser Radar

• Need for quick and accurate 3-D information to complete telerobotic tasks

• Advantages over radio wave based RADAR
  - Shorter minimum range
  - Smaller beamwidth for higher resolution

• Video 3-D imaging techniques are computationally intensive and require a light source

• SONAR cannot be used in space applications
Why Frequency Modulated Continuous Wave (FMCW) Laser Radar

- Unambiguous Range Measurement

- High Resolution

- Faster and more accurate than Amplitude Modulated (AM) laser radars

- Insensitive to lighting conditions
FMCW LASER BLOCK DIAGRAM

CONTROL MICROPROCESSOR

RECEIVER & SIGNAL PROCESSOR

Laser & OPTICS

SCANNER

DISPLAY GENERATOR

CONTROL CONSOLE

TRANSMITTER & SCAN CONTROL

MONITOR

RANGE

BEAT FREQUENCY
Current Problems

• Radar too large to be moved by robot

• Delicate scanning mechanism

• Doppler Effect

• Solution - Fiber Optic Based Radar
INDIVIDUAL FIBER SENSOR

NINE SENSOR MATRIX
(Front View)
Neural Networks Modeling and Control of Dynamical Systems
Outline

1. Overview of Research
2. First Year Research Objectives - Started 5/91
3. Background
4. Current Work
5. Accomplishments from 5/91-9/91
6. Second Year Research Objectives
Overview

1. Determine Nonlinear modeling capabilities
2. Develop and demonstrate a network controller
3. Implement controller in hardware for real-time use
First Year Research Objective

1. Determine capabilities and limitation of neural networks as non-linear modelers

2. Determine the applicability of neural networks as system controllers.
Background

1. The initial problem
2. Overview of Neural Networks
The Problem

Input

Network

Output
Network Architecture
1. Train the network on the dynamics of a known system.
2. Analyze the learned weights and compare with the dynamic model.
Step Response of Network

Step response of the eighth order system.
(100x100x8 recurrent network)
Analysis

Linear System

\[ y(k) = ( h(0) + h(1) z^{-1} + \cdots + h(N) z^{-N} ) r(k) \]

Let us define the operator \( Z^{-1} \)

\[ Z^{-1} r(k) = [ r(k) \ r(k-1) \ \cdots \ r(k-N) ] \]

So

\[ y(k) = [ h(0) \ h(1) \ \cdots \ h(N) ] [ Z^{-1} r(k) ] \]

Neural Network

Let us assume linear node, then

\[ y(k) = W^0_2 [ Z^{-1} r(k) ] \]

where

\[ W^0_2 = W^0_1 W^1_2 \]

so

\[ [ h(0) \ h(1) \ \cdots \ h(N) ] = W^0_2 \]
Impulse Response

After being trained on a step response.

Impulse response of the eighth order system.
(100x100x8 recurrent network)
Extending The Work to Non-linear

We have shown for a linear dynamical system

\[ \dot{y}(t) = f(t, y(t), u(t)) \quad , \quad y(t) = \int h(\tau) \ u(t-\tau) \ d\tau \]

where \( y \) is the state vector
\( f(\ ) \) is the dynamical system
\( h(t) \) is the impulse
\( u(t) \) is the input

That \( h(t) \) can be extracted out of the neural network.

If the system \( f \) is non-linear and analytic, then

The general solution is

\[ y(t) = \int h(\tau) \ u(t-\tau) \ d\tau \quad + \quad \int \int h(\tau_1, \tau_2) \ u(t-\tau_1) \ u(t-\tau_2) \ d\tau_1 \ d\tau_2 \]
\[ + \int \int \int h(\tau_1, \tau_2, \tau_3) \ u(t-\tau_1) \ u(t-\tau_2) \ u(t-\tau_3) \ d\tau_1 \ d\tau_2 \ d\tau_3 \quad \cdots \cdots \]
Discrete Volterra Series

\[ y(t) = \int h_1(t) x(t-\tau) \, d\tau + \int \int h_2(\tau_1, \tau_2) x(t-\tau_1) x(t-\tau_2) \, d\tau_1 \, d\tau_2 + \cdots \]

Discreteizing we get

\[ y(k) = \sum_{n} h_1(n) x(k-n) + \sum_{n1} \sum_{n2} h_2(n1, n2) x(k-n1) x(k-n2) + \cdots \]

Where \( h_1 \) is a one dimensional finite impulse response and \( h_2 \) is a two dimensional finite impulse response.
Neural Networks and Volterra Series

We have shown that by taking the taylor expansion of the neural network equations and matching the terms in the Volterra series we get:

\[ h_{1}(k) = \sum_{j} W_{j} W_{j,k} (1 - \tanh(b_{j}))^{2} \]

\[ h_{2}(k,l) = \sum_{j} W_{j} W_{j,k} W_{j,l} (2 \tanh(b_{j}) - 2 \tanh(b_{j}))^{3} \]

\[ h_{3}(k,l,m) = \sum_{j} W_{j} W_{j,k} W_{j,l} W_{j,m} (-2 + 8 \tanh(b_{j}) - 6 \tanh(b_{j})) \]

Where \( W_{i} \) is the weight from the internal node to the output node.

\( W_{j,k} \) is the weight from the \( k \) input node to the \( j \) internal node.

\( b_{j} \) is the bias on the \( j \) hidden node.
Example

Imperfect Square - Law Device

\[ y(t) = f(t, x(t)) \]

The solution is

\[ h_1(t_1) = ae^{-t_1} \]

and \[ h_2(t_1, t_2) = be^{-(t_1+t_2)} \]
Results

\[ h_2(\tau_1, \tau_2) = 0.04 e^{-(\tau_1 + \tau_2)} \]

\[ h_2(\tau_1, \tau_2) = \sum_j W_{j, \tau_1} W_{j, \tau_2} (2 \tanh(b_j) - 2 \tanh(b_j)) \]
Accomplishments
In First Five Months 5/91 - 9/91

1. Analyzed analytic nonlinear systems with neural networks

2. Found analytical approach to the modelling

3. Extended linear theory to nonlinear theory
   Generating two publications
   1. Submitting to the IEEE Conference on Intelligent control
   2. Submitting to the International Journal of Neural Networks

4. Began beta testing of neural network control code.
Objectives for the Next Year

1. Finish Volterra series analysis

2. Investigate capabilities and limitations of a Neural Network with feedback. (this configuration should allow the neural network to learn models that the Volterra series cannot model)

3. Start Investigating the Neural Network as a Controller

4. Develop neural network hardware
Adaptive Artificial Neural Network for Autonomous Robot Control

Michael K. Arras, Peter W. Protzel, Daniel L. Palumbo

Institute for Computer Applications in Science and Engineering (ICASE)
NASA Langley Research Center, Hampton, Virginia

* This research was supported by the National Aeronautics and Space Administration under NASA Contract No. NAS1–18605.
Neural Network Controller for Robot Arm Positioning with Visual Feedback

Initial State of the Network
View from both Cameras

Camera 1

Camera 2

Initial State of the Network
Neural Network Controller for Robot Arm Positioning with Visual Feedback

State of the Network After Training

3-D Neural Network
Initial Training of the Arm

Learning Rate

Positioning Error

Learning Steps
Automatic Recovery From Cumulative Fault-Scenarios

**Learning Rate**

- Learning Rate vs. Learning Steps
- Peaks indicating cumulative fault scenarios:
  - Joint 5 breaks
  - Camera and arm positions change
  - Joint 3 breaks and 30% of the neurons fail

**Positioning Error**

- Positioning Error vs. Learning Steps
- Peaks indicating cumulative fault scenarios:
  - Joint 5 breaks
  - Camera and arm positions change
  - Joint 3 breaks and 30% of the neurons fail
Error Reduction by Iterative Fine Movements

Positioning Error

Joint 5 breaks
Camera and arm positions change
Joint 3 breaks and 30% of the neurons fail
No. of fine movements

Learning Steps

1000
2000
3000
4000
RMS ACTIVE DAMPING AUGMENTATION

Michael G. Gilbert
Michael A. Scott
Martha E. Demeo

Langley Workshop on Automation and Robotics for Space-Based Systems

December 10, 1991
RMS ACTIVE DAMPING AUGMENTATION
LaRC / JSC BRIDGE PROGRAM

**TASK 1:** Determine active damping control feasibility using existing hardware
**TASK 2:** Active damping controller design with (minimum) hardware changes
**TASK 3:** Ground evaluation of active damping control
**TASK 4:** Flight Demonstration

---

LaRC  
Charles Stark Draper Laboratory  
JSC

Feasible using existing hardware?  
Yes  
Ground evaluation

No  
Active controller design with minimum hardware change  
Flight demonstration
DRAPER RMS SIMULATOR

Baseline Simulation
- Includes flexibility of booms, joint housings, grapple, and orbiter sidewall
- Simulation of RMS operation software in orbiter GPC
- Models nonlinear gearbox effects, friction and stiction, time delays
- Includes joint encoders, tachometers, joint motors and servos

External Input Simulation
- Allows arbitrary external joint rate command inputs for Sys ID

CSI Controller Simulation
- Added 3-axis acceleration at tip, tachometer, and encoder feedback
- Digital dynamic compensator structure
- CSI controller implementation logic
MIMO ACCELERATION CONTROL LAWS IMPROVE DAMPING

Frequency and Damping Comparisons

<table>
<thead>
<tr>
<th>RMS Position</th>
<th>Open-Loop</th>
<th>Closed-Loop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\omega$ (Hz)</td>
<td>$\zeta$ (%)</td>
</tr>
<tr>
<td>1</td>
<td>0.18</td>
<td>0.12</td>
</tr>
<tr>
<td>2</td>
<td>0.17</td>
<td>0.09</td>
</tr>
<tr>
<td>3</td>
<td>0.14</td>
<td>0.13</td>
</tr>
</tbody>
</table>

(Results using SPAS payload accelerometer model)
POTENTIAL LOAD REDUCTION BENEFIT IDENTIFIED

Tip Displacement (Inches)

Standard RMS operation (solid line)
Active damping (dotted line)

Servo Torque (ft-lbs)

SECONDS
DRS MODIFIED TO MODEL DISTRIBUTED ACCELERATIONS

CSDL formulated accelerometer equations

- Two mid-boom and three link end locations
- Three axis accelerations at each location
- Full accounting of interbody forces and nonlinear motions

CSDL modified DRS delivered

- Optional inclusion of omega-cross terms
- Calculations validated by CSDL and LaRC

Used to define feedback acceleration locations
ACCELEROMETER LOCATION DEFINED

Added Accelerometers (3-Axis)

Shoulder Yaw

Elbow Pitch

Shoulder Pitch

Wrist Yaw

Wrist Pitch

Wrist Roll

X

Y

Z
OUTLINE

Introduction
Analytical Accomplishments
Initiation of Man-in-the-Loop Simulations
Schedule
Concluding Remarks
SES TEST GOALS AND OBJECTIVES

Goal:

Obtain quantitative and qualitative SES data supporting advocacy of RMS active damping augmentation flight demonstration

Objectives:

• Measurable reductions in RMS vibration decay time
• Quantitative reductions in predicted RMS loads due to payload handling and Shuttle FCS thruster firings
• No adverse Shuttle FCS interaction
• Qualitative performance improvements defined by trained RMS operators (flight crew members)
SES MODIFICATIONS TO SUPPORT RMS
ACTIVE DAMPING AUGMENTATION

Arm dynamics simulation (Phase 1):
- Calculation of arm accelerations at limited locations
- Damping model for flexible booms
- Off-line structural loads analysis capability

Flight software simulation (Phase 2):
- Implementation of active damping controller concept
  - Acceleration feedback signals
  - Damping joint rate commands added to position hold
  - Maximum 36th order controller
  - Gain scheduling (Phase 2b)
- Operational logic and interfaces to RMS and FCS software
<table>
<thead>
<tr>
<th>Activities</th>
<th>1991</th>
<th>1992</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SES Interfaces</strong></td>
<td></td>
<td></td>
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<tr>
<td>Requirements Document</td>
<td>![Red - Planned]</td>
<td>![Blue - Accomplished]</td>
</tr>
<tr>
<td>Test Plan</td>
<td>![Green - SES Testing]</td>
<td>![Red - Planned]</td>
</tr>
<tr>
<td>Meetings</td>
<td>![Blue - Accomplished]</td>
<td>![Red - Planned]</td>
</tr>
<tr>
<td><strong>Phase 1 - Accelerometer Simulation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formulation Delivery</td>
<td>![Red - Planned]</td>
<td>![Blue - Accomplished]</td>
</tr>
<tr>
<td>Simulation Development</td>
<td>![Blue - Accomplished]</td>
<td>![Red - Planned]</td>
</tr>
<tr>
<td>JSC Validation</td>
<td>![Red - Planned]</td>
<td>![Blue - Accomplished]</td>
</tr>
<tr>
<td>Engineering Study</td>
<td>![Red - Planned]</td>
<td>![Blue - Accomplished]</td>
</tr>
<tr>
<td><strong>Phase 2a - Point Design Controller</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control CR Delivery</td>
<td>![Red - Planned]</td>
<td>![Blue - Accomplished]</td>
</tr>
<tr>
<td>Simulation Development</td>
<td>![Blue - Accomplished]</td>
<td>![Red - Planned]</td>
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<tr>
<td>JSC Validation</td>
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<td>![Blue - Accomplished]</td>
</tr>
<tr>
<td>Engineering Study</td>
<td>![Red - Planned]</td>
<td>![Blue - Accomplished]</td>
</tr>
<tr>
<td><strong>Phase 2b - Gain Scheduled Controller</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified Control CR Delivery</td>
<td>![Red - Planned]</td>
<td>![Blue - Accomplished]</td>
</tr>
<tr>
<td>Simulation Development</td>
<td>![Blue - Accomplished]</td>
<td>![Red - Planned]</td>
</tr>
<tr>
<td>JSC Validation</td>
<td>![Red - Planned]</td>
<td>![Blue - Accomplished]</td>
</tr>
<tr>
<td>Engineering Study</td>
<td>![Red - Planned]</td>
<td>![Blue - Accomplished]</td>
</tr>
<tr>
<td><strong>Final Report</strong></td>
<td></td>
<td>![Red - Planned]</td>
</tr>
</tbody>
</table>
CONCLUDING REMARKS

Analysis and control law design work progressing:
  • Applying advanced system identification methods (OKID)
  • MIMO control laws and implementation logic
  • Accelerometer calculations have been added to the non-real time simulation code
  • Potential RMS loads reduction benefit from active damping

Man-in-the-loop simulation effort has been initiated:
  • Working with JSC to use the Systems Engineering Simulator
  • Requirements document near signature
  • Engineering assessment of accelerations scheduled for April 1992
  • Active Damping Augmentation testing in June and August 1992
A SPACE CRANE CONCEPT FOR PERFORMING ON-ORBIT ASSEMBLY

JOHN T. DORSEY
SPACECRAFT STRUCTURES BRANCH

PRESENTED AT:
1991 NASA Langley Workshop on Automation and Robotics for Space-based Systems

December 10, 1991
BRIEFING OUTLINE

- WHY IS IN-SPACE CONSTRUCTION NEEDED?
- SPACE CRANE CONCEPT
- CONCLUDING REMARKS
IN-SPACE ASSEMBLY AND CONSTRUCTION ENHANCES FUTURE MISSIONS PLANNING FLEXIBILITY

Launch vehicles ➔ component masses and sizes

Assembly Options and Infrastructure

Missions ➔ Total Mass and Volume

Maximum number of mission options and planning flexibility

General On-Orbit Construction and Assembly Capability Required
IN-SPACE ASSEMBLY AND CONSTRUCTION FACILITY CONCEPT

- Mobile Base Spacecrane
- Equipment Storage Pallet
- ISAAC Facility (5 m Bay)
- Modular Aerobrake Construction
- Positioning & Attachment End Effectors
- Lunar Transfer Vehicle Assembly
SPACE CRANE

The Capability to Position and Control Spacecraft Components Precisely and Safely During Assembly Will be Achieved by Developing a Structural Space Crane Type Arm, Having Multiple Articulating Joints for Dexterity, and that can Ultimately be Operated in an Automated Mode

FEATURES

• Strength to Move and Control Large Spacecraft Components Safely
• Passive and Active "Stiffness" to Maintain a Stable and Secure Position
• Highly Controllable Large Angle Motion with Dynamic Control for Stable Trajectories
• Passive and Active Vibration Damping to Achieve Required Precision
• Reconfigurable/Adaptable Geometry to Reduce the Amount of Required On-Orbit Infrastructure
• Scaleability (Larger or Smaller Sizes) for a Variety of Applications
• Robustness and Reuseability for Long Life

NASA
FUNDAMENTAL CHARACTERISTIC

DURING NORMAL OPERATIONS, THE SPACE CRANE IS A SYSTEM THAT IS CONTINUOUSLY CHANGING IT'S STATE (STIFFNESS, VIBRATION MODES, VIBRATION FREQUENCIES) DUE TO:

- PAYLOADS

- ARTICULATION ANGLES

HOW DO WE CONTROL THIS DEVICE?
SPACE CRANE RESEARCH APPROACH

DEVELOPMENT PHILOSOPHY

- KEEP IT SIMPLE: START WITH BASIC STRUCTURE AND ADD ONLY THOSE SYSTEMS WHICH ARE REQUIRED TO MEET THE PERFORMANCE OBJECTIVES.

- ASSESS AND CHARACTERIZE THE PERFORMANCE AT EACH LEVEL OF COMPLEXITY WITH ANALYSIS AND TESTS.

HIERARCHY

- POSITIONING CONTROL
  Open Loop - Hardware Accuracy
  Closed Loop - Sensor Feedback (Vision for example)

- VIBRATION CONTROL
  Bare Structure Performance
  "D" Strut Passive Dampers
  Preshaped Command Input
  Active Damping (Feedback)
SPACECRAFT COMPONENT POSITIONING
AND ASSEMBLY TEST-BED

Active Suspension System

Crane

Actuators

Payload

End Effector

Payload Storage Pallet

Rotary Joint
ARTICULATING JOINT TESTBED

- USES PREVIOUSLY DEVELOPED HARDWARE, WITH EXCELLENT PERFORMANCE CHARACTERISTICS, FOR THE TRUSS BOOMS

- ALLOWS RESEARCH TO FOCUS ON THE ARTICULATING JOINT AND SPACE CRANE CONTROLS PROBLEMS

- CAN BE RAPIDLY RECONFIGURED

- GIVES RAPID COMPONENT REPLACEMENT AND/OR MODIFICATION CAPABILITY
CONCLUDING REMARKS

- HAVING IN-SPACE ASSEMBLY AND CONSTRUCTION CAPABILITY WILL PROVIDE A GREAT DEAL OF FLEXIBILITY FOR FUTURE MISSION PLANNING AND SPACECRAFT DESIGN

- THE SPACE CRANE HAS MANY DESIRABLE FEATURES AND CAPABILITIES FOR AN ON-ORBIT ASSEMBLY DEVICE AND THUS, SHOULD BE AN INTEGRAL COMPONENT IN ON-ORBIT ASSEMBLY SCENARIOS
ANALYSIS AND TESTING OF A SPACE CRANE ARTICULATING JOINT TESTBED

PRESENTED BY

THOMAS R. SUTTER AND K. CHAUNCEY WU
SPACECRAFT STRUCTURES BRANCH
SPACE CRANE CONCEPT WITH MOBILE BASE

TRUSS BOOM

ARTICULATING JOINT 1

ORBITING CONSTRUCTION PLATFORM

MOBILE BASE

TRUSS BOOM

JOINT 2

JOINT 3

POSITIONING AND ATTACHMENT END EFFECTORS

LINEAR ACTUATORS

○ double-hinged nodes
○ single-hinged nodes

ARTICULATING JOINT

NASA Langley Research Center
MECHANICAL VERSUS STRUCTURAL
ARTICULATING JOINT

SHUTTLE RMS

ELBOW JOINT
(MECHANCIAL)

MOTOR MODULE

SPACE CRANE

ARTICULATING JOINT
(STRUCTURAL)

LINEAR BALL SCREW
ACTUATOR

NASA Langley Research Center
ARTICULATING JOINT TEST BED AND REFERENCE TRUSS

Y-DISPLACEMENT

ARTICULATING JOINT

Y-DISPLACEMENT

APPLIED LOAD

BACKSTOP

REFERENCES TRUSS

2 3 4 5 6 8 9

2 3 4 5 6 8 9
STATIC AND DYNAMIC CHARACTERIZATION COMPLETED FOR SPACE CRANE REFERENCE TRUSS CONFIGURATION

**STATIC CHARACTERIZATION**

- Y-DEFLECTION
- REFERENCE TRUSS CONFIGURATION
- APPLIED LOAD

**APPLIED LOAD, lbf**

<table>
<thead>
<tr>
<th>DEFLECTION, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>-300</td>
</tr>
</tbody>
</table>

- EXPERIMENT (445 lbf/in)

**DYNAMIC CHARACTERIZATION**

- FIRST THREE CALCULATED FREQUENCIES: 6.77 Hz, 7.02 Hz, AND 24.42 Hz

**ACCELERATION/FORCE, g's/lbf**

<table>
<thead>
<tr>
<th>FREQUENCY, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
</tr>
</tbody>
</table>

- 6.79
- 7.00
- 24.84

EXPERIMENT
IMPROVED LINEAR ACTUATORS REDUCE ARTICULATING JOINT TEST BED BACKLASH

ARTICULATING JOINT TEST BED (AJTB) Y-DEFLECTION LINEAR ACTUATORS

ARTICULATING JOINT DETAIL

APPLIED LOAD, lbf

ORIGINAL ACTUATORS

IMPROVED ACTUATORS

APPLIED LOAD, lbf

-300 -200 -100 0 100 200 300

DEFLECTION, in

-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2

0.21 IN BACKLASH 0.09 IN 3 LOAD CYCLES

1 LOAD CYCLE

NASA Langley Research Center Sutter Wu - 91354
1-DOF SPACE CRANE SLEW MANEUVER

"Finite Element" Dynamic Model

Node 18
- Motion in X-Y plane only
- Truss members modeled as axial springs
- No EAL interface required
- Easy to model discrete dampers

Actuators

Actuator Extension Time History

\[ \Delta L, \text{ m} \]

\[ L_0 = 1 \text{ m} \]

Node 18 Position

\[ t = 0 \text{ s} \]

\[ t = 10 \text{ s} \]
Boom 2 Tip Transient Response
Finite Element Dynamic Model
D-Struts in Bay 1

Flexible - rigid body arc length, m

Time, seconds
1-DOF SPACE CRANE SLEW MANEUVER

"Component Mode" Structural Dynamics

- Booms modeled with beam elements
- Transverse shearing of beams included
- Lowest three flexible-body modes used
- Clamp-free boundary conditions applied

\[ EI = 7.64 \text{ MN-m}^2 \]
\[ \rho A = 10.7 \text{ kg/m} \]

Applied Rotation Time History

Boom 2 Tip Position

\[ \theta_{\text{applied}}(t) \]

\[ \text{t} = 10 \text{ s} \]

\[ \text{t} = 0 \text{ s} \]

\[ \text{X-coordinate, m} \]

\[ \text{Y-coordinate, m} \]
Boom 2 Tip Transient Response
Shear-Corrected Component Modes
Torque Driver Profile

Flexible - rigid body arc length, m

Time, seconds
Peak Root Member Force vs. Slew Time
Torque Driver Profile

- No tip mass
- 1000 kg tip mass
- 5000 kg tip mass

Longeron Euler buckling

Peak root member force, N

Slew time, seconds
Proposed Approach: Design actuator extension profile externally

Use LabVIEW 2 to implement the extension profile and measure the transient response and loads

Actuator Extension Time History

\[ L_0 = 1 \text{ m} \]

Time, seconds

\[ \Delta L, \text{m} \]

0 0.1 0.2 0.3 0.4 0.5

0 2 4 6 8 10

LabVIEW 2
Automated Assembly of Large Space Structures

Marvin D. Rhodes
Spacecraft Structures Branch
TELEROBOTIC ASSEMBLY FACILITY

- Truss
- Robot arm with end effector
- Pallet storage
- Y motion base
- X motion base
- Pallets with truss struts
Photo of Truss Joint Connector in the Locked and Unlocked Condition
ROBOT END EFFECTOR

Joint receptacle

Truss node

Strut holder

Truss strut

Receptacle fingers
### Assembly Projected Time

<table>
<thead>
<tr>
<th>Activity</th>
<th>Current Test (Min-Sec)</th>
<th>Projected (Min-Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Move to Canister Acquire Point</td>
<td>0.37</td>
<td>0.20</td>
</tr>
<tr>
<td>Acquire Strut in End Effector</td>
<td>2.08</td>
<td>0.41</td>
</tr>
<tr>
<td>Move Arm To Rest Position</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Position Motion Base Components</td>
<td>0.46</td>
<td>----</td>
</tr>
<tr>
<td>Move Arm to Install Position</td>
<td>1.30</td>
<td>1.15</td>
</tr>
<tr>
<td>Install Strut</td>
<td>2.49</td>
<td>0.43</td>
</tr>
<tr>
<td>Return Arm to Rest Position</td>
<td>1.13</td>
<td>1.00</td>
</tr>
<tr>
<td>Total Assembly Time</td>
<td>9.10</td>
<td>4.06</td>
</tr>
</tbody>
</table>

Projected Time Assumes Parallel Processing and Distributed Control
Current Operation Involves 48 Communication Commands/Strut @ 1 Sec/Command
Typical Truss Assembly Break Down

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time (Min)</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Move arm to canister</td>
<td>62.98</td>
<td>6.71%</td>
</tr>
<tr>
<td>Acquire strut</td>
<td>218.30</td>
<td>23.26%</td>
</tr>
<tr>
<td>Move arm to rest point</td>
<td>12.13</td>
<td>1.29%</td>
</tr>
<tr>
<td>Position robot base and turntable</td>
<td>79.27</td>
<td>8.45%</td>
</tr>
<tr>
<td>Move arm to install point</td>
<td>153.62</td>
<td>16.37%</td>
</tr>
<tr>
<td>Install strut</td>
<td>287.63</td>
<td>30.65%</td>
</tr>
<tr>
<td>Return arm to rest position</td>
<td>124.48</td>
<td>13.27%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>938.42</strong></td>
<td></td>
</tr>
</tbody>
</table>
AUTOMATED STRUCTURES ASSEMBLY FACILITY
CURRENT CONTROL HIERARCHY

OPERATOR

EXECUTIVE COMPUTER (MICRO VAX II GPX)

EXECUTIVE PROGRAM

ROBOT END-EFFECTOR

ROBOT COMPUTER (MOTOROLA 68000)

MOTION BASE COMPUTER (80286 PC)

MOTION BASE COORDINATOR

MENU INTERFACE

SERIAL INTERFACE

STEP SIGNALS

TURN TABLE  X DRIVE  Y DRIVE
Assembly Problem Summary

On Average There Are 30-50 Operator Intervention Problems Encountered During an Assembly/Disassembly Test

66% Are Positioning Errors Associated with Joint Receptacle Capture

33% Are Positioning Errors Associated with Inserting the Strut into the Receptacle

1% Result from Struts Length Errors

Correction of All Except Strut Length Errors Are Handled by the Operator from the Console by Adjusting the Robot Position or Force/Torque Balance Repositioning (Corrected by Accurate Positioning Using the Proposed Vision System)

Strut Length Errors Require Going-Over-The-Fence (Corrected by Better Guidance in Joint)
Observations and Results

Hardware Design

Grappling the receptacle for strut installation is recommended
Passive guidance is required for positioning of mating components
Positive actuation required for mechanism operation

Software Design and System Control

Complete system database required to control all operations
Operator's role in system control key to software design
Every operation must be interruptible and reversible
System must be under computer control
Concise naming conventions is vital to operator control
Sensor Monitoring and Error Recovery

Full instrumentation of each end-effector component is essential.

Video camera coverage is necessary for error recovery operations.

Automatic roll-back to preexisting state is very desirable feature.

Compliant moves provided by force/torque feedback.
Recommendations/Conclusions

Graphic simulations and component bench testing will not substitute for full hardware test experience

Significant portion of system capability empirically developed

Automated assembly is a viable option for in-space construction
Current Plans/Developments

Automated Machine Vision Guidance-E. Cooper
Distributed Microprocessor Control-B. Doggett
Installation of Large Panels-P. Quach
Rule Based Expert System Programming-C. Allen

Future Work-R. Will
Parallel System Control
Computer Graphics
Automated Path and Sequence Planning
Other Structural Configurations
Development of a Machine Vision Guidance System for Automated Assembly of Space Structures

Eric G. Cooper
Automation Technology Branch

P. Daniel Sydow
Spacecraft Structures Branch
Automated Structural Assembly Robot Vision

Objective:

Provide position verification of the node receptacle with respect to the end effector

Approach:

Fabricate custom camera/lighting hardware and adapt the 4 point target location algorithm developed in the Intelligent Systems Research Laboratory (ISRL)

Develop robust target discrimination techniques

Results:

Consistent and robust target identification and position estimation in the ASAL environment
Machine Vision Requirements

Camera and light assembly must be attached to robot end-effector

Enable the operator to monitor and provide assistance

Provide position information with no manipulator servoing to locate the target

Discriminate between similar targets within the field of view

Provide positional accuracy of at least 0.25 inches
Vision Hardware and Targets

Polished Front Face

45° Typ.

0.700 ID

1.35 OD

A

Section AA

Old Target

A

Ring Light Mount

Beam Splitter

Focused Light Mount

New Target

1.00

0.125

0.50

1.00

11/64

2.000

1.250

0.695

0.500

0.800
Reflective Efficiency

Luminance Factor
(Number of times brighter than a perfect white diffuser)

Observation Angle
Rotating motion base

(a) Schematic of Automated Structural Assembly Laboratory.

(b) Hardware in Automated Structural Assembly Laboratory.

Figure 1. Automated Structural Assembly Laboratory.
Target Identification

Image Processing Hardware

Acquire Blobs

- Frame Grab
- Threshold

Candidate Target Blobs

Blob Constraints

- Size
- Shape

Triangle Constraints

- Ratios
- Slope
- Leg Length
- Area
- Angle

Remaining 2-dimensional target data

Quad Projection

Pose Estimator

Linear Homogeneous Transformation Matrix
Pose Estimation Algorithms - Functional Description

**INPUT:**
- Target points in target coordinate system 
  \( \begin{bmatrix} T_x' \\ T_y' \\ T_z' \end{bmatrix} \)
- Corresponding image point projections 
  \( \{(x_i, y_i)\} \)

**PROCESSING:**
- Algorithms differ, but all are based on the perspective projection equations:
  \[
  x = \frac{c_x}{Z}, \quad y = \frac{c_y}{Z}
  \]
  where
  \[
  \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = c_H \begin{bmatrix} t_x' \\ t_y' \\ t_z' \end{bmatrix}
  \]
- Given a sufficient number of feature points, the pose can be determined
- Additional points increase the accuracy of the pose estimation

**OUTPUT:**
- Target pose with respect to the camera frame; i.e., 
  \( c_H \)
Triangle Constraints

- Ratios
- Slope
- Leg Length
- Area
- Angle

5 Point Target
Figure 2. Joint receptacle target.

Figure 3. Truss node with joint receptacle targets.
Figure 4. Camera and light assembly.

Figure 5. End-effector mounted camera and light assembly.
Figure 6. Robot arm at typical vision approach point.
(a) Vision system view at range of $\approx 24$ in.

(b) Vision system view at range of $\approx 18$ in.

Figure 8. Typical incremental approach.
(c) Vision system at range of \( \approx 12 \) in.

(d) Vision system view at range of \( \approx 6 \) in.

Figure 8. Concluded.
(a) Processed image after blob-size constraint applied.

(b) Processed image after blob shape constraint applied.

Figure 9. Sequential discrimination of target from background.
(c) Processed image after exhaustive triangle generation.

(d) Processed image after application of ratio test equations.

Figure 9. Continued.
(e) Processed image after triangle slope constraint applied.

(f) Processed image after length, area, and angle constraints applied.

Figure 9. Continued.
(g) Processed image after target lock-on and pose estimation. Top two lines of key give position vector in inches and millimeters, respectively. The bottom line gives rotation vector in radians.

Figure 9. Concluded.
Vision System Results from Optical Bench Tests (X Axis)

Z Axis Camera Position
- 8" (3.5")
- 12" (5.8")
- 16" (7.5")
- 20" (10")

Numbers in parentheses indicate width of region

Maximum allowable position error

Absolute Error, (in)

Relative Position in Region of Interest
Vision System Results from Optical Bench Tests (Y Axis)

Absolute Error, (in)

Z Axis Camera Position
- O 8" (3.0"
- □ - 12" (4.5"
- ● - 16" (5.8"
- • - 20" (7.0"

Numbers in parentheses indicate width of region

Maximum allowable position error

Relative Position in Region of Interest
Vision System Results from Optical Bench Tests (Z Axis)
Future Work

Implement remote light control to both enhance automation and provide an additional tool for operator assistance.

Fabricate a camera alignment fixture.

Demonstrate vision control on a complete assembly / disassembly of the ASAL truss structure.
END-EFFECTOR
MICROPROCESSOR

by

WILLIAM R. DOGGETT
Why?

- require one interface to all end-effectors in ASAL
  - each with unique control and sensing requirements
  - common command interface

- require concurrent capability

- must reduce number of signal lines required to operate each end-effector

- desire to relieve merlin robot of end-effector responsibility
AUTOMATED STRUCTURES ASSEMBLY FACILITY
PURPOSED CONTROL HIERARCHY

OPERATOR

EXECUTIVE COMPUTER

EXECUTIVE PROGRAM

ROBOT

END-EFFECTOR

ROBOT COMPUTER

END-EFFECTOR COMPUTER

MOTION BASE COMPUTER

MOTION BASE COORDINATOR

STEP SIGNALS

MENU INTERFACE

SERIAL INTERFACE

TURN TABLE

X DRIVE

Y DRIVE
END-EFFECTOR
SOFTWARE STATE TRANSITION DIAGRAM

INITIALIZE

CONTROL LOOP

WAIT FOR COMMAND

EXECUTE COMMAND

PAUSED

COMMAND PARSER

SUPervisory

COMMand Parser

EXECUTABLE

CONTINUE

REVERSE

SUPERVISORY

PAUSE

SUPERVISORY

REVERSE

CONTINUE

REVERSE

LEGEND

--- dashed lines indicate interrupts

bold lines indicate normal operation

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BLOCK DIAGRAM FOR

IDEAL

INSTALL COMPOSITE

begin

CLOSING_RECEPTACLE
action = close receptacle

EXTENDING
action = extend insertion

LOCKING
action = lock nut

UNLATCHING
action = unlatch strut

RETRACTING
action = retract insertion

OPENING_RECEPTACLE
action = open receptacle

COMPLETE
free resources

return
to control loop

INSTALL
BLOCK DIAGRAM FOR INSTALL COMPOSITE

LEGEND
BOLD software states
ITALIC function names

INSTALL

INSTALL_REVERSE

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CONCLUSIONS

IMPROVED MODULARITY

CONSISTENT INTERFACE TO THE 3 END-EFFECTORS

SUPPORT FOR CONCURRENT OPERATIONS

SUPPORT FOR PAUSE/REVERSE AT ANYTIME

SUPPORT FOR OPERATOR OVERRIDE

POTENTIAL FOR INCREASED RELIABILITY
Panel Installation Development
in
Automated Structures Assembly Lab

Cuong Quach
Design Requirements for Panel Installation Process

- High packing efficiency of panels in canister imperative
- Panels must fit into existing truss hardware with minimum modification to nodes.
- The inter-panel gap minimized to about .15 in.
- Minimize the number of mechanisms on the end effector
- End effector must be attachable to current robot
Facility view with panel installed
Executive System Software Design

and

Expert System Implementation

Cheryl L. Allen
SOFTWARE REQUIREMENTS

* Assemble and disassemble a tetrahedral truss in an automated mode
* Display and control information in support of a supervised autonomy mode of operation
* Support advanced system integration
* Accommodate hardware and procedural upgrades
Design layout of the automated assembly system.
Menu display for automated composite command (Fetch & Connect).
EXPERT SYSTEM FEATURES

An expert system is a computer program which uses knowledge and reasoning techniques to solve problems that normally require the services of a human expert.

* Inference Engine
  -- program that applies domain knowledge to known facts to solve problems
  -- KES uses a goal-directed method of inferencing

* Knowledge Base
  -- contains known facts that make up the experts knowledge
  -- KES contains attributes, classes, rules, and demons

* Rules
  -- infer attribute values
  -- KES uses If/Then constructs to represent rules
Legend:

Strut installation/removal:
1. Direct
2. Capture sequence
3. Pyramid completion
4. Free

End effector actions:
5. Capture or release second cantilevered node
6. Close fingers on end with no node
7. No nodes on either end of strut, close remaining end
8. Capture or release end of strut
9. No strut in hand

Complete robot arm state diagram and logic.
EXPERT SYSTEM BENEFITS

* Concise encapsulation of logic into rules
  -- directs sequence of moves necessary to assemble and disassemble a strut,
      determine tray operations, control panel installation/removal,
      command motion base and end effector at the device level

* Embedded within existing Fortran executive
  -- uses KES for decision making while leaving familiar operator interface intact

* Reduced amount of code for maintenance
  -- 20 if/then rules replaced approximately 850 lines of
      Fortran code

* Eased system upgrades
  -- implemented panel functions in just over 1 month
FUTURE WORK IN AUTOMATED ASSEMBLY OF LARGE SPACE STRUCTURES

Ralph Will
Automated Assembly of Large Space Structures

Project Development

"Dumb" assembly of planar truss using taught points & dedicated robot positions

Expanded truss assembly with payloads, panels, sensor guidance and graphics simulation

Curved truss structure, system dynamics and coordinated motion

"Smart" assembly of complex integrated system with sensor guidance and collision avoidance path planner
Current System Upgrade Requirements

* Taught Paths and Points Are Not Viable
  - Sensor/Vision Feedback
  - Path Planner/Collision Avoidance

* Flat Truss Is Not Useful
  - Curved Truss/Generalized End Effector

* Serial System with Excessive Communication
  - Distributed Architecture & Embedded Microprocessors

* Single-Task Operation
  - Panel Installation
  - Beam Assembly

* Need Flexibility of Knowledge-Based Artificial Intelligence
  - Expert System Executive
  - Automated Path Planning
  - Automated Sequence Planning
ASAL 1992 OBJECTIVES

I. Complete end-to-end assembly/disassembly of combination Truss/Panel structure using:
   - Machine vision for struts
   - Expert system executive
   - End effector microprocessors

II. Static manipulator arm will develop:
   - Generalized end effector sequences & procedures for curved truss, supported by expert system
   - VX-Works based distributed architecture for in-loop force/torque & path planning

III. Real-time graphics simulation to:
   - Develop generalized end effector paths
   - Study assembly sequence planning
   - Study operator interfaces

IV. Design end effector for curved Precision Segmented Reflector (PSR) truss joints which are not specifically designed for robotic operations

V. Assemble tetrahedral beam
On the Use of Torque-Wheels For the Control of Large, Flexible, Space-based Telerobotic Arms

D. Ghosh, R. C. Montgomery and S. P. Kenny
NASA Langley Research Center
Hampton, VA 23665

1991 NASA Langley Workshop on Automation and Robotics for Space-based Systems

December 10, 1991
Hampton, Va
Presentation Outline

- PROBLEM
- POTENTIAL SOLUTION -- END-POINT CONTROL
- MODELLING, ANALYSIS, AND CONTROL SYSTEM
- EVALUATION TASK
- SYSTEM SIMULATOR
- STUDIES WITH-AND-WITHOUT TORQUE-WHEELS
- CONCLUSIONS AND FUTURE PLANS
THE PROBLEM

Unpredicted Endpoint Response

Desired Motion

Correct Input
Potential Solution
- End-Point Control with Inertial Components -
System Model Used

\[ l_1, m_1 \]

\[ l_2, m_2 \]

\[ \theta_1 \]

\[ \theta_2 \]

TORQUE-WHEEL, m_3

END POINT
Joint Motor Modelling

Torque to Arm

Output Arm Angle, $\theta_a$

Motor Gain

Armature Rate, $\dot{\theta}_h$

Command Input

$T_h$

$\theta_h$

Gear Spring

Armature Shaft

Bearling Friction

$K_b$
Analysis Equations
Energy Method Used

Equations of Motion
\[
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = \frac{\partial W}{\partial q_i} - \frac{\partial F}{\partial \dot{q}_i}
\]

Lagrangian \quad L = T - V

Raleigh Dissipation \quad F

Virtual Work \quad W
Analysis Equations
Energy Method Used

(Continued)

Shoulder Joint Motor

\[ I_{s_1} \ddot{\theta}_{s_1} = k_{x_1} ( \theta_1 - \theta_{s_1} ) + k_{v_1} ( \dot{\theta}_1 - \dot{\theta}_{s_1} ) + T_{E_1} \]

Shoulder Link

\[
\left( \frac{m_1}{3} + m_2 + m_3 \right) l_1^2 \ddot{\theta}_1 \\
+ \left( \frac{m_2}{2} + m_3 \right) l_1 l_2 \dot{\theta}_2 \cos(\theta_1 - \theta_2) \\
+ \left( \frac{m_2}{2} + m_3 \right) l_1 l_2 \dot{\theta}_2^2 \sin(\theta_1 - \theta_2) \\
+ k_{x_1} ( \theta_1 - \theta_{s_1} ) = -k_{v_1} ( \dot{\theta}_1 - \dot{\theta}_{s_1} ) - T_{E_2}
\]
Analysis Equations

Energy Method Used
(Continued)

Elbow Joint Motor

\[ I_{s2} \ddot{\theta}_2 = k_x (\theta_1 - \theta_{s1}) + k_v (\dot{\theta}_1 - \dot{\theta}_{s1}) + T_{E2} \]

Forearm Link

\[
\left( \frac{m_2}{3} + m_3 \right) l_2^2 \ddot{\theta}_2 + \left( \frac{m_2}{2} + m_3 \right) l_1 l_2 \left[ \dddot{\theta}_1 \cos(\theta_1 - \theta_2) \\
- \dot{\theta}_1^2 \sin(\theta_1 - \theta_2) \right] + k_x (\theta_2 - \theta_{s2}) =
\]

\[ = - k_v (\dot{\theta}_2 - \dot{\theta}_{s2}) + T_{TW} \]
Control System
Evaluation Task

Arrest the Motion of the Arm

38.4 kg, 60 N-m @ 5 Hz

6.7 m, 204 kg

30 deg.

6.7 m, 204 kg

30 deg.

1 m/s
System Simulator

- Arm Dynamics
- Motors
- Shoulder
- Elbow
- Wheel
- Voltage Commands
- Torque
- Joint Angles and Rates
- Computer
- D/A
- A/D
- Hand Controls
Torque-Wheel Commands

Arresting Task

![Diagram showing the relationship between \( \Delta q_2 \), \( G \), and the Torque-Wheel Output, with a note indicating where the stop cmd issued here.]

Time, sec.

Stop cmd issued here
Performance With and Without Torque-Wheels
End-Point Motion for Arresting Task

End Point Vertical Position, mm

Joint Motors Only
Torque-Wheel and Joint Motors

Stop cmd issued here

82% reduction in overshoot

Time, sec.
Experimental Facility Planned
Conclusions and Future Plans

Conclusion -- Torque-wheels can be of value in suppressing vibrations -- 82% reduction in overshoot for abrupt stop commands.

- Future simulator evaluations:
  include reaction mass actuators manual control detailed models of flexibility

- Hardware evaluations
Modeling, Control, and Simulation of Flexible Link Robotic Systems

Sean P. Kenny

Spacecraft Controls Branch
NASA Langley Research Center

December 10, 1991
### INTEGRATED SOFTWARE ENVIRONMENT

<table>
<thead>
<tr>
<th>MODELING</th>
<th>CONTROL</th>
<th>SIMULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAPLE</strong>&lt;br&gt; <em>(Symbolic Mathematics)</em></td>
<td><strong>MATLAB</strong>&lt;br&gt; <em>(Control Design)</em></td>
<td><strong>GRAPHICS WORKSTATION</strong></td>
</tr>
<tr>
<td>- Symbolic Matrix Inversion for Nonlinear Models.</td>
<td>- Classical&lt;br&gt; - State Space&lt;br&gt; - Robust&lt;br&gt; - Digital</td>
<td>- Interactive.&lt;br&gt; <em>(man-in-the-loop control)</em></td>
</tr>
<tr>
<td>- Automated &quot;C&quot; Code generator.</td>
<td></td>
<td>- Interface to MATLAB and MAPLE.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- &quot;X Windows&quot; Portability.</td>
</tr>
</tbody>
</table>
MODELING SOFTWARE: MAPLE (*SYMBOLIC MATHEMATICS*)

- **OBJECTIVE:**
  
  -> Develop a software environment to automate the process of implementing Hamilton’s or Lagrange’s equations of motion.

- **ADVANTAGES:**
  
  -> Fewer errors.
  
  -> Reduce the number of floating point operations in simulations by simplifying complex expressions, e.g. symbolic matrix inversion, and matrix-vector multiplication.
  
  -> Provide a practical way to generate reliable equations.

- **DISADVANTAGES:**
  
  -> Extremely memory intensive.
  
  -> Difficulties handling multiple complex mode shape expressions.
MODELING SOFTWARE: MAPLE M.I.T. developed applications package

- CAPABILITIES:
  - Planar motion of a flexible manipulator (base fixed relative to inertia space.)
  - Up to 9 links.
  - Inertial or relative coordinates
  - Individual links can be rigid or flexible, but:
    I. A Bernoulli-Euler is assumed (no shear.)
    II. An assumed modes method (user specifies mode shapes.)
  - Stiffening effects due to rotation can be included.
  - Joints can have masses (including tip mass), and flexibility but no inertias.
# Modeling Software:
# M.I.T. Sample Input Data File

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COORDS:= inertial</td>
<td>Coordinate system used</td>
</tr>
<tr>
<td>FORESHORTEN:= no;</td>
<td>Foreshortening effect</td>
</tr>
<tr>
<td>ORTHOG:= yes;</td>
<td>Orthogonal mode shapes</td>
</tr>
<tr>
<td>NL:= 1;</td>
<td>Number of links</td>
</tr>
<tr>
<td>n1:= 2;</td>
<td>Number of modes per link</td>
</tr>
<tr>
<td>qstar1:= [TH1,Q11,Q12];</td>
<td>List of generalized coords.</td>
</tr>
<tr>
<td>m01:= 0;</td>
<td>Root mass</td>
</tr>
<tr>
<td>mL1:= m0;</td>
<td>Tip mass</td>
</tr>
<tr>
<td>k1:= infinity;</td>
<td>Joint stiffness</td>
</tr>
<tr>
<td>EI1:= EI;</td>
<td>Beam stiffness</td>
</tr>
<tr>
<td>rhoA1:= rhoA;</td>
<td>Beam mass per unit length</td>
</tr>
<tr>
<td>phi11:= &lt; sin(Pi*x/L)</td>
<td>Mode shape 1</td>
</tr>
<tr>
<td>phi12:= &lt; sin(2<em>Pi</em>x/L)</td>
<td>Mode shape 2</td>
</tr>
</tbody>
</table>
CONTROL DESIGN INTERFACE

MODELING
- MAPLE "C" CODE POST PROCESSOR

SIMULATION
- UPLOAD GAINS INTO REAL TIME SIMULATION

CONTROL
- MATLAB MEX PREPROCESSOR (EXECUTABLE SCRIPT)
- DESIGN CONTROLLER & SAVE GAIN MATRICES
REAL TIME SIMULATION

PROCESS 1

GRAPHICS
X Windows & PIXRECT

PROCESS 2

DYNAMICS & CONTROL

SHARED MEMORY
UNIX System Calls

SUBROUTINES:
- INITIALIZATION
- SYSTEM MODELS
- MATLAB - CONTROL GAINS
- ODE SOLVER
- LQR CONTROL
- SCREEN TRANSFORMATIONS

PROCESS 3

INPUT DEVICE
Dimension 6 or Mouse
Velocity Control
CLOSING REMARKS

- While not a panacea for all robotics modeling problems, symbolic mathematics programs represent a valuable tool for generating equations of motion for flexible link robotic systems.

- Desk top workstation simulators provide an economical environment to evaluate man-in-the-loop control, as well as the active damping characteristics of robotic systems.
PASSIVE DYNAMIC CONTROLLERS FOR NON-LINEAR MECHANICAL SYSTEMS

Jer-Nan Juang, Shih-Chin Wu, Minh Phan, and Richard W. Longman

NASA Langley Research Center
Hampton, VA 23665
MOTIVATION

● FEATURES OF A DEVELOPED VIRTUAL PASSIVE CONTROLLER FOR VIBRATION CONTROL OF LINEAR SYSTEMS
  ■ energy dissipative
  ■ robust in stability to system uncertainties
  ■ interpreted physically

● PROPOSED MODEL-INDEPENDENT SECOND-ORDER DYNAMIC CONTROLLER IS EXTENDED TO NON-LINEAR MULTI-BODY MECHANICAL SYSTEMS
OBJECTIVE

● DEVELOP ACTIVE MODEL-INDEPENDENT CONTROLLERS FOR SLEWING AND VIBRATION CONTROL OF NON-LINEAR MULTI-BODY FLEXIBLE SYSTEMS, INCLUDING FLEXIBLE ROBOTS
PASSIVE STABILIZATION

PASSIVE STABILIZING ELEMENTS

MECHANICAL SYSTEM
APPROACH

- THEORY FOR LINEAR SYSTEMS
  - second-order differential equations
  - energy dissipative
  - robust in stability to system uncertainties
  - interpreted physically

- EXTENSION TO NON-LINEAR SYSTEMS IS BASED ON
  - Work-Energy Rate principle
  - Liapunov stability theory
BASIC CONCEPT
(Work-Energy)

○ WORK-ENERGY RATE PRINCIPLE
  For holonomic and scleronomic mechanical systems

\[ \frac{dT}{dt} = u^T \dot{x}_a \]

where

\( T = \) Total kinetic energy
\( u = \) Generalized control force
\( x_a = \) Vector of generalized coordinates

where control force is applied
BASIC CONCEPT
(Liapunov Theory)

- STANDARD LIAPUNOV STABILITY THEORY
  - Positive definite Liapunov function

\[ L = L(x_a, \dot{x}_a, \ddot{x}, \dddot{x}) \]

where \( \dddot{x} = \text{Vector of remaining generalized coordinates} \)

- System is asymptotically stable if

\[ \frac{dL}{dt} < 0 \]
LIAPUNOV FUNCTION
(Displacement Feedback)

- POSITIVE SEMI-DEFINITE LIAPUNOV FUNCTION

\[ \begin{align*}
L &= T + \frac{1}{2} \dot{x}_c^T M_c \dot{x}_c + \frac{1}{2} (x_a - x_c)^T K_{c_1} (x_a - x_c) + \frac{1}{2} x_c^T K_{c_2} x_c \\
\end{align*} \]

where \( x_c \) = controller coordinates

- NEGATIVE SEMI-DEFINITE TIME DERIVATIVE OF LIAPUNOV FUNCTION

\[ \frac{dL}{dt} = -\dot{x}_c^T D_c \dot{x}_c \leq 0 \]

- Asymptotic stability can be accomplished even though the Liapunov function is only positive semi-definite and its time derivative is only negative semi-definite.
DYNAMIC CONTROLLER
(Displacement Feedback)

\[ M\ddot{x} + f(x, \dot{x}) = Bu \]
\[ x = \begin{bmatrix} x_a \\ \bar{x} \end{bmatrix} \]

● SYSTEM

● DYNAMIC CONTROLLER

\[ M_c\ddot{x}_c + D_c\dot{x}_c + (K_{c1} + K_{c2})x_c = K_{c1}x_a \]
\[ u = -K_{c1}(x_a - x_c) \]
LIAPUNOV FUNCTION
(Displacement & Acceleration Feedback)

● POSITIVE SEMI-DEFINITE LIAPUNOV FUNCTION

\[ L = T + \frac{1}{2}(\dot{x}_a + \dot{x}_c)^T M_c (\dot{x}_a + \dot{x}_c) + \frac{1}{2} x_c^T K_{c1} x_c + \frac{1}{2} (x_a + x_c)^T K_{c2} (x_a + x_c) \]

where \( x_c \) = controller coordinates

● NEGATIVE SEMI-DEFINITE TIME DERIVATIVE OF LIAPUNOV FUNCTION

\[ \frac{dL}{dt} = -\dot{x}_c^T D_c \dot{x}_c \leq 0 \]

● Asymptotic stability can be accomplished even though the Liapunov function is only positive semi-definite and its time derivative is only negative semi-definite.
DYNAMIC CONTROLLER
(Displacement & Acceleration Feedback)

\[ M \ddot{x} + f(x, \dot{x}) = Bu \; ; \; \; x = \begin{bmatrix} x_a \\ \bar{x} \end{bmatrix} \]

\[ M_c \ddot{x}_c + D_c \dot{x}_c + (K_{c1} + K_{c2})x_c = -M_c \ddot{x}_a - K_{c2} x_a \]

\[ u = -M_c (\ddot{x}_a + \ddot{x}_c) - K_{c2} (x_a + x_c) \]
PHYSICAL INTERPRETATION
(Velocity Feedback)

- VELOCITY FEEDBACK IMITATES
PHYSICAL INTERPRETATION  
(Displacement Feedback)

○ VELOCITY FEEDBACK IMITATES

\[ k_{c_1} \quad m_c \quad d_c \quad k_{c_2} \]

\[ x_a \quad x_c \]

○ EMULATION OF VELOCITY FEEDBACK BY MAKING

\[ k_{c_1} \text{ large}, \quad k_{c_2} \text{ small}, \quad m_c \text{ small} \]
PHYSICAL INTERPRETATION
(Displacement & Acceleration Feedback)

- DISPLACEMENT AND ACCELERATION FEEDBACK IMITATES

- EMULATION OF VELOCITY FEEDBACK BY MAKING

\[ k_{c1} \text{ small, } k_{c2} \text{ large, } m_c \text{ small} \]
APPLICATION

A Six-Degree-of-Freedom Robot

SHP: Shoulder Pitch Joint
SHY: Shoulder Yaw Joint
ELP: Elbow Pitch Joint
WRP: Wrist Pitch Joint
WRY: Wrist Yaw Joint
WRR: Wrist Roll Joint
CASE STUDY

Initial Position
x=15.3162
y=0.3048
z=0.0

Final Position
x=10.3162
y=5.3048
z=5.0

SHY = -0.451 rad = -26 deg
SHP = -0.311 rad = -18 deg
ELP = 1.211 rad = 70 deg

Angular displacement, velocities and/or acceleration of SHY, SHP and ELP joints are used for feedback.
CASE STUDY
(continued)

• Case 1:
  Displacement and velocity feedback

• Case 2:
  Displacement feedback

• Case 3:
  Displacement and acceleration feedback
SIMULATION RESULTS
(Displacement and velocity feedback)

y-Position of the End Effector
SIMULATION RESULTS
(Displacement and velocity feedback)

z-Position of the End Effector
SIMULATION RESULTS
(Displacement and velocity feedback)

Modal Displacement of First Mode of the Lower Arm
SIMULATION RESULTS
(Displacement feedback)

x-Position of the End Effector for Different Values of Control mass with Large Control Stiffness
SIMULATION RESULTS
(Acceleration & displacement feedback)

Elbow Pitch Displacement for Different Values of Control Stiffness
SIMULATION RESULTS
(Acceleration & displacement feedback)

Shoulder Pitch Displacement for Different Values of Control Mass
SIMULATION RESULTS
(Acceleration & displacement feedback)

Shoulder Yaw Displacement for Different Values of Control Damping
CONCLUSIONS

A ROBUST CONTROL DESIGN HAS BEEN DEVELOPED

- For large angle position control and vibration suppression
- Applicable to multiple-body flexible dynamic systems
- Model-independent
- Guaranteed stability
- Can use position, velocity, and/or acceleration measurements
- Physical meaning of controller parameters useful for tuning
A NASA Langley workshop on Automation and Robotics for Space-Based Systems was held on December 10, 1991. This conference proceedings document presents the overhead slides from each speaker at this event. The purpose of this in-house workshop was to assess the state-of-the-art of automation and robotics for space operations from a LaRC perspective and to identify areas of opportunity for future research. The workshop was sponsored by the Guidance, Navigation, and Control Technical Committee, chaired by Mr. Raymond C. Montgomery. Nineteen talks were given, reflecting a high level of interest in the field of automation at NASA Langley. Over half of the presentations came from the Automation Technology Branch, covering telerobotic control, EVA and IVA robotics, hand controllers for teleoperation, sensors, neural networks, and automated structural assembly, all applied to space missions. Other talks covered RMS active damping augmentation, space crane work, modeling, simulation, and control of large, flexible space manipulators, and virtual passive controller designs for space robots.