Electrical Actuation Technology Bridging

(NASA-CP-3213) ELECTRICAL ACTUATION TECHNOLOGY BRIDGING
(NASA) 753 p

Unclas

H1/20 0186498

Proceedings of a workshop held in
Huntsville, Alabama
September 29–October 1, 1992
Electrical Actuation Technology Bridging

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Preface

This document contains the proceedings of the NASA Electrical Actuation Technology Bridging (ELA-TB) Workshop held in Huntsville, Alabama, September 29—October 1, 1992. The workshop was sponsored by NASA Office of Space Systems Development and Marshall Space Flight Center (MSFC). The workshop addressed key technologies bridging the entire field of electrical actuation including systems methodology, control electronics, power source systems, reliability, maintainability, and vehicle health management with special emphasis on thrust vector control (TVC) applications on NASA launch vehicles. Speakers were drawn primarily from industry with participation from universities and government. In addition, prototype hardware demonstrations were held at the MSFC Propulsion Laboratory each afternoon. Splinter sessions held on the final day afforded participants the opportunity to discuss key issues and to provide overall recommendations. All presentations are included in this document.

The workshop organizers express their appreciation to the session chairmen, speakers, and participants, whose efforts contributed to the technical excellence of the workshop.
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⁴Paper presented in Session V on agenda.
The 1992 Electrical Actuation (ELA) - Technology Bridging Workshop was held at the Radisson Suite Hotel in Huntsville, Alabama, September 29 - October 1, 1992. This workshop was sponsored by NASA Headquarters/Code DD and hosted by the Component Development Division of the Propulsion Laboratory at the Marshall Space Flight Center. The workshop addressed key technology issues in the field of electromechanical actuation including system design, control electronics, power source systems, vehicle health monitoring, reliability, and maintainability, with special emphasis on thrust vector control (TVC) applications on NASA launch vehicles. In addition, the workshop provided the opportunity for discussion of near-term power source developments and ELA system requirements between the ELA systems and the power source communities.

Approximately 150 individuals from both government and industry participated in the workshop. Attendance is listed starting on page 3. The final workshop agenda is listed starting on page 11.

One of the more productive outputs of the workshop resulted from the splinter sessions. These sessions afforded participants the opportunity to discuss key issues and to provide overall recommendations. Most frequently emphasized was the need for detailed requirements for actuator, power source, and control electronics. These requirements are essential to perform detailed system trade studies in order to meet the critical element of a hot fire test on the SSME Technology Test Bed (TTB). A listing of suggested topics provided to each splinter session group, along with a summary output from each group, is provided starting on page 1.

Hardware demonstrations were held at the MSFC Propulsion Laboratory each afternoon of the workshop. Basic performance criteria were demonstrated by the following:

- Boeing/Allied Signal EHA TVC Prototype
- Honeywell Prototype Redundant TVC and Health Management
- LeRC/GDSS Induction Motor Prototype TVC
- MSFC Prototype TVC Actuator
- Boeing Turbo-Alternator
- Moog Prototype TVC Actuator
- MSFC and Textron SSME Propellant Control Valve Actuator

The GHe turbo-alternator was developed by Boeing and Allied Signal under the JPO-ADP Program. The primary objective for this program was to demonstrate a helium driven turbo-alternator suitable for powering electrically driven thrust vector control actuators. The hardware consisted of a single stage axial impulse turbine directly driving a 50 kW 2-pole toothless
permanent magnet alternator. The power conversion and control scheme used was a 3-phase rectified bridge and speed control loop for adjusting alternator output. The electrical power quality objective for this equipment was a modified version of MIL-STD-704 desired to minimize corona effects during launch vehicle operation. The upper transient value of 2730 was imposed for that reason, and a nominal bus voltage of 220 volts was selected. The GHe turbo-alternator was demonstrated successfully under a multitude of no load and full load conditions and is currently completing tests at Allied Signal's AiResearch Division.

The electromechanical actuator (EMA) developed under contract by HR Textron is to replace the hydraulic main oxidizer valve (MOV) on the space shuttle main engine (SSME). The unit was delivered to MSFC one week prior to the workshop; as a result, no test data was presented other than acceptance test performed at HR Textron. The plans for this EMA for the next year or year and one-half encompass characterization tests, vibration, shock EMI, EMC, flow tests, and flight simulation laboratory (FSL) tests. The summation of these tests assure that the EMA meets the requirements imposed on the hydraulic MOV actuator and qualifies it to go to Technology Test Bed for an engine hot fire test.

A table of TVC prototype hardware comparisons is found on page xvii, along with color photocopies of the demonstrated hardware.

The general consensus of the workshop was that ELA technology has been demonstrated to be feasible for SSME/STME class TVC systems, as shown by the performance capabilities of the workshop prototype hardware. However, an overall strategy towards transferring this technology to a flight program, along with the development of several key tools, is still undefined. Specific requirements must also be provided in order to focus the ELA program. Recommendations were made to hold a power source Technical Interchange Meeting (TIM) within 6 months at Kennedy Space Center. The next ELA workshop was recommended to be held no sooner than 12 months from now, focusing on full-power TVC/ELA demonstrations with redundancy management capabilities.

Proceedings from the 1992 ELA Technology Bridging Workshop are being distributed with a video summary of the prototype hardware demonstrations. The successful completion of this workshop represents a major milestone in the development of ELA systems for TVC applications. The support of NASA Headquarters/Code DD in achieving this success is gratefully acknowledged.
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MARSHALL SPACE FLIGHT CENTER

AGENDA
FOR
TUESDAY, SEPTEMBER 29, 1992

7:40 Check-in

8:00 Session I. ELA Program Overviews
    1. NASA HQ Perspective	 Paul Herr/Code DD
    2. KSC/STS Hydraulic Operations	 Carey McCleskey/KSC
    3. ELA-TB Program Overview	 Gale Sundberg/LeRC

9:15 Break
    4. NLS Keynote Speaker
    5. DOD ELA Program Overview

10:00 Session II. ELA Systems Methodology
    1. EMA Avionics Design Methodology	 John Harbison/MSFC
    2. EHA Design Methodology	 John Anderson/Boeing

11:00 Lunch

12:00 Session III. ELA Control Electronics
    1. DC Motor Control Electronics	 Justino Montenegro/MSFC
    2. AC Induction Motor Control Electronics	 Ken Schreiner/GDSS
    3. DC Motor Micro-Controller Design	 Collin Hugget/Allied Signal
    4. TVC Engine Start Transient Response	 Jeff Ring/Honeywell

1:30 Session IV. ELA Prototype Designs & Test Results
    1. Boeing/Allied Signal - EHA TVC Prototype
    2. Honeywell Prototype Redundant TVC and Health Management

2:30 Session V. ELA HARDWARE DEMONSTRATIONS

<table>
<thead>
<tr>
<th>Group I</th>
<th>Group II</th>
<th>Group III</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:45 Depart Radisson</td>
<td>EMA Motor/Gear Optimization - George Doane/UAH</td>
<td>Depart Radisson</td>
</tr>
<tr>
<td>3:00 Boeing/ASAC Demo</td>
<td>Propellant Control Valve EMA &amp; BIT - Matt Lister/Aerojet</td>
<td>Space Station Tour</td>
</tr>
<tr>
<td>3:20 Honeywell Demo</td>
<td>Depart Radisson</td>
<td>Space Station Tour (con’t)</td>
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<tr>
<td>3:45 Depart MSFC</td>
<td>Boeing/ASAC Demo</td>
<td>Boeing/ASAC Demo</td>
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<tr>
<td>4:05 Open</td>
<td>Honeywell Demo</td>
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<tr>
<td>4:25 Open</td>
<td>Depart MSFC</td>
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<td>4:45 Open</td>
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<tr>
<td>5:15 Close of Business</td>
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</table>

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NASA ELECTRICAL ACTUATION TECHNOLOGY BRIDGING WORKSHOP
MARSHALL SPACE FLIGHT CENTER

AGENDA
FOR
WEDNESDAY, SEPTEMBER 30, 1992

7:40   Check-in

8:00   Session VI. ELA Power Source Systems
1. Bipolar Lead-Acid Batteries       Chairman: David Hall/MSFC
  Doug Pierce/Johnson Controls
2. Silver Zinc Batteries            Curtis Brown/Eagle-Picher
3. Bipolar Lithium Batteries        Franz Goebel/Yardney
4. Advanced Flywheel Technology     David Eisenhauer/SatCon

8:45   Break
5. Turbo-Alternators                Cliff Jacobs/Sundstrand
6. NLS GH2 Turbo-Alternator         John Anderson/Boeing
7. ELA Power Source Simulators      Mike Bradway/LESC

9:30   Session VII. ELA Operations
1. ELA Operations Test Bed          Chairman: Carey McCleskey
2. Cryogenic Ground Support Applications
3. High Technology Test Bed         Carey McCleskey/KSC
                                   Bill St. Cyt/SSC
                                   Bob Brogdon/Lockheed

10:00  Lunch

1:00   Session VIII. ELA Prototype Designs & Test Results
1. LeRC/GDSS Induction Motor Prototype TVC
2. MSFC TVC Prototype
3. Boeing Turbo-Alternator

Chairman: Monica Hammond/MSFC

2:15  Session IX. ELA HARDWARE DEMONSTRATIONS

<table>
<thead>
<tr>
<th>Group I</th>
<th>Group II</th>
<th>Group III</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:15</td>
<td>Depart Radisson</td>
<td>Break</td>
</tr>
<tr>
<td>2:30</td>
<td>LeRC/GDSS Demo</td>
<td>ELA Gear Train, Roller &amp; Ball Screw Components</td>
</tr>
<tr>
<td>2:50</td>
<td>MSFC TVC Demo</td>
<td>Kurt Niederpruem/ ITW Spiroid</td>
</tr>
<tr>
<td>3:10</td>
<td>Boeing Turbo-Alt.</td>
<td>Depart Radisson</td>
</tr>
<tr>
<td>3:30</td>
<td>Depart MSFC</td>
<td>LeRC/GDSS Demo</td>
</tr>
<tr>
<td>3:50</td>
<td>Open</td>
<td>MSFC TVC Demo</td>
</tr>
<tr>
<td>4:10</td>
<td>Open</td>
<td>Boeing Turbo-Alt.</td>
</tr>
<tr>
<td>4:30</td>
<td>Open</td>
<td>Depart MSFC</td>
</tr>
<tr>
<td>4:50</td>
<td>Open</td>
<td>MSFC TVC Demo</td>
</tr>
<tr>
<td>5:10</td>
<td>Open</td>
<td>Boeing Turbo-Alt.</td>
</tr>
<tr>
<td>5:20</td>
<td>Open</td>
<td>Depart MSFC</td>
</tr>
</tbody>
</table>

5:30  Close of Business

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NASA ELECTRICAL ACTUATION TECHNOLOGY BRIDGING WORKSHOP
MARSHALL SPACE FLIGHT CENTER

AGENDA
FOR
THURSDAY, OCTOBER 1, 1992

7:40  Check-in

8:00  Session X. EMA FDIR and VHM
1. EMA Health Management Using Smart Sensors
   Jeff Schoess/Honeywell
2. Intelligent BIT on EMA
   Erv Hanson/LeRC
3. Fault Tolerant System Test for ELA
   Norm Osborn/Martin Marietta
4. TVC FMEA and Failures in Test
   Rae Ann Weir/MSFC
Chairman: Fred Huffaker/MSFC

10:00 Session XI. Splinter Session Assignments
1. System Designs
   Dave Renz/LeRC
2. Control Electronics
   Justino Montenegro/MSFC
3. Power Source Systems
   David Hall/MSFC
4. Operations and Ground Support
   Carey McCleskey/KSC
5. Redundancy and Health Management
   Don Brown/JSC

11:00 ELA Working Lunch (Radisson Magnolia Room)

12:00 Splinter Session Recommendations
Chairman: John Sharkey/MSFC

1:00  Session XII. ELA Prototype Design & Test Results
Chairman: Monica Hammond/MSFC
1. Moog Prototype TVC Actuator
2. MSFC & Textron SSME Propellant Control Valve Actuators
3. Allied Signal TVC EMA Prototype

2:15  Session XIII. ELA HARDWARE DEMONSTRATIONS

<table>
<thead>
<tr>
<th>Group I</th>
<th>Group II</th>
<th>Group III</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:15  Depart Radisson</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td>2:30  Moog Demo</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td>2:50  MSFC/Textron Demo</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td>3:10  Allied-Signal EMA Demo</td>
<td>Depart Radisson</td>
<td>Depart Radisson</td>
</tr>
<tr>
<td>3:30  Depart MSFC</td>
<td>Moog Demo</td>
<td>Large Space Structures Tour</td>
</tr>
<tr>
<td>3:50  Open</td>
<td>MSFC/Textron Demo</td>
<td>Large Space Structures Tour</td>
</tr>
<tr>
<td>4:10  Open</td>
<td>Allied-Signal EMA Demo</td>
<td>Large Space Structures Tour</td>
</tr>
<tr>
<td>4:30  Open</td>
<td>Depart MSFC</td>
<td>Moog Demo</td>
</tr>
<tr>
<td>4:50  Open</td>
<td>Open</td>
<td>MSFC/Textron Demo</td>
</tr>
<tr>
<td>5:10  Open</td>
<td>Open</td>
<td>Allied-Signal EMA Demo</td>
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<tr>
<td>5:20  Open</td>
<td>Open</td>
<td>Depart MSFC</td>
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5:30 Close of Business
# TABLE OF COMPARISONS

## Designed Actuator Parameters for Workshop Prototypes

<table>
<thead>
<tr>
<th>Actuator Parameters</th>
<th>Boeing/Allied Signal EHA TVC Prototype</th>
<th>Honeywell Prototype Redundant TVC</th>
<th>LeRC/GDSS Induction Motor Prototype TVC</th>
<th>MSFC Prototype TVC Actuator</th>
<th>Moog Prototype TVC Actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force (lb)</td>
<td>50,000</td>
<td>40,000</td>
<td>48,000</td>
<td>35,000</td>
<td>48,000 *</td>
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<tr>
<td>Stroke (in)</td>
<td>11.5</td>
<td>14</td>
<td>+/- 5.4</td>
<td>+/- 6</td>
<td>+/- 5.5 *</td>
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<tr>
<td>Speed (in/sec)</td>
<td>3.3</td>
<td>12</td>
<td>7.4</td>
<td>5 *</td>
<td>5.2 *</td>
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<tr>
<td>Output Power (HP)</td>
<td>25</td>
<td>75</td>
<td>34.6</td>
<td>25</td>
<td>38</td>
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<td>Input Power (KW)</td>
<td>35</td>
<td>70</td>
<td>70</td>
<td>27 *</td>
<td>30 *</td>
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<tr>
<td>Weight (lb)</td>
<td>300 *</td>
<td>230 *</td>
<td>300 *</td>
<td>380 *</td>
<td>337.3 *</td>
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<tr>
<td>Bandwidth (Hz)</td>
<td>7</td>
<td>4</td>
<td>3.2</td>
<td>3 *</td>
<td>8 *</td>
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<tr>
<td>Acceleration (in/sec²)</td>
<td>180</td>
<td>200</td>
<td>52</td>
<td>62.81 *</td>
<td>60 *</td>
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<tr>
<td>Redundancy</td>
<td>3 *</td>
<td>4 *</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Power Electronic Unit</td>
<td>Digital PWM</td>
<td>Hybrid PWM</td>
<td>Digital PDM</td>
<td>Analog PWM</td>
<td>Analog PWM</td>
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<tr>
<td>Cooling Required</td>
<td>Internal Oil</td>
<td>Passive</td>
<td>Forced Air</td>
<td>Passive</td>
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*NOTE: Test Verified Parameter*
SESSION I

ELA PROGRAM OVERVIEWS
ADVANCED DEVELOPMENT
BRIDGING PROGRAMS OVERVIEW

Presentation to:
NASA Electrical Actuation
Technology Bridging Workshop

September 29 - October 1, 1992
Radisson Suite Hotel
Huntsville, AL

Paul Herr
Advanced Programs Division
NASA Headquarters

Office Of Space Systems Development
ADVANCED DEVELOPMENT

Demonstrate and Apply Promising Technologies And/Or Procedures To a Level That Meets Flight Program Requirements
THE TECHNOLOGY MATURATION PROCESS

**LEVEL**

1. Basic Principles Observed and Reported
2. Conceptual Design Formulated
3. Conceptual Design Tested Analytically Or Experimentally
4. Critical Function/Characteristic Demonstration
5. Component/Brassboard Tested In Relevant Environment
6. Prototype/Engineering Model Tested In Relevant Environment
7. Engineering Model Tested In Space
8. "Flight-Qualified" System
9. "Flight-Proven" System

TECHNOLOGY DEVELOPMENT

ADVANCED DEVELOPMENT

OPERATIONAL SYSTEMS
ADVANCED DEVELOPMENT

Advanced Development

Technology Developers

Technology Users
TECHNOLOGY TRANSFER/INSERTION PROCESS

- User Identification of Need
- Define Level of Difficulty
- Identification of Payback
- Code R Technology Development
  - Advanced Development
  - Initiation of Bridging Programs
  - Technology Validation
- Acceptance by User

TIME (In Years)

0

5

TECHNOLOGY TRANSFER/INSERTION IS A PROCESS REQUIRING STRONG COMMITMENT AND SUPPORT FROM TECHNOLOGY DEVELOPERS AND USERS
ANATOMY OF BRIDGING PROGRAMS

- EACH BRIDGING TASK FOCUSED ON AN OBJECTIVE DEFINED BY USER(S)
  - Demonstration Payoff Benefits Are Defined "Before The Fact"
  - Leverages and Concentrates Limited Funds and Special Skills From Both Governemnt and Industry Toward Specific Objective(s)

- SMALL GROUP INCLUDES ONLY PARTICIPANTS/CONTRIBUTORS WITHIN PROCESS
  - Establishes A "New Way Of Doing Business"

- PRECIPITATES "CULTURAL CHANGE" WITHIN THE NASA INSTITUTIONAL INTER-CENTER, AND PROGRAM OFFICE STRUCTURE

- INCORPORATES ALL R&T CONSTITUENCIES AT INITIATION OF THE TASK

- OF THE FOUR BRIDGING PROGRAMS, THE ELA TASKS ARE HIGHLY INTEGRATED, TECHNICALLY ADVANCED AND MOST SUCCESSFUL
  - Showcase For The "Bridging Programs" Concept
  - Demonstration Model For Other Tasks To Emulate
ADVANCED DEVELOPMENT "BRIDGING PROGRAM"

Ground Rules

- PROJECT DIRECTED TO HIGH PRIORITY OSSD TECHNOLOGY NEEDS

- PROJECT DIRECTED AT SPECIFIC END POINT TECHNOLOGIES

- PROJECT SERVING AS A MECHANISM FOR TECHNOLOGY TRANSFER WITHIN NASA

**BRIDGING PROGRAMS ARE “PILOT PROJECTS” WHICH PROVIDE A MECHANISM TO TRANSFER TECHNOLOGY FROM THE TECHNOLOGY DEVELOPER TO THE TECHNOLOGY USER**
ADVANCED DEVELOPMENT OVERVIEW

OSSD (OSF) Technology Requirements

- DURING 1991, EARLY 1992 OSF POLLED ALL PROGRAM OFFICES (SSF, STS, ELV's, etc.) TO IDENTIFY AREA'S OF TECHNOLOGY REQUIREMENTS.

- LARGE LIST OF REQUIREMENTS WERE GROUPED & PRIORITIZED INTO 21 MAJOR CATEGORIES
  - 16 Were NASA Unique
  - 5 Were Industry Driven

- LIST OF 21 WERE PRESENTED TO OAST (Code R)
  - OAST Technology Managers Incorporated Majority Within On-going Programs

- BASED ON MULTI-APPLICATIONS AND HIGH PAYOFF POTENTIAL FOUR PILOT BRIDGING PROJECTS WERE SELECTED FOR IMPLEMENTATION
  - Three Are Now Underway (Initiated In FY91)
  - Fourth (IVHM) Selected For FY93
# OSSD (OSF) Technology Requirements Evaluation

## Technology Areas

### Program Unique Technologies

| 1 | Vehicle Health Management |
| 2 | Advanced Turbomachinery Components and Models |
| 3 | Combustion Devices |
| 4 | Advanced Heat Rejection Devices |
| 5 | Water Recovery and Management |
| 6 | High Efficiency Space Power Systems |
| 7 | Advanced Extravehicular Mobility Unit Technologies |
| 8 | Electromechanical Control Systems/Electrical Actuation |
| 9 | Crew Training Systems |
| 10 | Characterization of Al-Li Alloys |
| 11 | Cryogenic Supply, Storage, and Handling |
| 12 | Thermal Protection Systems for High Temperature Applications |
| 13 | Robotic Technologies |
| 14 | Orbital Debris Protection |
| 15 | Guidance, Navigation and Control |
| 16 | Advanced Avionics Architectures |

### Industry Driven Technologies

- Signal Transmission and Reception
- Advanced Avionics Software
- Video Technologies
- Environmentally Safe Cleaning Solvents, Refrigerants and Foams
- Non-Destructive Evaluation

### OSSD Bridging Programs
ADVANCED DEVELOPMENT "BRIDGING PROGRAMS"

Currently underway:

- ELECTRICAL ACTUATION (ELA)

- AUTONOMOUS GUIDANCE, NAVIGATION AND CONTROL (AGN&C)

- ALUMINUM-LITHIUM ALLOYS

Planned:

- INTEGRATED VEHICLE HEALTH MANAGEMENT (IVHM)
ELECTRICAL ACTUATION
Bridging Activities

OBJECTIVES

Develop and demonstrate a high power/high performance electromechanical actuator in primary flight control applications

PAYOFFS

- Elimination of high pressure hydraulic systems
- Elimination of central hydraulic APU's, hazardous/toxic fluids
- Reduction of labor intensive tests, prep time, and ops. costs
- Improved dispatch reliability, operability and abort recovery
- Improved launch window (late-hold capability)
- Reduced standdown time-rapid changeout/retest
ELA BRIDGING TEAM

JSC
- Project management & integration
- Flight dynamic requirements definition
- Fault tolerance/redundancy management strategies definition

MSFC
- Thrust vector control and propulsion control valve applications

KSC
- EMA checkout and operational concepts
- Costs/benefits analysis

LeRC
- EMA/power component development
- EMA/power system integration development and demonstration

SSC
- Development of SSME test stand for valve application for EMA demo
- Costs/benefits analysis of ground test ops. (quantify saving of elimination of hydraulic valve)
ADVANCED DEVELOPMENT "BRIDGING PROGRAMS"
AGN&C

OBJECTIVE

To develop and demonstrate autonomous guidance, navigation and control technologies in areas of:
- New sensors and sensing devices
- Ground and onboard guidance algorithms
- Navigation and control algorithms
- Vehicle monitoring systems for autonomous ascent GN&C systems

PAYOFFS

Increased launch probability
Improved ascent/entry wind measurement technology
Improved abort planning and failure adaptability
Reduced cost from improved operations
AGN&C FY91 LOW POWER LIDAR DEMONSTRATIONS

TEST PLAN

CONDUCT DAILY EXPERIMENTS TO ENABLE EXTRAPOLATION TO A FULL POWER SYSTEM CONSISTING OF CALIBRATION USING HARD TARGET AND BACKSCATTER PROFILES

CONDUCT EXPERIMENTS TO ESTABLISH RELATIVE PERFORMANCE DATA BASE:

- Jimisphere
- Rawinsonde
- Radar Wind Profiler
- Instrumented Shuttle Training Aircraft
- Tower Mounted Anenometer Network
Aluminum-Lithium
Bridging Activities

OBJECTIVES

Validate the readiness of Aluminum-Lithium (Al-Li) alloys for Space Transportation Needs

Demonstrate the viability of Al-Li alloys by a sublength, full diameter External Tank demo build

Identify processes and hardware required for the manufacture of an Al-Li cryotank.

PAYOFFS

Weight reductions allow robust designs and increases in safety and reliability

Design studies indicate 10-15% potential weight savings
AL-Li BRIDGING TEAM

MSFC
- Al-Li Alloy Characterization (ALCOA 2090 and Weldalite)
- Weld Processes/Techniques Definition
- Demo/Build/Test a sub-length full diameter external tank

LaRC
- Al-Li Alloy Characterization
  - Superplastic forming
  - Net shaped forming
- Automated Weld Process and NDE Processes for Fabrication

AL-Li Bridging Program
PROPOSED FY93 NEW BRIDGING TASKS

OSSD TECHNOLOGY ASSESSMENT ACTIVITIES HAVE RESULTED IN IDENTIFICATION OF POTENTIAL NEW BRIDGING TASKS IN:

• INTEGRATED VEHICLE HEALTH MANAGEMENT
  – Engine/Propulsion Systems/ Components
  – TPS/Structural Element Measurements
  – Advanced Transducer/Sensor Demos
  – Other Subsystems (Power, GN&C, ECLSS)

IVHM BRIDGING PROGRAMS OBJECTIVE:
• To Integrate And Demonstrate Practical Systems Level IVHM Concepts To Prove That Significant Operational Benefits And Cost Savings Will Be Gained By Implementation Of Future Launch Vehicles And Other Space Transportation Elements
TARGET VEHICLE SET

TIME

Near Term (5-10 Yrs)

EXISTING
TARGET 1
ELVs
- Titan
- Delta
- Atlas

TARGET 2
SHUTTLE
- MPS
- OMS/RCS
- ORBITER SYSTEMS
- SRB
- OPS

NEW
TARGET 3A
EXPENDABLE
- NLS
- CTV
- HLLV

TARGET 3B
REUSABLE
- ACRV
- SSF
- etc.

TARGET 3C
SHUTTLE DERIVED
- MPS
- SRB
- CTV

Far Term (10-20 Yrs)

FUTURE
TARGET 4
- PLS
- HL20

TARGET X
Lunar Lander
TLI
Mars Transfer
etc.

18 September 92
Integrated Vehicle Health Management Technology Bridging Program
# BENEFITS/DRIVERS

## TOP PRIORITY

<table>
<thead>
<tr>
<th>Item</th>
<th>COST</th>
<th>RELIABILITY</th>
<th>OPERABILITY</th>
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<tbody>
<tr>
<td>Real time engine diagnostics</td>
<td>X</td>
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<td>X</td>
</tr>
<tr>
<td>Leak detection</td>
<td>X</td>
<td></td>
<td>X</td>
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<td>IVHM Architecture</td>
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<td>Ground processing Integration</td>
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<td>X</td>
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<td>IVHM for EMA</td>
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<td>X</td>
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<tr>
<td>OMS/RCS</td>
<td>X</td>
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<tr>
<td>IVHM Cost/Payback analysis*</td>
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## DESIRABLE

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<th>Item</th>
<th>COST</th>
<th>RELIABILITY</th>
<th>OPERABILITY</th>
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<tbody>
<tr>
<td>Post flight/test data analysis for engines</td>
<td>X</td>
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<tr>
<td>IVHM for mission operations</td>
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<tr>
<td>Automated Inspection techniques for engines</td>
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<tr>
<td>Flight/ground test plume spectroscopy</td>
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<td>Laser pyros</td>
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<td>SSF Fault Management system</td>
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<tr>
<td>Hybrid Reliability/fault tolerance/cost tool</td>
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* Application required for all demos
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<tr>
<th>OBJECTIVE</th>
<th>FACILITY</th>
<th>BENEFIT</th>
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<tbody>
<tr>
<td>REAL TIME ENG. DIAG.</td>
<td>SENSOR &amp; SW VALIDATION</td>
<td>SAFE SHUTDOWNS-TEST, HOLD-DOWNS, FLIGHT</td>
</tr>
<tr>
<td>LEAK DETECTION</td>
<td>AUTOMATIC MONITORING FOR LEAKING FLUIDS</td>
<td>MSFC MULTIPURPOSE H2 TESTBED &amp; SSC</td>
</tr>
<tr>
<td>IVHM ARCHITECTURE</td>
<td>UTILIZE TEST BED TO VALIDATE AVIONICS SUPPORT FUNCTIONS</td>
<td>JSC - JAEEL</td>
</tr>
<tr>
<td>GROUND PROCESSING INTEGRATION</td>
<td>DEMO GND. PROCESSING FOR PLANNING/SCHED.</td>
<td>KSC ENGINEERING DEVELOPMENT LAB</td>
</tr>
<tr>
<td>IVHM FOR EMA</td>
<td>DEMO VHM FOR EMA SYST. INCLUDING PWR. &amp; AV. INTERFACES</td>
<td>MSFC COMPONENT LAB, CONTRACTOR LAB</td>
</tr>
<tr>
<td>OMS/RCS</td>
<td>DEVELOP NON-INTRUSIVE SENSORS/SOFTWARE FOR RCS PRESSURE REG. &amp; VALVES.</td>
<td>OMS/RCS FLEET LEADER TEST ARTICLE - WSTF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>REDUCE TURNAROUND, IMPROVE SAFETY, MINIMIZE FLUID LINE DISCONNECTS.</td>
</tr>
</tbody>
</table>
CURRENT BRIDGING PROGRAMS
SUPPORT CENTAUR EVOLUTION

Al-Li Alloy Structures
• 11% Lower weight than 2219 Al

EMA (ELA) TVC
• Enables automated end-to-end C/O
• Assembly & C/O Savings >1000 hours
• Improved reliability - Failure probability reduced by factor of 8
• 35 lb. Weight reduction
• Eliminate engine driven hydraulic pumps & system
• Eliminate ground hydraulic support equipment

EMA (ELA) Fluid Systems Valves
• Compatible with automated health monitoring & BIT
• 60% Reduction in C/O time with BIT
• Compatible with fault tolerant design

Automated Ground Health Management System (IVHM)
• 3 Day reduction in on-stand processing time
• Eliminates 30 stripchart recorders
• Modular infrastructure for growth/upgrades
• Efficient anomaly analysis and isolation
• Integrated control and display system
• Avoids break in inspection, setup, C/O, analysis and closeout when problems occur

Adaptive Guidance Navigation & Control (AGN&C)
• Automated mission planning with 6:1 reduction in planning time
• Reassignment of payloads in 5 days
ADVANCED DEVELOPMENT "BRIDGING PROGRAMS"

Summary

- "BRIDGING" THE GAP BETWEEN TECHNOLOGY DEVELOPERS AND USERS IS KEY TO SUCCESSFUL TECHNOLOGY TRANSFER/INSERTION

- CURRENT BRIDGING PROGRAMS ARE SERVING AS "PILOT PROJECTS" FOR TECHNOLOGY TRANSFER/INSERTION PROCESS WITHIN NASA
  - To date, technical progress is good
  - Demonstrating how well small intercenter groups work together
  - Stimulating significant interest with all NASA centers
  - Industry cooperation/cost sharing is gaining momentum

- BRIDGING PROGRAMS OFFER "NEW WAYS OF DOING BUSINESS"
  - Leverages technical excellence from NASA centers and industry
  - Places agency "gain sharing" ahead of "not invented here"
  - Focuses on needs of user
  - Recognizes budget and schedule constraints

- ATTENTIVE MANAGEMENT OF TECHNOLOGY BRIDGING IS VITAL FOR EFFECTIVE TECHNOLOGY TRANSFER
ELECTRIC ACTUATION

TECHNOLOGY BRIDGING PROJECT WORKSHOP

STS HYDRAULIC VS. ELA OPERATIONS SRB ASSESSMENT

(ELECTRIC SRB AFT SKIRT CONCEPT)

Carey M. McCleskey, NASA/KSC
Haley W. Rushing, ASSI/KSC
LAUNCH SITE ELECTRIC ACTUATION STUDY

PRIMARY SRB TVC LAUNCH SITE WORK FLOW / SEQUENCE(S)

1. SPENT SRB RECOVERY
2. HANGAR AF
3. TVC DESERVICE FACILITY
4. REMANUFACTURE FACILITY (ARF)
5. AFT SKIRT TEST FACILITY
6. RPSF
7. VAB
8. PAD (S)

LC -39

ORIGINAL PAGE IS OF POOR QUALITY
ASSEMBLY AND REFURBISHMENT FACILITY (ARF)

MANUFACTURING BUILDING

LOGISTICS STORAGE AREA

BREAK ROOM

MACHINE SHOP

STRUCTURES REPAIR AREA

HIGH BAY

FORWARD ASSY BUILDUP AND QUEUEING

ACO TEST STATION

FORWARD ASSY SUBSYSTEM AND ELECTRONICS AREA

TPS PREPARATION AND FINISH AREA

ENVIROM TEST LAB

Fig 2.2.1.2.1-1
ARF MANUFACTURING BUILDING TVC AREAS

SYMBOLS

- 100 K AREA
  (10843 SQ FEET)

- NON CLEAN AREA
  (1089 SQ FEET)

- EXPLOSIVE PROOF & 100 K AREA

APU/HYDRAULICS
TYPE TVC
ARF MANUFACTURING BUILDING TVC AREAS

SYMBOLES:
- MANUFACTURING AREAS FOR APU/HYDRAULICS WHICH ARE NOT NEEDED FOR ELECTRICAL TVC SYSTEM
- MANUFACTURING AREAS FOR ELECTRICAL ACTUATION SYSTEM (3490 SQUARE FEET)
AFT SKIRT TEST FACILITY AREAS vs OPERATIONS
<table>
<thead>
<tr>
<th>OPERATION/FUNCTION</th>
<th>CURRENT SRB AREA</th>
<th>NEW PROJECT WITH APU/HYD REQ</th>
<th>NEW PROJECT WITH EMA REQ.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ROOM</td>
<td>SQ FT*</td>
<td></td>
</tr>
<tr>
<td>PRE CLEAN</td>
<td>M109</td>
<td>839*</td>
<td>YES</td>
</tr>
<tr>
<td>FINAL CLEAN</td>
<td>M109A**</td>
<td>666</td>
<td>YES</td>
</tr>
<tr>
<td>TANK FARM (OUTSIDE AREA SEE NOTE 1)</td>
<td>-</td>
<td>-</td>
<td>YES</td>
</tr>
<tr>
<td>TUBE &amp; HOSE FACILITY</td>
<td>M110</td>
<td>2526</td>
<td>YES</td>
</tr>
<tr>
<td>CLEAN RM ANTE ROOM</td>
<td>M119A</td>
<td>529</td>
<td></td>
</tr>
<tr>
<td>AREA CORRIDOR</td>
<td>M119</td>
<td>155</td>
<td></td>
</tr>
<tr>
<td>LRU MAINTENANCE SHOP (COMP ASSEMBLY)</td>
<td>M116</td>
<td>550</td>
<td>YES</td>
</tr>
<tr>
<td>HYDRAULIC PUMP ROOMS (CATS TEST MEDIA)</td>
<td>M117</td>
<td>250*</td>
<td>YES</td>
</tr>
<tr>
<td>HYDRAULIC &amp; HYDRAZINE COMP ACCEPTANCE TEST</td>
<td>M118</td>
<td>898</td>
<td>YES</td>
</tr>
<tr>
<td>CLEAN ROOM ANTE ROOM</td>
<td>M117A</td>
<td>440</td>
<td></td>
</tr>
<tr>
<td>SUB ASSEMBLY AREA ANTE ROOM (PRE CLEAN TO HOSE SHOP)</td>
<td>M120</td>
<td>1431</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>M120A</td>
<td>158</td>
<td></td>
</tr>
<tr>
<td>AFT SKIRT TEST BAYS</td>
<td>M126***</td>
<td>1174</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>M127</td>
<td>1158</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1158</td>
<td></td>
</tr>
<tr>
<td>TOTAL SQ FT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100K AREA</td>
<td>10843</td>
<td>10843</td>
<td></td>
</tr>
<tr>
<td>NON CLEAN AREA</td>
<td>1089</td>
<td>1089</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>11932</td>
<td>11932</td>
<td></td>
</tr>
</tbody>
</table>

* NORMAL MANUFACTURING AREA i.e. NOT 100K CLEAN

** EXPLOSION PROOF AREA

*** M126, ASSEMBLY CELL CURRENTLY USED AS INSF/WORK STATION

NOTE 1: OUTSIDE & WEST OF ROOMS 109 & 109A; TANKS FOR THE

<table>
<thead>
<tr>
<th>DEIONIZED WATER</th>
<th>SUPPLY -3000 GALS</th>
<th>255 GALS WASTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FREON</td>
<td>SUPPLY -225 GALS</td>
<td>225 GALS WASTE</td>
</tr>
<tr>
<td>ALCOHOL</td>
<td>SUPPLY -3000 GALS</td>
<td>3000 GALS WASTE</td>
</tr>
</tbody>
</table>
### SRB CIL LRU's ASSESSMENT

### SUMMARY

<table>
<thead>
<tr>
<th></th>
<th>APU/HYDRAULICS</th>
<th>ELA *</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TOP 20</strong></td>
<td>9</td>
<td>0 TO 1</td>
</tr>
<tr>
<td><strong>CRIT 1</strong></td>
<td>194</td>
<td>1</td>
</tr>
<tr>
<td>(Includes items in the TOP 20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CRIT 1 R</strong></td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td><strong>TOTAL TVC</strong></td>
<td>202</td>
<td>4 TO 5</td>
</tr>
</tbody>
</table>

| **TVC + TVC ELECT SUPPORT LRUS** | 205 | 8 TO 9** |
| **TVC % OF SRB CIL LRU's**      | 34 % | 2 % of reduced SRB CIL’s with deletion of APU/HYD TVC |

*Assumes no LRU's explosive or which propagate fire

**Includes CAT 1 ATVC INTERFACE BOX, + 2 CAT 1R CABLE HARNESS, + 1 CAT 1R POWER HARNESS
## SRB TVC AFT SKIRT ASSEMBLY AND REFURBISHMENT*

**APU/HYDRAULICS vs ELECTROMECHANICAL ACTUATION**

<table>
<thead>
<tr>
<th>OPERATION</th>
<th>APU/HYDRAULIC WORK DAYS</th>
<th>ELA WORK DAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESERVING</td>
<td>5</td>
<td>NOT APPLICABLE</td>
</tr>
<tr>
<td>DISASSEMBLY FROM AFT SKIRT AND MODULE</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>OFFLINE BUILDUP</td>
<td>38</td>
<td>4</td>
</tr>
<tr>
<td>IN SKIRT BUILDUP</td>
<td>32</td>
<td>10</td>
</tr>
<tr>
<td>AFT SKIRT SERVICE &amp; CHECKOUT</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>(NOTE FOR ELA NO SERVICING REQUIRED)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>100</strong></td>
<td><strong>20</strong></td>
</tr>
</tbody>
</table>

* LRU/COMPONENTS INSPECTION, REFURBISHMENT, TEST AND CHECKOUT IS COVERED AS A COST ITEM.
## SRB TVC
### APU/HYDRAULICS VS. ELECTROMECHANICAL ACTUATION
#### LRU/COMPONENTS INSPECTION REFURBISHMENT, TEST AND CHECKOUT COSTS

<table>
<thead>
<tr>
<th>LRU/COMPONENT</th>
<th>MISSION SET AVERAGE COST</th>
<th>LRU/COMPONENT</th>
<th>MISSION SET ESTIMATED COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-Site Vendor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyd. Power Unit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APU</td>
<td>590,000</td>
<td>Electric Power Battery/each mission</td>
<td>$80/160 K*</td>
</tr>
<tr>
<td>Hyd. Pump</td>
<td>22,000</td>
<td>Actuator Assembly</td>
<td>63/125 K</td>
</tr>
<tr>
<td>Actuators</td>
<td>323,600</td>
<td>Controller**</td>
<td>2.2 K</td>
</tr>
<tr>
<td>On-Site Contract</td>
<td>216,328</td>
<td>ELA</td>
<td>$149,000 to $287,000</td>
</tr>
<tr>
<td>(TBE) (Reservoirs, Accumulators, Manifests, check valves, filters, etc.)</td>
<td>$1,151,928</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Depends on Battery Type Selected

** Assumed protected from salt water contact and requires on-site bench test and inspection only.
# INTEGRATED OPERATIONS

## APU/HYDRAULICS VS. EMA

<table>
<thead>
<tr>
<th>OPERATION</th>
<th>APU/HYD SERIAL HOURS</th>
<th>EMA SERIAL HOURS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECOVERY/SAFING</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>SIT (PART 1) VAB</td>
<td>27</td>
<td>6.5 (1 Shift)</td>
</tr>
<tr>
<td>SIT (PART 2) PAD</td>
<td>42</td>
<td>14.5 (2 Shifts)</td>
</tr>
<tr>
<td>TVC FUELING PAD</td>
<td>42</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>115 eh</strong></td>
<td><strong>20.5 (3 shifts)</strong></td>
</tr>
</tbody>
</table>
STUDY ASSUMPTIONS FOR THE SRB ELECTRICAL ACTUATION THRUST VECTOR CONTROL (TVC)

There are no launch site operations differences between the ELA schemes being considered.

- Induction motor with resonant controller
- Permanent magnet brushless DC motor and controller

The controllers will incorporate a Health Management System

Manufacturing and electrical shop environment are adequate for ELA (clean bench for LRU internal disassembly for modifications or repair only)

Items cost economical to refurbish will be recovered and reused (all major functional LRUs). (The LRUs are protected from internal salt water intrusion.)

Expendable items are cables and ancillary hardware (fasteners, bonding straps, clamps) which have salt water contact.

Fueling, servicing, bleeding, pressurizing, and deservicing operations with the associated fluids and gases sampling, certification, and air entrainment checks are not required.
STUDY ASSUMPTIONS FOR THE SRB ELECTRICAL ACTUATION THRUST VECTOR CONTROL (TVC) (Continued)

O TVC "Scape Suit" hazardous operations with associated area clears, and health and fire department support, are eliminated.

O Protection against high voltage DC contact by personnel for launch operations will be provided in the design.

O POWER SOURCE

O Chemical batteries (long term) are expendable; require no activation; and can be stored in an ambient environment. Battery life after installation shall nominally be one year with a minimum of 120 days. Short term and interim chemical batteries (primary, reserve, or high temp) will provide a pad stay time which supports 24, 48, and 72 hours' scrub turn-around. Primary and reserve batteries shall accommodate two (2) low-rate trickle charge without requiring removal, throwing away, and replacement in the event of contingency rollback.

O Flywheel battery controller will include a health management system; be capable of being charge up from ground umbilical source; meet 24, 48 and 72 hours' scrub turnaroud requirement without spin up (recharge); provide self containment protection against credible failure modes.
EMA CONTROL SYSTEMS DESIGN OPERATIONS PROVISIONS

O LRUs will be readily accessible for Installation and Removal. The movement of control surfaces and engine nozzles for access shall not be required. Connectors shall be visible and within "easy" reach from personnel support structures.

O External pods providing for TVC system (controllers, power source, cables, and ancillary hardware) protection from salt water contact and for external removal and reinstallation are to be considered. This would facilitate the recovery and reuse of multi-mission hardware and alleviate requirements for complete disassembly and rebuild.

O Operations and maintenance requirements at the LRU and system level, including failure detection and isolation, will be implemented in the HMS and BITE (automated test) with no requirement for external stimuli. This will include redundancy tests. The procedures and software implementing these requirements shall be modular; capable of stand-alone application; provide for new version or technology enhancement; and verified at the post-manufacturing/assembly level. Thermal profiles of the LRUs shall be developed and checked during LRU acceptance test and used for failure prediction/health status.

O The HMS system, OMRS system, and Launch Processing systems shall be "TRULY" operations "USER FRIENDLY" with automatic display of the critical TVC operations and parameters necessary for launch testing. The HMS system, failure prediction, failure trend, and LRU component history (waivers/deviations, open work, approved changes) data busses will provide for access, running of sequences, and display of data to the TVC LPS console for contingency, troubleshooting, and engineering evaluation.

O Factory environment (temperature and cleanliness) shall be adequate for normal LRU processing. Contingency internal LRU operations shall, if required, be performed using "Clean Bench."

O Fasteners with locking and self-capture features are to used for LRUs' installation and on access covers respectively.

O Bonding straps, when required, will be provided with the LRU and nominally installed during Post-Manufacturing, Checkout/ACO PMC buildup and test.

O LRUs will be internally protected against electrostatic charge during mate/demate of connectors with no requirements for protective clothing and grounding of personnel.
<table>
<thead>
<tr>
<th>REQUIREMENT</th>
<th>Actuator</th>
<th>Controller</th>
<th>Power Supply</th>
<th>TVC Subsystem</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>Isolation at LRU level performed at post-manufacturing checkout/assembly checkout</td>
</tr>
<tr>
<td>Power-Up Sequence</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Verifies TVC subsystem operation and compatibility with Launch Area GSE power source and Launch Processing System (LPS).</td>
</tr>
<tr>
<td>Verify LRU Health and Status</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Automatic GO-NO GO test with Launch Processing System asking the on-board TVC HMS to perform status check including redundancy. NOTE: On-board and ground processing S/W previously run at post-manufacturing/ACO°</td>
</tr>
<tr>
<td>Control System Verification</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>Vehicle guidance and control system previously verified at PMC before delivery for launch operations processing. Launch operations GN&amp;C system health and status checks performed. Test verifies command and proper response of TVC system interfaced to vehicle system, including normal operations and redundancy checks. Test is to be run with actuators unconnected to nozzle. Envelope/clearance tests, if required, have been performed during PMC. Contingency test or re-test at LRU level to be within capability of the control health management system.</td>
</tr>
<tr>
<td>Countdown Demonstration</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>Performed as separate test on first flow, after major modification affecting launch sequence, etc. Verifies control system network compatibility, system operation, and launch countdown.</td>
</tr>
<tr>
<td>FRF</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>Not required by EM TVC; verifies TVC control in conjunction with engine firing when required for MPS engine changeout, MPS modification, etc. verification.</td>
</tr>
<tr>
<td>Launch</td>
<td></td>
<td></td>
<td></td>
<td>X*</td>
<td>Verifies TVC system end-to-end performance and readiness for launch while running through the automated power-up, bite checks, HMS self tests, flight critical measurements, and command system test profile. The command system test profile is to be run as soon as practical after transition to internal power.</td>
</tr>
</tbody>
</table>

* TVC system configured for launch and closeout.
ELECTRICAL ACTUATION TECHNOLOGY BRIDGING PROGRAM

GALE R. SUNDBERG
NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135

ELA-TECHNOLOGY BRIDGING PROJECT WORKSHOP
MARSHALL SPACE FLIGHT CENTER, ALABAMA

SEPTEMBER 29, 1992
ELA TECHNOLOGY BRIDGING PROJECT WORKSHOP

- GOVERNMENT/INDUSTRY/ACADEMIA ELECTRICAL ACTUATION/POWER SYSTEMS TECHNICAL INTERCHANGE MEETING

- NASA ELA TECHNOLOGY BRIDGING PROJECT REVIEW

- SEVERAL DEMONSTRATIONS OF ELECTRICAL ACTUATION SYSTEM TECHNOLOGIES

- PROVIDE A FORUM FOR NASA TO SHARE/DISCUSS ELA/POWER GOALS, PROGRESS, ISSUES AND PLANS

- OPEN WINDOWS OF OPPORTUNITY FOR TECHNOLOGY ACCEPTANCE AND TRANSFER
Technology "Bridging" Concept

- "Technology Bridging" is a process that was spawned by the Strategic Avionics Technology Working Group (SATWG).

- It is a technology development and demonstration process that "bridges" technology providers and users.

- It is a joint endeavor between government, industry and academia.
- It employs principles of concurrent engineering.
- It produces credible costs-to-benefits assessment.
- It's objective is to facilitate technology transition, from the lab to the customer's project.

- Once the technology is incorporated into a program's advanced development phase, the bridging project focuses on other applications of the technology, or terminates, allowing resources to be transferred to other technology initiatives.
Electrical Actuation Technology Bridging Project Objectives

- Leverage NLS & industry IRAD ELA technology development to meet multiple NASA program actuation system requirements
- Develop and demonstrate a representative advanced technology, high-power (40-70 Hp) electrical actuation system suited for primary flight control (thrust vector & aerosurface control) applications. Customer/Program targets include: NLS, ASRM, CELVs
- Develop and demonstrate low-energy, high-reliability ELA systems suited for flight/ground fluid control (Propellant Control Valve, GSE) and future space transfer vehicle and remote surface vehicle (SEI) applications. Customer/Program targets include: KSC/SSC-GSE, NLS/ELV PCVs, ACRV F/C, and SEI (Rovers, Excavators, Cranes, OMV, OTV, Lander)
- Develop metrics to assess/validate cost benefits of electrical vs. conventional hydraulic actuation systems (flight and ground)
- Define and implement a cooperative, customer-focused technology development and transition process as a "pilot" for the agency
- Successfully transition proven ELA system technology into first available target program(s)
Electrical Actuation Technology Need

- PAYOFFS
  - Eliminate maintenance-intensive, high-pressure hydraulic systems
  - Eliminate centralized hydraulics and hazardous/toxic fluids
  - Reduce labor-intensive testing and vehicle preparation time
    (support rapid change-out & retest)
  - Reduce recurring launch processing & ops costs (~10% labor & GSE)
  - Improve program reliability, operability and abort recovery
  - Improve late hold capability and extend launch window
  - Reduce stand-down and vehicle turn-around times
  - Multiple national technology spin-off applications
    -- electric auto
    -- motorized machinery/appliances
    -- more-electric airplane
EMA'S APPLICABLE TO NATIONAL SET OF LAUNCH VEHICLES

<table>
<thead>
<tr>
<th>REQUIREMENTS</th>
<th>20 Hp EMA FOR COMMERCIAL BLV</th>
<th>40 Hp EMA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CENTAUR ENGINE PRE-VALVE</td>
<td>TITAN III STAGE 1*</td>
</tr>
<tr>
<td>STALL LOAD (LBS)</td>
<td>1610 X</td>
<td>29,790</td>
</tr>
<tr>
<td>DYNAMIC LOAD (at actuation rate) (LBS)</td>
<td>1191 X</td>
<td>11,330</td>
</tr>
<tr>
<td>ACTUATION RATE (DEG/SEC)</td>
<td>6 X</td>
<td>10</td>
</tr>
<tr>
<td>ACTUATION POWER (HP)</td>
<td>0.5 2.1</td>
<td>4.3</td>
</tr>
</tbody>
</table>

* ('Applicable TVC for ALS and MOOG Position Statement', MOOG, INC., Missile System Div., East Aurora, NY 14052)
X - PARAMETER NOT APPLICABLE/AVAILABLE
NATIONAL LAUNCH SYSTEM

ELECTRICAL ACTUATOR COMPONENT HARDWARE TRADES

INVERTER/CONTROLLER UNIT
- HIGH FREQUENCY AC LINK: PULSE POPULATION DENSITY
- HIGH VOLTAGE DC LINK: PULSE WIDTH MODULATION

POWER/SIGNAL CABLES
- LOW INDUCTANCE
- LOW EMI/EMC

ELECTRIC MOTOR
- INDUCTION
- SWITCHED RELUCTANCE
- PERMANENT MAGNET

POWER SOURCE
- BATTERY
- FUEL CELL
- TURBO ALTERNATOR

ACTUATOR
- BALL SCREW
- ROLLER SCREW
- ELECTROHYDROSTATIC

STME/SSME AND FLIGHT CONTROLS
ELA Technology Bridging Team/Roles

JSC
- Project Mgmt. & Integration
- Systems Studies/Sim/Eval. of Xfer Vehicle/SEI Applications
- FT&RM & VHM Concepts

ACRV

LeRC
- ELA/Power System Advanced Development
- NLS Leveraged Technology Utilization

GSE

SSC
- Define/Demo/Implement ELAs for Ground Test Facility (Fluid Control Valves)
- GSE Cost/Benefits Study - Hydraulics vs. ELA

KSC
- Ops Cost Benefits Study ELA vs. Hydraulics
- Launch Processing Analysis

ASRM

MSFC
- Thrust Vector Control & Prop. Control Valve ELA Devel. & Test

NLS

Advanced Development Program (Test Articles)
## ELA Technology Bridging Project Top-Level Schedule

<table>
<thead>
<tr>
<th>Functional Activity</th>
<th>Timeframe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NLS EMA Advanced Development</strong></td>
<td>FY'91</td>
</tr>
<tr>
<td><strong>Project Planning/Integration</strong></td>
<td>FY'92</td>
</tr>
<tr>
<td><strong>Rockwell SE&amp;I</strong></td>
<td>FY'93</td>
</tr>
<tr>
<td><strong>Ops Analysis/Cost Benefits</strong></td>
<td>FY'94</td>
</tr>
<tr>
<td><strong>MSFC Advanced Development/Testing</strong></td>
<td>FY'95</td>
</tr>
<tr>
<td><strong>GSE Evaluation/Implementation</strong></td>
<td></td>
</tr>
<tr>
<td><strong>STV Class Eval./Test/Development</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Power Source Tech. Eval./Recomm./Select.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Technology Demos &amp; Proof-of-Concept</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Technology Transition</strong></td>
<td></td>
</tr>
</tbody>
</table>

- 25 Hp IM/SS
- 40 Hp PM & IM IM/SS SS
- 60 Hp Red./IM
- 60 Hp Red. PM & IM

Electrical Actuation Technology Bridging
# SRB HYDRAULIC VS ELECTRIC LIFE CYCLE COST OVERVIEW

## INTRODUCTION

- SRB TVC LAUNCH SITE PROCESS
- LIFE CYCLE COST ANALYSIS INTERIM RESULTS
- LAUNCH SITE OPERATIONS REDUCTIONS
  - HUMAN RESOURCES (MAN-HRS)
  - EQUIPMENT
  - FACILITY
- BATTERY ISSUES

## SRB TVC LIFE CYCLE COST ELEMENTS

(System Costs = $3.3M Per Flight)

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXPENDED/REPAIRED HWY (8.8%)</td>
<td></td>
</tr>
<tr>
<td>DESIGN CTR SUPPORT (8.5%)</td>
<td></td>
</tr>
<tr>
<td>AUXILIARY PWR UNIT (16.7%)</td>
<td></td>
</tr>
<tr>
<td>METAL ACTUATORS (8.7%)</td>
<td></td>
</tr>
<tr>
<td>HYDRAULIC ACTUATORS (8.7%)</td>
<td></td>
</tr>
<tr>
<td>HYDRAULIC PUMPS (8.7%)</td>
<td></td>
</tr>
<tr>
<td>WASTE HANDLING (1.0%)</td>
<td></td>
</tr>
<tr>
<td>CHEMICAL ANALYSIS (1.0%)</td>
<td></td>
</tr>
<tr>
<td>SHUTTLE VEH PROCESSING (3.6%)</td>
<td></td>
</tr>
<tr>
<td>BOOST PROD MANPOWER (48.4%)</td>
<td></td>
</tr>
</tbody>
</table>

## SRB TVC HYD VS ELA (INTERIM RESULTS)

(Cost Savings = $2.0M Per Flight)

- COMPONENT REPAIR
- AFT SHRT REMANUF
- SHUTTLE VEH PROCESS
- DESIGN CTR PROCESS
- MISCELLANEOUS

**CONFIRMATION STUDY ON ELA COST SAVINGS APPROVED FOR FY 1992**
NASA HQ CODE D REVIEW
LAUNCH SITE OPERATIONS REDUCTIONS

PROCESSING TIME REDUCTIONS (DAYS)

<table>
<thead>
<tr>
<th>PROCESS ACTIVITY</th>
<th>APU/HYD</th>
<th>ELA</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECOVERY/SAFING</td>
<td>0.5</td>
<td>0</td>
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<tr>
<td>DESERVICE/DISASS'Y</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>COMPONENT DISASS'Y</td>
<td>15</td>
<td>4</td>
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<tr>
<td>AFT SKIRT REMANUF</td>
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<td></td>
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<tr>
<td>OFF-LINE ACTIONS</td>
<td>38</td>
<td>8</td>
</tr>
<tr>
<td>IN-SKIRT BUILD-UP</td>
<td>32</td>
<td>6</td>
</tr>
<tr>
<td>SERVICE, TEST &amp; C/O</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>LAUNCH VEHICLE INTEG</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>PAD OPERATIONS</td>
<td>3.5</td>
<td>1</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>106</td>
<td>24.5</td>
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</table>

77% REDUCTION

GROUND SUPPORT EQUIPMENT

<table>
<thead>
<tr>
<th>APU</th>
<th>HYD</th>
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</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="APU" /></td>
<td><img src="image2.png" alt="HYD" /></td>
</tr>
</tbody>
</table>

HAZARDOUS OPERATIONS

- HYDRAZINE HAZARD
- SCORPES SUITS/TECHNICIANS
- BREATHING AIR SERVICES
- FIRE/MEDICAL SUPPORT
- STORAGE & HANDLING

FURTHER BENEFITS

- **GSE COUNT CURRENTLY AT 588 ITEMS** - ELA FAR LESS
- LESS UNSCHEDULED MAINT/PROBLEMS THROUGH LARGE REDUCTIONS IN VEHICLE COMPONENT & GSE COUNTS
- LARGE REDUCTION IN FLUID COMMODITIES HANDLING AND SERVICES:
  - HYDRAULIC FLUID
  - HYDRAZINE
  - ALCOHOL, FREON, HP GN2, BREATHING AIR, CLEANING AGENTS, DETERGENTS, ETC.
- FACILITY AREA FROM 12,000 TO 3500 SQ. FT. WITH NO REQUIREMENT FOR TWO OF THE FACILITIES

JUNE 4, 1992
OBJECTIVE:

- DEMONSTRATE EMA/POWER SUBSYSTEMS FOR TVC AND ENGINE EFFECTORS
- INTEGRATE CONTROLS WITH AVIONICS AND PROPULSION INTERFACES

PAY-OFFS:

- ELIMINATION OF HYDRAULICS AND ASSOCIATED EQUIPMENT/FLUIDS
- REDUCE CHECK-OUT FLOWS/OPS. COSTS
- REDUCE STAND DOWN TIME/COSTS
- IMPROVE DISPATCH RELIABILITY, LAUNCH ON DEMAND

PRODUCTS/DELIVERABLES:

(1) VEHICLE TVC REQUIREMENTS & EMA/POWER SYSTEM REQUIREMENTS

(2) 25 Hp INVERTER/CONTROLLER BREADBOARD H/W DEMO (HIGH POWER, 20 kHz RESONANT LINK, FIELD-ORIENTED CONTROL OF MOTOR)

(3) 40 Hp EMA SUBSYSTEM DEVELOPED AND DEMONSTRATED ( MOTOR CONTROLLER, ADVANCED INDUCTION MOTOR AND ACTUATOR)

(4) 60 Hp FULL SCALE EMA TVC SUBSYSTEM DEMONSTRATED (POWER SOURCE, CONTROLLER, MOTOR, ACTUATOR IN AVIONICS SYSTEM)
ELECTRICAL ACTUATORS FOR EARTH-TO-ORBIT
BASED UPON NLS ADP DEVELOPMENT

- **BATTERIES**
  - BIPOLAR LITHIUM; MASS = 2 kW/Lb.

- **POWER PROCESSING - RESONANT LINK**
  - FREQUENCY = 40 to 60 kHz
  - MASS = 0.5 to 1.5 Lb./Hp

- **INDUCTION MOTOR**
  - STEADY-STATE FREQUENCY = AS REQUIRED
  - FREQUENCY AT PEAK HORSEPOWER = 750 Hz (approx.)
  - MASS = 0.25 Lb. PER PEAK Hp

- **SYSTEM MASSES (AT 60 Hp PEAK FOR NLS)**
  - TOTAL SINGLE ENGINE - TWO ACTUATOR SYSTEMS = 520 Lbs.
  - COMPARABLE, MODERN DISTRIBUTED HYDRAULICS = 850 Lbs.
FULL SCALE, 60 HP NLS DEMONSTRATION SYSTEM

- MOTOR CONTROLLER
  - DEDICATED DC-LINK, RESONANT POWER PROCESSOR
  - 60 kHz, 75 KVA
  - SHARED MICRO-COMPUTER CONTROL, FIBER-OPTIC INTERFACES TO PROCESSOR AND MOTOR
  - PRIMARY CONTROL ALGORITHMS CONTAINED IN SOFTWARE

- MOTOR
  - ADVANCED, LIGHTWEIGHT (<20 LBS) THREE-PHASE INDUCTION MOTOR
  - 38 Hp CONTINUOUS, 70 Hp PEAK AT 14,700 RPM
  - LOW LOSS, LOW INERTIA ROTOR
  - HIGH TEMPERATURE OPERATION TO 200 C

- LINEAR ACTUATOR
  - BALL SCREW WITH DUAL MOTOR DRIVE
  - 48,200 LB FORCE, 5.4 INCH EXTENSION
  - WEIGHT IS ABOUT 225 LBS
LeRC 40 Hp Electromechanical Actuator for Thrust Vector Control Applications

Electronic Motor Drive by General Dynamics Space Systems

Induction Motor by Sundstrand Corporation

Mechanical Actuator by Moog, Inc.
MSFC ADVANCED DEVELOPMENT PROGRAM

• THRUST VECTOR CONTROL SYSTEMS
  - DUAL CHANNEL 50 HP FEASIBILITY DEMONSTRATION UNIT
  - QUAD CHANNEL 60 HP SSME/SRB DEMONSTRATION UNIT
  - NLS TRIPLE-REDUNDANT DERIVED REQUIREMENTS AND SPECIFICATION

• ENGINE CONTROL VALVE SYSTEMS
  - MSFC SIMPLEX SSME MAIN OXIDIZER VALVE (MOV)
  - HR TEXTRON SSME MOV PROTO-FLIGHT UNITS
  - AEROJET STME PROPELLANT CONTROL VALVE UNITS
MSFC 60 Hp EMA Actuator With Quad Permanent Magnetic Motors

- 4 Channel 15 Hp Permanent Magnet DC Motors
- 9.6:1 Single Pass Gear Reduction w/ 0.4 Inch Roller Screw Lead
- Rated Load of 60,000 Lbf
- Rated Velocity of 5 inch/sec
- Maximum Stroke of ± 5.25 inch
- 4.2 Hz Control Bandwidth
MSFC / Aerojet Main Engine EMA
Propellant Valve Actuator

- Dual Redundant STME PVA
- Microcontroller Design w / BIT
- 0.485 Hp DC Permanent Magnet Motors
- 28 Volts 36 Amps Motor Controller
- 180:1 Harmonic Gear Reduction
- 7-9 Hz Control Bandwidth
- Internal Health Monitoring
- Reports its Status to Engine Controller
EMA TEST FACILITIES AT MSFC:

- INERTIA LOAD SIMULATORS
  - SSME AND SRB TEST BEDS
  - SRB AND SSME COMMAND PROFILES
  - FLIGHT-TYPE (Ag-Zn) BATTERY OPERATIONS (FY - 93)
  - SRB FLIGHT LOADS AND COMMAND PROFILES (FY-93)
- RATE vs HYDRAULIC LOAD TEST BEDS
- ENGINE CONTROL VALVE FLOW TEST FIXTURES
- SSME HUNSTVILLE SIMULATION LABORATORY (HSL)
- SSME TECHNOLOGY TEST BED
- TEST STAND 116 CRYOGENIC FLOW FACILITIES
NASA

MSFC_TEST PROGRAM PARTICIPANTS:

- THRUST VECTOR CONTROL TEST ARTICLES (SSME & LOAD FIXTURES)
  - MSFC TVC SYSTEMS (DC PERMANENT MAGNET MOTORS)
    - DUAL 50 HP UNIT (TESTING IN PROGRESS)
    - QUAD 60 HP UNIT ASSEMBLY & CHECKOUT (AUGUST, 1992)
  - LeRC/GENERAL DYNAMICS DUAL REDUNDANT 60 HP INDUCTION MOTOR TVC (JULY, 1992)
  - HONEYWELL IRAD 30 HP TVC & VHM DEMONSTRATION (AUGUST, 1992)
  - MOOG IRAD TVC DEMONSTRATIONS (TBD)
  - BOEING/ALLIED-SIGNAL TURBO-ALTERNATOR & ELECTRO-HYDROSTATIC TVC (SEPT. 1992)

- ENGINE CONTROL VALVES TESTING
  - MSFC SIMPLEX PROPELLANT VALVE ACTUATOR TESTING IN FLOW FACILITY AND HSL
  - HR TEXTRON MAIN OXIDIZER VALVE SSME QUALIFICATION TEST SERIES (JUNE, 1992 ATP)
  - AEROJET PROPELLANT VALVE ACTUATOR TESTING IN THE HSL (FY-93)

- SSME TECHNOLOGY TEST BED DEMONSTRATIONS (FY-94)
  - MSFC QUAD 60 HP TVC
  - HR TEXTRON MOV
ELECTRICAL ACTUATOR (ELA) /ELECTRO-MECHANICAL ACTUATOR (EMA) FEASIBILITY STUDY

Objective

- Determine the feasibility of replacing hydraulic/pneumatic actuators with ELAs in Ground Testing of Propulsion Systems to enhance operational efficiency of ground operations.

- Perform rigorous test program for ELA hardware evaluation prior to propulsion system and flight vehicle application and to gain early operational experience in a relevant environment.

Need

- Enhance operational efficiency and reliability of facility ground systems.

- Reduce the cost of labor intensive hydraulic systems in ground operations.

Approach

- Determine the applicability of EMA technology to support Static Test Firing of Rocket Engines and other test articles at SSC.

- Perform in-house testing to establish capabilities, reliability and cost effectiveness of replacing hydraulic/pneumatic actuators with Electrical Actuators.

- Coordinate SSC ELA activity with JSC, MSFC, LeRC and KSC.
SSC GROUND APPLICATIONS

- Variable position valve for NASP Heat Flux Test Facility
- Automation of High Pressure Gas Facility
- CTF Test Cell
- Seal Configuration Tester
- Selected Facility Support System Valves
JSC Electrical Actuation Test Facility

Load servo controller and pilot valve assembly

Inertial mass

Pre-set safety stops

Load cell 1

Load cell 2

EMA unit under test

EMA mounting adaptor

End bracket assembly

Low friction linear bearings

Load mass table

Hydrostatic Bearing Actuator Assembly

Structural Base Beam (I-beam w/reinforcing stiffeners added)
SUMMARY

ELECTRICAL ACTUATORS CAN REPLACE HYDRAULICS IN LAUNCH VEHICLES

MAJOR ELECTRICAL ACTUATION ELEMENTS DEVELOPED, UNDER EVALUATION

TECHNOLOGY CAN PROVIDE STANDARDIZED, MODULAR TVC HARDWARE

ELECTRICAL ACTUATION ADVANCES COULD HELP U.S. COMPETITIVE POSITION
NLS Keynote speaker

Paper Not Available
WHY Power-By-Wire?

EFFICIENCY
- POWER EXTRACTED FROM ENGINES
- HEAT MANAGEMENT

MAINTAINABILITY
- ELIMINATE HYDRAULIC DISCIPLINE
- LESS SUPPORT EQUIPMENT (AGE)

DESIGN IMPLICATIONS
- WEIGHT SAVINGS
- IMPROVED SURVIVABILITY
- REDUCED VULNERABILITY
- SIMPLER SYSTEM

OPERATIONS
- HIGHER A/C SORTIE RATE
- LOWER LIFE CYCLE COSTS
- MOBILITY
- MANPOWER
MORE-ELECTRIC AIRCRAFT

- FLIGHT LINE SUPPORT EQUIPMENT/MAINTENANCE REDUCED BY MORE-ELECTRIC TECHNOLOGIES

- REPLACING CENTRALIZED HYDRAULICS WITH POWER-BY-WIRE OFFERS MAJOR SYSTEM LEVEL PAYOFFS
MORE ELECTRIC AIRCRAFT VISION

- REDUCE/ELIMINATE HIGH MAINTENANCE SUBSYSTEMS/DISCIPLINES (CENTRAL HYDRAULICS, BLEED PNEUMATICS, GEARBOXES, HAZARDOUS FLUIDS, AEROSPACE GROUND EQUIPMENT (AGE))

- FOCUS U.S. R&D EFFORTS IN AIRCRAFT POWER, SUBSYSTEMS AND ELECTRIC ACTUATION

- REDUCE LIFE CYCLE COSTS THROUGH IMPROVEMENTS IN COMPONENT RELIABILITY AND REDUCED O&S COSTS
- 30 TO 50% REDUCTION IN AEROSPACE GROUND EQUIPMENT (AGE)
- MAJOR SYSTEM LEVEL IMPROVEMENTS IN BATTLE DAMAGE TOLERANCE/MAINTAINABILITY/SUPPORTABILITY/VULNERABILITY
- ELIMINATE CENTRAL HYDRAULIC SYSTEM/HYDRAULIC MAINTENANCE/FIRE HAZARD
- IMPROVED AIRCRAFT PERFORMANCE FROM RESIZED ENGINES AND REDUCED WEIGHT – 600-1000#
- IMPROVED FLIGHT CONTROL, BRAKING, COOLING
SYSTEM LEVEL PAYOFFS

- FIGHTERS - RETROFIT ANALYSIS/750 AIRCRAFT
  - 60 - 129 ADDITIONAL AIRCRAFT
  - 11 - 15% REDUCED MAINTENANCE MANPOWER
  - 10 - 12% VULNERABILITY IMPROVEMENT

- TRANSPORT - RETROFIT ANALYSIS - ELECTRIC ACTUATION ONLY/267 AIRCRAFT
  - 3.3 - 5.9 ADDITIONAL AIRCRAFT
  - UP TO 182 MANPOWER REDUCTION PER FLEET
  - UP TO 58% TURNAROUND TIME IMPROVEMENT

- HELICOPTERS
  - MORE ELECTRIC ENGINE - 15% IMPROVED RELIABILITY, 22% REDUCED WEIGHT, AND 2% REDUCED FUEL

- COMMERCIAL AIRCRAFT
  - MORE THAN 2% FUEL SAVINGS
REDUCE SUPPORT EQUIPMENT REQUIREMENTS

1. Electric Generator
2. Hydrazine Servicing Cart
3. Hydraulic Servicing Cart
4. High Pressure Air Cart
5. Air Conditioner
6. Hydraulic Mule

Flight Line Battery Support Shop (Not Shown)

16 C-141s Required to Support 24 F-16s
POWER-BY-WIRE
FLIGHT CONTROL ACTUATION

Wright Lab Funded Programs

- *Electrically Powered Actuation Design (EPAD)* Validation Flight Test Program
- *ElectroHydrostatic Actuation (EHA)* for Large Aerodynamic Surface Applications
- *C-141 Electric Starlifter Power-By-Wire* Reliability & Maintainability Flight Test Program
- *Flight Control Systems Actuation Technology*
- *Switch Reluctance Motor Development*
FLIGHT CONTROL ACTUATION

Other Wright Lab Activities
- Supporting Lockheed HTTB PBW Flight Tests
- OC/ALC & Parker Aileron EHA Demo
- Lucas Rudder IAP Demo
- Support Focusing IRAD for PBW Development
- Plan Stabilator Actuator Flight Test Demo
- FIGS Electric Stab Actr Program
- MEA Secondary Power + Electric Stab Actr
- Plan PBW Flight Control System Demo
- More Electric Aircraft Ground/Fit Tests
- More Electric AFTI F-22 Demonstrator
- Plan Rotary/Thin Wing PBW Actuator Dev
POWER-BY-WIRE
FLIGHT CONTROL ACTUATION

1990 Technology Assessment

CAPABILITY
- Moderate Horsepower, Low Power Density
  ✓ 3-5 HP
  ✓ 1-3 HP/Ft$^3$
  ✓ 10,000-15,000 LbF
  ✓ 4-6 In/Sec
  ✓ 1-3 Hz

LIMITATION
- Only Trailing Edge Surface Applications
- Transport Class Aircraft

RISK
- PBW for Fighter Surface Application
- EHA from Lab Tests to Flight Tests
- HYDRAULIC POWER SOURCE ELIMINATED
- DUAL POWER REDUNDANCY
- PRIMARY CONTROL SURFACE APPLICATION
THE ELECTRIC STARLIFTER
RAMTIP PROJECT #8817

FIGL/4950 TW/
LOCKHEED-SUNSTRAND
C-141 EMAS

ElectroMechanical
(EMA)

MAC/RAMTIP
TECHNOLOGY INSERTION

C-141 POWER-BY-WIRE
AIRCRAFT
ELECTRIC STARRLIFTER
PROJECTED C-141 OPERATIONAL R&M PAYOFFS

OPERATIONAL AVAILABILITY

3.3-5.9 C-141’s Additional

SORTIE GENERATION

+2000/YR/Fleet

RELIABILITY & MAINTAINABILITY

MTBMA Increased 28%
MTTR Reduced 50%
MMHrs/A-C/Yr Reduced 55%
2 Level Maint
Troubleshoot Time Cut 83%
ELECTRIC ACTUATION

- C-141 ELECTRIC STARLIFTER -- DEMONSTRATE THE R/M/S OF ELECTRIC ACTUATION IN OPERATIONAL ENVIRONMENT (2X RELIABILITY, LRU CONCEPT, 16 ACTUATORS)

C-141 POWER-BY-WIRE AIRCRAFT

FIRST FLIGHT - 4QFY94

DELIVERY TO AMC 1QFY95
POWERS-BY-WIRE
FLIGHT CONTROL ACTUATION

1993 Technology Assessment

CAPABILITY
• Moderate Horsepower, Moderate Power Density
  ✓ 5-7 HP
  ✓ 15-25 HP/Ft$^3$
  ✓ 15,000-20,000 LbF
  ✓ 4-6 In/Sec
  ✓ 4-7 Hz

LIMITATION
• Only Trailing Edge Surface Applications
• Transport & Fighter Aileron/Rudder

RISK
• High HP PBW Act’r for Stiffness Driven Surface
  (i.e. Horizontal Stabilator, Elevator, Canard)
ELECTRICALLY POWERED ACTUATION DESIGN (EPAD) VALIDATION PROGRAM

JOINT AF, NAVY, NASA PROGRAM

FUTURE AIRCRAFT

OPPORTUNITIES

DERIVATIVE AIRCRAFT
and
BLOCK UPGRADES
GOALS OF EPAD

- Flight Test Demonstrate PBW Technology On Primary Flight Control Surface On A Fighter A/C
- Transfer PBW Technology To Industry And Other Gov Agencies
- Baseline Information For Navy A/X Program
FLIGHT TEST OBJECTIVES

- MEASURE PERFORMANCE UNDER ACTUAL FLIGHT CONDITIONS
  - ✓ COMBINED LOADS (SURFACE): INERTIAL, AERODYNAMIC AEROELASTIC
  - ✓ COMBINED ENVIRONMENTS: NOISE, TEMP, VIBRATION EMI
  - ✓ REAL MANEUVERS/OPERATIONS: RAPID FLT CHANGES, TRIM CHANGES, REAL FLT DYNAMICS
  - ✓ REAL TIME COMPARISON TO ELECTROHYDRAULIC ACTUATOR RESPONSE, TRANSIENTS, TEMP POWER CONSUMED

- SEARCH FOR UNEXPECTED

- DOCUMENT RESULTS
C-130 HIGH TECH TEST BED (HTTB)

Electric Actuator Flight Test Programs

Item: Linear IAP
Function: Rudder
Vendor: Lucas Aero
Sponsor: Lockheed/Lucas/WL

Item: Linear EMA
Function: Trim Tabs
Vendor: Sundstrand
Sponsor: Lockheed & Sundstrand

Item: Rotary EMA
Function: Stability Control Augmentation System
Vendor: Sundstrand
Sponsor: Lockheed/Sundstrand

Item: Linear EHA
Function: Left Aileron
Vendor: Parker Hannifin
Sponsor: AFLC/MMIRC
C-130 HIGH TECH TEST BED (HTTB)
Left Aileron EHA "Trial Fit"
ELECTRIC ACTUATION

- INTEGRATED ACTUATION PACKAGE FOR HTTB
- RUDDER SUCCESSFULLY DEMONSTRATED

FULLY REDUNDANT, POWER-BY-WIRE ACTUATION SYSTEM
- ±15 VAC POWERED
- 5750 LBS MAX OUTPUT FORCE
- 4 Hz ± 2% NO LOAD FREQUENCY RESPONSE
- DIGITAL ELECTRONIC PUMP CONTROL UNIT (EPU)
- ADAPTABLE FOR FLY-BY-LIGHT

LOCKHEED'S HIGH TECHNOLOGY TEST BED AIRCRAFT (HTTB)
POWER-BY-WIRE
FLIGHT CONTROL ACTUATION

1996 Technology Goals

CAPABILITY
- High Horsepower, High Power Density
  ✓ 15 - 35 HP
  ✓ 20-25 HP/ft$^3$
  ✓ 30,000-55,000 LbF
  ✓ 7-20 In/Sec
  ✓ 7-15 Hz

LIMITATION
- PBW Act’n System Effects on A/C Electric System
- Environmental (Thermal/Vibration) Tolerances

RISK
- PBW Act’r Embedded Fault Tolerance
- No PBW Flight Control Actuation Sys Ground/Flt Test
ElectroHydrostatic Actuator (EHA) for Large Aero Surface Applications

DUAL CHANNEL EHA

CONTRACTOR:
General Electric - A/C Control Systems

SUBCONTRACTOR:
Northrop Corp - Aircraft Division
ELECTROHYDROSTATIC ACTUATOR (EHA)
For LARGE AERO SURFACE APPLICATIONS

OBJECTIVE

Develop EHA System Capable of Meeting A Fighter Flight Critical Surface Performance AND Control & Power Redundancy Management Requirements

- Select Critical Surface Application (YF-23)
- Trade Study System & Subsystem Technologies
- Design EHA System Using Trade Results
- Develop EHA Subsystems & Test
- Build EHA System Via Subsystems Integration
- Laboratory Test EHA System
- Verify System & Subsystem Models
- Document Results
ELECTROHYDROSTATIC ACTUATOR (EHA)
For LARGE AERO SURFACE APPLICATIONS

PURPOSE

Expand Power-By-Wire Actuator Technologies To Include Large, Flight Critical Surface Applications

- Expand PBW Act'n Performance to Flight Control Extreme (EHA/EMA - Fighter Aileron, IAP/EMA/EHA - Transport Aileron) (2-3X Higher Force/Rate, 4-6X Higher HP)

- Provide Tech Base for Future Flight Test Demo (More Electric Stabilator Actuator - Proposed 6.3)

- Provide Opportunity to Address & Answer Redundancy Management Issues & Implement into A Design

- Provide Electrical Power Loads, Distribution & Management Requirements to MADMEL (WL/POO) (Management And Distribution of More Electric Power - 63216)

- Impact More Electric Airplane Critical Technology List
POWER-BY-WIRE
FLIGHT CONTROL ACTUATION

Wright Lab Funded Programs

- Electrically Powered Actuation Design (EPAD) Validation Flight Test Program

- ElectroHydrostatic Actuation (EHA) for Large Aerodynamic Surface Applications

- C-141 Electric Starlifter Power-By-Wire Reliability & Maintainability Flight Test Program

- Flight Control Systems Actuation Technology

- Switch Reluctance Motor Development
PURPOSE

(Why Are We Doing This?)

- Provide Actuation Technology for Current & Future Military Aircraft Which is Simpler and/or Less Expensive Than Current State of the Art

- Provide Tech Integration & Test for EPAD Actuators (EHA, EMA & Smart) with Electrical Power, FCC & Aero Space on NASA F/A-18 Testbed

- Provide Flight Control Actuation Support to Ongoing Wright Laboratory Programs
  - WL/FIG (EPAD, VISTA, LAMARS)
  - WL/MLB (NON-FLAMMABLE FLUID)
BENEFITS

• PROVIDES AF, OTHER DoD & GOV'T AGENCIES, and INDUSTRY with UNIQUE FLIGHT CONTROL ACTUATION INDEPENDENT TEST & EVALUATION CAPABILITY

• PROVIDES ADVANCED FLIGHT CONTROL ACTUATION TECHNOLOGIES FOR MILITARY & COMMERCIAL TRANSPORTATION APPLICATIONS

• GIVES WRIGHT LAB CREDIBILITY AS ACTUATION VOICE

• MAKES A GREAT TOUR STOP IN WRIGHT LAB!
SWITCHED VARIABLE RELUCTANCE (SVR) MOTOR FOR ELECTRIC ACTUATION

RESEARCH ISSUES
- Power Requirements
- Force, Rate, Torque
- Thermal Environment
- Fly-By-Wire Control
- Fault Tolerance

Mr David Homan, WL/FIG DSN 785-8679

PRINCIPAL INVESTIGATOR:
Massachusetts Institute of Technology - Lincoln Laboratory

ORIGINAl PAGE IS OF POOR QUALITY
SWITCHED VARIABLE RELUCTANCE (SVR) MOTOR FOR ELECTRIC ACTUATION

Mr David Homan, WL/FIGL, DSN 785-8679

RESEARCH ISSUES

• Can A SVR Motor Meet Flight Control Requirements for Actuator Force, Rate, Torque & Environment?

• Develop & Test SVR Motor to Verify Capabilities & Identify Inefficiencies for Further R&D

BENEFITS/PAYOFFS

• Contributes to "More Electric" Aircraft Technology Base

• Simpler & More Robust than Current AC & DC Motors

• Provides Alternative to Current State-of-the-Art AC & Brushless DC Motor Driven Actuators.
POWER-BY-WIRE
FLIGHT CONTROL ACTUATION

IN SUMMARY...

• Wright Laboratory Control Systems Development & Applications Branch (WL/FIGS) Is A Technology Leader In Flight Control Actuation Development

• Power-By-Wire Actuation Is The Technology That Makes A More Electric Airplane Feasible

• Inhouse & Contracted Efforts Underway to Expand PBW

• Planning Activities Underway For Future PBW Work

• Supporting Users & Industry To Transition Tech
ELA/EMA Control
with
Resonant Power Processors

Jim Mildice
ELA/EMA Control with Resonant Power Processors

ELA/EMA System Elements

- Fixed force + inertia + rates + acceleration - set primary requirements
- Rotary to linear conversion + gear train for speed matching
- Prime mover - electrical to mechanical conversion (several AC technologies available)
- Control of motor speed, direction, and output torque
- Energy storage (battery) or conversion (machinery) elements

The system in this discussion is a large servo-type hardware and software assembly typically found in large launch vehicle TVC applications, or aerosurface control of large aircraft. It can be broken into major elements according to the block diagram above.

The load is defined by the steady-state forces required to provide the actual movement and the acceleration of the inertias of the masses to be moved. The dynamic responses are defined by the vehicle dynamics and the external forces acting on the vehicle. Loads are typically in the 25,000- to 50,000-pound range for an NLS-2 class vehicle.

Because of the short time allocated for this discussion, we have decided to provide a summary of General Dynamics conclusions about the actuator, motor, and power processing and control elements of the block diagram, along with the most important reasons for those choices. There have been detailed presentations and demonstrations about these elements, with full justifications for the selections. If you wish any of that data, please refer to the Bibliography and the end of this data package.

Many power source options are available. Because of high peak loads, they are usually sized by the system peak power demands, and technologies having high specific power rather than high specific energy are desirable. The choice between batteries and rotating machines is usually driven by operations and test considerations.

This presentation will then focus on, and discuss the most important considerations driving ELA/EMA system design, system inertias and how they drive the entire configuration and its capability.
Actuator

- Three primary system choices
  - Ballscrew technology is well-established
  - Rollerscrew technology has some performance advantages
  - Electro-hydrostatic actuators are available where the "softness" of hydraulics is still required

- Motor and gear train inertia is the most important mechanical parameter for TVC applications
  - Normal gear reductions isolate the load inertia
  - Design for maximum power transfer makes desirable for the two inertias to be about equal
  - These inertias are the primary driver for peak input power requirements
    - They size the power processor/motor controller
    - They determine the energy source size and character

Even though the required motions for most ELA's are rotary (engine rotation about its gimbal point, control surface rotation about its root, etc.), vehicle physical limitations and form factors usually require that the load be moved by a linear thrust. The actuator provides the conversion from rotary motor input to linear output thrust. Rotary power requirements can typically be between 25- and 75-horsepower for our applications.

Three primary rotary-to-linear thrust mechanisms under current use and consideration are listed above. The mechanical "screw" technologies are straightforward.

Electro-hydrostatic, sealed, self-contained, single-actuator hydraulic systems can be mechanically simple and solve many of the present distributed hydraulic system operability, leak, and contamination problems. Since the motors and controllers that drive them are very much the same whether or not variable speed and direction control are included, the most efficient overall system design uses a variable-speed/direction controller, motor, and hydraulic pump, and eliminates the complexities of servo valves, force amplifiers, and other fluid hardware.

It's easy to design a small, high-speed motor/gear train system to drive the steady-state load, and the resulting large-ratio gear system also reduces the reflected usual load inertias so that they become small when compared to other inertias in the system. That means that the motor and gear train inertias dominate the power requirements for inertia acceleration and bandwidth, and the peak power input and peak-to-average ratio are fully under the TVC system designer's control.
Motors used in modern systems are all AC types, often interfaced to DC power systems with power processors to provide the appropriate input waveforms. The make up a class of so-called “brushless DC" motors which can include any type of AC prime mover. Well-designed motors and actuators for these applications typically require 25- to 50-horsepower for the constant load, and an equal amount of power for acceleration of inertias.

The “classical DC" motors shown above are commutator types. The significance of this configuration is that not even this age-old DC motor actually has DC in the internal fields that cause it to rotate. Its rotor current is actually square-wave AC created by a mechanical reversing switch. That reversing switch has a sliding contact system, mounted on the motor output shaft, and is made up of a “commutator” and brushes.

The development of good power semiconductor switches and high-field magnetic materials allowed a design which eliminated the commutator and brushes. It placed the constant field (produced by a magnet) on the rotor, and switched the alternating AC field to the stator with external switch networks, and we had the so-called “brushless DC" motor; really nothing more than a permanent magnet AC motor with an external switched, multi-phase inverter. When we supply this same motor AC from the power system instead of DC, we eliminate the switches and call it a permanent magnet AC motor, a small version of which we can find in analog electric clocks.

AC induction motors also eliminate the commutator and brushes, and supply power to create the magnetic field on the rotor through transformer action. The transformer frequency is the difference between the rotating magnetic field supplied by the stator and the actual speed on the rotor (the “slip”).

Switched reluctance motors use external switches to create a rotating magnetic field from the stator in the same way as the original “brushless DC" permanent magnet design. However, a notched, soft iron rotor replaces the permanent magnets, and it follows the rotating field when the magnetic forces try to minimize the reluctance of the magnetic path, in a way similar to a stepping motor.

### Motor Type Characteristics

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Stator Power</th>
<th>Rotor Power</th>
<th>AC Syntheses</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Classical&quot; DC</td>
<td>DC</td>
<td>AC, sq. wave</td>
<td>Sliding contact, mechanical, rotary switch (commutator)</td>
</tr>
<tr>
<td>(permanent magnet)</td>
<td>Magnet</td>
<td>AC, sq. wave</td>
<td>Sliding contact, mech, mechanical, rotary switch (commutator)</td>
</tr>
<tr>
<td>&quot;Brushless DC&quot;</td>
<td>AC</td>
<td>Magnet</td>
<td>External electronic switch</td>
</tr>
<tr>
<td>(permanent magnet)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Induction</td>
<td>AC</td>
<td>Magnetically-coupled low-frequency, AC</td>
<td>AC power source or external electronic switch</td>
</tr>
<tr>
<td>AC Synchronous</td>
<td>AC</td>
<td>AC, DC, or permanent magnet</td>
<td>AC power source or external electronic switch</td>
</tr>
<tr>
<td>Switched Reluctance</td>
<td>Sequenced Pulses</td>
<td>None - rotor is magnetic iron</td>
<td>External electronic switch</td>
</tr>
</tbody>
</table>
ELA/EMA Control with Resonant Power Processors

Control Parameter Comparison

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Torque</th>
<th>Speed</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Classical&quot; DC</td>
<td>No independent control of torque and speed</td>
<td>Input voltage controls output power</td>
<td></td>
</tr>
<tr>
<td>(permanent magnet)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;Brushless DC&quot;</td>
<td>Input voltage</td>
<td>Frequency</td>
<td>External electronic switch network synthesizes variable-voltage, variable-frequency inputs to mimic classical DC performance</td>
</tr>
<tr>
<td>Permanent Magnet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Induction</td>
<td>Slip (rotor freq), Input voltage &amp; slip</td>
<td>Stator frequency</td>
<td>External electronic switch network synthesizes variable-voltage, variable-frequency inputs for independent torque/ speed control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Synchronous</td>
<td>Input voltage</td>
<td>Input frequency</td>
<td>External electronic switch (same as AC Induction)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switched Reluctance</td>
<td>Input voltage</td>
<td>Field rotation speed</td>
<td>External electronic switch (same as AC Induction)</td>
</tr>
</tbody>
</table>

If we want to control both torque and speed independently, The classical DC motors are not really adequate. We only have control of the input voltage, and we get a constant power output for a constant input. The product of torque (load) and speed is a constant for constant inputs. If we increase the load, the speed decreases. The control seems simple. If we have a particular load, we just turn up the voltage until we get the speed we want. But speed or torque are never uniquely related to input.

At first, brushless DC motors had power processors which mimicked the classical DC characteristics, to reinforce the name “brushless DC”. But if we have large motors (tens of horsepower), “turning up” DC sources that are 100's of volts and/or 100's of amperes is very undesirable. Therefore, switching regulator functions were incorporated into the control algorithms for the stator switches, and we gained the ability to independently control torque and speed through input voltage and frequency, respectively, with signal level inputs.

The power transferred to the induction motor rotor via transformer action is controlled by both input voltage and the transformation frequency (the slip frequency). For a fixed voltage, the slip changes to vary the output power and match the load. The difference in rotational speeds between the stator field and the rotor is often about 3% to 5%, so the typical slip frequency for a 400-Hz motor would be about 20-Hz.

The switched reluctance motor is not unlike a stepping motor with regard to its control. Windings distributed around the stator are alternately sequenced to produce a rotating field, which "pulls" the magnetic iron rotor along, trying to minimize the reluctance of the motor air gap. Like the classical brushless DC, the input voltage controls the air gap flux (field strength) and the frequency of rotation controls the speed.
ELA/EMA Control with Resonant Power Processors

Motor Selection Summary

- Optimized motors from all the candidate classes have about the same mass and volume for the same requirements (peak outputs are in the 3-HP/lb. range)
- Basic control parameters are similar for all the candidate classes (motors are multi-phase and we must have independent control of input voltage and frequency)
- Feedback for torque and speed control is simplified for Induction motors (speed feedback vs. accurate rotor position for other types)
- Modern control algorithms give Induction motors dynamic advantages for servo systems ("field oriented control" provides optimum response)
- Induction or switched-reluctance motors significantly simplify the mechanical designs of redundant systems (eliminate the requirement to decouple an inactive/failed motor)

General Dynamics is focusing on Induction motors for ELA/EMA development and implementation

The choice of “best” motor for high-power TVC applications cannot be made using the usual trade study approach, since all the usual trade parameters (mass, volume, cost, etc.) are close enough to each other for the primary candidates to make them non-discriminators. Even if they were significantly different, the are small compared to the rest of an EMA TVC system, and do not significantly influence system technology choice. The control algorithms and the design of the power output stage are also about the same for all three types. Even the somewhat easier feedback handling for the induction motor is still not enough to make it an obvious choice. So other considerations lead us to choices for specific applications or power ranges.

The “slip” power transfer relationship makes the induction motor significantly more robust in terms of load changes. For example, when our optimized Sunstrand induction motor is operating at full speed and its most efficient operating point, it has about 2% slip (14,700 RPM). If its load were doubled, the slip would increase to about 4% to transfer additional output power and the speed would decrease to only 14,400 RPM. A permanent magnet Brushless DC assembly under the same conditions would decrease its speed from 15,000 RPM to 7,500 RPM (half speed), and the switched reluctance motor would stall; until the controller could increase the input to match the new load.

The biggest discriminator has to do with redundant systems, where multiple motors are used to drive a load. If there is a short circuit failure in a motor or its controller, the fixed magnetic field in the permanent magnet rotor makes that motor type function as a generator, supplying power to the fault, and loading the system. If the system is to work properly after one such failure, the remaining motor(s) must provide enough excess power to both drive the real load and the fault load, or the faulted unit must be mechanically decoupled. This added complexity is sufficient to disqualify permanent magnet motors (in the brushless DC design) from use in redundant systems.

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Controller Operational Definition

The controller/power processor must provide the following primary functions:

- Synthesize a multi-phase AC waveform appropriate to running several AC motor types
  (*There is no such thing as a DC Motor*)
- Provide variable frequency for speed control
- Provide independent variable voltage/current for output torque control

In TVC applications, it must also:
- Provide closed-loop output position control in response to guidance steering commands

The power processing and control block provides all the above functions. The power processing/inversion function is obvious if we have AC motors and DC power sources. But in addition to that interface function, we must also control speed and output torque. We have already discussed the desirability of independent control of those quantities.

In addition, typical TVC control loops provide engine position control for the outermost loop, in response to steering signals from the guidance and vehicle control function. Good system design demands that we add the additional position control functions into the controller, providing a variable rate/position loop, with rate proportional to position error.

Because of high output powers, high efficiencies and low losses are important to the problem of thermal control in flight.
Resonant power processing has so many advantages, that it would be hard not to select it for high-power applications. The only “con” is the fact that it has not been widely used in our industry, and designers are not as familiar with the technology. For low power applications of motor control (in the limits of much of our present experience) the issue does not have much effect on overall system performance. We can easily remove the heat from a small amount of extra power lost to efficiency, and the effect on energy sources can also be small. A little bit of added high-frequency noise can be filtered, also with little overall system impact.

But these “annoyances” in small systems become major problems in large ones. Going from 10% losses to 5% losses in a 50-KW/50-HP system eliminates 2500-watts that the batteries don’t have to supply and the thermal control system doesn’t have to accommodate. Clearly, these considerations are no longer negligible for a launch vehicle or aircraft.

Since the two primary motor controller implementations (switched-mode and resonant power processing) both synthesize low-frequency motor currents, they may be selected on their own merits, and not impact the motor interface. Resonant power processing is the obvious choice, for the reasons shown above.
The most important factor influencing EMA TVC design is Motor and Actuator Inertia
This flow diagram is designed to show the interrelationships between the various elements from which EMA TVC requirements are derived; and the constrained end product of an EMA implementation.

At the far right are the output products which have the strongest constraints. They are discussed in more detail on Page 12. However, it is obvious that we would like to control the rest of the system to minimize peak power requirements.

On the vehicle requirements side, payload, environment, physical mass and volume, and dynamic response are the base sources for the actuator size and power requirements. But it’s the mass acceleration side of the path that has the biggest impact.

For most actuator designs, the large effective gear reduction involved will make the effect of accelerating the engine system mass small when compared to the moments of inertia in the motor rotor and the actuator. About the best we can do is make the vehicle total load and the motor/actuator inertia effects about equal. And if we don’t optimize the motor and actuator from a moment of inertia point-of-view, we can easily find an EMA for a 25-horsepower vehicle requirement requiring a 100-horsepower equivalent power input.

Since they are so highly-leveraged, it is fortunate that we have full control over motor and actuator moments of inertia and matching. But also, since they are so highly-leveraged, they are the elements with which we must take the most care, when we design them.
Primary Design Drivers

• Acceleration of system inertias drives peak power requirements
  • Step function response and bandwidth size transient drive torque capability
  • Input power is proportional to drive torque

• Motor and gear train inertia have the greatest effect on peak power requirements
  • Maximum efficiency for power transfer dictates equal power allocations for the load and the inertia
  • Load inertias are small contributors, when reflected to the input through the mechanical advantage of the gear train
  • Maximum efficiency for power transfer dictates equal inertias for the motor and gear train

• Non-optimum designs can have peak powers that are four times the steady-state power

Physical vehicle component parameters and vehicle dynamics are the base sources for the TVC system requirements. Thrust loads, gimbal bearing friction, feed system constraints, etc. determine the steady-state loads against which the actuator must push or pull. When we add the inertia of the movable masses in the engine system, and how fast we must accelerate them, we can size the actuator and its performance. For example, on NLS, the worst case generates a requirement for a 32,000-lb linear thrust and 32-horsepower if the rates are included. Motor and actuator steady-state mechanical losses are comparatively small (probably less than 5%).

But if we consider the power to accelerate the actuator masses and the motor rotor, we find that its difficult to get them down to 32-horsepower. And if we were to use conventional aerospace PM motor designs, it would not be unusual to get the acceleration power requirement to 100-horsepower by itself; making the total peak input exceed 130-horsepower, for a 32-horsepower system.
Primary Design Limitation Factors

- Even with modern power processing technology and components, systems are primarily limited by "flyable" power processing capability
  - Component limitations
  - Thermal control capability
- Energy storage elements for these applications are primarily sized by peak power demands
  - Battery size or rotating machinery drive components both impact vehicle design
- Motor input power capability limits frequency response and step response

Power processing capability is limited by the capability of the flight-capable technology currently available in our industry. Signal processing and control capability is more than adequate. But if we look toward power processing components, IGBT's are the most promising, and even they are at their best in the newer resonant circuit topologies. While larger units and parallel controllers are possible, practical equipment design considerations push us toward trying to keep system peak powers below 100-horsepower.

When the energy storage requirements get large (to provide very high peak powers), the mass and volume of batteries get large enough to impact vehicle design. If we choose turbine-driven alternators for greater physical efficiency, the fluid systems to run them add complexity, impact propulsion system design, and compromise operability.

Finally, since input power capability limits torque and actuator acceleration, frequency response and step response are also limited. While our vehicle dynamics analyses have shown that an NLS-type vehicle only requires a 2-Hz system response (and that is no problem), higher bandwidth systems will allow us to have active control of stiffness and damping, to control vehicle high frequency effects.

The bottom line says the we would like to design EMA TVC hardware with low transient power requirements.
ELA/EMA Control with Resonant Power Processors

Summary

- Resonant power processors / motor controllers are the best choice for high-power ELA/EMA's with both DC and AC sources
- Induction motors are best for redundant, high-power, TVC assemblies
- Power capability is the limiting factor in ELA/EMA performance
  - Step response
  - Frequency response and bandwidth
- Motor/actuator inertia is the single most important (and often neglected) mechanical design parameter for integrated high-power TVC systems

Notes:
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Power Switching
"Enabling Technology"

**High power devices**

Bi-Polar /FET hybrids available 1990
50-100 amp, 600 volt

IGBT developed/in testing, available 1992
100-400 amp, 120 volt
high voltage/small size

MCT in development, available 1997
100-300 amp, 1200 volt
high temp/small size
Electric Actuation (ELA) Options

**EMA**
- No Hydraulics

**EHA**
- Nondistributed Hydraulics

---

**Diagram:**
- Electric Power Source → Servo Controller → Reversible Electric Motor
- Feedback from System Interface

**EMA Diagram:**
- Gear Drive → Ball Screw or Roller Screw Actuator
- LVDT

**EHA Diagram:**
- Expansion Reservoir
- Reversible Piston Actuator
- LVDT
EMA/EHA Design Methodology

Requirements Assessment
- System
- Power source
- Actuator
- Requirements Sensitivity

Conceptual Design
- System Schematics
- Thermal Management
- Concept Layouts
- Preliminary Stress Analysis
- Weight Projections
- Component Sizing

Performance Assessments
- Subsystem Modeling
- System Simulations
- Control Loop Stability
- System Response
- Fault Transient Response
- PSS Power Quality
- Growth assessment

Operability Assessments
- Interface Connections
- Test Checkout
- Health Monitoring
- Control Sensors
- Bit Sensors

Reliability Assessments
- Preliminary System Reliability
- Preliminary MTBF
- Preliminary FMEA
- Prime Reliable Components
- Life Limited Parts

Cost Assessments
- Reusable LCC
- Expendable LCC
- DDT&E
- Theoretical First Unit
- Average Production

Risk Assessments
- Cost
- Technical Development
- Schedule
- Supply Source
- Risk Mitigation
EHA Selection

- No single point failures
- Non-jamming piston/cylinder
- Fault tolerant redundancy management
- Relief valve channel disengagement
- Transient Load Relief
- Relief valve instantaneous response
- Thermal Management
- Fluid immersed motor
- Self contained Hydraulics
- No hydraulic lines/fittings
- Proven rod seal design
- Limited fluid volume
- Inherent Damping
- Zero Backlash
Brushless DC Motor/PWM Control Selection

Permanent Magnet Motor Selection

- Options: Permanent Magnet Motor, Induction Motor, Switched Reluctance
- PM lowest inertia/highest torque/best dynamic response
  - Highest efficiency
  - Highest reliability
  - Excellent thermal capacity (low rotor losses)

Digital PWM Control Methodology Selection

- High power density
- PDM in R&D stage/no payoff for this application

Application of Existing Technologies

- Commercial Aircraft
- Space
- Military qualified hardware exists
  - J-STARS 15 hp redundant antenna drive
  - Flown in "Desert Storm"
EHA Load-Sharing Simulator Failure

Holding Load

During Slew
Electric Actuation Drivers

- Power Switching Technology
- Technology Maturity
- Operability (Test, Checkout, Maintenance)
- Reliability
- Fault Tolerance
- Channel Load Sharing
- Redundancy Management
- Thermal Management/Regenerative Energy
- Transient Load Relief
- Packaging/Sizing
- Voltage Level
- Performance (Frequency Response, Load/Stroke, Duty Cycle)
UNIVERSITY OF ALABAMA IN HUNTSVILLE

ELECTROMECHANICAL ACTUATOR

AND

MOTOR OPTIMIZATION

TASKS

PRESENTED TO THE

ELA TECHNOLOGY BRIDGING PROJECT WORKSHOP

by

GEORGE B. DOANE III

HUNTSVILLE AL      SEPTEMBER 1992
TASK ONE

Examine EMA-TVC Subsystem Specifications

Prove Feasibility of EMA/TVC Subsystem By Means of a Point Design Meeting NLS/SSME Requirements

Demonstrate Point Design Characteristics by Simulation

Drive Out Potential Problem Areas

Establish Critical Component Specifications
Subsystem Specifications

The static and dynamic specifications applicable to the EMA as applied to the NLS are mostly yet to be determined on a definitive basis. However, it is known that many of the physical parameters of the new engine will be close to those of the current SSME. The structure to which the engines will be attached is likewise undetermined at this time. However, past experience with a number of launch vehicles suggests that at least as far as natural frequencies of the structure are concerned current SSME values are typical. Assuming they are within a representative range it will not be too difficult to tune the designs arising from present knowledge to accommodate the eventual actual values.

Following SSME practice leads to a stall force requirement as well as a horsepower rating. It has been customary in the past to rate hydraulic actuators in terms of horsepower even though they are used over a range of speeds i.e. around zero to plus and minus maximum velocity values. In the current design this power is to be reached at 5 in/sec actuator stroking velocity. It is more informative to examine torque speed curves over the whole operating envelope. This is particularly true when dealing with electric motors as the actuating component because they are capable of delivering much power or torque in off nominal conditions (provided the situation requiring much current does not last too long).

The number of motors and their horsepower rating was suggested by MSFC and may implement various redundancy schemes.

Three charts drawn directly from Rockwell documents specifying the SSME actuation system frequency and transient allowable envelopes are shown.
Examine EMA-TVC Subsystem Specifications

Stall Loads Specified by MSFC (60 Kips)

Three Motor Configuration Specified by MSFC

Each Motor to Produce 10 Horsepower at 5 in/sec Actuator Stroking Velocity

Each Motor to be Capable of 15 Horsepower at 5 in/sec

Maximize Power to Load During Accelerated Motion

Posses Robust Recovery From Saturated State

Frequency Domain Specifications

SSME Document
Flight Dynamics Requirement

Time Domain Specifications
SSME Document
Large and Small Amplitude
NOTE:
COMMAND AMPLITUDE = 2 TO 5% MAXIMUM

TYPICAL

FINAL STEADY STATE POSITION

POINTS OF INTEREST

<table>
<thead>
<tr>
<th>TIME (SEC)</th>
<th>ENGINE DEFLECTION (PERCENT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UPPER CURVE</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.025</td>
<td>60</td>
</tr>
<tr>
<td>0.075</td>
<td>125</td>
</tr>
<tr>
<td>0.150</td>
<td>125</td>
</tr>
<tr>
<td>0.250</td>
<td>125</td>
</tr>
<tr>
<td>0.300</td>
<td>120</td>
</tr>
<tr>
<td>0.500</td>
<td>SEE NOTE</td>
</tr>
</tbody>
</table>

NOTE: LIMIT CYCLING SHALL NOT EXCEED 3.0 PERCENT OF RATED HALF STROKE PEAK TO PEAK DURING A 10 SECOND PERIOD. HUNTING OR DRIFTING DURING A ONE MINUTE PERIOD SHALL NOT EXCEED THE THRESHOLD REQUIREMENTS OF TABLE IV.
NLS Derived Specifications

Preliminary work accomplished by the MSFC flight dynamics personnel working in the flight control area produced some preliminary equivalent system small angle response specifications in the frequency domain. While the point design meets these specifications they are included here for completeness sake.
Small Angle Time Domain Specifications From Flight Mechanics

Second Order System

Bandwidth................................................. 4.2 Hz

Damping Ratio........................................... 0.7 of Critical

TVC Commands In Range of............................ 0.25 Degree

Specifications Above Translate Into

Minimum Gimbal Velocity..................... 4.7 deg/sec

Minimum Gimbal Acceleration............ 120 deg/sec/sec
DESIGN APPROACH

The mechanical layout used in this study was suggested by various in-house designs extant at MSFC. MSFC also suggested that a range of the roller screw ratio not to exceed one inch per revolution and a spur gear step down ratio not to exceed ten were appropriate.

Because of a desire to minimize the electric current from the supply when accelerating the load, the technique of matching the actuator mechanical impedance to the load mechanical impedance was adopted. A fortuitous byproduct of this approach turned out to be that it yielded, when properly formulated, a unique solution for the two reduction ratios (rather than for the ratio of the two as other formulations do). Of course it was still necessary to produce specified stall torque which in turn was not necessarily compatible with the impedance matching criteria. This effect was investigated for a range of available motors producing the specified horsepower at different speeds. It was found that a relatively more massive motor turning at slower speed minimized the "detuning" from the matched impedance case necessary to meet the required stall force condition. From this investigation a motor specification for speed and inertia was developed.

At this early stage of investigation the nonlinearities considered were the torque saturation of the motor and the stroke constraint of +5 inches. Friction was assumed zero or nearly so and gear backlash was not modeled. Modeling this latter phenomenon awaits laboratory experiment because various anti backlash measures were either being incorporated or contemplated at the time of this design work.

To demonstrate that it is feasible to substitute this type of actuator for the previously used hydraulic one the design used the specifications previously applied to hydraulic actuator designs for the SSME and also followed the well verified design methods of the hydraulic actuators i.e. the type of feedback and the design methods used. This approach proved to produce very acceptable results.

A good deal of digital simulation was used both during the design phase of the work and to verify the designs in off nominal operation. An example of the latter was to perform a check on the unloaded or "out of the box" stability of the actuator servo design.
Design Approach

Assume Use of Roller Screw With Maximum Lead of 1 Inch Per Revolution

Assume Use of One Spur Gear Pass

To Minimize Acceleration Power Use Mechanical Impedance Matching
Also Maximizes LOAD Acceleration (Hence Bandwidth)

Assume Major Nonlinearities Are Torque Saturation and Stroke Constraint
+,- 5 Inches

Generally Base Design On Previous Hydraulic Experience

Use OTT Servo Techniques (Frequency/NYQUIST and Root Locus)
No Conditional Stability Was Allowed For Any Configuration

Use Simulation Liberally to Aid In Design and to Verify Results
Modeling Notes

The equations of motion of the actuator system with its motor load were written assuming that the various constituent pieces behaved as a collection of springs and masses. The motor was modeled as a spring and a mass in series as was previous practice. The various springs were combined in series/parallel as appropriate and an equivalent spring derived and used in the model. In the process some very stiff springs became negligible in the model. This model is implemented in the 4656 "iron horse" simulators e.g. the 8 Hz mode. The resulting four state model was constructed so that the physical quantities were readily available. It will be noted that this form of a model makes the actuator and the engine (and their states) readily identifiable. Damping was neglected in the basic model (and was only used very sparingly when numerical problems in such things as frequency responses arose). The justification for this was that structural damping tends in practice to be quite small (0.5% of critical is often used) and that it probably would err on the side of stability conservatism. The drawback was that the simulated system tends to be a little faster in response than is found in the laboratory where some friction is found.
Model Used

Four State Model

Mass of the Actuator
Mass of the Engine (Load)
Spring Constant Representing the Compliance of the
Engine and the Support Structure

Simulation Model Developed From The Equations Of Motion
Gearing Optimization

The gearing was optimized to produce impedance matching or, what is the same thing, maximum load acceleration. The method is straightforward and generally follows the seminal work by Petersen in the 1950s. The expression for the load acceleration is written and then maximized with respect to the available gear ratios. The key to obtaining a closed form, unique solution lies in assuming (as Petersen did) that the larger of the spur gears has an inertia equal to that of the smaller gear times the gear ratio raised to the fourth power. As is seen in the accompanying slides substitution of the proposed design's numerical parameters produces the desired answers. For this design it was shown that the dominating effects are the inertia of the motor and the inertia of the load and that other parameter changes produce negligible perturbations in the design. The details of the differentiations and the solution of the resulting algebraic equation were all carried out by a symbolic manipulation computer program.
Optimization of Gearing

Maximize Load Acceleration
Minimize Acceleration Power Requirement

These Produce The Same Result

Proceed by Maximizing The Load Acceleration
There is a Unique Closed Form Solution for
the Spur gear and the Roller Screw Ratios IF
One Assumes That the Inertia Of the Larger of the
Spur Gears Is N^4 Times the Inertia of the
Smaller Gear

An Example
Acceleration of the Load

\[
\alpha_{\text{Load}} = \frac{\text{Torque}}{J_{3,\text{Motor}} \left[ \frac{2 \pi n}{l} \right] + [J_{\text{pinion gear}} (3 + n^2)] \left[ \frac{2 \pi n}{l} \right] + J_{\text{Roller Screw}} \left[ \frac{2 \pi n}{n_1} \right] + M_{\text{Engine}} \left[ \frac{1}{2 \pi n} \right]}
\]

Mechanical Parameters

\[
J_{3,\text{Motor}} = \frac{(3)(565)(15)^{3/2}}{(5)(3000)^{5/3}} = 0.0315598 \text{ in-lbs-sec}^2
\]

\[
J_{\text{pinion gear}} = 0.00004768 \text{ in-lbs-sec}^2
\]

\[
J_{\text{Roller Screw}} = 0.016 \text{ in-lbs-sec}^2
\]

\[
M_{\text{Engine}} = 55 \frac{\text{lbs}}{\text{sec}^2} \text{ in}
\]

Substituting to Obtain Denominator Expression

\[
\alpha_{\text{Load}} = \frac{\text{Torque}}{[0.0315598] \left[ \frac{2 \pi n}{l} \right] + [(0.00004768)(3 + n^2)] \left[ \frac{2 \pi n}{l} \right] + [0.016] \left[ \frac{2 \pi n}{n_1} \right] + [55] \left[ \frac{1}{2 \pi n} \right]}
\]
Let Computer Take Derivatives of Denominator With respect to n and l

\[ D1 = \frac{0.198296}{1} + \frac{0.100531}{n} + \frac{8.75352}{2} + \frac{0.000599165}{1} + \frac{1}{n} + \frac{2}{l} \]

\[ D2 = \frac{0.000299582}{(3. + n)} + \frac{8.75352}{n} + \frac{0.198296}{1} + \frac{0.100531}{n} + \frac{0.000299582}{(3. + n)} + \frac{1}{n} + \frac{2}{l} + \frac{2}{l} \]

Set Equal to Zero and Let Machine Find Solutions for n and l

\( l \rightarrow 0.663194, \ n \rightarrow 4.28002 \)
Servo Design

Earlier SSME servo design practice was followed. Note that states of the load are not measured although there are systems in existence which do so.

As previously mentioned classical techniques i.e. frequency response and root locus were used in the servo design process. The results were verified by extensive simulations with the aforementioned nonlinearities included. An effort was made to make the electronic or signal gain paths as low gain as possible. However, the desire for high system bandwidth resulted in higher than desired signal gain and therefore some attention to signal noise control will probably be necessary.

The resulting system's step and frequency responses are shown in two slides. It is seen that the system meets the linear specifications.
Disturbance Response

It has proven impossible, at least for this author, to obtain accurate characterization of the engine start/stop transient forces as seen by the actuator. Inspection of raw force data obtained during firings of the MSFC Technology Test Bed, for example, reveals a highly oscillatory response of the strut force and the engine position. This is probably due to the fact that the so-called struts or stiff arms are anything but stiff. They are in reality a pre stressed spring made up of a series stack of Bellville like washers. Indeed a little reflection shows that the arms and hence the actuators when used must give or yield to relieve loads on the engine structure so as not to damage it.

Hydraulic actuators have very high output impedance to motion caused by forces applied to them. Pressure relief to limit loads may be incorporated in the form of pressure relief valves and so on but never the less they are relatively immune to start/stop transient caused motion. This is not inherently true of this form of electric actuator. The gearing used in them is of high efficiency and therefore may be back driven. This latter fact means that large amplitudes of motion are possible unless something is done to prevent them. Of course the amplitude of the motion is a direct function of the force applied by the start/stop transients depending upon magnitude, duration and one supposes on the particular function of the force versus time.

MSFC suggested that square shouldered pulses of 20, 40 and 60 kip amplitude and 400 milliseconds duration be investigated. This was done using the model developed from the servo design effort. At the 60 kip amplitude unacceptably large engine motion response occurred.

This result leads to the largest potential problem arising from the investigation. There are two approaches to understanding it better and coping with it. First some effort expended in investigating the start/stop transients is in order and second some overt response limiting measures should be undertaken. One simple scheme is explained later.
DISTURBANCE RESPONSES

Disturbance Pulse Characterization

Sharp Cornered Rectangular Pulses
20, 40, 60 KIPS Amplitude
400 Milliseconds Duration

Notes

Amplitude Uncertain
Duration Unspecified In Engine Specifications

LARGEST POTENTIAL PROBLEM ARISING IN THE ENTIRE INVESTIGATION
A Possible Start/Stop Transient Motion Limiting Solution

It is well known that shorting a separately excited e.g. permanent magnet electric motor across its terminals inhibits motion of the motor shaft. This is due to the back emf causing large currents to flow in the armature. Discussion with MSFC electronics experts revealed that a current limited "short circuit" could be implemented with the existing MSFC controller electronics design with little modification. Given a discrete signal announcing engine start or stop then the controller could be reconfigured for some small length of time to absorb the transient and then reconfigured back to its primary or position controlling mode.

With this established the simulation was exercised with a variety of gains in the short circuit current (i.e. actuator velocity to current) loop. It was found that up to a point increasing the gain produced desired results but that higher and higher gains became progressively ineffective. However the amplitude of motion resulting was quite acceptable especially in view of the fact that discussions with the configuration designers disclosed that the engines would not hit each other (at least in the design as it then stood) regardless of the phase of the various motors' motion.
One Simple Solution to Start/Stop
Transient Phenomenon
Reconfigured Controller Approach to Controlling
Response to Start/Stop Transient
Mechanical Stop Design

It is generally understood that limits will be built into the command software to prevent commanding an against the stop condition for the actuator. It is also understood that limits will be built into the servo electronics so that they will not attempt to respond to commands of an against the stop nature.

If in spite of all the foregoing precautions the actuator does go against the stop it is good practice to incorporate mechanical stops in the design which would enable the electronics to regain control or at least not allow the actuator to oscillate. To investigate this possibility the simulation was built with elastic stops whose compliance could be varied. It was found that indeed if a soft enough stop could be built the desired stable response would be obtained. This is documented in the following slides which at least bracket the desired value.
Mechanical Stop Design Considerations

Hard or Mechanical Stop Design To Prevent Limit Cycles or Instability

Elastic Stop Assumed

Three Different Compliance Values Were Investigated And The Results Are Displayed Below
CONCLUSIONS OF TASK ONE

Electromechanical Actuator Is Feasible

Conventional Design Techniques Based on Previous Actuators Are Applicable

Serious Effort Should be Expended to Characterize Start/Stop Transient Force Parameters
TASK TWO

Based On the Results of the First Task
Examine Various Motor Design Approaches
Design a Motor for the Actuator

Verify Techniques Used in the Motor Design Area
Validating Against Existing Motors
Construct/Test Designed Motor
General Approach

Take Conservative Approach to Initial Motor Design

Meet Motor Specifications Laid Down in Task One

Use Finite Element Analysis Techniques Especially for the Magnetic Circuit Analyses

Allow Sufficient Difference Between Peak Back EMF and Maximum Amplifier Controlled Terminal Voltage So That Amplifier Can Control Phase Currents

Investigate Analytically Promising Unconventional or Different Approaches to Motor Configurations e.g. Slotless Motor
Torque vs. Torque Angle

Air Gap Flux Density vs. Various Radial Air Gap Widths
SESSION III

ELA CONTROL ELECTRONICS
25KW

ELECTRONIC CONTROLLER

FOR THE 25HP EMA
ELECTROMECHANICAL ACTUATOR (EMA)
ELECTRONIC CONTROLLER

STME EMA PERFORMANCE REQUIREMENTS

• STALL FORCE: 60,000 LBS
• RATED LOAD: 40,000 LBS
• EFFECTIVE MOMENT ARM: 29.8 INCHES
• RATED VELOCITY: 5.0 IN./SEC.
• DYNAMIC FORCE: 40,000 LBS AT 5 IN./SEC. = 30.3 HP
• STROKE: +/- 4.4 INCHES
• ACCELERATION: 2 RAD/SEC²
• BANDWIDTH: 4Hz AT +/-2% OF FULL STROKE
• REDUNDANCY: FAIL OPERATE
  3 CHANNELS REQUIRED
• SUPPLY VOLTAGE: 270 VDC, NOMINAL
  ACCEPTABLE TO CORONA EXPERTS
DERIVED REQUIREMENTS

- EQUIVALENT GEAR RATIO (SPUAR + SCREW): 8,000: 1 (TYPICAL)

- MAXIMUM MOTOR SPEED: 12,000 - 14,000 RPM

- PEAK POWER: 87K WATTS TOTAL

  29 K WATTS/CHANNEL

- PEAK SUPPLY CURRENT: 365 AMPS @ 240VDC (3 CHANNELS)

- MOTOR ROTOR INERTIA: 3 X 10^4 FT LB SEC^2
CANDIDATE MOTOR TYPES

- PERMANENT MAGNET BRUSHLESS DC
- VARIABLE FREQUENCY INDUCTION
- SWITCHED RELUCTANCE
BASELINE MOTOR:

PERMANENT MAGNET BRUSHLESS DC (PMBDC)

• HIGHEST OUTPUT POWER TO WEIGHT RATIO
• HIGHEST EFFICIENCY
• HIGH TORQUE TO INERTIA RATIO
• IDEAL THERMAL CHARACTERISTICS - NO HEAT IN ROTOR
• FULLY AND EASILY CONTROLLED
• POTENTIAL FOR HANDLING ENGINE START-UP TRANSIENT BY SHORTING WINDINGS
• DRAG CAUSED BY SHORTED WINDING OR SHORTED TRANSISTOR IS LESS THAN HARD OVER FAILURE.
• PM MOTOR/FLYWHEEL FLOATING ON POWER BUS HAS POTENTIAL FOR SUPPLYING CURRENT SURGE.
SHORTED MOTOR PERFORMANCE

TYPICAL PERFORMANCE FOR EMA'S BY
AEROJET/MSFC
LR/TEXTRON/MSFC
MOOG
AIR RESEARCH/J STARS
MSFC(2)
HONEYWELL
ELECTRONIC CONTROLLER TYPES

- 6 TRANSISTOR, 6 STEP, PULSE WIDTH MODULATED (PWM)

- 6 TRANSISTOR, SINUSOIDAL PWM

- 8 TRANSISTOR, 6 STEP, PWM
6 TRANSISTOR SINUSOIDAL PWM

REQUIRES LINEAR RESOLVER

HIGHER BANDWIDTH

MOST EFFICIENT

MOTORS NOT READILY AVAILABLE FOR TESTING
SIX TRANSISTOR, 6 STEP PWM CONTROLLER

- SIMPLEST

- SENSITIVE TO MOTOR L/R AND LEAD LENGTH

- REQUIRES HIGH FREQUENCY SWITCHING

- ASSOCIATED TRANSISTORS HAVE HIGH ON LOSS, LOWER SWITCHING LOSS

- EFFICIENCY IS IMPORTANT

- CONTROLLER SELF STANDING (NOT ON COLD PLATE): MUST INCLUDE ENOUGH HEAT SINK WEIGHT TO KEEP TEMPERATURE AT A SAFE LEVEL.
Electromechanical Actuator
Electronic Controller

270 VDC

MSFC 6 TRANSISTOR INVERTER
PULSE WIDTH MODULATION SINUSOIDAL OR SIX STEP

SIX STEP
EIGHT TRANSISTOR, 6 STEP PWM CONTROLLER

- LEAST SENSITIVE TO MOTOR L/R

- LOW SWITCHING FREQUENCIES

- ASSOCIATED TRANSISTORS HAVE LOW ON LOSS, HIGHER SWITCHING LOSS

- EFFICIENCY IS IMPORTANT

- CONTROLLER SELF STANDING (NOT ON COLD PLATE): MUST INCLUDE ENOUGH HEAT SINK WEIGHT TO MAINTAIN TEMPERATURE AT A SAFE LEVEL.

* ALL CONTROLLERS INCLUDE ONE EXTRA POWER TRANSISTOR FOR MANAGING ENERGY DURING BRAKING (KINETIC ENERGY)
Electromechanical Actuator
Electronic Controller

FIGHT TRANSISTOR INVERTER
LOW SPEED SWITCHING
2 KHZ TYP.
NOT SENSITIVE TO MOTOR L/R
SIX STEP ONLY
LOWER CONDUCTION LOSS
MORE PARTS
EFFICIENCY >95%

MSFC 8 TRANSISTOR
6 STEP INVERTER
PULSE WIDTH MODULATION
25KW CONTROLLER FEATURES

- CURRENT LOOP OPERATION
- POSITION LOOP OPERATION WITH RESOLVER
- 14KHZ PWM FREQUENCY
- FOUR QUADRANT OPERATION
- OPTICALLY ISOLATED IGBT DRIVERS
- ADJUSTABLE CURRENT LIMIT
- OPERATING VOLTAGE: 270VDC
- RATED CURRENT: 100 AMPS
- PEAK CURRENT: 150 AMPS
- POWER SWITCHES: IGBT'S
- DYNAMIC BRAKING LOAD BANK (CONTROLLED)
- ANALOG LOW POWER ELECTRONICS
25kW SERVO DRIVE SYSTEM - BLOCK DIAGRAM
25HP MOTOR *

- PERMANENT MAGNET, 3 PHASE BRUSHLESS D. C. MOTOR
- 12 POLE
- SAMARIUM COBALT MAGNETS
- HALL EFFECT DEVICES FOR COMMUTATION SENSING
- 9200 RPM NO LOAD SPEED
- EFFICIENCY (MEASURED) >92%
- 4000 OZ-IN @ 7000 RPM

* OFF THE SHELF, INEXPENSIVE, NOT OPTIMIZED FOR EFFICIENCY
TEST RESULTS

- CONTROLLER (POWER INVERTER) HAS BEEN DEMONSTRATED AT 54 HP PEAK

- RESPONSE TIME: 130m SEC, FROM 7,000 RPM TO -7,000 RPM

- CONTROLLER EFFICIENCY: >95%

- LINEARITY TEST WITH AND WITHOUT INTEGRATOR IN POSITION LOOP
FREE RUNNING MOTOR DECELERATION/ACCELERATION CURRENT (50A/DIV)
(-9250 RPM TO + 9250 RPM)

BATTERY VOLTAGE: 270VDC
Electromechanical Actuator
Electronic Controller

\[ X = 2.8185 \text{ Hz} \]
\[ Y = -11.345 \text{ dB} \]

\[ Y = -11.345 \text{ dB} \]

2% COMMAND
STEP RESPONSE

VERTICAL SCALE: 1.25 IN/DIV
Grasping Linearity Test in SSME Simulator

MSEC Dual 50 HP TVEMNA
Electromechanical Actuator
Electronic Controller

PEAK EFFICIENCY (IMPLIED)
98.4%
95%

AMPLIFIER POWER LOSS
& EFFICIENCY

8-TRANSISTOR 6-STEP INVERTER
(NOT OPTIMIZED)

POWER LOSS

LOAD CURRENT

EFFICIENCY %

AMPLIFIER POWER LOSS

0 20 40 60 80 100

100

1600

1200

800

400
50MS/DIV
POWER INVERTER VOLTAGE PROFILE AND BATTERY CURRENT
REQUIRED TO ACCELERATE MOTOR WHEN ACTUATOR
COMMAND TO EXECUTE A 0.5 IN STEP.
TRACE 1: INVERTER INPUT VOLTAGE (20V/DIV)
TRACE 2: BATTERY OUTPUT CURRENT (20A/DIV) @ 240 VDC
50MS/DIV
POWER INVERTER VOLTAGE PROFILE AND ACTUATOR
MOTOR CURRENT WHEN ACTUATOR COMMANDED TO
EXECUTE A 0.5 IN STEP.
TRACE 1: INVERTER INPUT VOLTAGE (20V/DIV)
TRACE 2: MOTOR CURRENT (50A/DIV)
BATTERY VOLTAGE: 240VDC
Electromechanical Actuator
Electronic Controller

SAFE OPERATING AREA

\[ I_C \text{ MAX. (PULSED)} \]

\[ I_C \text{ MAX. (CONTINUOUS)} \]

\[ I_C \text{ OPERATION} \]

\[ \text{COLLECTOR-CURRENT } I_C (A) \]

\[ \text{COLLECTOR-EMITTER VOLTAGE } V_{CE} (V) \]

\[ * \text{SINGLE NONREPETITIVE PULSE } T_c = 25^\circ C \]

\[ \text{CURVES MUST BE DERATED LINEARLY WITH INCREASE IN TEMPERATURE.} \]
Electromechanical Actuator
Electronic Controller

TRANSISTOR LOSS AND EMI

SWITCHING LOSS
AT 100 AMPS
270 VOLTS, 15 KHZ

CONDUCTION LOSS
AT 100 AMPS
2.5 VOLTS X 100 AMPS
250 WATTS

TOTAL LOSS
250 + 51
= 301 WATTS PEAK

TRANSISTOR RATING
200 AMP CONT., 400 PEAK
600 VOLT
800 WATTS

400 AMP, 600 VOLT, 1400 WATT UNITS AVAILABLE

AVAILABLE THIS SUMMER
600 AMP, 600 VOLT UNITS

EMI
DEDICATED POWER SOURCE
MOTOR/CONTROLLER IN CLOSE PROXIMITY
MOTOR/CONTROLLER TOTALLY ENCLOSED
SHIELDED CABLE

6750 WATTS PEAK
Pavg = .5 X 6750 x 1 x 10^-6 x 15 x 10^3
= 50.6 WATTS

POWER

200 WATTS
RESONANT POWER CONVERSION

and

INDUCTION MOTOR CONTROL

Ken Schreiner

General Dynamics
Space Systems Division
Resonant Power Conversion Advantages vs. PWM

- Lower component stresses and improved efficiency with zero voltage or zero current switching
- Increased switching frequency to control high frequency, low inertia motors
- Lower noise and EMI
- Decreased thermal loads
- Decreased battery capacity requirements
There are Two Resonant Converter Options

High-frequency AC resonant distribution
- Uses zero current switching resonant inverter to generate high frequency bus
- Motor controller 'steers' AC half-sine pulses to low frequency output
- Advantages where redundancy required and high fault currents may need to be interrupted

Resonant DC converter
- Adds an inductor and capacitor to the normal six switch bridge to perform resonant zero voltage switching
- Advantages where high efficiency and high power required in dedicated configuration
DC Resonant Topology

POWER STAGE

Vdc

Cclamp

Lres

Cdc

Cres

Vlink

To motor

Link Voltage

Line-to-Line Voltage
DC Resonant Link Operation

1. Bridge switches conduct - build up inductor current
2. Resonant rise/fall of link voltage
3. Clamp diode conducts - turn on clamp switch
4. Clamp switch conducts
5. Bridge diodes conduct - turn on bridge switches
The Resonant DC Link Converter Has

- Higher overall efficiency than PWM or AC Resonant Topologies
- Fewer Switches and Reactive Components Than AC Resonant
- No-Load Switch Losses are Light
- ALS Will be Using a Single-String Actuator Topology
- Easy to Synchronize Zero Voltage Switching
Resonant switching is superior to hard switching

- Better switch utilization
- Lower losses
- Lower device stresses
Induction Motor Control
Why Induction Machines?

- Motor is rugged
- Motor temperature limited by insulation rating only
- Field extinguished by reducing motor voltage
- Motor losses comparable to dc motor losses
Induction Machine Control Concepts

\[ T = \frac{3pLm\lambda dr}{4Lr} \cdot I_{qs} = Kt \cdot I_{qs} \]
\[ \omega_s = \frac{R_r L_m I_{qs}}{L_r \lambda dr} = K_s \cdot I_{qs} \]
State Variable Position Controller

- Generates motor torque command
Current 2 to 3 Axis Frame Transformation

• Transforms dc torque and flux currents to three phase current commands
Machine Parameter Sensitivity

- Proper motor control requires knowing the following parameters:
  - $L_m$
  - $L_r$
  - $R_r$

- $L_m$ and $L_r$ are a function of flux level and can be obtained from lookup tables

- $R_r$ can be determined from measurements of rotor flux
Slip Gain Controller Implementation

- Maintains proper vector orientation of the induction machine
SUMMARY

Use of Emerging Technologies has Resulted in:

- Power converters with reduced losses and increased reliability
- Induction machines that are rugged and efficient
- Increased controller performance

Construction of the full scale controller is nearing completion with design verification early next year at MOOG.
ELECTRIC THRUST VECTOR CONTROL FOR NATIONAL LAUNCH SYSTEM (NLS)

SEPTEMBER 28, 1992

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
AGENDA

• ALLIED-SIGNAL AEROSPACE COMPANY

• ELECTRIC ACTUATION NEEDS

• POWER SOURCE/ACTUATION CAPABILITIES

• ELECTRIC ACTUATION SYSTEM SOLUTIONS

• SUMMARY/RECOMMENDATIONS
AN ADVANCED TECHNOLOGY COMPANY WITH PRIMARY BUSINESSES IN AEROSPACE, ELECTRONICS, AUTOMOTIVE, AND Engineered Materials.

1991 SALES: $11.8 BILLION
98,000 EMPLOYEES

ALLIED-SIGNAL AEROSPACE CO.

- AIRSEARCH
- BENDIX
- BENDIX/KING
- GARRETT

$5.3 BILLION

AUTOMOTIVE SECTOR

- AUTOLITE/FRAM
- SPARK PLUGS/FILTERS
- BENDIX GROUP
- FRICTION MATERIALS
- BRAKE SYSTEMS
- GARRETT GROUP
- TURBOCHARGERS
- INTERCOOLERS

$4.1 BILLION

ENGINEERED MATERIALS SECTOR

- UOP PROCESS DIVISION
- NORPLEX/OAK DIVISION
- FLUORINE PRODUCTS DIV.
- PLASTICS AND PERFORMANCE MATERIALS
- FIBERS DIVISION

$2.4 BILLION

RESEARCH CENTER
ELECTRICAL ACTUATION NEEDS
HOW TO SIGNIFICANTLY REDUCE COST OF FUTURE SPACE FLIGHT

- IMPLEMENTATION OF FAULT TOLERANT

- OPERATION IN PRESENCE OF FAULTS (FAULT MASKING)

- BUILT-IN-SYSTEM/COMPONENT TEST
WHAT DOES FAULT TOLERANCE IMPOSE ON SUCH SYSTEMS AS TVC

- POWER SOURCE
  - MULTIBUS DISTRIBUTION
  - FAILURE OF SINGLE BUS DOES NOT IMPACT PERFORMANCE

- ACTUATION
  - MULTI CHANNEL APPROACH
  - FIRST CHANNEL FAILURE TRANSPARENT
  - SECOND CHANNEL FAILURE RESULTS IN SAFE (NULL) SYSTEM
3 CHANNEL FAULT TOLERANCE
TWO ENGINE T.V.C. SYSTEM

M/MC = MOTOR/MOTOR CONTROLLER
PS = POWER SOURCE

#1 ENGINE

#2 ENGINE

1 M/MC 2 M/MC 3 M/MC
1 M/MC 2 M/MC 3 M/MC

PS #1
PS #2
PS #3
WHAT ARE POWER SOURCE REQUIREMENTS

- BIDIRECTIONAL POWER BUS
- TIGHT VOLTAGE REGULATION (MIN. LOAD KVA)
- PROVIDE DISSIPATION/STORAGE FOR REGENERATED POWER
- FULLY TESTABLE WITH ONLY ELECTRICAL POWER SUPPLIED
POSSIBLE SOLUTION – GH₂ TURBOALTERNATOR/POWER CONDITIONER

P.M. GENERATOR

RECTIFIER CHOPPER

POWER CONTROLLER

GH₂

PM ROTOR
WHAT ARE ACTUATOR REQUIREMENTS?

- FULLY TESTABLE WITH ELECTRICAL POWER
- FULL REGENERATIVE CAPABILITY (MINIMIZES HEAT LOAD)
- HIGH EFFICIENCY
- FIRST FAULT TRANSPARENT (REPORTED) TO VEHICLE
- SECOND FAULT CAUSES SAFE (NULL) OF ACTUATION

- FREQUENCY RESPONSE
  - TORQUE LOOP > 1000 HZ
  - SPEED LOOP > 50 HZ
  - POSITION LOOP > 10 HZ
BLOCK DIAGRAM FOR MULTICHANNEL FAULT TOLERANT SYSTEM

#1

#2

#3

Allied-Signal Aerospace Company
AirResearch Los Angeles Division

IG-14434
HOW IS REDUNDANCY IMPLEMENTED?

- ALL CHANNELS ARE SYNCHRONIZED WITH RESPECT TO COMPUTATIONAL FRAME
- DATA IS EXCHANGED BETWEEN CHANNELS AT FRAME RATE SO THAT LOCAL CHANNEL HAS GLOBAL DATA
- LOCAL CHANNEL USES IDENTICAL GLOBAL DATA TO COMPUTE SPEED AND TORQUE COMMANDS
- LOCAL SPEED/TORQUE TRANSMITTED GLOBALLY
- TORQUE COMMANDS ARE IDENTICAL, AND THIS USED TO BALANCE MULTI CHANNEL ACTUATOR
HOW IS REDUNDANCY IMPLEMENTED? (CONT’D)

- GLOBAL DATA IS VOTED AT “VOTING PLANE” THAT HAS ABILITY TO ELIMINATE FAULTY DATA BUT MAINTAIN CHANNEL INTEGRITY

- FOR TVC – VOTING PLANE IS AT TORQUE CMD

- IF NON IDENTICAL COMPUTED GLOBAL DATA, FAULTY COMPUTATION IS REJECTED

- IF SENSED STATE VARIABLE DIFFER BY > “ε”, FEEDBACK IS ELIMINATED

- IF FAILURE CLEARS ITSELF – (P/S FAILURES) RESYNCHRONIZATION OF CHANNEL IS AUTOMATIC
HOW IS HEALTH MANAGEMENT ACCOMPLISHED

- EACH CHANNEL HAS GLOBAL DATA AND LOCAL DATA AVAILABLE

- COMPARISON OF DATA ENABLES COMPLETE CHANNEL HEALTH EVALUATION BASED UPON GLOBAL AND LOCAL DATA

- HEALTH MAINTAINENCE RESIDES AT SUBSYSTEM LEVEL AND IS NOT PASSED "UP THE LINE"
WHAT DOES THIS IMPOSE UPON ACTUATOR DEVICES

- MULTI-CHANNEL APPROACH

- ALL CHANNELS EQUALLY SHARE LOAD

- EACH CHANNEL IS RATED \( \left( \frac{1}{N-1} \right) \) SYSTEM REQUIREMENTS

- FAULT TOLERANT ARCHITECTURE BE UTILIZED
FROM SYSTEM PERSPECTIVE – WHAT IS IMPACT ON PEAK POWER UTILIZING 3 CHANNELS

- CONSIDER ALL MOTORS ARE DESIGNED WITH CONSTANT L/D PARAMETERS. FOR SINGLE MOTOR TO PERFORM TASK $L_1, D_1$

\[
\begin{align*}
\text{TORQUE} & = K_1 D^2 L \\
\text{INERTIA} & = K_2 D^4 L \\
\frac{\text{TORQUE}}{\text{INERTIA}} & \propto \frac{1}{D^2}
\end{align*}
\]

FOR A 3 MOTOR SYSTEM, EACH MOTOR RATED 1/2 OF SINGLE MOTOR

\[
\text{TORQUE}_{3\text{ MOTOR}} = \frac{1}{2} \text{TORQUE}_{1\text{ MOTOR}} = \frac{1}{2} K_1 D_1^2 L_1 = K_1 D_2^2 L_2
\]
WHAT IS IMPACT ON PEAK POWER - (CONT'D)

\[
\text{TORQUE/3 MOTOR} = K_1 D_2^2 L_2 = \frac{1}{2} K_1 D_1^2 L_1 \\
\frac{L}{D} \text{ IS CONSTANT, } \frac{L_1}{D_1} = \frac{L_2}{D_2} \\
\therefore D_2 = D_1 (1/2)^{1/3}
\]

\[
\frac{\tau}{I} \bigg|_{1 \text{ MOTOR}} = \frac{K_1}{K_2 D_1^2} = (1/2)^{2/3} \\
\frac{\tau}{I} \bigg|_{3 \text{ MOTOR}} = \frac{K_1}{K_2 D_1^2} = 0.63
\]

i.e., POWER TO ACCELERATE MOTOR INERTIA IS REDUCED BY 37% FOR SINGLE MOTOR CONFIGURATION
ELECTRICAL ACTUATION SYSTEM
SOLUTIONS
ALAD/BOEING PROVIDES STATE-OF-THE-ART ELECTRICAL ACTUATION SUBSYSTEMS

- EMA
- ELIMINATES HYDRAULICS
- POWER ON DEMAND
- FIBER OPTIC FEEDBACK

Diagram:

- ELECTRICAL POWER SOURCE
- SERVO/MOTOR CONTROLLER
- REVERSIBLE ELECTRIC MOTOR
- SYSTEM INTERFACE
- OPTIC TRANSDUCER
- EXPANSION RESERVOIR
- PISTON ACTUATOR
- REVERSIBLE PISTON PUMP
- OPTIC TRANSDUCER

- EHA
- NONDISTRIBUTED HYDRAULICS
WHAT ARE POSSIBLE T.V.C. SYSTEM SOLUTIONS?

ACTUATOR: ELECTROMECHANICAL
          ELECTROHYDRAULIC
MOTOR:   PERMANENT MAGNET
          INDUCTION
          SWITCHED RELUCTANCE
INVERTER: HARD SWITCH
          SOFT SWITCH
CONTROL: PULSE WIDTH MODULATION
          PULSE DENSITY MODULATION
# HOW TO EVALUATE THE DIFFERENT MOTORS

<table>
<thead>
<tr>
<th></th>
<th>INDUCTION</th>
<th>PM</th>
<th>S/R</th>
<th>IMPACT</th>
<th>SIG-TVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>TORQUE/INERTIA</td>
<td>HIGH</td>
<td>HIGH</td>
<td>LOW</td>
<td>POWER SOURCE</td>
<td>HIGH</td>
</tr>
<tr>
<td>POWER FACTOR</td>
<td>0.6 – 0.7</td>
<td>0.8 – 1</td>
<td>?</td>
<td>CONTROLLER KVA SYSTEM WT.</td>
<td>HIGH</td>
</tr>
<tr>
<td>TORQUE PULSATIONS</td>
<td>NONE</td>
<td>NONE</td>
<td>HIGH</td>
<td>CONTROL LOOP</td>
<td>HIGH</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>GOOD</td>
<td>BETTER</td>
<td>GOOD</td>
<td>THERMAL DESIGN SYSTEM WT.</td>
<td>HIGH</td>
</tr>
<tr>
<td>SENSORS</td>
<td>SPEED</td>
<td>ROTOR POS SPEED</td>
<td>ROTOR POS SPEED</td>
<td>RELIABILITY</td>
<td>LOW</td>
</tr>
<tr>
<td>VARIABLE FLUX</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>NONE</td>
<td>LOW</td>
</tr>
<tr>
<td>SELF EXCITATION</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>ACTUATOR DESIGN UNDER FAULT</td>
<td>HIGH</td>
</tr>
<tr>
<td>HIGH TEMP. ROTOR</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>ACTUATOR TEMP &lt;200°C</td>
<td>LOW</td>
</tr>
</tbody>
</table>
HARD SWITCHING VS. SOFT SWITCHING

- SWITCHING LOSSES ARE ELIMINATED WHEN SOFT SWITCHING IS INCORPORATED

- RESONANT CIRCUIT MUST OPERATE - CONTINUOUSLY - AND HAS LOSSES ASSOCIATED WITH IT
HARD SWITCHING INVERTER SCHEMATIC

EMI FILTER

POWER INVERTER
SOFT SWITCHING INVERTER SCHEMATIC

- ADDED PARTS INCREASE COST, WEIGHT, REDUCE RELIABILITY
PULSE WIDTH COMPARED TO PULSE DENSITY MODULATION

**PWM**

- AVERAGE VALUE OF OUTPUT IS INFINTELY ADJUSTABLE
- CONTROLLABILITY IS EXCELLENT
- FREQUENCY LIMITED TO 20 – 50 KHZ

**PDM**

- AVERAGE VALUE OF OUTPUT CONTROLLED BY MISSING PULSES
- ADEQUATE CONTROLLABILITY AT HIGH FREQUENCY
- FREQUENCY > 50 KHZ
# HOW TO EVALUATE THE DIFFERENT CONTROL OPTIONS

<table>
<thead>
<tr>
<th></th>
<th>PDM</th>
<th>PWM</th>
<th>IMPACT</th>
<th>SIGNIFICANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOTOR EMI</td>
<td>LOW</td>
<td>HIGH</td>
<td>NONE</td>
<td>LOW</td>
</tr>
<tr>
<td>SUPPLY EMI</td>
<td>HIGH</td>
<td>LOW</td>
<td>SUBHARMONIC FREQUENCIES</td>
<td>HIGH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EMI FILTER</td>
<td></td>
</tr>
<tr>
<td>OPERATING FREQ.</td>
<td>&gt; 50 KHZ</td>
<td>&gt; 20 KHZ</td>
<td>LOAD RIPPLE</td>
<td>LOW</td>
</tr>
<tr>
<td>LEAKAGE DISPLACEMENT</td>
<td>LOWER dv/db</td>
<td>HIGHER dv/db</td>
<td>FILTER WEIGHT</td>
<td>LOW</td>
</tr>
<tr>
<td>CURRENTS</td>
<td></td>
<td></td>
<td>(COMMON MODE)</td>
<td></td>
</tr>
<tr>
<td>FAULT TOLERANCE</td>
<td>LOW</td>
<td>HIGH</td>
<td>S.E.E. BECOME BURN OUT</td>
<td>HIGH</td>
</tr>
<tr>
<td>DEVICE RATING</td>
<td>&gt;1.5 PU VOLTAGE + CURRENT</td>
<td>1 PU</td>
<td>COST, SIZE</td>
<td>HIGH</td>
</tr>
<tr>
<td>LOOP FREQUENCY RESPONSE</td>
<td>APPROX. 200 Hz</td>
<td>&gt;2000 Hz</td>
<td>CONTROLLABILITY</td>
<td>HIGH</td>
</tr>
</tbody>
</table>
WHAT ARE RECOMMENDATIONS FOR TVC

- PWM/PM MOTORS ARE MATURE SYSTEM
- ANY POWER LEVEL REQUIRED FOR TVC IS ACHIEVABLE WITH TODAY'S TECHNOLOGY
- TECHNOLOGY IS DEVELOPED AND WELL UNDERSTOOD
- PWM/PM PROVIDES ROBUST SYSTEM
- ALL ADVANCES IN POWER AND CONTROL ELECTRONICS WILL EQUALLY HELP PWM/PDM
- WHERE TEMPERATURES < 200 °C ARE ENCOUNTERED, PWM, PM IS THE PREFERRED SYSTEM
- FOR TEMPERATURES > 200 °C - INDUCTION MOTORS/PWM BECOMES PREFERRED SYSTEM
TITAN IV STAGE 1 BOOSTER
TVC PERFORMANCE PREDICTIONS
FOR
ELECTROMECHANICAL ACTUATORS

Jeff Ring
Advanced Programs
(813) 539 - 5672
TITAN IV TVC STAGE 1 BOOSTER EMA PERFORMANCE STUDY

Honeywell

- Specified Performance Requirements
  (Cylinder Assembly, Actuating, Linear - Booster Engine Control, PD4600008)
  - Stroke = ± 1", Figure 11
  - No Load Velocity Limit = 3.5 in/sec, Para. 3.1.1.14.3
  - Loaded Velocity Limit = 2.5 to 3.5 in/sec, Para. 3.1.1.14.3
  - Output Load Capability = 30000 lb, Para. 3.1.1.2
  - Closed Loop Bandwidth = 8 hz, Table 1

- Specified Load Parameters
  - Engine Inertia = 518 slug - ft², Para. 3.1.1.20
  - Engine Natural Frequency = 13.5 hz, Para. 3.1.1.20
  - Engine Moment Arm = 14.34 in, Para. 3.1.1.20

- Motor/Actuator Design Conducted

- Closed Loop Feedback Controller Designed

- Motor/Actuator/Load/Controller modeled and simulated

- Performance evaluation conducted
The procedure for evaluating EMA performance for the Titan IV stage 1 booster TVC involved several steps. The first step was to determine the performance requirements. These requirements were obtained from the Martin Marietta Cylinder Assembly, Actuating, Linear - Booster Engine Control, PD4600008 document. The key requirements for stroke, no-load and loaded velocity limits, output load capability, and closed loop bandwidth were extracted from this document as indicated above.

The EMA is coupled to a compliant load. This load is characterized by the engine inertia, natural frequency, and moment parameters listed above. This information is used as a data base to construct a dynamic load model.

The next step was to develop a "strawman" motor/actuator design that can achieve the specified performance requirements. A math model of the strawman motor/actuator and compliant load was used to conduct a closed loop feedback control algorithm. This algorithm was incorporated into the motor/actuator/load model and a stability and performance analysis was conducted.
INTEGRATED DESIGN APPROACH IS NECESSARY

Honeywell

PERFORMANCE REQUIREMENTS
- No Load Velocity Limit
- Bandwidth
- Stroke
- (\% Linear Range)
- Output Load Capability

MOTOR CAPABILITY INPUTS
- Maximum Motor Speed
- Mechanical Time Constant
- Winding Resistance
- Electrical Time Constant

CONTROL LOOP
- Gain
- Shaping

ACTUATOR
- Gear Ratio

MOTOR
- Rotational Acceleration Limit
- Maximum Torque
- Motor Inertia
- Torque Gain
- Back EMF
- Minimum Battery Voltage
- Maximum Current
- Winding Inductance

Load Dynamics
- Motor/Actuator Dynamics
  - Torque Gain
  - Motor Inertia
  - Gear Ratio
- Load Damping
- Load Inertia
- Stiffness

Inputs

Calculations
INTEGRATED DESIGN APPROACH IS NECESSARY

An integrated design approach should be followed for EMA TVC systems. This is apparent from the interrelationships which exist between the functional elements of the EMA system block diagram above. The control loop, actuator, and motor designs are dependent on the performance requirements, motor state of the art capabilities, and load coupling dynamics. Off the shelf actuation systems will not be "optimized" for performance, size, weight, power, and etc. because they have not taken fully into consideration application specific interrelationships. A custom design which utilizes an integrated design approach and comprehensive system analysis is therefore necessary when maximum performance and minimum size, weight, and power are crucial.
### Summary of Stage 1 EMA Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Roller Screw Gear Ratio</td>
<td>50.86</td>
<td>rad/in</td>
</tr>
<tr>
<td>$K_A$</td>
<td>Actuator Stiffness</td>
<td>100000</td>
<td>lb/in</td>
</tr>
<tr>
<td>$K_e$</td>
<td>Back EMF</td>
<td>.41</td>
<td>volt/rad/sec</td>
</tr>
<tr>
<td>$K_m$</td>
<td>Torque Sensitivity</td>
<td>.303</td>
<td>ft-lb/amp</td>
</tr>
<tr>
<td>$J_m$</td>
<td>Motor Inertia</td>
<td>$5.41 \times 10^{-3}$</td>
<td>slug-ft$^2$</td>
</tr>
<tr>
<td>$V_{BATTERY}$</td>
<td>Battery Voltage</td>
<td>73</td>
<td>volts</td>
</tr>
<tr>
<td>$I_{max}$</td>
<td>Maximum Current</td>
<td>81</td>
<td>amps</td>
</tr>
<tr>
<td>$\omega_{max}$</td>
<td>Maximum Motor Speed</td>
<td>1700</td>
<td>rpm</td>
</tr>
<tr>
<td>$R$</td>
<td>Winding Resistance</td>
<td>.23</td>
<td>ohms</td>
</tr>
<tr>
<td>$L$</td>
<td>Winding Inductance</td>
<td>.23</td>
<td>mhenries</td>
</tr>
</tbody>
</table>
SUMMARY OF STAGE 1 EMA PARAMETERS

A "strawman" motor/actuator design was conducted which does not violate current state of the art motor limitations and which will meet the specified Titan IV stage 1 booster TVC performance requirements. Defining EMA parameters, their description and numerical values are listed.
LOAD CAPABILITY AND VELOCITY LIMITS REQUIREMENTS ACHIEVED

- Output Load Capability Verification

\[
\text{Stall Current} \times \text{Torque Sensitivity} \times \text{Gear Ratio} \times \text{Number of Motors} = \text{Stall Force}
\]

81 amps \times 0.303 \text{ ft-lb/amp} \times (50.86 \text{ rad/in}) (12\text{ in/ft}) \times 2 = 29960 \text{ lbs}

- Velocity Limits Verification

\[
\frac{\text{No Load Motor speed}}{\text{Gear Ratio}} = \text{No Load Velocity Limit}
\]

1700 \text{ rpm} \left( \frac{2\pi}{60} \frac{\text{ rad/sec}}{\text{ rpm}} \right) \times 50.86 \text{ rad/in} = 3.5 \text{ in/sec}

1411 \text{ rpm} \left( \frac{2\pi}{60} \frac{\text{ rad/sec}}{\text{ rpm}} \right) \times 50.86 \text{ rad/in} = 2.9 \text{ in/sec}

\[
\text{MOTOR SPEED (rpm)}
\]

\[
\text{TORQUE (ft-lb)}
\]

\[\text{TL @ 20000 lb}\]

\[\text{T}_{\text{max}}\]
LOAD CAPABILITY AND VELOCITY LIMITS REQUIREMENTS ACHIEVED

The "strawman" motor/actuator design is validated by verifying that the output load capability, no load motor speed, and loaded motor speed performance requirements are satisfied. The output load capability (29960) is computed by multiplying the stall current (81 amps) by the torque sensitivity (.303 ft-lb/amp), gear ratio (50.86 rad/in), and number of motors (2). The velocity limits are calculated by dividing the no load/loaded motor speed by the gear ratio. The loaded motor speed of 1411 rpm was obtained using the torque-speed curve shown above and selecting the spec'd load torque corresponding to a 20000 lb force.
MOTOR/ACTUATOR/LOAD DYNAMICS MODELED & SIMULATED

Honeywell
MOTOR/ACTUATOR/LOAD DYNAMICS MODELED & SIMULATED

The block diagram above mathematically represents the dynamic behavior of the motor, actuator, and load. The open loop transfer function between the motor input command voltage and the position outputs defines a fourth order system (4 integrators, where S is the Laplace transform variable). The characteristic roots are therefore defined by a quartic equation containing a single complex root pair describing the load dynamics and a single first order root and free integrator root defining the motor/actuator.

The motor drive circuitry bandwidth is very high with respect to the motor/actuator/load dynamics and can be modeled as a simple gain Kd. The motor torque is computed by multiplying the motor current by the number of motors (n) and the torque sensitivity (Km) and then subtracting the load torque feedback (Tm). The motor rate is computed by dividing the commanded torque by the motor inertia (Jm) and integrating. Integrating the motor rate yields the motor position. The screw position is computed by dividing the motor position by the coupling ratio (1/N1N2). The developed force across the actuator is computed by multiplying the actuator stiffness (Kt) by the difference between the screw and engine positions. The engine load acceleration is computed by dividing the developed force by the load mass (La^2 / (12 * Jl)). The load dynamics are modeled as a second order very lightly damped system. Load damping is defined by the magnitude of the parameter B.

Two sensors are used for feedback control. An LVDT senses screw position and a Hall Sensor/Tach senses motor rate.
Filter phase stabilizes motor/load dynamics (quadratic dipole)
Patent Awarded
A unique control structure has been defined that results in a minimal order system and as a result reduces implementation complexity and cost. The structure includes a filter which combines sensed position from an LVDT and motor rate from a Hall/Tach sensor. This not only results in an excellent broadband estimate of engine position but also phase stabilizes the motor/load dynamics (lag/lead quadratic dipole). Desired stability margins are achieved by simple lead/lag loop shaping and gain selection.
STABILITY MARGINS ARE ACCEPTABLE

Gain Margin = ∞
Phase Margin = 50°
The open loop frequency response with the control loop broken at the position sensor is shown above. The gain and phase margins are computed from these two plots. At the 0 db crossover frequency of 3 hz, the system phase is -130 deg. Therefore, the phase margin is -130° + 180° = 50°. The system phase never reaches -180°, therefore the gain margin is infinite.
COMPARABLE DYNAMIC RESPONSE IS PREDICTED

Honeywell

CLOSED LOOP GAIN

Bandwidth > 9 Hz

FREQUENCY (her tz)
The closed loop frequency response (sensed position/commanded position) is shown above. A 9 Hz bandwidth ( frequency @ -3db ) exceeds the 8 Hz bandwidth specification for Titan IV stage 1. The response is relatively flat out to 9 Hz and then rolls off at 80 dB/decade.
**STEP RESPONSE IS FAST AND WELL BEHAVED**

Honeywell

![Graph showing position step response with rise time of 60 msec](image-url)
STEP RESPONSE IS FAST AND WELL BEHAVED

The load position time response to a unit position step command is shown above. The rise time (60 msec) is very fast - indicative of the high bandwidth. The response shape is dominated by a well damped second order mode. The "ringing" present is due to a very lightly damped second order mode that represents the engine load dynamics. These oscillations become negligible after 2 seconds. The load position overshoot is approximately 40%.
<table>
<thead>
<tr>
<th>Approach</th>
<th>Philosophy</th>
<th>Implementation</th>
<th>Evaluation/Comments</th>
</tr>
</thead>
</table>
| Active Control| "Back drive" Actuator during startup transient  | Sense load force, pass sensor output through a high pass filter and feedback as additional component of motor command | • Adds system damping  
• Force sensor dynamic range limit  
• Motor accelerations required exceed current state of the art capabilities  
• Motor inertia must be reduced by a factor of 5 to 10 for this approach to be feasible |
| Passive Control| Dissipate startup transient energy using passive mechanical elements | Spring/Damper in series with actuator                                           | • Smaller actuator required when space is allocated for passive mechanical elements  
• Position offset for static loads  
• Weight penalty |
| Soften Actuator| Reducing stiffness reduces force developed at actuator | Appropriate material selection, screw cross section                           | • Constrains achievable bandwidth  
However, Stage 1 bandwidth rqmt's  
• Lowest cost, weight, technical risk solution |
STAGE 1 TVC ACTUATION PERFORMANCE REQUIREMENTS
CANDIDATE ENGINE STARTUP TRANSIENT SOLUTIONS EVALUATED

A single active control and two passive control design approaches for attenuating the transient loads at engine startup have been evaluated. The philosophy behind each approach along with implementation requirements are presented above. At the present time, we believe that adjusting the actuator stiffness (to soften) is the best approach. We have been able to demonstrate for Titan IV stage 1 booster TVC, both closed loop frequency response performance, start up transient considerations, and position offsets under static loads can be met with current state of the art EMA's.
STAGE 1 ENGINE START TRANSIENT MODELED AND SIMULATED BASED ON TEST DATA
STAGE 1 ENGINE START TRANSIENT MODELED AND SIMULATED BASED ON TEST DATA

A worse case Titan IV stage 1 engine startup transient time history signature is shown above. Differential pressure ($\Delta p$) is plotted versus time (sec). The maximum $\Delta p$ is seen to be approximately 6375 psid. For a piston area of 9.88 sq in, we can predict a worse case force of 63000 lb on the EMA. The engine start transient can be seen to have a duration of approximately 20 msec and be triangular in shape. The subsequent ringing after the startup transient (time > 20 msec) represents the hydraulic actuator response.
EMA developed force to a 63000 lb startup transient and achievable closed loop bandwidth are logarithmic functions of actuator stiffness as shown above. Cutting the transient induced force developed across the EMA in half requires reducing the actuator stiffness by a factor of 10. But reducing the actuator stiffness by a factor of 10 cuts the achievable bandwidth by a factor of two. Therefore, a compromise between bandwidth and transient induced EMA forces must be made. The range of suitable actuator stiffnesses (Ka) is bounded by the 30000 lb maximum developed force envelope and the 8 hz closed loop bandwidth requirement s. The actuator stiffness corresponding to these two requirements can be directly read off the above plots, i.e.

\[ 45000 \text{ lb/in} < K_a < 130000 \text{ lb/in}. \]

An actuator stiffness of 100000 lb/in was selected for subsequent analysis.
Actuator Stall Force Not Exceeded During Worst Case Startup Transient (Actuator Stiffness = 100,000 lb/in)

Honeywell
ACTUATOR STALL FORCE NOT EXCEEDED DURING WORST CASE
STARTUP TRANSIENT (ACTUATOR STIFFNESS = 100,000 LB/IN)

The solid line in the above time history trace represents the engine start transient applied as a load force
disturbance. The dashed line represents the resulting developed force across the EMA. The peak developed
force (28000lb) occurs just prior to 50 msec. Given an actuator with a 100000 lb/in stiffness, our analysis predicts
that the developed force to a worse case startup transient will not exceed the 30000 lb specification.
SATURATION CURRENT AND STROKE LIMITS AVOIDED DURING WORST CASE STARTUP TRANSIENT (ACTUATOR STIFFNESS = 100,000 LB/IN)
SATURATION CURRENT AND STROKE LIMITS AVOIDED DURING
WORST CASE STARTUP TRANSIENT
(ACTUATOR STIFFNESS = 100,000 LB/IN)

The above two plots demonstrate that the engine startup transient load alleviation is accomplished without exceeding the current capabilities of the motor (81 amps) and the actuator stroke (±1 in).
SESSION IV

ELA PROTOTYPE DESIGNS AND TEST RESULTS
EHA Prototype Demonstration

NASA Electrical Actuation Technology Bridging Workshop @ MSFC

9/29/92

Mike Kirkland
Allied-Signal
1992 IR&D ELECTROHYDROSTATIC ACTUATOR (EHA)

BASIC COMPONENTS OF THE 3-CHANNEL SYSTEM
1992 IR&D EHA DESIGN

• FAIL OPERATE - FAIL-SAFE
  • NO SINGLE POINT FAILURE MODES OTHER THAN STRUCTURE/MOUNTING
  • A SINGLE FAILURE LEAVES TWO CHANNELS FULLY OPERATIONAL. AFTER A SECOND FAILURE, ONE CHANNEL IS STILL OPERATIONAL AT DIMINISHED HP.

• MODULARIZED DESIGN
  • THREE 8.3-HP POWER MODULES MOUNTED ON A TRIPLEX ACTUATOR (25-HP TOTAL)

  NOMINAL LENGTH: 47.33 INCHES

  STROKE: ± 5.7 INCHES
3-channels provide fail-op - fail-safe capability.
EHA PERFORMANCE

PRESENT CONFIGURATION: HALF-SIZE MOTOR/PUMPS FULL-SIZE ACTUATOR/MANIFOLDING

OUTPUT HP: 25 (3 CHANNELS FORCE SUMMED)

RATE: 3.3 IN./SEC

FORCE: 50,000 LB. GENERATED (ABLE TO WITHSTAND 100,000 LB.)
The EHA is presently configured with motors one-half the horsepower of the eventual NLS configuration.

Upgrade can be accomplished by replacing the motor/pump assemblies.
EHA schematic illustrates redundancy and isolation of the three channels for fault-tolerant operation.

Operation of the bypass valve of any one channel connects both pressure sides of the piston to reservoir effectively disconnecting the failed channel.
EHA ADVANTAGES

HIGH RELIABILITY
- No Single-Point Failure Mode

MATURE TRANSIENT LOAD PROTECTION
- Hydraulic Relief Valve

MATURE FAILED CHANNEL DECOUPLER
- Hydraulic Bypass Valve (solenoid operated)

WET MOTOR
- Hydraulic Fluid Cools Motor
- Cooler Running Motor is More Reliable
- Allows Smaller Motors with Lower Inertia
- Lower Weight Motors and Controllers

HYDRAULIC CHARACTERISTICS
- Inherent Damping
- Zero Backlash
The EHA provides the well understood advantages of hydraulics along with the energy-saving advantage of power on demand electric actuation.
TRANSIENT TEMPERATURES FOR EHA MOTOR / PUMP
Chart shows the advantage of the EHA wet motor. Without coolant, the motor winding temperature would be considerably higher. Analysis was performed for continuous 70% (extremely conservative) of peak horsepower for a 10-minute mission. Winding temperature remains below 300°F.
IR&D EHA
BUILT-IN TEST CAPABILITY

EXISTING CAPABILITIES

ROMTEST
RAMTEST
A/D Test
CPU Test
Power Supply Test
Watch Dog Timer Test
Inverter Test
Inverter Overtemperature
Motor Overcurrent
Motor Overspeed
Reservoir Level Sensor
Position Sensor Fail
Bypass Valve Continuity
Excitation Fail
  Motor Rotor Position
LVDT
Current Sensor

ADDITIONAL FAULT TOLERANT CONTROLLER TECHNOLOGY

Comparison of Multiple Position Feedback Signals
Comparison of Multiple Motor Speed Signals
Eliminate Faulty Feedback Signals Using Only Healthy Signals for All Control Channels
Soft Failure Detection - Degraded Performance of One Channel Compared to Others
The EHA digital controller provides extensive health monitoring capabilities. Recent advancements incorporating interchannel communication and exchange of data provides more reliable load sharing, fault masking capability and soft failure detection.
EHA DEMONSTRATION at NASA 9/29/92
Test Configuration: Speed Limit - 2.9 in/sec; Current Limit - 15 amps/motor

1) OPERATION WITH TWO CHANNELS (SINGLE FAULT SIMULATION)
   A. Sine Command, 0.1 Hz, ± 3 in amplitude
   B. Sine Command, 0.5 Hz, ± 1 in amplitude
   C. Frequency Sweep 1 to 10 Hz, ± 0.1 in amplitude
   D. Step Command ± 0.5 in, ± 1.0 in, ± 2.0 in at 0.15 Hz

2) SINGLE CHANNEL OPERATION (SIMULATION OF SECOND FAULT)
   A. Sine Command, 0.1 Hz, ± 3 in amplitude
   B. Sine Command, 0.5 Hz, ± 1 in amplitude

IMPROVED PERFORMANCE IS EXPECTED IN FUTURE TESTING WITH INCREASED SPEED AND CURRENT LIMITS
Sequence of tests for demonstration of the EHA at NASA MSFC.

The actuator has just begun development testing and has not yet been adjusted to its full capacity.
EHA STEP RESPONSE
(20,000 lb. load; 1-inch step)
Speed Limited to 2.3 in/sec
Preliminary test results at Allied Signal with 20,000 lb. load mass and 2.3 in/sec speed limit. Step response data shows zero overshoot.
EHA FREQUENCY RESPONSE
(± 0.1 in.; NASA Test Load 9/27/92)
EHA frequency response testing at NASA MSFC. Data illustrates actuator capability of 6.7 Hz at -3 dB.
EHA IR&D PLANS THRU 1992

- COMPLETE PERFORMANCE CAPABILITY TESTING
  - Peak Load/Stall Load Testing
  - Increased Speed and Current Limit Testing
  - Testing with Increased Gains

- COMPLETE FABRICATION OF FAULT-TOLERANT CONTROLLER

- FAULT INJECTION/FAULT-TOLERANT DEMONSTRATION
Testing has just begun on the EHA. Testing to the full limits of the actuator capability are planned for this year.
HONEYWELL EMA SYSTEM OVERVIEW

PRESENTED AT MARSHALL SPACE FLIGHT CENTER
SEPTEMBER 29, 1992

PRESENTED BY Z. ZUBKOW
HONEYWELL SPACE SYSTEMS GROUP
CLEARWATER, FLORIDA
EMA SYSTEM OVERVIEW

ACTUATOR POSITION COMMAND IS SENT VIA COMPUTER. CRITICAL SIGNALS ARE MONITORED FOR HEALTH.

CONNECTORS WILL BE PROVIDED FOR TIE IN TO MAS C AND ANALOG LOOP BYPASS.
• USE HIGH TORQUE LOW SPEED MOTOR
  - ACTUATOR IS BACK-DRIVEABLE
  - VERY HIGH ACCELERATIONS ARE POSSIBLE DUE TO
    LOW GEAR RATIO

• USE REDUNDANT MOTOR WINDINGS ON COMMON SHAFT
  - NO CLUTCHES OR SPUR GEARS
  - FAILED MOTORS CAN BE ELECTRICALLY DISCONNECTED

• USE DC BRUSHLESS MOTOR
  - GOOD THERMAL DISSIPATION (NO COOLING REQUIRED)
  - SIMPLE ELECTRONICS (CAN BE MOUNTED RIGHT ON
    ACTUATOR)
INTEGRATED CONTROLLER WITH
DUAL REDUNDANT MOTORS, DRIVERS AND ELEX

COMMUTATION AND CONTROL ELEX
ANALOG LOOP AND HEALTH MONITOR
1553 INTERFACE AND I/O

IGBT DRIVE MODULES
BENEFITS OF INTEGRATED CONTROLLER

- REDUCED EMI
  - HIGH POWER PWM LINES ARE VERY SHORT
- POWER LOSSES MINIMIZED SINCE PWM LINES ARE SHORT
- REDUCED LINE LENGTH OF LVDT SIGNALS
- NO EXTRA CONTROLLER BOX(S) REQUIRED
- SIMPLE CONSOLIDATED DESIGN
Dual Redundant 270 Volt 100 Amp Per Channel Controller
Integrated EMA and Controller
CRUCIAL SIGNALS ARE MONITORED AND SENT BACK VIA MIL-STD 1553 INTERFACE

- MOTOR CURRENTS
- LVDT POSITIONS (ACTUAL POSITION)
- COMMANDED POSITION (CHECKS D/A AND A/D FUNCTIONS)
- CURRENT COMMAND SIGNAL (FOR COMPARISON WITH ACTUAL MOTOR CURRENT)
- TEMPERATURE (THERMISTORS EMBEDDED IN WINDINGS OF EACH MOTOR)
- 1553 BUILT-IN-TEST
- LOW VOLTAGE POWER SUPPLY VOLTAGES
- TACHOMETER
SECOND STAGE
EMA

1553 TOP LEVEL DESIGN CONCEPT

Designer:
Richard Herrera
5/7/91

1553 board Ch1

TRANSMIT (monitor)
RECEIVE (command)

1553 RTU

CH1 (A,B)

CH2 (A,B)

1553 Board Ch2

TRANSMIT (monitor)
RECEIVE (command)

1553 RTU

BC1

BC2

1553 BUS CONTROLLERS
### RECEIVE FROM BUS CONTROLLER

A command to receive three data words will be issued by the bus controller to the EMA RTU every 50Hz.

<table>
<thead>
<tr>
<th>RTU ADDRESS</th>
<th>T/R</th>
<th>WORD COUNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>00010</td>
<td>0</td>
<td>00001</td>
</tr>
<tr>
<td>00011</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### FIRST WORD RECEIVED

**LSB**

<table>
<thead>
<tr>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Position Command (D/A Converter)

<table>
<thead>
<tr>
<th>DIGITAL INPUT CODING</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATAWORD</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>000H</td>
</tr>
<tr>
<td>3FFH</td>
</tr>
<tr>
<td>FFFH</td>
</tr>
</tbody>
</table>

### SECOND WORD RECEIVED

<table>
<thead>
<tr>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>R12</td>
<td>R1</td>
<td>R1</td>
<td>R1</td>
<td>R1</td>
<td>R1</td>
<td>R1</td>
<td>R1</td>
<td>R1</td>
<td>R1</td>
<td>R1</td>
</tr>
</tbody>
</table>

HALR1-HALLR12

Update Hall Count Bit
0 = Don't Update
1 = Update

### THIRD WORD RECEIVED

<table>
<thead>
<tr>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

ANALOG ENABLE 1 (BIT 0)
0 = Disable
1 = Enable

ANALOG ENABLE 2 (BIT 1)
0 = Disable
1 = Enable

CHANNEL 1

CHANNEL 2
TRANSMIT DATA FORMAT

SECOND STAGE
EMA

TRANSMIT TO BUS CONTROLLER

- A command to transmit eleven data words to the bus controller will be issued every 50 Hz.

SUBADD

<table>
<thead>
<tr>
<th>RTU ADDRESS</th>
<th>T/R FIELD</th>
<th>WORD COUNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>00010</td>
<td>1</td>
<td>0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>01011</td>
</tr>
</tbody>
</table>

11 0

- MOTOR CURRENT
- TEMP
- TEMP2
- TORQUE
- TORQUE AVE
- HALL TACH
- LVDT POS
- TORQUE R
- POS COM CHK

11 0 2 0

- HALLDI 1-12
- ANALOG STAT 1-23

NINE ANALOG INPUTS DIGITIZED BY A/D

All nine words are 12 bits wide
1553 bits 12-15 are don't care bits

<table>
<thead>
<tr>
<th>A/D CONVERTER DIGITAL OUTPUT CODING</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANALOG INPUT VOLTAGE</td>
</tr>
<tr>
<td>-10V</td>
</tr>
<tr>
<td>0.00 V</td>
</tr>
<tr>
<td>-10V</td>
</tr>
</tbody>
</table>

12 BIT DISCRETES
1553 BITS 12-15 ARE DON'T CARE BITS

THREE BIT DISCRETES
1553 BITS 3-15 ARE DON'T CARE BITS
ANALOG LOOP BOARD

MAJOR FUNCTIONS

• POSITION COMPARATOR
  - COMPARES LVDT TO COMMENDED POSITION

• LEAD-LAG
  - CONDITIONS POSITION COMPARATOR SIGNAL INTO TORQUE COMMAND

• LVDT LIMIT DETECT
  - DETECTS IF ACTUATOR POSITION IS AT STROKE LIMIT

• ANALOG STATUS ENCODER
  - ALLOWS 1553 TO MONITOR POSSIBLE ANALOG ERRORS
MOTOR CONTROLLER BASELINE

- DESIGN GOAL OF 100 AMPS CONTINUOUS AT 270VDC
- QUAD-REDUNDANT OUTPUT TRANSISTOR DESIGN: 4 X 30 AMPS
- 20 KHZ PULSE-WIDTH-MODULATOR (PWM) FREQUENCY MIN
- SIX-STEP COMMUTATION
- ±10VDC TORQUE COMMAND INPUT:
  0V = NO TORQUE
  1V = 10 AMPS MOTOR CURRENT
- CONTROL ELECTRONICS ELECTRICALLY ISOLATED FROM 270 VDC SUPPLY AND MOTOR
- OVERCURRENT DETECTION FOR EACH OF FOUR OUTPUT TRANSISTOR MODULES
- ACTIVE LOW SHUTDOWN SIGNAL WILL PREVENT SPURIOUS TORQUE APPLICATION AT POWER-UP
SECOND STAGE EMA TEMPERATURE PROFILE
HOLDING 1450 POUNDS

MAXIMUM ALLOWABLE TEMPERATURE = 155 DEG C

Test was started after actuator had completed Frequency response tests, therefore initial temperature was higher than room temp.
SESSION V

DEMONSTRATION
SESSION VI

ELA POWER SOURCE SYSTEMS
BATTERIES: BLDG 4475

FLYWHEELS: BLDG 4487

TURBO-ALTERNATORS: BLDG 4656
## MSFC Flight Program History

<table>
<thead>
<tr>
<th>Program Name</th>
<th>Launch Date</th>
<th>Time of Operation</th>
<th>Regime</th>
<th>Battery Type</th>
<th>Capacity</th>
<th>Cell Manuf.</th>
<th>Battery Manuf.</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explorer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2/58</td>
<td>4 mos.</td>
<td>LEO</td>
<td>Ni-Cd</td>
<td></td>
<td>Sonotone</td>
<td></td>
<td>Explorer 1 — First free-world satellite, solar array, and Ni-Cd battery power system</td>
</tr>
<tr>
<td>3</td>
<td>3/58</td>
<td>3 mos.</td>
<td>LEO</td>
<td>Ni-Cd</td>
<td></td>
<td>Sonotone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7/58</td>
<td>4 mos.</td>
<td>LEO</td>
<td>Ni-Cd</td>
<td></td>
<td>Sonotone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pegasus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2/65</td>
<td>3+ yrs.</td>
<td>LEO</td>
<td>Ni-Cd</td>
<td></td>
<td>Gulton ?</td>
<td></td>
<td>Three satellites with multi-battery SA/Ni-Cd system for large micro-meteroid satellite</td>
</tr>
<tr>
<td>2</td>
<td>5/65</td>
<td>3+ yrs.</td>
<td>LEO</td>
<td>Ni-Cd</td>
<td></td>
<td>Gulton ?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>7/65</td>
<td>3+ yrs.</td>
<td>LEO</td>
<td>Ni-Cd</td>
<td></td>
<td>Gulton ?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skylab ATM</td>
<td>5/73</td>
<td>6 yrs. incl.</td>
<td>LEO</td>
<td>Ni-Cd</td>
<td>20 Ah</td>
<td>GE</td>
<td>MSFC MDAC-E</td>
<td>First manned space station; two SA/Ni-Cd power systems (ATM &amp; OWS) with total capability of &gt;8 kW; operated in parallel; EPS reactivated after more than 4 years in &quot;orbital storage&quot;</td>
</tr>
<tr>
<td>OWS</td>
<td>5/73</td>
<td>4 yrs. storage</td>
<td>LEO</td>
<td>Ni-Cd</td>
<td>33 Ah</td>
<td>EPI-J</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEAO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8/77</td>
<td>19 mos.</td>
<td>LEO</td>
<td>Ni-Cd</td>
<td></td>
<td>SAFT-America</td>
<td>TRW</td>
<td>Three satellites with multi-battery SA/Ni-Cd power system built by TRW for MSFC; no battery failures</td>
</tr>
<tr>
<td>2</td>
<td>11/78</td>
<td>30 mos.</td>
<td>LEO</td>
<td>Ni-Cd</td>
<td></td>
<td>SAFT-America</td>
<td>TRW</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>9/79</td>
<td>27 mos.</td>
<td>LEO</td>
<td>Ni-Cd</td>
<td></td>
<td>SAFT-America</td>
<td>TRW</td>
<td></td>
</tr>
</tbody>
</table>
### MSFC Flight Program History

<table>
<thead>
<tr>
<th>Program Name</th>
<th>Launch Date</th>
<th>Time of Operation</th>
<th>Regime</th>
<th>Battery Type</th>
<th>Capacity</th>
<th>Cell Manuf.</th>
<th>Battery Manuf.</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST</td>
<td>4/90</td>
<td>30 mos. (active)</td>
<td>LEO</td>
<td>Ni-H$_2$</td>
<td>88 Ah</td>
<td>EPI-J</td>
<td>EPI-J</td>
<td>First reported, non-experimental use of Ni-H$_2$ batteries in LEO; multi-battery SA/Ni-H$_2$ 2.4 kW power system built by LMSC for MSFC; first flight-qualified BPRC (MSFC patent) developed for Ni-Cd batteries before change to Ni-H$_2$</td>
</tr>
<tr>
<td>CRRES</td>
<td>7/90</td>
<td>B1-5 mos. B2-15 mos.</td>
<td>MEO</td>
<td>Ni-Cd</td>
<td>15 Ah</td>
<td>GAB</td>
<td>Ford Aerospace</td>
<td>Battery 1 failed after 5 months of operation; battery 2 failed after 15 months of operation; excessive on-orbit overcharge likely major contributor to failures</td>
</tr>
<tr>
<td>AXAF-I *</td>
<td>*1999</td>
<td>Elliptical</td>
<td>TBD</td>
<td>TBD</td>
<td>30 Ah</td>
<td>TBD</td>
<td>TBD</td>
<td>TRW is the prime contractor for this effort</td>
</tr>
<tr>
<td>AXAF-S *</td>
<td>*1999</td>
<td>Polar</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>This is an MSFC in-house project</td>
</tr>
</tbody>
</table>

* — Planned flights

---

*MSFC Battery Activity*
# MSFC Secondary Battery / Cell Testing Summary

## Hubble Space Telescope Support:

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Cell Manufacturer</th>
<th>Cell Type</th>
<th>Capacity</th>
<th>Completed Cycles</th>
<th>Regime</th>
<th>%DOD</th>
<th># of Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 40 Battery 1 *1</td>
<td>EPI-J</td>
<td>Ni-Cd RSN55</td>
<td>55 Ah</td>
<td>23211</td>
<td>LEO</td>
<td>13 - 16</td>
<td>22</td>
</tr>
<tr>
<td>Type 40 Battery 2 *2</td>
<td>EPI-J</td>
<td>Ni-Cd RSN55</td>
<td>55 Ah</td>
<td>6641</td>
<td>LEO</td>
<td>13 - 16</td>
<td>22</td>
</tr>
<tr>
<td>Type 41 *4</td>
<td>EPI-J</td>
<td>Ni-Cd RSN55</td>
<td>55 Ah</td>
<td>25891</td>
<td>LEO</td>
<td>13 - 16</td>
<td>22</td>
</tr>
<tr>
<td>GE Battery *3</td>
<td>GE</td>
<td>Ni-Cd</td>
<td>50 Ah</td>
<td>23872</td>
<td>LEO</td>
<td>13 - 16</td>
<td>22</td>
</tr>
<tr>
<td>Six Battery System *5</td>
<td>EPI-J</td>
<td>Ni-Cd RSN55-15</td>
<td>55 Ah</td>
<td>21856</td>
<td>LEO</td>
<td>13 - 16</td>
<td>132</td>
</tr>
<tr>
<td>Six Four-Cell Packs 6</td>
<td>EPI-J</td>
<td>Ni-Cd RSN55-15</td>
<td>55 Ah</td>
<td>29850</td>
<td>LEO</td>
<td>13 - 16</td>
<td>24</td>
</tr>
<tr>
<td>Fourteen-Cell Pack</td>
<td>EPI-J</td>
<td>Ni-H₂ RNH30-1</td>
<td>30 Ah</td>
<td>31000</td>
<td>LEO</td>
<td>6 - 9</td>
<td>14</td>
</tr>
<tr>
<td>Three Four-Cell Packs</td>
<td>EPI-J</td>
<td>Ni-H₂ RNH90-3</td>
<td>90 Ah</td>
<td>20145</td>
<td>LEO</td>
<td>6 - 9</td>
<td>12</td>
</tr>
<tr>
<td>Six Battery System</td>
<td>EPI-J</td>
<td>Ni-H₂ RNH90-3</td>
<td>90 Ah</td>
<td>18100</td>
<td>LEO</td>
<td>6 - 9</td>
<td>132</td>
</tr>
<tr>
<td>Flight Spare Battery</td>
<td>EPI-J</td>
<td>Ni-H₂ RNH90-3</td>
<td>90 Ah</td>
<td>17600</td>
<td>LEO</td>
<td>6 - 9</td>
<td>22</td>
</tr>
</tbody>
</table>

* - Test has been terminated
1 - First cell failure at 14 months
2 - First cell failure at 14 months; DPA showed excessive cadmium migration
3 - Cell divergence at >14,000 orbits; >100 mV at 19,000 orbits; capacity as low as 30 Ah
4 - Cell divergence at >10,000 orbits; capacity as low as 20 Ah
5 - Built with reject positive plates; met system reqt. of 36 Ah/battery thru 4 yrs.; had cell short in B3 at 18,300 orbits
6 - Cells from flight battery lots; continues to meet system reqt. after 5½ yrs.
### MSFC Secondary Battery / Cell Testing Summary

**Other Testing:**

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Cell Manufacturer</th>
<th>Cell Type</th>
<th>Capacity</th>
<th>Completed Cycles</th>
<th>Regime</th>
<th>%DOD</th>
<th># of Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twelve-Cell Pack</td>
<td>EPI-J</td>
<td>Ni-H$_2$, RNH35-3</td>
<td>33 Ah</td>
<td>21315</td>
<td>LEO</td>
<td>22</td>
<td>12</td>
</tr>
<tr>
<td>Four Four-Cell Packs</td>
<td>EPI-J</td>
<td>Ni-H$_2$, RNH90-3</td>
<td>90 Ah</td>
<td>58</td>
<td>Elliptical</td>
<td>30</td>
<td>16</td>
</tr>
<tr>
<td>Reconditioning</td>
<td>EPI-J</td>
<td>Ni-H$_2$, RNH90-3</td>
<td>90 Ah</td>
<td>5500</td>
<td>LEO</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>Parametric Tests</td>
<td>EPI-J</td>
<td>Ni-MH, RMH10-1</td>
<td>10 Ah</td>
<td></td>
<td>LEO</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>AXAF-S Ni-MH</td>
<td>EPI-J</td>
<td>Ni-MH, RMH10-1</td>
<td>10 Ah</td>
<td></td>
<td>LEO</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>SEDS / UAH</td>
<td>EPI-J</td>
<td>Ni-MH, RMH10-1</td>
<td>10 Ah</td>
<td></td>
<td>LEO</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>SEDS Satellite</td>
<td>EPI-J</td>
<td>Ni-MH, RMH10-1</td>
<td>10 Ah</td>
<td></td>
<td>LEO</td>
<td>30</td>
<td>8</td>
</tr>
</tbody>
</table>
FLYWHEELS:
BLDG 4487;
TWO CONTAINMENT VAULTS
ON-GOING CMG TESTING
TURBO-ALTERNATORS:
BLDG 4656;
HIGH PRESSURE HELIUM
HIGH PRESSURE NITROGEN
3000 PSI HYDRAULICS
JOHNSON CONTROLS BATTERY GROUP INC.

BIPOLAR LEAD/ACID BATTERY

NASA ELECTRICAL ACTUATION

TECHNOLOGY BRIDGING

WORKSHOP

AT

MARSHALL SPACE AND FLIGHT CENTER
HUNTSVILLE, ALABAMA

SEPTEMBER 30, 1992

PRESENTED BY

WILLIAM O. GENTRY
DOUGLAS C. PIERCE
MONOPOLAR AND BIPOLAR CURRENT PATH SCHEMATICS

MONOPOLAR CONFIGURATION

TWO CELL / 4-VOLT SYSTEM

![Monopolar Configuration Diagram]

BIPOLAR CONFIGURATION

TWO CELL / 4-VOLT SYSTEM

![Bipolar Configuration Diagram]
BIPOLAR/MONOPOLAR COMPARISON
DISCHARGE RATE 1 AMP/CM²
JCBGI
BIPOLAR LEAD/ACID ADVANTAGES

- PROVEN LEAD-ACID CHEMISTRY

- SEALED, MAINTENANCE FREE OPERATION

- SHORTER CURRENT PATH
  - LOWER INTERNAL BATTERY RESISTANCE

- REDUCED WEIGHT AND VOLUME

- SUBSTANTIAL POWER ADVANTAGES OVER MONOPOLAR
  - $\approx 100\%$ INCREASE IN POWER DENSITY FOR QUASI
  - $\approx 140\%$ INCREASE IN POWER DENSITY FOR TRUE
  - $\approx 75\%$ INCREASE IN SPECIFIC POWER FOR QUASI
  - $\approx 150\%$ INCREASE IN SPECIFIC POWER FOR TRUE

- MEANS OF VARYING STACK VOLTAGE WITHOUT RE-TOOLING

- PACKAGING FLEXIBILITY
BIPOLAR BATTERY COMPARISON

FOLDED BIPOLAR PLATE

NEGATIVE ACTIVE MATERIAL SIDE

FRAME PLASTIC

EXPANDED LEAD GRID MATERIAL

SUBSTRATE MATERIAL

GRID / SUBSTRATE INTERFACE SEAL

POSITIVE ACTIVE MATERIAL SIDE

TRUE BIPOLAR PLATE

NEGATIVE ACTIVE MATERIAL SIDE

FRAME PLASTIC

POSITIVE / NEGATIVE SUBSTRATE INTERFACE

NEGATIVE SUBSTRATE MATERIAL

POSITIVE SUBSTRATE MATERIAL
TRUE/QUASI BIPOLAR COMMON POINTS

- LEAD-ACID TECHNOLOGY

- FRAME DESIGN

- ASSEMBLY TECHNIQUES
  - IR WELDING
  - VIBRATION WELDING

- ACTIVE MATERIAL

- SEPARATOR

- FORMATION AND ACID FILL TECHNIQUES

- TERMINATION DESIGN

- INITIAL CONTAINMENT DESIGN
TRUE/QUASI BIPOLAR DIFFERENCES

- INSERT MATERIAL
  - QUASI- FOLDED LEAD GRID ELECTRODE
  - TRUE- COMPOSITE TRUE BIPOLAR SUBSTRATE

- MANUFACTURABILITY

- FAILURE MODES
  - QUASI- GRID CORROSION, FOLD SEAL LEAK
  - TRUE- ACTIVE MATERIAL DEGRADATION

- CELL SPACING AND CELL SIZE WILL BE SMALLER IN TRUE BIPOLAR

- HIGHER PERFORMANCE CHARACTERISTICS IN TRUE BIPOLAR

- SMALLER MASS, SMALLER VOLUME
JCBGI QUASI BIPOLAR STATUS

- CURRENTLY HAVE TWO DIFFERENT SIZE PLATES: 520, 940 cm²

- DEMONSTRATED 30 SEC AVERAGE POWER OF 210 W/kg at 80% DOD

- DEMONSTRATED HIGH SPECIFIC POWER: 1.5 kW/kg FOR 12 SECONDS

- DEMONSTRATED OVER 100 CYCLES AT TWO INDEPENDENT LOCATIONS

- BUILT NINE 430 VOLT BATTERY STRINGS

- INCREASED PRODUCTION FROM FIFTY 12 VOLT BATTERIES PER YEAR TO THIRTY 40 VOLT BATTERIES PER WEEK

- INCREASED FORMATION SUCCESS RATE FROM 10% TO 80%

- CONTAMINATION DURING PROCESSING HAS CAUSED CYCLE LIFE PROBLEMS
POROSITY IN PLASTIC COMPOSITES

- HIGH FILLER LOADINGS LEAD TO POROSITY
- DIFFICULT TO PREVENT
- PROCESS/PRODUCT INVESTIGATIONS
  - RESIN IMPREGNATION OF POROUS COMPOSITES
  - COMPRESSION MOLDING IMPROVEMENTS
  - LOWER FILLER LOADINGS THROUGH BETTER DISPERSION
  - HIGHER CONDUCTIVITY FILLERS
JOHNSON CONTROLS QUASI BIPOLAR BATTERY
MSFC DISCHARGE

BATTERY VOLTAGE (VOLTS)

SYSTEM POWER (kW)

TIME (SECONDS)
JCBGI QUASI BIPOLAR FUTURE WORK

- ELIMINATE MATERIAL PROBLEMS THAT HAVE CAUSED CYCLE LIFE PROBLEMS THROUGH HIGH LEVELS OF CONTAMINATION

- DEMONSTRATE 100 CYCLE CAPABILITY ON 20 CELL BATTERY AND A 200 CELL STRING

- OVERCOME CELL INCONSISTENCIES WHICH LIMIT BATTERY PERFORMANCE

- DEVELOP A RECHARGE REGIME THAT WILL ENSURE UNIFORM CHARGING OF HIGH VOLTAGE STRINGS
  - LARGER DATA BASE IS NEEDED

- REFINISH ACID MANAGEMENT SYSTEM TO PERMIT A TOTALLY CLOSED SYSTEM

- IMPLEMENT RECENT DESIGN MODIFICATIONS
TRUE BIPOLAR ADVANTAGES

- LOWER INTERNAL RESISTANCE THAN QUASI BIPOLAR

- SHORTER, MORE UNIFORM CURRENT PATH

- LARGER ACTIVE AREA

- SUBSTANTIAL VOLUME AND WEIGHT SAVINGS

- HIGHER POWER APPLICATIONS QUASI

- LOWER LEAD CONTENT: LOWER MASS

- IMPROVED MANUFACTURABILITY

- ELIMINATES PRESENT FAILURE MECHANISMS
  - LEAD GRID CORROSION ON CHARGING
  - FOLD SEAL LEAKS
  - CONTAMINATION
JOHNSON CONTROLS BIPOLAR RAGONE PLOT
QUASI-TEST DATA    TRUE-LABMM

SPECIFIC ENERGY (Wh/kg)

SPECIFIC POWER (kW/kg)
TRUE BIPOLAR DEVELOPMENT

- POSITIVE SUBSTRATE COMPONENT DEVELOPMENT
  - ELECTROCHEMICAL STABILITY AT POSITIVE POTENTIALS
  - HIGH CONDUCTIVITY
  - NON-POROUS
  - MANUFACTURABLE
  - HUNDREDS OF MATERIALS HAVE BEEN SCREENED: FEW QUALIFIED

- POSITIVE SUBSTRATE COMPONENTS HAS BEEN IDENTIFIED
  - IMPROVE CONDUCTIVITY OF MATERIAL
  - OPTIMIZE COMPOUNDING PROCEDURES
TRUE BIPOLAR DEVELOPMENT

- NEGATIVE SUBSTRATE MATERIAL ALREADY IDENTIFIED
  - STABLE AT NEGATIVE POTENTIALS
  - HIGHLY CONDUCTIVE
  - NON-POROUS
  - EASY TO MANUFACTURE
  - NOT STABLE AT POSITIVE POTENTIALS

- NO MATERIAL HAS BEEN IDENTIFIED THAT IS STABLE AT BOTH ELECTRODES

- INTERFACE BETWEEN POSITIVE AND NEGATIVE
  - PROTECT NEGATIVE FROM POSITIVE POTENTIAL AND POSITIVE FROM NEGATIVE POTENTIAL
  - MAINTAIN CONDUCTIVITY WITH EACH SIDE
JCBGI TRUE BIPOLAR DEVELOPMENT
FOR WPAFB

- A 270 VOLT BATTERY SYSTEM IS TARGETED FOR THE MORE ELECTRIC AIRCRAFT

- DEVELOP A LEAD-ACID TRUE BIPOLAR SUBSTRATE WITH THE FOLLOWING GOALS

  - 0.025" TOTAL SUBSTRATE THICKNESS
  - \( \leq 2 \) ohm-cm RESISTIVITY
  - 400 cm\(^2\) ACTIVE AREA
  - \( \leq 150 \) mg/cm\(^2\) AREA DENSITY

- DELIVER TWO INTERIM TRUE BIPOLAR BATTERIES. A 54 VOLT BATTERY IS SCHEDULED FOR DELIVERY IN AUGUST 1994.
<table>
<thead>
<tr>
<th>REQUIREMENTS MET</th>
<th>BATTERY DIMENSIONS</th>
<th>BATTERY VOLUME</th>
<th>BATTERY WEIGHT</th>
<th>W/kg</th>
<th>W/cm3</th>
<th>W-hr/kg</th>
<th>W-hr/cm3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Engine Starting APU Starting Hybrid Emergency</td>
<td>17.6&quot;x15.5&quot;x15.5&quot;</td>
<td>2.45 ft³</td>
<td>450 lbs</td>
<td>747.9</td>
<td>2.2</td>
<td>12.25</td>
<td>0.036</td>
</tr>
<tr>
<td>Main Engine Starting Ground Power Emergency Power APU Starting Hybrid Emergency</td>
<td>27.4&quot;x19.7&quot;x19.7&quot;</td>
<td>6.15 ft³</td>
<td>1000 lbs</td>
<td>62.2</td>
<td>0.16</td>
<td>31.08</td>
<td>0.081</td>
</tr>
<tr>
<td>Scenario 1 30 minute ground power capacity</td>
<td>36.2&quot;x19.7&quot;x19.7&quot;</td>
<td>8.13 ft³</td>
<td>1349 lbs</td>
<td>46.1</td>
<td>0.12</td>
<td>34.56</td>
<td>0.092</td>
</tr>
<tr>
<td>Scenario 2 45 minute ground power capacity</td>
<td>16.5&quot;x4.33&quot;x4.33&quot;</td>
<td>0.18 ft³</td>
<td>33 lbs</td>
<td>705.0</td>
<td>2.1</td>
<td>11.75</td>
<td>0.036</td>
</tr>
</tbody>
</table>
WPAFB TRUE BIPOLAR PROGRESS

- PERFORMANCE MODELING

- CONDUCTIVE FILLER DEVELOPMENT

- POROSITY CONTINUES TO BE A PROBLEM

- ORDERED AN ENHANCED COMPRESSION MOLD

- RECEIVED CONDUCTIVE FILLER IN PROTOTYPE SIZED BATCHES
  - ALLOWS FOR LARGER COMPOUNDING TRIALS
  - CAN BE USED IN NEW COMPRESSION MOLD

- INTERFACE MATERIAL HAS BEEN IDENTIFIED
WPAFB NEXT STEPS

- STATISTICALLY DESIGNED COMPOUNDING TRIALS TO OPTIMIZE LOADING LEVEL

- REFINE COMPOUNDING PROCEDURES

- TEST DIFFERENT PLASTIC RESINS

- USE MATERIAL FROM COMPOUNDING TRIALS IN COMPRESSION MOLD

- STABILITY TEST TO QUALIFY NEW FORMULATIONS
LABM3 SIMULATION
TRUE BIPOLAR BATTERY, 7 20-CELL MODULES
18 A FOR 114 SEC, 180 A FOR 6 SEC
20 DEGREES C, 6/10/92

DISCHARGE VOLTAGE

TIME (MINUTES)

KW

Volts

Power
Advanced Battery Characteristics
for ELA Applications

Johnson Controls Bipolar Lead/Acid Battery

<table>
<thead>
<tr>
<th></th>
<th>QUASI BIPOLAR</th>
<th>TRUE BIPOLAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Voltage</td>
<td>1.0-2.15 V/cell</td>
<td>1.0-2.15 V/cell</td>
</tr>
<tr>
<td>Nominal Voltage</td>
<td>2 V/cell</td>
<td>2 V/cell</td>
</tr>
<tr>
<td>Plateau Voltage</td>
<td>1.2-2.1 V/cell</td>
<td>1.2-2.1 V/cell</td>
</tr>
<tr>
<td>Voltage Rise Time (delay)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Average Current</td>
<td>as needed</td>
<td>as needed</td>
</tr>
<tr>
<td>Maximum Pulse Current</td>
<td>1000 amps; 15 sec</td>
<td>1500 amps; 20 sec</td>
</tr>
<tr>
<td>Rated Discharge Current</td>
<td>0 to 1000 amps</td>
<td>0 to 1500 amps</td>
</tr>
<tr>
<td>Current Density</td>
<td>max 1.2 A/cm²</td>
<td>max 1.5 A/cm²</td>
</tr>
<tr>
<td>Specific Energy (Wh/kg)</td>
<td>38</td>
<td>44</td>
</tr>
<tr>
<td>Inverse Power Density (L/kW)</td>
<td>0.253</td>
<td>0.088</td>
</tr>
<tr>
<td>Maximum Pulse Power</td>
<td>1.2 kW/cell; 15 sec</td>
<td>1.8 kW/cell; 20 sec</td>
</tr>
<tr>
<td>Transient Response Time</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Specific Power (kW/kg)</td>
<td>1.5 to 2.0</td>
<td>3.0 to 3.5</td>
</tr>
<tr>
<td>Total Energy Storage Capacity</td>
<td>90 Wh/cell</td>
<td>120 Wh/cell</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>100+</td>
<td>300+</td>
</tr>
<tr>
<td>Open Circuit Voltage</td>
<td>2.15 V/cell</td>
<td>2.15 V/cell</td>
</tr>
<tr>
<td>Safety Issues</td>
<td>Lead; Acid</td>
<td>Lead; Acid</td>
</tr>
<tr>
<td>Thermal Operating Range (C)</td>
<td>-30 to +65</td>
<td>-30 to +65</td>
</tr>
<tr>
<td>Charging Time; Retention</td>
<td>3 hours; weeks</td>
<td>2 hours; weeks</td>
</tr>
<tr>
<td>Capacity</td>
<td>15 Ah; 940cm²</td>
<td>20 Ah; 1000cm²</td>
</tr>
<tr>
<td>Mass</td>
<td>0.85 kg/cell</td>
<td>0.60 kg/cell</td>
</tr>
<tr>
<td>Stage of Development</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>
ELECTROMECHANICAL ACTUATION

POWER SOURCE STUDY

SILVER OXIDE - ZINC

SECONDARY

RESERVE PRIMARY

BIPOLAR
POWER SOURCE REQUIREMENTS

VOLTAGE 260 - 200 VDC
BASE ELECTRICAL LOAD: 5.7 KW FOR 570 Seconds (9.5 Minutes)
PULSE LOAD: (5) 0.5 Sec. pulses of 53.2 KW
Spaced By 10 Sec. Minimum
60 Day Minimum Activated Life
Minimum Maintenance After Installation
Testable at All Points Before Launch
Low Weight and Volume
High Reliability
No Special Provisions for Shipping, Storage, or Testing
Proven Safety
Power Output vs Load Rate
Secondary SOZ, 60AH
Eagle-Picher Ind.
Voltage Regulation US Cell Capacity
High Rate Secondary SOZ
Eagle Picher Ind.

Battery Output - VDC

Cell Capacity - Amperes Hours

5.7 KW Load

53.2 KW Load
SECONDARY SILVER ZINC DESIGN FOR MINIMUM WEIGHT

MAXIMUM ENERGY POINT ON CURVE APPROX. 20 C SUPPLY 53.2 KW AT 200 VDC MIN
MAXIMUM VOLTAGE NOT REGULATED

318 CELLS 12.3 AH
WEIGHT - 170 LB.
VOLUME - 1.53 FT³
AT 53.2 KW LOAD
210 VDC, 253 AMPS
AT 5.7 KW LOAD
478 VDC, 11.9 AMPS
SECONDARY SILVER ZINC
DESIGN FOR VOLTAGE CONTROL

SUPPLY 53.2 KW AT 200 VDC MIN
SUPPLY 5.7 KW AT 260 VDC MAX

162 CELLS, 50 AH
WEIGHT - 358 LB.
VOLUME - 3.16 FT³
AT 53.2 KW LOAD
  210 VDC, 253 AMPS

AT 5.7 KW LOAD
  250 VDC, 22.8 AMPS
RESERVE PRIMARY SILVER ZINC

SUPPLY 53.2 KW AT 200 VDC MIN

SUPPLY 5.7 KW AT 260 VDC MAX

158 CELLS, 5.7 AH

WEIGHT - 88 LB.

VOLUME - .85 FT$^3$

APPROXIMATE 15 MINUTE ACTIVATED LIFE

ACTIVATED LIFE UP TO 6 HR AVAILABLE WITH 20% WEIGHT AND VOLUME INCREASE
BIPOLAR SECONDARY SILVER ZINC

SUPPLY 53.2 KW AT 200 VDC MIN

SUPPLY 5.7 KW AT 260 VDC MAX

162 CELLS, 12.8 AH

WEIGHT 114 LB, VOLUME .70 FT³

120 DAY ACTIVATED LIFE
WEIGHT REDUCTION
FOR
CONVENTIONAL SECONDARY SILVER - ZINC

1. ACTIVATED LIFE  30 TO 60 DAYS
2. RAISE OPERATING TEMPERATURE
3. REFINE PHYSICAL CONFIGURATION
   A. MULTICELL MONOBLOCK
   B. INTERNAL INTERCELL CONNECTORS
   C. LIGHTWEIGHT CONTAINER MATERIAL - TITANIUM
4. INCREASE MAXIMUM VOLTAGE LIMIT
Power Output vs Activated Life
Secondary SOZ, 60AH
Eagle-Picher, Ind
High Rate
Lithium Battery Technology

presented to the

Electrical Actuation Technology
Bridging Workshop

September 29 – October 1, 1992
Marshall Space Flight Center
Huntsville AL

Yardney Technical Products, Inc.
82 Mechanic Street Pawcatuck CT 06379
Energy Density and Operating Voltage of Lithium Batteries and Most Common Commercial Batteries
Summary of Lithium Cell and Battery Technology

Active and Reserve Batteries

- Monopolar and Bipolar
  - Bobbin Cells
  - Wound Cells
  - Disc Cells
  - High Rate Batteries
  - Special Applications (ALWT)

- Cathode Development Standard and
  - Catalyzed Thickness from .001 inch to .125 inch

- Electrolyte Development – Balanced and Acitic
- Mechanical Designs to withstand up to 30,000 G's
- Batteries from 3.65 Volts to 120 Volts
Capacity Losses on Storage at Room Temperature after One Year

<table>
<thead>
<tr>
<th>Type</th>
<th>Approximate Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leclanche</td>
<td>12 – 15% per year</td>
</tr>
<tr>
<td>Alkali–Mn–O₂</td>
<td>3 – 5% per year</td>
</tr>
<tr>
<td>Silveroxide–Zinc</td>
<td>5 – 10% per year</td>
</tr>
<tr>
<td>Mercury–Zinc</td>
<td>2 – 3% per year</td>
</tr>
<tr>
<td>Lithium</td>
<td>0.5 – 2% per year</td>
</tr>
</tbody>
</table>
Advantages of Lithium Thionyl Chloride

- -40° to +150° C. operating temperatures
- Long storage life
- High energy density
- Stable voltage
- Hermetically sealed
- Design versatility
- Reliable
- Excellent safety record
- Manufacturability
Hazards above 180°C
Passivation of Anodes
Toxicity of Electrolyte
Lithium Thionyl Chloride
Disadvantages of
Development of a High Power Bipolar Li/SOCl₂ Battery

Yardney Technical Products, Inc.
82 Mechanic Street
Pawcatuck CT 06379

Sponsors: Wright Patterson Air Force Base
September 1986 – July 1990

General Dynamics
May 1991 – October 1991
High Rate Primary Lithium Battery
Achievements Under WRDC Sponsorship

- Design and evolution of a sealed high rate bipolar Li/SOCl2 battery
- 25kW pulsed discharge of an 80 cell module using 20ms pulses at 10% duty cycles
- Demonstration of practical pulse energy density of 1.9kW/lb.
- Demonstration of 100mA/cm² continuous and 400mA/cm² pulsed discharge
- Development of procedures for:
  - making .002-.010 inch carbon cathodes
  - heat sealing Tefzel insulators
  - filling electrolytes
## High Rate Pulse Discharge of 25kW 80 Cell Module

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>103</td>
<td>206</td>
<td>2</td>
<td>189</td>
<td>19.5</td>
<td>20.6</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>103</td>
<td>206</td>
<td>4</td>
<td>198</td>
<td>20.4</td>
<td>21.1</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>103</td>
<td>206</td>
<td>20</td>
<td>190</td>
<td>20.5</td>
<td>21.0</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>206</td>
<td>412</td>
<td>2</td>
<td>143</td>
<td>29.4</td>
<td>34.6</td>
<td>1.9</td>
</tr>
<tr>
<td>5</td>
<td>206</td>
<td>412</td>
<td>4</td>
<td>150</td>
<td>30.9</td>
<td>35.0</td>
<td>1.9</td>
</tr>
<tr>
<td>6</td>
<td>206</td>
<td>412</td>
<td>20</td>
<td>6 [⁴]</td>
<td>28.8</td>
<td>35.0</td>
<td>1.9</td>
</tr>
</tbody>
</table>

[1] 10% duty cycle  
[2] Pulse voltage increased as battery warmed  
[3] Based on highest pulse voltage. Battery weight is 18.6 lbs.  
[4] Battery vented during previous pulse train. Lost current capability after six seconds. However, it delivered maximum power of 35kW.
EFFECT OF PLATINIZED CARBON ON VOLTAGE CONTINUOUS DISCHARGE AT 25 mA/cm²

ROLLING CATHODES

PLATINIZED SAB/BP CARBONS

STANDARD SAB/BP CARBONS

CELL VOLTAGE (V)

DISCHARGE TIME (min)
COMPARISON Pt'd AND STD CARBONS ON EOPV

80%SAB/20%BP

2% Pt on SAB (Johnson Matthey)
5.3% Pt on BP (Prototech)

STANDARD CARBON MIXTURE

20 Second Discharge at 25A
Cell Voltage after 19th second of pulse

- 20-second pulse, 10% duty cycle, continuous pulse discharge
- Current density 50mA/cm²
Effect of Platinized Carbon on Cell Voltages vs Current Density in 1.6M LiGaCl₄/SOCl₂

<table>
<thead>
<tr>
<th>Cathode Composition</th>
<th>Current Density (mA/cm²)</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>3.27</td>
<td>3.04</td>
<td>2.85</td>
<td>2.70</td>
<td>2.44</td>
<td>2.21</td>
<td>1.99</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>BP W/5.3% Pt</td>
<td>3.26</td>
<td>3.07</td>
<td>2.92</td>
<td>2.78</td>
<td>2.55</td>
<td>2.40</td>
<td>2.26</td>
<td>2.11</td>
<td></td>
</tr>
<tr>
<td>SAB w/8.5% Pt</td>
<td>3.36</td>
<td>3.25</td>
<td>3.15</td>
<td>3.06</td>
<td>2.91</td>
<td>2.76</td>
<td>2.63</td>
<td>2.48</td>
<td></td>
</tr>
<tr>
<td>Both carbons platinized</td>
<td>3.32</td>
<td>3.23</td>
<td>3.15</td>
<td>3.08</td>
<td>2.94</td>
<td>2.81</td>
<td>2.69</td>
<td>2.57</td>
<td></td>
</tr>
</tbody>
</table>
### Table 1
Full-Size [1] Single Cell Test Summary

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Composition [2]</td>
<td>Thiol chloride Electrolyte</td>
<td>Voltage @ 250mA/cm² (V)</td>
<td>Time (min.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Standard</td>
<td>1.6M LiGaCl₄</td>
<td>1.99</td>
<td>19.45</td>
<td>4.52</td>
<td>0.46</td>
</tr>
<tr>
<td>2</td>
<td>Standard</td>
<td>1.57M LiAlCl₄</td>
<td>1.93</td>
<td>11.00</td>
<td>2.77</td>
<td>0.298</td>
</tr>
<tr>
<td>3</td>
<td>BP w/5.4% Pt</td>
<td>1.6M LiGaCl₄</td>
<td>2.26</td>
<td>19.91</td>
<td>4.62</td>
<td>0.458</td>
</tr>
<tr>
<td>4</td>
<td>SAB w/8.5% Pt</td>
<td>1.6M LiGaCl₄</td>
<td>2.63</td>
<td>14.33[7]</td>
<td>3.44</td>
<td>0.343</td>
</tr>
<tr>
<td>5</td>
<td>Both carbons platinized</td>
<td>1.6M LiGaCl₄</td>
<td>2.69</td>
<td>17.50</td>
<td>4.12</td>
<td>0.461</td>
</tr>
</tbody>
</table>

---

[1] Ten-inch diameter electrode components
[2] 80% SAB / 20% BP
[3] Initial thickness; test cell thickness was adjusted so that the combined cathode/separat final thickness was 90% of their combined initial thicknesses.
[4] The 53.2kW power output requires a load current density of 250mA/cm²
[5] Continuous discharge 24.5 mA/cm² follows the last series of five half-second pulses at ten second intervals (5% of duty cycle).
[6] Cathode volume corrected for channels
VOLTAGE DELAY:
- Low temperature storage
- Pre-discharge conditioning
  - MESP
  - Centaur
- 1.6M LiGaCl₄ / platinized cathodes
- Additives: PVC, SO₂, GaCl₃, SO₂, Li₂O, GaCl₃

RECHARGEABLE:
- No problem with millisecond charge pulses

HANDLING:
- Designed for shock and vibration
- Insulate terminals
- Low temperature storage

SAFETY:
- Battery will not overheat within load range

BATTERY CHECK PRIOR TO LAUNCH:
- OCV
- Leaks/corrosion
- Pre-discharge conditioning
- Verify rate by pulse load testing
EMA Performance Requirements

- 200 Volts
- 53 kW Pulses (Five pulses, 0.5 seconds each)
- 12.5 Amp background current for 600 seconds

Design Approach:

- Bipolar Li/SOCl Battery
- Two parallel battery stacks, with 80 cells in each stack
- 125 Ampere (maximum current)
- 250 mA/cm² (maximum current density)
HIGH RATE SOCl₂ CELL

DISCHARGED AT 260mA/cm²

VOLTAGE (volts)

TIME (sec)

□ 100%BP-5%PT
HIGH RATE SOCl₂ CELL

80%BP-5%PT  20%SAB-2%PT

VOLTAGE (volts)

TIME (sec)

50mA/cm²

100mA/cm²

150mA/cm²

200mA/cm²

314  334  374  414  454  494  534  574  614  654  674  694

294  310  378  390  458  562  570  662
HIGH RATE SOCl$_2$ CELL

DISCHARGED AT 260mA/cm$^2$

VOLTAGE (volts)

TIME (sec)

80%BP5%P - 20%SAB2%P
Figure 5A: Tefzel/nickel sandwich prior to compression molding

OD - 11.0"

ID - 10.25"

0.030"

0.003" NICKEL SUBSTRATE

1/8" Tefzel/nickel overlap

Figure 5B: Tefzel/nickel substrate configuration after compression molding

TOP HALF OF CAPTURE MOLD

EXCESS TEFZEL

BOTTOM HALF OF CAPTURE MOLD

Average insulation ring height is 0.0224" for 1 mil substrate mold
EMA Power Module Design Concept

ELECTRICAL

- Voltage Range – 200 to 260 volts
- Base Power – 5.7kW for 570 seconds
- Pulse Power – 53.2kW, 5 pulses (each 0.5 sec. with 10 sec. separation)

MECHANICAL

- 2 Parallel Submodules – 80 cells each
- Module Diameter – 11.5 inches
- Module Height – 7.5 inches
- Module Weight – < 30 lbs.
ELECTROMECHANICAL ACTUATION TECHNOLOGIES

Presented by:
SatCon Technology Corporation
12 Emily Street
Cambridge, MA 02139

Presented to:
Electrical Actuation Technology Bridging Workshop
September 29 - October 1, 1992
Huntsville, Alabama
FLYWHEEL ENERGY STORAGE SYSTEM
ASSEMBLED SYSTEM
FLYWHEEL ON HUB
INTEGRATED FLYWHEEL HUB MOTOR/GENERATOR ROTOR
CENTRAL SHAFT FOR INTEGRATING MOTOR/GENERATOR STATOR, MAGNETIC BEARINGS AND TOUCH-DOWN CERAMIC BEARING
Weight measurements of the IPACS assembly (wheel energy 7.2 MJ)
Weights as measured and best estimates (*)

**Mechanical System**

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flywheel (Fiber structure only)</td>
<td>25.0</td>
</tr>
<tr>
<td>Motor/Generator Hub</td>
<td>5.0</td>
</tr>
<tr>
<td>Central Shaft + Bearing Assembly + Motor/Generator Backiron</td>
<td>13.6</td>
</tr>
<tr>
<td>Frame</td>
<td>12.0</td>
</tr>
<tr>
<td>Containment (*) Estimate of light, thin shell containment</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Total: 55.6 kg

**Electronics System**

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter for Motor/Generator (3kW)</td>
<td>5.0</td>
</tr>
<tr>
<td>Magnet Bearing Switching Amplifiers (*)</td>
<td>10.0</td>
</tr>
<tr>
<td>+ Sensor Electronics (*)</td>
<td></td>
</tr>
</tbody>
</table>

Total: 15.0 kg

Analog Amplifiers currently in use
(extreme conservative choice to cover all possible variations of power and frequency response requirements)

Total: 60.0 kg
HUB AND BACK IRON

ONE MAGNETIC BEARING + MOUNTING SHAFT
MAGNETICALLY SUSPENDED MOMENTUM WHEEL COMPONENT LAYOUT
DISTURBANCE ACCOMMODATING CONTROLLER
BLOCK DIAGRAM
<table>
<thead>
<tr>
<th></th>
<th>TELDIX DR-68 Momentum Wheel</th>
<th>SatCon Low Vibration Momentum Wheel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Mass</strong></td>
<td>8 Kg</td>
<td>8.3 Kg</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td>350 mm Diameter, 120 mm Height</td>
<td>384 mm Diameter, 88 mm Height</td>
</tr>
<tr>
<td><strong>Steady State Power</strong></td>
<td>&lt; 26.5 Watts</td>
<td>&lt; 10 Watts in 1g, &lt; 5 Watts in 0g</td>
</tr>
<tr>
<td><strong>Maximum Wheel</strong></td>
<td>--</td>
<td>0.03 rad/sec in 1g, 0.08 rad/sec in 0g (min. required 7.6x10^-3)</td>
</tr>
<tr>
<td><strong>Precession Rate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Torque Vibration at GOES Spacecraft Mass Center</strong></td>
<td>Forces at 6000 rpm with 0.75 gm cm residual static imbalance F = 4.7 N</td>
<td>Forces at 6600 rpm assuming 0.75 gm cm static imbalance F = 0.27 N</td>
</tr>
<tr>
<td></td>
<td>Measured at 6000 rpm</td>
<td>Simulated including measurement error</td>
</tr>
<tr>
<td></td>
<td>Tx = 7.46 Nm</td>
<td>Tx = Ty = Tz &lt; 0.7 Nm</td>
</tr>
<tr>
<td></td>
<td>Ty = 6.83 Nm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tz = 7.46 Nm</td>
<td></td>
</tr>
</tbody>
</table>

**MOMENTUM WHEEL PARAMETERS**
Objective: Design flywheel energy storage system based on induction machine to interface with 20 kHz pulse-density modulation (PDM) converter.

Specifications:
- Usable energy: 250 kJ
- Peak output power: 36 kW
- Output power risetime: 1 kW/mSec
- Average output power: 4 kW

Goals:
- Efficiency (round trip): 80%
- Power density: 2 kW/kg
- Energy density: 100 kJ/kg
- Absorb energy at 40 kHz
- Low machine loss with PDM waveform
- High-efficiency machine-control algorithm
FLYWHEEL ASSEMBLY LAYOUT

SIZE: 12 inch dia. X 4 inch ht.
BASELINE SYSTEM WITH DC PRIME SOURCE

- PRIME POWER
  - DC
  - PARALLEL-OUTPUT SERIAL RESONANT CONVERTER
  - PULSE-DENSITY MODULATION CONVERTER
  - CURRENT REGULATOR
  - 20 kHz DISTRIBUTION BUS
  - SERVO REGULATOR
  - PULSE-DENSITY MODULATION CONVERTER
  - INDUCTION MACHINE
  - ACTUATOR
  - MECHANICAL FEEDBACK
  - FLYWHEEL
<table>
<thead>
<tr>
<th><strong>SUMMARY</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SPEED</strong></td>
<td>24,000 rpm</td>
</tr>
<tr>
<td><strong>MASS</strong></td>
<td>22 kg</td>
</tr>
<tr>
<td><strong>VOLUME</strong></td>
<td>450 cubic inches</td>
</tr>
<tr>
<td><strong>ROUND-TRIP EFFICIENCY</strong></td>
<td>85%</td>
</tr>
<tr>
<td><strong>VACUUM</strong></td>
<td>16 torr</td>
</tr>
<tr>
<td><strong>TEMPERATURE RISE</strong></td>
<td>15 deg. K</td>
</tr>
</tbody>
</table>
Power Source Presentation
A 270 Volt DC System With a High Speed Turboalternator Is a Practical Option for Launcher TVC Power, as Shown by

- DC Power System Development
- Progress in Turboalternator Technologies
Hybrid 270 Vdc Technology Demonstration System
F-22 Electric Power System

Wound Field Synchronous Generator, Integral Rectifier

270 Vdc Bus

115/200 Vac, 400 Hz Bus

400 Hz Inverter

Two 400 Hz ac Converters

One Auxiliary 270 Vdc Generator

Two Main 270 Vdc Generators

Three Generator Control Units
270 Vdc System Issues

Power System Transients

Power System Stability

Voltage Distortion
- EMI Suppression and Control
- Conductor Layout
- Generator/Regulator Architecture

Launcher TVC Power Issues
Electromagnetics

Switched Reluctance

Permanent Magnet Brushless
Summary

- The State-of-the-Art in 270 Vdc Power Can Support the Weight, Cost, Reliability, and Performance Goals for New Helicopters and Fighter Aircraft

- Enabling Technologies Exist for Development of Very Densely Packaged Turboalternator Power Sources for Launcher TVC
GH2 Turbo-Alternator

NASA Electrical Actuation Technology Bridging Workshop @ MSFC

9/30/92

John Anderson
(206) 773-0188

BOEING
TVC PSS Options

- Turbo-Alternators
  - GH2
  - H2O2
  - Hydrazine

- Batteries
  - AgZn
  - Bipolar Lithium
  - Advanced AgZn

- Others
  - Fuel Cells
  - Flywheels
<table>
<thead>
<tr>
<th></th>
<th>GH2 Turbo-Alt</th>
<th>AgZn Battery</th>
<th>Li/SOCI2 Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ability to handle high peak/average current ratio</td>
<td>high</td>
<td>moderate</td>
<td>moderate</td>
</tr>
<tr>
<td>Ability to supply continuous peak power</td>
<td>high</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>Voltage Droop Control</td>
<td>high</td>
<td>moderate</td>
<td>moderate</td>
</tr>
<tr>
<td>Reliability</td>
<td>high</td>
<td>high</td>
<td>unknown</td>
</tr>
<tr>
<td>Operability (MTBF)</td>
<td>high</td>
<td>TBD</td>
<td>unknown</td>
</tr>
<tr>
<td>Test/Checkout Capability</td>
<td>high</td>
<td>moderate</td>
<td>moderate</td>
</tr>
<tr>
<td>Technology Maturity</td>
<td>high</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Availability</td>
<td>high</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Safety</td>
<td>high</td>
<td>moderate</td>
<td>low</td>
</tr>
<tr>
<td>Size (inches)</td>
<td>10 dia x 20 long (3 for 2 engines)</td>
<td>7.5 x 8.3 x 12 (9 for 1 engine)</td>
<td>11 dia x 8 long (2 for 1 engine)</td>
</tr>
<tr>
<td>Weight (lbs/engine)</td>
<td>60</td>
<td>405</td>
<td>60</td>
</tr>
<tr>
<td>Cost ($K/engine)</td>
<td>225</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>
GH2 PSS Selection

- Continuous Power Supply
- Peak Power Load Capability
- Voltage Droop Control
- Low Weight
- Test & Checkout
- On Pad Power-up
- Application of Existing Technologies
## GH2 PSS Operations Savings

### Shuttle Hydrazine APU

<table>
<thead>
<tr>
<th>Generic Vehicle Function</th>
<th>Hours</th>
<th>People</th>
<th>Man Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>APU H2O VLVS R&amp;R/Deservice POSU</td>
<td>32.0</td>
<td>5</td>
<td>160.0</td>
</tr>
<tr>
<td>APU H2O Deservice/Service</td>
<td>80.0</td>
<td>8</td>
<td>640.0</td>
</tr>
<tr>
<td>APU H2O Service Secure</td>
<td>4.0</td>
<td>4</td>
<td>16.0</td>
</tr>
<tr>
<td>APU Lube Oil Service POSU</td>
<td>8.0</td>
<td>5</td>
<td>40.0</td>
</tr>
<tr>
<td>APU Lube Oil Service</td>
<td>26.0</td>
<td>10</td>
<td>260.0</td>
</tr>
<tr>
<td>APU Lube Oil Service POI</td>
<td>8.0</td>
<td>4</td>
<td>32.0</td>
</tr>
<tr>
<td>APU Catch Bottle Drain</td>
<td>96.0</td>
<td>23</td>
<td>2208.0</td>
</tr>
<tr>
<td>APU Lube Oil Deservice POSU</td>
<td>64.0</td>
<td>10</td>
<td>640.0</td>
</tr>
<tr>
<td>APU Lube Oil Deservice</td>
<td>9.0</td>
<td>10</td>
<td>90.0</td>
</tr>
<tr>
<td>APU Fuel Valve Resistance Check</td>
<td>40.0</td>
<td>5</td>
<td>200.0</td>
</tr>
<tr>
<td>APU Leak and Functional POSU</td>
<td>16.0</td>
<td>10</td>
<td>160.0</td>
</tr>
<tr>
<td>APU Leak and Functional</td>
<td>176.0</td>
<td>10</td>
<td>1760.0</td>
</tr>
<tr>
<td>APU Leak and Functional POI</td>
<td>48.0</td>
<td>8</td>
<td>384.0</td>
</tr>
</tbody>
</table>

**Launch Pad**

| Service Auxiliary Power Unit                  | 24.0  | 34     | 816.0     |
| Retract RSS                                   | 8.0   | 11     | 84.0      |
| "Hot Fire" Auxiliary Power Unit               | 8.0   | TBD    |           |
| Extend RSS                                    | 8.0   | 11     | 84.0      |

**Total**

<table>
<thead>
<tr>
<th>Hours</th>
<th>People</th>
<th>Man Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>655.0</td>
<td>7574</td>
<td></td>
</tr>
</tbody>
</table>

### NLS GH2 Power Source

<table>
<thead>
<tr>
<th>Common Core Function</th>
<th>Hours</th>
<th>People</th>
<th>Man Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>APU H2O VLVS R&amp;R/Deservice POSU</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APU H2O Deservice/Service</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APU H2O Service Secure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Equivalent Function</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Equivalent Function</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Equivalent Function</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Equivalent Function</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APU Leak and Functional POSU</td>
<td>16.0</td>
<td>10</td>
<td>160.0</td>
</tr>
<tr>
<td>APU Leak and Functional</td>
<td>176.0</td>
<td>10</td>
<td>1760.0</td>
</tr>
<tr>
<td>APU Leak and Functional POI</td>
<td>48.0</td>
<td>8</td>
<td>384.0</td>
</tr>
</tbody>
</table>

**Total**

<table>
<thead>
<tr>
<th>Hours</th>
<th>People</th>
<th>Man Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>240.0</td>
<td>2304</td>
<td></td>
</tr>
</tbody>
</table>

**Possible Saving of 415 Processing Hours**

**Possible Saving of 5270 Processing Man Hours**

---

GH2 Turbo-Alternator

RECTIFIER
FILTER CAPACITOR
FIN HEAT EXCHANGER
INLET FLANGE
VORTEX VENTURI EXHAUST DUCT
TURBINE
FOIL BEARINGS (TYP)
DATA BUS
CONTROL LOGIC
PLR DRIVER
PLR
FILTER INDUCTOR
POWER CONNECTOR

90 hp
45 hp
10 dia x 20 long
TBD
58 lbs
41 lbs
GH2 Turbo-Alternator Block Diagram

- GH2
- Control/Shutdown Valve
- Impulse Turbine
- Permanent Magnet Alternator
- Rectifier/Filter
- Output 220 Vdc
- Voltage Regulator
- Speed Control
- Load Control
- PLR
GH2 Turbo-Alternator Voltage Regulation

Power Output

- Regulation for steady state and increases in load current provided by turbine speed control

- Regulation for decreases in load current provided by PLR (transient) and turbine speed (steady state)

Regeneration

- Regulation provided by PLR

Output/Internal Fault

- Turbine shut down limits fault current to safe duration
GH2 Voltage Response
Opposing load

0 to 320 A current ramp

<table>
<thead>
<tr>
<th>Steady-State Operating Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply pressure</td>
</tr>
<tr>
<td>Exhaust pressure</td>
</tr>
<tr>
<td>Bus current</td>
</tr>
<tr>
<td>Bus voltage</td>
</tr>
<tr>
<td>TVC power</td>
</tr>
<tr>
<td>Load resistor power</td>
</tr>
<tr>
<td>Turbine speed</td>
</tr>
<tr>
<td>Turbine mass flow rate</td>
</tr>
</tbody>
</table>

MIL-STD-704D voltage limits scaled for 220V
GH2 PSS Distribution

PSS Failure / Off-axis Movement

( Active-Active-Active)

- PSS 1 (45 hp)
  - 11.25
  - 0
  - Engine hp requirement: 30 hp any axis
- PSS 2 (45 hp)
  - 11.25
  - 7.5
- PSS 3 (45 hp)
  - 11.25
  - 7.5
  - Engine hp requirement: 30 hp any axis
<table>
<thead>
<tr>
<th>Issue</th>
<th>SEP 92 GHe Demo</th>
<th>Oct 92 GH2 Design</th>
<th>FY 93 GH2 Fab/Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Control</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>GHe Operation</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>GH2 Operation</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>GH2 Materials Compatibility</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Foil Bearing GH2 Operation</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Control Valve Performance</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>GH2 Static Sealing</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>PLR thermal Management</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Size</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Weight</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Cost</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TVC Power Source Design Drivers

- Voltage Level / corona effects
- Duty Cycle Margin / available energy
- Voltage Droop Control / actuator performance
- Distribution & Redundancy / single-fault-tolerant, fault isolation
- Weight / total system
- Test & Checkout / operability
- Prelaunch Power-Up Capability
- Technology Maturity
ELECTRICAL ACTUATION

TECHNOLOGY BRIDGING PROGRAM

POWER SOURCE SIMULATOR

Presented at

ELA & Power Systems Workshop

NASA - MSFC

September 30, 1992

NASA-JSC: Don Brown

Lockheed ESC: Mike Bradway
ELA-TB & ELAPSS Principals & Roles

NASA Headquarters OSSD
Advanced Development

SATWG

NASA ELA Technology Bridging Program
- ELA & Power Systems Reqmts.
- ELA Technology Devel. & Demo Plans
- ELAPSS Project Direction

ELA/Power Source Systems Commercial Industry
- Power Source Devices SOA,
- Performance Characteristics,
- ELAPSS Hardware & Software Elements

NASA-JSC ELAPSS PROJECT
- ELAPSS Project Mgmt.,
- ELA-TB Program Interface,
- System Engrg. & Integration,
- H/W & S/W Procure. & Devel.,
- ELAPSS Assembly & Test

ELA Technology Bridging Program Power Source Simulator

September '92 Review
## Potential ELA Technology Space Applications

<table>
<thead>
<tr>
<th>ELA Space Applications</th>
<th>Actuator Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Transfer Vehicles (PLS, ACRV)</td>
<td>5 - 5.0 kW</td>
</tr>
<tr>
<td>Propellant Control Valve</td>
<td>5 kW</td>
</tr>
<tr>
<td>Orbiter Nose-Wheel Steering</td>
<td>10 - 12 kW</td>
</tr>
<tr>
<td>Commercial ELVs (Atlas, Titan, Delta)</td>
<td>12 - 20 kW</td>
</tr>
<tr>
<td>Orbiter Main Engine (SSME)</td>
<td>23 kW</td>
</tr>
<tr>
<td>Orbiter Elevons</td>
<td>28 kW</td>
</tr>
<tr>
<td>Space Shuttle SRB Thrust Vector Control</td>
<td>83 kW (pk)</td>
</tr>
<tr>
<td>NLS Thrust Vector Control (configuration dependant)</td>
<td>50 - 70 kW</td>
</tr>
<tr>
<td>Heavy Lift Launch Vehicle</td>
<td>70 - 120 kW</td>
</tr>
<tr>
<td>Planetary Surface Vehicles (Rover, Digger, etc.)</td>
<td>5 - ? kW</td>
</tr>
</tbody>
</table>

**September '92 Review**
## Baseline ELA Requirements for NLS and SRB

<table>
<thead>
<tr>
<th>Requirement</th>
<th>NLS TVC Reqmts.</th>
<th>SRB TVC Reqmts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power:</td>
<td>59 kW</td>
<td>83 kW</td>
</tr>
<tr>
<td>Base Power</td>
<td>5.7 kW</td>
<td>6.8 kW</td>
</tr>
<tr>
<td>Average Power</td>
<td>8.2 kW</td>
<td>33.1 kW</td>
</tr>
<tr>
<td>Voltage</td>
<td>200 Vdc</td>
<td>200 Vdc</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>.5 sec.</td>
<td>1.5 sec.</td>
</tr>
<tr>
<td>Pulse Frequency</td>
<td>10 sec.</td>
<td>4.25 sec.</td>
</tr>
<tr>
<td>Energy / Pulse</td>
<td>7.4 Wh</td>
<td>32 Wh</td>
</tr>
<tr>
<td>Max. No. of Pulses</td>
<td>54</td>
<td>29</td>
</tr>
<tr>
<td>Operating Time</td>
<td>9.5</td>
<td>2.1</td>
</tr>
<tr>
<td>Total Energy</td>
<td>1.3 kWh</td>
<td>1.16 kWh</td>
</tr>
</tbody>
</table>
ELA System Power Source Alternatives

- A variety of ELA systems and requisite power source combinations are being considered for many different applications (launch vehicle TVC, PCV, Orbiter flight control, steering, braking, GSE fluid control, planetary surface equipment).

- Each ELA and system application means unique power characteristics to maximize system operation and efficiency, while minimizing costs.

- ELA power source alternatives include:
  - high power density batteries
  - advanced fuel cells
  - $\text{gH}_2$ turbine-driven alternators
  - flywheel energy storage devices

- Each power source type is viable and appropriate for a specific ELA application and set of program/vehicle constraints.
ELAPSS Purpose & Scope

- The ELA Technology Bridging Programs integrated ELA & power systems test & demonstration plans require power output capability which characterizes all power source options for the variety of ELA applications.

- Acquisition or development of actual power source devices is not practical within ELA-TB Program budget and schedule constraints.

- The ELAPSS will provide a programmable power source emulation capability to meet all NASA ELA application/system test & demonstration needs.

- One ELAPSS can be developed to emulate the defined operating characteristics of any power source using commercially available hardware and applications software.
ELAPSS Purpose & Scope (cont'd.)

- A modular design will allow the ELAPSS to be reconfigured to support multiple ELA system sizes, redundancy schemes, and integrated ELA/power system performance and fault testing.

- The ELAPSS will provide a permanent power source simulator capability for use on current and future NASA programs.

- The ELAPSS will be a portable piece of NASA GSE for use at any NASA center with the facility to support it.

- The ELAPSS will be developed with commercial components for more timely development & use, more cost effective replication, and future expansion of power source emulation capability.

- The ELAPSS allows very robust power degradation and fault testing capability via automated test sequences or manual commands from an operator control console.
ELA Technology Bridging Program Power Source Simulator

JSC Navigation, Control & Aeronautics Division

ELAPSS Project Flow

1. PROJECT PLAN
   - Project Requirements

2. STATEMENT OF WORK
   - Technical Requirements

3. FUNCTIONAL REQUIREMENTS
   - STUDIES
4. FUNCTIONAL REQUIREMENTS REVIEW
5. COST ANALYSIS

6. DETAILED DESIGN
   - STUDIES

7. DETAILED DESIGN REVIEW

8. PROCURE AND/OR BUILD

9. INTEGRATE & TEST

10. DELIVER TO NASA

---

September '92 Review
ELAPSS Development Approach

- Industry ELA Power Reqmts.
- ELA-TB Power Reqmts. Def.
- ELAPSS Systems Requirements
- Battery Reqmts. Analysis
- Fuel Cell Reqmts. Analysis
- Alternator/Flywheel Reqmts. Analysis
- ELAPSS System Design Concept
- ELAPSS Design/ Cost Trades

ELAPSS Project Technical Coordination & Integration
- Review by Committee
- Task Agreements via EMs

Iterate ELAPSS Reqmts. & Design

ELA Technology Bridging Program Power Source Simulator

JSC Navigation, Control & Aeronautics Division

September '92 Review
ELAPSS Functional Diagram

ELAPSS

POWER SOURCE

POWER INTERFACE

LOAD BANKS

DATA ACQUISITION AND STORAGE

MODE GENERATOR

OPERATOR INTERFACE

AC INPUT POWER

DC OUTPUT POWER

ELECTRICAL ACTUATORS

ELAPSS FUNCTIONAL BLOCK DIAGRAM

ELA Technology Bridging Program Power Source Simulator

September '92 Review
Electrical Actuation Power Source Simulator (ELAPSS)

REQUIREMENTS

* ELAPSS will provide power for a variety of non-flight Electrical Actuators - up to 120 kW at 28, 120, 200 and 270 Vdc.

* ELAPSS will be able to provide nominal power or emulate Batteries, Fuel Cells, Turbo Alternators and Flywheels.

* ELAPSS will be able to provide off-nominal power in either nominal or emulation power modes. Off-nominal power could be EMI injection, power source faults and line faults.

* ELAPSS will be able to absorb returned energy from the ELA.

* ELAPSS will be able to support redundant ELA testing.
BASIC DESIGN CONCEPT

The proposed Electrical Actuator Power Source Simulator will have following basic components:

- A programmable switch-mode DC Power Supply
- PWM Power Amplifiers
- A microcomputer based instrumentation and control system
DC POWER SUPPLY:
The DC Power Supply provides variable dc power for the power amplifiers from the utility power. To insure that the system output will respond as fast as the amplifiers are capable, it has a large capacitor bank at the output terminal. The DC power supply is separate module in the ELAPSS system and hence, can be reconfigured easily.

PWM POWER AMPLIFIERS:
These are high power Pulse Width Modulated switching amplifiers that can be designed as master-slave system to allow paralleling multiple modules to meet high power need. Each amplifier contains power modules consisting of a full H-bridge switching stage. The input to the power module is a 81 kHz control signal. The output of each power module is a series of power current pulses at 81 kHz rate whose width is proportional to the analog control signal.
PWM POWER AMPLIFIERS (Contd):

The PWM output is then applied to a low pass filter to eliminate the 81 kHz and its harmonics. The resultant output is DC with little ripple content.

The PWM switchmode type of amplifiers is important for this design because it allows a large output voltage range without dissipating excessive amounts of heat.

---

**Diagram Description:**
- **Switching Stage**: Input DC signal is fed into the switching stage. The control signal is applied here.
- **PWM**: The PWM signal is generated from the 81 kHz OSC.
- **Filter CKT. To Remove 81 kHz Signals**: This stage filters out the 81 kHz signals, allowing only the DC output to pass.
- **Controlled DC Output Voltage**: The final output is a controlled DC voltage.
- **Control Input from Computer**: Indicates the input signal for the control of the switching stage.

---

**PWM Amplifier Concepts**

---

*ELA Technology Bridging Program Power Source Simulator*
MICROPROCESSOR CONTROLLER:

This consists of an industrial PC and instrumentation and control modules. The system load current is monitored by current sensor and processed by an analog to digital converter (ADC). The data read from the ADC module is used by the microprocessor to calculate the voltage control signal for proper simulation output. This control signal is then sent to the power amplifiers via a digital-to-analog converter.
OFF-NOMINAL OPERATION

IN ADDITION TO THE BASIC SYSTEM COMPONENTS, THE FOLLOWING MODULES ARE REQUIRED FOR DEGRADED OR OFF-NOMINAL MODE OF OPERATION:

- **NOISE GENERATOR:**
  A signal generator and wide band amplifiers may be used to inject noise into the output line to degrade output power.

- **LOAD BANKS:**
  These are active control MOSFET off the shelf modules which act as current sinks to absorb return energy from the ELA under test. These devices are turned on by the micro-computer controller.

Both the noise generator and the load banks are commercially available modules.
ELAPSS Design Drivers

- High power output capability:
  - 60 - 90 kW TVC requirements for NLS, ASRM (SRB)
  - 90 kW peak power required to meet SRB TVC ELA reqmts.
    (SRB start transient and roll manuever load profiles)

- Dual & Quad redundant ELA system test capability
  - NASA-MSFC building a quad 60 kW system (4 - 15 kW motors)
  - NASA-LeRC building dual 60 & 80 kW systems

- EMI characteristics of the power bus with switching loads

- Return energy absorption capability (from each channel)

- ELA power transients (engine start, roll manuever) exceed the response time of fastest programmable power supply available
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**ELAPSS Project Schedule (FY'92)**
ELAPSS Value To NASA

- Supports verification of any NASA ELA systems performance & fault tolerance/redundancy with appropriate representative power source emulation

- A programmable portable ELAPSS capability supports multiple ELA applications testing at any NASA site with supporting facility

- ELAPSS provides a permanent resource to NASA - a link in the chain of end-to-end integrated power/avionics advanced development and test capability for any vehicle/surface system

- Modular, commercial ELAPSS design provides multiple ELA/power system testing flexibility, and allows easy reconfiguration, expansion or replication as required

- Supports the NASA "bridging" concept - new way of doing business - resource sharing among centers & programs
SESSION VII
ELA OPERATIONS
ELECTRIC ACTUATION

TECHNOLOGY BRIDGING PROJECT WORKSHOP

STS HYDRAULIC VS. ELA OPERATIONS SRB ASSESSMENT

(ELECTRIC SRB AFT SKIRT CONCEPT)

Carey M. McCleskey, NASA/KSC
Haley W. Rushing, ASSI/KSC
WHY AN ELA OPERATIONS TEST BED?

If a **Concurrent Engineering** approach to design is to be used, the launch site operations customers will need to gain **knowledge, skills and abilities** in the following areas:

1. **Skill in handling high power busses**
   - Signal measurement between LRU's GSE requirements & characteristics
   - Switching and bus redundancy/isolation characteristics

2. **Knowledge of power source characteristics**
   - Battery handling and maintenance
   - Flywheel operation

3. **Ability to handle personnel safety issues**
   - Batteries
   - High voltage lines

4. **Knowledge of actuator operation**
   - Locking operation and characteristics
   - Actuator initialization
   - General operating characteristics (Current monitoring / torque equalization / velocity summing)

5. **Experience in system-level issues**
   - Data management
   - Fault management
   - Energy management (charge/discharge cycles)
Agenda

- Motivation
- SRB TVC Ops Study Results & Video
- Future Plans
ELECTRIC ACTUATION OPERATIONS

Motivation

- Operational experience with Shuttle
  - Heavy servicing and deservicing requirements
  - Replacement often difficult
  - Heavy infrastructure overhead
    - Facility
    - Ground Support Equipment
    - Toxic Commodities

Objective

- Identify Life Cycle Cost of Current Technology
- Conduct specific one-for-one trades with electric actuation technology Life Cycle Cost opportunities

Flight Control Candidates for study:

- Orbiter (APU/Hyd - Aero/TVC/Prop/Ldg-Decel)
- SRB Thrust Vector Control System
HYDRAULIC VS ELECTRIC LIFE CYCLE IMPACT

OPERATIONAL BENEFITS SUMMARY

- REFURBISHMENT COSTS APPROX 2/3 REDUCTION
- REFURBISHMENT/CHECKOUT TIME 3/4 REDUCTION
- 8400 SQ FT REDUCTION IN FACILITY REQUIREMENTS (+ CLEAN ROOM + FLUID SERVICES)
- HUNDREDS AND HUNDREDS OF GSE ITEMS ELIMINATED - VERY FEW INTRODUCED

SRB TVC WORK FLOW/SEQUENCE

SRB TVC LIFE CYCLE COST ELEMENTS
(System Costs = $ 3.3M Per Flight)

- EXPENDED/REPAIRED HW (1.5%)
- HYDRAULIC ACTUATORS (9.7%)
- HYDRAULIC PUMPS (0.7%)
- DESIGN CTR SUPPORT (8.0%)
- AUXILIARY PWR UNIT (10.7%)
- WASTE HANDLING (1.0%)
- SHUTTLE VEH PROCESSING (5.0%)
- CHEMICAL ANALYSIS (1.2%)
- BOOSTER PROD MANPOWER (49.4%)

SRB TVC HYD VS. ELA (INTERIM RESULTS)
(Cost Savings = $ 2.0M Per Flight)

CONFIRMATION STUDY ON ELA COST SAVINGS APPROVED FOR FY 1992

SEPT 29 - OCT 1, 1992
Future Plans

- Continue updating SRB TVC Life Cycle Costs
- Support New Launch System studies
- Begin identifying Orbiter costs in greater detail
- Establish capability to support operational demonstrations for the investigation of:
  - Safety
  - Ground support equipment (GSE)
  - Facility requirements
  - Operability investigations:
    - Installation
    - Replacement
    - Test and problem isolation
    - Servicing & maintenance
    - Processing flow analysis & resource usage
    - Launch commit criteria and hold impact
NASA Electrical Actuation
Technology Bridging Workshop

ELA Ground Support Applications
at the

John C. Stennis Space Center

W. W. St. Cyr
Technology Development Division
Science & Technology Laboratory
POTENTIAL ELA GROUND APPLICATIONS AT SSC

- Variable position valve of NASP High Heat Flux Test Facility
- Automation of High Pressure Gas Facility
- CTF Test Cell
- Seal Configuration Tester
- Selected Facility Support System Valves
GOALS OF ELA PROGRAM AT SSC

- Determine significant advantages and disadvantages of using ELA's for facility valve actuation.
- Compare operating characteristics of ELA's to those of hydraulic control valves.
- Establish reliability of commercially available ELA hardware when used on facility control valves.
- Determine the compatibility of ELA control interfaces with existing facility data acquisition and control systems.
PROGRESS TO DATE / PROGRAM STATUS

- Requirements have been established for specific applications.
- Identified commercial hardware for ground support applications. 
- Developed test plan.
- Electrical Actuator (commercial hardware) in Procurement.
- Adapting test plan to commercial hardware.

Commercial hardware to be evaluated:

- ELA hardware to be tested Oct/Nov on Seal Configuration Tester,

- Field application and evaluation of ELA during 2nd, 3rd and 4th quarter of FY93.
ELA SPECIFICATIONS

Manufacturer: Raco International, Bethel Park, PA
Stroke: 7.9"
Thrust: 5000 lbs
Rod Speed: 6 ips peak running (5.5 Hz max)
Lead: 12 mm Ball Screw
Motor: Brushless Digital Servo
Direct Drive, 1550 RPM
Mounting: Front Flange & Trunnion Brackets
Length: Approx. 6'
Accessories: Power Release Brake, Spring loaded front clevis, Stroke limit switches, Rotary encoder for linear displacement
ELA SERVO MOTOR HIGHLIGHTS

- 3 Phase Brushless Servo Motor
- Position Repeatability: Better than one arc-minute
- Maximum Speed: 1550 RPM
- Continuous Torque: 80 lb.ft.
- Rotor Inertia: 0.0093 lb.ft.sec²
- Load Inertia Range: 0 to 0.0465 lb.ft.sec²
ELA CONTROLLER HIGHLIGHTS

- 10 kHz PMW Switching Frequency
- 55 Amp/Phase Continuous Current
- 110 Amp/Phase Peak Current
- 230 V RMS Nominal Voltage
ELECTRICAL ACTUATOR TESTBED

LABVIEW CONTROL PANEL

LINEAR ACTUATOR CONFIGURATION
(INSTALLED ON OXYGEN SEAL TESTER)
ELA TESTBED MEASUREMENTS

- Load (10 kHz sampling)
- Linear Position (10 kHz sampling)
- Linear speed and acceleration (derived from position)
- Motor current draw
- Motor temperature
- Total run time
- Wear characteristics of critical ELA drive components
I. LOAD CELL PLATE DETAIL
SCALE = 1/4

- DRILL THRU & TAP
5/16" ON ø 2.625 B.C.
TYPICAL 6 PLACES

- LOAD CELL MOUNTING PLATE
EXTENDING

- FRONT MOUNTING FLANGE

- SPRING LOADED ADAPTER

- Ø .55 DRILL ON
Ø 10.4 B.C. TYPICAL
8 PLACES

FLANGE DETAIL

NOTE:
1. ALL DIMENSIONS ARE IN INCHES.
2. ACTUATOR IS SHOWN IN RETRACTED POSITION.
3. THRUST TUBE DIAMETER 2.4"
4. QUOTATION #3879.
POWER-BY-WIRE FLIGHT DEMONSTRATIONS
ON LASC'S HTTB
Lockheed
High Technology Test Bed
HTTB
High Technology Test Bed Program

- Provides a Flying, Operational-Environment Laboratory

- Goals
  - Establish Real-World Mission Characteristics
  - Develop Flight-Tested Hardware
  - Serve as a Focus for Systems Integration
  - Demonstrate Technological Commitment
  - Conduct Applicable Research Projects
HTTB Technologies

- Short Takeoff and Landing
- Fly-by-Wire
- Voice I/O
- Infrared
- High Pressure Hydraulics
- High Speed Data Bus
- Fiber Optics
- Autonomous Navigation
- Head-Up Display
- Digital Flight Control
Lockheed Airborne Data System (LADS)

- Recording System Installed
- Multiple Measurements Available
- Modular/Expandable
- Real-Time Data
- Processed Output in Engineering Units
- Scan Rates to 160/Sec
HTTB Advanced Avionics

- Navigation Systems
  - Baseline Delco
  - Laser Nav
  - High Accuracy Gimbal
  - F³
  - Litton LN92/Collins GPS
- Head Up Display (HUD)
- Forward Looking Infrared (FLIR)
- Digital Flight Control System (DFCS)
- Doppler/Kalman
- Digital ADF
- TACAN
HTTB Advanced Avionics

- Cockpit Management System
- MIL-STD-1553B Data Bus
- Radar - Bendix APS-133 High Resolution Radar
- Radar Altimeter
- Digital Air Data Computer
- Global Positioning System
Mobile Data Center
Power-by-Wire Flight Demonstrations On LASC's HTTB
Power-by-Wire Advantages for C-130

- Better Reliability and Supportability
- Damage Tolerance Design (Reduced Vulnerability)
- Jam Resistant
- Energy Efficient (Power "On-Demand")
- Rapid Deployment Capability at Low Temperatures
- Backdrive Capability
- Reduced Fire Risk
- Field Level Hazardous Waste Reduction
Electro Hydrostatic Actuator - Left Aileron
Integrated Actuator Package - Rudder
SESSION VIII

ELA PROTOTYPE DESIGN AND TEST RESULTS
General Dynamics EMA Testing at NASA MSFC

Jim Mildice
General Dynamics
Space Systems Division

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Motor Controller Design - *(General Dynamics)*

- **Power Output Stage**
  - Three-phase, bidirectional motor interface
  - High-frequency (20-KHz) AC power input
  - Bilateral output switches, to perform integral, synchronized AC input rectification, and low-frequency motor current synthesis and control
  - Pulse-population regulation, with zero current switching

- **Control**
  - Embedded microprocessor control for all functions except motor current regulation
  - Software in ROM
  - Analog motor current regulation loop, with computer-generated reference
  - All communications and interfaces via serial data busses
General Dynamics EMA Testing at MSFC

Motor Controller Capability

- **Power Inputs**
  - Power Stage Voltage = 300-V,RMS, single-phase, AC
  - Frequency = 20-KHz
  - Total Power = 44.0-KVA (maximum)

- **Command Inputs**
  - Digital, serial data bus - RS-232

- **Feedback**
  - Analog, motor resolver outputs
  - Analog, motor current

- **Outputs**
  - Variable Voltage = zero to 200-V,RMS,L-L; three-phase AC
  - Variable Frequency = zero to 750-Hz
  - Power = 40-KVA (maximum)
General Dynamics EMA Testing at MSFC

Induction Motor - *(Sunstrand)*

- **Electrical Characteristics**
  - Input Voltage = 115-volt,RMS,L-N; three-phase
  - Input Frequency at Full Speed = 750-Hz
  - Power Factor = 0.753
  - Efficiency = 89.9%

- **Mechanical Characteristics**
  - Rated Power = 69.3-HP(peak); 34.6-HP(steady state)
  - Full Rated Speed = 14,700RPM @ Full Load
  - Operating Torque = 148.4 in-lb
  - Maximum Torque = 400 in-lb
  - Specific Weight = 3.32-HP/lb(peak); 1.7-HP/lb(steady state)
  - Specific Volume = 1.6-HP/cu.in(peak); 3.1-HP/cu.in(steady state)
  - Moment of Inertia = 0.0103 in-lb-sec-sec
General Dynamics EMA Testing at MSFC

Redundant Actuator - *(Moog)*

- **Performance**
  - Force Rating = 48,000-lb (operating); 100,000-lb (maximum)
  - Extension = ±5.4-inches
  - Maximum required Rate = 7.4-inches/second
  - Engine Start Transient relief = force feedback with integral load cell

- **Mechanical Design**
  - Design compatible with roller screw or ball screw output
  - Dual (redundant) motor mounts with torque summing in the gear train (no mechanical decoupling)
  - Length = 47.33-inches, pin-to-pin
  - Weight = 300-lb (non-optimized prototype)
  - Moment of Inertia (at the motor shaft) = 0.0089 in-lb-sec-sec
General Dynamics EMA Testing at MSFC

Tests Performed

- **Compatible Operation**
  - Low power test to verify EMA/Controller/Facility compatibility
  - Full power operation to verify EMA/Controller/Facility compatibility

- **Step Response**
  - Step function position commands from (+) to (-) 0.05- to 2.5-inches
  - Maximum rate achieved ≈ 6-inches/second (consistent with input power limitation)

- **Frequency Response for various displacements**
  - Combinations of frequencies and displacements from 0.1-Hz @ ±0.05-inch to 4.0-Hz @ ±0.25 inch
  - Small signal bandwidth ≈ 20-radians
  - Typical power (slew rate) limited frequency response ≈ 2.0-Hz @ ±0.5-inches
General Dynamics EMA Testing at MSFC

Special Conditions and Limits
(for this test only)

- Engine position control loop software/system response designed to NLS-2 requirements
  - Position control loop bandwidth limited to 20-radians
- High-frequency AC controller input power limited to 10-KVA by the inverter capability
  - Step response limited to approximately 6-inches/second
  - Large signal frequency response is slew-rate limited. Limiting typically starts at about 2.0-Hz @ ±0.5-inches
Small Signal Frequency Response

Data is consistent with the design for a critically-damped, second-order system with a 20-radian (3.2-Hz) bandwidth.
General Dynamics EMA Testing at MSFC

Frequency Response Limit

- Expected Position Output: \( (A \sin(\omega t)) \)
- Required Rate Output: \( (B \cos(\omega t)) \)
- Required Acceleration: \( (-C \sin(\omega t)) \)

Maximum Required Slope is a function of cosine Amplitude and Frequency

Maximum Slope Capability is a function of Acceleration Limits

Power Input Limits Maximum Acceleration
Frequency Response

- Limited input power limits the torque available for acceleration
  \[ \text{Torque}_{\text{accel}} = \text{Torque}_{\text{total}} - \text{Torque}_{\text{load+friction}} \]

- At the limit, acceleration is constant, the maximum rate change slope is constant, and the system becomes "slew rate" limited

- The constant value rate change slope, for a "slew rate" limited system \((\text{Maximum Slope Capability})\) must be larger than the \text{Maximum Required Slope} for the rate output
  - If it is not, the output amplitude is limited

- After we work through the math, Slew Rate limit for frequency response is:
  \[ f_{\text{SR}} \leq \frac{\text{SR}}{(2\pi \times B_{\text{pk}})} \]
General Dynamics EMA Testing at MSFC

Step Response Average Rates

Step Response is consistent with power limits
Step Response Typical Characteristic

Step = 0.5-inches  
Max Rate = 4.5-in/sec  
(no power limiting)

Step = 2.0-inches  
Max Power-limited  
rate = 6.0-in/sec
General Dynamics EMA Testing at MSFC

Summary

- General Dynamics EMA testing at MSFC was satisfactorily completed during the week of September 8-11
- Evaluated test results were within expected ranges
  - Small-signal bandwidth ≈ 20-radians
  - Power-limited maximum rate ≈ 6.0-inches/second
  - Accuracy & Linearity are better than the resolution of the data
- Maximum potential capability was not demonstrated due to the following:
  - Control system bandwidth was designed to meet the NLS-2 requirement of 20-radians
  - Motor controller power input was limited by the capability of the source, which resulted in a limited large-signal amplitude-bandwidth
Design of A High Power Prototype Electromechanical Actuator For Thrust Vector Control

Rusty Cowan
NASA
George C. Marshall Space Flight Center

NASA ELA-TB Workshop
September 29 - October 1, 1992
AGENDA
EMTVC Actuator

- Introduction - Why EMA?
- Design - EMTVC Actuator
  - Baseline Parameters
  - Major Components
- Testing
- EMTVC Actuator Program Development
- Conclusions
WHY ELECTROMECHANICAL?

- HYDRAULIC SYSTEM INSPECTION TIME
  - ORBITER ON BOARD HYDRAULIC COMPONENTS-APPROX 300
  - ORBITER GROUND SUPPORT COMPONENTS-APPROX 140

- CLEANER, LESS CUMBERSOME

- PROVIDES ALTERNATE TVC SYSTEM

- LOW MAINTENANCE

- PROVEN TECHNOLOGY

- HISTORICAL HYDRAULIC HEADACHES
  - EXCESSIVE MAINTENANCE AND GROUND SUPPORT (INCREASES COST AND MAN-HOURS)
  - FLUID CONTAMINATION (FILTERING)
BASELINE REQUIREMENTS
SRM, SSME, NLS CLASS

• PROTOTYPE PHILOSOPHY
  • LOW COST
  • QUICK TURNAROUND
  • LEARN FROM EXPERIENCE

• ESTABLISHED PARAMETERS
  (SRM, SSME, NLS CLASS)
  • RATED DYNAMIC CAPACITY OF 35KLB
  • MAXIMUM STROKE OF +/- 6.00 IN
  • RATED VELOCITY OF 5 IN/SEC
  • CONTROL - TWO CHANNEL REDUNDANT
    (FAIL/OP REDUNDANCY)
  • POSITION ACCURACY - < 0.050 IN
EMTVC ACTUATOR
MAJOR COMPONENTS/SCHEMATIC DIAGRAM

- BATTERIES
  - Energy Storage
  - Two Pass Low Backlash
- ELECTRONIC CONTROLLER
- MOTORS
  - Permanent Magnet Brushless, DC
- GEAR TRAIN
- LINEAR SCREW
  - Resolvers (Position Feedback)
  - Roller Screw
- ATTACH POINTS
LINEAR SCREW
ROLLER/BALL SCREW COMPARISON

• ROLLER SCREW
  • ABILITY TO HANDLE TRANSIENT LOADS
  • HIGHER LOAD CAPACITY
  • SLEEK NUT DESIGN (No Recirculation Channel)
  • SKF SP/PR 48/10
  • 1.89 DIA. SHAFT
  • 0.4 IN. LEAD
  • RATED LOAD OF 40095 LB
GEAR TRAIN

- SPUR, 20 DEG INVOLUTE
- CALCULATED TORQUES
  - OUTPUT = 2228 IN-LB
  - INTERMEDIATE = 303.9 IN-LB
  - INPUT = 243.1 IN-LB
- REQUIRED OUTPUT RPM TO MAINTAIN VELOCITY OF 5 IN/SEC, RPM = 761
- HORSEPOWER REQUIRED = 26.9
- MATERIAL - 8620 Steel Alloy
  (Case Hardening Qualities)
- GEAR REDUCTIONS (8.75:1 Total)
  - 1ST GEAR PASS, 1.25:1, 7000-5600 RPM
  - 2ND GEAR PASS, 7.00:1, 5600-800 RPM
MOTORS
THREE-PHASE, PERMANENT MAGNET, BRUSHLESS, DC

- BASIC CHARACTERISTICS:
  - NO LOAD SPEED: 9300 RPM @ 270v
  - 5.5 in. O.D. x 5.045 in. L
  - WEIGHT: 17 lb
  - OFF-THE-SHELF

- EASILY CONTROLLED - KNOWN DESIGN

- HIGH EFFICIENCY

- BROAD SPEED RANGE

- HIGH TORQUE/WEIGHT/EFFICIENCY

- GOOD THERMAL PROPERTIES

- LARGE # OF POLES
  (NOMINAL DRAG TORQUE IN REDUNDANT SYSTEM)
TESTING
EMA

• DYNAMIC TESTS
  • LINEARITY, GAIN, HYSTERESIS
  • FREQUENCY RESPONSE (OUTPUT/INPUT)
  • PISTON VELOCITY
  • STEP RESPONSE WITH INERTIAL LOAD APPLIED

• REDUNDANCY MANAGEMENT CONFIGURATION

• DYNAMIC LOAD SIMULATOR - MSFC, HUNTSVILLE, AL.
EMA DEVELOPMENT

GOALS

- 60HP QUAD EMA - NEXT GENERATION
- NLS Prototype Subsystem
- FAIL/OP, FAIL/OP, FAIL/SAFE
- 30HP (500K LB-1500K LB THRUST VEHICLE)
- ASRM
- SSME
- NLS
- 10HP (J-II CLASS, 200K LB THRUST)
- LUNAR MARS TRANSPORT
- 1HP (RL-10 CLASS, 20K LB THRUST)
- LUNAR MARS LANDER
CONCLUSIONS

EMA

- LESSONS LEARNED
  - GEAR TRAIN (BACKLASH, MANUFACTURING)
  - MOTOR (SHAFTS)

- FEASIBILITY?
  - DATA LOOKS GOOD! (John Sharkey)

- DEVELOP DEFINITION & SPECIFICATIONS FOR TVC
  EM CONTROL SYSTEM
  - LAB SIMULATION TEST
  - VALIDATION TEST (ENGINE HOT FIRE)

- THINGS TO CONSIDER
  - SYSTEM WEIGHT
  - POWER SOURCE
  - MAINTENANCE
  - COST
MSFC IN-HOUSE ACTUATOR TEST RESULTS
SYSTEM DESIGN SPECIFICATIONS

- 3 Hz. Bandwidth (2 to 5% of full stroke)
- Less than 25 degrees of Phase Lag at 1 Hz.
- .050 in. accuracy
- Rate of 5 in/sec.
- Less than 20% overshoot
- Load of 35,000 lbs.
A MSFC TEST PLAN WAS WRITTEN TO COMPLY WITH THE ELA ROCKWELL DEVELOPED ACTUATOR TEST PLAN. DUE TO A FAILURE OF THE LOAD-VS-RATE TEST BED, THE LAST TWO TESTS WERE NOT PERFORMED. UPON MODIFICATION OF THE TEST BED, THESE TESTS WILL BE RUN AND THE RESULTS DOCUMENTED.
MSFC TVC ACTUATOR TEST PLAN

- Frequency Response Tests
- Linearity/Hysteresis Tests
- Step Response Tests
- Rate-vs-Load Tests
- Backdrive and Breakaway Friction Tests
THIS IS A BLOCK DIAGRAM OF MSFC'S TEST SETUP. HIGH POWER WAS PROVIDED FROM A 270 VOLT BATTERY BANK AND LOW OR AVIONIC POWER FROM A 28 VOLT POWER SUPPLY. COMMAND WAS PROVIDED BY A FUNCTION GENERATOR OR IT WAS COMPUTER GENERATED. THE ACTUATOR WAS MOUNTED IN THE INERTIA LOAD SIMULATOR. THE CONTROLLER RECEIVES TWO SIGNALS (MOTOR COMMUTATION, ACTUATOR POSITION) FROM THE ACTUATOR. DATA ACQUISITION CONSISTED OF AN 8-CHANNEL SYSTEM WITH A 200 HZ SAMPLE RATE. DATA TAKEN INCLUDED COMMAND, ACTUATOR POSITION, LOAD POSITION, BATTERY CURRENT, AND MOTOR CURRENT.
THE ENVELOPE ON THE FREQUENCY RESPONSE CHART IS THE SSME SMALL SIGNAL REQUIREMENT. DATA SHOWS THE RESPONSE MEETS SSME SPECIFICATIONS. DATA ABOVE 4 OR 5 HZ HAS STARTED LOSING COHERENCE, AS CAN BE SEEN IN THE NEXT CHART. THE BANDWIDTH OF THE SYSTEM IS APPROXIMATELY 4 HZ. THE RESPONSE ALSO MEETS THE >-25 DEGREES OF PHASE LAG AT 1 HZ REQUIREMENT.
Frequency Response with SSME Envelope Requirements
THE BASIC CONTROL SYSTEM BLOCK DIAGRAM SHOWS THE THREE CONTROL LOOPS (CURRENT, RATE, AND POSITION), ACTUATOR, AND LOAD. THE LOAD CORRESPONDS TO THE SSME WITH SLIGHTLY MORE DAMPING DUE TO FRICTION IN THE INERTIA LOAD SIMULATOR. THE FIRST SET OF DATA IS WITH A CONTROLLER CONFIGURATION LACKING THE RATE LOOP. TEST DATA IS LATER SHOWN, WHICH WAS TAKEN AFTER THE RATE LOOP WAS IMPLEMENTED.

THE NEXT VIEWGRAPH SHOWS THE SIMULATED FREQUENCY RESPONSE (FREQUENCY IN RADIANS). THE MODEL FollowS ACTUAL TEST DATA CLOSELY.
THESE ARE EXAMPLES OF BOTH SMALL AND LARGE STEP RESPONSES. THE SMALL STEP SHOWS AN OVERSHOOT OF 16 PERCENT AND ALSO MEETS THE SSME SMALL STEP REQUIREMENTS. THE LAYER STEP HAS A 13 PERCENT OVERSHOOT. THE MAXIMUM RATE IS ALMOST 7 IN/SEC WHICH EXCEEDS THE DESIGN REQUIREMENT.
THE NEXT TWO VIEWGRAPHS COMPARE MOTOR AND BATTERY CURRENT FOR THE 0.25 INCH STEP. THE POLARITY ON BATTERY CURRENT IS REVERSED AND SLIGHTLY OFFSET, BUT THE TIME AXES ARE IDENTICAL. THIS SHOWS THAT THE CAPACITOR ON THE CONTROLLER ACCOMMODATES THE INITIAL CURRENT REQUIREMENT. ONE CAN SEE BATTERY CURRENT RAMPS UP AND THERE IS NOT A LARGE INSTANTANEOUS CURRENT DRAIN FROM THE POWER SOURCE. ALSO, NOTE THAT BATTERY CURRENT IS NOT REQUIRED DURING THE BRAKING PORTION OF THE STEP RESPONSE, EVEN THOUGH THE MOTOR ITSELF CONTINUES TO CARRY CURRENT IN THE REGENERATION MODE.
THE NEXT TWO VIEWGRAPHS SHOW LINEARITY FOR BOTH SMALL AND LARGE EXCURSIONS. THE POSITION ERROR FALLS WITHIN THE NOISE OF THE DATA AND MEETS THE 0.050 INCH ACCURACY REQUIRED, WITH THE LARGE EXCURSION ERROR BEING ABOUT 0.030 INCH.
AFTER COMPLETION OF THE TEST PLAN ON THE INITIAL CONTROLLER CONFIGURATION, IT WAS DECIDED TO IMPLEMENT A RATE LOOP. PRELIMINARY RESULTS EFFECTIVELY REDUCE THE OVERSHOOT BUT SHOW THE MAXIMUM RATE WAS REDUCED TO LESS THAN 4 IN/SEC AND ALSO A REDUCTION IN BANDWIDTH. THE NEXT STEP WILL BE TO TUNE THE RATE LOOP TO MEET ALL DESIRED SPECIFICATIONS.
Step Response With Rate Loop
THIS VIEWGRAPH SHOWS THE STS-44 SRB COMMAND PROFILE AND THE TVC/EMA RESPONSE. THE NEXT VIEWGRAPH SHOWS THE POSITION ERROR BETWEEN COMMAND AND RESOLVER DATA FOR THE ACTUATOR. IN COMPARISON TO THE ACTUAL HYDRAULIC DATA, THE EMA ERROR IS SMALLER, ALTHOUGH FOR THE EMA SYSTEM NO FLIGHT TYPE LOADS (WIND GUSTS, ETC.) WERE APPLIED.
STS - 44- SRB Command Profile

PRELIMINARY 25 HP TVC/EMA RESPONSE TO STS-44-SRB COMMAND PROFILE
Position Error of 25 H.P. TVC EMA For Command Profile
A new gear system is on order which will allow MSFC to implement a two motor configuration on this actuator. While awaiting delivery of these gears, the rate and position loops of the controller will be tuned to meet all desired specifications. Testing will resume with data being used to validate the actuator model. This model will be used for simulation in addition to test data to define and implement a redundancy management scheme for the two motor actuator.
FUTURE PLANS

- Tune rate and position loops to meet desired specifications
- Demonstrate Rate vs Load capability
- Demonstrate Simulated Flight Load Capability
- Use test data to validate model
- Implement a two motor configuration
- Using model and test data, define and implement redundancy management scheme
ITW SPIROID

ITW Spiroid, A Division of Illinois Tool Works, is a manufacturer of proprietary, custom gear forms, roller screws, and index rings. These products come in the form of Spiroid + Helicon right angle gearing, Concurve spur gears, Spiracon roller screws, and Endicon index rings.

ITW Spiroid provides their products for a large number of diverse applications. Approximately 50% of our volume goes to both military and commercial markets. Military applications include such equipment as the Apache Helicopter, M109 Howitzer, F15 Fighter Aircraft, and the Harpoon and RAM Missiles. Commercial applications include Hand Tools, Laser Imaging Devices, Machine Tool + Fixturing Devices, Tundish Car Actuators, and Aircraft Flap Actuators.

Spiroid/Helicon - Right Angle Gearing

<table>
<thead>
<tr>
<th>Spiroid</th>
<th>Helicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:1 - 400:1</td>
<td>4:1 - 400:1</td>
</tr>
<tr>
<td>High Contact Ratio</td>
<td>High Contact Ratio</td>
</tr>
<tr>
<td>Higher Capacity</td>
<td>High Capacity</td>
</tr>
<tr>
<td>Good Efficiency</td>
<td>Better Efficiency</td>
</tr>
</tbody>
</table>

Possible Cross Shaft Design
Backlash Control
Material Variability

These gear forms have the widest center distance of any right angle, face type gear form thereby producing the highest contact ratios possible. This allows for high capacity in small space envelopes thus affecting packaging, weight, and power density.

Concurve Spur Tooth Gears

This gear form is a variation of an involute spur tooth form where the tooth profile has a relatively constant radius of curvature from the tip of the tooth to the root of the tooth. This distributes the contact stress evenly up and down the tooth flank. Involute spur gear teeth tend to have ever increasing contact stress as you move from tip to root of the tooth.
The even distribution of stress in Concurve gears allows for higher loads and lower numbers of pinion teeth due to this feature. Therefore, pinions with as few as 4 teeth and ratios up into the 20's:1 are possible. Removal of gear passes, higher loads, higher ratios and downsizing are all possible.

**Spiracon Roller Screws**

Spiracon Roller Screws offer several advantages over Ball Screws and Acme Screws. The basis for these advantages lie in a discussion of the type of contact that exists between members within the nut itself.

Acme Screws have line contact between members. They have great capacity for this reason. However, there is so much contact and with the elements sliding upon each other, the efficiency is extremely low, usually around 20%. Thus motors tend to be very large to overcome this inefficiency.

Ball screws have point type contact between members. Imagine a ball riding in a trough of slightly larger curvature. A small point exists between these two members upon which the load will be carried. For this reason they have limited capacity. However, due to this small contact area and the rotation of all internal components, ball screws are generally very efficient.
Spiracon Roller Screws have line type contact between members. These lines create a large area over which the load is carried thus decreasing the stresses on the components. Higher capacities, longer life and reduced size are all possible. All internal components do rotate however, because of the increase in contact area, roller screws are slightly less efficient than ball screws.

Endicon Index Rings

Endicon Index Rings consist of 2 mirror image gear halves with teeth machined such that intimate contact exists between the two halves. They can be used as indexing devices, couplings, centering devices, etc. They have been used previously in such applications as Indexing Tables, Multi-Stage Turbine Blade Alignment devices, Robotic end effector joints and Blind Assembly Robotic couplings.
NATIONAL LAUNCH SYSTEM
TURBOALTERNATOR PSS
DEMONSTRATOR UNIT

SEPT. 29, 1992
HIGH-SPEED, DIRECT-DRIVE
TURBINE-DRIVEN PSS
The basic components of the PSS are shown here along with how they interface with each other and the exterior load.
This cross section of the hydrogen powered PSS turboalternator shows the single two pole toothless alternator rotor directly driven by the single stage axial impulse turbine. A vortex venturi provides passive overspeed protection. Also shown are the radial and the axial foil bearings. The electrical power conditioning and speed control electronics are installed around the periphery of the turboalternator. All cooling is provided by the gaseous hydrogen.
This schematic shows the simple rectifier design power conditioner. The output voltage level is a function of the electrical load and the rpm.
This alternate inverter-type power conditioner is less dependent on rpm. The inverter operates in an upchopping mode, eliminating voltage droop due to speed and load changes.
This is a cross-section of the helium powered turboalternator demonstration unit. It consists of heavy hogged out structures and utilizes oil mist lubricated angular contact ball bearings. The arrangement of the turboalternator components is similar to that of the hydrogen demonstrator unit.
Pictured are the details and subassemblies which make up the PSS helium demonstrator turboalternator.
This is the schematic of the PSS setup for the development and demonstration tests. The power converter can be operated in either the rectifier or inverter (upchopper) mode.
The majority of these tests have been accomplished. Application and shedding of the maximum electrical load as a step function under various conditions is not yet complete.
GHe TEST PLAN OVERVIEW

- VIBRATION SURVEYS
- VORTEX VENTURI EFFECTIVENESS
- TURBINE PERFORMANCE
- WINDING RESISTANCE AND INDUCTANCE
- NO LOAD VOLTAGES
- SPINDOWN TESTING
- STEADY STATE LOADS
- TRANSIENT LOADS
- LOAD REGULATION
- OPERATING AND SOAKBACK TEMPERATURES
- PRESSURE DIFFERENTIALS
Shown here are the traces of rpm and helium pressure to the turbine as the turboalternator; was started up under load, was run in the rectifier mode, accomplished an output voltage (and current) increase by switching to the upchopper mode, had additional partial load applied and shed as step changes, and was shut down.
This is another stripchart recording of the test described on the previous page. It shows traces of the currents, DC output voltage, rpm and turbine nozzle pressure. The output voltage is closely regulated during the load changes.
The major similarities and differences between the helium and hydrogen powered PSS demonstrator units are shown.
# PSS TURBOALTERNATOR DESIGN COMPARISONS

<table>
<thead>
<tr>
<th></th>
<th><strong>Helium Demonstrator</strong></th>
<th><strong>Hydrogen Demonstrator</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Output</strong></td>
<td>35 kw at 220 vdc</td>
<td>35 kw at 220 vdc</td>
</tr>
<tr>
<td><strong>RPM</strong></td>
<td>65,000</td>
<td>60,000</td>
</tr>
<tr>
<td><strong>Voltage Control</strong></td>
<td>Rectifier &amp; Upchopper</td>
<td>Rectifier or Upchopper</td>
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<tr>
<td><strong>Speed Control Valve</strong></td>
<td>Limit Cycling</td>
<td>Proportional</td>
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<tr>
<td><strong>Bearings</strong></td>
<td>Ball/Oil Mist</td>
<td>Foil/GH₂</td>
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<tr>
<td><strong>Weight</strong></td>
<td>180 lbs.</td>
<td>75 lbs.</td>
</tr>
<tr>
<td><strong>Packaging</strong></td>
<td>Two Separate Components</td>
<td>Wrap-Around Electronics</td>
</tr>
</tbody>
</table>

THE CAPABILITY TO DEVELOP THE REQUIRED 35 KW ELECTRICAL POWER HAS BEEN DEMONSTRATED
SESSION IX

DEMONSTRATION
SESSION X

EMA FDIR AND VHM
IVHM ADVANCED DEVELOPMENT PROGRAM

Phase 0
- Target Veh/SS Selection & IVHM Needs Identification

Early Demo Selection

INTEGRATED PLAN
- Customer needs
- High leverage IVHM opportunities
- Integrated plan

Phase 1
- VIM Concept Design & Analysis for Selected Veh/SS
  - Methodologies & tools
  - VHM conceptual designs
  - Cost/benefit quantification
  - Technology: adv dev needs
  - Metrics for demo's

Early Demo Implementation
- Early high impact demonstration of VHM feasibility & potential

Supporting Tools Development

Phase 2
- VHM Adv Dev & Simulations for Selected Veh/SS
  - Software simulations
    - Verification that selected VHM features will work
    - Data to support verification of cost/benefit est.
    - Initiation of adv dev for selected VHM items
    - Refined evaluation of alternative VHM features/technologies

Phase 3
- HW in the Loop Demos for Selected Subsystems
  - Hardware in-the-loop demo

18 September 92

Integrated Vehicle Health Management Technology Bridging Program
VHM Development Plan
Schedule

<table>
<thead>
<tr>
<th>Phase</th>
<th>FY92</th>
<th>FY93</th>
<th>FY94</th>
<th>FY95</th>
<th>FY96</th>
<th>FY97</th>
<th>FY98</th>
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<td>CY92</td>
<td>CY93</td>
<td>CY94</td>
<td>CY95</td>
<td>CY96</td>
<td>CY97</td>
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<td>Integrated Plan</td>
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<td>Far</td>
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<td>Prel. Plan</td>
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<td>Phase 1</td>
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<td>Concept Design &amp; Analysis</td>
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<td>Early Demos</td>
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<td>HW Demos</td>
<td>Fit Demos?</td>
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TASK PRIORITY
PHASE 0

TOP PRIORITY
- Real time engine diagnostics
- Leak detection
- IVHM Architecture
- Ground processing Integration
- IVHM for EMA
- OMS/RCS

TARGETS SUPPORTED
- ELV, STS
- ELV, STS
- ELV, STS
- STS
- ELV, STS
- STS

IVHM Cost/Payback analysis*

DESIRABLE
- Post flight/test data analysis for engines
- IVHM for mission operations
- Automated Inspection techniques for engines
- Flight/ground test plume spectroscopy
- Laser pyros
- SSF Fault Management system
- Hybrid Reliability/fault tolerance/cost tool

Application required for all demos
EMA Health Management
Using Smart Sensors

NASA Electrical Actuation Technology Workshop

Honeywell Systems & Research Center

Jeff Schoess
1 October 1992
EMA Health
Management Agenda

- Role of Health Management -- A Honeywell Perspective
- Launch Vehicle Management Approach
  * NLS Avionics Configuration
  * Vehicle Integration Logic Flow
  * Functionality Definition
- Key Building Block Technology --- Smart Sensors
- Recent Technical Progress
  * 2 HP EMA Motor Current Health Monitoring
  * 28 HP EMA Test Evaluation
- Smart Structures Technology --- Launch Vehicle Application
- Summary
Systems and Research Center

Mission: Applied research for Honeywell's space and aviation business

Technologies
- Control Systems
- Displays
- Computer Systems
- Sensors
- Microsystems/Circuits
- Signal Processing

Resources
- 460 people
- 280 engineers/scientists/technicians
- $45M Total Funding
- $32M Contracts
- $9M IR&D
- $4M Divisions

Honeywell

Minneapolis

Phoenix

Bloomington
Health Management Philosophy

Human
Health management is more than not being sick—it's a way of life aimed at reducing your risk of serious illness

Launch System
Health management is more than determining that a system is working nominally—it's a system design aimed at reducing the risk of system- and mission-threatening failures

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Honeywell Perspective—A Systems View

A health management system—
- Monitors, evaluates and diagnoses system health; it integrates the following elements:
  - Nominal system status/configuration/nominal operation/checkout data
  - On-line condition and safety monitoring
  - Predictive and preventive diagnosis
  - Fault detection, isolation, recovery (including BIT)
  - Explanation and recommendation facility
  - Integrated maintenance database

- Is part of an integrated launch system controls architecture that provides life-extending control to maintain assets and reduce replacement costs, as required
Health-Monitoring Systems

The Present Situation

- Fault Sensors → Output Out of Range
- System Wear/Degradation
  - Usage/Time Clock
  - Scheduled Inspections
- System-to-Ground Support for Fault Diagnosis, Repair, and Maintenance
- Abort Mission
Health-Monitoring Systems

The Future

Environment → Environment Sensors

System Wear/Depreciation

Usage → Usage Sensors

Real-Time Computer Analysis of Data

Mission-Critical Fault

Reconfigure Controls or System

Abort Mission

Alert User

Store Fault Data

Alert Ground Support

Maintenance-Related Fault
Advanced Launch System Health Management Approach

Guidance, Navigation and Control Subsystem

- Guidance Control and Health Management
- TVC Commands
- Thrust Commands
- EMA Drive Elect
- Propulsion Control
- Smart Sensors
- Engine

Avionics Suite

- GN&C
- Comm
- Telemetry
- Range Safety
- Fuel Mgmt

Launch Control

Umbilical

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Systems and Research Center
HLV Baseline Avionics Configuration

Downlink Tlm
Uplink Cmd

Ground Inhibits
Ground Data
Vehicle Sensed Motion
Ground Power

Telemetry Tracking and Command
Environmental Control
Electrical Power

Mission Management
Vehicle Health Monitor (VHM)

Propulsion
Structures

GPS
Vehicle Sensed Motion
Celestial Reference

Side-Mount Stage Avionics

Acronyms
OMS Orbital Maneuvering System
RCS Reaction Control System
METVC Main Engine Thrust Vector Control
GPS Global Positioning System
SHM Subsystem Health Monitoring
CHM Component Health Monitoring

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VHM Integration Logic Flow

Subsystem Health Data
- Fault Anomalies
- Component Usage
- Remaining Life
- Built-In-Test
- Sensor Management
- Significant Events
- Diagnostics

Sensor Data Processing

VHM Subsystem

Local Decisionmaking
- Fault Containment
- Alternate Function Selection
- Situation Assessment
- System Reconfigure
- Recommendations

Control Processing

Vehicle Actuators

Subsystem Control
- Alternate Mode Selection
- Degraded Mode of Operation
- Component Lockup

Vehicle Mission Requirements

Status
Smart Structures Functionality Definition

Vehicle Goals
- Fault avoidance
- Reduced maintenance on schedule/demand
- Remaining life

System Goals
- Automated checkout
- Real-time monitoring
- Integrated Maintenance
- Fault prognosis/diagnosis
- Information management and control

Subsystem Goals
- Resource allocation
- Fault prediction, detection, isolation
- Redundancy management
- Local data management and control
- Significant event detection

Smart Sensor
- Fault detection and isolation
- Self-test
- Local data qualification
- Time-stamping of data
- Data reasonability tests

Honeywell
Systems and Research Center
# Time and Stress Measurement Device

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Function</th>
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<tbody>
<tr>
<td>Temperature</td>
<td>Data Processing and Time Keeping</td>
</tr>
<tr>
<td>Humidity</td>
<td></td>
</tr>
<tr>
<td>Shock</td>
<td>Large Data Memory</td>
</tr>
<tr>
<td>Vibration</td>
<td></td>
</tr>
</tbody>
</table>

---

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Time and Stress Measurement Device (TSMD)

A TSMD is a miniature electronic device or component which senses environmental stress parameters that can cause failures in electronic systems. These parameters are

- Vibration
- Shock
- Temperature
- DC voltage
- Voltage transients

TSMD processes the stress data and stores it in nonvolatile memory.

The TSMD is designed to accumulate stress data for months or years of use.

A real-time reference maintained by the TSMD can show the date and time of particular stress events.
Two-Horsepower
Electromechanical Actuator
# Motor Current Health Assessment Matrix

<table>
<thead>
<tr>
<th>Motor Analysis</th>
<th>Signature</th>
<th>Failure Mode Effects</th>
<th>Motor Current Signature</th>
<th>Frequency Domain</th>
<th>Type of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Failure Modes</td>
<td>1 Loose/Corroded Electrical Connector</td>
<td>Loss of power due to open/short circuit</td>
<td>Random transients</td>
<td>-</td>
<td>Degraded</td>
</tr>
<tr>
<td></td>
<td>2 Motor Winding Failure</td>
<td>Torque loss, power supply transient</td>
<td>Decreasing trend</td>
<td>Frequency shift</td>
<td>Catastrophic</td>
</tr>
<tr>
<td></td>
<td>3 Motor Gear Disengagement</td>
<td>Loss of motor actuation</td>
<td>Decreasing trend</td>
<td>Amplitude increase/decrease</td>
<td>Catastrophic</td>
</tr>
<tr>
<td></td>
<td>4 Motor Gear Tooth Breakage</td>
<td>Gear wear</td>
<td>Random transients</td>
<td>Amplitude frequency shift</td>
<td>Degraded</td>
</tr>
<tr>
<td></td>
<td>5 Lubrication Failure</td>
<td>Motor gear lockup</td>
<td>Start transient</td>
<td>-</td>
<td>Catastrophic</td>
</tr>
<tr>
<td></td>
<td>6 Gear Shaft Stiffness</td>
<td>Shaft wear</td>
<td>Start transient</td>
<td>-</td>
<td>Degraded</td>
</tr>
<tr>
<td></td>
<td>7 Motor Bearing Failure</td>
<td>Bearing race wear, ball bearing wear</td>
<td>-</td>
<td>Amplitude increase/decrease</td>
<td>Catastrophic</td>
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<tr>
<td></td>
<td>8 Gear Interface Slop</td>
<td>Gear wear</td>
<td>Start/stop transients</td>
<td>Frequency shift</td>
<td>Degraded</td>
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<tr>
<td></td>
<td>9 Motor Speed Slip</td>
<td>Intermittent operation</td>
<td>-</td>
<td>Frequency shift</td>
<td>Degraded</td>
</tr>
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<td>10 Linear Actuator Stiction</td>
<td>Actuator wear</td>
<td>Start/stop transients</td>
<td>-</td>
<td>Degraded</td>
</tr>
<tr>
<td></td>
<td>11 Actuator Obstructions</td>
<td>Burn-out motor mechanisms</td>
<td>Increasing trend</td>
<td>Frequency shift</td>
<td>Catastrophic</td>
</tr>
</tbody>
</table>
EMA Test 1: Loose Actuator Bearing Anomaly

Event A: Start Transient End-Stroke

Detailed View of Motor Current

LVDT Position (commanded)

Motor Current

LVDT Position (actual)
EMA Test 2: Tightened Actuator Bearing Characteristics

![Graph showing LVDT position and motor output over time.]

- LVDT Position (commanded)
- Motor Current
- Load Stiction Effects

Event A: End-Stroke Start Transient
EMA Bearing Wear Failure Prediction Example

SPIKES-NOTICED

Increase Trend in EMA Current

WAIT

Increase Trend in EMA Current

Decrease Trend in EMA Current

EMA-CURRENT-INCREASE
Action: Post a Caution

Increase Trend in Bearing Temperature No. 1 or No. 2

IMMINENT-BEARING-FAILURE
Action: Post a Warning

Decrease Trend in EMA Current

Spike Trend in EMA Current

Honeywell

Systems and Research Center
EMA Motor Winding Failure Priority 2

**Test Objective**—to detect a motor winding failure due to emulated failure of winding conductor or motor slot insulation

**EMA Failure Mode**—a failure of the EMA motor winding assembly; three possible failure scenarios:

- Normal to open circuit due to winding conductor failure (vibration, fatigue) or mechanical disconnect
- Normal to short circuit due to insulation breakdown, wear
- Short to open circuit due to excessive conductor heating

**FMEA Characterization Procedure**

1. Attach load to EMA actuator and command to move attached load at frequency of 0.5 Hz
2. Perform test sequence in table and record results

<table>
<thead>
<tr>
<th>Type of Failure Mode</th>
<th>Characterization</th>
<th>Circuit Designation</th>
<th>Measured Parameters</th>
<th>Expected Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Circuit</td>
<td>Short-to-station (local test)</td>
<td>1A to ground</td>
<td>Current_1A, Torque, Temp_IR</td>
<td>Significant torque loss (1/2 of submotor)</td>
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<tr>
<td></td>
<td>Winding-to-winding (local test)</td>
<td>1A to 1B</td>
<td>Current_1A, 1B, Torque, Temp_IR</td>
<td>Torque loss (2/3 of submotor), Torque drag effect</td>
</tr>
<tr>
<td></td>
<td>Submotor-to-submotor (global test)</td>
<td>1A to 2A</td>
<td>Current_1A, 2A, Torque, Temp_IR</td>
<td>Increased equivalent inductive load, Torque ripple effect, Ground current fault</td>
</tr>
<tr>
<td>Open Circuit</td>
<td>Winding node 1A</td>
<td>—</td>
<td>Current_1A, Torque</td>
<td>Torque loss (torque ripple effect)</td>
</tr>
</tbody>
</table>
Motor Winding Failure Schematic

PWR-82333 Smart Power Bridge

EMA Temperature Sensor

Hall Current Sensor

1A 2A 2B

Submotor 1 Submotor 2

Submotor 3 Submotor 4

SIMS Test Interface

Current_1A_Bufr
Current_1B_Bufr
Current_1C_Bufr
Current_2A_Bufr
Temp IR
EMA Torque

EMA Torque Sensor

Hall Current Sensor
Signal and Data Acquisition Systems

Objective:
Smart Sensor Networks for Vehicle Health Monitoring

Features:
Detect and Isolate Potential Fault Anomalies via Built In Test (BIT)
Evaluate Subsystem Health Status/Recommend Corrective Action

Applications
Structural Monitoring of Aging Aircraft
Launch Vehicle Integrity Assessment
Helicopter Mechanical System Monitoring
Space Platform Damping and Pointing
Nuclear Reactor Monitoring
Smart Structure Concept

Skin-Deep, Smart Sensors May Blanket Future Aircraft to Detect and Isolate Internal Structural Damage Characteristics

Piezo AE Sensing Array Elements

TSMD Hybrid

Fiber-Optic Transceiver Module
Smart Sensors

Lessons Learned

- Reduces wire weight significantly
- Supports multisensor commonality and modularity
- Supports significant local information processing, communication, and integration
- Permits low-power implementations
- Permits BIT at low system levels
- Allows I/O interface standardization
- Permits multiple applications to be met by one package (e.g., through reranging)
- Supports fault tolerance through redundant transducer packaging

Technology Readiness Level

- TRL 9
- TRL 8
- TRL 7
- TRL 6
- TRL 5
- TRL 4
- TRL 3
- TRL 2
- TRL 1

Needs

- Selection of applications
- Selection of packaging approach
- Development of high-temperature components
- Selection of standards

Honeywell
Lessons Learned

- Health monitoring algorithms do not require dedicated health monitoring sensors
- Predictive diagnostic algorithms can be developed for specific cases for systems that have a design heritage
- Maintenance systems pay for themselves through productivity improvements
- Data filter state monitoring and trend monitoring algorithms are computationally efficient
- Development requires close cooperation among domain experts, users, and maintenance system designers

Technology Readiness Level

- TRL 9
- TRL 8
- TRL 7
- TRL 6
- TRL 5
- TRL 4
- TRL 3
- TRL 2
- TRL 1

Needs

- Language selection
- Verification and validation methodology development
- System-level demonstration
  - Diagnosis through maintenance aiding
  - Incorporation of technology building blocks
Intelligent Built-In Test for Electric Actuators

Irving Hansen
NASA Lewis Research Center
Cleveland, Ohio
DISTRIBUTED POWER/CENTRALIZED CONTROL

SOURCE

CONTROL

TRADE - CONTROL WIRE FOR POWER WIRE
ATTEMPT TO MONITOR FROM CENTRAL MEASUREMENTS
UTILITY - STATE ESTIMATION Routines

LESSON: SPACE STATION EXPERIENCE

2^{200} COMBINATIONS - 1.5 MILLION LINES OF CODE WHEN ABANDONED

LESSON: THREE MILE ISLAND - SENSED THAT COMMAND WAS SENT NOT THAT VALVE HAD MOVED
BROWNS FERRY - PUT POWER WIRE AND CONTROL WIRE IN SAME CONDUIT

LESSON: "DON'T LET SOFTWARE PEOPLE DESIGN YOUR POWER SYSTEM"
BUILT IN TEST

NON INTRUSIVE - ("FIRST DO NO HARM")
SYSTEM STATUS, REDUNDANCY STATUS, PROBABLE HEALTH
CALIBRATION AND VERIFICATION OF BIT AT EVERY CHECKOUT CONTINUOUSLY
FROM DESIGN TO DEPLOYMENT
   (e.g. TESTBED, ACCEPTANCE, QUALITY TEST, PREFLIGHT)

RAPID RESPONSE, HIGH PROBABILITY OF CORRECT DECISION
SYSTEM ELEMENTS MODELED AS TWO PORT, FOUR TERMINAL NETWORKS

INPUT PARAMETER
OUTPARAMETER
FORWARD GAIN
REVERSE GAIN

{ SMALL SIGNAL MODELS }
(TOP DOWN) - SYSTEM REQUIREMENTS

VEHICLE HEALTH MANAGEMENT

GENERAL:

• FAILURE TOLERANCE (ROBUSTNESS e.g., FAIL OP, FAIL OP, FAIL SAFE)
  (QUAD REDUNDANCY A SOLUTION NOT A REQUIREMENT)

• DETECTION - BUILT IN TEST
• CONTAINMENT - DESIGN AND PROTECTION
• ACCOMMODATION - REDUNDANCY MANAGEMENT
FUZZY LOGIC

THE LOGIC OF HANDLING FUZZY INFORMATION
ADJECTIVES - MORE, LESS, FASTER, SLOWER (FUZZY QUANTIZATION)
CRISP SETS - 0,1 PRECISE QUANTIZATION
APPLICATION TO BUILT IN TEST OF TWO PORT NETWORKS
INPUT - ERROR SIGNAL (OR COMMAND)
OUTPUT - CURRENT OR VOLTAGE
FORWARD GAIN - RATIO OF OUTPUT TO INPUT

} CRISP DATA

e.g. FUZZY LOGIC AND EXPERT SYSTEM APPLICATIONS - B. K. BOSE, UNIVERSITY OF TENNESSEE, KNOXVILLE

"IF SPEED LOOP IS NEAR ZERO, AND ERROR RATE OF CHANGE IS SLIGHTLY POSITIVE, THEN CONTROL SHOULD BE A SMALL NEGATIVE"

RESULT - CONTINUOUS NON INTRUSIVE MONITOR OF SERVO GAIN
## FUZZY LOGIC RULE TABLE

### MOTOR CURRENT

<table>
<thead>
<tr>
<th>POSITION ERROR</th>
<th>VERY SMALL</th>
<th>SMALL</th>
<th>NORMAL</th>
<th>LARGE</th>
<th>VERY LARGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERY SMALL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMALL</td>
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<tr>
<td>NORMAL</td>
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<tr>
<td>LARGE</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>VERY LARGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **FAILURE**
- **OUT OF TOLERANCE**
- **OK**
EMA SPECIFIC REQUIREMENTS

(BOTTOM UP) - DESIGN ARCHITECTURE FOR:

COMPONENT LEVEL - DIAGNOSTICS (NEURAL NETWORK, NOT IN REAL TIME)  
(EVENTUAL INCIPIENT FAILURE DETECTION)

SUBSYSTEM LEVEL - RAPID DETECTION (NOT INTRUSIVE MEASUREMENT, WIDE  
DYNAMIC RANGE, FOUR QUADRANT OPERATION)

APPROACH TAKEN - FUZZY LOGIC OBSERVED (CONTINUOUS MONITOR OF INPUT  
(COMMAND) AND OUTPUT (CURRENTS & POSITION)

EVALUATION & CALIBRATION - HYBRID ANALOG COMPUTER AT PURDUE UNIVERSITY  
(ALLOWS MAJOR FAULTS TO BE INTRODUCED WITHOUT  
ENDANERING PERSONNEL OR EQUIPMENT)
Rapid, VHM System For Electrical Actuation/Power/Avionics

**Task Objectives/Benefits**

**Objective(s):**
Develop and demonstrate automated, rapid self-check systems for advanced electrical actuators and effectors, power and avionic systems including more-electric ground support equipment (GSE)

**Applicable Vehicles:**
ELV, NLS, Upper Stages, STS Upgrades, AMLS, ACRV

**Benefits:**
- Transfer rapid prototyping steps to improve vehicle assembly, ground operations and launch sequencing
- Demonstrate "bottoms-up" HW/SW platform for interface to total IHM system
- Reduce launch system costs
- Improve launch system operability, reliability and safety

**Technology Description**

**NASA Technology Readiness Level:** 5

**Specifications:**
- Distributed intelligence/controls/monitoring in electrical equipment both on vehicle and in GSE
- Rapid, smart Built-in-Test (BIT) using embedded microprocessors (DSP) with fuzzy logic for self-check and correction
- Minimize requirements for sensors, data transfer/storage and centralized computing
- Real-time pre-, post-, and in-flight health assessment and analysis
- Accurate and reduced-order models/simulations for rapid prototyping, testing and fault studies
- Use LeRC developed Framemaker for graphic visualization

**Demonstration/Bridging Approach**

**Task(s):**
1. Develop specific elements to existing (SBIR II) detailed models/simulations of vehicle and GSE systems under normal and fault conditions
   a. Insert fault, document parameter variations
   b. Validate model predictions, characteristics on subsystem hardware
2. Integrate HW/SW for rapid BIT on existing DSPs to demonstrate health indicators on selected electrical equipment (EMAs and power system)
3. Test/demonstrate BIT under fault conditions and selected fault modes to validate technology/models
4. Develop interfaces to top level IHM system and automate responses to detected fault modes
5. Validation assessment of technology

**Available Facilities:**
LeRC Technology Demonstration Facility, Autonomous Power System, EMA Laboratory, and University of Purdue Hybrid Computer Facility

**Schedule/Cost**

<table>
<thead>
<tr>
<th>TASK</th>
<th>FY 93</th>
<th>FY 94</th>
<th>FY 95</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1a</td>
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<td></td>
<td></td>
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<tr>
<td>1b</td>
<td></td>
<td></td>
<td></td>
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<td>2</td>
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<td>4</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**RESOURCES**
- FY 93: 0.15 M
- FY 94: 0.3 M
- FY 95: 0.3 M

LeRC Contact: Gale R. Sundberg, (216) 433-6152
FAULT TOLERANT SYSTEM TESTING

Norm Osborne and Dave Wilks
Fault-Tolerant System Test Bed

- Objective of Test Bed
  - Fault Detection Functional Tests
  - Health Monitoring Function Tests
  - System Performance Testing
  - System Optimization Demonstration
  - System Development
  - Subsystem Development
Fault-Tolerant System Test Bed
Relationship with IR&D/CR&D--Real-Time Lab

D-47D FT&HM
Titan IV FT DEV.

Fault Tol.
Computer

D-80S ELV
LaRC CR&D
D-18D AGN&C

Expert Designer

- SUN 4
- KMS
- CASE
- Matlab
- EZ-Post

6- DOF
Table

- FT Bus
- POP
- FTPP

- IMU

D-28D ADV ACT
CR&D 93

Actuator
Test Bed

- TIV Adv Act
- NLS
- Development

Real-Time
Dynamics

- Concurrent
- POST Simulation
- SUN4 Interface

ARCS
Network

3-Axis
Table

- Rate Gyro
Fault-Tolerant System Test Bed
EMA/ARCS TOPOLOGY

ARCS RACK
- 68020 Microprocessor
- FOC Algorithms
- Velocity Loop Closure
- DC/AC Transform
Fault-Tolerant System Test Bed
Redundancy with Induction Motors

- All Software Approach Allows Fault Tolerant Embedded Computer Applications—such as Pair-of-Pairs or FTPP
- Motor Drive Can Be Either Pulse Placement or Pulse Width Modulation
- INDUCTION Motor Output Drives a Simple Gear Train

Diagram:
- Pair-of-Pairs
- Pair-of-Pairs
- PPM
- PPM
- IND
- Simple Gear

MARTIN MARIETTA
Fault-Tolerant System Test Bed
Actuator Test Bed Layout
1993 FTA/HM Lab Demonstration Overview

Diagram:
- 3 Axes Table
- IMU
- Flight Ctrl Computer
- FPPP
- PAGE
- LOSC
- Engine Controller
- Work Station
- SIMS
- LCU
- Actuator
Fault-Tolerant System Test Bed

Summary

• Flexible Test Bed
  - Systems
  - Component
  - Functional
  - Performance

• Multiple User
  - Internal Research and Development
  - Airforce
  - NASA (multiple center)
FMEA'S AND FAILURES IN TEST
During the time frame from November 1991 to the time of this workshop, 20 failures were recorded during testing of EMA's. Failures documented include those during the development and test of Marshall's in-house actuator and hardware brought in for test and demo. Failures were divided into two categories. The first category includes problems identified as areas which still require investigation. These are listed under Credible Failures/Problems.

Problems associated with EMI and grounding were seen with each piece of hardware brought into the lab. High power electronic problems accounted for the largest number of failures. This may be due to the fact that some development failures were documented for this presentation. It was soon discovered in the lab, with the rotational forces associated with these actuators, that more attention must be paid to the structural interfacing, at least for test purposes. The other category contains failures which include problems considered not to be applicable to a flight type actuator. These are the Noncredible Failures. For example, the motor failures which were documented occurred due to using off-the-shelf and not necessarily optimized hardware. This is not to say that a shorted motor would not be a credible failure, but failures of that nature have not been seen in test.
FAILURES IN TEST

20 Failures were recorded at Marshall during EMA testing activities. These include failures during development and test of Marshall’s actuator and failures in hardware brought in for test and demo.

Credible Failures/Problems
- EMI/Grounding
- High Power Electronics
- Testing/Vehicle Structural Interfacing

NON CREDIBLE FAILURES
- Motor
- Low power circuitry
- Power
An attempt was made to determine a plausible fault tree for the EMA. Due to the different design philosophies, including EHA's, a single fault tree would probably exclude some of the failure modes of those designs I am less familiar with. What has been prepared are two levels of a fault tree with the first level being generic to all designs. Each actuation system may be broken down into sub-components: a power source, the control electronics, motor, actuation mechanism, sensors, and interfaces. While each actuator may have a different design philosophy, each utilizes some from of each of the sub-components listed. The next level is more particular to the design philosophy. This level includes a breakdown of each actuation sub-component into the elements which could cause a failure. The next step would be to identify each fault particular to an element. With each fault, a signature of the failure and a means of detecting it is important.
# ELECTRICAL ACTUATION SYSTEM

## FAULT TREE

<table>
<thead>
<tr>
<th>Component</th>
<th>Faults/Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POWER</strong></td>
<td>• High Power</td>
</tr>
<tr>
<td></td>
<td>• Short</td>
</tr>
<tr>
<td></td>
<td>• Open</td>
</tr>
<tr>
<td></td>
<td>• Explosion</td>
</tr>
<tr>
<td></td>
<td>• Avionics Power</td>
</tr>
<tr>
<td><strong>CONTROL ELECTRONICS</strong></td>
<td>• Low Power</td>
</tr>
<tr>
<td></td>
<td>• Sensors</td>
</tr>
<tr>
<td></td>
<td>• High Power</td>
</tr>
<tr>
<td></td>
<td>• PWM</td>
</tr>
<tr>
<td></td>
<td>• Current Bridge</td>
</tr>
<tr>
<td></td>
<td>• Regeneration</td>
</tr>
<tr>
<td></td>
<td>• Supporting Electronics</td>
</tr>
<tr>
<td><strong>MOTOR</strong></td>
<td>• Windings</td>
</tr>
<tr>
<td></td>
<td>• Drive Shaft</td>
</tr>
<tr>
<td></td>
<td>• Commutation Sensors</td>
</tr>
<tr>
<td></td>
<td>• Magnets</td>
</tr>
<tr>
<td><strong>ACTUATOR</strong></td>
<td>• Gear Train</td>
</tr>
<tr>
<td></td>
<td>• Roller/Ball Screw</td>
</tr>
<tr>
<td><strong>INTERFACES</strong></td>
<td>• Cabling</td>
</tr>
<tr>
<td></td>
<td>• Connectors</td>
</tr>
<tr>
<td></td>
<td>• Structural Attach Points</td>
</tr>
<tr>
<td><strong>SENSORS</strong></td>
<td>• Current</td>
</tr>
<tr>
<td></td>
<td>• Rate</td>
</tr>
<tr>
<td></td>
<td>• Position</td>
</tr>
<tr>
<td></td>
<td>• Force</td>
</tr>
</tbody>
</table>
Task: Develop and implement a Vehicle Health Management (VHM) platform for Electromechanical TVC actuation systems using actual hardware and vehicle simulations in the loop.
MSFC is proposing to upgrade existing facilities in order to implement a platform for the testing and development of Vehicle Health Management (VHM) for electromechanical actuators. The proposed platform will incorporate hardware, including power sources and vehicle as well as hardware simulation. The first step will be to determine the requirements and tools to implement a VHM hierarchy, working with a bottoms up philosophy. From there, each level of technology will be demonstrated until a full actuation system VHM level is attained. This platform will be used by MSFC to investigate VHM algorithms, redundancy, etc. It is our hope that NASA and Industry will take advantage of these facilities for further development of EMA's.
HARDWARE DEMONSTRATION OF VHM SYSTEM

- Establish Requirements, Sensor Suites, and Algorithms for VHM hierarchy
  - BIT
  - Component Level
  - System Level

- Implement VHM Platform with hardware in the loop
  - Component Level Health Management
  - Vehicle Simulation
  - System Level VHM

- Demonstrations
  - TVC EMA System
    (MSFC, Moog, Honeywell, Allied Signal, Boeing, GD)
  - Apply similar techniques to EMA Valve Actuation System
MSFC EMA/TVC PLATFORM FOR VEHICLE HEALTH MANAGEMENT DEMONSTRATIONS

VEHICLE HEALTH MANAGEMENT SYSTEM

EMA HARDWARE IN THE LOOP

VEHICLE AXCENT TRAJECTORY SIMULATION

SIMULATED ENGINE TVC SYSTEMS
FACILITIES, HARDWARE AND SUPPORT

- Component Development Laboratory (Bldg. 4656)
  Two inertia load simulators, soon to be equipped with programmable force generators.

- Prototype EMA hardware

- In-house support may be obtained from EB and ED laboratories

- Contractor support will be required for software development.

- Contractors will be invited to use test platform.
Summary/Status

- Detailed Design Of The EMA Assembly Complete
- Digital Closed Loop Control Approach Demonstrated
- Performance Characteristics For Major Components Demonstrated
- Fabrication Of Electronics In Progress
- Fabrication/Assembly Of EMA Scheduled For Completion In FY 1993
Tests Confirmed Operating Characteristics Of The EMA Components

**Motor Driver Circuit Board**

- Test Of Basic Drive Circuit Functionality
  - Output Commutation
  - PWM Frequency Characterization
  - Speed vs. Input Voltage Linearity
  - Forward /Reverse Operation

- Test Of Health Monitoring Circuitry
  - Drive Current Sensing
  - Board Temperature Sensing/Conditioning
  - Motor Temperature Sensing/Conditioning

**Microcontroller Circuit Board**

- Evaluation Of 87C196KC As The Controller For EMA System
  - Closed Loop Control
  - Sensor Interfacing

- Test Of RTD Converter Circuit With 87C196KC Microcontroller
Tests Confirmed Operating Characteristics Of The EMA Components

**Gear Reducer**
- Acceptance Tests For Efficiency, Backlash, Torque, Torsional Stiffness, And Input Speed
- Cryogenic Tests Of The Gear Reducer To Verify Thermal Resistance
- Efficiency Tests At Low Temperature

**Motor Assembly**
- Speed-Torque Characterization Tests
- Test Of Drag Torque Resulting From Failed Motor
EMA Temperature Profile Has Been Characterized By Test
Performance Tests Demonstrated
Stable Operation Over Load Range

100 lb.-in.

Position

173°/sec.

Velocity

565 lb.-in.

143°/sec.

340 lb.-in.

90°

0.2 sec.

154°/sec.
EMA System Was Tested To Verify Proof Of Concept

- Step Response
- Position Accuracy

- Slew Rate

- Holding Torque
- Duty Cycle

- Frequency Response (Gain)

- Frequency Response (Phase)
Microcontroller PCB Design Is Based Upon The 87C196KC Microcontroller
Dual Redundant Electronics Provide Reliable Control System Design

Microcontroller PCB

- Functions As RTU For MIL-STD-1553B Serial Data Link
- Performs Basic Control And Health Monitoring Functions Using Embedded Firmware
- Performs Resolver To Digital Conversion For Position Feedback
- Highly Integrated Design

Motor Driver PCB

- Performs Motor Commutation And Power Switching
- Serves As Power Source (DC-DC Conversion, Filtering And Distribution) For On-Board Components
- Provides Signal Conditioning For Sensor Signals
Basic Commutation Function Is Performed By Motor Controller IC
Motor Selection Provides Ample Margin

Propulsion Division

Motor Speed (RPM)

Operating Region (Available Torque)

24 VDC 28 VDC 32 VDC

With Shorted Winding & Safety Factor

GGV MPV

Output Torque (in-lb)
Motor Assembly Design
Focuses On Reliability

FEATURES

- Redundant High Torque Brushless DC Motors
- Common Motor Drive Shaft (Eliminates Clutch Mechanisms)
- Duplex Bearings For High Vibration Environment
- Mounting Cavities For Integral Dual Channel Electronics
Gear Reduction Is Accomplished Using Harmonic Drive Design

**FEATURES**

- Single Stage Reduction
- High Torque Capacity
- High Torsional Stiffness
- Zero Backlash
- Compact Design
EMA Provides Redundant Closed Loop Digital Control
The EMA Assembly Consists Of 4 Major Components
Combined EMA Features Provide A Unique Technology

**Technology**
- Modular, Self Contained Actuator
  - Electromechanical Design Eliminates Problems Associated With Hydraulics And Pneumatics
  - Complete Electrical/ Electromechanical Redundancy For Increased Reliability
  - Integrated Electronic/ Mechanical Package Which Can Be Mounted Directly To Cryogenic Valves
  - Application Of Digital Technology For Local Closed Loop Control, Communication And Health Monitoring

**Replaces**
- Hydraulic And Pneumatic Actuator Technology

**Application**
- Modular Design And Simplified Interface Allows Adaptation To Any On/Off Or Modulating Valve Application
Objective

- Demonstrate A Reliable, Low Cost Propellant Effector System Using An Electromechanical Actuator

Approach

- Phase I - Preliminary Design
  - Requirements Definition
  - Preliminary Design of Valve And EMA
  - Testing Of Low Cost Technologies
  - Trade Studies

- Phase II - Detailed Design
  - Detailed Design Of EMA
  - Detailed Analyses; Reliability, Thermal, Structural, Vibration
  - Dynamic Model EMA
  - Fabricate Three Full Size EMA Assemblies
  - Test Valves At MSFC
Space Transportation Main Engine Electromechanical Actuator Design

29 September 1992
SESSION XI

SPLINTER SESSIONS
SESSION I: ELA SYSTEMS

1. Assess ELA technology readiness as demonstrated by the performance capabilities of the Workshop prototype hardware. Has feasibility been definitively established?

2. Identify Critical Path elements on completing ELA Technology Bridging development by FY-95, considering:
   - ELA systems demonstrations (actuator/controller/power source)
   - SSME Technology Test Bed (TTB) hot fire demonstration
   - a mechanism for NASA & Industry to down-select candidate ELA systems for TTB

3. Discuss the utility of a NASA ELA System Design Handbook as an output from ELA Technology Bridging.

4. Outline an ELA advocacy strategy for transformation of ELA-TB development into flight systems for:
   - early HLLV by FY-96, including industry supported cost/schedule/procurement plans.
   - SRM/ASRM retro-fits
   - Centaur retro-fit

5. Assess the vitality of Industry supported ELA prototype developments; will NASA support be necessary?

6. Assess the pros & cons of ELA technology fly-offs under ELA-TB, including
   - EMA vs EHA
   - ELA and PSS systems compatibility
   - Roller vs Ball screw transmissions

7. Recommend the format for the next ELA TIM/Workshop/Conference: WHAT, WHEN & WHERE.
SESSION I. ELA SYSTEMS

October 1, 1992

Question 1. Yes, ELA has demonstrated technology readiness and has established feasibility. **Note**: The whole group agreed with this.

Question 2. The critical element of the ELA Bridging program is the hot fire test. This is not the only thing but it is essential if we are to sell this technology to a program manager.

Question 4. NASA has to focus in on a target and provide system requirements. This is a must for evaluating various systems fairly.

Question 5. Industry cannot continue to support this kind of effort very long without a program to aim toward. Money is tight.

Question 6. Have to do system studies to drive out system requirements.

Question 7. TIM - Yes, where or when?
SESSION II: ELA CONTROL ELECTRONICS

1. Assess ELA technology readiness as demonstrated by the performance capabilities of the Workshop prototype hardware. Has feasibility been definitively established?

2. Identify Critical Path elements on completing ELA Technology Bridging development by FY-95, considering:
   - ELA systems demonstrations (actuator/controller/power source)
   - SSME Technology Test Bed (TTB) hot fire demonstration
   - a mechanism for NASA & Industry to down-select candidate ELA systems for TTB
   - special emphasis on EMI

3. Discuss the utility of a NASA ELA System Design Handbook as an output from ELA Technology Bridging.

4. Assess the vitality of Industry supported ELA prototype developments; will NASA support be necessary?

5. Assess the pros & cons of ELA technology fly-offs under ELA-TB, including
   - Permanent Magnet vs Induction Motors
   - PWM vs PDM
   - Analog vs digital vs hybrid electronics
   - IGBTs vs MCTs

6. Recommend the format for the next ELA TIM/Workshop/Conference: WHAT, WHEN & WHERE.
SESSION II: ELA CONTROL ELECTRONICS

October 1, 1992

Question 1. Feasibility has been established, but full power level has not been demonstrated. Before full power can be demonstrated the following issues must be resolved:
   a. EMI must be addressed
   b. Packaging of power devices (Air Force is currently working on packaging)
   c. Motor optimization
   d. Flight current sensors
   e. Single event upset
   f. Start transients
   g. Batteries.

Question 2. FY 95 is feasible if funding and above questions are answered.
   - Must identify (EMI, performance, etc.) requirements and specifications.
   - In order to meet FY 95, there must be cost sharing between government and industry.
   - On TTB hot fire demonstrations, a common TTB requirement for all vendors is needed.
     a. Is TTB our most effective/realistic test?
     b. Does it simulate flight profiles?
     c. Could performance requirements be full demonstrated at vendor facilities?
   - Each company should be allowed access to TTB/test fixture.
   - Government splinter session recommendation is demonstration at a common test facility.

Question 3. NASA ELA System Design Handbook is not recommended. A system requirements and specification document is preferred.

Question 4. Program Office should show time and hardware commitments for ELA hardware. Recommend cost sharing and Cooperative Research Agreements.

Question 5. Fly-offs should not be required. Requirements should be to meet performance requirements at full power. System design should not be a factor, rather system requirements.

Question 6. Next ELA meeting should be a full power demonstration (approximately 1 year from now with location yet to be selected).
SESSION III: ELA POWER SOURCE SYSTEMS

1. Identify the critical PSS parameters/requirements which need to be provided by ELA designers in order to "optimize" the combined ELA/PSS systems.

2. Outline the means by which NASA's ELA Technology Bridging can elicit these requirements.

3. Identify any specific ELA (performance) requirements that would distinguish ELA PSS developments from other, related PSS developments, such as DOE and automobile manufacturers.

4. Discuss the utility & implementation of an ELA-TB consignment unit for PSS prototype development:
   - a programmable IGBT-based power load with power-demand profiles
   - a "portable" ELA test unit (Motor/controller/geared loads, etc)
   - power profiles to simulate worst case flight trajectories & launch pad checkouts (steps, slews, FRFs, etc)

4. Discuss the utility & implementation of an ELA-TB Power Source Simulator for PSS prototype development:
   - generation of analytical models for a programmable Power Source Simulator
   - protection of proprietary data in supplying such data (e.g., a floppy disc data transfer with execute-only

5. Sketch a Timeline of related Power Source technology development with respect to:
   - ELA - Technology Bridging with a completion date in FY-95.
   - early HLLV ELA systems to support a CY-96/97 launch

6. Recommend the format for the next ELA TIM/Workshop/Conference: WHAT, WHEN & WHERE.
Questions 1 & 2:
The PSS parameters/requirements needed by both NASA's ELA Technology Bridging Team and PSS vendors for definition and design are as follows:

- Power profiles which include: base power, voltage limits, peak power, total energy, rise times, regulation requirements, and frequency/spacing of current pulses.

- Start transient loads.

- Ascent profiles/worst case scenarios from Flight Dynamics area.

- Corona and EMI Specs and allowances.

- Redundancy and reliability numbers.

- Failure modes.

- Environmental requirements, acoustics, vibration, thermal, etc.

- Processing, handling, shelf life, pad access, and activation.

- Regeneration tolerance.

- Propellant availability.

- Pre-launch check-out, start-up times, GSE availability and use.

- Load impedances.

- Data and documentation expected from vendors.

Question 3:
ELA PSS requirements that are specifically ELA demands include: launch/flight environments, high current spikes, high voltage, and rise times.
Question 4:
The implementation of an ELA-TB consignment unit for PSS development was decided to be non-advantageous to NASA ELA-TB.

Question 5:
The development of a power source simulator is a good idea. This type project is currently underway with JSC's ELAPSS project.

Question 6:
A credible timeline can not be generated until more Power Source requirements are defined.

Question 7:
The Feb/Mar time frame was decided upon for the next ELA-TB TIM. Requirement updates and technology advancements should be the main topics for the Power Source Systems session.
SESSION IV: ELA OPERATIONS

1. Outline the means by which ELA operational requirements may be identified under ELA-Technology Bridging and ultimately translated into CEI specifications.

2. Discuss the means to effective utilize an ELA Operations Test Bed at KSC, including
   - use of NASA and Industry consignment units
   - pros & cons of focusing on a specific mission/application (SRM/ASRM aft skirt)

3. Assess the requirements, pros & cons of an ELA-TB sponsored development of a GSE-CART unit (BIT, power source simulator, ground handling & installation, etc)

4. Assess the NASA need, and the commercial/industry technology readiness, to support SSC/KSC/MSFC/JSC cryogenic flow control operations.

5. Recommend the format for the next ELA TIM/Workshop/Conference: WHAT, WHEN & WHERE.
SESSION IV. ELA OPERATIONS

October 1, 1992

OBJECTIVES - CONCURRENT ENGINEERING

* Need a representative hardware platform to drive out real operational requirements and prioritize.

* Need operation environment for:
  - Feedback to designers (and researchers)
  - Safety design feedback
  - Realistic timelines
  - Validate/recommend changes to prototype OMRSD/LCC.

* Near term/mid-term/long-term approach to concurrent engineering.

IMPLEMENTATION

Two pronged approach:

1. Form process improvement and design improvement teams.

2. Consider utilizing SRB AFT skirt as platform to meet the objectives.
## Organization

### Solid Rocket Booster TVC Group

<table>
<thead>
<tr>
<th>TEAM</th>
<th>CHARTER</th>
<th>TEAM COMPOSITION</th>
</tr>
</thead>
</table>
| Processing Improvement Team   | To take action to reduce *remanufacturing and processing task durations, man-hrs and IPR/PR count* of the Solid Rocket Booster's thrust vector control system by 25% in 24 months. Also, recommends any needed OMRS changes, vehicle design changes (large, medium and small), and retrofit approaches as *coordinated with the Design Improvement Team*. | NASA MSFC/EE11  
NASA Flt Ctls/TV-GDS-22  
NASA APU-Hyd/TV-FSD-21  
USBI-DAE/TO-1  
LSOC Flt Ctls/LSO-215  
LSOC APU-Hyd/LSO-356  

*Design Sponsors:*
1. MSFC Propulsion Lab  
2. USBI/MSFC |
| Design Improvement Team       | To take actions needed to *modify the SRB TVC system* such that a 25% reduction within 48 months (and another 25% within 96 months) occurs in the following areas:  
1. Aft Skirt TVC Build-up & ACO  
2. Veh Processing Task Durations  
3. Man-hrs  
4. FMEA/CIL count  
5. LRU/GRU count  
6. Logistics *recurring costs*  
7. GSE count  
The Design Team will *coordinate and reach agreement with the Processing Team* on all design modification and retrofit strategies. The Design Team will also aid the Processing Team on recommendations for OMRSD improvements. | NASA MSFC/EP64  
NASA MSFC/EL  
NASA MSFC/EB  
RIC-DNY/APU-Hyd  

*Processing Sponsors:*
1. NASA Flt Ctls/TV-GDS-22  
2. NASA APU-Hyd/TV-FSD-21  
3. USBI-LSS |
SESSION V: ELA REDUNDANCY & HEALTH MANAGEMENT

1. Assess the state-of-the-art and technology readiness level of Health management systems in supporting ELA-TB development by FY-95, including - Built-in-Test
   - Redundancy Management
   - Vehicle Health & TVC subsystem Health Management

2. Assess the redundancy management levels/capabilities/limitations of ELA prototype systems as demonstrated at the Workshop, including:   - three channel EHA actuator (Boeing/Allied Signal)
   - eight channel Permanent Magnet EMA (Honeywell)
   - three channel Permanent Magnet EMA (Allied Signal)

3. Discuss the means to effective utilize an ELA/TVC Health Management Test Bed at MSFC/JSC, including
   - use of NASA and Industry ELA prototype systems (actuators & power source)
   - protection of vendor proprietary data/software in a NASA test bed

4. Assess the vitality of Industry/IRAD health Management development w.r.t ELA/TVC systems; will NASA support be mandatory?

5. Recommend the format for the next ELA TIM/Workshop/Conference: WHAT, WHEN & WHERE.
OBJECTIVES:

• Identify technology requirements associated with ELA redundancy management (RM) and health management (HM) and those areas that represent a potential high return on investment for Bridging Program funds.

  Technology shortfalls
  Technology demonstrations
  Tools and other support requirements

  What cost : benefit metrics can we identify?

• Define the interfaces between ELA RM & HM and overall Integrated Vehicle Health Management (IVHM).

• Identify proper relationship(s) between the following technologies/disciplines:

  Design for Testability
  BIT/BITE
  Boundary Scan
  Smart Sensor technology insertion options
  Sensor reduction/elimination (i.e. commutation support sensors)

• Discuss recommended NASA approach to fault tolerance and RM for actuators.

  i.e. should a single EMA be used in a flight critical application?

  What guidelines should drive selection of actuation technology, i.e. EMA vs. EHA, PM DC vs. induction, etc.?

• Identify white paper products that would be valuable:
EMA vs. EHA selection considerations and criteria
Motor selection
Failure recovery approaches (i.e. lock-up vs. return to null)

PARTICIPANTS

MDSSC - Delta Launch Vehicle EMA
Univ. of Alabama - characterize roller screws and ball screws
R A Weir MSFC CDL
Aerojet
LeRC
LaRC - GN&C avionics I/F
Allied Bendix
Moog Boeing NLS TVC
Jack B NLS
Bill St. Cyr SSC
Fred H.

Good x-section of disciplines and interests.

APPROACH

Answer J Sharkey questions.
Identify significant omissions.

*ELA requirements id and collection mechanism required.* Support immediate term, through demos, to long term. MSFC ELA requirements QFD (joint team in place). Focus is on NLS. Target completion by February 1993.

************************************************************************
************************************************************************

Subsystem level maturity is good - global strategies and tools are still lacking. Integration of technologies is not mature; the technology elements are.

White papers. Concentrate on the way we do fault management. Concern on what audience would be. ELATB would collect, catalog and publish. Don will generate a list of potential targets.
Standalone versus "cooperative" VHM approaches.

NLS says need integrating glue to transition from health monitoring to IVHM. Elimination of unnecessary sensors; use data captured in normal control signals, etc. LeRC has started this effort (university supported study); would use excess controller processing power.

Realistic failure analysis/fault tree data required. - Follow up to Rae Ann's data.

FOUR TRACKS FOR IVHM DEVELOPMENT

ARCHITECTURE

FLIGHT SUPPORT SYSTEMS (GROUND/FLIGHT)

TOOLS

ELA TECHNOLOGY is ready now - Boeing. Architectural decisions will drive subsystem design philosophies. Work is required to tie operations and development together. NLS says smart sensors have option to do processing at lowest level but there must be reporting to a central level to support launch processing, flight control. Local analysis with avionics suite for coordination. This seems to be a uniform approach.

FDIR and data requirements are different for ELV Vs reusable.

How much reliability is needed? Tied to human rating issues.

Q2

Boeing/Allied EHA - advantages of hydraulic bypass are undeniable. Fail op/fail safe (return to null). No real RM demo has been offered yet. How far down must we take redundancy? Should rotor shafts and bearings be considered? What are credible failures? Up front involvement of R&QA needed.

For 8 channel, they have had several failures and the system continued to run. This is really used as a 4 channel device. The motor shaft is common to all.

Trade between redundancy content and HM.
Q3

MAST approach is to not allow proprietary content. To date, there have been no proprietary issues associated with ETA TB. Use of vendor/contractor facilities and capabilities as appropriate is desirable (in fact, mandatory). Networking of facilities would be valuable and cost effective to support specific end-to-end test objectives.

Would ELAPSS be a good asset for the CDL? There is not a problem in getting power for actuators (batteries, power supplies). The ELAPSS will never obviate final integrated system test requirement, however.

Facility here will continue to be a place we use to demo items. Proprietary issues should not be a problem. Do we need to address EMI/EMC issues? Can ELAs and avionics devices share the same power sources? Group seems to feel no.

Q4

Budgets are universally slim and getting slimmer. This includes IRAD funding as well. Question exists as to where resources will come from to "customize" ELA development to date to conform to desired architectures and IVHM requirements. NLS seems to be the only "carrot" out there. Maybe we should let aircraft people take (or maintain) the lead for ELA development.

TTB I/F would be a good demo to "sell" ELA capabilities since we are essentially proposing a replacement of something that does work.

Q5

Papers and demo mix was good. Recommend continued emphasis on demos in future TIMs and other forums.

Avoid having meeting span fiscal year transition!
SESSION XII

ELA Prototype Design and Test Results
INTRODUCTION

- Objectives of Moog's 38 HP EMA IR&D PROGRAM
- Design Criteria
- Hardware Description
- Test Results

MOOG
Missile Systems Division
OBJECTIVES

- Demonstrate EMA Performance for 30-50 HP TVC Application
- Design, Build, and Test Single String EMA Hardware
- Compare to Known Hydraulic System Performance
- Baseline SSME TVC Requirements
- Design Actuator To Accommodate
  - Ballscrew
  - Rollerscrew

MOOG
Missile Systems Division
Initiated Moog Funded IR&D Activity 1990

- Demonstrate Single String EMA
- No Effort to Optimize Weight
- Include Dual Motor Capability
- Utilize "Bolt-On" Motors to Permit Motor Comparison
- Designed to Handle Start-up Transient Loads Structurally
- Controller not Flight Packaged

Future Considerations

- Redundancy
- Impact Loads
- Motor Selection
- Power Source
- Flight Weight Controller and Actuator

MOOG
Missile Systems Division
**DESIGN CRITERIA**

(Based on SSME TVC Requirements)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>270 VDC</td>
</tr>
<tr>
<td>Output Travel</td>
<td>± 5.5 in.</td>
</tr>
<tr>
<td>Rated Power</td>
<td>38 HP</td>
</tr>
<tr>
<td>- Output Force</td>
<td>48,000 lb.</td>
</tr>
<tr>
<td>- Output Velocity</td>
<td>5.2 in/sec.</td>
</tr>
<tr>
<td>Impulse Load Capacity</td>
<td>100,000 lb.</td>
</tr>
<tr>
<td>Frequency Response at ± 2% Command</td>
<td>&lt;80 deg. phase at 3 Hz</td>
</tr>
<tr>
<td>Acceleration</td>
<td>60 in/sec²</td>
</tr>
<tr>
<td>Pin to Pin Length at Mid stroke</td>
<td>47 in.</td>
</tr>
</tbody>
</table>
MOOG IR&D EMA TVC ACTUATION SYSTEM

Electrical Power

Position Command

Controller

Gearing

Motor

Ballscrew or Rollerscrew

LVDT Position Transducer

MOOG
Missile Systems Division
Electromechanical Actuator
Dual Torque - Summed Motors

OUTPUT TRAVEL ................................... ±5.5 IN
STALL FORCE ....................................... 48,000 LB
MAXIMUM IMPULSE LOAD ..................... 100,000 LB
ACCELERATION ................................. 60 IN/SEC^2

RATED POWER ..................................... 38 HP
- OUTPUT FORCE ................................. 48,000 LB
- OUTPUT VELOCITY ......................... 5.2 IN/SEC
DUTY CYCLE ...................................... 10 MIN
- AVERAGE LOAD ................................ 15,000 LBS
SUPPLY VOLTAGE .............................. 270 VDC
FORCE - VELOCITY TEST DATA
MOOG 38 HP EM TVC SYSTEM
ON SSME TEST FIXTURE
TEST DATA
LOAD POSITION FREQUENCY RESPONSE (± 5% COMMAND)
MOOG 38HP EM TVC ACTUATION SYSTEM ON SSME SIMULATOR
0.5 IN STEP RESPONSE
ON SSME SIMULATOR
(LOAD POSITION)
<table>
<thead>
<tr>
<th></th>
<th>BALLSCREW ACTUATOR</th>
<th>ROLLERSCREW ACTUATOR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Efficiency</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at Stall</td>
<td>70%</td>
<td>61%</td>
</tr>
<tr>
<td>at Power Point</td>
<td>78%</td>
<td>71%</td>
</tr>
<tr>
<td><strong>Friction</strong></td>
<td>1650 lbs.</td>
<td>1500 lbs.</td>
</tr>
<tr>
<td><strong>Stiffness (Locked Rotor)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Midstroke</td>
<td>$1.47 \times 10^6$ lb/in</td>
<td>$1.5 \times 10^6$ lb/in</td>
</tr>
<tr>
<td>Extend</td>
<td>$1.34 \times 10^6$ lb/in</td>
<td>$1.38 \times 10^6$ lb/in</td>
</tr>
<tr>
<td><strong>Acceleration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One Motor</td>
<td>130 in/sec$^2$</td>
<td></td>
</tr>
<tr>
<td>Two Motors (One Driving)</td>
<td>65 in/sec$^2$</td>
<td></td>
</tr>
</tbody>
</table>
## PERFORMANCE RESULTS OF MOOG BRUSHLESS EM TVC SYSTEM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SSME Spec</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Response</td>
<td>&lt;25 deg. Phase at 1 Hz</td>
<td>Meets Requirement</td>
</tr>
<tr>
<td>(± 2% Command)</td>
<td>&lt;80 deg. Phase at 3 Hz</td>
<td></td>
</tr>
<tr>
<td>Rated Power Point</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Force</td>
<td>48,000 lbs.</td>
<td>Meets Requirement</td>
</tr>
<tr>
<td>Output Velocity</td>
<td>5.2 in/sec.</td>
<td></td>
</tr>
<tr>
<td>Output Travel</td>
<td>± 5.5 in.</td>
<td>Meets Requirement</td>
</tr>
<tr>
<td>Actuator Stiffness</td>
<td>790,000 lb/in.</td>
<td>Meets Requirement</td>
</tr>
</tbody>
</table>

MOOG

Missile Systems Division
ELECTROMECHANICAL PROPELLANT CONTROL ACTUATORS

MARThA B. CASH
EP\64

OCTOBER 1, 1992
# DESIGN REQUIREMENTS

<table>
<thead>
<tr>
<th>DESIGN REQUIREMENT</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>VALVE OPEN/CLOSE TRAVEL</td>
<td>84° 45' - 85° 30'</td>
</tr>
<tr>
<td>VALVE POSITION ACCURACY</td>
<td>± 3% OF 85° (MAX.)</td>
</tr>
<tr>
<td></td>
<td>± 1.3% OF TOTAL TRAVEL FROM 50-60% OPEN</td>
</tr>
<tr>
<td>VALVE RATE (DEG./SEC.)</td>
<td>360 (MAX.)</td>
</tr>
<tr>
<td>ATMOSPHERIC PRESSURE (TORR)</td>
<td>SEA LEVEL TO 1 X 10⁻⁷</td>
</tr>
<tr>
<td>AMBIENT OPERATING TEMP. (°F)</td>
<td>-50 TO 130</td>
</tr>
<tr>
<td>ACTUATOR CONTROLLER AMBIENT OPERATING TEMP. (°F)</td>
<td>40 TO 110</td>
</tr>
<tr>
<td>ACTUATOR NON-OPERATING TEMP. (°F) FOR 2 HRS.</td>
<td>-200 TO 10</td>
</tr>
<tr>
<td>LIFE (HRS)</td>
<td>8</td>
</tr>
<tr>
<td>LOAD (MAX.) (IN.-LB.)</td>
<td>4500</td>
</tr>
<tr>
<td>WEIGHT (LBS.)</td>
<td>70</td>
</tr>
</tbody>
</table>
# DESIGN PARAMETERS

<table>
<thead>
<tr>
<th>DESIGN PARAMETERS</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVDT ERROR BAND</td>
<td>2% OF THE FULL SCALE</td>
</tr>
<tr>
<td>RVDT EXCITATION</td>
<td>20 VOLTS, PEAK TO PEAK AT 2000 Hz</td>
</tr>
<tr>
<td>GEAR RATIO</td>
<td>85:1</td>
</tr>
<tr>
<td>CLOSED LOOP THRESHOLD UNDER LOADING</td>
<td>0.025% OF FULL TRAVEL</td>
</tr>
<tr>
<td>MAX. CURRENT (AMP.)</td>
<td>40</td>
</tr>
<tr>
<td>LINE BUS VOLTAGE (VOLT)</td>
<td>270</td>
</tr>
<tr>
<td>VALVE RATE (DEG./SEC.)</td>
<td>245 (NOMINAL)</td>
</tr>
<tr>
<td>RESOLVER EXCITATION</td>
<td>4 VOLTS RMS PEAK TO PEAK AT 10 kHz</td>
</tr>
<tr>
<td>FREQUENCY RESPONSE</td>
<td>-3 db AT 10 Hz (NOMINAL)</td>
</tr>
<tr>
<td>ACTUATOR LOADING (IN.-LB.)</td>
<td>90° PHASE LAG AT 10 Hz (MAX.)</td>
</tr>
<tr>
<td>HELIUM PRESSURE (PSI)</td>
<td>AS DEFINED IN FIGURE 1</td>
</tr>
<tr>
<td>PNEUMATIC SHUTDOWN VALVE CLOSING TIME (FROM FULL OPEN)(SEC.)</td>
<td>700 TO 800</td>
</tr>
<tr>
<td></td>
<td>1.4 TO 3.1</td>
</tr>
</tbody>
</table>
EXTENDED LOCKUP TEST (ATP para. 4.11.4)

P/N X41009110

Date SEP 15 1992 Operator 148

Comments Loaded

S/N X001

<table>
<thead>
<tr>
<th>Item</th>
<th>Required</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Direction Sense</td>
<td>CCW</td>
<td>CCW</td>
</tr>
<tr>
<td>Load</td>
<td>MOVA</td>
<td>MOVA</td>
</tr>
<tr>
<td>Reduced Power</td>
<td>Minimum</td>
<td>MIN</td>
</tr>
<tr>
<td>Encoder Reading (Start of Lockup)</td>
<td>1894 ± 2 bits</td>
<td>1894</td>
</tr>
<tr>
<td>Encoder Reading After 10 Min Lockup</td>
<td>1846</td>
<td>1846</td>
</tr>
<tr>
<td>Total Drift After 10 Min Lockup</td>
<td>82 bits max</td>
<td>48</td>
</tr>
<tr>
<td>Load Direction Sense</td>
<td>Active</td>
<td>ACTIVE</td>
</tr>
<tr>
<td>MOV Load</td>
<td>Remove</td>
<td>REMOVED</td>
</tr>
</tbody>
</table>
**ACTUATOR SLEW RATE (ATP Para 4.9)**

(Please 1 of 3)

P/N X41009110

Date **SEP 15 1992**

Operator **149**

Serial No. **X001**

Comments: **Loaded**

<table>
<thead>
<tr>
<th>Required</th>
<th>Shaft Position</th>
<th>Input Signal</th>
<th>MFVA Load</th>
<th>Slew Rate %/Sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open-Close-Open</td>
<td>+30 ± 1 mA</td>
<td>MOV Load Fig. 11</td>
<td>143 min.</td>
</tr>
<tr>
<td></td>
<td>Open-Close-Close</td>
<td></td>
<td></td>
<td>340 max.</td>
</tr>
<tr>
<td>(Failsafe Switch only Energized)</td>
<td>Close to Open</td>
<td>+30</td>
<td>Data Fig. 1</td>
<td>161 %/s</td>
</tr>
<tr>
<td></td>
<td>Open to Close</td>
<td>-30</td>
<td>Data Fig. 2</td>
<td>172 %/s</td>
</tr>
<tr>
<td></td>
<td>Reversal to Closed</td>
<td>+30</td>
<td>Data Fig. 3</td>
<td>152 %/s</td>
</tr>
<tr>
<td></td>
<td>Reversal to Opened</td>
<td>-30</td>
<td>Data Fig. 4</td>
<td>157 %/s</td>
</tr>
</tbody>
</table>
ACTUATOR SLEW RATE (ATP Para 4.9)

(Please 2 of 3)

P/N X41009110

SEP 15 1992

1.00V 2.00V

+,0.00s 200/*

3s 1 STOP

1. STOP

2. STOP

t1 = 20.00ms t2 = 312.0ms Δt = 292.0ms 1/Δt = 3.425 Hz

Vdc/div

2.0 Vdc/div

sec/div

0.2 sec/div

1.2 sec/div

TO OPEN

CLOSED
ACTUATOR SLEW RATE (ATP Para 4.9)

(Paee 3 of 3)

P/N X41009110 S/N X001

**SEP 992**

---

**OPEN**

**CLOSE**

\[ t_1 = 1.356 \text{ s}, \quad t_2 = 1.704 \text{ s}, \quad \Delta t = 348.0 \text{ ms}, \quad 1/\Delta t = 2.874 \text{ Hz} \]

\[ t_1 = 1.544 \text{ s}, \quad t_2 = 1.544 \text{ s}, \quad \Delta t = 300.0 \text{ ms}, \quad 1/\Delta t = 3.333 \text{ Hz} \]
PNEUMATIC SHUTDOWN DATA SHEET (ATP Para 4.11.3)

Date: SEP 15 1992  Operator: HR

Serial No.: X001

Comments: Leaned

<table>
<thead>
<tr>
<th>Item</th>
<th>Required</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pneumatic Pressure, psig</td>
<td>695 ± 10 MPVA</td>
<td>695</td>
</tr>
<tr>
<td>Starting Encoder, bits*</td>
<td>2168 to 2179 MPVA</td>
<td>2171</td>
</tr>
<tr>
<td>Ending Encoder, bits*</td>
<td>253 to 276 MPVA</td>
<td>253</td>
</tr>
<tr>
<td>Shutdown Time, sec</td>
<td>1.17 to 2.27</td>
<td>1.58</td>
</tr>
</tbody>
</table>

* Cross out non-applicable line.

Diagram:

- RVDT #1 Demodulated Output
- 2VDC/div
- 5 sec/div for MPVA
- 1.0 sec/div for MFVA

Equations:

- $t_1 = -150 \text{ ms}$
- $t_2 = 1.450 \text{ s}$
- $\Delta t = 1.580 \text{ s}$
- $1/\Delta t = 632.9 \text{ mm/s}$
FAIL-OPERATE PERFORMANCE (ATP Para 4.11)

P/N X41009110

Date SEP 15 1992  Operator 148

Serial No.  X001

Comments: Loaded

<table>
<thead>
<tr>
<th>Item</th>
<th>Required</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 Input</td>
<td>+24 M amp</td>
<td>+24</td>
</tr>
<tr>
<td>#2 Input</td>
<td>-24 M amp</td>
<td>-24</td>
</tr>
<tr>
<td>Fail-Op Energized</td>
<td>20 M amp</td>
<td>20</td>
</tr>
<tr>
<td>Failsafe Energized</td>
<td>20 M amp</td>
<td>20</td>
</tr>
<tr>
<td>Ending Encoder Reading</td>
<td></td>
<td>777</td>
</tr>
<tr>
<td>Starting Encoder Reading</td>
<td></td>
<td>758</td>
</tr>
<tr>
<td>Diff. = Uncontrolled Actuator Travel</td>
<td>78 bits max.</td>
<td>19</td>
</tr>
</tbody>
</table>

Encoder Reading @ Travel Reversal: 777 Bits

Encoder Reading @ Fail-Op Energized: 758 Bits

Δ Position = Uncontrolled Actuator Travel: 19 Bits
FUTURE TEST PLANS

FUNCTIONAL

FREQUENCY RESPONSE
RATED LOAD/VELOCITY
LINEARITY
STABILITY
PERFORMANCE

ENVIRONMENTAL

VIBRATION/SHOCK
EMI/EMC

FLIGHT SIMULATION LABORATORY

REDUNDANCY
FAULT INJECTIONS
ENGINE SIMULATIONS (HARDWARE IN-THE-LOOP)

FLOW

WATER FLOW/CRYOGENICS WITH MOV

TTB

ENGINE HOT FIRE
EMA DESIGN GROUPS

ELECTRONIC CONTROLLER

Information & Electronics
Systems Laboratory
Control Electronics Branch
(EB24)

Propulsion Laboratory
Control Mechanisms &
Propellant Delivery Branch
(EP64)

MECHANICAL
ELECTROMECHANICAL PROPELLANT CONTROL SYSTEM ACTUATOR

- DESIGN
  - MECHANICAL
  - ELECTRONICS/CONTROLLER

- TESTING
  - STATUS

- FUTURE PLANS
MECHANICAL COMPONENTS

- Motor
- Harmonic Drive
- Resolver
- Output Spline
ELECTRONIC CONTROLLER

- PROVIDES CONTROL TO MOTOR
- PROVIDES EXCITATION TO RESOLVER
- CONTAINS ENERGY DISSIPATING DEVICE
CONTROLLER BLOCK DIAGRAM

MECHANICAL OUTPUT

ENERGY DISSIPATION

HARMONIC DRIVE

MOTOR

CURRENT FEEDBACK LOOP

COMMUTATION LOGIC

PWM

HALL EFFECT DEVICE

POSITION FEEDBACK LOOP

COMMAND

ELECTRICAL INPUT

RESOLVER
TESTING

- Developed and Verified Model
- Unloaded Testing
  - Frequency Response
  - Velocity
- Loaded Testing
  - Frequency Response
MODEL AND EMA FREQUENCY RESPONSE TESTS
EQUIPMENT NEEDED TO COMPLETE TESTING

- 4000 Watt Controller
- Valve Simulator
HYDRAULIC AND EMA FREQUENCY RESPONSE TESTS
FUTURE TEST PLANS

- Steady State Position Accuracy
- Temperature Tests
- Vibration Tests
- Comparison Between EMA And Hydraulic
TRANSIENT COMPENSATION EMA

Bill Fellows

September 29, 1992
ALLIED-SIGNAL RESEARCH
ELECTROMECHANICAL ACTUATOR (EMA)

SPECIFICATIONS

TRIPLE 11 HP MOTORS
POWER: 270 VDC
FORCE: 35,000 LB
TRAVEL: 10 INCHES
TRAVEL TIME: 2 SECS
BANDWIDTH: 13 HZ
WEIGHT: 102 LB
LENGTH: 46 INCHES
(EXTENDED)

FEATURES

- REPLACES HYDRAULIC ACTUATORS
- FAULT TOLERANT ELECTRONICS
- BUILT-IN TEST CAPABILITY
- RATE AND POSITION COMMANDS
- FORM AND FIT COMPATIBLE WITH HYDRAULIC ACTUATORS
- HIGH EFFICIENCY
SYSTEM DESCRIPTION

FOR THE PURPOSE OF MODELING, A SYSTEM COMPRISED OF TWO ALLIED-SIGNAL F20 MOTORS WAS UTILIZED. THIS SYSTEM WILL MEET THE PERFORMANCE REQUIREMENTS OF THE TITAN IV FIRST STAGE. THE BLOCK DIAGRAM FOR THE SYSTEM IS SHOWN. THE REDUNDANCY ASPECTS OF HAVING TWO MOTORS IS NOT SHOWN - THE MOTORS ARE LUMPED INTO ONE FOR THIS STUDY. THE GEAR RATIO IS APPROXIMATELY 37:1 INTO A 0.625 LEAD BALLSCREW, FOR AN OVERALL GEAR RATIO OF 5400:1. THIS PROVIDES A 30,000 LB. OUTPUT OF THE ACTUATOR AT 3.5 IN-SEC. THE LIMIT LOAD OR STRUCTURAL CAPACITY OF THE ACTUATOR IS ASSUMED TO BE 60,000 LBS. MINIMUM, WHICH IS AT LEAST TWICE THE RATED OUTPUT. THE FORCE FEEDBACK INTO THE CONTROLLER HAS AN ELECTRICAL BIAS OF 40,000 LBS.
EM TVC TRANSIENT LOAD COMPENSATION

- If the reacted force on the actuator is instrumented, it may be fed back to the servo loop to cause a reduction in stiffness when the load tries to exceed the rated load.
GENERAL DESCRIPTION OF ACTIVE COMPENSATION

The basic philosophy of the compensation is to detect the applied load and when it is going to exceed the maximum actuator required output use this load term to cause the actuator to back away from the excess transient. The response of the TVC system while operating under normal loads does not have to be as high as the transient load. In normal operation, the engine inertia and loads have a significant effect on the actuator response capabilities. When reacting to a transient load, the engine inertia is the mover and the response capability of the actuator to move out of the way is the response of the actuator motor alone, i.e., the motor must accelerate with the help of an aiding load. This means that a system with an operational frequency response of 4 Hz may have no problem compensating for a 15 Hz transient load.

As an example of the above, a preliminary sizing indicates that a TVC actuator using two Allied-Signal F20 brushless DC motors will meet the performance requirements of Titan IV. When in normal operation and moving the Titan IV engine, the frequency response is in the order of 7 or 8 Hz. The response capability when reacting to a transient load is in the order of 19 Hz. This is compatible with requirements for compensating a 12 Hz transient input.
EM TRANSIENT LOAD COMPENSATION MODEL

NOMENCLATURE

- $F_x$: LOAD
- $X_c$: POSITION COMMAND
- $X$: ACTUAL POSITION
- $K_E$: BACK EMF CONSTANT
- $\Omega$: MOTOR SPEED
- $R$: RESISTANCE
- $L$: INDUCTANCE
- $J_m$: MOTOR POLAR MOMENT OF INERTIA
- $K_L$: COMBINED GEAR RATIO
- $K_T$: TORQUE CONSTANT
- $I_m$: MOTOR CURRENT
- $G_p, G_c, G_I$: GAIN CONSTANTS
- $T_1, T_2$: LEAD COMPENSATOR TIME CONSTANTS

Allied-Signal Aerospace Company
MODEL AND RESULTS

Using the system described, a 12 Hz transient was applied which had a peak uncompensated force of 105,000 lbs. This level was selected high because complete data on the transient characteristics are not available. For comparison, two energy levels of transients were used: a 1500 in-lb. and a 7500 in-lb. The controller in the model has a 40,000 lb. deadband which is 10,000 lbs. over the rated output. This means that under static conditions, the actuator will be rigid for any loads under 40,000 lbs. The reaction and results of the modeled system to the 1500 in-lb. level is shown. The ability of the system to reduce the load at the 7500 in-lb. level is limited by the speed limitation of the actuator, not its frequency response. In other words, it cannot move enough distance in the time to further reduce the transient. Even with this limitation, the load was reduced from about 105,000 lbs. to 55,000 lbs., well within the structural limit requirements. At the 1500 in-lb. energy level, the force was reduced to 40,000 lbs. In either case, it can be seen that the compensation significantly reduces the peak load to within structural limitations which is taken to be 60,000 lbs.
LOAD ON RIGID ACTUATOR

COMPENSATED LOAD

\[ \text{LB FORCE} \times 10^3 \]

\[ T = \text{SECONDS} \]

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

-20 0 20 40 60 80 100 120 140
MASS LOADED STEP RESPONSE
6600 POUNDS
FREQUENCY RESPONSE

THE FREQUENCY RESPONSE OF THE TEST UNIT WAS RUN BOTH UNLOADED AND WITH A 6600 LB. INERTIA LOAD. THE RESULTS SHOW THAT THE RESPONSE EXCEEDS 10 Hz IN BOTH CASES.
GAIN AND PHASE
6600 POUND LOAD AND NO - LOAD

LOG FREQUENCY (Hz)

GAIN (dB)

PHASE (DEGREES)

- LOADED GAIN - 6600 #
- LOADED PHASE
- NO - LOAD GAIN
- NO - LOAD PHASE

Allied- Signal Aerospace Company
AiResearch Los Angeles Division
SESSION XIII

DEMONSTRATION
This document contains the proceedings of the NASA Electrical Actuation Technology Bridging (ELA-TB) Workshop held in Huntsville, Alabama, September 29–October 1, 1992. The workshop was sponsored by NASA Office of Space Systems Development and Marshall Space Flight Center (MSFC). The workshop addressed key technologies bridging the entire field of electrical actuation including systems methodology, control electronics, power source systems, reliability, maintainability, and vehicle health management with special emphasis on thrust vector control (TVC) applications on NASA launch vehicles. Speakers were drawn primarily from industry with participation from universities and government. In addition, prototype hardware demonstrations were held at the MSFC Propulsion Laboratory each afternoon. Splinter sessions held on the final day afforded the opportunity to discuss key issues and to provide overall recommendations. Presentations are included in this document.