SSTAC/ARTS REVIEW OF THE DRAFT INTEGRATED TECHNOLOGY PLAN (ITP)

Volume VI: June 26-27

Controls and Guidance

Briefings from the June 24-28, 1991 Conference McLean, Virginia

National Aeronautics and Space Administration Office of Aeronautics, Exploration and Technology Washington, D.C. 20546
SSTAC/ARTS REVIEW OF THE DRAFT ITP
Mclean, Virginia
June 24-28, 1991

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Controls and Guidance

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Overview of Guidance and Controls Programs

NASA Headquarters
OAET/Code RC

June 26, 1991

John Di Battista

GUIDANCE AND CONTROL PROGRAM

OBJECTIVE:

Advance critical areas of enabling and enhancing transportation and spacecraft guidance and control technologies that support civil, commercial, science, and exploration missions for the 1990's and beyond. The technology program consists of research and technology development in:

- Guidance Technology
- Controls Technology
- Computational Controls Technology
GUIDANCE AND CONTROLS RESEARCH AND TECHNOLOGY PROGRAM BASIS

• NATIONAL AERONAUTICS AND SPACE ACT OF 1958

...Space activities...shall be conducted so as to contribute materially to...

(4) The establishment of long-range studies of the potential benefits to be gained from, the opportunities for, and the problems involved in the utilization of aeronautical and space activities for peaceful and scientific purposes;

(5) The preservation of the role of the United States as a leader in aeronautical and space science and technology and in the application thereof to the conduct of peaceful activities within and outside the atmosphere;...

Space Technology to Meet Future Needs...Joe Shea Committee 1987

SPACERRAFT

...concepts such as adaptively controlled structures should be developed ....pg 104

TRANSPORTATION VEHICLES

There is a need for modern technology in future vehicles of all classes to enable new capabilities such as heavier lift capacity, to improve reliability, and to lower cost ....pg 15

GUIDANCE AND CONTROLS PROGRAM HISTORY

- 1958 - 1980............. RESEARCH AND TECHNOLOGY PROGRAM TO SUPPORT RIGID BODY SPACECRAFT CONTROL WITH FLEXIBLE APPENDAGES AND PROVIDE CONTROL SUBSYSTEM COMPONENT TECHNOLOGY

1984..........................SDIO SUPPORT TO CONTROLS INITIATED
- 1978 - 1984.............. DARPA ACTIVE CONTROL OF FLEXIBLE STRUCTURES (ACOSS) PROGRAM
- 1980.....................PROGRAM INITIATED TO SUPPORT LARGE COMPLEX AND FLEXIBLE SPACECRAFT
- 1982..............CODE R CONTROLS STRUCTURES INTERACTION PROGRAM INITIATED
- 1988.............PROGRAM PLANNING INITIATED TO PROVIDE ADVANCED GUIDANCE TECHNOLOGY (ADVANCED LAUNCH SYSTEM TECHNOLOGY PROGRAM) - 1989
- 1989.............COMPUTATIONAL CONTROLS PROGRAM IDENTIFIED
GUIDANCE AND CONTROLS
PROGRAM

HISTORY
CONTINUED

1989 -1991..........................EXPLORATION TECHNOLOGY PROGRAMS IN
AUTONOMOUS RENDEZVOUS AND DOCKING AND
AUTONOMOUS LANDER

1990...............................LAUNCH VEHICLE AVIONICS PLANNING
INITIATED BY STRATEGIC AVIONICS WORKING GROUP

GUIDANCE AND CONTROL
PROGRAM

APPROACH:

• IDENTIFY TECHNOLOGY NEEDS THROUGH STUDIES, FUTURE MISSION
  REQUIREMENTS AND GUIDANCE FROM CODE M.S, OTHER
  GOVERNMENT AGENCIES AND COMMERCIAL PROVIDERS,THE SSTAC
  AND THE STRATEGIC AVIONICS WORKING GROUP, AND OTHERS.
• IDENTIFY THE CENTERS WITH THE BEST CAPABILITIES AND
  FACILITIES FOR THE IDENTIFIED TECHNOLOGY AREAS
• DEVELOP A COORDINATED PROGRAM USING INPUTS FROM
  CENTERS AND NASA HEADQUARTERS
• ESTABLISH PARTNERSHIPS BETWEEN THE CENTERS, INDUSTRY,
  UNIVERSITIES, AND OTHER GOVERNMENT LABORATORIES
• BASE PROGRAM ELEMENTS CARRY OUT GENERIC RESEARCH AND
  TECHNOLOGY
• FOCUSED PROGRAM ELEMENTS HAVE ADVANCED BRASSBOARD
  DEMONSTRATION WHICH CONTRIBUTING TO TECHNOLOGY
  TRANSFER, AND WHEN APPROPRIATE, PARTICIPATE IN FLIGHT
  EXPERIMENTS
• TRANSFER TECHNOLOGY TO THE USER FOR USE IN DEVELOPMENT
  OF OPERATIONAL FLIGHT SYSTEMS
GUIDANCE AND CONTROLS PROGRAM

BENEFITS:

• CRITICAL ENABLING GUIDANCE AND CONTROLS TECHNOLOGIES ARE PROVIDED IN ACCORDANCE WITH THE NATION'S LONG RANGE GOALS TO MAINTAIN THE PREMANCE OF OUR SPACECRAFT AND TRANSPORTATION VEHICLES

AND ENABLE THE DEVELOPMENT OF THE FOLLOWING TECHNOLOGIES:

• PROVIDE NEW AND EFFICIENT ADAPTIVE GUIDANCE ALGORITHMS
• PROVIDE HIGHLY RELIABLE DISTRIBUTED FAULT TOLERANT CONTROL SYSTEMS TECHNOLOGY
• PROVIDE ROBUST CONTROLS TECHNOLOGY FOR LARGE COMPLEX SPACE SYSTEMS INCLUDING SYSTEM IDENTIFICATION, ADAPTIVE CONTROL, PRECISION METROLOGY, SENSORS AND ACTUATORS
• PROVIDE COMPUTATIONAL CONTROLS TECHNOLOGY ENABLING ORDERS OF MAGNITUDE INCREASES IN THE ABILITY TO DESIGN, SYNTHESIZE, ANALYSE AND SIMULATE LARGE COMPLEX SPACE SYSTEMS

GUIDANCE AND CONTROLS PROGRAM

WORK BREAKDOWN STRUCTURE
GUIDANCE & CONTROLS PROGRAM

ORGANIZATIONAL CHART

GUIDANCE & CONTROLS PROGRAM

STATE OF THE ART:

Guidance Technology
- Shuttle
- Planetary S/C and Probes

Fault Tolerant Distributed Controls
- Shuttle/Titan/Atlas-Centaur/Delta

Spacecraft Control
- Rigid Body Control Theory
- Gains Adjusted on Orbit to Accommodate Deployed Configuration Controls

Computational Controls
- Efficient Computational Algorithms
- Real Time H/W in the Loop Simulations
- Parallel Processing
- User Friendly Interface

Today
- Precalculated Loads / weather
- Spinning Gyros / Image Disectors
- Star Trackers
- Ballistic Planetary Entry with Aerodynamic Deceleration
- Shuttle Triple Redundancy with Actuator Force Flight
- Titan/Delta Single String S-Level Parts
- Contour Dual String Redundancy
- AIPS Fault Tolerant Architecture Technology
- Galileo Span / Despan Control
- Hubble, Ulysses, & Mariner
- Flexible Appendage Thermal System / Control System Interaction
- Ground Based Large Space System Controls Testbeds
- Order N Algorithms / Symbolic Logic
- Discos, Treetops, Matrix X, etc
- Space Station Dynamics Simulation
- Craft Cassini Control Simulator Interface

Goals
- Day of Launch: Loads / Lidar Wind Sounders
- Fiber Optics Rotation Sensor Aeromaneuvering
- AIPS Architecture Implementation with B-Level Parts
- Launch on Schedule with Fault
- Vehicle Health Management
- Robust S/C Control with On Orbit System ID and Adapt Controls for Complex S/C including Growth S/S, Multi-Instrument Platforms and Large Segmented Telescopes
- Parallelized Order N Algorithms
- Parallel Processing on Supercomputers with real time H/W in the loop simulations
- Maintain like Interface

CG1-5
GUIDANCE AND CONTROLS
PROGRAM FACILITIES

• PLS SIMULATOR
• AIRLABS
• ACES/CASES
• SCOLE
• CARL

GUIDANCE & CONTROLS
PROGRAM

ACCOMPLISHMENTS:
• Developed Generic 100 Faster Space Station Controls Simulator with Order N Algorithms, Symbolic Equation Manipulator and Parallel Processing
• Demonstrated Navigational Grade Fiber Optics Rotation (FORS) Gyro
• Developed Teetop, Conops and Order N Discos Controls/Simulation Codes
• Developed SHAPES Sensor for Large 100 M Antenna Control
• Provided Controls Algorithms Technology to Hubble Space Telescope for Solar Array Thermal Pumping Problem Fix
• Provided Real Time PLS Controls Simulator
• Provided Adaptive Guidance LIDAR Winds Aloft Technology
• Demonstrated distributed fault tolerant Advanced Information Processing System Breadboard
• Developed for demonstration Astro Solid State CCD Star Tracker Saving Mission
• Developed robust efficient adaptive control system identification and control algorithms technology for large complex systems
GUIDANCE & CONTROLS PROGRAM

PICTURES
OF
SS Workstation
FORS
HUBBLE
PLS
LIDAR
ASTRO
AIPS
ETC

GUIDANCE & CONTROLS PROGRAM

PROGRAM MILESTONES:

GUIDANCE PROGRAM
PERFORM LIDAR WINDS PROFILE TESTS AT KSC --1991
DEVELOP STOCASTIC ETO GUIDANCE ALGORITHMS
AND TRAJECTORY DESIGN TOOLS-- 1992
COMPLETE READBOARD OF A.I BASED STAR TRACKER --1993
COMPLETE FORS SINGLE AXIS ENGINEERING MODEL--1993

CONTROLS PROGRAM
COMPLETE SPACECRAFT MCONTROL SYSTEM DESIGN GUIDELINE
DOCUMENT--1992
COMPLETE RMS CONTROL SYSTEM UPGRADE DESIGN PLAN--1992
DEMONSTRATE PRECISION STRUCTURE (INTERFEROMETER)
SHAPE MEASUREMENT--1992
COMPLETE PRELIMINARY MICRO GYRO DESIGN--1993
VALIDATE AIPS CHARACTER ARCHITECTURE--1995

COMPUTATIONAL CONTROLS
UPGRADE DISCO WITH FLEXIBLE ORDER N DISCO --1992
MBODY MODEL REDUCTION COMPONENT REP. S/W--1994
10 MSEC REALTIME SYSTEM SIMULATION (400
STATE CAPABILITY)--1996
GUIDANCE & CONTROLS PROGRAM

RELATED NASA PROGRAMS:
- CODE R CONTROLS STRUCTURES INTERACTION PROGRAM
- CODE M BRIDGING TASK IN ADAPTIVE GUIDANCE
- CODE R AERONAUTICS CONTROLS PROGRAM
- CODE R NASP GUIDANCE AND CONTROLS PROGRAM

RELATED GOVERNMENT PROGRAMS
- SDIO CONTROLS PROGRAMS IN COMPLEX SYSTEMS AND ADVANCED AVIONICS PROGRAM
- DOD ADVANCED LAUNCH SYSTEM (ALS) PROGRAMS IN ADAPTIVE GUIDANCE AND FAULT TOLERANT AVIONICS

GUIDANCE AND CONTROLS PROGRAM

RESOURCES ($,M)

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NEW AREAS FOR AUGMENTATION REQUESTED:

- TRANSPORTATION VEHICLE AVIONICS - 1993
- AUTONOMOUS RENDEZVOUS & DOCKING - 1994
- AUTONOMOUS LANDER - 1994
- PLATFORM G.N&C - 1994
- PRECISION POINTING - 1994
- MICROMACHINES - 1995

Transportation Technology
Earth-To-Orbit Transportation

Earth-to-Orbit Vehicle Avionics

OBJECTIVES
- Programmatic
  Develop vehicle avionics which support minimization of life cycle costs; multi-program implementation; integrated flight and ground infrastructure; continuous customer driven requirements; effective technology utilization and evolution; minimization of life cycle costs; ability to recover and fly with failures; modular, scalable, maintainable and robust; increased performance and long term sale operations; rapid prototyping, demonstration, and multi-test bed supportability.
- Technical
  The specific areas of technology development are avionics architectures technologies and required advanced software; vehicle health management (VHM) advanced technology concepts; guidance, navigation, and control advanced algorithms and development environments; electrical actuators technology development; advanced power management and control systems; landing and recovery systems technology development.

SCHEDULE
- Identify critical avionics technology requirements (1993-1996)
- Define VHM advanced technology concepts (1993-1996)
- Complete advanced power management architecture definition (1993)
- Define GN&C design tools for rapid prototyping (1994)
- Define GN&C advance algorithms (1993-1998)
- Define electrical actuation (ELA) power systems (1993)
- Advance recovery system Phase IIIA at MSFC (1993-1995)
- Define requirements for modeling and large scale test of advanced recovery system (1995-1997)

RESOURCES:
- 1993 $7.0 M
- 1994 $11.0 M
- 1995 $23.0 M
- 1996 $35.0 M
- 1997 $36.5 M

PARTICIPANTS:
- Avionics Architecture: ARC, JSC, & LaRC
- Avionics Software: ARC, JSC, & LaRC
- Vehicle Health Management: LaRC & MSFC
- Guidance, Navigation, & Control: LaRC, JSC, & JPL
- Electrical Actuation: LaRC & SSC
- Landing/Recovery Systems: JSC & MSFC
- Power Management & Control: LeRC
OBJECTIVES

- Programmatic
  Develop vehicle avionics which support minimization of life cycle costs, multiple program implementation, integrated flight and ground infrastructure, continuous customer driven requirements, effective technology utilization and evolution, minimization of life cycle costs, ability to recover and fly with failures, modular, scalable, maintainable and robust, increased performance and long term safe operations, rapid prototyping, demonstration, and multi-test bed supportability

- Technical
  The specific areas of technology development are avionics architectures technologies and required advanced software; vehicle health management (VHM) advanced technology concepts, guidance, navigation, and control advanced algorithms and development environments; electrical actuators technology development, advanced power management and control systems, landing and recovery systems technology development

RESOURCEs

- 1993 $ 5.0 M
- 1994 $ 9.0 M
- 1995 $15.0 M
- 1996 $32.0 M
- 1997 $44.3 M

SCHEDULE

- Identify critical technology areas for architecture development (1994-1996)
- Develop test bed concepts for architecture and software requirement definitions (1995-1997)
- Define operational and environmental requirements for VHM support to transfer vehicle (1993-1995)
- Define and develop VHM methods and concepts (1994-1996)
- Develop GN&C rapid prototyping requirements and test bed approach (1994-1997)
- Develop GN&C sensor requirements and algorithms for transfer vehicle (1994-1997)
- Identify key design concepts for tether control in support of micro-g management, power generation, etc. (1993-1995)
- Develop new control strategies for zero-m and verify thru detail dynamic simulations (1995-1999)
- Support technology development and system design using magnetostatic actuator servo models
- Complete requirements for ultra reliable, universal, modular smart power backbone system (1995)

PARTICIPANTS

Avionics Architecture - ARC, JSC, & LaRC
Avionics Software - ARC, JSC, & LaRC
Vehicle Health Management - LaRC & MSFC
Guidance, Navigation, & Control - LaRC, JSC, & JPL
Electrical Actuation - LeRC & SSC
Landing/Recovery Systems - JSC & MSFC
Power Management & Control - LeRC

TASK SCHEDULE/MILESTONES

- Identify avionics technology requirements (1983-96)
- Demonstrate avionics architecture concepts (SW and HW) components (1995-2000)
- Define advanced VHM concepts (1993-96)
- Demonstrate advanced VHM applications (1995-2000)
- Complete power management architecture definition (1994)
- Power management test (1996)
- Power management system demonstration and ground checkout and definition flight modules (1999)
- Define GN&C design tools for rapid prototyping (1995)
- Demonstrate GN&C rapid prototyping (1996)
- Define GN&C advanced algorithms (1994-96)

PARTICIPANTS

Avionics Architecture - JSC
Avionics Software - JSC
Vehicle Health Management - MSFC
Guidance, Navigation, & Control - JSC, MSFC
Power Management & Control - MSFC

CG1-10
**Objectives**

**Programmatic**
- Develop autonomous landing technology which supports technology that enables planetary exploration spacecraft to land safely in the face of surface hazards and close to areas of mission interest: autonomous GN&C technology; advanced sensor development

**Technical**
- The specific areas of technology development are concept definition and analysis of technology to facilitate navigation for precision landing; hazard detection and avoidance during terminal descent; sensor development modeling and algorithm development for Mars terrain navigation; Mars terrain definition

**Schedule**
- Requirements definition (1993)
- Alternate sensor models and algorithms development at system and sensor levels (1994)
- Prototype of sensors, algorithms and computer simulations selected for implementation (1994); designed/development (1995), landing test bed simulation (1997)

**Resources**
- 1991 $0.5 M
- 1992 $--- M
- 1993 $2.0 M
- 1994 $4.5 M
- 1995 $6.0 M
- 1996 $7.0 M
- 1997 $7.3 M

**Participants**
- System Engineering - JSC & JPL
- Precision Landing - JSC & JPL
- Hazard Detection and Avoidance - JSC, JPL, & ARC
- Sensor Development - JSC, JPL, & ARC

**Objectives**

**Programmatic**
- Develop autonomous rendezvous and docking (AR&D) system technology for spacecraft in low geosynchronous Earth orbits and in planetary orbits in the discipline areas of sensors, GN&C technology, and mechanisms

**Technical**
- The specific areas of technology development are define user requirements; conduct mission studies and analyses to define performance requirements; identify and evaluative AR&D system conceptual designs against user requirements; define requirements for prototype hardware and software

**Schedule**
- Define user requirements for AR&D technology (1992-1993)
- Conduct mission studies and analysis for performance requirements (1993-1994)
- Identify conceptual designs (1994-1996)
- Definition of requirements for prototype hardware and software (1996-1998)

**Resources**
- 1991 $0.5 M
- 1992 $--- M
- 1993 $2.0 M
- 1994 $5.0 M
- 1995 $7.0 M
- 1996 $7.3 M
- 1997 $7.7 M

**Participants**
- GN&C Radar Sensors & Mechanisms - JSC
- Vision Processing - MSFC
- Neural Networks and AI - ARC
- Interplanetary AR&D Algorithm Requirements - JPL

April 25, 1991
DRS-QUAD13
SPACE PLATFORMS TECHNOLOGY
EARTH ORBITING PLATFORMS

OBJECTIVES
PROGRAMMATIC
DEVELOP TOOLS AND METHODOLOGY FOR THE DESIGN AND ANALYSIS OF MULTI-INTEGRATED CONTROLS SYSTEMS

TECHNICAL
- POINTING ACCURACY (PLATFORM)  ARC-SECOND
- POINTING ACCURACY (PAYLOAD)  SUB-ARC-SECOND
- LIFETIME  15 YEARS

RESOURCES

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*THIS ELEMENT IS CLOSELY COORDINATED WITH DEVELOPMENT EFFORTS IN NASA/OSA AND RELATED OTHER GOVERNMENT PROGRAMS. RESOURCES SHOWN ARE NASA GAOET ONLY.

SCHEDULE
1994
SYSTEM MODELING
1995
DESIGN METHODOLOGY
1997
ON-ORBIT CHARACTERIZATION
1999
FEATURE ASSISTED POINTING
2000
TESTBED EVALUATIONS

PARTICIPANTS
LARC
TOOL AND METHODOLOGY DEVELOPMENT AND EVALUATION. CONTROL ELEMENT DEVELOPMENT AND TEST
JPL
SENSOR DEVELOPMENT, SYSTEM IDENTIFICATION, CONTROL
GMRC
MODELING/ANALYSIS TOOL DEVELOPMENT AND VALIDATION. CONTROL ELEMENT DEVELOPMENT
GMRC
TESTBED DEVELOPMENT, CONTROL CONCEPT EVALUATIONS

SPACE PLATFORMS TECHNOLOGY
DEEP SPACE PLATFORMS

OBJECTIVES
PROGRAMMATIC
DEVELOP AND VALIDATE KEY TECHNOLOGIES FOR THE GNC OF DEEP SPACE PLATFORMS

TECHNICAL
- LIFETIME 15 YEARS
- AUTONOMOUS OPERATIONS
- ADAPTIVE GUIDANCE
- ALGORITHM VERIFICATION

RESOURCES

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SCHEDULE
1994
ASSESS GNC REQUIREMENTS
1995
ASSESS BOX IN GUIDANCE METHODOLOGY
1997
DEVELOP ADVANCED TRAJECTORY CONTROL ALGORITHMS
1999
COMPLETE DEVELOPMENT OF GNAC COMPONENTS
2000
DEVELOP SOFTWARE AND CONDUCT SYSTEM EVALUATIONS

PARTICIPANTS
LARC
TECHNOLOGY ASSESSMENTS. GNAC TOOLS AND METHODOLOGY DEVELOPMENT/REVIEWS, HARDWARE DEVELOPMENTS
JPL
ATTITUDE AND METROLOGY SENSORS. CONTROL METHODOLOGY

CG1-12
PRECISION POINTING

OBJECTIVES

DEVELOP PRECISION POINTING TECHNOLOGY FOR INSTRUMENTS AND TELESCOPES

CRITICAL DRIVER MISSIONS:

FOR MULTIPLE INSTRUMENT POINTING:
NEXT EOS, GEOPAT

FOR TELESCOPE POINTING: ST-NO, MOI

TECHNOLOGY CHALLENGE

INCREASE SPACE BASED TELESCOPE POINTING CAPABILITY BY TWO ORDERS OF MAGNITUDE BEYOND HST

INCREASE REMOTE SENSING INSTRUMENT POINTING CAPABILITY BY 2-ORDERS OF MAGNITUDE

INCREASE RELIABILITY, LIFETIME AND EFFICIENCY OF POINTING COMPONENTS

DELIVERABLES

1996 FINE GUIDANCE SENSOR FOR SMMM
1998 AUTONOMOUS FEATURE TRACKING SYSTEM DEMO FOR EOS-A2
2000 LINE OF SIGHT TRANSFER
2002 TARGET REFERENCE POINTING DEMO FOR GEOPAT
2005 AUTONOMOUS POINTING SYSTEM EXECUTIVE FOR EOS-A3
2006 HIGH RELIABILITY/LIFETIME PERFORMANCE GYROS FOR ST-NO

PARTICIPANTS/RESOURCES

JPL, LANL, GSFC

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MAJOR FACILITIES: NONE

INFORMATION SCIENCE & CONTROLS

THRUST(S) SUPPORTED

- SCIENCE
- EXPLORATION

OBJECTIVES:

Develop and demonstrate a new class of sensor/instrument using state-of-the-art micro machining technologies for in-situ measurements such as: surface characterization, sub surface characterization, planetary atmospheric analysis and far IR atmospheric science.

PAYOFF

- Lightweight, small, economical instruments.
- Custom design.
- Ease & economy of duplication with VLSI lab. tech.
- Form critical in-house expertise.
- Science & exploration mission options are enabled with smaller instruments.

PRODUCTS (FY 1993 - FY 1996)

- Micro gyro - FY 95
- Micro seismometers - FY 96
- Micro gas analyzer - FY 97
- Vacuum micro electronics - FY 97
- Micro science instrument systems - FY 98

MICS

CENTERS: JPL, LANL
SUMMARY

- TRANSPORTATION AVIONICS TECHNOLOGY HAS HIGHEST PRIORITY TO RESPOND TO CODE M REQUEST
- CODE S RECOGNITION OF NEED FOR S/C CONTROLS RESEARCH AND TECHNOLOGY NOT STRONG IMPACTING AUGMENTATIONS PRIORITY
- BASE PROGRAM HAS BEEN SUCCESSFUL SEED BED FOR AUGMENTATION TECHNOLOGY PROGRAMS
- INCREASED MANAGEMENT ATTENTION & FUNDING REQUIRED FOR TECHNOLOGY TRANSFER
STRATEGIC AVIONICS TECHNOLOGY PLANNING
AND BRIDGING PROGRAMS

PRESENTATION
FOR
SSTAC CONTROLS COMMITTEE
NASA HEADQUARTERS

ALDO J. BORDANO
JOHNSON SPACE CENTER

SATWG BACKGROUND

A NASA STRATEGIC TRANSPORTATION AVIONICS TECHNOLOGY SYMPOSIUM
WAS HELD IN WILLIAMSBURG IN NOVEMBER 1989

AS A SYMPOSIUM FOLLOW-ON, A STRATEGIC AVIONICS TECHNOLOGY
WORKING GROUP (SATWG) WAS ESTABLISHED IN EARLY 1990 AND
MEMBERSHIP INCLUDES:

- AMES RESEARCH CENTER
- LEWIS RESEARCH CENTER
- JOHNSON SPACE CENTER
- MARSHALL SPACE FLIGHT CENTER
- KENNEDY SPACE CENTER
- STENNIS SPACE CENTER
- LANGLEY RESEARCH CENTER
- GODDARD SPACE FLIGHT CENTER
- JET PROPULSION LABORATORY

Strategic Avionics Technology Working Group
SATWG GOALS & OBJECTIVES

O SUPPORT DEVELOPMENT OF A STRATEGIC SPACE AVIONICS TECHNOLOGY PLAN

- AVIONICS TECHNOLOGY STRATEGIES AND GOALS
- LONG-RANGE ELEMENTS TO SUPPORT FUTURE PROGRAMS
- ELEMENTS TO SUPPORT EXISTING PROGRAMS INCLUDING OPERATIONAL INFRASTRUCTURE

O PROMOTE AN EFFECTIVE COMMUNICATION, COOPERATION, AND TEAM BUILDING ENVIRONMENT IN SPACE AVIONICS BETWEEN NASA, INDUSTRY AND GOVERNMENT AGENCIES

O DEVELOP COOPERATIVE PROGRAMS WITHIN ELEMENTS OF NASA

O PROMOTE IMPROVED TECHNOLOGY TRANSFER PROCESSES, SUCH AS "BRIDGING," BETWEEN TECHNOLOGISTS, DEVELOPERS, CONTRACTORS, AND PROGRAM MANAGERS

O DEVELOP INNOVATIVE IDEAS AND ACT AS A SUPPORT GROUP TO ALL NASA PROGRAMS

INCREMENTAL STRATEGIC TECHNOLOGY GOALS

Incremental steps toward achievement of Strategic Technology Goals

- ELV + SSF + CTV → NSTS
- HLLV + PLS
- STV + AMLS
- MARS PRECURSOR
- MARS

Infrastructure Support
- Launch Ops
- Mission Ops
- Payload Ops
- Spacecraft Ops
- Planetary Surface Ops

Strategic Avionics Technology Working Group
KEY STRATEGIC AVIONICS TECHNOLOGY THEMES

O CUSTOMER FOCUSED EMPHASIS - UTILIZE AND BUILD UPON:

- SHUTTLE/SPACE STATION EXPERIENCE
- ALS TECHNOLOGY DEVELOPMENT
- COMMERCIAL TECHNOLOGY - PRESENT AND FUTURE
- NASA ADVANCED TECHNOLOGY DEVELOPMENT
- EXPENDABLE LAUNCH VEHICLE EXPERIENCE
- DOD/DARPA TECHNOLOGY DEVELOPMENT

O SIGNIFICANT CHALLENGES

- BUILD FAULT - TOLERANCE AVIONICS CHEAPER, FASTER, AND SIMPLER
- IMPROVED TECHNOLOGY INSERTION
- CONSIDER HARDWARE / ARCHITECTURE DEVELOPMENT APPROACHES TO ADDRESS:
  - COMMONALTY, SCALABILITY, MODULARITY, AND LONG-TERM OPERABILITY REQUIREMENTS
  - INVESTIGATE OPEN ARCHITECTURE CONCEPTS

- EXPLORATION DRIVERS
  - MANNED/UNMANNED COMPATIBLE AVIONICS DESIGNS
  - VEHICLE HEALTH MANAGEMENT (AUTOMATED & INTEGRATED)
  - SPACE-BASED CHECKOUT, SUPPORTING PHASED ASSEMBLY
  - REMOTE IN-FLIGHT & SURFACE-SITE TRAINING
KEY STRATEGIC AVIONICS TECHNOLOGY THEMES

FOCUS AREAS FOR THE FUTURE

- TECHNOLOGY TO ENABLE CONTINUOUS IMPROVEMENT OF OPERATIONAL SYSTEMS INCLUDING BOTH FLIGHT ELEMENTS AND GROUND INFRASTRUCTURE

- TECHNOLOGY TO ADDRESS SIGNIFICANT FUTURE PROGRAM REQUIREMENTS
  - SPACE-BASED & REMOTE SURFACE OPERATIONS
  - LONG DURATION MISSIONS
  - ASSEMBLY IN SPACE
  - INTERACTION OF FLIGHT VEHICLES/ELEMENTS

- DIFFERENT PLANNING PROCESSES ARE REQUIRED

SATWG STRUCTURE

STRATEGIC AVIONICS TECHNOLOGY WORKING GROUP

SPACE AVIONICS ARCHITECTURE PANEL

VEHICLE HEALTH MANAGEMENT PANEL

COMMUNICATIONS & TRACKING PANEL

POWER MANAGEMENT & CONTROL PANEL

AVIONICS TECHNOLOGY BRIDGING TASKS

GUIDANCE, NAVIGATION & CONTROL PANEL

ADVANCED AVIONICS TECHNOLOGY STUDIES
SATWG ACTIVITIES & ACCOMPLISHMENTS

• INITIATED FY '91 TECHNOLOGY BRIDGING TASKS
  - ADAPTIVE ASCENT GUIDANCE NAVIGATION & CONTROL
  - ELECTRICAL ACTUATION / POWER SYSTEMS

• FIVE MAJOR PLANNING PANELS IN PLACE AND ACTIVE

• QUARTERLY INDUSTRY TECHNICAL INTERCHANGE MEETINGS ESTABLISHED

• STRATEGIES FOR CUSTOMER DRIVEN AVIONICS FACILITIES AND TEST BEDS BEING DEVELOPED

• COORDINATION OF CODE M AVIONICS TECHNOLOGY REQUIREMENTS INPUTS ACCOMPLISHED

Strategic Avionics Technology Working Group

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SATWG ACTIVITIES & ACCOMPLISHMENTS

• COORDINATION OF CODE R ADVANCED AVIONICS TECHNOLOGY REQUIREMENTS INPUTS ACCOMPLISHED

• SATWG INDUSTRY INTERFACE GROUP ESTABLISHED
  - CONSOLIDATED INDUSTRY FEEDBACK / RECOMMENDATIONS

• ACTIVE COOPERATIVE TECHNOLOGY TASKS
  - SPACE AVIONICS REQUIREMENTS STUDY
  - INS/GPS ORBITER APPLICATION STUDY
  - INS/GPS FLIGHT TEST FOR AUTOMATIC LANDING
  - ON-ORBIT RMS PERFORMANCE AND DYNAMICS
  - PLS GN&C SIMULATION STUDY
  - LIMITED FUNDING PRIME CONTRACTOR STUDIES -> "SEED PROJECTS"

Strategic Avionics Technology Working Group

CG2-5
INNOVATIVE TECHNOLOGY & PROGRAM DEVELOPMENT PROCESSES

O THREE PROCESS PROJECTS ARE PROPOSED AS A NEW BUSINESS APPROACH

#1 - AVIONICS TECHNOLOGY AND ADVANCED DEVELOPMENT PROCESS
#2 - AVIONICS DESIGN, DEVELOPMENT, TEST, AND EVALUATION PROCESS
#3 - AVIONICS OPERATIONS PROCESS

O TRENDS FOR PROCESS #1

- BECOMING MORE CUSTOMER FOCUSED
- TECHNOLOGY NEEDS DEVELOPED TO ADDRESS MULTIPLE PROGRAMS
- BECOMING MORE INTERDEPENDENT WITH PROCESS #2 AND PROCESS #3
  (EXAMPLE - MATERIALS, MANUFACTURING AND OPERATIONS COST)

O IMPLEMENTATION MODEL

- A TOP-DOWN / BOTTOM-UP / MIDDLE-IN APPROACH IS PROPOSED
  - TOP-DOWN = PROGRAM MANAGERS
  - BOTTOM-UP = TECHNOLOGISTS
- TYPICAL MIDDLE-IN FUNCTIONS
  - DEVELOP STRATEGIES ACROSS PROGRAMS TO TECHNOLOGY
  - UTILIZATION INCENTIVES TO PROGRAMS
  - CONNECT POCKETS OF TECHNICAL AND MANAGERIAL EXCELLENCE
  - IMPROVE NASA INSTITUTIONAL TECHNOLOGY, ENGINEERING, AND OPERATIONS ELEMENTS IN A TEAMWORK ENVIRONMENT
  - DEVELOP EARLY SPACE AVIONICS REQUIREMENTS AS A FOUNDATION FOR TECHNOLOGY AND ADVANCED DEVELOPMENT PLANNING
  - HORIZONTAL SE&I IS A PROPOSED TERM FOR THE MIDDLE-IN FUNCTION
INNOVATIVE TECHNOLOGY & PROGRAM DEVELOPMENT PROCESSES

O IMPLEMENTATION MODEL (CONT'D.)

• PLAN & IMPLEMENT PRIORITIZED AVIONICS TECHNOLOGY & ADVANCED DEVELOPMENT PROGRAMS
  - UTILIZE & BUILD UPON AVAILABLE TECHNOLOGY / EXPERIENCE
  - IDENTIFY & FORECAST TECHNOLOGY DEVELOPMENT PROGRESS
  - ESTABLISH "GAP" TECHNOLOGY RESEARCH & DEVELOPMENT

• SATWG TECHNOLOGY IMPLEMENTATION PROCESSES
  - TECHNOLOGY "BRIDGING" PROCESS
    -> JOINT USER / DEVELOPER TECHNOLOGY DEVELOPMENT EFFORT
  - TECHNOLOGY TRANSITION PROCESS
    -> GRADUAL PROGRESSION & TRANSFER OF DEMONSTRATED TECHNOLOGY
  - TECHNOLOGY UTILIZATION INCENTIVE PROCESS -> PROGRAMS
  - TECHNOLOGY INSERTION PROCESS -> IMMEDIATE APPLICATION

---

OTHER SPACE AVIONICS DEVELOPMENT STRATEGIES

O NASA/CONTRACTOR TEAMING STRATEGIES

• INVOLVES LEVELS OF COOPERATION WITHIN COMPETITIVE BOUNDARIES
• TEAMING PROCESS MUST INCLUDE APPROPRIATE INCENTIVES
• NASP TEAMING INCLUDES CONCEPT OF:
  - EQUALITY, EQUITABILITY OF WORK, WORKING TOWARD A COMMON GOAL

O AVIONICS LABORATORY / WORK STATION STRATEGIES

• CONSIDER ALTERNATIVES TO NEW BRICK AND MORTAR
• AVIONICS WORK STATION CONCEPT
• GENERIC AVIONICS TEST BED CONCEPT
  - LINK INTEGRATED ENVIRONMENTS
  - SUPPORT MULTIPLE PROGRAMS
• REMOTE UTILIZATION OF CONTRACTOR AVIONICS LABORATORIES
OTHER SPACE AVIONICS DEVELOPMENT STRATEGIES

O INFLUENCE THE DEVELOPMENT OF STANDARDS, INTERFACE SPECIFICATIONS, AND CHIP DEVICES, & OTHER INDUSTRY AVIONICS TRENDS

O CONSIDER A LIFE CYCLE PROCESS FOR DEVELOPMENT AND MAINTENANCE OF AVIONICS HARDWARE AND SOFTWARE

• OPERATIONS COSTS ARE THE NUMBER ONE TOTAL PROGRAM COST DRIVER FOR EXTENDED DURATION SPACE PROGRAMS

SATWG CALENDAR

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Strategic Avionics Technology Working Group
"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, users and customers.

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

- Once the customer has incorporated the technology into his advanced development program, the bridging project will either focus on other applications or terminate so that other technology area bridging projects may be initiated.
AUTONOMOUS GUIDANCE, NAVIGATION AND CONTROL

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

ELECTRICAL ACTUATION
Bridging Activities

OBJECTIVES
- Develop and demonstrate a representative high power, cost effective electrical actuation system suited for secondary objectives, including flight / ground fluid control valves and surface systems applications.

PAYOFFS
- Elimination of maintenance intensive high pressure hydraulic systems
- Elimination of central hydraulic APU's, hazardous / toxic fluids
- Reduction of labor intensive tests, preparation time, and operations costs
- Improved dispatch reliability, operability, and abort recovery
- Improved launch window (late hold capability)
- Reduced stand-down time, rapid change-out / retest
Electrical Actuation Technology Bridging Team

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

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

MSFC
- Thrust Vector Control & Propulsion Control Valve applications

KSC
- ELA checkout and operational concepts
- Costs / benefits analysis for Shuttle ops. processing

SSC
- Develop/demonstrate ELA technology for SSME test stand fluid control valve application
- Costs / benefits analysis of ground test ops. (quantify savings of eliminating hydraulic valves)

Electrical Actuation Technology Bridging

APPENDIX

STRATEGIC AVIONICS TECHNOLOGY WORKING GROUP
AND
SUB - PANEL CHARTERS

KENNETH J. COX
O PROVIDE A FORUM TO SUPPORT THE DEVELOPMENT OF A SPACE STRATEGIC AVIONICS TECHNOLOGY PLAN INCLUDING
O AVIONICS TECHNOLOGY STRATEGIES AND GOALS
O LONG-RANGE ELEMENTS TO SUPPORT FUTURE AND DEVELOPING PROGRAMS
O SUPPORT ELEMENTS FOR EXISTING PROGRAMS INCLUDING OPERATIONAL INFRASTRUCTURE
O GUIDELINES FOR FUNCTIONAL COMMONALTY OF AVIONICS ARCHITECTURES

O DEVELOP COOPERATIVE PROGRAMS BETWEEN CODE R AND CODE M/S

O PROVIDE FOR AVIONICS TECHNICAL INTERCHANGE BETWEEN NASA TECHNOLOGISTS, ADVANCED DEVELOPERS, PROGRAMS, OPERATORS, AND MAJOR AVIONICS CONTRACTORS

O PROMOTE IMPROVED TECHNOLOGY TRANSFER PROCESSES, SUCH AS "BRIDGING," BETWEEN TECHNOLOGISTS, DEVELOPERS, CONTRACTORS, AND PROGRAM MANAGERS

O DEVELOP INNOVATIVE IDEAS AND ACT AS A CONSULTING GROUP TO SUPPORT NASA NEW PROGRAMS

O DEVELOP AN ADVANCED AVIONICS ARCHITECTURE TECHNOLOGY PLAN FOR SPACE TRANSPORTATION AND EXPLORATION PROGRAMS WITH EMPHASIS ON LOWER LIFE CYCLE COST AND MORE EFFICIENT DDT&E COST

O DEVELOP AN EARLY TOP-LEVEL IDENTIFICATION OF AVIONICS ARCHITECTURE REQUIREMENTS AND DESIGN DRIVERS

O DEFINE SYSTEM ARCHITECTURE, SOFTWARE, AND HARDWARE STANDARDS FOR DEVELOPMENT AND VERIFICATION

O ESTABLISH AN OPEN ARCHITECTURE APPROACH

O INCORPORATE TOP-DOWN CONCEPTS INVOLVING MODULARITY, COMMONALITY, SCALABILITY, AND INTERFACE STANDARDS

O INVESTIGATE AVIONICS COMMONALITY UTILIZATION STRATEGIES BETWEEN
O EARTH TO ORBIT LAUNCH VEHICLES
O ORBITAL VEHICLES
O TRANSFER AND EXCURSION VEHICLES
O MOBILE AND FIXED SURFACE SYSTEMS

O FACILITATE SUPPORTABILITY AND LOGISTICS SUPPORT

ORIGINAL PAGE IS OF POOR QUALITY
O PROVIDE A FORUM FOR AVIONICS ARCHITECTURE TECHNOLOGY INTERCHANGE BETWEEN NASA, AEROSPACE INDUSTRY PARTNERS, DOD, AND THE COMMERCIAL SECTOR
O SUPPORT IDENTIFICATION OF AVAILABLE AND FUTURE TECHNOLOGY
O IDENTIFY CRITICAL TECHNOLOGY AREAS FOR NASA
O ESTABLISH INITIAL TEST BED STANDARDS FOR PARTICIPATING CENTERS

O DEVELOP AN IMPROVED TECHNOLOGY INSERTION PROCESS WITH A GOAL OF LOWER LIFE-CYCLE COST, FASTER PROJECT UTILIZATION, AND EVER-DECREASING OPERATIONAL COSTS
O FOCUS ATTENTION ON THE PROCESSES FOR THE DEVELOPMENT AND MAINTENANCE OF AVIONICS SOFTWARE OVER THE LIFE-CYCLE OF MAJOR SYSTEMS
O DEFINE CRITICALITY CATEGORIES BASED ON CREW SAFETY, MISSION SUCCESS, MISSION SUPPORT, AND ENGINEERING ANALYSIS THAT MAY PERMIT EARLY TECHNOLOGY ENHANCEMENT UPGRADES IN SELECTED AREAS
O EVALUATE METHODS FOR DEFINING EVOLVABLE REQUIREMENTS, DETERMINING REGRESSION TESTING POLICY AND ESTABLISHING REVERIFICATION CRITERIA

O DEVELOP INNOVATIVE IDEAS AND CREATE A CORPS OF EXPERTISE TO ACT AS A CONSULTING GROUP TO SUPPORT PROGRAMS

O SERVE AS THE FOCUS FOR AUTOMATED VEHICLE HEALTH MONITORING AND CHECKOUT ACTIVITIES; PROVIDE TECHNICAL INTERCHANGE AMONG NASA, DOD, AND PRIVATE SECTOR EFFORTS AND ADVOCACY FOR FURTHERING THE STATE-OF-THE-ART
O DEVELOP SYSTEM REQUIREMENTS AND ARCHITECTURAL CONCEPTS FOR AUTOMATED CHECKOUT AND MONITORING OF LAUNCH AND SPACE VEHICLES
O DEVELOP INTEGRATION STRATEGIES FOR THE INCORPORATION OF AUTOMATED CHECKOUT AND MONITORING SYSTEMS INTO FUTURE EARTH-TO-ORBIT, CREW RETURN, AND SPACE TRANSFER VEHICLES
O IDENTIFY AREAS FOR FUTURE RESEARCH AND TECHNOLOGY ACTIVITIES
O SERVE AS A CONSULTANT GROUP IN SUPPORT OF NASA PROGRAMS
O DEFINE AND PROVIDE FOR APPROPRIATE TEST AND DEMONSTRATIONS OF TECHNOLOGY AND SYSTEM CONCEPTS
O DEVELOP REQUIREMENTS AND PLANNING FOR TEST FACILITIES AND EQUIPMENT
O PUBLISH PERIODIC REPORTS PERTINENT TO ONGOING OR FUTURE PROGRAMS
COMMUNICATIONS AND TRACKING PANEL CHARTER

KENNETH J. COX

O DEVELOP AN ADVANCED COMMUNICATIONS AND TRACKING SYSTEMS TECHNOLOGY PLAN FOR SPACE TRANSPORTATION AND EXPLORATION PROGRAMS WITH EMPHASIS ON LOWER DDT&E COSTS, AND LOWER LIFE-CYCLE COSTS

O DEVELOP AN EARLY DEFINITION OF TOP LEVEL COMMUNICATIONS AND TRACKING SYSTEM REQUIREMENTS AND DESIGN DRIVERS

O DEFINE SYSTEMS ARCHITECTURE REQUIREMENTS AND STANDARDS FOR HARDWARE/SOFTWARE DEVELOPMENT AND VERIFICATION

O ESTABLISH AN OPEN ARCHITECTURE APPROACH, WHICH INCORPORATES MODULARITY, COMMONALITY, AND INTERFACE STANDARDIZATION

O INVESTIGATE STRATEGIES FOR MULTIPROGRAM DEVELOPMENT OF COMMON AND NEAR-COMMON ELEMENTS, COMMUNICATIONS SERVICES STANDARDS, TRACKING AND NAVIGATION SENSOR STANDARDS

O PROVIDE A FORUM FOR COMMUNICATIONS AND TRACKING SYSTEMS TECHNOLOGY INTERCHANGE BETWEEN NASA, AEROSPACE INDUSTRY PARTNERS, DOD, AND THE COMMERCIAL SECTOR

O SUPPORT IDENTIFICATION OF AVAILABLE TECHNOLOGY

O DEVELOP PROJECTIONS OF FUTURE TECHNOLOGY CAPABILITIES

O IDENTIFY CRITICAL TECHNOLOGY AREAS FOR NASA PROGRAMS

O IDENTIFY CURRENT AND PLANNED TEST BED CAPABILITIES AT PARTICIPATING CENTERS, AND ESTABLISH STANDARDS AND PROCEDURES FOR UTILIZATION

COMMUNICATIONS AND TRACKING PANEL CHARTER (CONT'D)

KENNETH J. COX

O DEVELOP AND FOSTER INNOVATIVE IDEAS AND CREATE A CORPS OF EXPERTISE TO ACT AS A COMMUNICATIONS AND TRACKING SYSTEMS CONSULTING GROUP TO SUPPORT NASA PROGRAMS. PURSUE TECHNOLOGICAL ADVANCES WHICH WILL PROVIDE:

O GREATER SPECTRUM EFFICIENCY

O AUTOMATED SYSTEM MANAGEMENT AND CONTROL

O GRACEFUL SYSTEM DEGRADATION AS THE RESULT OF FAILURES

O GREATER RF/EMI IMMUNITY

O VERY LOW POWER CONSUMPTION

O NEW AREAS OF SPECTRUM UTILIZATION

O HIGHER IMAGE PROCESSING RATES

O INCREASED MATURITY LEVELS OF SENSOR FUSION

O HIGHER LEVELS OF CAPABILITY FOR AUTONOMOUS OPERATIONS

ORIGINAL PAGE IS OF POOR QUALITY
O DEVELOP AN ADVANCED POWER MANAGEMENT AND CONTROL SYSTEM TECHNOLOGY PLAN FOR SPACE TRANSPORTATION AND EXPLORATION PROGRAMS INCLUDING:

O ADVANCED INTEGRATED ELECTRICAL POWER SYSTEM TECHNOLOGIES TO SUPPORT FUTURE AND DEVELOPING PROGRAMS

O LONG RANGE STRATEGIES AND GOALS TO ENSURE FAULT TOLERANT POWER FOR ALL MISSION SCENARIOS

O DEVELOP OPERATIONAL INFRASTRUCTURES TO SUPPORT FUTURE TRANSPORTATION AND EXPLORATION PROGRAMS

O PROVIDE GUIDELINES FOR FUNCTIONAL COMMONALTY OF ELECTRICAL POWER MANAGEMENT AND CONTROL ARCHITECTURES ACROSS PROGRAMS

O PROVIDE A FORUM FOR ELECTRICAL POWER MANAGEMENT AND CONTROL TECHNOLOGY INTERCHANGE AMONG NASA, DOD, INDUSTRY AND THE COMMERCIAL SECTOR

O IDENTIFY AREAS FOR FUTURE RESEARCH AND TECHNOLOGY DEVELOPMENT ACTIVITIES

O DEFINE REQUIREMENTS FOR TECHNOLOGY DEVELOPMENT EFFORTS

O DEVELOP TEST FACILITIES AND EQUIPMENT

O DEVELOP AND PROVIDE FOR APPROPRIATE TESTS AND DEMONSTRATIONS OF TECHNOLOGY APPLICATIONS AND SYSTEMS CONCEPTS

O DEVELOP AN IMPROVED TECHNOLOGY INSERTION PROCESS TO REDUCE PERCEIVED RISK, LOWER OPERATIONAL AND LIFE-CYCLE COSTS, AND MAXIMIZE SYSTEM OPERABILITY AND POWER AVAILABILITY

O THE GN & C PANEL IS ESTABLISHED TO PROVIDE A FORUM TO FACILITATE THE EXCHANGE OF INFORMATION AMONG TECHNOLOGY DEVELOPERS, USERS, AND THE SPACE AVIONICS COMMUNITY, AS A WHOLE

O THE PANEL WILL GATHER & DISSEMINATE USER NEEDS / REQUIREMENTS, AND IDENTIFY & CATALOG TECHNOLOGY STATUS VIA LIVING DOCUMENTS

O FUTURE GN & C TECHNOLOGY PROJECTIONS & CAPABILITIES WILL BE RESEARCHED & MADE AVAILABLE

O THE PANEL WILL BE RESPONSIBLE FOR FOSTERING TECHNOLOGY INTERCHANGE BETWEEN NASA, DOD, AND THE COMMERCIAL SECTOR

O THE PANEL CHARTER DOES NOT INCLUDE THE DIRECTION OR MANAGEMENT OF TECHNOLOGY DEVELOPMENT
Integrated Technology Plan Overview

Avionics Technology Plan

Integrated Technology Plan Elements

5.2.7 ETO Vehicle Avionics
5.2.7.1 Avionics Architecture
5.2.7.2 Avionics Software
5.2.7.3 Vehicle Health Management
5.2.7.4 GN&C
5.2.7.5 Electrical Actuators
5.2.7.6 Landing/Recovery Systems
5.2.7.7 Power Management & Control

5.3.8 Transfer Vehicle Avionics
5.3.8.1 Avionics Architecture
5.3.8.2 Avionics Software
5.3.8.3 Vehicle Health Management
5.3.8.4 GN&C
5.3.8.5 Tether Control
5.3.8.6 Electrical Actuators
5.3.8.7 Power Management & Control
5.3.9 Autonomous Landing
5.3.10 Autonomous Rendezvous & Docking
Presentation will cover each Identified Integrated Technology Plan Element and Subelement as follows:

- Overview (at the element level 5.X.X)
- Current & Related Programs (at the subelement level 5.X.X.X)
- Proposed Technology Program (at the subelement level 5.X.X.X)
- Program Benefits (at the subelement level 5.X.X.X)

Note: The Integrated Technology Plan Report for these elements and subelements is over 100 pages. This presentation will be a high level summary of that report.

The next generation of space transports will need to have increased mission safety, more autonomy for reduced crew workload, and reduced operational costs.

- Avionics Architecture - for increased avionics performance
- Avionics Software - addresses mission and safety features in software operating systems kernel
- Vehicle Health Management - for self diagnosing and self compensating integrated systems
- Power Management and Control - for reliable, universal, modular, electrical power bus systems
- Guidance, Navigation, and Control - offers efficient computational algorithms and sensors, software tools to analyze complex body dynamics, and enhanced launch and land on demand probability
- Electrical Actuation Systems - replaces hydraulic systems to enhance system reliability, reduced operational cost
- Advanced Landing & Recovery Systems - for enhanced booster recovery and landing technology

The following advanced vehicles will all require some combination of these advanced technologies:

- HLV, NLS, PLS, CTV, ACRV, ALS, and ELV's

ETO and Transfer Vehicle Avionics technology development share common goals which invites and in fact, for cost effectiveness, dictates collaboration and interfacing between the two areas of development.
### 6.2.7.1 ETO Vehicle Avionics: Avionics Architecture

#### Current & Related Programs

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### 5.2.7.1 ETO Vehicle Avionics: Proposed Technology

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### 5.2.7.1 ETO Vehicle Avionics: Avionics Architecture Program Benefits

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<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
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<tr>
<td>Architecture/ETO Technology</td>
<td>• Definition of interfaces and standards including performance criteria to establish and verify architecture concepts.</td>
<td>• Development of flexible architectures for reduced development and life cycle costs</td>
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<tr>
<td>• Real-Time Distributed Processing</td>
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<td>• Compatibility with ground systems in both performance and architecture</td>
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<tr>
<td>• Develop and prototype via test beds advanced flight data system distributed and multiple heterogeneous processors, memory, buses and other key components operating in real-time.</td>
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<td>• Development of more flexible launch commit criteria and increases in mission safety</td>
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<td>• More effective use of data fusion to increase the machine processing of information for the manned interface.</td>
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<td>• Determine sensitivity factors governing real-time processing performance.</td>
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<td>• High Capacity Processing</td>
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<tr>
<td>• Develop requirements and prototypes for 32 bit and 64 bit processing components, memories and buses; specialized high speed coprocessors such as i960 and R4000; and multi-megabyte memory alternatives and technologies.</td>
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<td>• Non-Stop Computing</td>
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<td>• Develop, build and demonstrate system models exhibiting multi-fault tolerant system and component behavior and which exhibit reconfigurable capability to determine the issues, costs and requirements</td>
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<td>• Determine the technologies needed to test, verify and certify non-stop computing capabilities for space flight operations</td>
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<tr>
<td>• Avionics Displays and Controls</td>
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<tr>
<td>• Define requirements for advanced human-tended display and control interfaces, aids and alternative sensory mechanisms</td>
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<td>• Develop prototype and demonstrate advanced visual environment or holographic display and high fidelity voice control interfaces</td>
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<td>• Determine the technologies needed to test, verify and certify advanced human-machine interface capabilities for flight operations</td>
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### 5.2.7.2 ETO Vehicle Avionics: Avionics Software Current & Related Programs

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<td>• Space Applications GN&amp;C Characteristics and Methods Defined</td>
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<td>• Space Applications GN&amp;C Family Generated and other Applications Identified</td>
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<td>• Space Applications Characteristics and Methods Defined for additional Applications</td>
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<td>• Space Applications Combined Demonstration with Target Avionics Platform</td>
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<td>• Applications-to-RODB Data Type Analysis</td>
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<td>• Matrix-X Simulation Development</td>
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### TECHNOLOGY

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<thead>
<tr>
<th>Software/ETO Technology</th>
<th>Benefits</th>
<th>WHY</th>
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<tbody>
<tr>
<td>Real-Time Distributed Processing</td>
<td>Establishes capability and performance of operating systems distributed across multiple buses, networks and vehicles</td>
<td>Assessment of distributed operating system and services requirements</td>
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<tr>
<td>Develop and demonstrate software models exhibiting multi-fault tolerant system and component behavior and reconfigurable capability with and without human controls</td>
<td>Additional processing capability and performance for the on-board data system.</td>
<td>Compatibility with ground systems in both performance and architecture</td>
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<tr>
<td>Software Reusability</td>
<td>Determination of requirements and components for fault resistant computing for evaluation of concepts, costs and implementation difficulty.</td>
<td>More flexible launch commit criteria and increases in mission safety</td>
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<tr>
<td>Develop and build Computer Aided Systems Engineering (CASE) tool data repository filters for exchanging data between different CASE tools for flight software development</td>
<td>Establishes generic flight software system elements for reuse across any program</td>
<td>Lower development and life cycle costs for the software element</td>
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<tr>
<td>Avionics Software</td>
<td>Determination of effective human interface mechanisms as the complexity and amount of information increase</td>
<td>Aids human data comprehension and response</td>
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### BENEFITS

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<tr>
<th>Avionics Displays and Controls</th>
<th>Navigation, Control &amp; Aeronautics Division</th>
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<tbody>
<tr>
<td>Develop and prototype knowledge based visual, voice and other sensory display and control aids to support human operation of complex systems</td>
<td>A. J. Bordano/EG</td>
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<tr>
<td>Determine the technologies needed to test, verify and certify advanced human-machine interface software</td>
<td>6/26/91</td>
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### WHY

- Establishes capability and performance of operating systems distributed across multiple buses, networks and vehicles
- Additional processing capability and performance for the on-board data system.
- Establishes generic flight software system elements for reuse across any program
- Determination of effective human interface mechanisms as the complexity and amount of information increase
- Aids human data comprehension and response

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### 5.2.7.3 ETO Vehicle Avionics: Vehicle Health Management

**Current & Related Programs**

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<td>Application of AI/Expert Systems to VHM</td>
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<tr>
<td>Knowledge Based Autonomous Test Engineer (KATE)</td>
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<td>Integrated Health Management Lab</td>
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<td>Acoustic/Ultrasonic Fault Prediction &amp; Detection</td>
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<td>Fault Isolation Expert System</td>
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**Proposed Technology**

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<td>Open Architecture Standard Development and Promulgation</td>
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<td>KSC NSTS Orbiter Processing flow VHM technology insertion/demonstration</td>
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<td>Development/demonstration of embedded closed loop sim</td>
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<td>Demonstrate acoustic diagnosis of turbomachinery</td>
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<td>Compare cost/benefits of physical and analytic redundancy in VHM Test Bed</td>
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<tr>
<td>Demonstrate Robust Flight Control Implementations</td>
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<tr>
<td>Develop system level fault tolerance design tools</td>
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<tr>
<td>Flight demo of VHM/Fault Management Implementation</td>
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### 5.2.7.3 ETO Vehicle Avionics: Vehicle Health Management Program Benefits

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<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated vehicle checkout</td>
<td>• Expedite pre-launch operations; minimize personnel cost</td>
<td>• Delays, launch aborts and recycles are too expensive in direct &amp; indirect costs; more efficient operations</td>
</tr>
<tr>
<td>Autonomous vehicle health management</td>
<td>• Maximize mission capabilities, performance; enhanced mission success probability</td>
<td>• Alleviates and curtails effects of in-flight failures and degradations</td>
</tr>
<tr>
<td>VHM system architecture and software</td>
<td>• Enables incremental adoption of VHM concepts and new hardware; minimizes technical risk; improves efficiency and robustness</td>
<td>• Different systems, technologies and sensors will develop at different times</td>
</tr>
<tr>
<td>VHM sensors</td>
<td>• Increased knowledge of complex equipment's health condition</td>
<td>• Prognosis and timely fault detection capabilities are required for complex equipment operating in extreme environments</td>
</tr>
<tr>
<td>Residual lifetime estimation, dynamic health &amp; status assessment</td>
<td>• Enhanced mission success</td>
<td>• Component health is continuously monitored and incipient failures are detected before they become acute</td>
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<tr>
<td></td>
<td>• Improved performance margins</td>
<td>• Performance redlines can be calculated dynamically and need not rely on statistical estimates of &quot;beginning of life&quot; (optimistic) or &quot;end of life&quot; (pessimistic) projections of system capabilities</td>
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<tr>
<td></td>
<td>• Improved cost effectiveness of processing and maintenance operations</td>
<td>• System elements may be repaired when needed as opposed to following a periodic (overly conservative) schedule</td>
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### 5.2.7.4.1 ETO Vehicle Avionics: GN&C Algorithms Current & Related Programs

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<td>Autonomous Launch Vehicle Reconfiguration</td>
<td>Q2 Q3 Q4</td>
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<td>Q1 Q2 Q3 Q4</td>
<td>Q1 Q2 Q3 Q4</td>
<td>Q1 Q2 Q3 Q4</td>
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<tr>
<td>• Baseline requirements for current vehicles</td>
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<td>Advanced GPS Navigation Techniques</td>
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<tr>
<td>• Initial tests in aircraft</td>
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<tr>
<td>Autonomous Rendezvous/Docking GN&amp;C</td>
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<tr>
<td>• Baseline requirements under development</td>
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<td>Numeric/AI Guidance Techniques</td>
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<td>Advanced GPS Navigation Techniques</td>
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<td>Autonomous Rendezvous/Docking GN&amp;C</td>
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**TECHNOLOGY**

- **Autonomous Launch Vehicle GN&C Reconfiguration**
  - Identify new approaches to current launch vehicle algorithms and processes that reduce or eliminate recurring engineering analysis, computer simulation and FRR activities

- **Atmospheric Adaptive Entry GN&C**
  - Develop a GN&C system that can actively control heat rate, heat load or temperature while maintaining an accurate landing point

- **Numeric/AI Guidance Techniques**
  - Utilize artificial intelligence techniques to provide accurate, reliable guidance solutions using exact environment models

- **Parallel Processing GN&C Methods**
  - Develop new approaches and algorithms that can be effectively used on parallel processing computers

- **Advanced GPS Navigation Techniques**
  - Develop new algorithms and environment models to improve GPS navigation accuracy for ETO vehicles

- **Autonomous Rendezvous/Docking GN&C**
  - Develop algorithm concepts and approaches to support autonomous rendezvous

**BENEFITS**

- Recurring launch operations costs can be reduced through automation and improvements to current GN&C algorithms and operations approaches

- Improved thermal protection margin and reduced sensitivity to atmospheric and system uncertainties

- Accurate, autonomous space vehicle navigation

- Recurring costs reduced through automation and improvements to current GN&C algorithms and operations approaches

**WHY**

- Elimination of manpower intensive activities is needed for the next generation of launch vehicles

- Entry vehicle landing accuracy and thermal protection system requirements are driven by the ability of the GN&C system to adapt to dispersed atmospheric conditions

- Changing environmental conditions can degrade doppler measurements

- Current AR&D operations rely heavily on ground based manual procedures
5.2.7.4.2 ETO Vehicle Avionics:
GN&C Sensors
Current & Related Programs

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<tr>
<td>Optical Sensors for GN&amp;C Applications</td>
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<tr>
<td>• Optical Sensors for GN&amp;C Applications</td>
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<tr>
<td>• Set requirements and proof of concept testing for the High</td>
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<tr>
<td>Resolution Attitude Rate Sensor</td>
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<tr>
<td>Inertial Components and Systems for GN&amp;C Applications</td>
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<tr>
<td>• Evaluate inertial components for vendor specification compliance and vehicle applications</td>
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<tr>
<td>• Evaluate state-of-the-art inertial sensors for launch vehicle, orbital vehicles, and payload packages</td>
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<tr>
<td>• Develop inertial sensor packages for payload inertial measurements</td>
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<tr>
<td>• Maintain database of state-of-the-art and proposed inertial sensor and system technologies</td>
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5.2.7.4.2 ETO Vehicle Avionics:
GN&C Sensors
Proposed Technology

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<tbody>
<tr>
<td>Typical Schedule for GN&amp;C Sensor Investigation</td>
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<tr>
<td>Specify requirements for sensor and system hardware</td>
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<tr>
<td>Specify requirements for software algorithms and databases</td>
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<tr>
<td>Reinvestigate current technology for required hardware and software</td>
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<tr>
<td>Investigate and develop various algorithms</td>
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<tr>
<td>Design, build, and laboratory test of prototype system</td>
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<tr>
<td>Field test of prototype system in laboratories, and/or remote observatories and sites</td>
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GN&C Sensor Investigation

- Autonomous Attitude Determination System Development
- Optical Rate Sensor Development
- Horizon/Terrain Mapping/Feature Recognition Sensor Development
- Magnetostrictive Sensor
- Fiber-Optic Gyro Research and Development
- Vibrating Beam Accelerometer
- Coriolis Accelerometer Inertial Measurement Unit (CAIMU)
- Capacitive, Magnetic Suspension IMU (QUBIK)
- Multiple Receiver GPS IMU
- Gravity Wave/Laser Thermo Electric Detector (GW/TED)
- Electrostatic/Micromachined Accelerometer with Hybrid Electronics (EMA)
- Integrated Fiber-Optics Gyro GPS/Inertial Navigation System (IFOPSINS)
## 5.2.7.4.2 ETO Vehicle Avionics: GN&C Sensors

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
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<tbody>
<tr>
<td>Optical Rate Sensor</td>
<td>Precision vehicle attitude rates using optical imaging techniques</td>
<td>Provides reliable imaging real time navigation support for Earth orbit missions</td>
</tr>
<tr>
<td>Autonomous Attitude Determination System</td>
<td>Precision vehicle attitude using optical imaging techniques</td>
<td>Provides reliable real time navigation system for Earth orbit missions</td>
</tr>
<tr>
<td>Horizon Sensor</td>
<td>Precision navigation capabilities using optical imaging techniques</td>
<td>Provides reliable real time navigation support for Earth orbit missions</td>
</tr>
<tr>
<td>Terrain Mapping/Feature Recognition System</td>
<td>Precision navigation capabilities using optical imaging and storage techniques</td>
<td>Provides reliable real time support for Earth orbit missions</td>
</tr>
<tr>
<td>Magnetoresistive Sensor</td>
<td>Azimuth determination in a smaller, lighter, less costly, less power package</td>
<td>Provide light weight, low power consumption azimuth sensor for low earth orbit satellites</td>
</tr>
<tr>
<td>Interferometric Fiber-Optic Gyro (IFOG), Most mature</td>
<td>High Mean Time Before Failure (MTBF) low power, angular rate sensor</td>
<td>Provide highly reliable autonomous navigation and angular rate sensing</td>
</tr>
<tr>
<td>Resonant Fiber-Optic Gyro (RFOG), Least mature</td>
<td>High MTBF, low power, RLG compatible angular rate sensor</td>
<td>Provide highly reliable autonomous navigation and angular rate sensing</td>
</tr>
<tr>
<td>Fiber Optic Gyro Closed Loop</td>
<td>High angular rate inertial sensor with improved rail linearity</td>
<td>Provide highly reliable autonomous navigation and angular rate sensing</td>
</tr>
<tr>
<td>Vibrating Beam Accelerometer</td>
<td>Precision, low power, small, reliable acceleration measurement</td>
<td>Provide highly reliable autonomous navigation and linear acceleration measurement support</td>
</tr>
<tr>
<td>Constrained Acceleration Inertial Measurement Unit</td>
<td>Small, low power/paint count IMU, Only accelerometer required for complete system</td>
<td>Provide highly reliable compact autonomous navigation support</td>
</tr>
<tr>
<td>Capacitive, magnetic suspension IMU (QUBIK)</td>
<td>Single sensor provides all inertial sensing requirements</td>
<td>Provide highly reliable compact autonomous navigation support</td>
</tr>
<tr>
<td>Multiple Receiver GPS IMU</td>
<td>Calculate attitude from relative positions of GPS receivers on common vehicle</td>
<td>Provide navigation for launch and low Earth orbit vehicles</td>
</tr>
<tr>
<td>Gravity Wave/Lens Tilt Effect Detector</td>
<td>Calculate relativistic effects of massive bodies on trajectory and GPS time-keeping</td>
<td>Provide more accurate navigation support for launch trajectories and for GPS navigation systems</td>
</tr>
<tr>
<td>Electrostatic/Lens Accelerometer</td>
<td>High sensitivity, small size, low power</td>
<td>Provide compact autonomous navigation and acceleration measurement support</td>
</tr>
<tr>
<td>Integrated Fiber-Optic Gyro Sensors</td>
<td>High MTBF, self-calibrating Inertial Navigation System</td>
<td>Provide highly reliable navigation support for low Earth orbit missions</td>
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### NASA 5.2.7.5 ETO Vehicle Avionics: Electrical Actuation Current & Related Programs

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<td>General Dynamics 25-40 Horsepower EMA DDT&amp;E Program (SATWG ELA Technology Bridging Program)</td>
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<td>JSC Actuator Test Set and Facility Development and Operation</td>
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<td>Honeywell TVC EMA Development Project</td>
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<td>Assessment of ETO actuation task requirements and ELA suitability</td>
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<td>System Engineering to identify design parameters and sensitivities; key trade criteria</td>
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<td>Evaluate Parker-Hannifin Nosewheel Steering EHA at JSC ATS</td>
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### 5.2.7.5 ETO Vehicle Avionics: Electrical Actuation Program Benefits

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<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
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<tbody>
<tr>
<td>Electromechanical Actuation (EMA)</td>
<td>- Expedite pre-launch operations; minimize personnel costs</td>
<td>- Hydraulic system eliminated; preflight control system checkout is expedited, does not entail hazardous operations</td>
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<td>- Operational safety increased</td>
<td>- Hazardous fluids, stored energy systems, fluid replenishment operations eliminated</td>
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<td>- Distributed system is more fault/damage tolerant</td>
<td>- Distributed system elements; no central single point failures, no fluid couplings to burst or leak</td>
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<td>- Greatly reduced risk of system failures</td>
<td>- Very low system part count</td>
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<tr>
<td>Electrohydrosocial Actuation (EHA)</td>
<td>- Expedite pre-launch operations; minimize personnel costs</td>
<td>- Centralized hydraulic system eliminated; preflight control system checkout is expedited, does not entail periodic hazardous operations</td>
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<tr>
<td></td>
<td>- Operational safety increased</td>
<td>- Hazardous fluids, stored energy systems, fluid replenishment operations eliminated</td>
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<tr>
<td></td>
<td>- Greatly reduced risk of system failures</td>
<td>- Very low system part count</td>
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<td>- Directly applicable in flight-critical applications</td>
<td>- EHA's provide inherent load-sharing ability</td>
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<td>- Overload capacity is similar to conventional hydraulics</td>
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<td>- Actuator can be backdriven with adjustable impedance (variable damping capability)</td>
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<tr>
<td>ELA (all technologies)</td>
<td>- Inherently supports basic constructs of VHM initiative</td>
<td>- Simple electrical and command interface with host vehicle</td>
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<td>- Expedite launch system processing and checkout operations</td>
<td>- Obviates need for external hydraulic support carts</td>
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<td>- Allows system level functionality test at low cost in terms of manpower, time, and special configurations/test support equipment requirements</td>
<td>- Long &quot;shelf life&quot; without need for constant servicing</td>
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<tr>
<td>Magnetostrictive and other direct acting</td>
<td>- Increased reliability</td>
<td>- Extremely low parts count (for magnetostrictive, 1 moving part)</td>
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<td>- Unit cost is reduced</td>
<td>- Devices are mechanically relatively simple</td>
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<td>Demonstrate &amp; Evaluate a 10 Horsepower ELA device</td>
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<td>Demonstrate &amp; Evaluate a 75 Horsepower ELA device</td>
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<td>Design and Qualify a Family of ELAs for Flight Critical Applications</td>
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<td>Integrate an ELA Propulsion Control Valve in SSC SSME Test Stand</td>
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<td>Develop and Validate ELA Fault Management/VHM Strategies</td>
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<td>Demonstrate ELA Fault Management/VHM Strategies in VHM Test Bed</td>
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<td>Flight Demonstration of a Flight Critical ELA</td>
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**Johnson Space Center - Houston, Texas**

5.2.7.5 ETO Vehicle Avionics: Electrical Actuation Program Benefits

Navigation, Control & Aeronautics Division
A. J. Bordano/EG
6/26/91

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**TECHNOLOGY**

- Electromechanical Actuation (EMA)
- Electrohydrosocial Actuation (EHA)
- ELA (all technologies)
- Magnetostrictive and other direct acting
### 5.2.7.6 ETO Vehicle Avionics:
#### Landing/Recovery Systems
#### Current & Related Programs

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<td>• Multi-Body Simulation</td>
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<td>• Baseline set of requirements for multi-body simulation</td>
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### 5.2.7.6 ETO Vehicle Avionics:
#### Landing/Recovery Systems
#### Proposed Technology

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**CG3-13**
### 5.2.7.6 ETO Vehicle Avionics: Landing_Recovery Systems Program Benefits

#### TECHNOLOGY
- **Parachute Aero Sciences**
  - Multi-body simulation development for realistic modeling of parachute system dynamics
  - Computational fluid dynamics code development to model the unsteady flow physics
  - Wind tunnel testing to acquire database for conducting trade studies and assessing scaling effects
  - Flight demonstration to test integrated system performance
- **Advanced Recovery System (ARS) Phase IIIA**
  - Augmented ARS Phase IIIA program for demonstration of flared landing capability
  - Landing flare wind tunnel program to acquire database for procedures development and assessment of scaling effects
- **Parachute GN&C**
  - Inertial simulation capability for realistic modeling of integrated system performance
  - Definition/testing of representative sensor/avionics configuration for assessing environmental effects
  - GN&C software requirements and code development for assessment of system performance

#### BENEFITS
- Realistic modeling of parachute inflation, dynamics of multiple parachutes in a cluster and landing flare simulation
- Provides improved understanding of parachute flowfields to assist in canopy structural design
- Provides database for use in system simulation trade studies
- Physical testing of integrated system
- Further advance knowledge of large scale gliding parachute systems
- Provides database for use in improving definition of flare and development of scaling parameters
- Realistic modeling of integrated system to assess sensor and effector requirements, guidance and flight control algorithms and definition of avionics configuration
- Provides real-time feedback of environmental effects such as winds and density variation to improve landing accuracies
- Provides integrated GN&C system to support parachute landing systems development

#### WHY
- Allows for systems trade studies to yield more optimum design and reduced flight testing requirements
- Provides improved design process and reduced testing requirements
- Provides validation of design tools and assessment of scaling parameters
- Demonstrates deployment, precision flared landing capabilities
- Provides validation of design tools and assessment of scaling parameters
- Allows for systems trade studies to improve system design and improve landing accuracies
- Reduces landing zone requirements by compensating for environmental effects
- Provides integrated system assessment and demonstration of flared landing and targeting accuracies

### 5.2.7.6 ETO Vehicle Avionics: Landing_Recovery Systems Program Benefits (Continued)

#### TECHNOLOGY
- **Impact Systems Test Bed**
  - Test bed design/fabrication to evaluate candidate impact attenuation systems
  - Landing system test to assess candidate impact attenuation system performance
- **Advanced Instrumentation**
  - Measurement system development for enhancing system design and validation of design tools
  - Experimental validation of measurement techniques to assess instrumentation accuracies and capabilities to measure flow properties

#### BENEFITS
- Provide capability to evaluate candidate impact attenuation system concepts
- Provides physical testing of candidate systems and concepts
- Provides system to measure local pressures on parachute canopy and loads in suspension lines
- Provides assessment of instrumentation intrusion on local flow field

#### WHY
- Reduces impact conditions for variety of dispersed flight conditions and allows for land landings
- Provides integrated system assessment of impact attenuation capabilities and system certification
- Improve ability to validate new design tools and enhance confidence in system performance
- Improved design process through better understanding of canopy shape and attitude sensitivities

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### 5.2.7.7 ETO Vehicle Avionics: Power Management & Control

**Current & Related Programs**

- Advanced (High Capacity) Fuel Cell Development
- JSC Integrated Actuator/Power System Test Set Facility Development and Operation
- Flywheel Energy Storage Technology Investigation
- Power System Management Expert Systems Development and Demonstration
- Shuttle Power Distribution Brassboard Lab Development and Operations
- Advanced Motor Controller Technology Development

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#### Proposed Technology

**1993**
- Develop and Demonstrate Fault Tolerant Power System Architectures
- Identify Requirements for, Establish Specification of "Integrated Utilities" Interface
- Demonstrate PMAC concepts in VHM Test Bed
- Demonstrate PMAC Concepts in Flight Test Vehicle
- Demonstrate Flywheel Energy Storage Technology
- Develop and Demonstrate High Energy Density Battery Systems

**1994**

**1995**

**1996**

**1997**

---

**CG3-15**
5.2.7.7 ETO Vehicle Avionics: Power Management & Control Program Benefits

TECHNOLOGY | BENEFITS | WHY
--- | --- | ---
• Autonomous reconfiguration among series/parallel circuit paths | • Expedite pre-launch operations; minimize personnel costs | • PMAC implementation supports automated vehicle checkout
 | | • System is more robust and fault tolerant
• Integrated modular service backbone | • Vehicle integration task is simplified | • All required services are provided across a unified interface
 | | • Integrated "utilities bus" characterized by high level of integration and multiplexing, saves weight
• High frequency power distribution and control | • Vehicle performance is improved | • System components are lighter; efficiencies are higher
• High energy density battery systems | • Enhanced mission success probability | • Eliminates requirements for more complex and technically risky dynamic power generation systems for launch vehicles
• Enhanced fuel cells | • Enhanced mission success | • Fuel cell system reliability is increased
 | | • Vehicle performance is increased
• Advanced energy storage and power conditioning devices (i.e. flywheels), advanced motor controllers | • Enhanced compatibility with electrical actuation (ELA) technology; improved system efficiencies | • Power supply, regulation, and conditioning technology is matched to the unique requirements of ELAs

5.3.8 Transfer Vehicle Avionics Overview

- The next generation of transfer vehicles will need to have increased mission safety, more autonomy for unmanned operation or reduced crew workload, and reduced operational costs.
- Transfer Vehicle and ETO Avionics technology development share common goals which invites and in fact, for cost effectiveness, dictates collaboration and interfacing between the two areas of development.
- The goals of the NASA Transfer Vehicle Avionics Technology Development Program are:
  - Build on a foundation provided by similar work for the ETO Vehicle Avionics Technology Development Program.
  - Provide the capability to develop self contained transportation systems for long duration missions where ground support are not readily available.
  - Advance technologies in vehicle avionics architecture, software, health management, GN&C, electrical actuators, and power management and control for short and long duration missions.
- These technology goals are intended to improve efficiency and safety (reliability, robustness, failure tolerance), decrease crew workload, and reduce cost of production/operation in the next generation of Space Transportation Systems.
- A major technology challenge arises in the development of self contained space transportation systems necessary to operate without logistic supply lines, for protracted periods of dormancy, for long term exposures to charged particle/radiation and changing environment expected of the interplanetary space and planet surfaces.
### 5.3.8.1 Transfer Vehicle Avionics:
#### Avionics Architecture Proposed Technology

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<td>• LDF Processing Inflight Mass Data Collection, Trend Analysis, and System Performance Prototype Development</td>
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<td>• Multi-Systems and Multi-Vehicle (MS&amp;MV) Processing Requirements Definition (Including Robotics)</td>
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### 5.3.8.1 Transfer Vehicle Avionics:
#### Avionics Architecture Current & Related Programs

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### 5.3.8.1 Transfer Vehicle Avionics: Avionics Architecture Program Benefits

#### TECHNOLOGY
- **Transfer Vehicle Architecture**
  - Long Duration Flight Architecture
  - Develop predictive models which account for cumulative space effects and alternative response mechanisms
  - Prototype and demonstrate candidate architectures including embedded simulations for inflight health status monitoring and training
  - Prototype and demonstrate inflight mass data collection, trend analysis, and system performance forecasting
  - Multi-Systems and Multi-Vehicle Processing
  - Define architectures to use in multi-system and multi-vehicle operations, including advanced robotic architectures
  - Develop and prototype flight data systems of off-Earth systems, Earth-based data systems and alternative mission control center concepts
  - Multi-Systems and Multi-Vehicle Networks
  - Develop and prototype advanced inter-processor communication (local area networks) hardware and inter-vehicle communication (wide area networks) hardware
  - Investigate new test, certification, and verification technologies for advanced network hardware
  - Resynchronization Processing
  - Define requirements for stopping and recovering from single and multiple processing failures for operating under fault conditions and for re-synchronizing processing threads in both single and multiple vehicles
  - **Avionics Displays and Controls**
    - Define requirements for advanced human-tended display and control interfaces, aids and alternative sensory mechanisms
    - Develop, build, prototype and demonstrate advanced visual, environmental display and high fidelity voice control interfaces

#### BENEFITS
- Definition of architectures and standards to evaluate concepts and systems before design commitment
- Evaluation of the data systems with heterogeneous components and alternate combinations of humans and robotics
- Efficient data communication in both local and wide area environment
- Realistic testing of time -to- data synchronization and faults recovery across single and multiple vehicles
- Efficient data fusion processes to eliminate comprehension overload on the human senses

#### WHY
- Establish criteria for long duration flight stresses such as dormancy
- Development of standards for operating at different levels of autonomy across multiple vehicles
- Effective data communication
- Satisfy mission performance and success criteria
- Acceptability of advanced human-machine interfaces

### 5.3.8.2 Transfer Vehicle Avionics: Avionics Software Current & Related Programs

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A. J. Bordano/EG 6/26/91

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5.3.8.2 Transfer Vehicle Avionics: Avionics Software Program Benefits

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<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
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<tr>
<td>Transfer Vehicle Software</td>
<td>• Better understanding of the software requirements operating under degrading or aging system components</td>
<td>• Software to support time degradation effects</td>
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<tr>
<td>• Long Duration Flight Algorithm and Remote Control Model</td>
<td>• Assessment of software features for operation across heterogeneous systems and vehicles</td>
<td>• Operations across a remote and diverse fleet</td>
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<tr>
<td>• Alternative Long Duration Algorithm and Remote Control Prototype</td>
<td>• Development of data communication for interacting non-Earth based mission</td>
<td>• Efficient data communication both inter and intra vehicles</td>
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<tr>
<td>• Case Tool Development for Auto Code Print, Data Exchange, Config</td>
<td>• Establish and demonstrate software recoverability for both inter and intra vehicles</td>
<td>• Support to long duration and remote missions</td>
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<tr>
<td>• Multi-Systems/Vehicle (MS&amp;MV) Interface and SW Requirements</td>
<td>• Provides effective approaches for increasing software support to human data comprehension</td>
<td>• Human-machine interface evaluation and acceptance</td>
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<td>• MS&amp;MV Flight Data System Interface Development</td>
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### 5.3.8.3 Transfer Vehicle Avionics: Vehicle Health Management Proposed Technology

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<tr>
<td>• Application of AI/Expert Systems to VHM</td>
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<td>• Knowledge Based Autonomous Test Engineer (KATE)</td>
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<td>• STS OMS/RCS Upgrade</td>
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<td>• Open Architecture &amp; Integrated VHM Study</td>
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<td>• Anomaly Propagation Tracker</td>
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<td>• Integrated Health Management Lab</td>
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<td>• Failure Environment Analysis Tool</td>
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<td>• RAMTIP</td>
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<td>• Fault Isolation Expert System</td>
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### 5.3.8.3 Transfer Vehicle Avionics: Vehicle Health Management Current & Related Programs

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<td>• Development/Operation of VHM test bed - Transfer system emphasis</td>
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<td>Q3 Q4</td>
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<td>• VHM Functional Allocation and Partioning Trade Study</td>
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<td>• Sensor technology development (smart/autonomous sensors, smart skin)</td>
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<td>• Open Architecture Standard Development and Promulgation</td>
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<td>• Development/demonstration of embedded closed loop simulation</td>
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<tr>
<td>• Compare cost/benefits of physical and analytic redundancy in VHM Test Bed</td>
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<tr>
<td>• Develop system level fault tolerance design tools</td>
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<tr>
<td>• Flight demonstration of VHM/Fault Management Implementation</td>
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</table>
### 5.3.8.3 Transfer Vehicle Avionics: Vehicle Health Management Program Benefits

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<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
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</table>
| Automated vehicle checkout
  - performed continuously and without human intervention | * Increased prospects of system survival and mission success in harsh environments | * VHM allows superior insight into system conditions; supports both human and machine-based decisions |
| Autonomous vehicle health management | * Maximize mission capabilities, performance; enhanced mission success probability | * Alleviates and circumvents effects of in-flight failures and degradations; VHM techniques allow weight and power savings by substituting software intelligence for some physical redundancy |
| VHM system architecture and software | * Enables incremental adoption of VHM concepts and new hardware; minimizes technical risks; improves efficiency and robustness | * Different systems, technologies and sensors will develop at different times |
| VHM sensors (physical sensing devices, analytic and other synthetic redundancy techniques) - use of "smart skin" for structures and propellant system elements
  - Distributed sensor architecture | * Improved knowledge of complex equipment's health condition | * Prognostic and timely fault detection capabilities are required for complex equipment operating in extreme environments |
| Residual lifetime estimation, dynamic health & status assessment - mission operations will not be compromised by being forced to rely on devices and systems of questionable reliability | * System is physically and functionally redundant and can withstand large scale physical insult without total loss of functionality | |
| | * Enhanced mission success | * Component health is continuously monitored and incipient failures are detected before they become acute |
| | * Improved performance margins | * Performance redlines can be calculated dynamically and need not rely on statistical estimates of "beginning of life" (optimistic) or "end of life" (pessimistic) projections of system capabilities |
| | * Improved cost effectiveness of processing and maintenance operations | * System elements may be repaired when needed as opposed to following a periodic (overly conservative) schedule |

### 5.3.8.4.1 Transfer Vehicle Avionics: GN&C Algorithms Current & Related Programs

|-------------|------|------|------|------|------|
| Autonomous Navigation in Interplanetary Space
  * Preliminary concept development | | | | | |
| Autonomous Rendezvous/Docking GN&C
  * Baseline requirements under development | | | | | |

**NASA**

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### 5.3.8.4.1 Transfer Vehicle Avionics: GN&C Algorithms

#### Program Benefits

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<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
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<tbody>
<tr>
<td>Precision Orbit GN&amp;C</td>
<td><strong>Development of new approaches and algorithms for maintaining extremely precise orbits</strong></td>
<td>Allows efficient use of geosynchronous orbits and Earth/Moon, Earth/Sun, Sun/Mars libration points</td>
</tr>
<tr>
<td>Low Thrust Vehicle GN&amp;C</td>
<td><strong>Development of new GN&amp;C algorithms for use on extremely low thrust to weight transfer vehicles</strong></td>
<td>Will allow effective use of advanced propulsion systems such as nuclear electric</td>
</tr>
<tr>
<td>Advanced Analytical Propagation</td>
<td><strong>Development of new analytical orbit propagation techniques for onboard use</strong></td>
<td>Analytic approaches are computationally more efficient than numeric approaches and provide more assurance of convergence</td>
</tr>
<tr>
<td>GN&amp;C for Vehicles Utilizing Artificial Gravity</td>
<td><strong>Development of GN&amp;C algorithms for vehicles which use spinning structures to provide artificial gravity for crew members</strong></td>
<td>Allow efficient operation of transfer vehicles while simultaneously providing a healthy crew environment</td>
</tr>
<tr>
<td>Autonomous Navigation in Interplanetary Space</td>
<td><strong>Development of autonomous navigation techniques and algorithms for use on deep space missions</strong></td>
<td>Reduce or eliminate requirement for Earth based navigation tracking</td>
</tr>
<tr>
<td>Numerical/AI Guidance Techniques</td>
<td><strong>Utilization of artificial intelligence techniques to provide assured convergence of numeric guidance algorithms</strong></td>
<td>Accurate, reliable guidance solutions using exact environment models</td>
</tr>
<tr>
<td>Parallel Processing GN&amp;C Methods</td>
<td><strong>Development of new approaches and algorithms that can be effectively used on parallel processing computers</strong></td>
<td>Complex GN&amp;C computations can be performed with onboard parallel processing</td>
</tr>
<tr>
<td>Autonomous Rendezvous/Docking GN&amp;C</td>
<td><strong>Development of new GN&amp;C algorithms and approaches to support autonomous rendezvous</strong></td>
<td>Recurring cost savings can be reduced through automation and improvements to current GN&amp;C algorithms and operations approaches</td>
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**NASA**

**Description**

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<td>Precision Orbit GN&amp;C</td>
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<td>Low Thrust Vehicle GN&amp;C</td>
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<td>Autonomous Navigation in Interplanetary Space</td>
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<td>Numerical/AI Guidance Techniques</td>
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<td>Parallel Processing GN&amp;C Methods</td>
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<tr>
<td>Autonomous Rendezvous/Docking GN&amp;C</td>
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### 5.3.8.4.2 Transfer Vehicle Avionics: GN&C Sensors

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<tr>
<td>Optical Sensors for GN&amp;C Applications</td>
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<tr>
<td>• Set requirements and proof of concept testing for the Continuous Stellar Tracking Attitude Reference (CSTAR)</td>
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<tr>
<td>• Set requirements and proof of concept testing for the High Resolution Attitude Rate Sensor</td>
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<td>Inertial Components and Systems for GN&amp;C Applications</td>
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<tr>
<td>• Evaluate inertial components for vendor specification compliance and vehicle applications</td>
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<tr>
<td>• Evaluate state-of-the-art inertial sensors for launch vehicle, orbital vehicles, and payload packages</td>
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<tr>
<td>• Develop inertial sensor packages for payload inertial measurements</td>
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<tr>
<td>• Maintain database of state-of-the-art and proposed inertial sensor and system technologies</td>
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### Proposed Technology

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<tr>
<td>Typical Schedule for GN&amp;C Sensor Investigation</td>
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<tr>
<td>• Specify requirements for sensor and system hardware</td>
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<tr>
<td>• Specify requirements for software algorithms and databases</td>
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<tr>
<td>• Research the current technology for required hardware and software</td>
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<tr>
<td>• Investigate and develop various algorithms</td>
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<td>• Design, build, and laboratory test of prototype system</td>
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<td>• Field test of prototype system in laboratories, and/or remote observatories and sites</td>
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### GN&C Sensor Investigation

- Autonomous Attitude Determination System Development
- Optical Rate Sensor Development
- Horizon/Terrain Mapping/Feature Recognition Sensor Development
- Magnetoelastic Sensor
- Fiber-Optic Gyro Research and Development
- Vibrating Beam Accelerometer
- Coriolis Accelerometer Inertial Measurement Unit (CAIMU)
- Capacitive, Magnetic Suspension IMU (QUBIK)
- Gravity Wave/Lens Thirring Eflac Detector (GWLED)
- Electrostatic/Micromachined Accelerometer with Hybrid Electronics (EMA)
### TECHNOLOGY

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Rate Sensor</td>
<td>• Precision vehicle attitude rates using optical techniques</td>
<td>• Provides reliable imaging real time navigation support for extended Lunar and Mars missions</td>
</tr>
<tr>
<td>Autonomous Attitude Determination System</td>
<td>• Precision vehicle attitude using optical imaging techniques</td>
<td>• Provides reliable real time attitude determination system for extended Lunar and Mars missions</td>
</tr>
<tr>
<td>Horizon Sensor</td>
<td>• Precision navigation capabilities using optical imaging techniques</td>
<td>• Provides reliable real time navigation support for Lunar and Mars exploratory missions</td>
</tr>
<tr>
<td>Terrain Mapping/Feature Recognition System</td>
<td>• Precision navigation capabilities using optical imaging and storage techniques</td>
<td>• Provide lightweight attitude sensor for Earth and Mars orbit that requires little power for operation</td>
</tr>
<tr>
<td>Magnetoresistive Sensor</td>
<td>• Provides azimuth determination in a smaller, lighter, less costly, less power package</td>
<td>• Provide highly reliable autonomous navigation and angular rate sensing for Lunar and Mars missions</td>
</tr>
<tr>
<td>Interferometric Fiber-Optic Gyro (FOG) Most mature</td>
<td>• High Mean Time Before Failure (MTBF) low power, angular rate sensor</td>
<td>• Provide highly reliable autonomous navigation and angular rate sensing for Lunar and Mars missions</td>
</tr>
<tr>
<td>Resonant Fiber-Optic Gyro (RFOG) Least mature</td>
<td>• High MTBF, low power, RLG compatible angular rate sensor</td>
<td>• Provide highly reliable autonomous navigation and angular rate sensing for Lunar and Mars missions</td>
</tr>
<tr>
<td>Fiber Optics Gyro Closed Loop</td>
<td>• High angular rate inertial sensor with improved rate linearity over Open Loop FOG’s</td>
<td>• Provide highly reliable autonomous navigation and angular rate sensing for Lunar and Mars missions</td>
</tr>
<tr>
<td>Vibrating Beam Accelerometer</td>
<td>• Precision, low power, small, reliable acceleration measurement</td>
<td>• Provide highly reliable autonomous navigation and linear acceleration measurement</td>
</tr>
<tr>
<td>Coriolis Acceleration Inertial Measurement Unit (IMU)</td>
<td>• Small, low power/pack IMU. Only accelerometers required for complete system</td>
<td>• Provide highly reliable compact autonomous navigation support for Lunar and Mars missions</td>
</tr>
<tr>
<td>Capacitive, Magnetic</td>
<td>• Single sensor provides all inertial sensing requirements</td>
<td>• Provide highly reliable compact autonomous navigation support for Lunar and Mars missions</td>
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<tr>
<td>Suspension IMU (OLUBIK)</td>
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<tr>
<td>Gravity Wave/Lens-Flying Effect Detector</td>
<td>• Calculate the general relativistic effects of massive bodies on vehicle trajectories</td>
<td>• Provide more accurate navigation support for interplanetary trajectories</td>
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<tr>
<td>Electrostatic/Micromachined accelerometer with hybrid electronics</td>
<td>• High sensitivity, small size, low power</td>
<td>• Provide compact autonomous navigation and acceleration measurement for Lunar and Mars missions</td>
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### NASA

5.3.8.5 Transfer Vehicle Avionics:

**Tether Control Current & Related Programs**

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<tr>
<td>Model and Tool Development resulted in an operational STOCS (engineering tool for Tether design and analysis).</td>
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<tr>
<td>Tether/Space Shuttle Interference Problems/Control Interactions and Tether Dynamics Analysis.</td>
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<tr>
<td>Pursue Flight Design Assessment engineering activity/reports/presentations</td>
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<tr>
<td>Initiate/continue effort to model the System Engineering Simulator to accommodate Tether problems</td>
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<tr>
<td>Modify/Update models in STOCS as required</td>
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<tr>
<td>Initiate/completer STOCS rehost to Cray computer</td>
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<tr>
<td>Initiate/completer checkout/validation of the first Tether Satellite System mission and analyze flight results.</td>
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<tr>
<td>Prepare for Tether Flight 2 and 3 and perform post flight analyses</td>
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A. J. Bordano/EG

CG3-24
### TECHNOLOGY BENEFITS WHY

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<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
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<tbody>
<tr>
<td>Remote Docking/Separation</td>
<td>• Determine capture and release scenarios for Space Station and Interplanetary Vehicle operations.</td>
<td>• Demonstration of performance advantages of using tethers for docking and separation. Establish hardware/software requirements for accurate rendezvous/docking.</td>
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<tr>
<td>Passive Attitude Control/Manage Micro-g</td>
<td>• Establish control concepts/micro-g management concepts for various modes of operation of space platforms and interplanetary vehicles.</td>
<td>• Potential for fuel saving and reduced contamination of solar arrays due to jet effluent impingement.</td>
</tr>
<tr>
<td>Alternate Propulsion</td>
<td>• Investigate the use of electrodynamic propulsion for orbital maneuvering using tethers.</td>
<td>• Micro-g management is difficult to achieve, sometimes requiring elaborate mounting schemes. Tethers may offer a more feasible option. Fuel and energy savings for long duration vehicles are possible if tethers can be used for passive control.</td>
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*CG3-25*
### 5.3.8.6 Transfer Vehicle Avionics: Electrical Actuation
#### Current & Related Programs

**Description**
- General Dynamics 25-40 Horsepower EMA DDT&E Program (SATWG ELA Technology Bridging Program)
- JSC Actuator Test Set and Facility Development and Operation
- Honeywell TVC EMA Development Project
- Assessment of ETO actuation task requirements and ELA suitability
- System Engineering to identify design parameters and sensitivities; key trade criteria
- Evaluate Parker-Hannifin Nosewheel Steering EHA at JSC ATS

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**Proposed Technology**
- Demonstrate & Evaluate a 10 Horsepower ELA device
- Demonstrate & Evaluate a Fractional Horsepower ELA device
- Design and Qualify a Family of ELAs for Transfer Vehicle Flight Applications
- Develop and Validate ELA Fault Management/VHM Strategies
- Demonstrate ELA Fault Management/VHM Strategies in VHM Test Bed
- Flight Demonstration of a Flight Critical ELA

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*Navigation, Control & Aeronautics Division*

A. J. Bordano/EG
### 5.3.8.6 Transfer Vehicle Avionics: Electrical Actuation Program Benefits

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<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
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</thead>
</table>
| **Electromechanical Actuation (EMA)** | • Expedite system checkout operations; minimize personnel costs  
• Operational safety increased  
• Distributed system is more fault/damage tolerant  
• Greatly reduced risk of system failures  
• System performance margins are expanded | • Hydraulic system eliminated; system checkout does not entail hazardous operations  
• Hazardous fluids, stored energy systems, fluid replenishment operations eliminated  
• Distributed system elements; no central single point failures, no fluid couplings to burst or leak  
• Very low system part count  
• Actuation system weight is reduced |
| **Electrohydraulic Actuation (EHA)** | • Expedite test and verification operations; minimize personnel costs  
• Operational safety increased  
• Distributed system is more fault/damage tolerant  
• Greatly reduced risk of system failures  
• Directly applicable to flight-critical applications | • Centralized hydraulic system eliminated; checkout is expedited, does not entail periodic hazardous operations  
• Hazardous fluids, stored energy systems, fluid replenishment operations eliminated  
• Distributed system elements; no central single point failures, no external fluid couplings to burst or leak  
• Very low system part count  
• EHAs provide inherent load-sharing ability  
• Overload capacity is similar to conventional hydraulics  
• Actuator can be backdriven with adjustable impedance (variable damping capability) |
| **ELA (all technologies)** | • Inherently supports basic concepts of Vehicle Health Management (VHM) initiative  
• Expedites launch system processing and checkout operations  
• Allows system level functionality test at low cost in terms of manpower, time, and special configurations/test support equipment requirements  
• Increases probability of mission success  
• Decreases reliance on logistics lifetime, requirements for repair | • Simple electrical and command interface with host vehicle  
• Obviates need for external hydraulic support carts  
• Long "shelf life" without need for constant servicing  
• Systems can withstand rigors of extended missions, long duty cycles, protracted dormant periods  
• Extremely low parts count (for magnetostrictive, i moving part!)  
• Devices are mechanically simple |
| **Magnetostrictive and other direct acting** | • Increased reliability  
• Unit cost is reduced | |

### 5.3.8.7 Transfer Vehicle Avionics: Power Management & Control Current & Related Programs

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<tr>
<td>Advanced (High Capacity) Fuel Cell Development</td>
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<tr>
<td>JSC Integrated Actuator/Power System Test Set Facility Development and Operation</td>
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<td>Flywheel Energy Storage Technology Investigation</td>
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<tr>
<td>Power System Management Expert Systems Development and Demonstration</td>
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<td>Shuttle Power Distribution Brassboard Lab Development and Operations</td>
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<td>Advanced Motor Controller Technology Development</td>
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CG3-27
8.3.8.7 Transfer Vehicle Avionics: Power Management & Control

**Proposed Technology**

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<tbody>
<tr>
<td>- Develop and Demonstrate Fault Tolerant Power System Architectures</td>
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<td>- Identity Requirements for, Establish Specification of &quot;Integrated Utilities&quot; Interface</td>
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<tr>
<td>- Demonstrate PMAC concepts in VHM Test Bed</td>
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<tr>
<td>- Demonstrate PMAC Concepts in Flight Test Vehicle</td>
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<tr>
<td>- Demonstrate Flywheel Energy Storage Technology</td>
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<tr>
<td>- Develop and Demonstrate High Energy Density Battery Systems</td>
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</table>

**Program Benefits**

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Autonomous reconfiguration among series/parallel circuit paths</td>
<td>- Expedite system checkout and self-test operations; minimize support personnel costs</td>
<td>- PMAC implementation supports automated vehicle checkout</td>
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<td></td>
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<td>- System is more robust and fault tolerant</td>
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<td></td>
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<td>- Supports gradual degradation rather than sudden total loss of functions</td>
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<tr>
<td>- Integrated modular service backbone</td>
<td>- Vehicle integration task is simplified</td>
<td>- All required services are provided across a unified interface</td>
</tr>
<tr>
<td></td>
<td>- Power, thermal, data capabilities are provided in a balanced fashion</td>
<td>- Integrated &quot;utilities bus&quot; characterized by high level of integration and multiplexing, saves weight</td>
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<tr>
<td></td>
<td>- Vehicle performance is improved</td>
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<tr>
<td>- High frequency power distribution and control</td>
<td>- Vehicle performance is improved</td>
<td>- System components are lighter, efficiencies are higher</td>
</tr>
<tr>
<td>- Multi-mode power generation systems</td>
<td>- Enhanced mission success probability</td>
<td>- Appropriate power generation method is available to match operational environment (low earth orbit, planetary surfaces, deep space)</td>
</tr>
<tr>
<td>- Enhanced fuel cells</td>
<td>- Enhanced mission success</td>
<td>- Fuel cell system reliability is increased</td>
</tr>
<tr>
<td></td>
<td>- Vehicle performance is increased</td>
<td>- Advanced fuel cells have a higher net energy density; power system is lighter for the same capacity</td>
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<td>- Supports requirements for closed loop vehicle systems</td>
<td>- Regeneration capability allows cell to produce water or hydrogen/oxygen</td>
</tr>
<tr>
<td>- Advanced Energy storage and power conditioning devices (i.e., flywheels), advanced motor controllers</td>
<td>- Enhanced compatibility with electrical actuation (ELA) technology; improved system efficiencies</td>
<td>- Power supply, regulation, and conditioning technology is matched to the unique requirements of ELAs</td>
</tr>
</tbody>
</table>
The goal of the NASA Autonomous Landing Technology Development Project is to enable safe, accurate, autonomous spacecraft landing using precision landing at a preselected safe location or on-board detection and avoidance of surface hazards to landing.

Mars and Lunar landings must be achieved safely regardless of surface hazards such as large rocks and steep slopes, be close to the area of mission interest, and occur without real time ground control.

Earth orbiting and return spacecraft, such as the PLS and ACRV, require landing to be achieved reliably and on short notice.

There are three areas of technology thrust:

- **Systems Engineering**: Systems engineering activities include - the evaluation of landing accuracy and the probability of safe landing for alternate landing approaches, and the development of detailed engineering models such as Lunar/Mars terrain models.

- **Precision Landing**: The principal objective of the precision landing work is the development of methods of navigation with respect to the landing site. A second objective of the precision landing work is the development of guidance and flight control algorithms that can compensate for environmental anomalies such as atmospheric density and wind variations while steering to a preselected safe landing site.

- **Hazard Detection & Avoidance Landing**: The objective of the autonomous hazard detection & avoidance work is to develop the sensors, algorithms, and operating strategy that will enable exploration spacecraft to detect during terminal descent a safe landing site.

---

### NASA

#### 5.3.9 Autonomous Landing

**Current & Related Programs**

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<tbody>
<tr>
<td><strong>System Engineering</strong></td>
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<tr>
<td>System Analysis</td>
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<tr>
<td>Baseline set of landing requirements for Mars Rover Sample Return (MRSR) class missions</td>
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<tr>
<td>Planetary Surface Models</td>
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<tr>
<td>An initial version of a Mars Surface Model</td>
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<tr>
<td><strong>Precision Landing</strong></td>
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<tr>
<td>Image Matching Navigation</td>
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<tr>
<td>A baseline set of requirements plus an initial approach to &amp; test of Hybrid Optical Image Matching Navigation</td>
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<tr>
<td><strong>Hazard Detection &amp; Avoidance</strong></td>
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<tr>
<td>Imaging Laser Radar</td>
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<tr>
<td>A baseline set of requirements for a detailed conceptual design of an Imaging Laser Radar</td>
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</tbody>
</table>
### 5.3.9 Autonomous Landing

**Program Benefits**

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<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
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<tbody>
<tr>
<td>System Engineering</td>
<td>• Tools to assess performance of alternate approaches to &amp; prior information requirements for alternate approaches to autonomous landing</td>
<td>• Allow selection of autonomous landing approach that meets the requirements and is affordable</td>
</tr>
<tr>
<td>- System Analysis</td>
<td>- Simulation of landing accuracy vs. performance of navigation, guidance &amp; control</td>
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<tr>
<td>- Simulation of probability of safe landing vs. hazard detection sensor &amp; vehicle performance</td>
<td>Tool to evaluate alternate man-machine interface for autonomous landing GN&amp;C system.</td>
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<tr>
<td>- Develop workstation prototype of man-machine interface for autonomous landing system</td>
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<tr>
<td>- Planetary Surface Models</td>
<td>- Prototype GN&amp;C algorithms for PLS using GPS navigation &amp; LIDAR based wind profiles</td>
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<tr>
<td>- Collect high resolution terrain maps for Earth analogs of Martian terrain types</td>
<td>- Image/Terrain matching navigation with respect to the landing site enables accurate landing</td>
<td>• Allows trade-off between lander robustness &amp; landing site selection while preserving required prob. of safe landing in area of mission interest</td>
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<tr>
<td>- Field test of prototype Navigation &amp; Hazard Detection sensors over Earth analogs of Mars terrain types</td>
<td>- Increased robustness of entry &amp; landing GN&amp;C to atmospheric variability</td>
<td>• Enables landing from Earth orbit to be carried out on short notice</td>
</tr>
<tr>
<td>Precision Landing</td>
<td>- • Hybrid Optical Image Matching Navigation</td>
<td>• Allows trade-off between lander robustness and level of prior information while maintaining required prob. of safe landing for the area of mission interest</td>
</tr>
<tr>
<td>- GN&amp;C for Landing from Earth Orbit</td>
<td>- Prototype GN&amp;C algorithms for PLS using GPS navigation &amp; LIDAR based wind profiles</td>
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<tr>
<td>- Develop Mars terrain model based on Viking, Mars Observer &amp; Earth analog data</td>
<td>- Demonstrate sensor performance under realistic field conditions</td>
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<tr>
<td>Hazard Detection &amp; Avoidance</td>
<td>- Imaging Laser Radar</td>
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<tr>
<td>- Hybrid Interferometric Imager</td>
<td>- Provides capability for detecting a safe landing site in an area that contains some surface hazards</td>
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### 5.3.10 Autonomous Rendezvous & Docking

**Overview**

- The goal of the NASA Autonomous Rendezvous & Docking Technology Development Project is to develop and integrate the technologies that provide the capabilities to perform autonomous rendezvous and docking operations in space.

- Rendezvous & docking operations in U.S. space programs to date have been in manned vehicles only, and with direct crew participation with heavy ground support.

- Development and demonstration of Autonomous Rendezvous & Docking Technologies will:
  - Permit unmanned spacecraft in Earth, Lunar and planetary orbits to operate without large ground support staffs for mission planning, training and conduct
  - Support manned spacecraft operations by augmenting the capabilities of the crew to perform rendezvous and docking without ground support.

- Autonomous Rendezvous & Docking capability is needed for:
  - Cargo Transfer Vehicle (CTV) operations in support of further SSF build-up
  - Spacecraft retrieval / servicing
  - Unmanned upper stage operations
  - In-space build-up and operations of Lunar/Mars exploration vehicles
  - In-space supporting facilities.
## 6.3.10 Autonomous Rendezvous & Docking (AR&D) Current & Related Programs

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<td>AR&amp;D Sensors</td>
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<td>• Functional requirements for AR&amp;D sensors will be identified and compared to the current state of the art.</td>
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<td>• Performed sensor trade study</td>
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<td>• Previous studies and advanced developments for a Laser Docking Sensor, Optical Correlator, and GPS Receiver Processor</td>
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<td>AR&amp;D GN&amp;C Software Algorithms</td>
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<tr>
<td>• Developed and demonstrated graphical playback simulation</td>
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<tr>
<td>• Developed and demonstrated docking simulation</td>
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<tr>
<td>• Functional requirements for new GN&amp;C algorithms will be identified and compared to the current state of the art.</td>
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<td>AR&amp;D Mechanisms</td>
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<td>• Identified baseline AR&amp;D mechanisms requirements</td>
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## 6.3.10 Autonomous Rendezvous & Docking (AR&D) Proposed Technology

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<td>AR&amp;D Sensors</td>
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<tr>
<td>• Evaluate GN&amp;C automatic rendezvous and docking techniques</td>
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<tr>
<td>• Ground demonstration of sensor</td>
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<td>• Flight experiments and demonstrations in a realistic operational environment against a typical mission scenario</td>
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<tr>
<td>AR&amp;D GN&amp;C Software Algorithms</td>
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<tr>
<td>• Preferred GN&amp;C algorithm will be selected and developed</td>
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<tr>
<td>• System validation simulations</td>
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<tr>
<td>• Simulation demonstration of GN&amp;C algorithm and individual elements</td>
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<tr>
<td>• Flight experiments and demonstrations in a realistic operational environment against a typical mission scenario</td>
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<tr>
<td>AR&amp;D Mechanisms</td>
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<tr>
<td>• Preferred AR&amp;D mechanisms will be selected and prototyped</td>
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<tr>
<td>• Ground testing of AR&amp;D mechanisms and individual elements</td>
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<tr>
<td>• Flight experiments and demonstrations in a realistic operational environment against a typical mission scenario</td>
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</table>
### 5.3.10 Autonomous Rendezvous & Docking

**Program Benefits**

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR&amp;D Sensors</td>
<td>• New light weight, low power, and reliable sensors</td>
<td>• Required to support autonomous rendezvous and docking proximity operations.</td>
</tr>
<tr>
<td></td>
<td>• Physical testing of active and passive, point-target and image-based, cooperative and non-cooperative, optical and radio frequency navigation sensor components</td>
<td>• Final testing phase for required AR&amp;D navigation sensor components</td>
</tr>
<tr>
<td>GN&amp;C Algorithms and Systems Simulation Development</td>
<td>• Recurring costs can be reduced through automation and improvements to current GN&amp;C algorithms and operations approaches</td>
<td>• Current AR&amp;D operations rely heavily on ground based manual procedures</td>
</tr>
<tr>
<td></td>
<td>• Assessment of man-machine interfaces for autonomous rendezvous/docking. Construction of support materials for future missions.</td>
<td>• Better understanding of man-machine advanced navigation systems interfaces for future missions</td>
</tr>
<tr>
<td></td>
<td>• Integrated AR&amp;D system suite</td>
<td>• Assessment of new sensor interfacing with other AR&amp;D system components</td>
</tr>
<tr>
<td>AR&amp;D Mechanisms</td>
<td>• Highly reliable, lightweight latches and low power latches, attenuators, etc.</td>
<td>• Support of AR&amp;D</td>
</tr>
<tr>
<td></td>
<td>• Integrated AR&amp;D system suite</td>
<td>• Assessment of individual mechanisms and integrated AR&amp;D system.</td>
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</tbody>
</table>
AVIONICS TECHNOLOGY PLAN

PRESENTATION

FOR

SSTAC CONTROLS COMMITTEE

NASA HEADQUARTERS

ALDO J. BORDANO
JOHNSON SPACE CENTER

AVIONICS TECHNOLOGY PLAN

- BACKGROUND

- CUSTOMER REQUIREMENTS

- TECHNOLOGY PLAN

- CONCLUDING REMARKS
BACKGROUND

• HARDWARE
  • COMPUTER PROCESSORS, BUSSES, NETWORKS, TRANSMITTERS/RECEIVERS
    INPUT/OUTPUT DEVICES, SENSORS, DISPLAYS AND CONTROLS

• SOFTWARE
  • DATABASES, ARTIFICIAL INTELLIGENCE, LANGUAGES, OPERATING SYSTEMS,
    APPLICATION SOFTWARE

• PACKAGING
  • MATERIALS, CONTAINERS, CONNECTORS, HEATING/COOLING COMPONENTS
    INSTALLATION METHODS

• POWER MANAGEMENT
  • CONVERTERS, SWITCHING, MATERIALS

• CHECKOUT AND TESTING
  • HEALTH MONITORING, BUILT IN TEST, EQUIPMENT, REDUNDANCY

BACKGROUND
(CONCLUDED)

• VERIFICATION AND VALIDATION
  • METHODOLOGIES, SIMULATIONS, FACILITIES
BACKGROUND

• SUBSYSTEM ELEMENT TECHNOLOGIES
  • HARDWARE COMPONENTS TO SUPPORT CURRENT AND FUTURE SPACE VEHICLE DEVELOPMENTS AND MISSION REQUIREMENTS (FIBER-OPTIC GYROS, VIBRATING BEAM ACCELEROMETER, LIDAR'S)
  • APPLICATION SOFTWARE TO SUPPORT CURRENT AND FUTURE SPACE VEHICLE DEVELOPMENTS AND MISSION REQUIREMENTS (ADAPTIVE GN&C, AUTOMATIC RENDEZVOUS AND DOCKING, AUTOMATIC LAND LANDING)

• SYSTEM TECHNOLOGIES
  • ARCHITECTURES, VEHICLE HEALTH MONITORING, POWER MANAGEMENT
  • FACILITIES, METHODOLOGIES, PROCEDURES
    • PROTOTYPING, MODELS, SIMULATIONS, LABS, TOOLS
    • VERIFICATION
    • CERTIFICATION
    • CHECKOUT

• GOAL
  • DEVELOP INTEGRATED AVIONIC TECHNOLOGY PLAN FOR SPACE TRANSPORTATION VEHICLES BASED ON NASA AND COMMERCIAL SECTOR NEEDS
    • IDENTIFY CRITICAL TECHNOLOGIES (ELEMENTS, SYSTEMS AND PROCESSES)
    • DETERMINE TECHNOLOGY GAPS
    • RECOGNIZE TRENDS
    • IDENTIFY TRADES
    • DEVELOP ROAD MAPS, SCHEDULES
CUSTOMER REQUIREMENTS

• AVIONIC ARCHITECTURES
  • MODULAR, STANDARDIZED, OPEN, SCALABLE, ROBUST, FAULT TOLERANT, MULTI VEHICLE
  • MINIMIZE DDT&E COSTS
  • SIGNIFICANTLY REDUCE OPERATIONS COST

• SENSORS
  • FOR THE MOST PART BEING DEVELOPED NEAR TERM ORExists TODAY

• FAULT TOLERANT METHODOLOGIES
  • SYSTEM ARCHITECTURES
  • VOTING ALGORITHMS
  • BUILT-IN TEST
  • FAULT RECOVERY (e.g., SPARES)

• DESIGN VERIFICATION AND VALIDATION METHODOLOGIES
  • CONCEPTS, APPROACH, TOOLS, FACILITIES
  • RAPID PROTOTYPING
  • APPLICATION SOFTWARE ARCHITECTURES (e.g., CORE GN&C)
  • AUTOMATED CODE GENERATION
  • TESTING METHODS

• SOFTWARE TECHNOLOGY
  • REAL TIME DISTRIBUTED OPERATING SYSTEMS
  • REDUNDANCY MANAGEMENT (FAULT DETECTION, ISOLATION, RECOVERY AND RECONFIGURATION)
  • MULTI PROCESSOR TASK SCHEDULING
  • MISSION MANAGERS

• AVIONICS PACKAGING TECHNOLOGIES ARE BEING DEVELOPED
CUSTOMER REQUIREMENTS

• POWER MANAGEMENT AND DISTRIBUTION TECHNOLOGIES ARE BEING DEVELOPED
  • NEW APPROACHES, ARCHITECTURES ARE PROPOSED

• SOFTWARE APPLICATION TECHNOLOGIES
  • ADAPTIVE GN&C
  • AUTOMATIC RENDEZVOUS AND DOCKING
  • AUTONOMOUS LANDING

• GROUND/SPACE BASED CHECKOUT TECHNOLOGIES
  • FAULT/TREND ANALYSIS
  • ON-LINE BUILT IN TEST
  • AUTONOMOUS CHECKOUT

CUSTOMER REQUIREMENTS

• AVIONIC ARCHITECTURES
  • CUSTOMIZED OPTIMIZED FOR SIZE, WEIGHT, POWER, PERFORMANCE VS OPEN MODULAR, SCALABLE, STANDARDIZED*
  • DISTRIBUTED VS SEMI DISTRIBUTED
  • FAULT DETECTION AND REDUNDANCY MANAGEMENT (HARDWARE VS SMART SOFTWARE METHODS)
  • PARTS (S LEVEL VS B LEVEL); SENSOR CONFIGURATIONS

• SENSOR AUGMENTATION
  • SUN SENSORS, STAR TRACKERS VS GPS

• DATA MANAGEMENT
  • COMPUTER PROCESSOR OPTIONS, MEMORY, SIZE, ETC.
  • LOCAL DATA BUS AND HIGH SPEED GLOBAL DATA BUS ISSUES
  • I/O INTERFACES
  • STANDARDS

* JIAWG, MASA, MPRAS & AIPS
CUSTOMER REQUIREMENTS
(CONCLUDED)

- POWER SOURCES
  - BATTERY TYPES (SILVER ZINC, LITHIUM, ETC.)

- PACKAGING
  - AIRCRAFT STANDARDS, SPACE UNIQUE REQUIREMENTS

- TESTABILITY
  - OPERATIONAL COSTS AND FLEXIBILITY, AUTONOMOUS
FOCUSED TECHNOLOGY PROGRAMS

TRANSPORTATION SPACEx SCIENCE EXPLORATION SPACE PLATFORMS OPERATIONS

TRANSPORTATION

Earth to Orbit

ETO Vehicle Avionics

Low Cost Commercial Transport

Space Transportation

Autonomous Landing

Autonomous Rendezvous & Docking

Transfer Vehicle Avionics

Technology Flight Experiments
Integrated Technology Plan Elements

5.2.7 ETO Vehicle Avionics
5.2.7.1 Avionics Architecture
5.2.7.2 Avionics Software
5.2.7.3 Vehicle Health Management
5.2.7.4 GN&C
5.2.7.5 Electrical Actuators
5.2.7.6 Landing/Recovery Systems
5.2.7.7 Power Management & Control

5.3.8 Transfer Vehicle Avionics
5.3.8.1 Avionics Architecture
5.3.8.2 Avionics Software
5.3.8.3 Vehicle Health Management
5.3.8.4 GN&C
5.3.8.5 Tether Control
5.3.8.6 Electrical Actuators
5.3.8.7 Power Management & Control
5.3.9 Autonomous Landing
5.3.10 Autonomous Rendezvous & Docking

Generic Outline

Presentation will cover each identified Integrated Technology Plan Element and Subelement as follows

- Overview (at the element level 5.X.X)
- Current & Related Programs (at the subelement level 5.X.X.X)
- Proposed Technology Program (at the subelement level 5.X.X.X)
- Program Benefits (at the subelement level 5.X.X.X)

Note: The Integrated Technology Plan Report for these elements and subelements is over 100 pages. This presentation will be a high level summary of that report.
5.2.7 ETO Vehicle Avionics Overview

The next generation of space transports will need to have increased mission safety, more autonomy for reduced crew workload, and reduced operational costs.

- Avionics Architecture - for increased avionics performance
- Avionics Software - addresses mission and safety features in software operating systems kernel
- Vehicle Health Management - for self diagnosing and self compensating integrated systems
- Power Management and Control - for reliable, universal, modular, electrical power bus systems
- Guidance, Navigation, and Control - offers efficient computational algorithms and sensors, software tools to analyze complex body dynamics, and enhanced launch and land on demand probability
- Electrical Actuation Systems - replaces hydraulic systems to enhance system reliability, reduced operational cost
- Advanced Landing & Recovery Systems - for enhanced booster recovery and landing technology

The following advanced vehicles will all require some combination of these advanced technologies:
- HLLV, NLS, PLS, CTV, ACRV, ALS, and ELV's

ETO and Transfer Vehicle Avionics technology development share common goals which invites and in fact, for cost effectiveness, dictates collaboration and interfacing between the two areas of development.

### 5.2.7.1 ETO Vehicle Avionics: Avionics Architecture Current & Related Programs

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<td>Flight Data System Open Architecture Requirements Definition &amp; Methodology Development</td>
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<td>Flight Data System Open Architecture Document</td>
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<td>Flight Data System System Profiles</td>
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<td>Flight Data System Open Architecture Performance Analysis and Trades</td>
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<td>Flight Data System Open Architecture Prototype Development</td>
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<td>Network Performance Model</td>
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<td>Bare 386 Real-time Kernel Investigation</td>
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CG4-9
### 5.2.7.1 ETO Vehicle Avionics: Avionics Architecture

**Proposed Technology**

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**Program Benefits**

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<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
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<tbody>
<tr>
<td>Architecture/ETO Technology</td>
<td>• Definition of interfaces and standards including performance criteria to establish and verify architecture concepts.</td>
<td>• Development of flexible architectures for reduced development and life cycle costs</td>
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<td>• The transfer of commercial technologies into space rated components will enable onboard processing capabilities to accommodate increased complexity of the avionics suite.</td>
<td>• Compatibility with ground systems in both performance and architecture</td>
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<td>• Non-stop requirements and multi-fault tolerant components can be used to test and evaluate concepts, their associated costs, and implementation difficulty.</td>
<td>• Development of more flexible launch commit criteria and increases in mission safety</td>
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<td></td>
<td>• Definition of requirements for advanced displays and controls, and prototypes of such devices can be used to present more effective human interface mechanisms to astronauts for evaluation.</td>
<td>• More effective use of data fusion to increase the machine processing of information for the manned interface.</td>
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</tbody>
</table>

**Why**

- Development of flexible architectures for reduced development and life cycle costs.
- Compatibility with ground systems in both performance and architecture.
- Development of more flexible launch commit criteria and increases in mission safety.
- More effective use of data fusion to increase the machine processing of information for the manned interface.
### 5.2.7.2 ETO Vehicle Avionics: Avionics Software Current & Related Programs

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<td>- Matrix-X Simulation Development</td>
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### 5.2.7.2 ETO Vehicle Avionics: Proposed Technology

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<td>- Launch Vehicle Advanced Human-Tended Avionics Displays and Controls Interface and Aids Requirements Definition</td>
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<td>- Avionics Human-Tended Alternative Sensory Mechanisms and Display Prototype Development</td>
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### 5.2.7.2 ETO Vehicle Avionics: Avionics Software Program Benefits

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<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>WHY</th>
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<tr>
<td>Software/ETO Technology</td>
<td>- Establishes capability and performance of operating systems distributed across multiple buses, networks and vehicles</td>
<td>* Assessment of distributed operating system and services requirements</td>
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<tr>
<td>- Real-time Distributed Processing</td>
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<tr>
<td>- Develop prototype and demonstrate distributed operating systems and services that operate in real-time over distributed and multiple processors.</td>
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<td>- Determine sensitivity factors governing distributed operating system and services for real-time processing performance.</td>
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<td>- High Capacity Processing:</td>
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<tr>
<td>- Develop and prototype software for 32/64 bit processors, specialized coprocessors such as 1960, R4000 and multi-megabyte memory alternatives associated with mass storage disk for space qualified components</td>
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<tr>
<td>- Non-Stop Computing</td>
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<tr>
<td>- Develop and demonstrate software models exhibiting multi-fault tolerant system and component behavior and reconfigurable capability with and without human controls</td>
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<tr>
<td>- Determine the technologies needed to test, verify and certify for flight operations</td>
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<td>- Software Reusability</td>
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<td>- Develop and build Computer Aided Systems Engineering (CASE) tool data repository filters for exchanging data between different CASE tools for flight software development</td>
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<td>- Define and test reusable software features for flight software specific operating systems, services and applications</td>
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<tr>
<td>- Avionics Displays and Controls</td>
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<tr>
<td>- Develop and prototype knowledge based visual, touch, voice and other sensory display and control aids to support human operation of complex systems</td>
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<tr>
<td>- Determine the technologies needed to test, verify and certify advanced human-machine interface software</td>
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### 5.2.7.4.1 ETO Vehicle Avionics: GN&C Algorithms Current & Related Programs

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<td>- Baseline requirements for current vehicles</td>
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<td>Advanced GPS Navigation Techniques</td>
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<td>- Initial tests in aircraft</td>
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<td>- Baseline requirements for advanced vehicles</td>
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**TECHNOLOGY**

- Autonomous Launch Vehicle GN&C Reconfiguration
- Atmospheric Adaptive Entry GN&C
- Numeric/AI Guidance Techniques
- Parallel Processing GN&C Methods
- Advanced GPS Navigation Techniques
- Autonomous Rendezvous/Docking GN&C

**BENEFITS**

- Recurring launch operations costs can be reduced through automation and improvements to current GN&C algorithms and operations approaches
- Improved thermal protection margin and reduced sensitivity to atmospheric and system uncertainties
- Accurate, reliable guidance solutions using exact environment models
- Perform complex GN&C computations onboard using parallel processing
- Accurate, autonomous space vehicle navigation
- Recurring costs reduced through automation and improvements to current GN&C algorithms and operations approaches

**WHY**

- Elimination of manpower intensive activities is needed for the next generation of launch vehicles
- Entry vehicle landing accuracy and thermal protection system requirements are driven by the ability of the GN&C system to adapt to dispersed atmospheric conditions
- Current numeric guidance schemes are not assured of always converging
- Sequential computation limits today's GN&C processing
- Changing environmental conditions can degrade doppler measurements
- Current AR&D operations rely heavily on ground based manual procedures

5.2.7.4.1 ETO Vehicle Avionics: GN&C Algorithms

Program Benefits

5/26/91

A. J. Bordano/EG

Johnson Space Center - Houston, Texas
CONCLUDING REMARKS

- TECHNOLOGY PLAN IS BASED ON "UNCONSTRAINED" INPUTS
- PRIORITIES WILL BE ESTABLISHED BASED ON USER REQUIREMENTS AND TECHNOLOGY GAPS
- HOWEVER, SOME THEMES HAVE CLEARLY EMERGED
  
  "TODAY'S AVIONICS SYSTEMS ARE CUSTOMIZED TO MAXIMIZE THE PERFORMANCE AND EFFICIENCY FOR A SPECIFIC VEHICLE APPLICATION. - - - TODAY, IN THE AIRCRAFT INDUSTRY, A COMMON MODULE APPROACH IS BEING STANDARDIZED IN ORDER TO ACHIEVE HIGH PRODUCTION RATES WHICH NOT ONLY LOWERS COST BUT ALLOWS COST TO BE AMORTIZED OVER MANY DIFFERENT AIRCRAFT WHICH CAN UTILIZE THE SAME COMMON MODULES. THIS APPROACH PROVIDES THE FLEXIBILITY, SCALABILITY, AND LOW COST CHARACTERISTICS NOW BEING SOUGHT IN THE SPACE INDUSTRY. A COST EFFECTIVE APPROACH FOR THE SPACE INDUSTRY WOULD CONSIDER USING A MODULAR SYSTEM WITH COMMON BUILDING BLOCKS SO THAT THE COST CAN BE SHARED OVER MANY VEHICLES AND PROGRAMS."

CONCLUDING REMARKS

- CRITICAL TECHNOLOGIES REQUIRED
  - AVIONICS ARCHITECTURES (PROTOTYPING, SYSTEM TRADES, TEST, ETC.) WHICH ARE MODULAR, STANDARDIZED, OPEN AND HAVE THE ABILITY TO CONFIGURE NEW OR REVISED SYSTEMS QUICKLY AND EFFICIENTLY WITH MINIMUM IMPACT ON COST AND SCHEDULE
  - ADVANCED SOFTWARE FOR REDUNDANCY MANAGEMENT (FAULT DETECTION, ISOLATION, RECOVERY - - - ) WHICH IS RELIABLE, FLEXIBLE WITHOUT HIGH OVERHEAD
  - ADVANCED SOFTWARE FOR DEVELOPMENT, VERIFICATION AND VALIDATION OF FLIGHT CODE WHICH UTILIZE NEW TEST METHODS AND SIGNIFICANTLY REDUCE LIFE CYCLE COSTS
  - ADVANCED SOFTWARE FOR AUTONOMOUS CHECKOUT
  - ADAPTIVE GUIDANCE, NAVIGATION AND CONTROL ALGORITHMS WHICH SUPPORT SAFE MISSION COMPLETION DURING NON NOMINAL CONDITIONS AND REQUIRE MINIMUM GROUND SUPPORT
VEHICLE HEALTH MANAGEMENT

AGENDA

- DEFINITION/SCOPE
- TECHNOLOGY NEEDS
- CURRENT ACTIVITIES/FUTURE PLANS
- SUMMARY
VIHM OVERVIEW

DEFINITION - Vehicle Health Management: The ability to verify and monitor vehicle health and to take appropriate corrective actions necessary to maintain the vehicle in a functional and/or safe state.

- vehicle checkout
- failure detection
- data processing
- system reconfiguration

ELEMENTS - Vehicle Health Management System includes:

- Sensors
- Data Collection and Processing Elements
- Algorithms/Decision Models

Totally autonomous vehicle or containing ground based elements.

Component/subsystem/system level elements

VHM OVERVIEW

SIMPLIFIED VHM SYSTEM

CG5-2
HM/AC Objectives/Requirements

VIIM OVERVIEW

- VHM is not new, but must take advantage of new technologies.

  - Increased Automation
    - streamline vehicle checkout
    - reduce ground/flight crew requirements
  
  - Better Detection/Prediction Methods
    - enhance troubleshooting
    - reduce hardware costs
    - improve probability of mission success
    - reduce maintenance costs

  - Improved Decision Making
    - quicken response time
    - provide consistent, reliable decisions
    - improve probability of mission success

  - Improved Reliability
    - reduce hardware costs
    - improve probability of mission success

CG5-3
### ETO VEHICLE AVIONICS - (TRANS.) 1

#### TECHNOLOGY PERFORMANCE OBJECTIVES

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<th>OBJECTIVE/REQUIREMENT</th>
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<td>SAFE SHUTDOWN/AUTOMATED SYSTEM MANAGEMENT</td>
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<td>GROUND CHECKOUT</td>
<td>LABOR INTENSIVE/TIME CONSUMING</td>
<td>INCREASED AUTOMATION/FASTER PROCESSING</td>
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<tr>
<td>MISSION OPERATIONS</td>
<td>MAN-IN-LOOP</td>
<td>INCREASED AUTONOMY</td>
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<td>TECHNOLOGY INSERTION</td>
<td>REQUIRES REDESIGN</td>
<td>PLUG-IN</td>
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<tr>
<td>APPX NEED DATE</td>
<td></td>
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</tbody>
</table>

---

No, I can't stop to consider any new fangled tools, I've got a battle to fight!!
ADVANCED AVIONICS TECHNOLOGY REQUIREMENTS

VEHICLE HEALTH MANAGEMENT

GENERAL REQUIREMENTS:

• DEVELOP FLIGHT AND GROUND AVIONICS SYSTEMS THAT ENABLE AUTOMATED VEHICLE CHECKOUT AND MONITORING TO REDUCE LAUNCH PROCESSING AND MISSION OPERATIONS COSTS.

ELEMENTS:

• INVESTIGATE SYSTEM ARCHITECTURES TO DETERMINE OPTIMAL CONFIGURATION TO SUPPORT AUTOMATED VEHICLE HEALTH MANAGEMENT. ARCHITECTURE MUST BE SUPPORTIVE OF NEW TECHNOLOGY INTEGRATION AS IT BECOMES AVAILABLE WITH A MINIMUM IMPACT TO THE FLIGHT VEHICLE OR GROUND SYSTEM.

• INVESTIGATE POTENTIAL SENSOR TECHNOLOGIES TO ENABLE THE MONITORING OF CRITICAL VEHICLE HEALTH PARAMETERS. BY SENSING CRITICAL PARAMETERS EFFECTIVELY, "GO/NO-GO" DECISIONS, FAULT DETECTION, AND HARDWARE LIFE PREDICTIONS CAN BE MADE IN A TIMELY, RELIABLE, AND CONSISTENT MANNER.

• DEVELOP SYSTEMS ENGINEERING METHODOLOGIES APPROACHES AND TOOLS TO SUPPORT DEVELOPMENT OF AN AUTOMATED HEALTH MANAGEMENT SYSTEM.

ADVANCED AVIONICS TECHNOLOGY REQUIREMENTS

VEHICLE HEALTH MANAGEMENT

ELEMENTS (CONT'D):

• DEVELOP SOFTWARE TECHNOLOGIES (E.G., EXPERT SYSTEMS) TO ALLOW DELEGATION OF DECISION MAKING FROM CHECKOUT PERSONNEL TO AUTOMATED HEALTH MANAGEMENT SYSTEM. THIS WILL ALLOW VEHICLE PROCESSING WITH A SMALLER TEST TEAM AND REDUCE THE CHANCE OF HUMAN ERROR.

• DEVELOP SIMULATION/DEMONSTRATION TECHNIQUES TO VERIFY PERFORMANCE OF THE HEALTH MANAGEMENT SYSTEM AND TO ESTABLISH CONFIDENCE IN AUTOMATED CHECKOUT AND CONTROL. TOTAL CONFIDENCE IS REQUIRED PRIOR TO ITS FULL IMPLEMENTATION ON A FLIGHT VEHICLE.
REPRESENTATIVE TECHNOLOGIES

• SENSORS
  - PLUME OPTICAL ANALYSIS
  - HYDROGEN LEAK DETECTION
  - REMOTE OPTICAL INSPECTION
  - BIT

• SOFTWARE
  - DATA TRENDING ALGORITHMS
  - NEURAL NETS
  - PARITY SPACE ALGORITHMS
  - MODEL BASED DIAGNOSTICS

• SYSTEMS TOOLS
  - COST/BENEFIT MODELLING
  - DIGRAFI TOOLS
  - SYSTEM SIMULATION

VIIM ACTIVITIES/PLANNING

• ESTABLISHED AS A SATWG (STRATEGIC AVIONICS TECHNOLOGY WORKING GROUP) PANEL
  • MSFC/LRC CO-CHAIR
  • EXTENSIVE NASA/INDUSTRY PARTICIPATION

• NASA/INDUSTRY MEETING, SEPT., 1990, INDIATLANTIC, FL

• VIIM WORKSHOP, LRC, DEC., 1990 (SPACE BASED VEHICLES)

• VIIM WORKSHOP, MSFC, JUNE, 1991 (E-T-O LAUNCH SYSTEMS)

• DEVELOP AND MAINTAIN VIIM TECHNOLOGY REQUIREMENTS (ON-GOING)

• JSC/KSC WORKSHOP (ORB/SSF), SEPT. 1991

• SENSOR WORKSHOP (SSC), FALL, 1991

• SOFTWARE WORKSHOP (ARC), SPRING, 1992
SUMMARY

VHM PANEL ACTIVITIES PROVIDE NASA FOCUS FOR VHM TECHNOLOGY NEEDS/PLANS

- ESTABLISH JOINT NASA/INDUSTRY DIALOGUE
- IDENTIFY AND PRIORITIZE TECHNOLOGY NEEDS
- SUPPORT TECHNOLOGY DEVELOPMENT EFFORTS
- IDENTIFY/SUPPORT BRIDGING TASKS

EFFORT WILL BE ON-GOING, LONG TERM ACTIVITY

ENHANCED VHM IS A KEY TO COST-EFFECTIVENESS AND MISSION SUCCESS OF FUTURE PROGRAMS
Briefing Contents

- Spacecraft Guidance Technology at LaRC
- Guidance Group Mission Statement
- Mission Statement Implementation
- Technical Program Summary
- Summary
SCB Guidance Group Mission

- To develop algorithmic technology for guidance of aeromaneuvering spacecraft subject to uncertainties
- To identify and advocate technology for subsystems needed by guidance algorithms; e.g. electro-optical sensors
- To actively interchange technology and requirements with industry

How the Mission is Accomplished

- "Program requirements" are imposed by characteristics of a proposed mission/system, e.g. ALS
- Guidance group focusses inhouse and grant-based academic research on program requirements
- Resulting technology is shared with industrial partners via Technology Interchange Tasks
Technology Interchange Tasks

• Industrial researchers exercise and demonstrate new technology with guidance group support

• "Lessons learned" and refined concepts and requirements feed back to guidance group

• Guidance group works with academics to enhance university research focus

Research Implementation Flow

Program Requirements

Guidance Research Program

Technology Transfer to Industry

Technology and Reqts. from Industry

Inhouse Work

Universities
Technical Program Summary

• Issues
• Algorithmic technology activity
  – goals
  – guidance synthesis techniques
    discrete time methods
    perturbation methods
    neural methods
  – globally convergent algorithms
• Validation/modelling support
• Technology interchange

Issues in Aeromaneuvering Spacecraft Guidance

• Highly constrained trajectories
• Limited control authority/sluggish rotational response
• Energy and/or constraint performance dominated by uncertain atmospheric effects
• Above issues are shared by:
  – launch systems
  – aerobrakes
  – aerospace planes
Algorithmic Technology Goal: Direct Statistical Guidance Synthesis (DSGS)

- Statistics of process uncertainties are direct inputs to a formal guidance synthesis algorithm
  - winds
  - hardware failures
  - plant uncertainties
- Benefits:
  - design directly for probability of achieving mission goals
  - reduce design/testing cycles for guidance design

Steps Toward DSGS

1. Develop technology for reliable, accurate deterministic optimal and suboptimal control synthesis

2. Extend problem formulations to include random process statistics

3. a. Validate in test bed
   b. Ensure that results have industrial applicability
Trajectory Optimization Techniques

- Focus is on numerical solution of optimal control necessary conditions in discrete time

- Inhouse, grant-based and contract work is implemented in "Variational Trajectory Optimization Tool Set" (VTOTS)
VTOTS Trajectory Prototyping Tool

GOAL:

- Fast, accurate solution of Variational Optimal Control Boundary Value Problems for:
  - trajectory/configuration optimization
  - guidance synthesis

- Very simple user interface: "OTIS-like" ease of use

VTOTS Participants

  - joint development of algorithmic theory and problem solution code
- McDonnell Douglas Space Systems Co.
  - OTIS to VTOTS adaptation
  - aeroheating capability
  - automatic mesh generation issues
- Cornell University
  - parallel Newton code for solving necessary conditions
Impediments to "OTIS-Like" Ease of Use

- Derivation of necessary conditions
- State Inequality constraints
- Boundary conditions
- Numerical stability
- Lack of "OTIS-like" user community

Derivation of Necessary Conditions

- Problem
  - derive costate ODEs by differentiating Hamiltonian
  - solve nonlinear equations for controls

- Solution
  - symbolic computation front end; user merely inputs plant and cost function
  - control equations represented as functions to be zeroed (solved) at discrete time steps
State Inequality Constraints

• Problem
  – pre-assume structure of active constraint arcs
  – construct trajectory structure using internal boundary conditions and conditions on time derivatives of constraints

• Solution
  – demonstrations and trades on several discrete time problem representations, with constraint necessary conditions represented by Mangasarian functions

  no apriori imposition of structure on problem

Boundary Conditions

• Problem
  – costate boundary conditions obtained via solution of nonsquare linear system for "undetermined multipliers"

• Solution
  – state and costate necessary conditions represented as an equivalent square nonlinear system in states and costates

  no analysis necessary for implementation
Numerical Sensitivity

- **Problem**
  - traditional methods for solution of necessary conditions highly nonconvergent

- **Solution**
  - discrete time representations converge robustly
  - globally convergent methods under development for initial guesses
  - analytic differentiation where possible; high-accuracy numerical differentiation techniques else

Lack of OTIS-Like User Community

- **Problem**
  - OTIS is an excellent package with strong following

- **Solution**
  - working with industrial partner to give VTOTS
    - similar "taste and feel" to OTIS
    - features for industrial utility
  - pending successful VTOTS development, conduct an OTIS/VTOTS flyoff
  - possibly seek co-sponsorship arrangement with Air Force
Examples of Perturbations

Singular Perturbations
\[ \begin{align*}
x & = f(x, y, u) \\
\varepsilon \dot{y} & = g(x, y, u)
\end{align*} \]

Regular Plant Perturbations
\[ \dot{x} = f(x, u) + \varepsilon g(x, u) \]

Regular Trajectory Perturbations (Linearization)
\[ \begin{align*}
& x = x + \delta x \\
& u = u + \delta u \\
& \dot{x} = f(x, u) \\
& \delta x = \frac{\partial f}{\partial x} \delta x + \frac{\partial f}{\partial u} \delta u
\end{align*} \]

Important Limitation of Discrete-Time Methods

\text{BANDWIDTH:}
- frequency content of optimal trajectory limited by discretization mesh density

- disturbances outside Nyquist frequency not represented

\[ \rightarrow \text{these may be important for constraint performance} \]
Perturbation Methods

Exploit alternate plant representations for guidance synthesis

VTOTS:
Solve optimal control problem via more tractable trajectory representation

PERTURBATION METHODS:
Approximate optimal control problem by expanding about solution of a convenient "neighboring" problem

Comments

- Guidance group supports research in all three perturbation categories; inhouse activity in regular perturbations

- Regular perturbations are applicable to launch vehicles

- Regular perturbation schemes can be exploited to restore high-frequency effects (e.g. wind gusts) to guidance schemes based on discrete-time optimal control
Candidate Hybrid Guidance Architecture

Neural Methods

- Current activity entirely contracted out
  - 2 universities (joint activity)
  - 1 SBIR Phase II contract

- Both efforts stress use of neural net as rapid interpolation system, but
  - different guidance architectures
  - different training methods
Globally Convergent Algorithms

- Activity supports
  - initial guess generation in VTOTS
  - calculation of global minima in direct optimization problems

- Two approaches under investigation
  - extensions to Chow-Yorke homotopy techniques
  - "genetic" minimization algorithms
Chow-Yorke Homotopy Techniques

- Extension of "continuation" method
  - avoids singularities which can destroy progress of calculations
  - failure can occur when calculations become smoothly unbounded
- Inhouse activity centers on procedures for preserving boundedness
- FORTRAN implementations for general functions and for VTOTS finite element discretization

Genetic Algorithm

- Non-derivative procedure for functional minimization
- At each iteration, a random population of solution candidates is modified by "reproduction, crossover and mutation" operations
- The "fittest" - lowest cost - population elements dominate "less fit" higher cost elements
- We're not sure how it works, but it performs impressively
Validation/Modelling Support

- Evaluation of candidate guidance schemes via Monte Carlo simulation

- Development of high quality simulations of pertinent random atmospheric phenomena for guidance validation

Stochastic Atmosphere Simulation

- Constructed and analyzed fidelity of Gaussian random model for synthetic KSC launchsite winds

- Procedure for controlling spatial frequency bandwidth of atmospheric variations in an inhouse trajectory simulation implementation of the GRAM model
Monte Carlo Guidance Evaluations

Two studies underway

- performance evaluation of a suboptimal analytic aerospace plane guidance rule for ascent

- optimal control-based launchsite wind profiler requirements study for Shuttle

Generic Hypersonics (GH) Guidance & Optimization Program at Langley

Technical Focus:
- Technology for trajectory and system optimization and synthesis of suboptimal aerospace plane guidance laws

Approach:
- Combined program of grant/contract/inhouse research and development
- Exploit leveraging opportunities from other Langley guidance activities

CG6-17
GH Guidance and Optimization Foci (I)

- Simplified procedures for solving variational optimal control problems

- Finite element discretizations of optimal trajectory boundary value problems (spinoff from Advanced Launch System)

- Use of variational optimal control formulations for system configuration optimization

GH Guidance and Optimization Foci (II)

Motivations for emphasis on variational methods

- direct treatment of sensitivity functions
  - useful for system optimization

- numerical schemes lead to solution of equations, rather than search for minima
System Optimization Studies

• Comparison of static and variational optimal control formulation of a system parameter optimization problem

TASK: choose thrust angle for max performance

a) direct optimization of energy rate at points along a fixed trajectory

b) optimal control of thrust angle for payload to orbit along identical trajectory

System Optimization Studies (II)

Exact calculation of state constraint sensitivity functions

• Constraint sensitivities obtained via quadrature of Lagrange multipliers on state constrained trajectory arcs

• Concept demonstration for dynamic pressure constraint on fuel optimal ascent of Langley Accelerator

• Results to be obtained via Variational Trajectory Optimization Tool Set (VTOTS)
Other Technology Interchange Activities

Active:
  • Codevelopment of VTOTS with MDSS

Pending:
  • Launch vehicle guidance exploiting regular perturbation of optimal return function
  • Aerobrake performance sensitivity to guidance and atmospheric knowledge assumptions

Summary

• Guidance group develops technologies for guidance of aeromaneuvering spacecraft
• Guidance group's program focusses inhouse and academic resources on industrial requirements
• Group implements technology interchange with industry by constructing opportunities for technology demonstration by industrial research groups
Autonomous Rendezvous & Docking Technology Development

Status & Plans

Why AR&D?

"...this initiative (Mars Rover/Sample Return) places a premium on advanced technology...to maximize the scientific return. It requires...a high level of sophistication in automation..."

Report of the NASA 90-Day Study (Nov 1989)
"Elements needing technology development include...autonomous rendezvous and docking...[which is] essential to the cost-effective return of samples from Mars as part of the robotic missions."

Advisory Committee on the Future of the U.S. Space Program (December 1990)
"Among the more critical technology topics that must be pursued are...automation and robotics, ...sensors..."

Report of the Synthesis Group, Executive Summary (May 1991)
"At Mars, we need Earth-independent operations, since round trip communications times will vary from seven to 40 minutes."
"Technology development is required in the following areas:
... (6) Automated rendezvous and docking of large masses"
Autonomous Rendezvous and Docking Technology Development

Background

- **Exploration Technology Program AR&D (Previously Pathfinder)**
  - Identified Subtask Technology Requirements
  - Developed Preliminary System Requirements
  - Docking Ground Demo (Sensor & Mechanism Hardware, GN&C) in FY91
  - AR&D Graphics Demo (Hardware Math Models, GN&C) in FY 90 & 91
- **Conducted Rendezvous, Proximity Operations, & Docking (RPOD) Quality Function Deployment (QFD)**
  - Team Members Include JSC Engineering & Operations Organizations plus Industry (General Dynamics, Martin Marietta, Lockheed, McDonnell Douglas, TRW, Draper Labs)
  - Conducted Customer Needs Survey, both Programmatic (LMEPO, CTVPO) & Technological (Code R, JSC, MSFC)
  - Results will Support Development of NASA Strategic & Tactical Plans in this Technology Area

![Diagram](image.png)
### Technology Readiness - Beyond LEO

<table>
<thead>
<tr>
<th>Level</th>
<th>1 Conceptual Design</th>
<th>2 Conceptual Design Tested</th>
<th>3 Critical Function Demo</th>
<th>4 Brickboard Demo'd</th>
<th>5 Prototype Demo'd</th>
<th>6 Engineering Model Tested in Space</th>
<th>Comments</th>
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<td>Basic Technologies are Being Developed.</td>
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#### Issues & Trades

- Functional Partitioning (Ground, Transfer Vehicle, SSF)
- System Acceptability/Mission Success/Safety
- Level of Independence
- Modularity/Flexibility
- Performance Requirements vs Mission Constraints (Sensors, Mechanisms, Control Effectors)
  - Fuel
  - Mechanism Intelligence
  - Sensor Handover Zones
  - Sensor Accuracy vs Mechanism Robustness
  - Environmental Effects (Thermal, Duration, Solar Radiation)

CG7-3
Autonomous Rendezvous and Docking Technology Development

Milestones

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<thead>
<tr>
<th>Earth Orbit</th>
<th>Lunar Missions</th>
<th>Mars Missions</th>
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<tbody>
<tr>
<td>FY92</td>
<td>FY93</td>
<td>FY94</td>
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<tr>
<td>Define User Requirements for AR&amp;D Technology</td>
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<tr>
<td>Develop Graphics Simulation for Lunar/Mars Environment</td>
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<tr>
<td>Conduct Mission Studies &amp; Analyses to Define System &amp; Performance Requirements</td>
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<tr>
<td>Develop &amp; Evaluate AR&amp;D System Concepts Suitable for User Requirements</td>
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<tr>
<td>Conduct Ground Demonstrations of Brassboard Integrated Systems &amp; Individual Elements</td>
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<tr>
<td>Conduct Flight Experiments &amp; Demonstrations in a Realistic Environment</td>
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</table>

Johnson Space Center - Houston, Texas

Navigation, Guidance & Aeronautics Division

Stephen Lamkin June 26, 1991
INTEGRATED TECHNOLOGY PLAN
for the
CIVIL SPACE PROGRAM

AUTONOMOUS LANDING

Controls Committee Review
McLean, VA
June 26-27, 1991

Ken Baker
ER2/Intelligent Systems Branch
Automation & Robotics Division
Engineering Directorate
Johnson Space Center

OBJECTIVES

Develop Technology to Enable Landing of Planetary Exploration Spacecraft:

• Safely in the Face of Surface Hazards Presented by Rough Terrain
• Accurately, i.e. Close to the Area of Mission Interest
• Autonomously, i.e. Without Real-Time Ground Control

BENEFITS

• Increased Probability of Safe Landing
• Reduced Structural Mass Needed to Make the Lander Robust Enough to Survive Touchdown
• Reduced Resources Needed to Survey Area of Mission Interest from Orbit Until Safe Landing Site Is Found
BASIC TECHNICAL APPROACH

Precision Landing

• **Scenario:**
  - Select, Prior to Deorbit, a Safe Landing Site Using High Resolution Orbital Imagery
  - During Descent, Maneuver Accurately Enough to Land Within That Site

• **Technology Need:** Sensor, Algorithm & On-Board Computer to Provide Navigation Measurements With Respect to the Surface of the Planet That Are:
  - Accurate and
  - Robust to Variations in Operating Conditions Such As: Observing Geometry, Illumination Geometry, etc.

On-Board Hazard Detection & Avoidance

• **Scenario:**
  - Aim the Lander At an Area That Is Expected A Priori to Contain Small, Safe Landing Sites Within Its Maneuver Range
  - In Real-Time Detect a Safe Site & Maneuver to Land There

• **Technology Need:** Sensor, Algorithm & On-Board Computer That Provide Reliable Detection of Landing Hazards Within the Current Terminal Maneuver Footprint

PATHFINDER STUDY RESULTS

Image Matching Navigation Using Visible Images (JPL, JSC)

• **Template Matching of Optical Images (JPL):**
  - Position Error on Simulated Mars Terrain: 0-50 Pixels
  - Possible Source of Errors; Distortion of On-Board Image vs. Reference Due to Lander Trajectory Dispersion
  - Size and Resolution of Reference Image

• **Hybrid Optical Image Matching (JSC):**
  - Synthetic Estimation Filters for Robust Detection of Landmarks
  - Taking Into Account Practical Limits of Real Optical Computing Devices
  - Being Tested on Images of Lab./Simulated Mars Terrain

Hazard Detection (JSC/ARC)

• Sensor Surveys That Included Laser Radar, Passive Computer Vision, Hybrid Interferometric Imaging & SAR, Identified Imaging Laser Radar as the First Choice, But:
  - Arrays of GaAlAs Laser Diodes & Si Avalanche Photo-Diode Detectors with Pre-Amps Need Improvement
  - Best Performance from LADAR/Mars Terrain Simulations Is
    \[
    \Pr \{ \text{Correct Detection of Hazard} \} = 0.95 \quad \Rightarrow \quad \Pr \{ \text{False Alarm} \} = 0.12
    \]
## WORK-breakdown Structure

<table>
<thead>
<tr>
<th>WBS CATEGORY</th>
<th>ACTIVITIES</th>
</tr>
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<tbody>
<tr>
<td>Systems Engineering</td>
<td>Determine Requirements&lt;br&gt;Develop Mars/Lunar Surface Models&lt;br&gt;Identify Candidate Approaches &amp; Associated Technology Development Needs&lt;br&gt;Collect Terrain Elevation Maps &amp; Images for Earth Analogs of Mars Terrain&lt;br&gt;Close Loop Sim. of Precision Landing and of Hazard Detection &amp; Avoidance&lt;br&gt;Select Most Promising Approaches for Development &amp; Field Test of Prototypes</td>
</tr>
<tr>
<td>Precision Landing</td>
<td>Develop &amp; Evaluate Selected Techniques Such As:&lt;br&gt;Track Orbital/Surface Beacon from Lander for Navigation Updates&lt;br&gt;Surface Image/Feature Matching for Navigation Updates Using Visible Images, Radar Images or Digital Terrain Maps&lt;br&gt;Develop Prototype Instruments, Such As:&lt;br&gt;Hybrid Optical Image Correlator&lt;br&gt;Imaging Radar&lt;br&gt;On-Board Digital Computer</td>
</tr>
<tr>
<td>Hazard Detection &amp; Avoidance</td>
<td>Develop &amp; Evaluate Selected Techniques Such As:&lt;br&gt;Active Detection via Imaging Laser Radar&lt;br&gt;Passive Computer Vision (Slope via Shape from Motion, Rock Detection via Shadows)&lt;br&gt;Hybrid Interferometric Imaging&lt;br&gt;Develop Prototype Instruments, Such As:&lt;br&gt;Imaging Laser Radar&lt;br&gt;Hybrid Interferometric Imager</td>
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### REFERENCES

CODE RC CONTROLS PROGRAM

OVERVIEW BRIEFING

FOR

CONTROLS COMMITTEE

OF THE

SPACE SYSTEMS & TECHNOLOGY ADVISORY COMMITTEE

CLAUDE R. KECKLER
NASA - LANGLEY RESEARCH CENTER

JUNE 27, 1991

OVERVIEW CONTENT

CONTROLS RESEARCH, AND DEVELOPMENT OF ANALYTICAL TOOLS, SOFTWARE PACKAGES, AND HARDWARE COMPONENTS AT:

- ARC
- GSFC
- JPL
- JSC
- LaRC
- MSFC
GOALS

- Design & validate controllers for rigid-body control and vibration suppression of the CSI Phase Zero Evolutionary model.

APPROACH

- Apply advanced control design techniques:
  - Linear-Quadratic-Gaussian (LQG)
  - Dissipative
  - $H_{\infty}$
  - Dissipative augmented LQG (HAC/LAC)
- Incorporate robustness in the designs
- Evaluate via simulation and actual testing
- Compare results

SCHEMATIC OF CONTROL PROBLEM

- Suppress "pseudo" rigid body and elastic motion in presence of disturb
- Design to be based on imperfect knowledge of the system
CONTROLLER COMPARISONS

CLOSED-LOOP: EXPERIMENTAL TIME HISTORIES
ACCELERATION #8 (IN/S^2)

CLOSED-LOOP DAMPING
EXPERIMENT VS ANALYSIS

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<td>H_\infty</td>
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<tr>
<td>LQG/SD</td>
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SPACECRAFT CONTROL LABORATORY
EXPERIMENT
(SCOLE) CONTROL LAWS

VIBRATION SUPPRESSION USING THRUSTERS

RIGID BODY BANG-BANG SLEW ONLY

BANG-BANG SLEW & VIBRATION SUPPRESSION

APPLICATION OF HOLOGRAPHIC STORAGE DEVICE

Sensing

Mission to planet Earth

Distributed sensing

Block diagram of distributed sensor applied to control of a flexible reflector
GRANTS

* MIT -
Develop faster photorefractive materials

* Johns Hopkins
Develop photorefractive thin films for large focal planes

* VPI
Analyse performance of interferometric sensor versus incoherent sensor for control of large reflector
Develop control laws for distributed sensing and processing

* UCLA
Develop optical processing for implementing control
NC/OC Pointing Performance Comparison
Based on March 30 SAGA Test Data

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<td>26.1</td>
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</table>

ND - No Data, ( ) Duration of the Measurement in Minutes

All Numbers are RMS pointing errors in milli-arcseconds (RSS of V2 & V3)
EOF - END OF NIGHT, EOD - END OF DAY
OC - ORIGINAL CONTROLLER (LOCKHEED)
OC - ORIGINAL CONTROLLER (LOCKHEED)
H-INFINITY CONTROLLER DESIGN, IMPLEMENTATION, & TEST

- GOAL: DESIGN AND IMPLEMENT AN H-INFINITY CONTROLLER DESIGN ON THE ACES FACILITY AND TEST IT FOR ROBUSTNESS AND PERFORMANCE

- H-INFINITY DESIGN WAS PERFORMED; HOWEVER, THE PERFORMANCE WAS POOR, BECAUSE OF THE REQUIREMENT FOR AN EXTREMELY RELIABLE SYSTEM MODEL

  MODEL OF SUFFICIENT FIDELITY IS NOT AVAILABLE FOR ACES

- EFFORT REFOCUSED ON REFINING MULTIVARIABLE MODELS (SYSTEM ID) AND ON PERFORMING CONTROLLER DESIGN USING EXPERIMENTAL FREQUENCY RESPONSE DATA

- INNOVATIVE MODELING TECHNIQUE HAS BEEN DEVELOPED FOR MULTI-INPUT MULTI-OUTPUT (MIMO) SYSTEMS
  - DETERMINANTAL MODELING
  - RESIDUE MATRIX IDENTIFICATION
TREETOPS ENHANCEMENT

GOAL: SIGNIFICANTLY UPGRADE TREETOPS CAPABILITY, EXPAND IT TO INCLUDE MODEL REDUCTION AND CONTROLLER DESIGN FUNCTIONS, AND INCREASE THE COMPUTATIONAL EFFICIENCY

PURPOSE: A USER-FRIENDLY ANALYSIS AND DESIGN TOOL IS NEEDED TO ANALYZE AND DEVELOP CONTROLLER METHODOLOGIES FOR COMPLEX MULTIBODY SYSTEMS

METHODOLOGY: ENHANCE THE TREETOPS CODE TO INCLUDE

- MODEL REDUCTION
- ORDER-N FORMULATION
- EQUILIBRIUM AND TRIM
- SENSITIVITY ANALYSIS
- INVERSE DYNAMICS
- SYMBOLIC REPRESENTATIONS
- THERMODYNAMIC ANALYSIS
- SYSTEM IDENTIFICATION
- GRAPHICAL USER INTERFACE
- CONTROLLER DESIGN

TREETOPS

- THE TREETOPS SUITE OF PROGRAMS HAS BEEN USED EXTENSIVELY IN THE ANALYSIS OF SPACECRAFT AND STRUCTURES INCLUDING
  - EFFECTS OF THE MOBILE TRANSPORTER AND MOBILE SERVICE CENTER MOTION ON SPACE STATION ATTITUDE CONTROL
  - SHUTTLE DOCKING AND BERTHING TO SPACE STATION USING THE REMOTE MANIPULATOR SYSTEM
  - SIMULATIONS OF ASTRO I AND ASTRO II, AXAF, GOES, & IUS
- THERE ARE 47 UNIVERSITIES, CORPORATIONS, AND GOVERNMENT AGENCIES CURRENTLY USING TREETOPS
- TREETOPS HAS BEEN EXTENDED FOR PARALLELIZATION AND VECTORIZATION ON THE COMPUTATIONAL CONTROLS WORKSTATION DELIVERED TO JSC

A SIMULATION EXAMPLE WITH 11 BODIES, 85 FLEX DOF'S, 16 RIGID DOF'S, INTEGRATED CONTROLLERS, AND ORBITAL ENVIRONMENT SHOWED A RUN TIME REDUCTION FROM 18900 TO 225 MINUTES VIA VECTORIZATION.
CONTROL SYSTEM DESIGN ANALYSIS
CURRENT RESEARCH THRUSTS

- INteractive Controls Analysis (INCA) Program
- Windowed Observation of Relative Motion (WORM) Program
- Analysis and Simulation Tools for Engineering Controls (ASTEC)
- System Identification (FY90 Code RC)
- Robust Control of Flexible Structures (FY91 Code RC)

INCA OVERVIEW

- Comprehensive Control System Design Analysis Package
- Developed in Close Coordination with GSFC Controls Analysts
- For Large (100th Order) or Small Order Systems
- Runs on VAX Computers with VMS Operating System
- Version 3.13 Available Through COSMIC
WORM OVERVIEW

- 2 and 3 Dimensional Plotting Package
- INCA-derived Interface
- Used as Simulation and On-orbit Telemetry Output Device and as a Quick Means to Massage Data via Functional Relations
- Runs on VAX Computers with VMS Operating Systems
- Version 2.32 Available Through COSMIC

ASTEC OVERVIEW

- Multi-platform Control System Design, Analysis and Simulation Package
- Window/Mouse Environment
  - Microsoft Windows 3.0 for PC
  - Macintosh
  - X-Windows for Unix Systems
- Common Portable Math Library for all Versions
- C++ Programming Language
- INCA-based Algorithms
MULTIBODY APPLICATION TECHNOLOGY

Biomechanics
Inverse Dynamics
Rolling/Sliding Joints
Generalized Joint Constraints

Molecular Dynamics
Non-linear Stability
Very Large Order Problems (100-500 DOF’s)
Clustering Concepts
Generalized Bodies
Massively Distributed Sensors/Actuators

Automotive
Real-time Man-in-the-Loop (50Hz goal)
Real-time Hardware-in-the-Loop
Visualization of Dynamic Systems
Parallel Processing Load Apportionment

Human Factors
Man/Machine Interaction Dynamics & Performance

Robotics
Intermittant Loop Closure with Impact
Inertial Contact through Seating
Geared Joints

Spacecraft
Modal Synthesis Methods for Noncollacation Problems
Discos callable by INCA for Nonlinear Simulation
Recursive Linearization for Multibody Systems
Discos Provided Linear Plant Model for INCA

JPL
ADVANCED GN&C ARCHITECTURE CONCEPTS

OBJECTIVE:
DEVELOP NEW GN&C SYSTEM ARCHITECTURES TO ENABLE GREATER
ON-BOARD AUTONOMOUS ROBUST CONTROL, STABILITY AND
PERFORMANCE

APPROACH:
• ADAPTIVE CONTROL FOR ROBUST STABILITY/PERFORMANCE OF
  SPACECRAFT OPERATING UNDER RAPID CHANGING CONFIGURATION
  OR ENVIRONMENT CONDITIONS
• IN-SPACE SYSTEM IDENTIFICATION FOR AUTONOMOUS ROBUST
  CONTROL SYSTEM SELF-TUNING AND SYSTEM AND/OR ENVIRONMENT
  CHARACTERIZATION
• REAL-TIME G&C ARCHITECTURE FOR ACCURATE FLIGHT PATH CONTROL
  OF AEROMANEUVERING VEHICLES FOR ORBIT CAPTURE AND LANDING
  APPLICATIONS
• EXPERIMENTALLY EVALUATE NEW CONTROL METHODOLOGIES AND
  DEMONSTRATE THEM AT A LEVEL OF MATURITY FOR FLIGHT
  APPLICATIONS
STABILIZATION & IDENTIFICATION

APPLICATION:
IN-SPACE SYSTEM IDENTIFICATION AND CONTROL TUNING TO ENABLE RELIABLE PRECISE STABILIZATION OF FUTURE SPACECRAFT
- MULTI-INSTRUMENT PLATFORMS
- LARGE ANTENNAS
- MULTI-APERTURE REFLECTORS
- INTERFEROMETER OBSERVATORIES

DESCRIPTION OF EFFORT:
ADVANCES NEW IN-SPACE ID TECHNOLOGY THROUGH
- CONCEPTUAL INNOVATIONS
- THEORETICAL DEVELOPMENT
- COMPUTER SIMULATION/VERIFICATION
- PHYSICAL GROUND EXPERIMENTS
- APPLICATION METHODS AND SOFTWARE DELIVERABLES
- FLIGHT EXPERIMENTS

PLANNED DEVELOPMENTS (FY'91-95)
- DEVELOP REDUCED VARIANCE SPECTRAL ESTIMATION OF THE PLANT TRANSFER FUNCTION
- DEVELOP THE ROBUSTNESS TO SYSTEM NOISE AND UNMODELED PLANT DYNAMICS
- DEVELOP THE CAPABILITY TO HANDLE LARGE DATA SETS
- EXTEND THE CAPABILITY OF THE NEW ID METHODS TO LARGER MULTIVARIABLE SYSTEMS
- DEVELOP THE FIRST GENERATION APPLICATION METHODS AND SOFTWARE TOOLS FOR MULTIVARIABLE ID/ROBUST CONTROL
- DESIGN, BUILD AND DEMONSTRATE A PROOF-OF-CONCEPT NEURAL NET MIMO ID/ROBUST CONTROLLER

CF9-14
APPLICATION:

ADAPTIVE CONTROLLERS ARE NEEDED FOR THE NEXT GENERATION SPACE SYSTEMS WHICH HAVE ANY OR ALL OF THE FOLLOWING ATTRIBUTES:

- HAVE SIGNIFICANT TIME-VARYING MASS PROPERTIES AND CHANGING DISTURBANCE ENVIRONMENT
- CANNOT BE TESTED FULLY ON THE GROUND DUE TO LOGISTIC CONSTRAINTS
- FLEXIBLE MODES AND/OR NON-COLLOCATED ACTUATOR/SENSOR CONFIGURATIONS
- UNCERTAINTIES DUE TO LARGE ANGLE ARTICULATION, FAST SLEW OR OTHER NONLINEAR EFFECTS

DESCRIPTION OF EFFORT:

DEVELOP ON-BOARD STABLE MULTIVARIABLE ADAPTIVE REGULATION AND TRACKING SYSTEM (SMARTS) CAPABILITY WHICH CAN CONTROL SPACECRAFT WITH

- VERY HIGH ORDER OF STATE VARIABLES (E.G. 100'S)
- MANY SENSORS AND ACTUATORS
- UNCERTAIN AND/OR CHANGING SPACECRAFT DYNAMICS, ENVIRONMENT AND MISSION SCENARIOS

SMARTS I: FOR SPACECRAFT WITH COLLOCATED SENSORS AND ACTUATORS
SMARTS II: FOR SPACECRAFT WITH SENSORS AND ACTUATORS THAT CANNOT BE COLLOCATED
SMARTS III: NEURAL BASED WITH LEARNING CAPABILITY
TASK 1. CONTROL OF SPACECRAFT

- ADVANCED CONTROL THEORY
  - DEVELOPMENT OF ROBUST CONTROL SYSTEM DESIGN TECHNIQUES FOR DISTURBANCE REJECTION IN FLEXIBLE SPACE STRUCTURES
  - DEVELOPMENT OF ADAPTIVE SYSTEM IDENTIFICATION AND CONTROL TECHNIQUES BASED ON ARTIFICIAL NEURAL NETWORKS.

- ADAPTIVE CONTROL
  - TESTING OF STATE SPACE SELF TUNING ADAPTIVE CONTROL ON SPACE STATION ATTITUDE CONTROL SIMULATOR

- INFLIGHT EVALUATION OF THE STRUCTURAL INTEGRITY OF SPACECRAFT
  - DEMONSTRATE FREQUENCY BASED LOCALIZATION TO SUPPORT STRUCTURAL HEALTH MONITORING OF FLEXIBLE SPACECRAFT.

- ADVANCED RCS LOGIC FOR FLEXIBLE MULTI-BODY SPACE VEHICLES
  - DEVELOP ADVANCED RCS LOGIC FOR FLEXIBLE MULTI-BODY SPACECRAFT INCLUDING SPACE STATION DURING ORBITER BERTHING
  - DEVELOP NEW RCS PHASE PLANE LOGIC TO ACCOMMODATE SIGNIFICANT STRUCTURAL MODE INTERACTION
Hardware:
- The front end processor is a Silicon Graphics machine.
- The high speed parallel processing unit uses 4 Intel 860 boards.
- Intel 860 benchmark numbers:

<table>
<thead>
<tr>
<th></th>
<th>SUN 68020</th>
<th>Data General 88000</th>
<th>SUN Sparc</th>
<th>Silicon Graphics R3000/3010</th>
<th>Intel 80860</th>
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<td>(1) Inversion of a 100x100 matrix</td>
<td>1.0</td>
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<td>8.6</td>
<td>18.5</td>
<td>47.1</td>
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<td>(2) Two-body dynamics simulation (approximately 10.8 MFLOPS)</td>
<td>1.0</td>
<td>4.5</td>
<td>5.4</td>
<td>18.0</td>
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Performance:
- Space Station Example is for the assemble complete configuration that includes the following:
  - 11 flexible bodies with flex modes up to 5Hz for 11 independently articulating flexible body configuration
  - Total of 101 system degrees of freedom (85 flex and 16 rigid) including core body (9 modes), 2 Alpha booms (6 modes), and 8 solar panels (8 modes each)
  - SSF PDR RCS and CMG controllers running at 5 Hz
  - Joint controllers for the solar panels
  - Complete orbital environment
- Flex body data obtained from NASTRAN for each body.

- Space Station dynamics simulated for one orbit (90 min) with the RCS control system in the attitude hold mode

- Computational performance (all times in min)

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<table>
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<tr>
<th>SSCOMP</th>
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<th>VAX-8850</th>
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<td>90</td>
<td>675</td>
<td>2025</td>
<td>235</td>
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- Current ongoing and future work involves
  - Upgrading the parallel controller
  - Completing the model database
  - Developing and completing the interface to IGES graphics
  - Enhancing the user interface as well as the simulation capabilities
Knowledge-based Control Technologies

- Adds enhanced robustness to RT fault management and control
- Provides graceful system degradation in fault-detected environment with minimum compromise to safety and reliability
- Provides automated monitoring of vehicle health and system status including trend analysis
- Integrates symbolic knowledge with numeric (algorithmic) knowledge

Elements of knowledge-based systems control technologies:

- Fault Diagnosis & Planning ➔ Symbolic or model-based controllers
- Neural Nets & Fuzzy Control ➔ Advanced Adaptive (Learning) Controls
- Model-based Reasoning ➔ "Smart" Structures & Optimal Adaptive Controls
Fuzzy Logic Control

Automatic Train Control
- Has been in successful application since July 1987 in Sendai, Japan
- Uses rules of the form,
  If speed of the train exceeds the speed limit,
  Then the maximum brake notch is selected.

Space Shuttle attitude control
- Under study at NASA JSC and NASA Ames, preliminary results show significant fuel savings over the conventional On-orbit digital autopilot
- Uses rules of the form,
  If attitude error is Negative Medium and attitude rate error is Negative Small,
  Then Acceleration (converted to Jet on/off command) is Negative Small

SUMMARY
- COMPREHENSIVE, DIVERSIFIED RESEARCH PROGRAM
- OBJECTIVES AIMED AT RELEVANT NATIONAL GOALS
- SIGNIFICANT MILESTONES/PROGRESS BEING ACHIEVED
- RESOURCES LIMITING PACE OF ACHIEVEMENTS
OVERVIEW OF JPL ACTIVITIES IN TRANSPORTATION GUIDANCE, NAVIGATION, AND CONTROL

LINCOLN J. WOOD
29 MAY 1991

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

PROGRAM ELEMENTS TO BE DISCUSSED

AEROMANEUVERING GUIDANCE, NAVIGATION, AND CONTROL (506-46-1 AND 506-46-2)

PATHFINDER/ETP AEROBRACING GN&C (591-42-3 AND 593-11-3)

PATHFINDER/ETP AUTONOMOUS LANDING (591-13-1 AND 591-13-2)

PATHFINDER/ETP AUTONOMOUS RENDEZVOUS AND DOCKING (591-21-2)
FY89/90 PRODUCTS - SUMMARY

0 ONBOARD, REAL-TIME GUIDANCE AND CONTROL ALGORITHMS
  0 SEVERAL NEW GUIDANCE ALGORITHMS FOR AEROASSISTED ORBIT TRANSFER,
    INCLUDING SIMPLE, NEAR-OPTIMAL SCHEMES
  0 PERTURBATION GUIDANCE ALGORITHMS WITH BOUNDED CONTROL
  0 RE-ENTRY VEHICLE MODELING
  0 ADAPTIVE AND NONADAPTIVE CONTROL ALGORITHM DEVELOPMENT
  0 GUIDANCE AND NAVIGATION ALGORITHMS FOR AEROMANEUVERING ENTRY TO
    LANDING
  0 MARS APPROACH NAVIGATION ACCURACY ASSESSMENT
  0 CHARACTERISTICS OF OPTIMAL AEROASSISTED TRAJECTORIES
    0 MINIMUM-FUEL PROPULSIVE AND AEROASSISTED TRANSFERS BETWEEN
      ARBITRARY ELLIPTICAL ORBITS
    0 OPTIMAL AEROMANEUVERING PLANE CHANGE TRAJECTORIES USING MULTIPLE
      ATMOSPHERIC PASSES
    0 MAXIMUM AEROMANEUVERING ORBIT PLANE CHANGES SUBJECT TO HEATING
      RATE CONSTRAINT
    0 COMPARISON OF COST FUNCTIONS FOR AEROMANEUVERING TRAJECTORY
      OPTIMIZATION PROBLEMS

PARTICIPANTS DURING FY89 AND FY90

0 JPL
  0 LINCOLN J. WOOD - TASK LEADER
  0 WILLIAM M. McENEaney/ALEX S. KONOPLIV/VIJAY ALWAR - GUIDANCE AND
    NAVIGATION
  0 DHEMETRIOS BOUSSALIS/ASIF AHMED/DON WANG - CONTROL SYSTEMS

0 UNIVERSITY OF MICHIGAN - PROFESSOR NGUYEN X. VINH (TRAJECTORY
  OPTIMIZATION)

0 UNIVERSITY OF TEXAS AT AUSTIN - PROFESSORS DAVID G. HULL AND JASON
  L. SPEYER (GUIDANCE)

0 RICE UNIVERSITY - PROFESSOR ANGELO MIELE (TRAJECTORY OPTIMIZATION
  AND GUIDANCE)
THREE NEW GUIDANCE ALGORITHMS DEVELOPED FOR AEROASSISTED ORBITAL TRANSFER

- BASED ON APPROXIMATE SOLUTION OF OPTIMAL CONTROL PROBLEM - LOH'S TERM ASSUMED DEPENDENT ON INDEPENDENT VARIABLE ONLY
- APPLICABLE TO BOTH COPLANAR AND NON-COPLANAR ORBIT TRANSFERS
- TWO ALGORITHMS MAXIMIZE EXIT SPEED FOR FIXED HEADING ANGLE, ALTITUDE, AND FLIGHT PATH ANGLE AT EXIT - MOST USEFUL FOR PRE-FLIGHT TRAJECTORY OPTIMIZATION
- THIRD ALGORITHM MINIMIZES CONTROL EFFORT FOR FIXED VELOCITY, HEADING ANGLE, ALTITUDE, AND FLIGHT PATH ANGLE AT EXIT
- INTENDED FOR ONBOARD, REAL-TIME GUIDANCE
- SIMPLE ENOUGH TO BE IMPLEMENTED ONBOARD
- PERFORMED WELL IN PRESENCE OF ATMOSPHERIC MODELING ERRORS IN PRELIMINARY TESTS

THREE UNIVERSITY CONTRACTS MONITORED

ADAPTIVE AND NONADAPTIVE CONTROL LAWS EVALUATED

- FOR COPLANAR SKIP TRAJECTORY
- USING BANK MODULATION FOR LIFT VECTOR CONTROL
- USING AERODYNAMIC FORCES AS WELL AS THRUSTERS FOR ROLL CONTROL

SIMULATION SOFTWARE EXPANDED TO INCLUDE OUT-OF-PLANE DYNAMICS

- FOR CONTROL LAW EXPANSION TO INCLUDE BOTH ROLL AND PITCH AXIS CONTROL

STUDY ON LEARNING AND DECISION-MAKING MODEL FOR HIGHER-LEVEL ADAPTATION COMPLETED

- METHODS TO COPE WITH GREATER RANGE OF UNCERTAINTY AND UNMODELED CHANGES, ESPECIALLY IN AUTONOMOUS OPERATIONS
FY90 PRODUCTS: JPL IN-HOUSE - CONTROL SYSTEMS (506-46-1)

RE-ENTRY VEHICLE MODELING

- Developed dynamic and kinematic equations of motion for use in design and analysis of control algorithms and development of simulation tools
- Derived aerodynamic coefficients and stability derivatives for biconic aeroshell
- Developed aeromaneuvering controls simulation program

CONTROL ALGORITHM DEVELOPMENT

- Conducted open-loop simulations to evaluate vehicle aerodynamic performance and stability characteristics
- Conducted preliminary investigation of effect of longitudinal normal modes of oscillation on hypersonic vehicle performance
- Extended planar control laws to 3-D vehicle dynamics and control
- Developed control law for suppression of dominant short-period normal mode of oscillation
- Qualitatively demonstrated pitch oscillation suppression via simulation

LJW-7

FY89/90 PRODUCTS: JPL IN-HOUSE - MARS APPROACH NAVIGATION (591-42-3)

- Accuracy of approach navigation has major impact on ability to perform aerocapture at Mars
- Estimates made of trajectory knowledge accuracy at entry interface, assuming various data types (funded jointly with JPL’s Exploration Initiative Studies Office - Codes SL and RZ)
- Earth-based radio metric data only (Doppler, range, and delta-DOR at anticipated accuracy levels of late 1990s)
- Earth-based plus vehicle-to-vehicle radio metric data (Mars orbiter in either 1/5-sol or areosynchronous orbit)
- Earth-based radio data plus onboard optical data (images of Deimos and Phobos)
- Earth-based tracking of both approach vehicle and Mars orbiter

Representative accuracy requirements at nominal entry time (L/D = 0.7, V-Infinity = 3.4 km/s, 500-km circular target orbit)

- 40 km in altitude
- 0.5 deg in flight path angle

CG10-4

LJW-9
Summary for Altitude Error

Summary for FPA Error

FY91 PLANS

0 CONTINUE DEVELOPMENT OF ONBOARD, REAL-TIME, NEAR-OPTIMAL GUIDANCE ALGORITHMS AND TEST WITH REALISTIC ERROR MODELS
0 EXTEND AEROCAPTURE GUIDANCE AND NAVIGATION S/W TO INCLUDE NAVIGATED STATE AS WELL AS REAL STATE FOR EVALUATING GUIDANCE ALGORITHM PERFORMANCE
0 PLANETARY APPROACH NAVIGATION AND GUIDANCE
   0 CONTINUE WORK IN PROGRESS WITH IMPROVED ERROR MODELING AND FURTHER VARIATION OF KEY PARAMETERS
   0 PERFORM PRELIMINARY ASSESSMENT OF RELATIVE MERITS OF VARIOUS DATA TYPES
0 COMPLETE UNIVERSITY RESEARCH
   0 DETERMINATION OF CHARACTERISTICS OF OPTIMAL AEROASSISTED TRAJECTORIES
   0 DEVELOPMENT OF GUIDANCE ALGORITHMS

CG10-5

LJW-11
PLANS FOR FY92 AND BEYOND (593-11-3)

FY92  IDENTIFY CANDIDATE GUIDANCE/ATMOSPHERIC SENSOR ARCHITECTURES
FY93  DEFINE NAVIGATION TECHNOLOGY
FY94  PERFORM CONCEPTUAL DEMONSTRATION OF GUIDANCE/NAVIGATION SYSTEM
FY96  BEGIN TESTBED VALIDATION OF LUNAR RETURN GN&C SYSTEM
FY97  DEFINE GN&C FOR FLIGHT TEST
FY98  BEGIN TESTBED VALIDATION OF GN&C SYSTEM FOR MARS

TASKS TO BE PERFORMED JOINTLY WITH LARC
A NASA PROGRAM AUGMENTATION:
COMPUTATIONAL CONTROL

G. K. MAN

BRIEFING TO SSTAC - 6/27/91

AGENDA

- OBJECTIVE
- MOTIVATION
- CURRENT LIMITS
- NASA TOOL DEVELOPMENT EXPERTISE
- TECHNICAL APPROACH
- RECENT ACCOMPLISHMENTS
- FOREIGN CAPABILITIES
- TECHNOLOGY TRANSFER
- PLAN
- SUMMARY
**INTRODUCTION**

**OBJECTIVE**

To develop a new generation of articulated multibody modeling, control design and simulation algorithms, and prototype software tools for spacecraft and robots:

- for design, functional and performance testing
- to handle high fidelity models (>100 states)
- to reduce mission risk and enhance productivity

**MOTIVATION**

Current tools severely limit comprehensive control design and verification and are inadequate for future needs:

- cannot handle high fidelity system
- excessive run time
- not user friendly
LIMITATION OF CURRENT TOOLS - GALILEO CASE STUDY

GALILEO SCAN PLATFORM POINTING CONTROL EXAMPLE

SPACECRAFT CONFIGURATION HIGHLY SIMPLIFIED MODEL (26 DOF)

- CRAY X-MP CANNOT SIMULATE HIGHLY SIMPLIFIED GALILEO MODEL IN REAL-TIME (FALLS SHORT BY A FACTOR OF 10)
- CURRENT SIMULATION TECHNOLOGY LIMITS NASA'S ABILITY TO VERIFY SPACECRAFT DESIGN (REAL-TIME HARDWARE-IN-THE-LOOP TESTING IS LIMITED TO HIGHLY SIMPLIFIED RIGID BODY SIMULATIONS)
- NEED FOR NEW INFRASTRUCTURE TOOLS HAS REACHED A CRITICAL POINT. NEW TOOLS ARE NECESSARY TO SUPPORT CURRENT AND FUTURE AGENCY MISSIONS.

SPACECRAFT COMPUTATIONAL CONTROL TOOL DEVELOPMENT EXPERTISE

NASA TECHNICAL CONTRIBUTIONS

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CG11-3
TECHNICAL APPROACH

- SPATIAL RECURSION ALGORITHMS (FACTOR OF N INCREASE IN SPEED)
- PARALLEL COMPUTING (SPEED INCREASE ~ # OF PROCESSORS)
- SYMBOLIC MANIPULATION (> FACTOR 5 IMPROVEMENT IN SPEED)
- OBJECT-ORIENTED ENVIRONMENT FOR NEW ALGORITHM DEVELOPMENT & IMPLEMENTATION
- PROBLEM-SPECIFIC ALGORITHMS AND SOFTWARE TO PROVIDE GOOD NUMERICAL CONDITIONING & COMPUTATIONAL EFFICIENCY
- STATE-OF-ART SOFTWARE & HARDWARE (E.G. LAPACK)

KEY PRODUCTS

REAL-TIME SIMULATION SYSTEM FOR SPACECRAFT HARDWARE-IN-THE-LOOP TESTING
INTEGRATED ANALYSIS & SIMULATION WORKSTATION
MODERN CONTROL DESIGN & ANALYSIS SOFTWARE

SELECTED RECENT ACCOMPLISHMENTS

- GSFC HAS ENHANCED DISCOS BY REPLACING THE ORDER N³ ENGINE BY AN ORDER N ENGINE FOR RIGID AND ELASTIC SYSTEMS. THE UPGRADED DISCOS IS UNDER BETA TESTING.

- JPL HAS DEVELOPED NEW HIGHLY EFFICIENT DYNAMICS ALGORITHMS FOR REAL-TIME SIMULATION (DARTS), BASED ON SPATIAL OPERATOR ALGEBRA, FOR SPECIALIZED COMPUTER ARCHITECTURES (E.G. PARALLEL COMPUTERS). CRAF/CASSINI HAS ADOPTED THIS NEW ALGORITHM FOR THE DEVELOPMENT OF A REAL-TIME SIMULATION CAPABILITY FOR SPACECRAFT TESTING.

- JSC AND LaRC HAVE DEVELOPED A NEW SPACE STATION COMPUTATIONAL CONTROL WORKSTATION (SSCOMP) FOR CONTROL DESIGN, ANALYSIS AND SIMULATION. THE SIMULATION CAPABILITY IS 120 TIMES FASTER THAN 1987 TECHNOLOGY FOR A 140 STATES SPACE STATION.

- MSFC HAS UPGRADED TREETOPS WITH A NEW ORDER N ALGORITHM. THE NEW CODE IS BEING USED BY JSC FOR THE SHUTTLE RMS.
IMPROVEMENT IN TECHNOLOGY FROM 1987

DEVELOPMENT OF ORDER N MULTIBODY SIMULATION CAPABILITY

![Graph showing run time in computational units vs. fidelity (number of elastic modes) for ORDER N '87 and ORDER N '91.]

NEW/EMERGING CAPABILITIES

- ORDER-N DISCOS
- DARTS
- SSCOMP
- ORDER-N TREETOPS

FEATURES OF THE DARTS ALGORITHM

GENERAL EQUATIONS OF MOTION FOR A SPACECRAFT:

\[ M(q)\ddot{q} + C(q,\dot{q}) = T \]

CONVENTIONAL ALGORITHM

- REQUIRE ORDER N^3 COMPUTATION
- COMPUTE THE MASS MATRIX M
- COMPUTE THE CORIOLIS AND CENTRIFUGAL FORCES C
- SOLVE THE LINEAR EQUATION
  \[ M\ddot{q} = T - C \] FOR \( \ddot{q} \)

DARTS ALGORITHM

- REQUIRE ORDER N COMPUTATION
- DOES NOT REQUIRE M, OR C OR SOLVING THE LINEAR EQUATION
- BASED UPON A SPATIAL OPERATOR EXPRESSION FOR M^-1
- RECURSIVELY COMPUTE \( \ddot{q} \)

THE DARTS ALGORITHM

- REDUCES COMPUTATIONAL TIME (FROM CUBIC TO LINEAR COMPUTATIONAL COMPLEXITY)
- IS HIGHLY PARALLELIZABLE
- IS RECURSIVE AND MODULAR RESULTING IN REDUCED SOFTWARE COSTS

CG11-5
ARCHITECTURE OF THE DARTS ALGORITHM

EXTERNAL AND ACTUATOR FORCES

1. RECURSION FROM EACH APPENDAGE TOWARDS BUS ONE AT A TIME

EFFECTIVE FORCES ON THE BUS

2. COMPUTE BUS ARTICULATED INERTIA

BUS ACCELERATION

3. RECURSION FROM BUS TOWARDS EACH OF THE APPENDAGES

MODAL AND HINGE ACCELERATIONS $q$

CRAF/CASSINI APPLICATION

REDUCES RUN TIME & HANDLES HIGH FIDELITY IN REAL-TIME

- LIMITED TO 4 RIGID BODIES

CONVENTIONAL ALGORITHM

- NEW CAPABILITY INCLUDES IMPORTANT AND DIFFICULT TO MODEL EFFECTS SUCH AS PROPELLANT SLOSH AND SPACECRAFT FLEXIBILITY (PREVIOUSLY UNABLE TO INCORPORATE) FOR SPACECRAFT TESTING

- ADDS 8-BODY SPACECRAFT, FLEXIBLE BUS, BOOMS & ANTENNA

- PROPellant SLOSH FOR 3 TANKS

DARTS ALGORITHM

- ALLOWS ANSWERING THE SAME DESIGN QUESTION IN LESS THAN 1/10 OF THE TIME

- A LARGE INCREASE IN MODEL FIDELITY IS OBTAINED WITH ONLY A SMALL INCREASE IN RUN TIME (THE RATE OF INCREASE OF RUNTIME IS REDUCED BY AN ORDER OF MAGNITUDE)

CG11-6
FEATURES OF SSComp

- THE PROTOTYPE SSComp IS AN INTEGRATED SELF-CONTAINED CAD PLATFORM FOR SPACE STATION G,N & C ANALYSIS
  - ORDER-N ALGORITHM FOR FLEXIBLE MULTI-BODIES SPACECRAFT
  - SYMBOLIC CODE GENERATOR
  - OBJECT ORIENTED INTERFACE
  - 3-D SOLID MODELING FOR ANIMATION
  - SILICON GRAPHICS COMPUTER WITH 4 I-860 BOARDS

- COMPUTATIONAL PERFORMANCE FOR ONE (90 MIN) ORBIT SIMULATION WITH RCS CONTROL SYSTEM IN ATTITUDE HOLD MODE (101 DEGREES OF FREEDOM)

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<th>SSComp</th>
<th>SGI</th>
<th>SUN-4</th>
<th>VAX-8850</th>
</tr>
</thead>
<tbody>
<tr>
<td>90(MIN)</td>
<td>675</td>
<td>2024</td>
<td>235</td>
</tr>
</tbody>
</table>

- SIGNIFICANCE
  THIS HIGH PERFORMANCE (A ORDER OF MAGNITUDE INCREASE IN SPEED) WORKSTATION IS THE MODEL FOR A FUTURE CONTROL ANALYSIS AND SIMULATION PLATFORM

FOREIGN CAPABILITY ISSUES

MAJOR FOREIGN MULTIBODY CAD PROGRAMS

<table>
<thead>
<tr>
<th>NUBEMN-</th>
<th>GERMANY</th>
<th>SYM-</th>
<th>YUGOSLAVIA</th>
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</thead>
<tbody>
<tr>
<td>NEWEUL-</td>
<td>GERMANY</td>
<td>SPACAR-</td>
<td>NETHERLANDS</td>
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<tr>
<td>MEDYNA-</td>
<td>GERMANY</td>
<td>AUTODYN-</td>
<td>BELGIUM</td>
</tr>
<tr>
<td>MESA VERDE-</td>
<td>GERMANY</td>
<td>PLEXUS-</td>
<td>FRANCE</td>
</tr>
<tr>
<td>DECAP-</td>
<td>ITALY</td>
<td>DAPHNE-</td>
<td>JAPAN</td>
</tr>
</tbody>
</table>

EMPHASIS - AUTOMOBILS, TRAINS, HELICOPTERS, SPORTS, ROBOTS, SPACECRAFT

- FOREIGN TECHNOLOGIES ARE ADVANCING AT A RAPID PACE:
  - EUROPEANS ARE BUILDING POWERFUL TOOLS BASED ON U.S. TECHNOLOGY
  - JAPAN IS ENTERING THE FIELD IN THE LAST 2 YEARS WITH AMBITIOUS GOALS
  - U.S. IS UNIQUELY QUALIFIED TO MAINTAIN THE LEADERSHIP ON HIGH PERFORMANCE COMPUTING AND SIMULATIONS BY BUILDING ON OUR NEW HARDWARE AND SOFTWARE TECHNOLOGIES
TECHNOLOGY TRANSFER

- MULTIAGENCY, UNIVERSITY AND INDUSTRY WORKING AND ADVISORY COMMITTEE TO FACILITATE COMMUNICATION
- EARLY RELEASE OF TECHNOLOGY TO U.S. INDUSTRY
- UNIVERSITY OF IOWA/NSF VERIFICATION LIBRARY FOR REQUIREMENTS AND BENCHMARK PROBLEMS
- ANNUAL TECHNOLOGY TRANSFER WORKSHOP/CONFERENCE TO DESEMINATE RESEARCH FINDINGS

PERFORMANCE OBJECTIVE & RESOURCE

<table>
<thead>
<tr>
<th>KEY PARAMETERS</th>
<th>PERFORMANCE OBJECTIVES</th>
</tr>
</thead>
<tbody>
<tr>
<td>- SYSTEM FIDELITY FOR CONTROL DESIGN (# OF STATES)</td>
<td>10 100 400</td>
</tr>
<tr>
<td>- RUN-TIME FOR REALTIME HARDWARE-IN-THE-LOOP TESTING OF A 150 STATES SYSTEM (MSEC)</td>
<td>100 10 &lt;10</td>
</tr>
<tr>
<td>- USER FRIENDLINESS (TIME TO SETUP A 100 STATES SIMULATION)</td>
<td>DAYS HOURS MINUTES</td>
</tr>
</tbody>
</table>

FUNDING REQUIREMENT FOR ALL CENTERS ($K)

<table>
<thead>
<tr>
<th>FY92</th>
<th>FY93</th>
<th>FY94</th>
<th>FY95</th>
<th>FY96</th>
</tr>
</thead>
<tbody>
<tr>
<td>3600</td>
<td>3600</td>
<td>3600</td>
<td>3600</td>
<td>3600</td>
</tr>
</tbody>
</table>
## SUMMARY

- Need for new generation tools has hit critical level
- NASA uniquely qualified to lead development of new tool
- NASA has made significant technical progress in key areas
  - Fast algorithms for hardware-in-the-loop simulation
  - New analysis workstation
- Preliminary program plan defined
- NASA ready for program start now
Fiberoptic Rotation Sensors (FORS): Technology Development and Transfer

Presentation to the
Space Science Technology Advisory Committee

Tysons Corner, Virginia
June 27, 1991

Randy Bartman
Optoelectronic Sensor Systems and Technology Group
Guidance and Control Section (343)

Overview

- Background Material
  - What is FORS?
  - Why are we pursuing it?
  - Brief history of FORS development

- FORS Engineering Model Development and Technology Transfer
  - Goal / Objectives / Assumptions
  - Schedule / Resources
  - Responsibilities

- Summary
What is FORS?

- All solid state optical gyro, based on the Sagnac effect
- Unique (NASA patent #4,662,751) optical processing technique is used to convert gyro rotation rate into an optical beat frequency
- Angular position is read by counting beats
- Implemented through the use of
  - Integrated optical circuits (AT&T Bell Labs, UTP)
  - Polarization-maintaining, low loss optical fiber
  - Semiconductor optical source, detectors operating at a wavelength of 1.3 μm

Note: Much of this technology is being developed by and for the telecommunications industry

FORS Principle of Operation - The Sagnac Effect

Two light beams (CW and CCW) start at the same time but race in opposite directions around a waveguide.

As the physical waveguide rotates, the attached "observer" (OBS) and the "start/finish line" (S/F) rotate with it...

... Giving an "unfair advantage" to CW in the race for S/F; although it travels no faster than CCW, CW arrives at S/F first because of S/F's rotation.

This "unfair advantage" manifests itself as a relative or "non-reciprocal" phase shift, Φs, between the CW and CCW beams. Suppose CW and CCW are light beams of wavelength λ, and the waveguide is an optical fiber of length L wound on a spool of diameter D: then Φs is given by

$$\Phi_s = 2\pi \frac{LD}{\lambda} \Omega$$

CG12-2
Fiberoptic Rotation Sensor Schematic

Why FORS?

- Navigational grade performance with improved lifetime, power, mass, cost, availability, flexibility
- All solidstate strapdown rotation sensor
  - No moving parts
  - Modular construction
- Optoelectronic technology →
  - Leverage telecommunications industry investments
  - Non-obsolescent
  - Potentially expanded vendor base
Inertial Sensors Comparison
DRIRU II vs. FORS

**• Characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>DRIRU II</th>
<th>FORS (equiv. perf.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long term drift</td>
<td>0.003 deg/hr</td>
<td>&lt; 0.003 deg/hr (goal)</td>
</tr>
<tr>
<td>Max. input rate</td>
<td>&lt; 4 deg/s</td>
<td>&gt; 100 deg/s</td>
</tr>
<tr>
<td>Operational life</td>
<td>4 - 5 years</td>
<td>≥ 12 years</td>
</tr>
<tr>
<td>Mass</td>
<td>17 kg</td>
<td>&lt; 10 kg</td>
</tr>
<tr>
<td>Power (low rate)</td>
<td>15 W</td>
<td>&lt; 10 W</td>
</tr>
<tr>
<td>Power (high rate)</td>
<td>23 W</td>
<td>&lt; 10 W</td>
</tr>
<tr>
<td>Unit cost</td>
<td>$2.1- $3.5 M</td>
<td>$1.3 M</td>
</tr>
</tbody>
</table>

**• Advantages of FORS and their implications**

- Greater lifetime: Allows extended (continuous) gyro operation during mission. This simplifies mission planning and/or increases operational flexibility.
- Reduced mass: Reduced launch cost (7 kg x $100 K/kg) and/or increased science payload
- Reduced power: Reduced power system cost (13 W x $80 K/W) and/or more power available for science payload
- Lower unit cost: Reduced by $0.8 M - $2.2 M / IRU

**FORS Scaling and Design Flexibility**

- Increasing the diameter of the coil and/or the length of fiber wound on it provides a straightforward means of improving FORS performance.

  - Take
    - Coll diameter $D = 50$ cm,
    - Fiber length $L = 10$ km,
    - Wavelength $\lambda = 1.3 \mu$m, and
    - "NEPS" $\phi = 1E-7$ rad ;
  - Then
    - "NERR" $\rightarrow \Omega = 0.00025$ deg/hr

- Conversely, FORS performance can be traded for reduced size, mass and/or cost

  - Take
    - Coll diameter $D = 8$ cm,
    - Fiber length $L = 1$ km,
    - Wavelength $\lambda = 1.3 \mu$m, and
    - "NEPS" $\phi = 1E-6$ rad ;
  - Then
    - "NERR" $\rightarrow \Omega = 0.16$ deg/hr

- The modular nature of FORS translates into great design flexibility, e.g. the ability to separate the passive, low-mass sensing coil(s) from the active electronics/optoelectronic components.
### JPL / CSDL Cooperative Development Effort

- MOU / MOA between JPL and Charles Stark Draper Laboratory for cooperative development of JPL's FORS technology
  - Goal 1: Demonstrate FORS technology readiness for use on CRAF/Cassini
  - Goal 2: Develop and build first FORS EM and flight units
  - Goal 3: Transfer FORS technology to American industry
Key JPL/CSDL Accomplishments 1989 - 1991

- MOU / MOA between JPL / CSDL signed (8/89)
- JPL FORS technology transfer to CSDL
- Design, fabrication of 3 FORS brassboards
- Static & dynamic tests of brassboards
- IRU design / packaging studies initiated
- Successful FORS Technology Readiness Review (9/90)
- Additional funding commitments from Codes Q&R (~2/91)
- Preliminary review of FORS EM Development Plan (5/91)
FORS: Demonstrated "nav-grade" performance

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>Pointing error req.$(3\sigma)$</th>
<th>Pointing error act.$(3\sigma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 sec</td>
<td>2.3 $\mu$rad</td>
<td>0.15 $\mu$rad</td>
</tr>
<tr>
<td>100 sec</td>
<td>43 $\mu$rad</td>
<td>3.1 $\mu$rad</td>
</tr>
<tr>
<td>2 hours</td>
<td>0.5 mrad</td>
<td>0.5 mrad **</td>
</tr>
</tbody>
</table>

* Craf/Cassini requirement
** Corresponds to rotation rate of 0.005°/hr
FORS Engineering Model Development Program

Goal

- Make available to NASA users a space-qualifiable Fiberoptic Rotation Sensor (FORS) Inertial Reference Unit (IRU)

- A FORS IRU will possess navigational grade performance and will offer significant advantages over current IRUs:
  - Improved lifetime
  - Lower power
  - Lower mass
  - Lower cost
  - Greater design flexibility
Objectives

- Develop, demonstrate engineering model* FORS four-axis IRU
  - Develop, demonstrate FORS single-axis EM
  - Develop, demonstrate flight-packaged, high reliability FORS optoelectronic components and interconnects
  - Fabricate additional single-axis FORS units
    - Conduct reliability, acceptance & long-term trend tests

- Transfer FORS technology to industry
  - Multi-vendor base

* Engineering model: Full flight functionality.
  Capable of being environmentally tested to flight environments.
  Same hardware, assembly techniques as flight hardware.
  Flight or nearly flight form factor.

Assumptions

- Time frame
  - Four-axis IRU EM by end of FY93
  - Earliest users: AXAF, SIRTF, EOS, HST

- Funding
  - Total cost: $10.7 M over FY91-93
  - Expected sources: NASA Codes Q, R, S(?), CSDL CSR

- One Integrated program with two major activity areas
  - FORS instrument development ("system design")
  - FORS optoelectronic component development

- Cooperative effort with Industry: JPL-led, industry-performed
  - FORS instrument: JPL / Charles Stark Draper Lab
  - FORS components: JPL / vendors
### FORS Engineering Model Development Program

<table>
<thead>
<tr>
<th>FY91</th>
<th>FY92</th>
<th>FY93</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **FORS Instrument Development**
  - Single Axis FORS $2.3M
    - Design, fab, test and analysis
  - Add. Single Axis FORS Units (9) $1.9M
    - Fab, test, use in IRU, trend tests
  - 4-Axis FORS IRU $1.7M
    - Design, fab, test and analysis

- **FORS Optoelectronic Components: Development & Test**
  - Component Aging, Radiation & Reliability Tests $1.4M
  - Component Failure Mode Analysis & Package Development $1.33M

### FORS Engineering Model Development

#### Responsibilities Matrix

<table>
<thead>
<tr>
<th>JPL</th>
<th>CSDL</th>
<th>Vendors</th>
</tr>
</thead>
<tbody>
<tr>
<td>FORS Instrument Development</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
- Overall management
- Mission / IRU reqs.
- Reliability / QA stds.
- Environmental test
- Full tech support
- Instrument design
- Instrument fab
- Functional test
- Tech transfer
- Tech / mgt. support

| FORS Optoelectronic Component Development |
- Failure modes
- Component reqs.
- Reliability / QA stds.
- Function / Env. tests
- Tech support
- Component reqs.
- Functional tests
- Specific components
- Comp. pv - develop.
- Reliability / QA stds.
- Function / Env. tests
- Mgt. support

- Failure modes
- Indirect
Summary

- Why FORS?
  - 0.01-0.001°/hr gyro for space applications
  - Reduced mass, power, cost and increased lifetime, reliability, design flexibility vs. spinning mass gyros

- Successful development program to date
  - Brassboards designed, fabricated and under test
  - Demonstrated 0.005°/hr performance

- Proceeding with development of Engineering Models
  - JPL-led, Industry-performed
  - Single-axis FORS EM by end of FY92

- Model for technology transfer
  - Multi-code funding (Codes R,Q,S)
  - Joint effort with Industry (CSDL, others)
PRECISION
INSTRUMENT & TELESCOPE
POINTING

OBSERVATION SYSTEMS PROGRAM AREA
OF THE
SPACE SCIENCE TECHNOLOGY PROGRAM

F. Hadaegh
F. Tollivar

Integrated Technology Plan for the Civil Space Program Review
Tysons Corner, Virginia, June 24-28, 1991

AGENDA

- TECHNOLOGY NEEDS
  - APPLICATION THRUSTS
  - INSTRUMENT POINTING
  - TELESCOPES AND INTERFEROMETERS

- INTEGRATED TECHNOLOGY DEVELOPMENT PLAN
  - CHALLENGES
  - APPROACH
  - DEVELOPMENT PROGRAM
  - SCHEDULE

- RECOMMENDATIONS
The Precision Instrument & Telescope Pointing Program will provide the 1-2 order-of-magnitude increase in precision pointing capability (i.e., pointing control, stability, and knowledge) required by numerous OSSA future missions.

- **Astrophysics Mission**
  - Moderate Optical Interferometer (MOI)
  - Imaging Interferometer (II)
  - Next Generation Space Telescope (ST-NG)
  - Large Deployable Reflector (LDR)
  - Lunar Based Interferometers and Segmented Reflectors

- **Earth Science Missions**
  - Advanced LEO/GEO Instruments

- **Solar System Exploration**
  - Toward Other Planetary Systems (TOPS 1 & 2)

**Precision Instrument & Telescope Pointing Application Thrusts**

- **Science Instrument Pointing**
  - Advanced LEO/GEO Earth Observations
  - Solar System Exploration Pointing

- **Telescope/Interferometer Pointing**
  - Advanced Astrophysics Missions
    - Space Interferometers
    - NG-ST
    - Submm-IR (SMMM, LDR)
PRECISION INSTRUMENT & TELESCOPE POINTING

POINTING NEEDS vs SOA

![Graph showing pointing needs vs SOA for various instruments and projects.](image)

INSTRUMENT POINTING NEEDS

CG13-3
Eos POLAR ORBITING PLATFORM

HIGH PRECISION SCAN PLATFORM

HUYGENS TITAN PROBE

CALIBRATION TARGET

REACTION WHEEL (4)

PROBE RELAY ANTENNA

12 BAY ELECTRONICS BUS

LGA 1

HGA

RPWS ANTENNA (4)

MAG BOOM

TURNABLE SHADE

RCS TANK

PRESS. TANK(2)

TURNABLE

THRUSTER POD (4)

MSC

LGA 2

MAIN ENGINE

CASSINI DEPLOYED REAR TRIMETRIC VIEW

CG13-4
**Instrument Changes As of Oct. 4, 1989**

- **MICROWAVE RADIOMETER (INSTRUMENT 1)**

### Precise Instrument & Telescope Pointing

**INSTRUMENT POINTING TECHNOLOGY REQUIREMENTS vs SOA**

<table>
<thead>
<tr>
<th>Pixel Size</th>
<th>EOS, CC State-of-Art (1991) LEO (1 arcsec = 3 m)</th>
<th>Advanced EOS/GEOPLAT/Solar Sys Exl. Needs LEO (1 arcsec = 3 m)</th>
<th>GEO (1 arcsec = 160 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>108 arcsec</td>
<td>10 arcsec</td>
<td>1 arcsec</td>
</tr>
<tr>
<td>Knowledge</td>
<td>50 arcsec</td>
<td>5 arcsec</td>
<td>0.5 arcsec</td>
</tr>
<tr>
<td>Stability</td>
<td>100 arcsec/100 sec</td>
<td>10 arcsec/100 sec</td>
<td>1 arcsec/100 sec</td>
</tr>
<tr>
<td></td>
<td>10 arcsec/1 sec</td>
<td>1 arcsec/1 sec</td>
<td>0.1 arcsec/1 sec</td>
</tr>
<tr>
<td></td>
<td>1 arcsec/0.01 sec</td>
<td>0.1 arcsec/0.01 sec</td>
<td>0.01 arcsec/0.01 sec</td>
</tr>
<tr>
<td>Dataset Coregistration</td>
<td>Via Ground Processing of Image Data</td>
<td>Registration to 1/2 Pixel Best Case</td>
<td>Via On-board Boresight Alignment Sensing</td>
</tr>
</tbody>
</table>

- **INSTRUMENTS LARGER & MORE MASSIVE**
- **MORE STRINGENT POINTING REQUIREMENTS**
- **MORE ELECTRICAL POWER & COOLING AREA**
- **STILL HIGH DATA RATES**
TELESCOPE & INTERFEROMETER POINTING NEEDS
# NEXT CENTURY ASTROPHYSICS PROGRAM: CANDIDATE MAJOR AND MODERATE MISSIONS: 1995 - 2020
( FOR TECHNOLOGY PLANNING PURPOSES)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ULTRA VIOLET</td>
<td>HUBBLE SPACE TELESCOPE</td>
<td>LUNAR TRANSIT TELESCOPE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VISIBLE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RELATIVITY</td>
<td>GRACE</td>
<td>SOFI</td>
<td></td>
<td></td>
<td>LAGOS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INFRARED</td>
<td>SIRTF</td>
<td>LARGE DEPLOYABLE REFLECTOR</td>
<td>SUBMM</td>
<td>SUBMM interferometer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUBMILLIMETER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RADIO</td>
<td>ADVANCED X-RAY FACILITY</td>
<td>X-RAY SPECTROSCOPY OBSERVATORY</td>
<td>ADVANCED VERY LONG BASELINE INTERFEROMETER</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-RAY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GAMMA RAY</td>
<td>NAE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GAMMA RAY SPECTROSCOPY OBSERVATORY</td>
</tr>
</tbody>
</table>

PNS 2/28/91

# ANGULAR RESOLUTION VERSUS WAVELENGTH FOR FUTURE ASTRONOMICAL SPACE INSTRUMENTS

![Graph showing angular resolution versus wavelength for future astronomical space instruments](image-url)
FUTURE LARGE OPTICAL SYSTEMS IN SPACE
## PRECISION INSTRUMENT & TELESCOPE POINTING

### MISSION REQUIREMENTS

<table>
<thead>
<tr>
<th>MISSION</th>
<th>TECHNOLOGY FREEZE DATE</th>
<th>APERTURE/ BASELINE</th>
<th>POINTING ACCURACY</th>
<th>POINTING STABILITY</th>
<th>MISSION DURATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGST</td>
<td>2004</td>
<td>10 m</td>
<td>50 nrad</td>
<td>5 nrad</td>
<td>15 YEARS</td>
</tr>
<tr>
<td>LTT</td>
<td>1995</td>
<td>2 m</td>
<td>TBD</td>
<td>TBD</td>
<td>10 YEARS</td>
</tr>
<tr>
<td>LAGOS</td>
<td>2009</td>
<td>10^7 km</td>
<td>TBD</td>
<td>0.3 prad</td>
<td>10 YEARS</td>
</tr>
<tr>
<td>MOI</td>
<td>1997</td>
<td>20 m</td>
<td>0.3 nrad</td>
<td>0.3 nrad</td>
<td>5 YEARS</td>
</tr>
<tr>
<td>SIRTF</td>
<td>1994</td>
<td>1 m</td>
<td>300 nrad</td>
<td>300 nrad</td>
<td>3 YEARS</td>
</tr>
<tr>
<td>LDR</td>
<td>2006</td>
<td>20 m</td>
<td>250 nrad</td>
<td>125 nrad</td>
<td>10 YEARS</td>
</tr>
<tr>
<td>NGOVLBI</td>
<td>2000</td>
<td>TBD</td>
<td>500 nrad</td>
<td>500 nrad</td>
<td>10 YEARS</td>
</tr>
<tr>
<td>FFT</td>
<td>1997</td>
<td>30 m</td>
<td>0.8 nrad</td>
<td>0.8 nrad</td>
<td>10 YEARS</td>
</tr>
<tr>
<td>SMMM</td>
<td>1995</td>
<td>3.65 m</td>
<td>2.5 mrad</td>
<td>1.25 mrad</td>
<td>2 YEARS</td>
</tr>
<tr>
<td>FUSE</td>
<td>1993</td>
<td>1 m</td>
<td>2.5 nrad</td>
<td>1.25 nrad</td>
<td>4 YEARS</td>
</tr>
<tr>
<td>SMMI</td>
<td>2006</td>
<td>1 km</td>
<td>TBD</td>
<td>TBD</td>
<td>10 YEARS</td>
</tr>
<tr>
<td>LI</td>
<td>2003</td>
<td>10 km</td>
<td>TBD</td>
<td>TBD</td>
<td>10 YEARS</td>
</tr>
<tr>
<td>HXIF</td>
<td>1999</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>10 YEARS</td>
</tr>
</tbody>
</table>
PRECISION INSTRUMENT & TELESCOPE POINTING

TECHNOLOGY CHALLENGES

• INCREASE SPACE BASED TELESCOPE POINTING Capability by 1-Order of Magnitude Beyond HST
  • 10 Fold Improvement in Precision/ Stability
  • Provide New Capabilities for Line-Of-Sight Transfer, Telescope Nodding and Multi-Aperture Pointing

• INCREASE REMOTE SENSING INSTRUMENT POINTING Capability by 2-Orders of Magnitude
  • 100 Fold Improvement in Precision/ Stability
  • Increase Science Throughput and Operational Efficiency via On-Board Pointing Automation
  • Provide New Capabilities in Target Referenced Pointing, Attitude Transfer and Instrument Co-Boresighting

• INCREASE RELIABILITY, LIFETIME AND EFFICIENCY OF POINTING COMPONENTS
  • 3 Fold Improvement in Reliability and Life of Critical Components

TECHNOLOGY DEVELOPMENT APPROACH

• FOCUSED DEVELOPMENT OF
  - Advanced Pointing System Architecture
  - Sensor and Actuator Brassboards
  - Hardware and Software Testbed Demonstrations

• Coordinate Planning and Implementation with OSSA Advanced Development
**Instruments**

- Sensors/Actuators
  - Extended Image/Feature Trackers
  - Autonomous Star Trackers
  - Attitude Transfer Systems
  - Reactionless Actuators
  - Image Motion Compensation

- Target-Referenced Pointing Tracking
  - Earth/Feature Based
  - Earth Coordinates (Longitude/Latitude)

- Instrument Co-Boresighting
  - Multiple Instruments
  - Multi-Spectral Image Registration

- Autonomous Pointing Executive
  - High Level Command Capability
  - On-Board Sequence Generation/Execution
  - Sequence Interrupt/Restart

- Systems Design, Analysis, Integration, and Testing

**Telescopes**

- Advanced Optical Sensors
  - Fine Guidance Sensors
  - Autonomous Star Trackers
  - Line-Of-Sight Transfer Systems

- Inertial Rotation Sensors/IRU's

- Precision Actuators
  - Superquiet High-Capacity Reaction Wheels and Control Moment Gyros
  - Momentum Compensated Pointing/Beam Steering Devices

- System Design, Analysis, Integration and Testing

---

**Schedule**

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<td>Gyros/IRU's</td>
<td>HIGH RELIABILITY PERFORMANCE GYROS</td>
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Budget($M) - This Plan: 5.0 7.0 9.0 11.0
PRECISION INSTRUMENT & TELESCOPE POINTING
RECOMMENDATIONS

• PROCEED WITH PROGRAM PLANNING AT 10-12 M$/YEAR LEVEL

• CONTINUE STRONG COORDINATION BETWEEN TECHNOLOGY DEVELOPERS AND USERS
  - FORM INTERCENTER TECHNOLOGY DEVELOPERS AND USERS WORKING GROUP
  - REVIEW OF GOVERNMENT/INDUSTRY CAPABILITIES
  - OSSA UPDATE OF MISSION REQUIREMENTS

• START EARLY (i.e., FY 93) TO INSURE AVAILABILITY OF TECHNOLOGY PRODUCTS TO NEAR TERM USERS (i.e., EOS, SMMM, and MOI)

APPENDIX
### Hubble Space Telescope
- **Name:** Hubble Space Telescope
- **Location:** Low Earth Orbit
- **Mission:** 15 years with servicing
- **Wavelength:** 0.1 - 1 micron (2.5 micron with upgrade)
- **Aperture Size:** 2.4 M
- **Optics Temperature:** Ambient
- **Design:** Moderate optical interferometer
- **Temperature:** 100 K
- **Filled-Size Telescope:** Lagos

### Lunar Telescope
- **Name:** Lunar Telescope
- **Location:** Moon
- **Mission:** 10 years
- **Wavelength:** 0.1 - 2.5 microns
- **Aperture Size:** 50 cm apertures
- **Optics Temperature:** Ambient

### Ultra Stabili
- **Name:** Ultra Stabili
- **Location:** 900 km Earth Orbit
- **Mission:** 10 years
- **Wavelength:** 0.1 - 1 micron
- **Aperture Size:** 30 m cross, dilute aperture
- **Optics Temperature:** Ambient

### Lagos
- **Name:** Lagos
- **Location:** Solar Orbit at L5 point
- **Mission:** 10 years
- **Wavelength:** 0.1 - 1.6 micron
- **Aperture Size:** 30 cm aperture
- **Optics Temperature:** Ambient

### IR-SUBMM-RADIO MISSIONS

<table>
<thead>
<tr>
<th>Name</th>
<th>SOFIA</th>
<th>SIRTF</th>
<th>SMILS</th>
<th>Large Deployable Reflector</th>
<th>Lunar SMM Interferometer</th>
<th>Advanced Orbiting VLBI</th>
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<tbody>
<tr>
<td>Location</td>
<td>C-141 Aircraft</td>
<td>High Earth Orbit</td>
<td>70,000 x 1,000 km Earth Orbit</td>
<td>100,000 km Earth Orbit</td>
<td>Moon</td>
<td>Highly Elliptical Earth Orbit and Earth</td>
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<tr>
<td>Mission Duration</td>
<td>10 years</td>
<td>3 - 6 years</td>
<td>2 - 4 years</td>
<td>10 - 15 years</td>
<td>10 years</td>
<td>10-10 years</td>
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<tr>
<td>Wavelength</td>
<td>IR Through Submillimeter</td>
<td>1.4 - 1200 microns</td>
<td>100 - 800 microns</td>
<td>30 - 2000 microns</td>
<td>100 - 800 microns</td>
<td>3 cm - 1.5 mm</td>
</tr>
<tr>
<td>Aperture Size</td>
<td>2.5 M</td>
<td>1 M</td>
<td>3.6 M</td>
<td>10 - 20 M</td>
<td>4 - 5 M apertures</td>
<td>1 km baseline</td>
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<td>Optics Temperature</td>
<td>Ambient</td>
<td>Liquid Helium Cooled</td>
<td>Ambient</td>
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### X-RAY, γ-RAY MISSIONS

<table>
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<th>Name</th>
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<th>Hard X-Ray Imaging Facility</th>
<th>Very High Throughput Facility</th>
<th>Gamma Ray Spectroscopy Observatory</th>
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<tr>
<td>Location</td>
<td>600 km Earth Orbit</td>
<td>Low Earth Orbit</td>
<td>Space Station Attached or Free Flyer</td>
<td>Moon</td>
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<tr>
<td>Mission Duration</td>
<td>15 years with servicing</td>
<td>2 - 4 years</td>
<td>10 years</td>
<td>20 years</td>
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<tr>
<td>Wavelength</td>
<td>0.05 - 10 keV</td>
<td>10 keV - 10 MeV</td>
<td>20 keV - 2 MeV</td>
<td>0.15 - 40 keV</td>
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<tr>
<td>Aperture Size</td>
<td>1,700 cm² Grazing Incidence Mirrors</td>
<td>325 cm² Area, 2600 cm³ VOLUME</td>
<td>20 x 20 M, 30 m² Coded Aperture</td>
<td>20 x 20 M, 30 m² Grazing Incidence</td>
</tr>
<tr>
<td>Optics Temperature</td>
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<td>Ambient</td>
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</table>

CG13-14
Microsensors and Microinstruments

W.J. Kaiser and T.W. Kenny

Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

Outline

Motivation for work on Micro-sensors and Micro-instruments.

Some examples of miniature sensors for in-situ measurements.

Research and development of the Electron Tunneling Sensor.

Application to Infrared Detection.

Conclusions
Motivation

Conventional Instruments often impose Mass, Volume and Power consumption which are incompatible with mission requirements.

Recent improvements in fabrication technology through 'Micro-machining' of silicon enable the construction of micro sensors and actuators. This technology offers:

- Large potential reductions in mass, volume, and power consumption of sensing instruments.
- High degree of flexibility in device design for optimization of performance characteristics.
- Array compatibility for multiple functions and redundancy.

Examples of successful commercial implementation of this technology exist.

Conventional Sensors

- Conventional sensors operate by converting the Signal to a displacement of one sensor component relative to the rest of the sensor. The sensor then uses a capacitive, inductive, or optical transducer to directly measure the relative displacement.

- Conventional sensors are often limited by noise in the transducer or the following electronics. The sensitivity of existing transducers is improved by increasing the volume, mass, or power consumption of the transducer.

- A more sensitive transducer would allow the design of smaller, lighter, or more sensitive devices.
Vacuum Tunneling Concept

The current typically increases by one order of magnitude for each 1 Å reduction in electrode separation.

Transducer Sensitivity Comparison

<table>
<thead>
<tr>
<th>Transducer Type</th>
<th>Capacitive</th>
<th>Tunneling</th>
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<tr>
<td>Active Area</td>
<td>10 μm x 10 μm</td>
<td>10 Å x 10 Å</td>
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<tr>
<td>Electrode Separation</td>
<td>1 μm</td>
<td>5 Å</td>
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<tr>
<td>Bias Voltage</td>
<td>1 Volt</td>
<td>100 mV</td>
</tr>
<tr>
<td>Measurement Frequency</td>
<td>200 kHz</td>
<td>DC - 10 MHz</td>
</tr>
<tr>
<td>Measurement Current</td>
<td>1.1 nA</td>
<td>1 nA</td>
</tr>
<tr>
<td>1 % Transducer Signal</td>
<td>90 Å</td>
<td>0.004 Å</td>
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</table>
Advantages of the Electron Tunneling Position Sensor

- Improved sensitivity.
  Approximately 20,000 x more sensitive than conventional transducers.
  Allows use of less sophisticated electronics.
  Sensitivity can be traded off to improve other characteristics, such as bandwidth, linearity, ...

- Microscopic active area.
  Less sensitive to contamination
  Allows construction of micron-scale sensors

- Low power consumption.

- Simple electronic control system.

- Compatible with silicon micromachining technology.

Tunnel Sensor Prototypes

- Piezoelectric bimorph as actuator with gold film and wire as tunneling electrodes. Featured sensitivity of ~ 10^-5 g. Demonstrated use of tunneling as displacement transducer in a useful device. Suffered from temperature sensitivity and complicated fabrication.

- Large micromachined folded cantilever with electrostatic deflection to control separation and indium tip for tunneling. First demonstration of electrostatic deflection in a tunneling device.

- Small micromachined cantilevers with integral tips for use as generic transducer components. Characterization as accelerometer gives sensitivity of 10^-8 g/√Hz at 1 kHz. Use in broad class of sensors under investigation.
Micromachining Process

- Grow thin oxide of both surfaces of double-polished (100) wafer
- Spin on resist
- Copy mask onto resist
- Etch oxide through mask
- Etch wafer

Tunnel Sensor Operation

- Apply a deflection voltage until tunnel current appears.
- Activate Feedback Loop to maintain constant tunnel current.
- If device experiences acceleration, spring will flex, producing a change in tunnel current.
Measured Current Noise

![Graph showing measured current noise vs frequency (Hz)]

Accelerometer Demonstration

Silicon Tunnel Sensor 3400 gm Seismic Mass Small Motor with Opto-Electronic Frequency Sensor and 1 gm Eccentric Mass

Foam Pad

Floor

Aluminum Blocks

CG14-6
Applications of the Electron Tunneling Transducer

- Accelerometers and Seismometers
- Force and Strain Sensors
- Magnetometers
- Infrared Detectors
- Pressure Sensors
- Microphones and Hydrophones
- Microscopic Particle Detectors

Operating ranges of Quantum IR Detectors
Infrared Detectors

Tunnel Sensor

- Tip
- Membrane
- Trapped Air
- Window

- Radiation absorbed by metallic film and converted to heat.
- Conduction of heat to gas causes thermal expansion which deflects membrane.
- Membrane deflection measured by tunnel sensor.

Features of the Infrared Tunnel Sensor

- **Speed**
  - Response to 10 kHz at peak sensitivity.
  - Response beyond 10 kHz with sensitivity decreasing as 1/f.

- **Size**
  - Active area of single element from 1 mm to less than 50 microns

- **Operating Temperature**
  - Can operate at any temperature above 20 K

- **Sensitivity**
  - Approximately 10X more sensitive than Pyroelectric Detector at 300 K.

- **IR Bandwidth**
  - Thin metallic film absorbs radiation throughout the Infrared with 50% efficiency.

- **Array Compatible**
  - Elements feature low power dissipation and can be microfabricated into 1-D and 2-D arrays.
Micromachined Instruments for In-Situ Science

Micro-Weather Stations for in-situ measurements in the planetary boundary layer.

- System needs include low mass, volume, and power consumption.
- Devices under development for measurement of pressure, wind velocity and direction, temperature, humidity and atmospheric aerosols.
- Goal: To integrate a set of sensors into a miniature package suitable for widespread deployment.

Micro-Seismometry Instrumentation

- System needs include low mass, volume, power consumption and high sensitivity.
- Devices under development for measurement of seismic signals.
- Goal: To produce sensitive, miniature seismometers.

Plans: Infrared Sensor

The improved sensor is operated in the following manner:

- Apply deflection voltage until tunneling current is observed.
- Activate feedback loop to maintain constant tunneling current.
- If radiation is applied, feedback loop applies correction to deflection electrodes. Variations in deflection voltage are processed as signal.
• Micro Weather Stations for in-situ measurements in the Martian planetary boundary layer (PBL)

• System need: Compact, low mass and low power stations for widely distributed measurements of PBL meteorology.

• Devices currently under development for measurement of pressure, temperature, wind velocity and direction, humidity, and atmospheric aerosols.

• Low power instrument, on-board processor.

• Development directed to fabrication of sensors for initial testing in environmental chamber.

• Micro seismometry instrumentation:

• System needs: Compact, low mass, and low power seismometers for wide distribution.

• Currently available seismometer systems are excessively massive (Approximately 4kg per measurement axis).

• Develop compact, single crystal silicon seismometer system.

• Extend current technology to include active electronic suspension of seismometer elements.

![Diagram of Micro Weather Stations](image1)

![Diagram of Micro Seismometry Instrumentation](image2)
## Micromachined Sensors, Actuators, and Instrument Examples

<table>
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<tr>
<th>Instrument</th>
<th>Applications</th>
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<tr>
<td>Micro instruments for meteorology</td>
<td>In-situ monitoring</td>
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<tr>
<td>- Temperature</td>
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<tr>
<td>- Pressure</td>
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<td>- Wind Velocity</td>
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<td>- Humidity</td>
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<td>- Aerosol detection</td>
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<tr>
<td>Micro inertial guidance and control</td>
<td>Compact vehicle navigation</td>
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<tr>
<td>Micro seismometers</td>
<td>Planetary science</td>
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<td>- Photomission</td>
<td>Resource mapping</td>
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<td>- Auger SDM</td>
<td>Wide sensor deployment</td>
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<td>Compact analytical spectroscopy</td>
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<td>Compact communication systems</td>
<td>Multi-node rf</td>
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<td>fiber-optic network</td>
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### DRAFT

MICROSENSORS AND MICROINSTRUMENTS WORKING GROUP

**LEADER**

C.A. Kuonen

**COORDINATOR**

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C. Cundari
R. Bache
S. Stroten
W. Weener

**PROGRAM OFFICES**

Y. Nakamura

**APPROVALS**

Earth Science & EOS

C. Rose

Atmospheric

G. Horner

Planetary

B. Thoren

Microgravity

R. Peterson

Spacecraft

M. Podolsky

ODD Commercial

Y. Nakamura

**TECHNOLOGY DEVELOPMENT**

W. Weener

- Microchemical Devices
- Micro-optical Devices
- Micro-power
- Microcommunications
- Microelectronics
- Microcircuits design
- Guidance & Control
- Microspacecraft

C.A. Kuonen

DRAFT 1-26-94
Conclusions

- Electron tunneling represents the first new transducer technology in recent history. The sensitivity of electron tunneling to changes in relative position exceeds that of all currently available motion transducers.

- Tunnel sensors can be constructed which are robust, operate in air, and in the presence of environmental noise sources.

- Silicon micromachining has been used to fabricate tunnel sensors which incorporate electrostatic deflection.

- Tunnel sensor components have been built for incorporation into a novel infrared detector that is expected to be important for many applications.

- Applications of the tunnel sensor to other types of measurement are being explored. Measurement of acceleration, pressure, temperature, magnetic fields and other signals with devices based on the tunnel sensor may be important.
MICRO GUIDANCE & CONTROL INITIATIVE

Fred Y. Hadaegh

June 27, 1991

SSTAC ITP - OAET/RC

MICRO GUIDANCE & CONTROL TECHNOLOGY INITIATIVE

TOPICS

OVERALL PURPOSE AND OBJECTIVES
MICRO G&C APPLICATION
PAYOFFS
SELECTED TASK THEMES & TECHNOLOGIES
TECHNOLOGY DEVELOPMENT PLAN
SUMMARY
ISSUES
MICRO GUIDANCE & CONTROL TECHNOLOGY

APPLICATIONS

The application needs for future space systems have been identified as follows:

- New Guidance and Control Capabilities
  - Distributed Micro-sensor System Identification
  - Multivariable Control of Structural Dynamics
  - Distributed Shape & Position Control of Mirror Arrays
  - Embedded Stabilization of Telescope & Instrument Optics
  - Distributed Micro-Inertial References
  - Embedded Health Monitoring of G&C Effectors

Typical application: Remote sensing platforms, interferometers & deployable reflectors

- Miniaturize Existing Capabilities
  - Attitude & Maneuver Control System
  - Micro-Inertial References
  - Microelectro-Optics for miniature cameras & remote sensors
  - Inertial Navigation Systems
  - Heading Reference Units
  - Mini-camera Pointing & Stabilization
  - Antenna Pointing & Stabilization

Typical application: Micro-spacecraft, micro-landers, micro-rovers

MICRO GUIDANCE & CONTROL TECHNOLOGY

- Overall Purpose: Develop new micro-miniaturized G&C system architectures and functions that meet the needs of future space systems

- Conduct advanced development through proof-of-concept demonstrations

- Transfer new technologies to NASA advanced development space programs

- Key Objectives: Develop the G&C micro-sensing, computation, and control architectures and functions that will enable:
  - 100/1 or more reduction in size, mass, and power
  - 10/1 or more recurring cost reduction and lower cost growth rates
  - Solid state reliability and reduced performance risk
  - Robust performance over temperature, vibration, radiation
  - Embedded health monitoring
  - Viable distributed fault tolerant G&C architectures
PAYOFFS

- 100/1 OR MORE REDUCTION IN SIZE, MASS, AND POWER
- 10/1 OR MORE RECURRING COST REDUCTION AND LOWER COST GROWTH RATES
- SOLID STATE RELIABILITY AND REDUCED PERFORMANCE RISK
- ROBUST PERFORMANCE OVER TEMPERATURE, VIBRATION, RADIATION
- EMBEDDED HEALTH MONITORING
- Viable DISTRIBUTED FAULT TOLERANT G&C ARCHITECTURES
- MASSIVELY DISTRIBUTED CONTROL CAPABILITY

SELECTED TASK THEMES

MAJOR ADVANCES IN MICRO G & C WILL BE INCORPORATED IN DEVELOPMENT PRODUCTS PLANNED UNDER SIX TASK THEMES:

- MASSIVELY DISTRIBUTED MICROSENSING FOR SYSTEM ID & CONTROL
  TO ENABLE SPACE INTERFEROMETERS/LARGE REFLECTORS
- LIGHT POWERED REMOTE PROCESSING NETWORK FOR G&C MICROSENSING
  TO ENABLE Viable DISTRIBUTED ID/CONTROL ARCHITECTURES
- MICRO G&C FOR MICRO-SPACECRAFT AND MICRO-ROVERS
  TO PROVIDE ESSENTIAL SYSTEM FUNCTIONS
- SIX-DEGREE-OF-FREEDOM MICRO-INERTIAL MEASUREMENT UNIT FOR
  MICRO-SPACECRAFT AND MICRO-ROVERS
  TO ENABLE G&C NAVIGATION SUBSYSTEMS
- ACTIVELY CONTROLLED MICROMACHINED DEFORMABLE MIRRORS FOR ADAPTIVE REFLECTORS
  TO PROVIDE OPTICAL PERFORMANCE NOT OTHERWISE FEASIBLE
- EMBEDDED HEALTH SENSING FOR G&C EFFECTORS
  TO PREDICT/MANAGE MISSION EFFECTIVENESS & LIFETIME
3-AXIS LIGHT POWERED SENSING SYSTEM

ENABLES

MASSIVELY DISTRIBUTED SENSING FOR I/D CONTROL

LARGE SPACE TRUSS STRUCTURE

REMOTE SIGNAL PROCESSOR FOR MOTION SENSORS

FEATURES:
1. Single chip implementation
2. Programmable measurement
   - Resolution, gain, offset
3. Low power, <10 mA for most measurements

CG15-4
MASSIVELY DISTRIBUTED MICRO SENSING FOR ID/CONTROL.

REMOTE PROCESSING NETWORK/STRUCTURE PHASED INTEGRATION AND TEST

INITIAL PHASE

SENSOR ELEMENT
- ANALOG COND. ELEC.

SENSOR + INTEGRATED ANALOG ELEC.
(ANALOG EXTERNAL INTERFACE)

INTERMEDIATE PHASE

SENSOR ELEMENT
- ANALOG COND. ELEC.
- DIGITAL ELEC.

INTEGRATED SENSOR + ANALOG + DIGITAL ELEC.
(DIGITAL EXTERNAL INTERFACE)

FINAL PHASE

SENSOR ELEMENT
- ANALOG COND. ELEC.
- DIGITAL ELEC.
- OPTO. ELEC./PWR INTERF.

FULLY INTEGRATED SENSOR + ANALOG + DIGITAL ELEC.
+FIBER OPTICS INTF. ELEC.
(OPTICAL EXTERNAL INTERFACE)

MICRO-SPACECRAFT G&C

IMU
\( \mu \) Imager
Sun Sensor
Encoder
CDS

\( \mu \) Computer

\rightarrow Reaction Wheels
\rightarrow Thrusiers
\rightarrow Articulation Motor
\rightarrow CDS

- Attitude Determination
- Attitude Control
- Articulation Control

G&C
Micro Devices

* Scaled down from conventional size, not silicon micromachined
MICRO-ROVER G&C

* Attitude and Position Determination
* Path Guidance
* Articulation Control

- IMU
- \( \mu \) Imager
- Odometer
- Encoder
- CDS

Miniature
Articulation Motor

\( \mu \) Computer

CDS

G&C
Micro
Devices

* Scaled down from conventional size, not silicon micromachined

Micromachined Deformable Mirror

Top view of deformable mirror assembly

Assembly consists of two micromachined silicon wafers mounted face-to-face and bonded together around their peripheries

"See-through" view of 100 x 100 "pixels", revealing the repetitive, life-like geometry of the mirror assembly

Magnified view of several pixels showing the overlapping "cross-and-post" pattern of the actuator / mirror support structure
Micromachined Deformable Mirror

EMBEDDED HEALTH MONITORING OF G&C EFFECTORS

Reaction Wheel Test Bed
A Micromachined Silicon Electron Tunneling Sensor

Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

- Tunnel Sensor Characteristics
- Applications

Electron Tunneling Sensors
A New Class of Position Transducer With Potential Application to Measurement of

- Acceleration
- Infrared Radiation
- Pressure
- Temperature
- Magnetic Fields
- Particle Flux

All with Similar Electronic Requirements.

In many cases, arrays of sensors will be fabricated on single chip for Redundancy, Signal Identification, Focal-Planes, and for Multiple-Function Packages.
Electron Tunneling

- In the early 1980's, Binnig and Rohrer at IBM invented a new technique, Scanning Tunneling Microscopy (STM), for studying the structure of surfaces with atomic-scale resolution.

- In STM, a 'Tip' is positioned several Angstroms above the surface of interest. With the application of a voltage bias between the tip and the surface, a small tunneling current is observed.

![Diagram of tunneling](image)

Advantages of the Electron Tunneling Position Sensor

- Improved sensitivity.
  Approximately 20,000 x more sensitive than conventional transducers.
  Larger signals allow use of less sophisticated electronics.
  Sensitivity can be traded off to improve other characteristics, such as bandwidth, linearity, ...

- Microscopic active area.
  Less sensitive to contamination
  Allows construction of micron-scale sensors

- Low power consumption.

- Simple electronic control system.

- Compatible with silicon micromachining technology.
Tunnel Accelerometer Operation

- Apply a deflection voltage until tunnel current appears.
- Activate Feedback Loop to maintain constant tunnel current.
- If device experiences acceleration, spring will flex, producing a change in tunnel current.

Accelerometer Components

- Counter-Electrode
- Spring and Tip
- Au Deflection Electrodes
- Alignment Holes
- Contacts
- Tip
Transducer Sensitivity Comparison

<table>
<thead>
<tr>
<th>Transducer Type</th>
<th>Capacitive</th>
<th>Tunneling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Area</td>
<td>10 μm x 10 μm</td>
<td>10 Å x 10 Å</td>
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<tr>
<td>Electrode Separation</td>
<td>1 μm</td>
<td>5 Å</td>
</tr>
<tr>
<td>Bias Voltage</td>
<td>1 Volt</td>
<td>100 mV</td>
</tr>
<tr>
<td>Measurement Frequency</td>
<td>200 kHz</td>
<td>DC - 10 MHz</td>
</tr>
<tr>
<td>Measurement Current</td>
<td>1.1 nA</td>
<td>1 nA</td>
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<tr>
<td>1 % Transducer Signal</td>
<td>90 Å</td>
<td>0.004 Å</td>
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</table>

Electron Tunneling Sensors

Present Proof-of Concept demonstrations rely upon off-chip electronics for simplicity and ease of modification.

Future completed devices will require integration of sensor and electronics.

Use of micromachined silicon for sensor structure will allow integration of sensor and electronics in the same silicon crystal.

Integrated sensors will be important for a broad class of NASA applications and will be candidates for technology transfer to industry.
Electron Tunneling Sensors

Generic Requirements for Tunnel Sensor Operation:

- Analog or Digital Feedback Loop for Control of Tunneling Current
- Operational Amplifiers for Amplification of 1 nA Current Located Near Transducer.
- Comparator Circuit for Sensing Force Applied to Transducer.
- Output Circuit for Applying Correction To Controlling Capacitor.
- Multiplexer for Selecting Individual Sensor
- Digital Signal Processor for Pre-Processing and Compression of Data.
- Interface Electronics

### MICRO-G&C TECHNOLOGY DEVELOPMENT PLAN

<table>
<thead>
<tr>
<th>MICRO-G&amp;C SYSTEMS</th>
<th>YEAR - 1</th>
<th>YEAR - 2</th>
<th>YEAR - 3</th>
<th>YEAR - 4</th>
<th>YEAR - 5</th>
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<tbody>
<tr>
<td>DISTRIBUTED ID/CONTROL</td>
<td>DEVEL DISTR. III SIGNAL DATA PROCESS METHODS</td>
<td>DESIGN NEW ACQUISITIONS &amp; SENSORS ACTUATION PLACEMENT SCHEMES</td>
<td>DESIGN EXPL FOR DISTR. III/UNIT</td>
<td>MULTIVARIABLE III/CONTROL IN PLAN DYNAMICS 3D DYNAMICS</td>
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<tr>
<td>IMU</td>
<td>DEVEL U/S SYSTEM REQUIREMENTS</td>
<td>INTEGRATION/EVALUATION/初 LINE IN SINGLE AXIS PROTOTYPE</td>
<td>INTEGRATION/EVALUATION OF 3 AXIS PROTOTYPE WITH BOARD ELECTRONICS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V/SPACECRAFT /V/ROVER</td>
<td>REQT DEVEL &amp; TRADE STUDIES</td>
<td>DEK/RK/FABRICATION AND TEST, SPACECRAFT AND ROVER Q&amp;C TEST SIMULATIONS IV &amp; III</td>
<td>INTEGRATE, AND DEMONSTRATE (Q&amp;C FUNCTIONING) WITH IV &amp; III</td>
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<td>HEALTH MONITORING</td>
<td>DEVEL DEVICES &amp; GENERIC ARCHITECTURES</td>
<td>DEK/RK/EVALUATION TESTED</td>
<td>TESTED PROJ: FABRICATION AND EVALUATION</td>
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<tr>
<td>ADAPTIVE OPTICS</td>
<td>REQT DEVEL &amp; TRADE STUDIES TEST UNIT &amp; CELL V ACTUATOR</td>
<td>INTER &amp; TEST V ACTUATOR MATRIX</td>
<td>INTEGRATE/TEST (HEAT) HIGHER DENSITY</td>
<td>V ACTUATOR (COLD-BASED MIRRORS) WITH IV &amp; III</td>
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<tr>
<td>COMPONENT TECHNOLOGIES</td>
<td>DEK/RK DEVELOP SIGNAL, S/C, ELECTRONICS</td>
<td>DEK/RK DEVELOP CONTROL &amp; COMM ELEC</td>
<td>INTEGRATE/FABRICATION SINGLE BOARD COMPUTER</td>
<td>FABRICATION MINIATURIZED HYBRID MICROCOMPUTER</td>
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<td>VLSI</td>
<td>DEVEL/ FABRICATION 1 AXIS SENSORS &amp; ACT</td>
<td>DEVEL/ FABRICATION MULTI AXIS SENSORS</td>
<td>DEVEL/ FABRICATION HIGHER DENSITY V ACTUATOR ARRAYS</td>
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<tr>
<td>JS SENSORS/ ACTUATORS</td>
<td>REQT DEVEL &amp; TRADE STUDIES</td>
<td>DEMONSTRATE LIGHT PVW SENSORS/ FIBER INTERFACE</td>
<td>PERFORM SIMULATION &amp; RELIABILITY STUDIES</td>
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<tr>
<td>FIBER OPTICS/ DATA COMM</td>
<td>DEVEL DATA COMM &amp; NETWORK ARCHITECTURE</td>
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</table>

CG15-12
SUMMARY

THIS INITIATIVE IS PLANNED TO:

• DEVELOP MICRO-G&C TECHNOLOGIES THAT MEET THE NEEDS OF FUTURE SPACE SYSTEMS

• ENABLE NEW CAPABILITY IN DISTRIBUTED CONTROL

• MAJOR REDUCTION IN G&C MASS, SIZE, POWER, PERFORMANCE RISKS, COSTS AND COST GROWTH

• HAVE SELECTED TASK THEMES WITH TIME-PHASED DEVELOPMENT PRODUCTS OVER FIVE YEARS

• HAVE TASKS AND PRODUCTS THAT ARE SYNERGISTIC IN SUPPORTING NEW G&C SYSTEM FUNCTIONS AND ARCHITECTURES
CONTROLS- STRUCTURES INTERACTION (CSI)

TECHNOLOGY PROGRAM SUMMARY

EARTH ORBITING PLATFORMS PROGRAM AREA
OF THE
SPACE PLATFORMS TECHNOLOGY PROGRAM

Jerry R. Newsom
NASA LaRC
June 26, 1991

CONTROLS- STRUCTURES INTERACTION

- CSI technology embraces the understanding of the interaction between the spacecraft structure and the control system, and the creation and validation of concepts, techniques and tools for enabling the interdisciplinary design of an integrated structure and control system, rather than the integration of a structural design and a control system design. (SSTAC 1987)
CONTROLS-STRUCTURES INTERACTION (CSI) TECHNOLOGY

GOAL:
DEVELOP VALIDATED CSI TECHNOLOGY FOR INTEGRATED DESIGN/ANALYSIS AND QUALIFICATION OF LARGE FLEXIBLE SPACE SYSTEMS AND PRECISION SPACE STRUCTURES

OBJECTIVES:
• To provide spacecraft dynamic response amplitude reductions of 50 percent, for any input or maneuver, with minimum increase in system mass.

• To enable the use of wide-bandwidth CSI control systems to achieve several orders of magnitude improvement in control and pointing capabilities.

• To predict the on-orbit performance of CSI systems within 10 percent of all amplitude, frequency, time and stability requirements based on the results of integrated analyses tuned/corrected by closed-loop ground and/or flight test data.

• To develop unified controls-structures modeling, analysis and design methods which allow a complete iteration on all critical design variables in a single integrated computational framework.

• To develop the capability to validate the performance of flight systems by analysis/ground tests.

CSI PROGRAM FOCUS MISSIONS

EARTH OBSERVATION PLATFORM

OPTICAL INTERFEROMETER

ASTROPHYSICS
• PURPOSE: To Quantify the Specific Advantages of CSI Technology for Future Missions Requiring Large Space Structures.

• APPROACH: Select a Future NASA Mission and Define Differences in the Spacecraft Design and Performance Capability Using Both the Conventional and CSI Approach.

• EXAMPLES: (1) Geostationary Platform  
  (2) Shuttle RMS  
  (3) Multipayload Platform
CSI PERFORMANCE IMPROVEMENT

Mission to Planet Earth Platform

Pointing Performance

Mesh Antenna

mm Wave Reflector

No Control

CSI Control

Mission Requirement

Pointing Jitter, radians

Maximum Antenna Diameter, m

CSI Technology Science Benefits

Low orbit
Rain mappers

Nimbus
DMSP Block 5

No CSI Control

Resolution Cells Too Large

With CSI Control

Marginal
Adequate
Ideal

Science Require. Met

Resolution Cell Size, Km

Max. Meas. Rain Rate, mm/hr

Light-Moderate
Heavy Rain
Very Heavy

ORIGINAL PAGE IS OF POOR QUALITY
POTENTIAL SPACE STATION ASSEMBLY BENEFITS DUE TO CSI (Timeline)

Draper RMS Simulator response
Payload 3500 lbs

RMS settling time

Potential CSI benefits

ACTIVE VIBRATION CONTROL OF THE SHUTTLE RMS

Typical RMS flexible mode
$f = 0.26$ Hz

TIP response without active vibration control

TIP response with active vibration control

CG16-5

ORIGINAL PAGE IS OF POOR QUALITY
GROUND TESTS AND TEST METHODS

**Objectives**
- To ascertain the applicability of theoretical CSI developments to complex hardware systems
- To develop ground test methods suitable for verifying that CSI spacecraft systems are adequate for flight

**Approach**
- Develop hardware testbeds
- Perform in-house analysis and tests
- Conduct guest-investigator studies
THE PHASE-ZERO EVOLUTIONARY MODEL: A CONTROLS-STRUCTURES INTERACTION TESTBED

EXPERIMENTAL RESULTS
OPEN AND CLOSED-LOOP RESPONSES

MODE 6
ACCELEROMETER 8
(IN/SEC^2)

MODE 8
ACCELEROMETER 2
(IN/SEC^2)

ORIGINAL PAGE IS OF POOR QUALITY
CEM LOS Pointing Results

Open- and Closed-Loop Test Data

Closed-Loop Simulation and Test Data

Real-Time Computer Hardware
SOFTWARE DEVELOPMENT OVERVIEW

• Entire software system developed at Langley (ACD/FSGB)
  - Real-Time Executive, Interfaces, Applications
  - RIU and 1553B interface software developed jointly with SED

• Software for all 1750A's and PC/AT will be written in Ada

• This is Langley's first production Ada project

• Similar Ada based 1750A systems are proposed for EOS missions

• Software system designed using object-orientated design methods
  - Allows software to evolve in step with hardware system
  - Testbed modules can be reused on future missions (CSI, EOS)

• Believed to be one of the first real-time distributed Ada based 1750A production systems anywhere.

GTM Testbed Description/Goals

Phase 0
Global LOS Pointing objective.
Uniform structure.
500 micro radians accuracy.
Active only, 8 accelerometers, 8 thrusters.
Implement LAC/HAC controller on structure with realistic dynamics of space platforms.

Phase 1
Global LOS Pointing objective.
Integrated controller & structure.
500 micro radians accuracy.
Active only, 8 accelerometers, 8 thrusters.
Quantify benefits of integrated controller & structure design and assess predictive accuracy.

Phase 2
Multi-Payload Pointing objective.
Phase 1 structure.
5 micro radians accuracy.
24 piezo struts, 3 gimbals.
Implement distributed/centralized controllers for multi-payload platforms.

Phase 3
Multi-Payload Pointing objective.
Redesigned structure.
5 micro radians accuracy.
24 piezo struts, 3 gimbals.
100 passive struts, optimal sensor actuator placement.
Verify integration of passive, active smart systems with multi-objective controller.

Phase 4
Integrated controller & structure
multi-payload free-flyer design.
5 micro radians accuracy. Integrated passive and active sensors/actuators and on-board power and computers.
Ground test experiment for CSI Class 1 & 2 flight demonstration.
CASES GTF (Ground Test Facility)

- **Status**: Partially Operational

  Test Articles:  Boom, MPESs, Tip Plate completed
  Boom/MPESS suspended

  Disturbance System: Integration nearing completion

  Computer System: Delivered, Tested
  CASES Software being developed

  Sensors & Actuators:
  AMED system: Final testing prior to integration
  BLTs tested
  BMT/TDS design in progress
  Auxiliary sensors obtained (Accels, Force, etc...)

  Electronics: Several subsystems complete
  (Mux/Demux, Reaction Wheel, Gyro, etc....)

- **Baseline Operational**: Aug/Sept 1991

GUEST INVESTIGATOR PROGRAM

- **GOAL**: OBTAIN BEST AVAILABLE CSI TECHNOLOGY EFFORT FROM RESEARCHERS IN ACADEMIA & INDUSTRY.

- **APPROACH**: GENERAL SOLICITATION OF PROPOSALS THROUGH NRA WITH INTERCENTER SELECTION TEAM.

- **STATUS**:

  **Phase I** - Completed
  Eight Investigators
  Two Test Beds
  LaRC - Mini-MAST
  MSFC - Advanced Control Evaluation for Structures (ACES)

  **Phase II** - Joint Program with the Air Force, Edwards AFB
  101 Proposals Received
  Five Winners Announced December 1990
  Three Test Beds
  LaRC - CSI Evolutionary Model (CEM)
  MSFC - Control, Astrophysics, and Structures Experiment In Space (CASES)
  AF - Advanced Space Structure Technology Research Experiments (ASTREX)

CC1510
# PHASE 1 GUEST INVESTIGATOR PROGRAM

<table>
<thead>
<tr>
<th>UNIVERSITY/INDUSTRY</th>
<th>PRINCIPAL INVESTIGATOR</th>
<th>PRIMARY THRUST</th>
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<tbody>
<tr>
<td>CAL TECH</td>
<td>Dr. John Doyle</td>
<td>Noncollocated Controller Design</td>
</tr>
<tr>
<td>MIT</td>
<td>Dr. W. Vander Velde</td>
<td>Off-Line and On-Line Sys. ID Algorithms</td>
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<tr>
<td>PURDUE</td>
<td>Dr. Robert Skelton</td>
<td>Noncollocated Controller Design</td>
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<tr>
<td>U. CINCINNATI</td>
<td>Dr. Randall Alleman/Dr. Slater</td>
<td>Off-Line System ID Algorithms</td>
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<td>U. TEXAS</td>
<td>Dr. Bong Wie</td>
<td>Collocated/Noncollocated Controller Design</td>
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<td>HARRIS</td>
<td>Dr. David Hyland</td>
<td>Noncollocated Controller Design</td>
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<tr>
<td>BOEING</td>
<td>Dr. Michael Chapman</td>
<td>Nonlinear Math Modeling</td>
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<tr>
<td>Dynamic Engin./VPI</td>
<td>Wilmer Reed</td>
<td>Design of Passive and Active Suspension Systems</td>
</tr>
</tbody>
</table>

## MAJOR LESSONS LEARNED

- Modeling sensors, actuators, and electronics as important as modeling structure
- Single-input single-output control design approach for flexible structure control can be effective
- System identification is an essential element for successful flexible structure control

# PHASE II GUEST INVESTIGATORS

<table>
<thead>
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<th>PRINCIPAL INVESTIGATOR</th>
<th>PRIMARY THRUST</th>
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<tbody>
<tr>
<td>Martin Marietta</td>
<td>Eric Schmitz</td>
<td>Smart Struts &amp; Controller Design</td>
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<td>LaRC CSI Evolutionary Model</td>
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<tr>
<td>Harris Corporation</td>
<td>David Hyland</td>
<td>Noncollocated Controller Design</td>
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<td>MSFC Ground CASES</td>
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<td>Boeing Aerospace</td>
<td>David Warren</td>
<td>CMG/RCS Pointing &amp; Slewing</td>
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<td>Air Force ASTREX</td>
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<td>MIT</td>
<td>Andy von Flotow</td>
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<td>Texas A&amp;M</td>
<td>Srinivas Vadali</td>
<td>Controller Design</td>
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<tr>
<td></td>
<td></td>
<td>Air Force ASTREX</td>
</tr>
</tbody>
</table>
INTEGRATED STRUCTURE/CONTROL DESIGN

STRUCTURE

DESIGN

CONTROL SYSTEM

SENSOR

COMPUTER

APPLICATIONS

PROBLEM CLASSIFICATION

Class 1: Pointing, vib. sup., no articulation

Class 2: Pointing, vib. sup., with articulation

Class 3: Nonlinear version of class 1

Class 4: General nonlinear with robotics

CG16-12
DESIGN PROBLEM I

- Design Variables - Dissipative controller gains
- Diameters of structural members

- Objective Function - For parameter $0 \leq \beta \leq 1$,
  Minimize $[\beta \cdot \text{Total Mass} + (1-\beta) \cdot \text{Controlled Performance}]$

- Constraints
  - Structural member sizes and RMS pointing error at large antenna

CONVENTIONAL VS. INTEGRATED
(Dynamic Dissipative Controller)
RMS $< 10 \mu$rad

<table>
<thead>
<tr>
<th></th>
<th>Controlled Performance</th>
<th>Structural Mass</th>
<th>Actuator Mass</th>
<th>Total Mass</th>
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<tbody>
<tr>
<td>Initial Design</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>Control-optimized Design $\beta=0.15$</td>
<td>1.30</td>
<td>1.0</td>
<td>1.45</td>
<td>1.18</td>
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<tr>
<td>Integrated Design $\beta=0.15$</td>
<td>4.03</td>
<td>0.66</td>
<td>1.44</td>
<td>0.97</td>
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CG16-13
INTEGRATED DESIGN VALIDATION

PHASE-1 CEM

OBJECTIVE: MINIMIZE THE AVERAGE CONTROL POWER WHILE MAINTAINING THE RMS LINE OF SIGHT (LOS) TO A SPECIFIED VALUE WITHOUT ANY INCREASE IN STRUCTURAL MASS (OVER PHASE-0 DESIGN).

DESIGN VARIABLES

STRUCTURE - EFFECTIVE CROSS-SECTIONAL AREAS OF 21 LONGERONS, BATTENS, AND DIAGONALS

CONTROL - ELEMENTS OF THE COMENSATOR AND GAIN MATRICES OF A DYNAMIC DISSIPATIVE CONTROLLER

SIMULATION RESULTS

![Simulation Results Graph]
JUSTIFICATION FOR ON-ORBIT CSI EXPERIMENTS

• DEVELOP UNDERSTANDING OF GRAVITY EFFECTS ON GROUND TESTING
  • Direct Gravity Effects: stiffness, modal coupling, damping
  • Indirect Gravity Effects via Suspension system dynamics: pendulous modes, local attachment loads, large angle articulation limitations, etc.

• QUANTIFY ACCURACY OF PREDICTIONS OF ON-ORBIT PERFORMANCE

• DEMONSTRATE NEW FLIGHT QUALIFICATION PROCEDURE
  • Dependent on on-orbit dynamic testing
  • Subsequent adjustment of controller parameters

CSIO FLIGHT EXPERIMENTS

• JITTER SUPPRESSION EXPERIMENT (JSX)
  • McDonnell Douglas Prime Contractor
  • Funded by OAET's In-Space Technology Experiments Program (In-STEP)

• MIDDECK ACTIVE CONTROL EXPERIMENT (MACE)
  • MIT Prime Contractor
  • Funded by In-STEP

• ADVANCED FREE-FLYER EXPERIMENT
  • LaRC/MSFC/JPL Conceptual Definition in Progress
JITTER SUPPRESSION FOR PRECISION SPACE STRUCTURES

MIDDECK ACTIVE CONTROL EXPERIMENT (MACE)

- Scanning and pointing payload #1
- Rate gyros
- Proof-mass actuators (4)
- Active members (2)
- Umbilical
- Linear accelerometers (13)
- Test article modules (stowage)
- Middeck lockers
- Reaction wheel actuator
- Rate gyro (torsion) (2)
- Payload #2
- 2 Axis gimbal motors
- Sequencer
- Control computer
- Data storage
- First flexible mode of free-floating test article < 2 Hz
SUMMARY

- CONTROLS-STRUCTURES INTERACTION (CSI) IS A KEY ENABLING TECHNOLOGY FOR FUTURE NASA SPACECRAFT

- PROPER IMPLEMENTATION OF CSI TECHNOLOGY OFFERS THE POTENTIAL FOR SIGNIFICANT IMPROVEMENTS IN CAPABILITY

- CSI IS EFFECTIVELY A NEW DISCIPLINE WHICH ENCOMPASSES AND INTEGRALLY MERGES STRUCTURES AND CONTROLS

- NASA HAS EMBARKED ON A MAJOR MULTI-CENTER EFFORT TO DEVELOP THIS TECHNOLOGY FOR PRACTICAL APPLICATION TO SPACECRAFT