University of Maryland Concepts and Technologies for Robotic Servicing of Hubble Space Telescope

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Presentation Overview

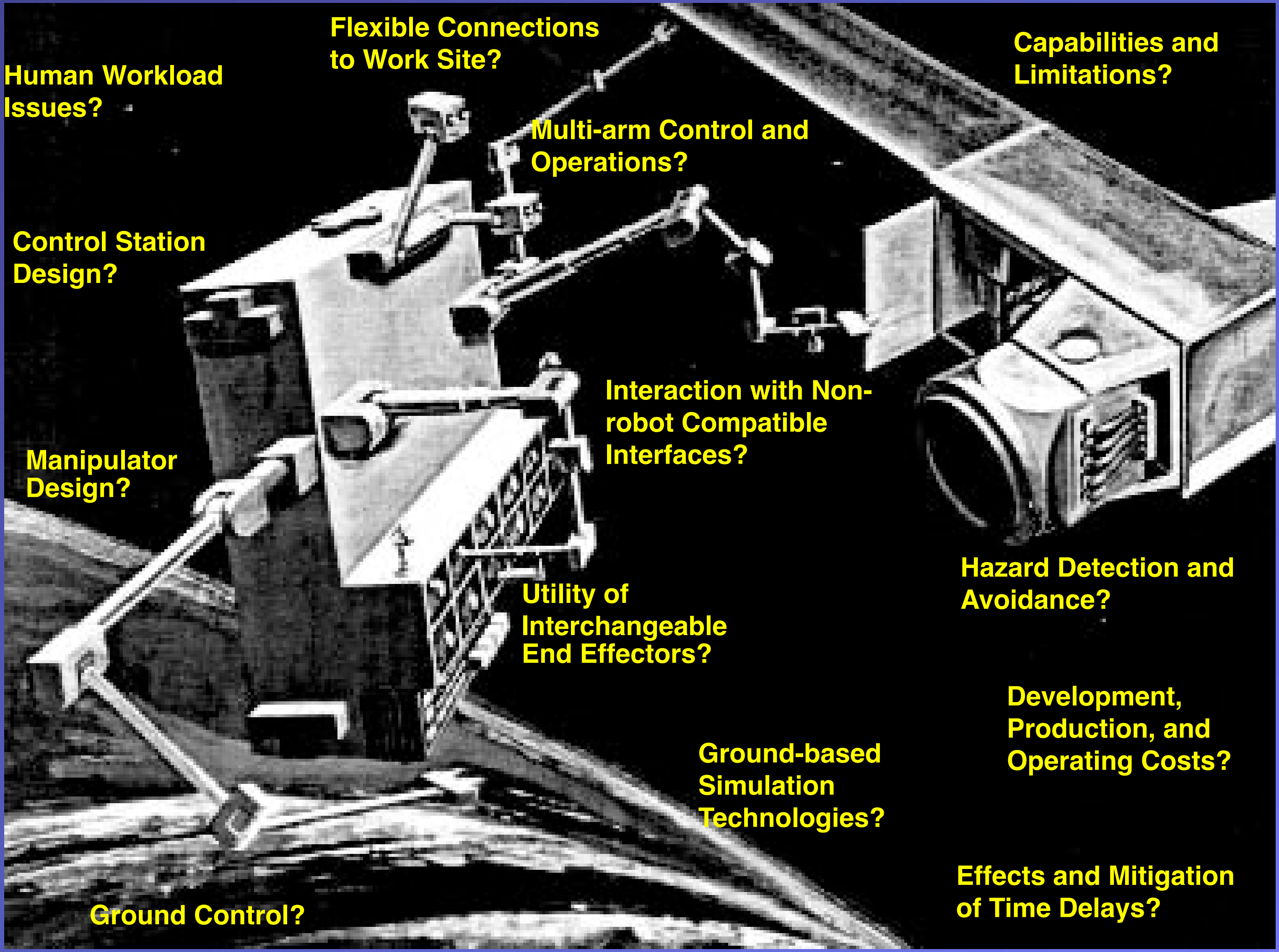
- Space Systems Laboratory background
- Relevant SSL technologies
- Ranger: system and experiences
- Recent HST studies
- Mission concepts
- Conclusions

ARAMIS Telerobotics Study

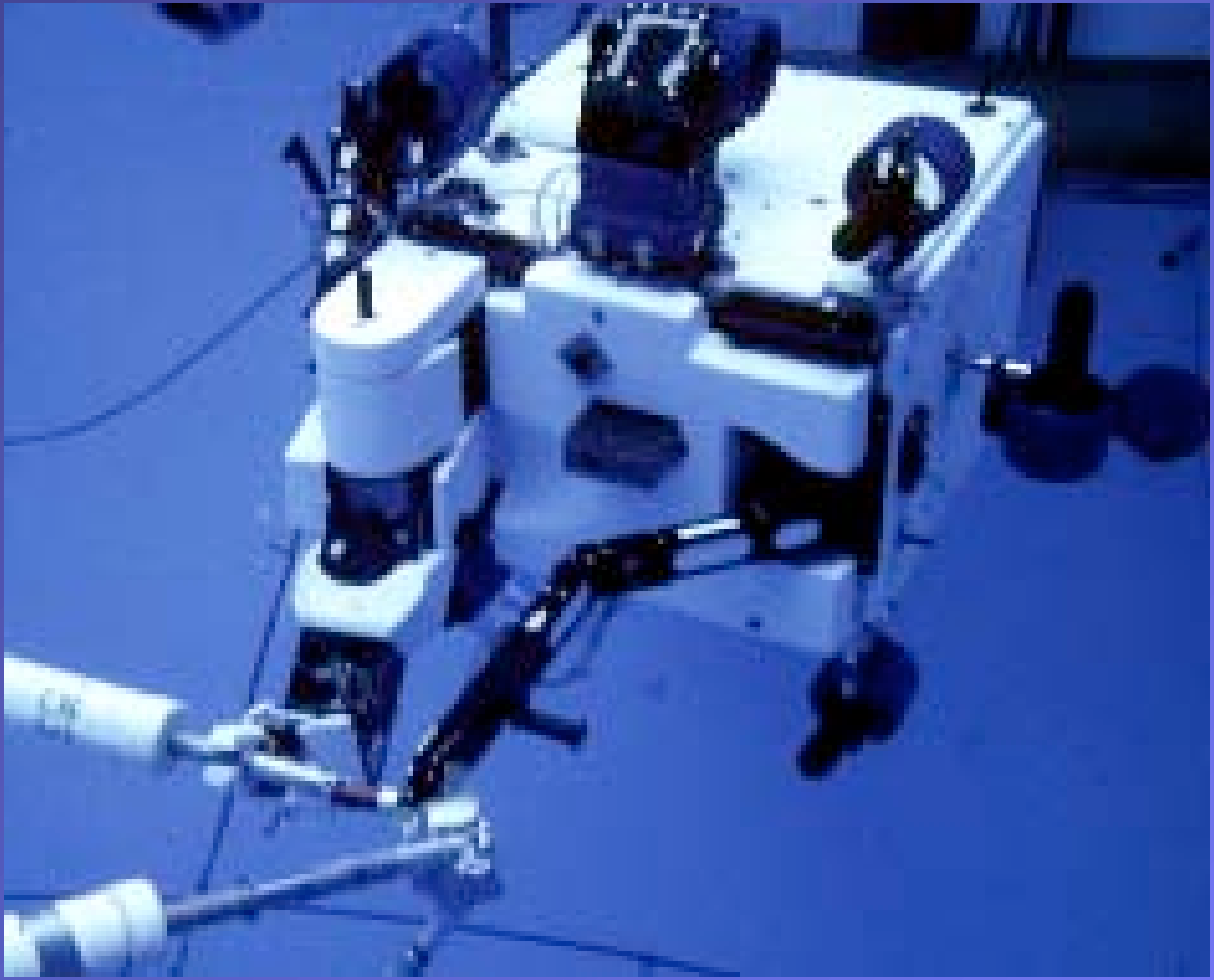
Survey of five NASA "Great Observatories" to assess impacts and benefits of telerobotic servicing - major results:

- Ground-controlled telerobotics is a pivotal technology for future space operations
- Robotic system should be designed to perform EVA-equivalent tasks using EVA interfaces
  - Maximum market penetration for robot
  - Maximum operational reliability
  - Designing to EVA standards well understood
- Fully capable robotic system needs to be able to do rendezvous and proximity operations, grapple, dexterous manipulation

Fundamental Concept of Robotic Servicing



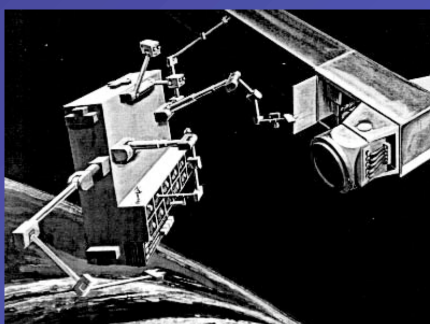
Beam Assembly Teleoperator

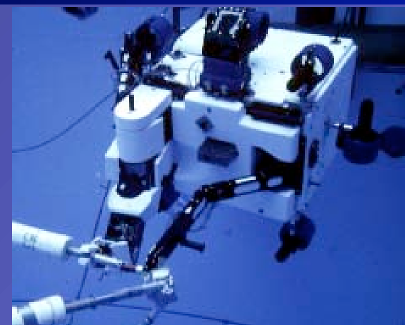


SSL Relevant Experience Timeline (1)

‘80 ‘81 ‘82 ‘83 ‘84 ‘85 ‘86 ‘87 ‘88 ‘89

SSL studies applications of automation, robotics, and machine intelligence for servicing Hubble and other Great Observatories for NASA MSFC

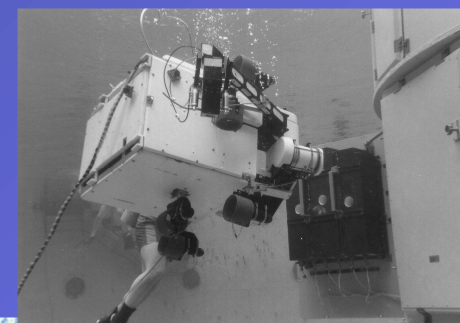




Initial operational tests of Beam Assembly Teleoperator

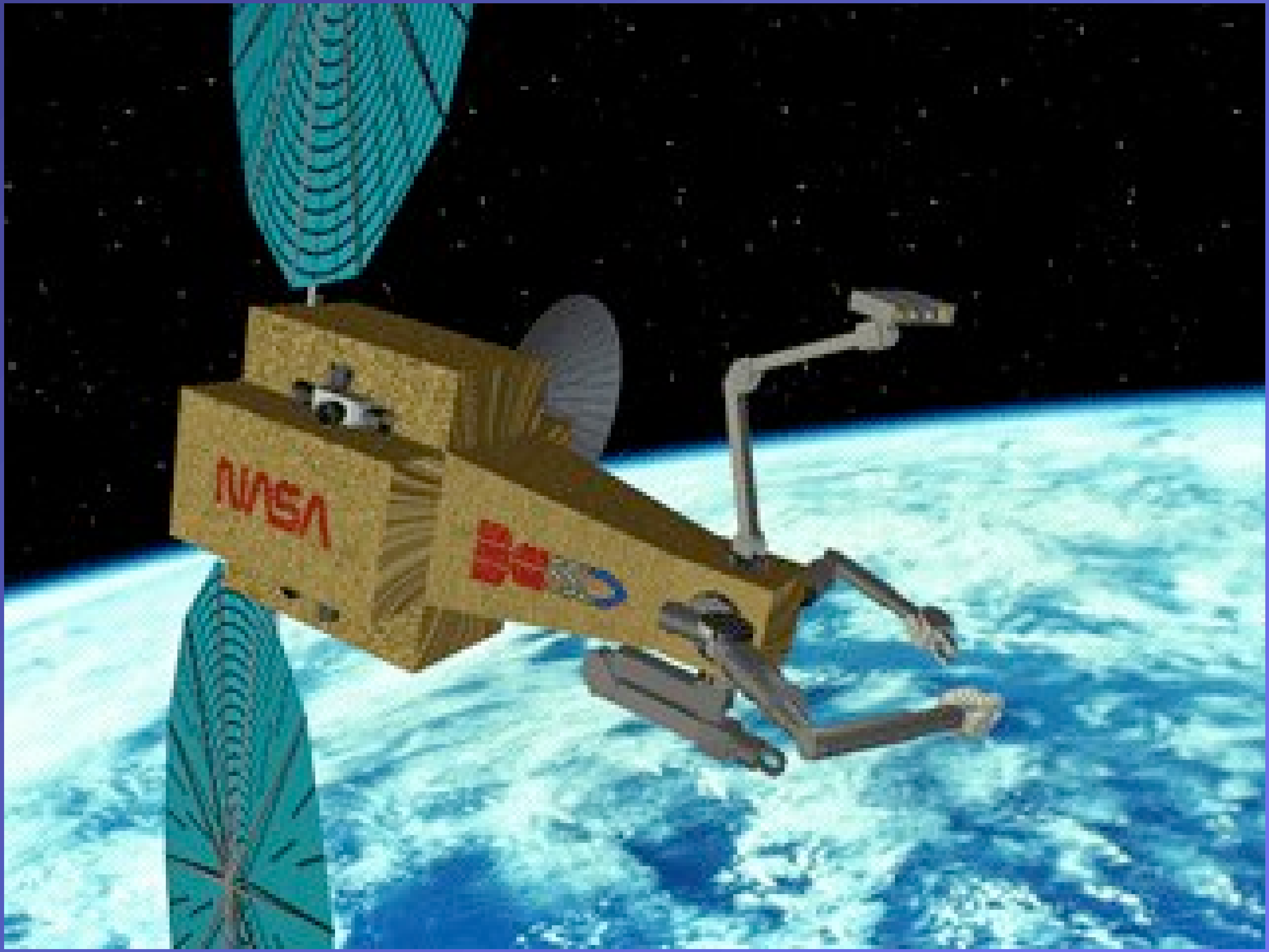
Experimental Assembly of Structures in EVA flies on STS 61-B

BAT used for extensive servicing tests on HST training mockup



SSL develops ParaShield flight test vehicle for suborbital mission

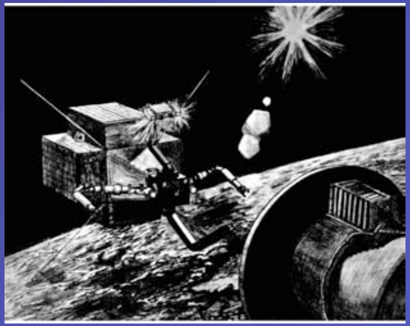
Ranger Telerobotic Flight Experiment



SSL Relevant Experience Timeline (2)

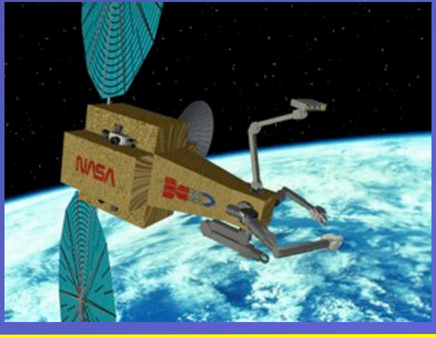
‘90 ‘91 ‘92 ‘93 ‘94 ‘95 ‘96 ‘97 ‘98 ‘99

SSL designs Ranger based on experience with HST servicing

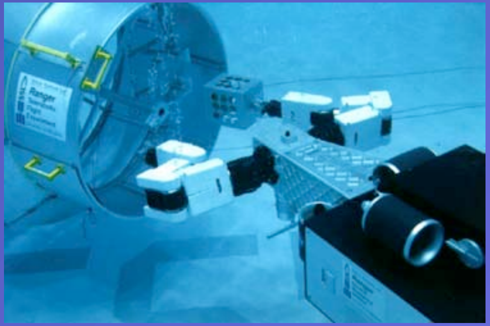


UMd NBRF opens

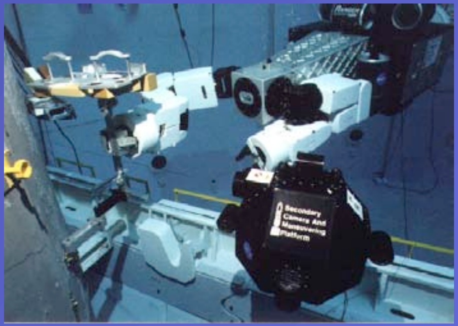
NASA selects Ranger TFX as low-cost robotic flight experiment



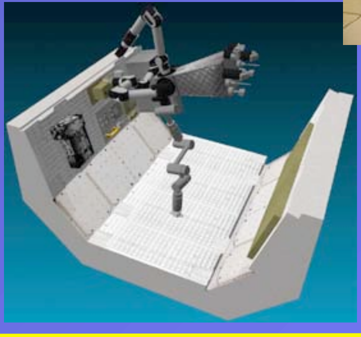
Ranger NBV operational



Ranger performs end-to-end HST servicing simulations



SSL directed to redesign Ranger for shuttle mission: Ranger TSX



Phase 0 PSRP

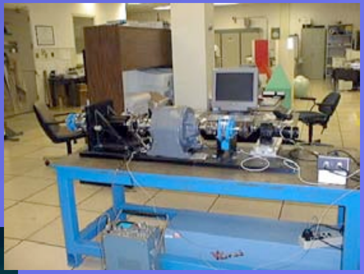
RTSX PDR

Phase 1 PSRP

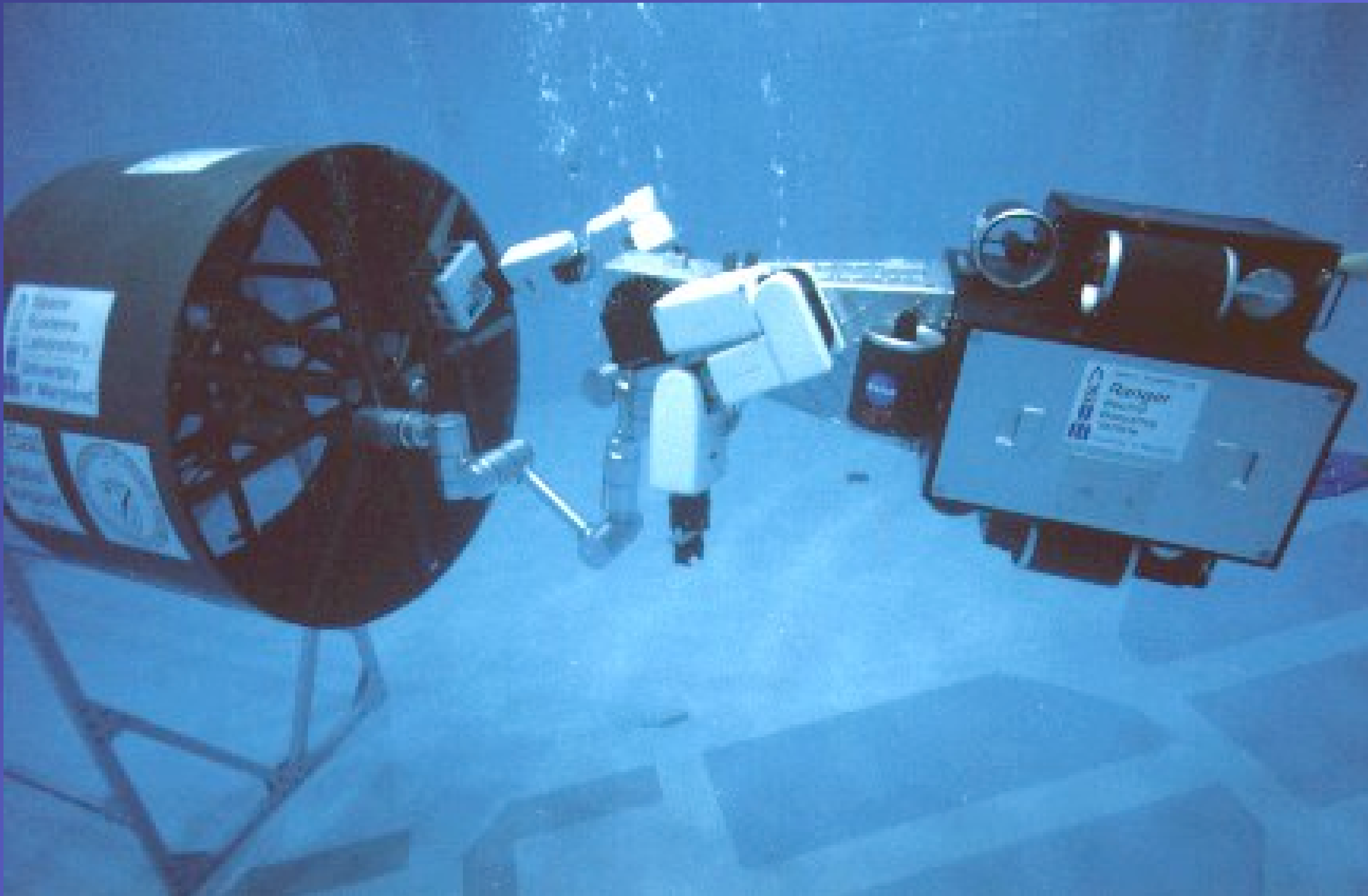
RTSX CDR

Phase 2 PSRP

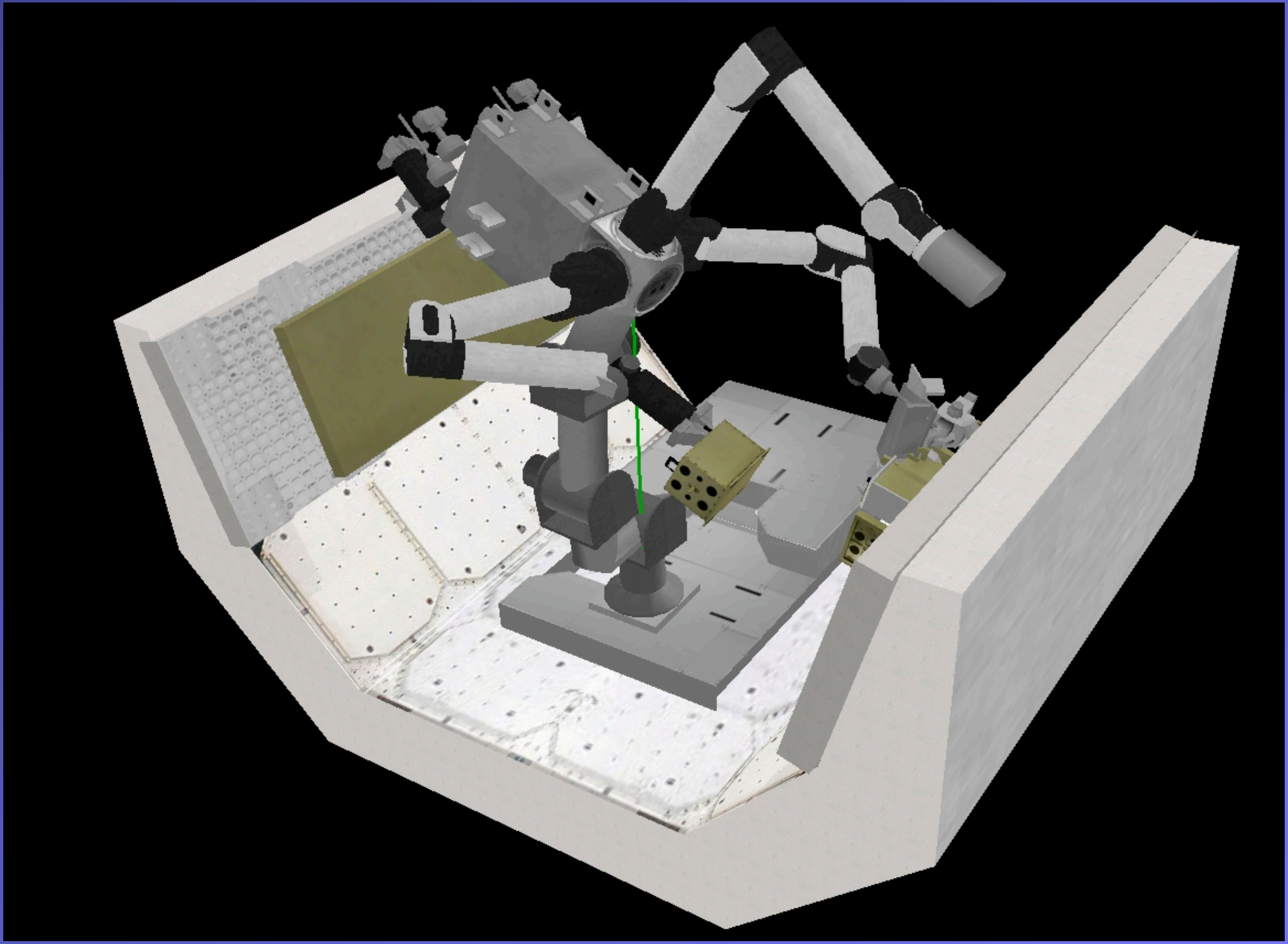
Environmental testing at JSC



Ranger Neutral Buoyancy Vehicle I



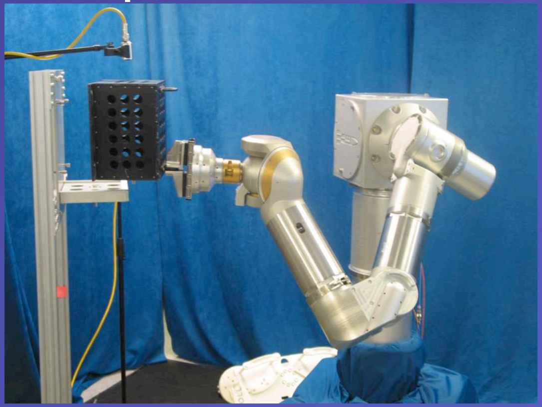
Ranger Telerobotic Shuttle Experiment



SSL Relevant Experience Timeline (3)

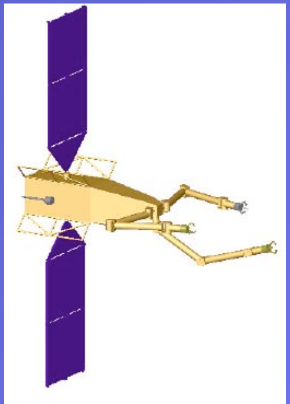
2000	2001	2002	2003	2004

Development of ECU operations timeline



Ranger TSX program cancelled

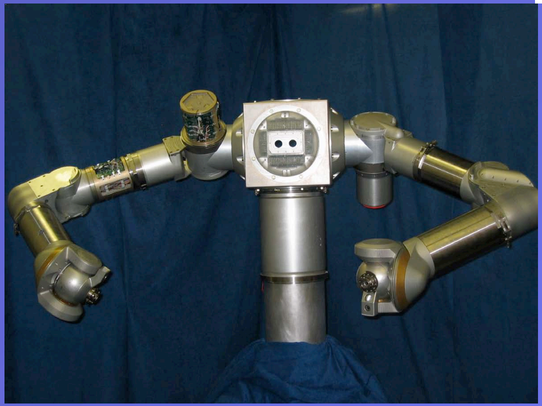
Modular miniature servicer development for DARPA



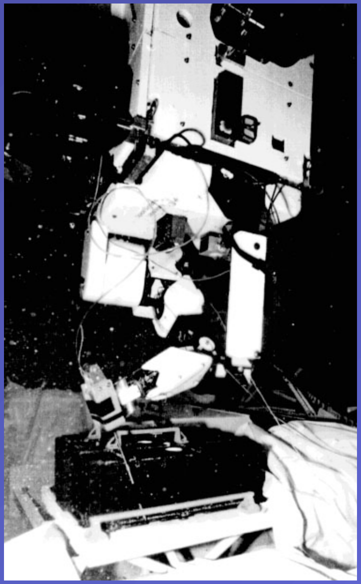
PXL in NB testing

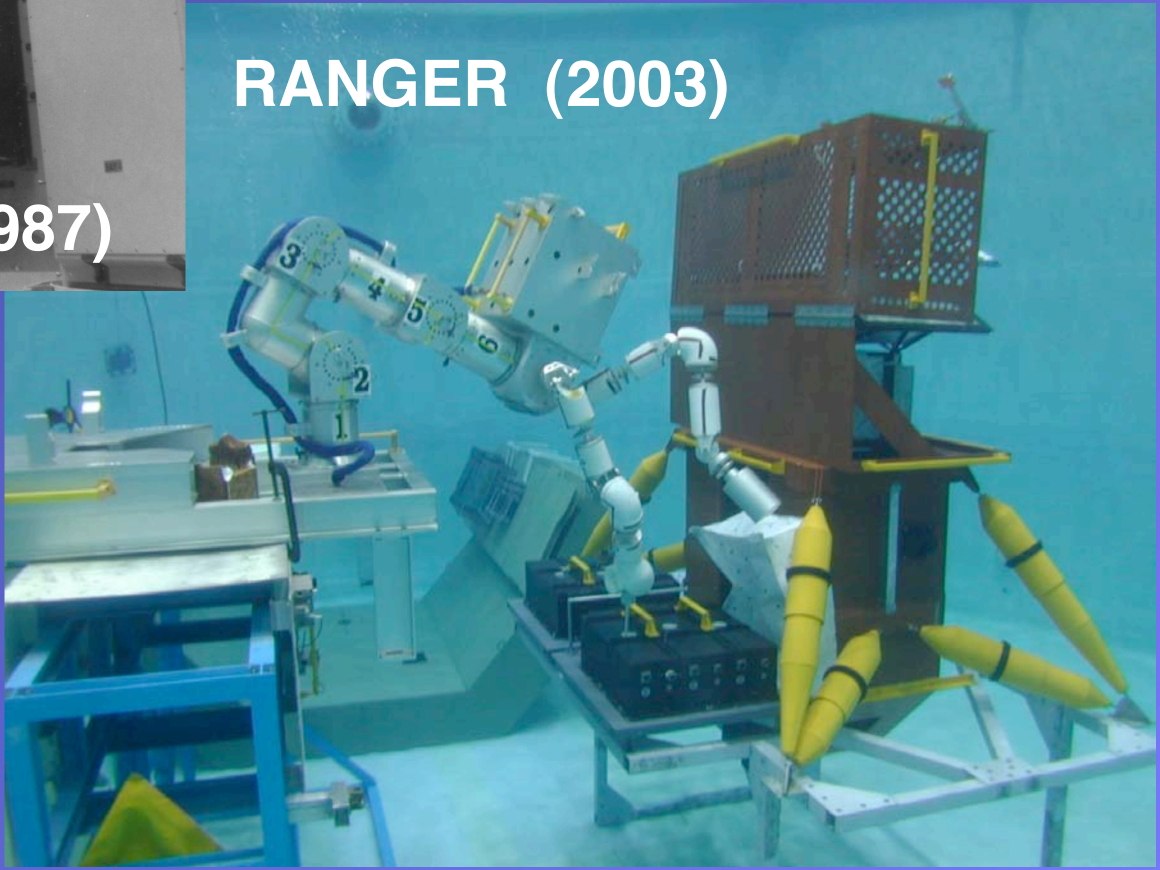
All-up mockup for public outreach

Dual-arm system in active test

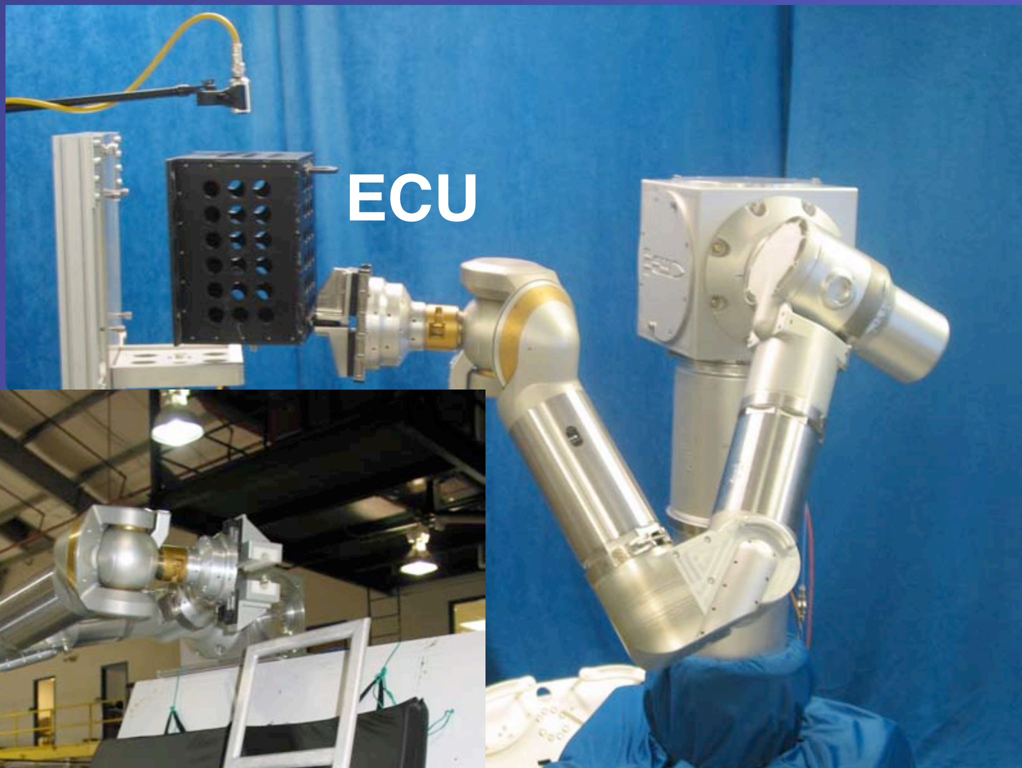


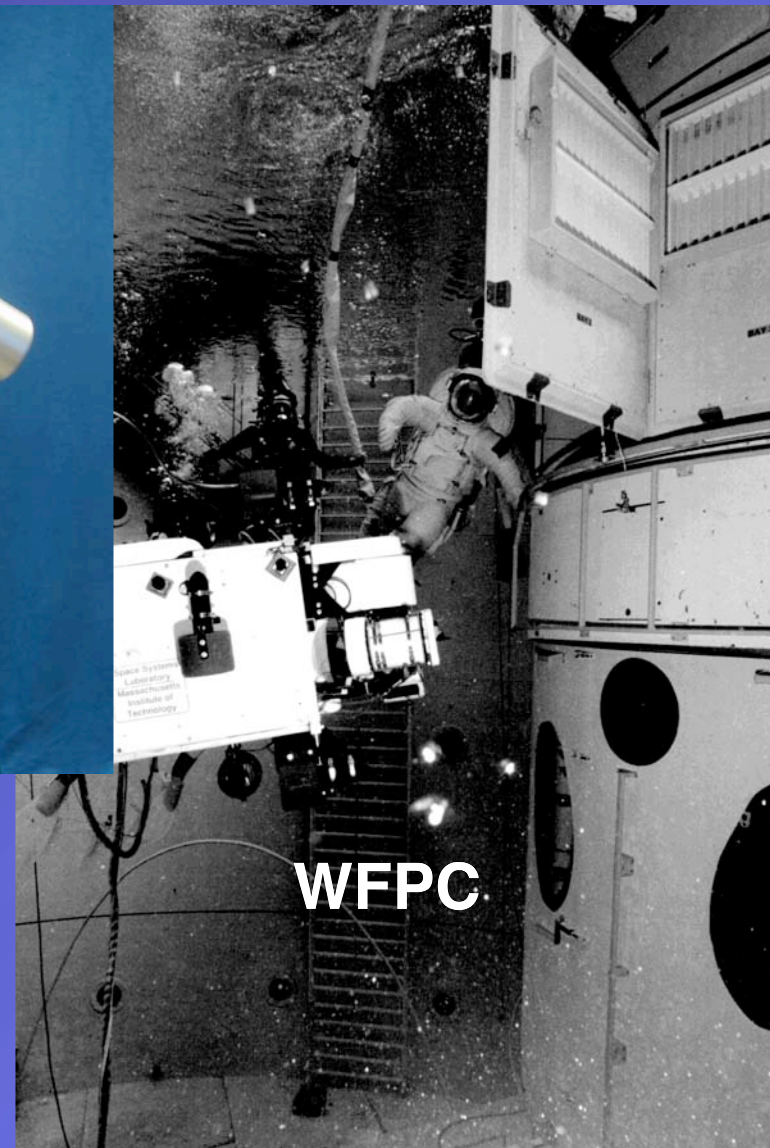
Robotic HST Servicing - Batteries



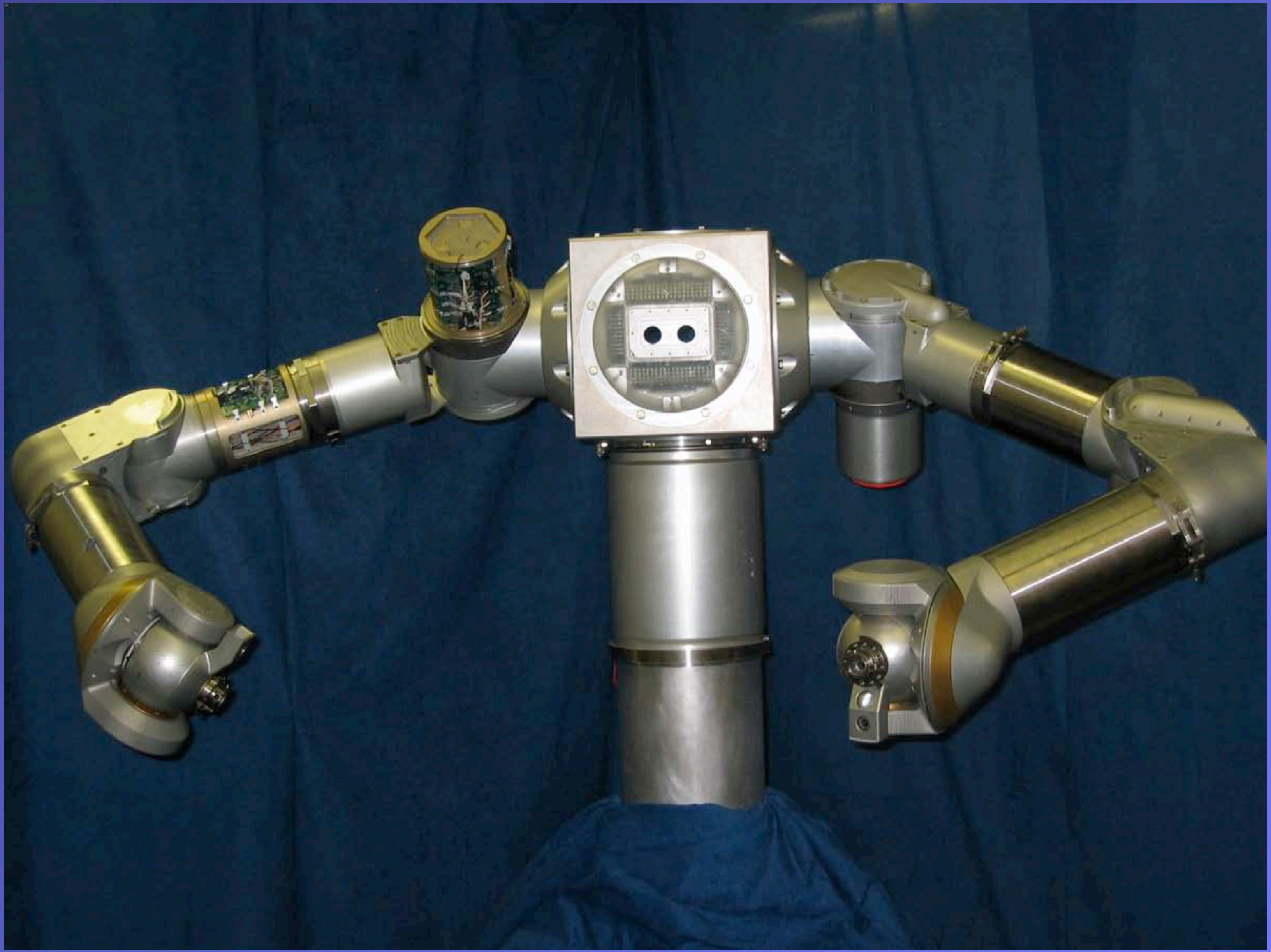


Robotic HST Servicing - Instruments

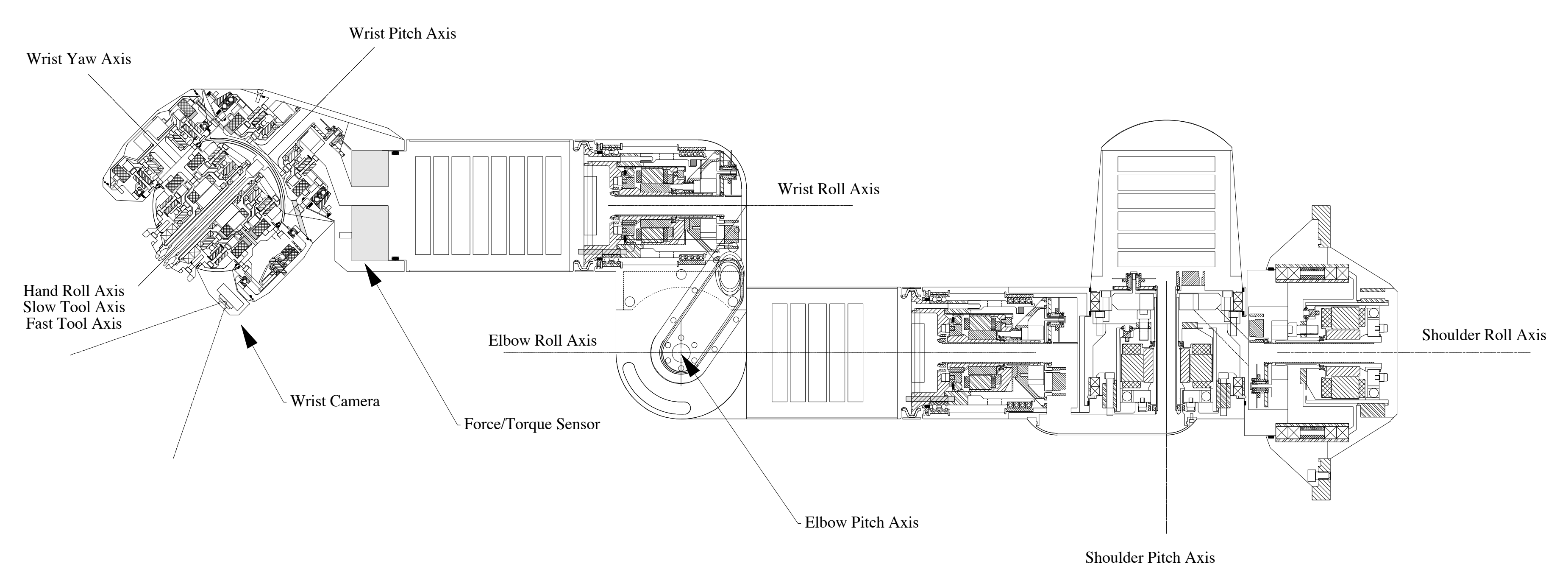




Ranger Flight Dexterous Arms



Dexterous Arm Cross-Section



Dexterous Arm Parameters

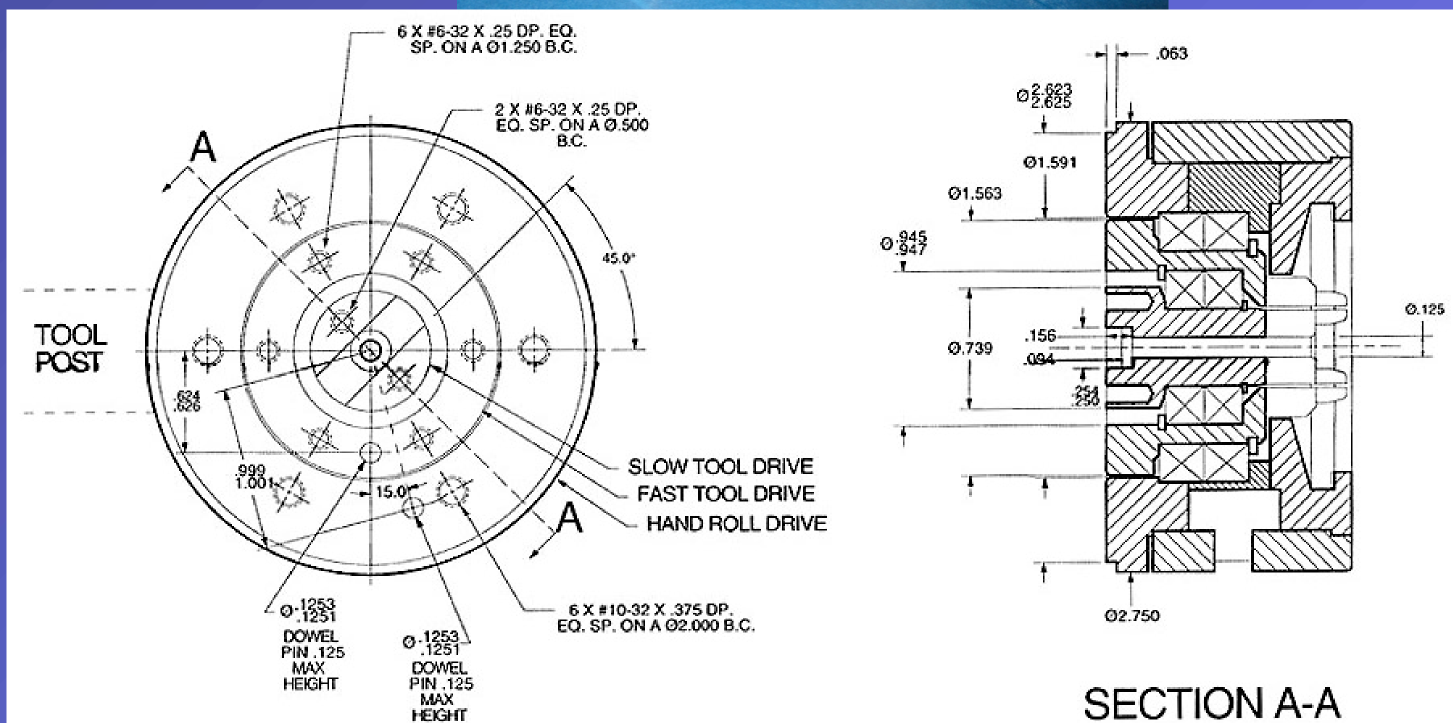
- Modular arm with co-located electronics
  - Embedded 386EX rad-tolerant processors
  - Only power and 1553 data passed along arm
- 53 inch reach mounting plate-tool interface plate
- 8 DOF with two additional tool drives (10 actuators)
- Interchangeable end effectors with secure tool exchange
- 30 pounds tip force, full extension
- 150 pounds (could be significantly reduced)
- 250 W (average 1G ops)

Interchangeable End Effector Mech.

- 3 Mechanical Interfaces
  - Hand Roll Drive
  - Fast Tool Drive
  - Slow Tool Drive
- No power or data interface

Each IEEM is approximately 2.75” Ø by 2”.

Weight is 2 lbs.



Tool Drives

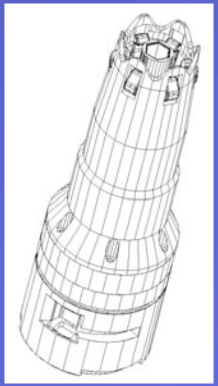
- Tool Drive Motor Controllers are primary method for commanding / sensing EE gripping force or output torque
- Tool Drive Motor Specifications
  - Hand Roll Drive (High Torque, Low Speed)
  - Slow Tool Drive (High Torque, Low Speed)
    - 52 ft-lbs, 139 °/s no load
  - Fast Tool Drive (Low Torque, High Speed)
    - 1 ft-lb, 15,675 °/s no load
    - Must add gearing to use

RTSX End Effectors

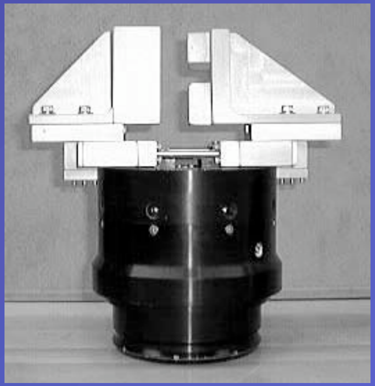
Bare Bolt Drive

Right Angle Drive

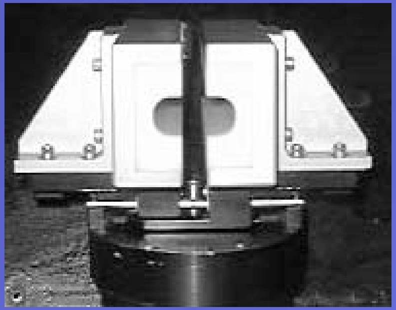
Microconical End Effector



Tether Loop Gripper

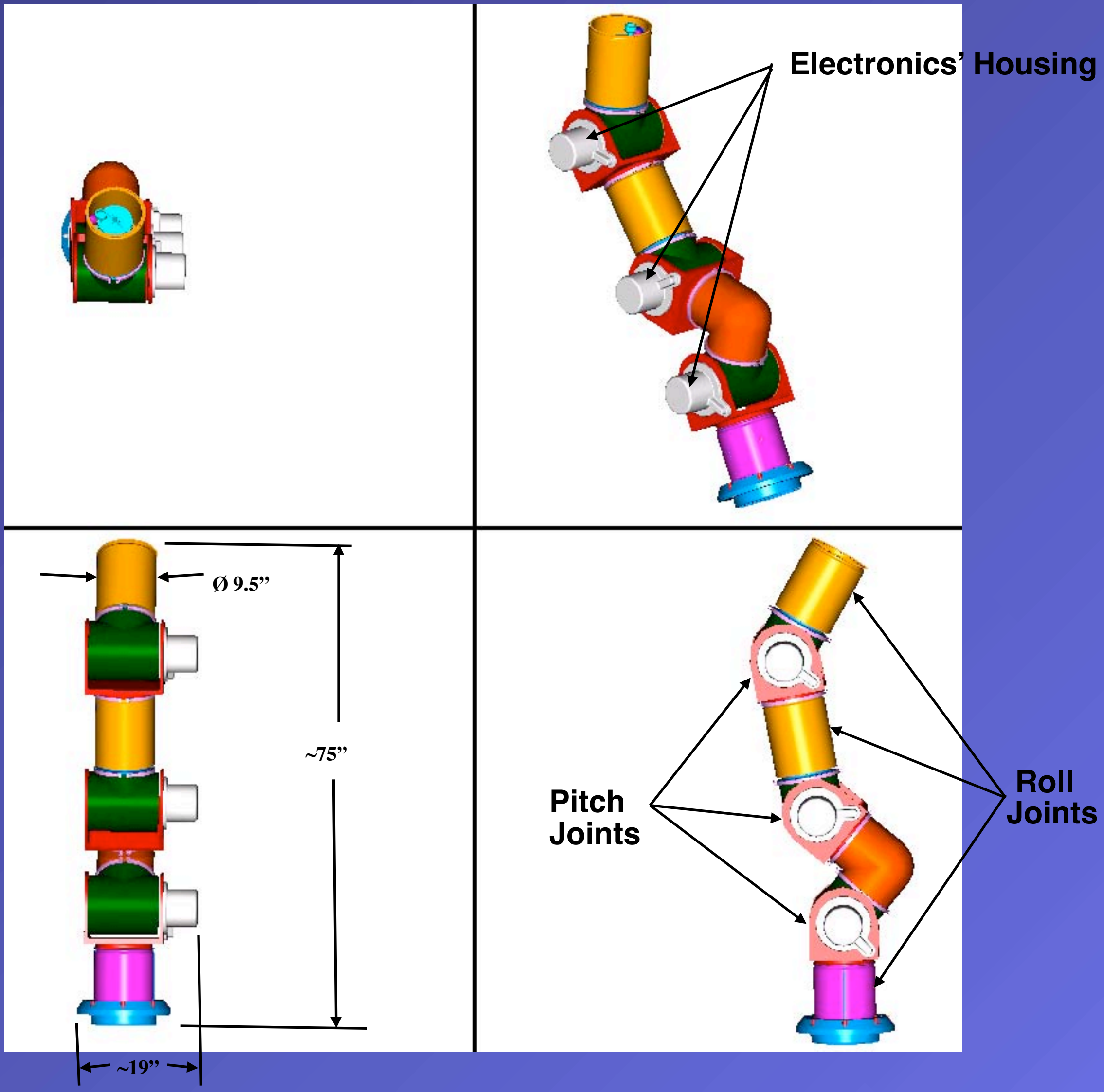


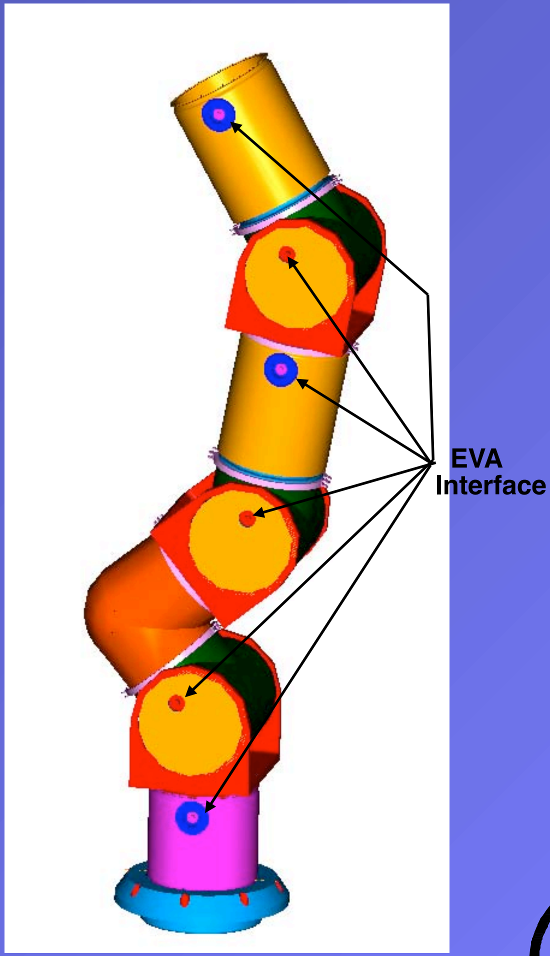
EVA Handrail Gripper



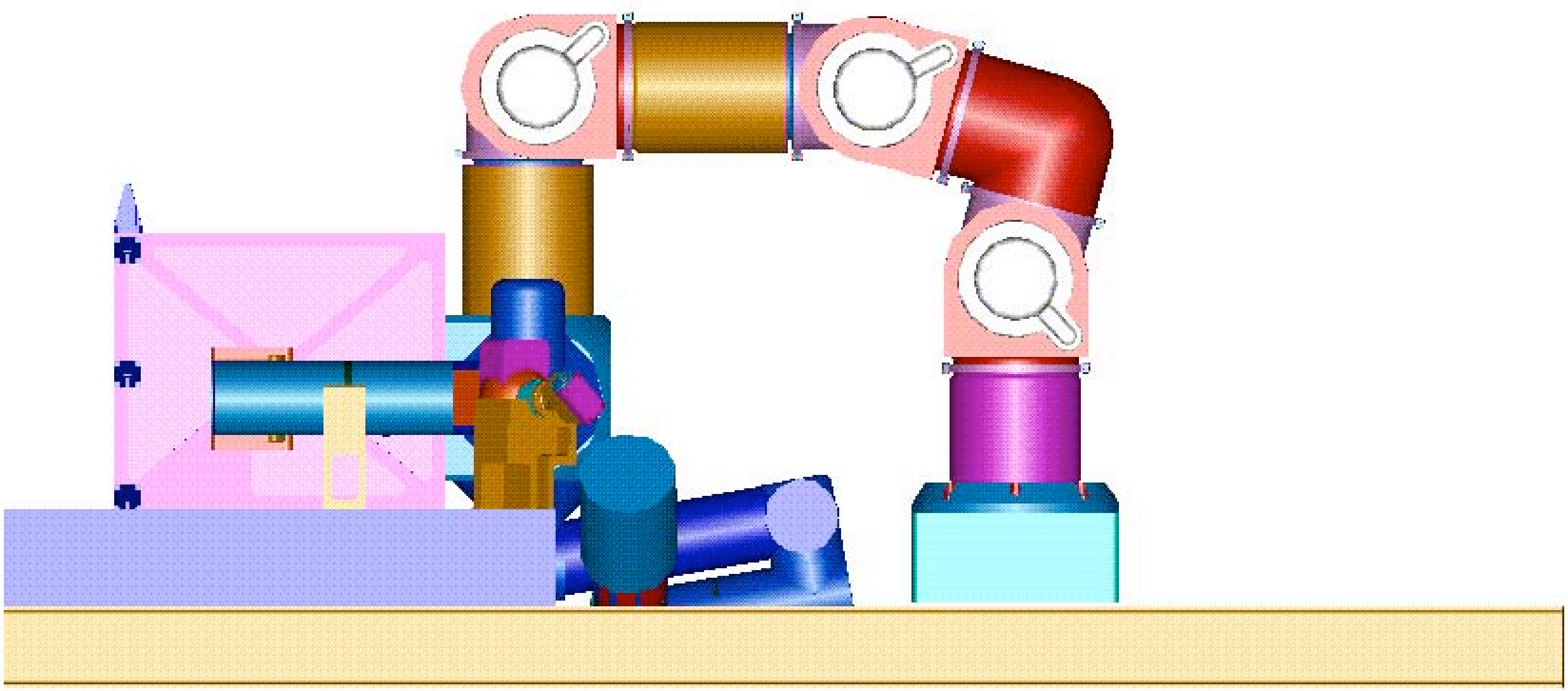
SPAR Gripper

Design:PXL Assembly



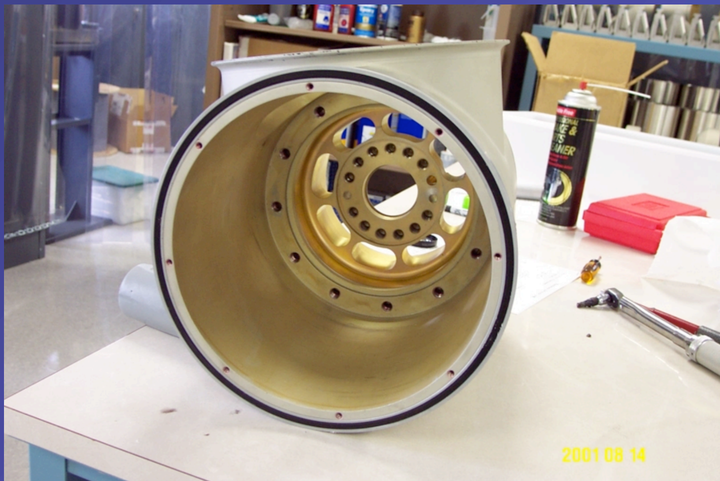


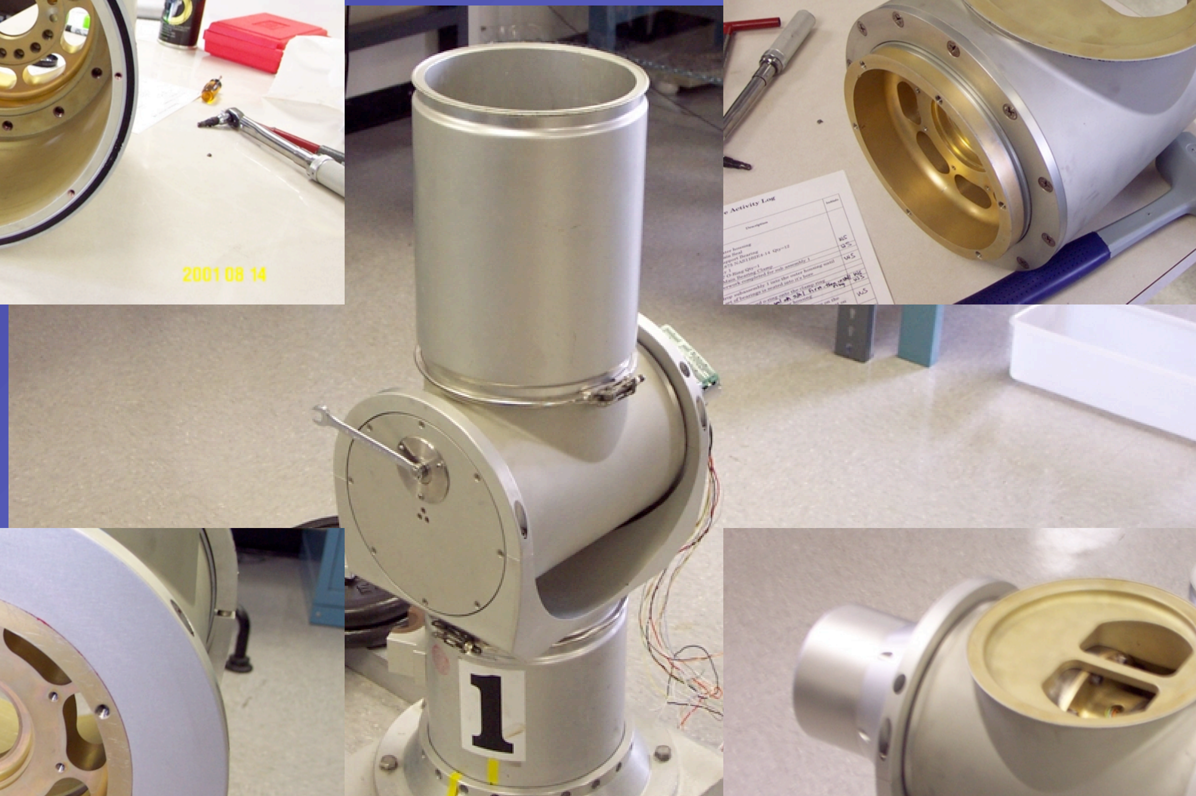
PXL in Stowed Configuration

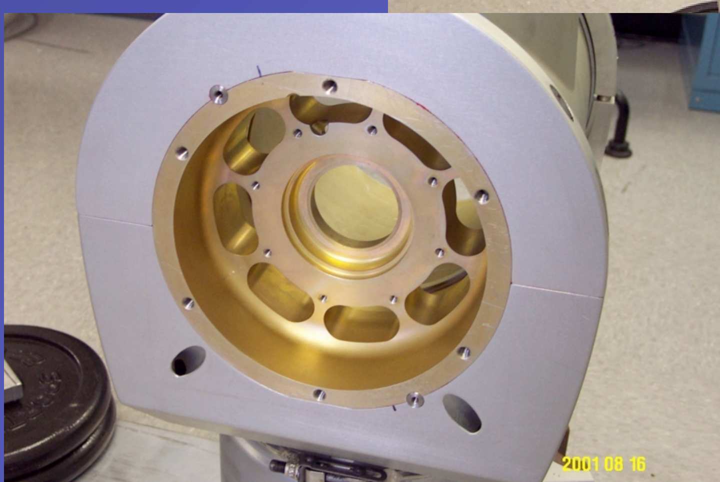


Side View

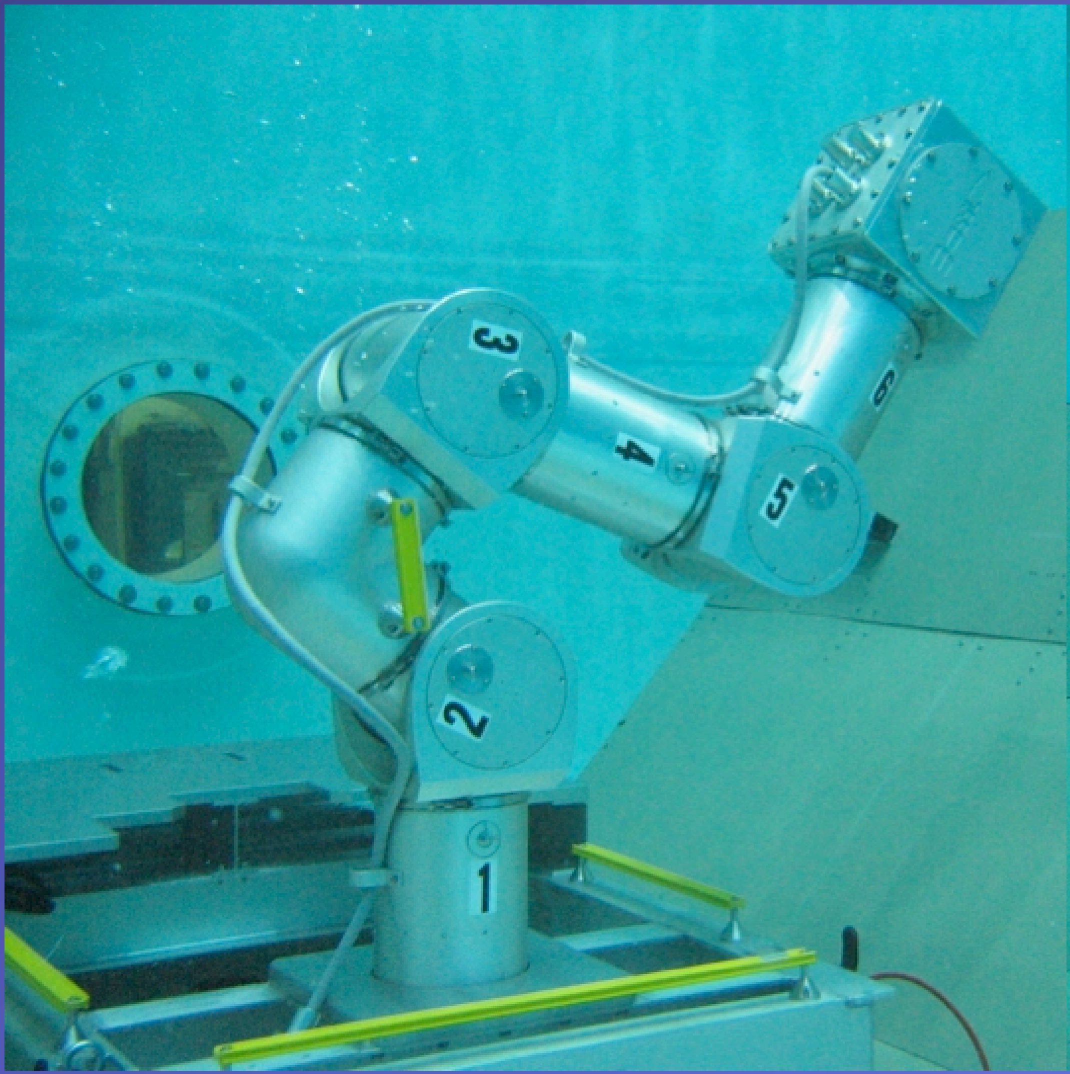
PXL Assembly and Testing





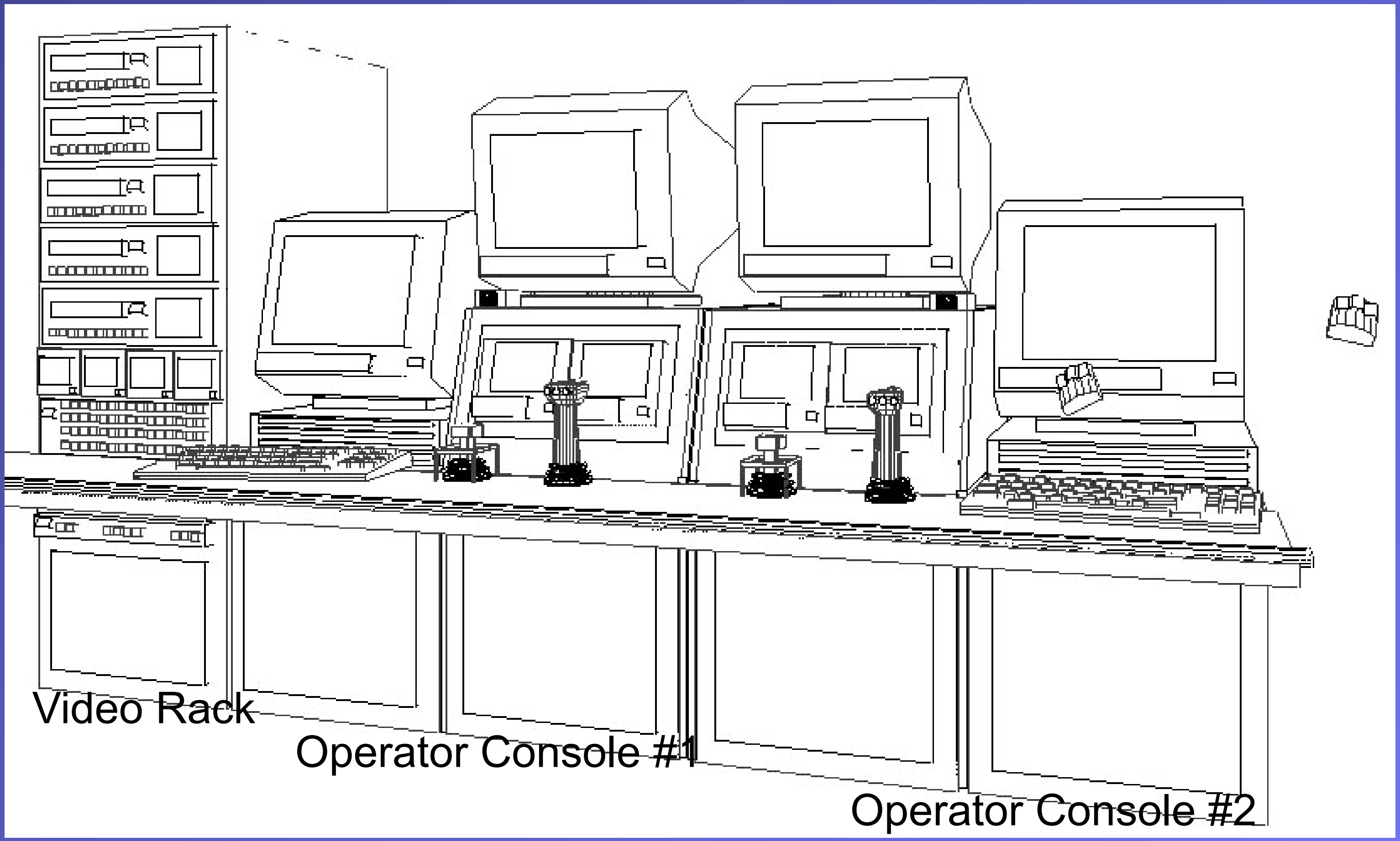


PXL Underwater Operations

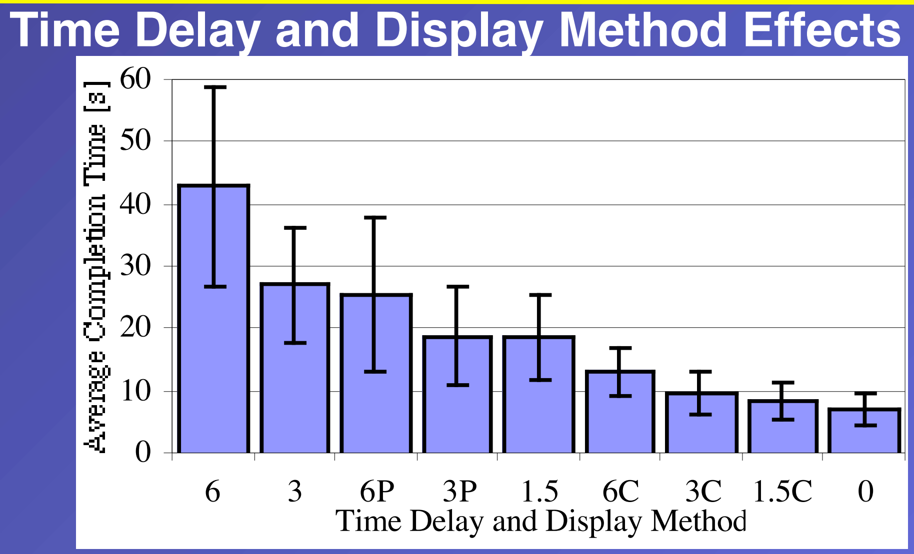


Ranger Control Station

Ground Control Station



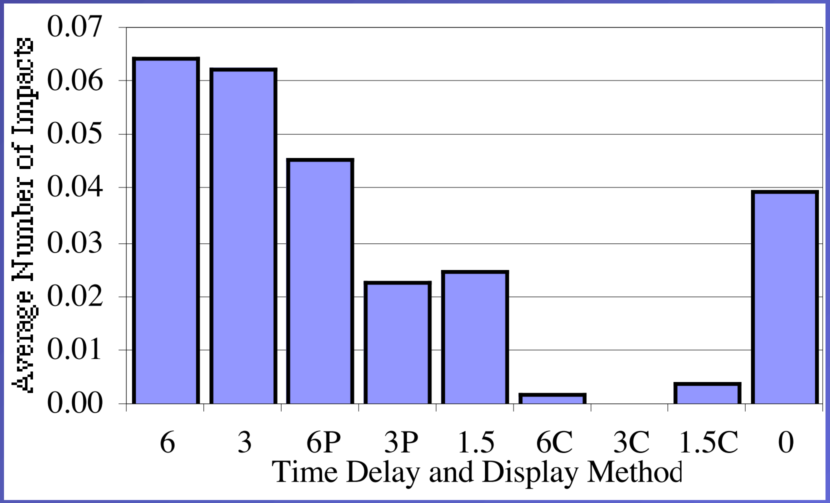
Commanded and Predictive Displays



- **The commanded display severely reduced the performance degradation with 0.01 statistical significance**
- **The commanded display reduced time delay effects on completion time up to 91% at 1.5-second delay**
  - **Subjects controlled the manipulator more accurately with the commanded display**
  - **Impacts were detected and compensated faster**
- **The predictive display also had better performance than time delay alone, at 0.01 statistical significance**
- **The minor calibration errors caused the predictive displays to be about half as effective as the commanded display, a 0.01 statistical significant difference**

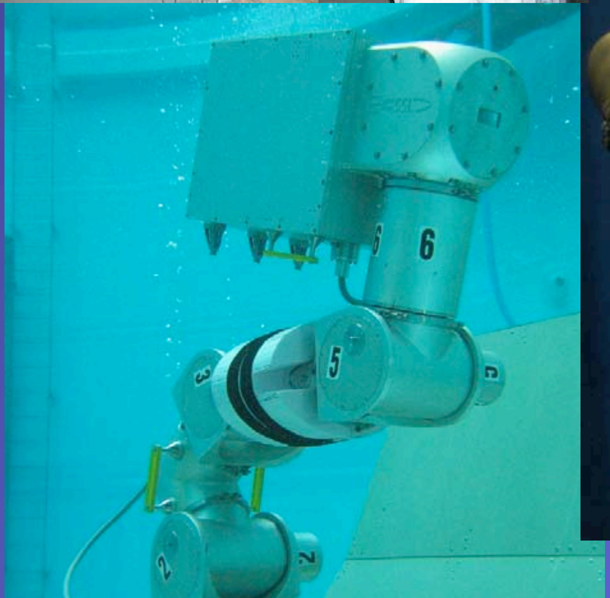
Impact Comparison

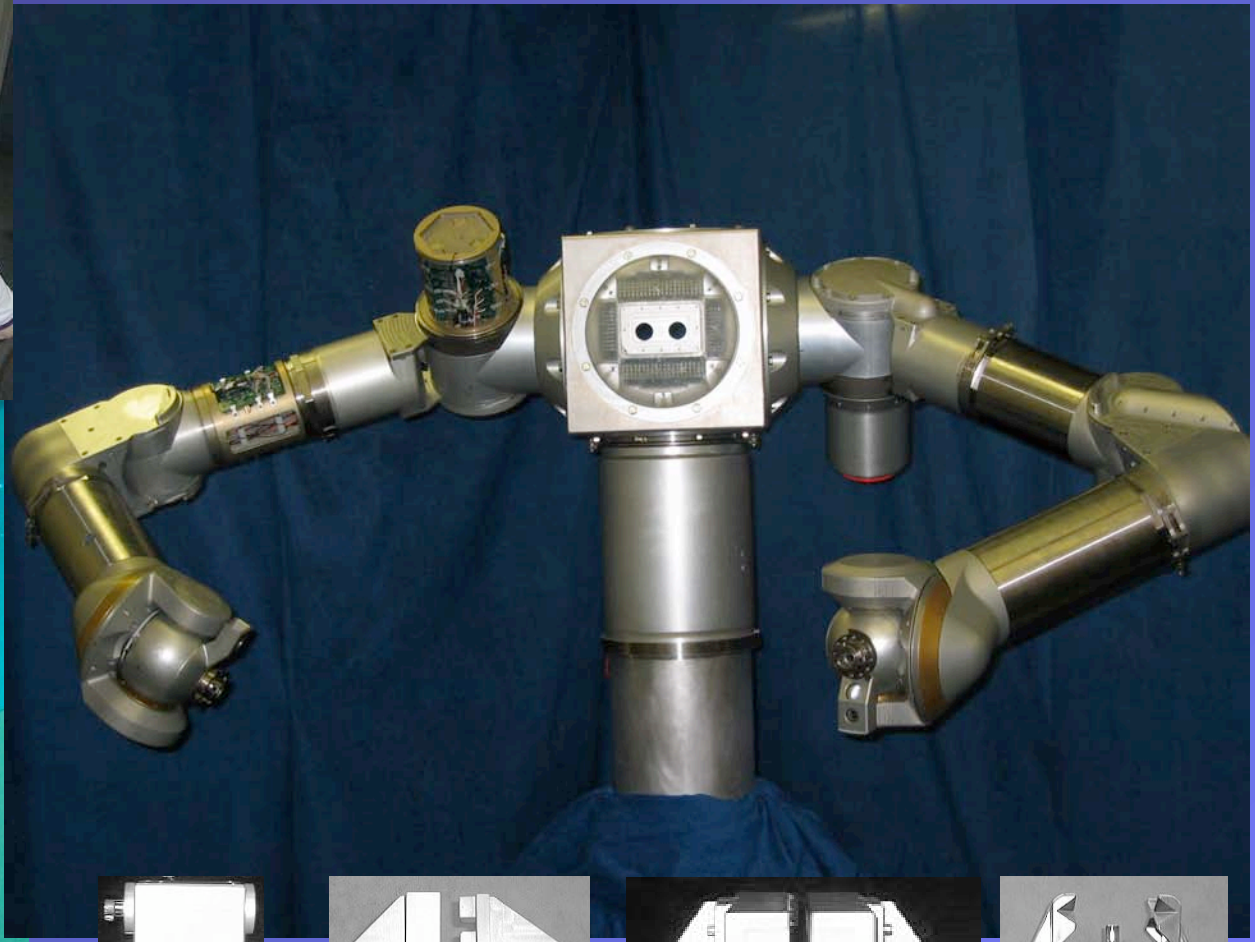
Commanded Display's Reduction of Impacts

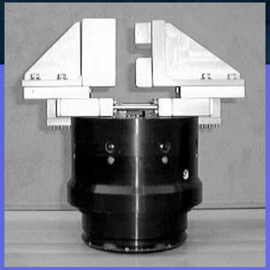


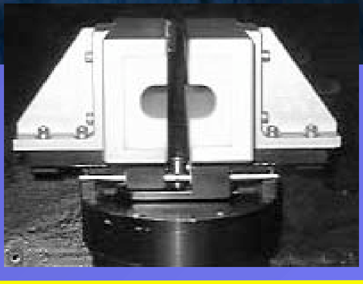
- **Time delay and predictive display usage had no statistical significant effects on number of impacts**
- **Use of the commanded display dramatically reduced errors, at 0.01 significant level, even when compared to no time delay**
- **Only 3 errors were made with a commanded display over 4 hours of testing including 4 subjects testing a total of 1440 trials.**
- **20 times more errors were made without a commanded display**
- **This reduction was due to subjects carefully positioning the commanded display to avoid an impact**

Ranger Spacecraft Servicing System









Ranger's Place in Space Robotics

How the Operator Interacts with the Robot

How the Robot Interacts with the Worksite

	Locally Teleoperated	Remote (Ground) Teleoperated	Supervisory/ Autonomous Control
Specialized Robotic Interfaces	SRMS/SSRMS MFD/SPDM AERCam		ETS-VII ROTEX Sojourner
Any EVA-Compatible Interface		Ranger TSX	
Any Human-Compatible Interface	Robonaut		

Missions Enabled by Space Robotics

How the Operator Interacts with the Robot

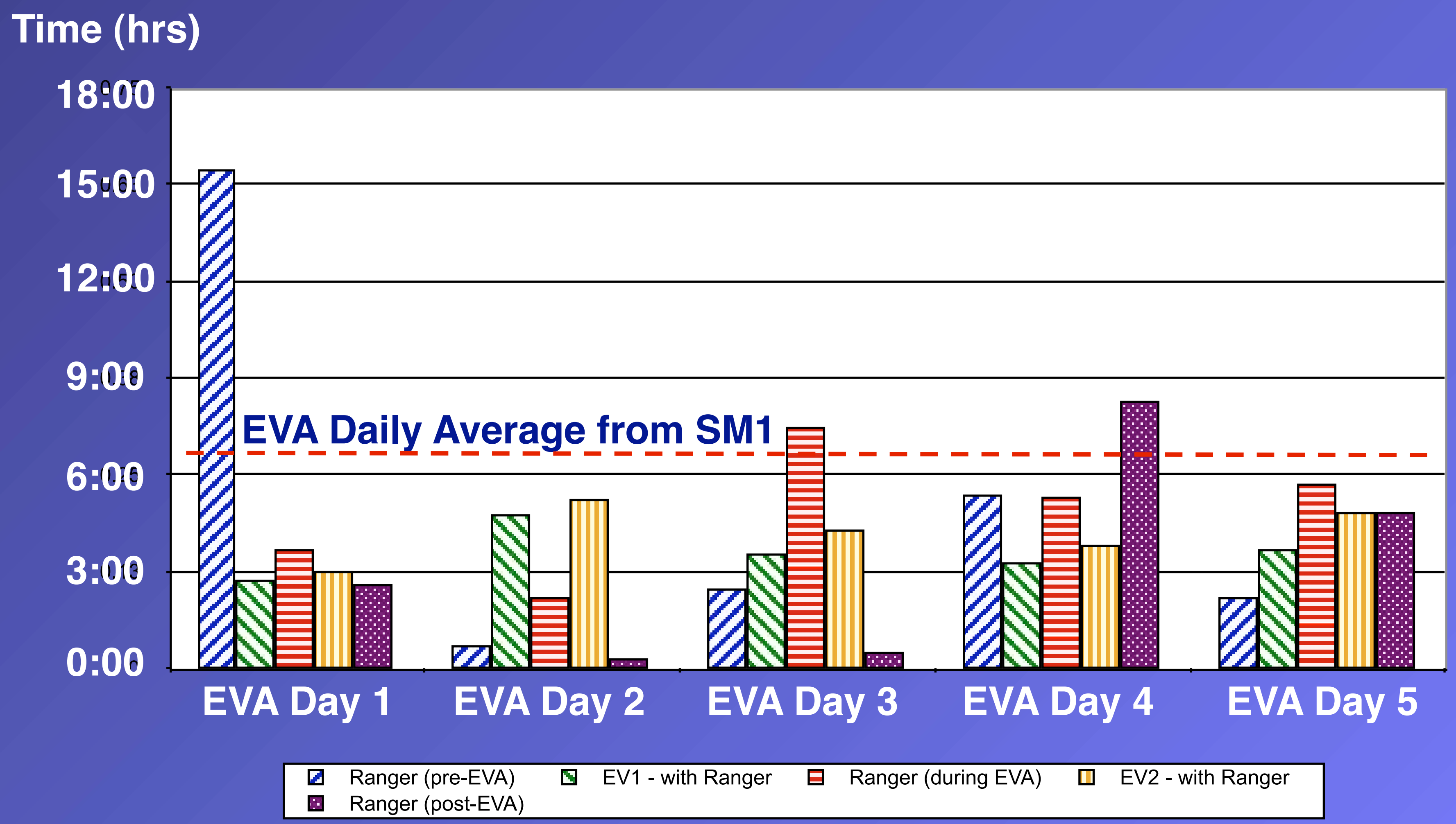
How the Robot Interacts with the Worksite

	Locally Teleoperated	Remote (Ground) Teleoperated	Supervisory/ Autonomous Control
Specialized Robotic Interfaces	• Payload Positioning • ISS Planned Robotic Servicing • Free-flying Cameras	• Lunar Long-Distance Surveying • Future ISS Servicing	• Planetary Rovers • Deep Space Visual Inspection
Any EVA-Compatible Interface	• All ISS Servicing • *NGST Ass'y/Servicing** • Aerobrake Ass'y	• Lunar Nearside Infrastructure • "Grand Observatories" Ass'y/Servicing • Mars EVA Robotic Assistant	• Mars Base Construction • Mars ISRU Servicing • Mars Geology/ Life Sciences
Any Human-Compatible Interface	• LEO Contingency Repairs • Telepresence	• Lunar/HEO Contingency Repairs • Dexterous Science Teleops	• Deep Space Contingency Repairs • Dexterous Science Ops

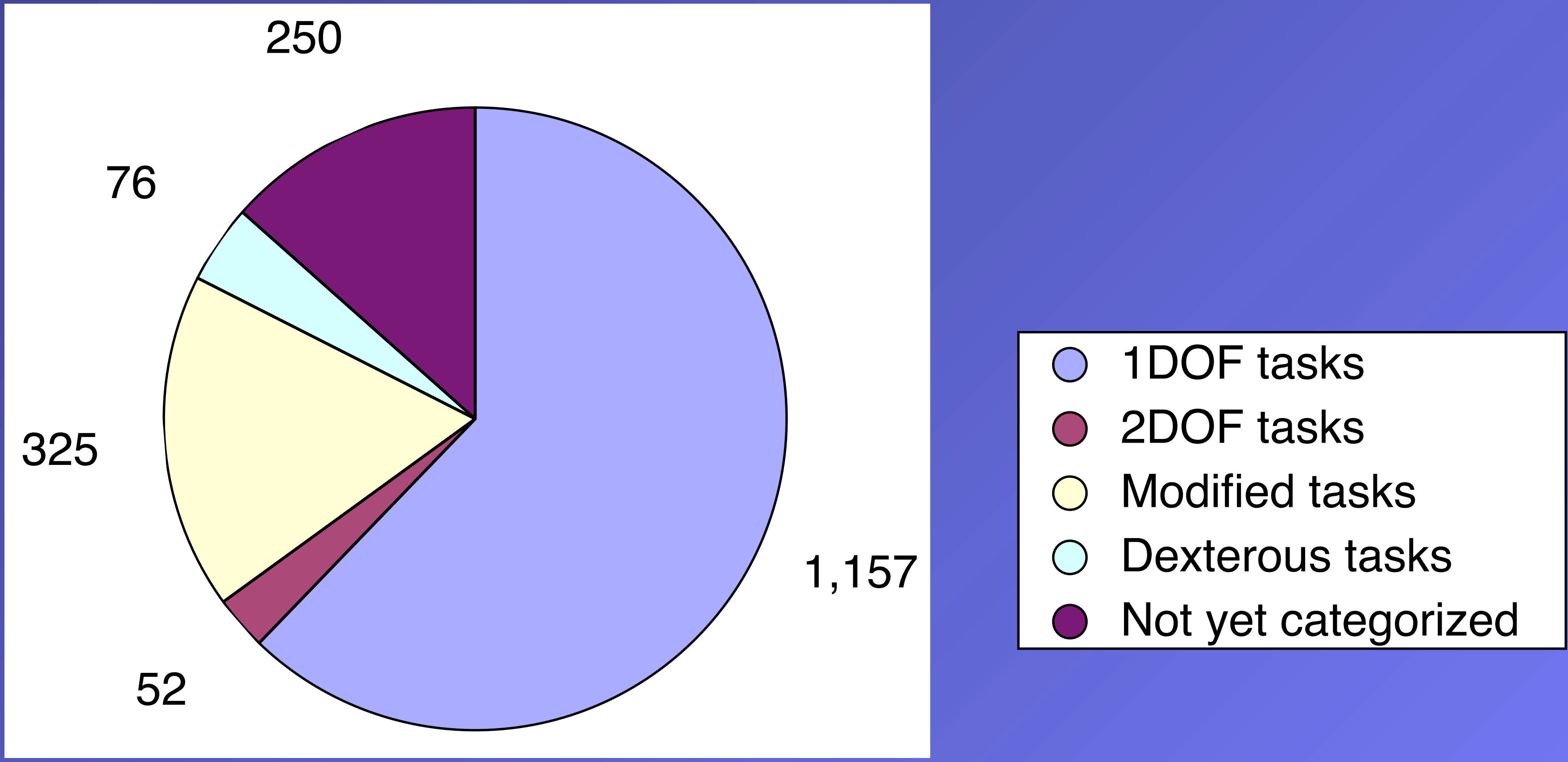
* Feasibility Study Currently Underway for NASA Goddard

← Missions Supported by Ranger Flight

Ranger Application to HST SM1



Grasp Analysis of SM-3B



Numbers refer to instances of grasp type over five EVAs
Total discrete end effector types required ~8-10

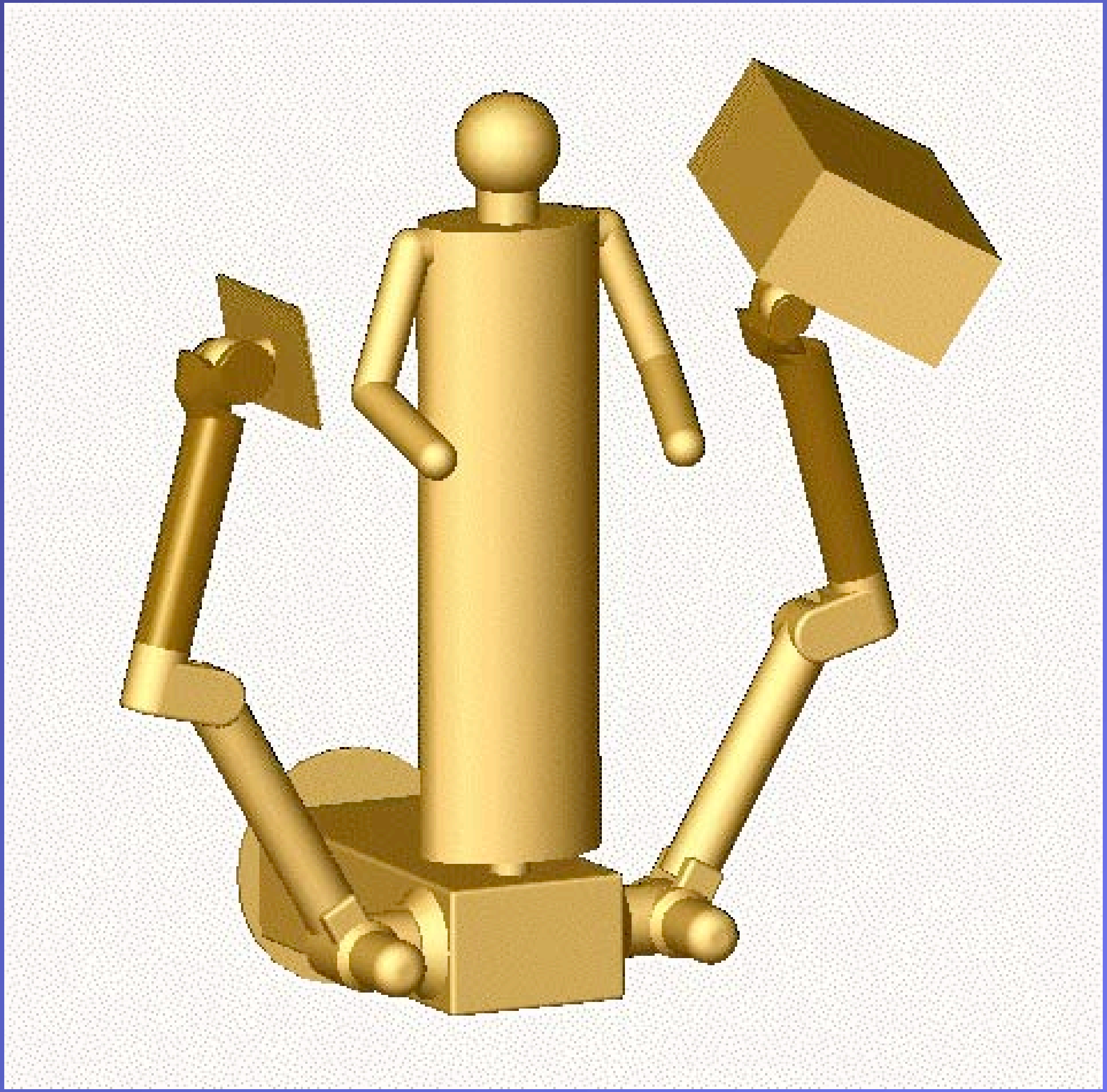
Results of Robot Dexterity Analysis

- Broke 63 crew-hrs of EVA activity on SM -3B into 1860 task primitives
- 13.4% not yet categorized
- Of categorized task primitives, 95.3% are viable candidates for 2DOF robotic end effectors
  - 71.8% 1DOF tasks
  - 3.2% 2DOF tasks
  - 20.2% tasks performed differently by robot than EVA (e.g., torque settings)
- 4.7% require additional dexterity
- All SM-3B robotic tasks can be performed by suite of 8-10 different end effectors

Baseline SM4 Task Allocations

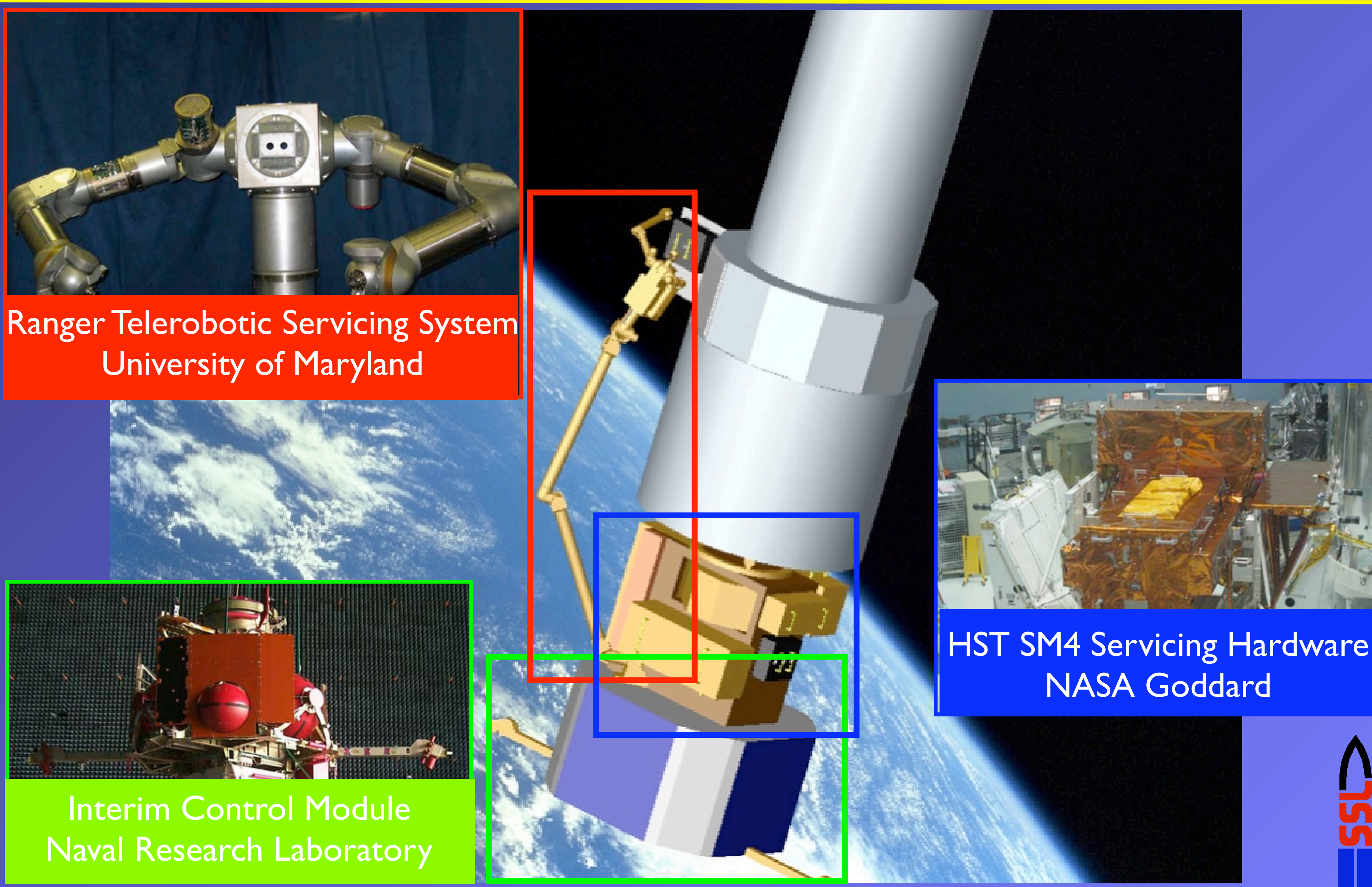
• RSUs (3)	3:00
• Battery Modules (2)	2:50
• COS	3:10
• WFC3	2:55
• ASCS/CPL	3:30
• FGS3	3:35
• NOBLs (3)	1:50
• ASCS/STIK	1:55
• DSC	1:00
• Setup & Closeout	5:00

HERCULES (Dual Arm; EVA Operations)

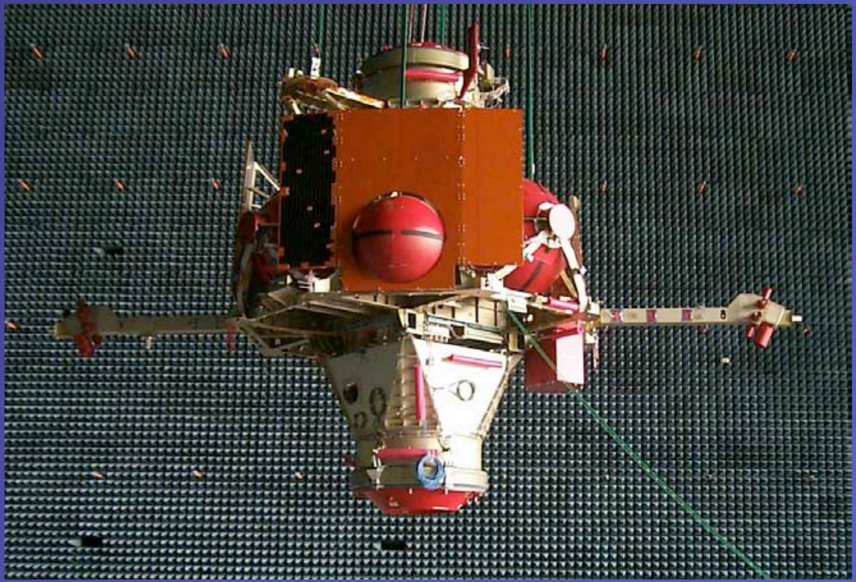


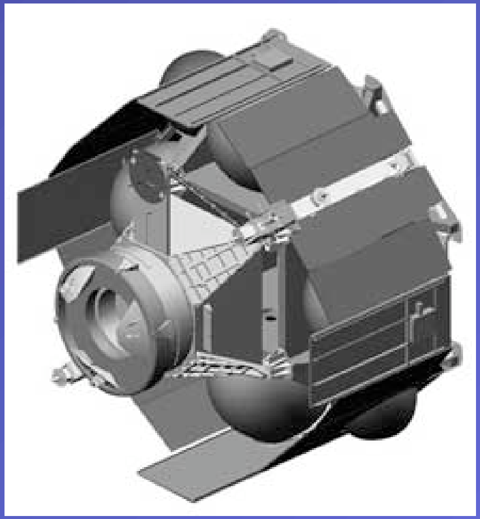
HERCULES Proof-of-Concept Testing

SM4R(obotic) Concept Overview



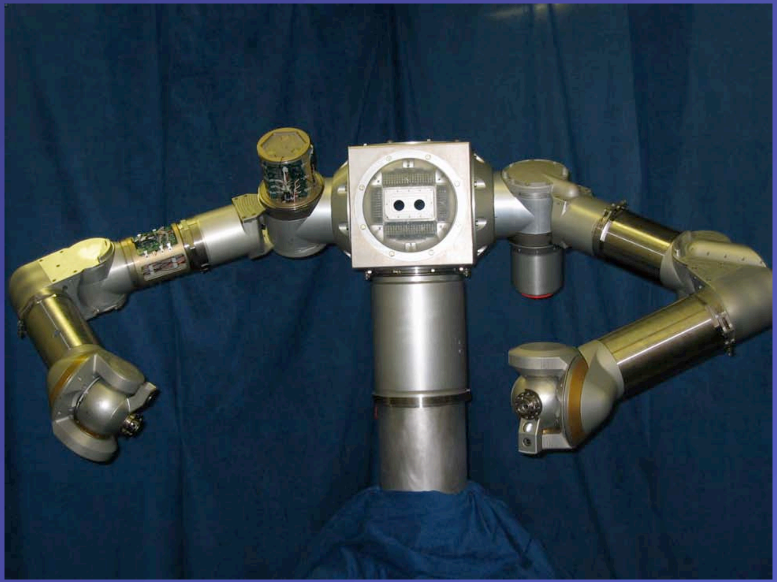
Maneuvering Spacecraft Bus - ICM

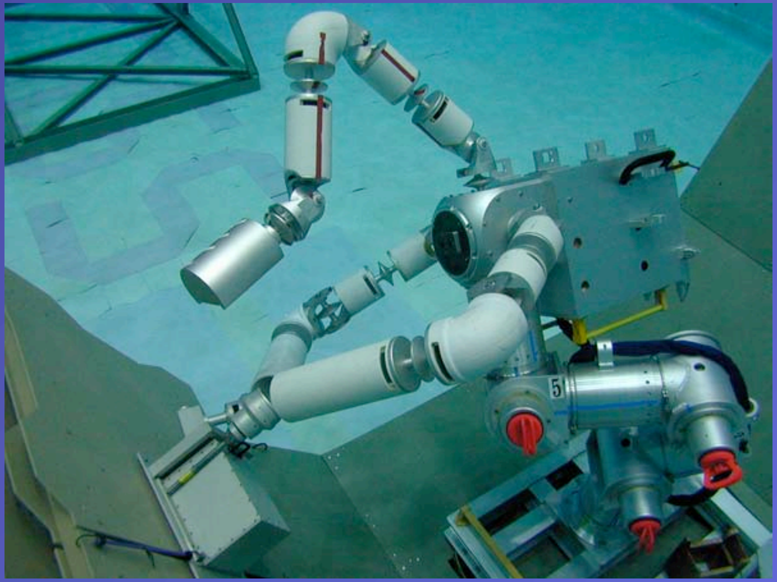




- Developed by Naval Research Laboratory for NASA ISS
- Sufficient payload on EELV for Ranger robotics, SM-4 servicing hardware, HST flight support hardware
- Sufficient maneuvering capability for extensive coorbital operations, followed by HST deorbit or boost to disposal altitude
- Currently in bonded storage at NRL

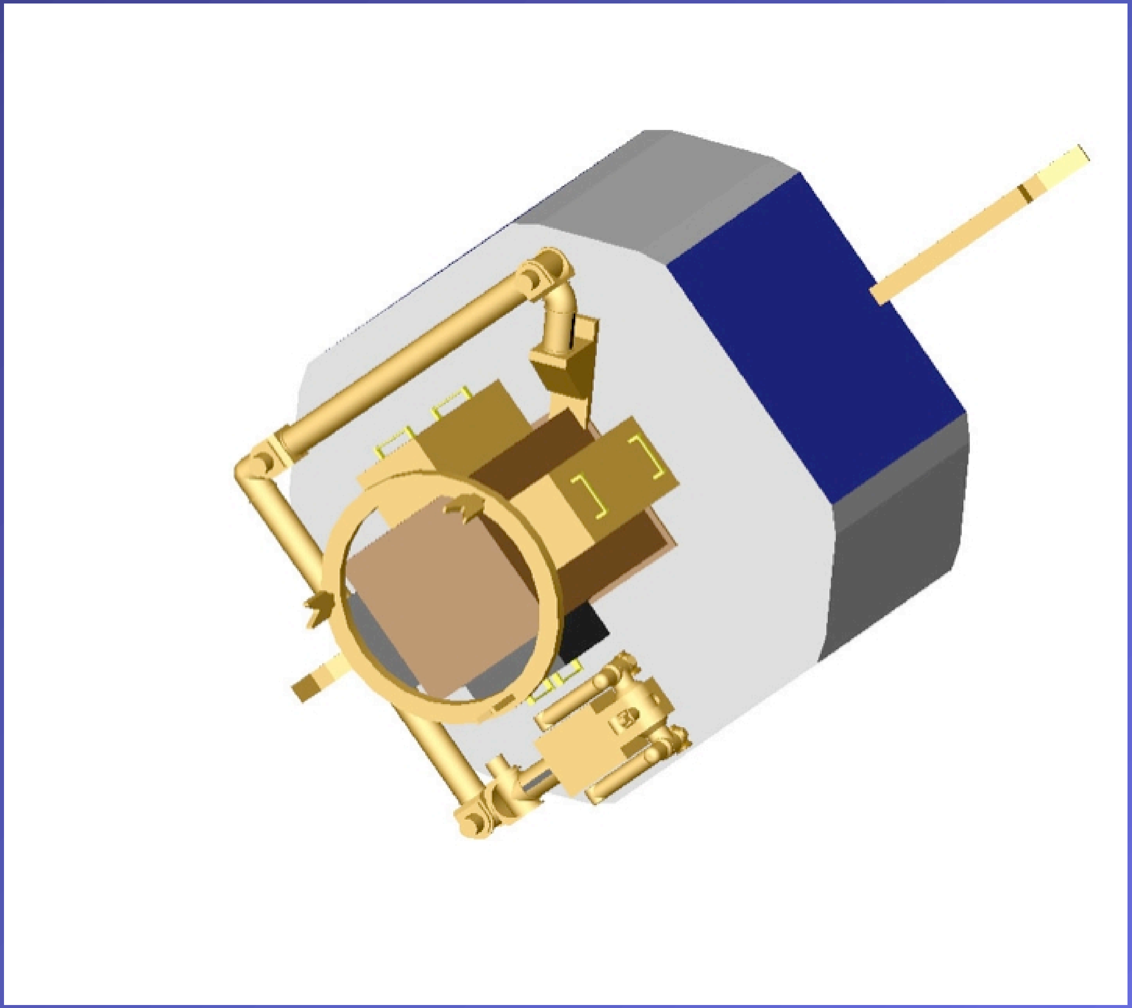
Dexterous Robotics - Ranger





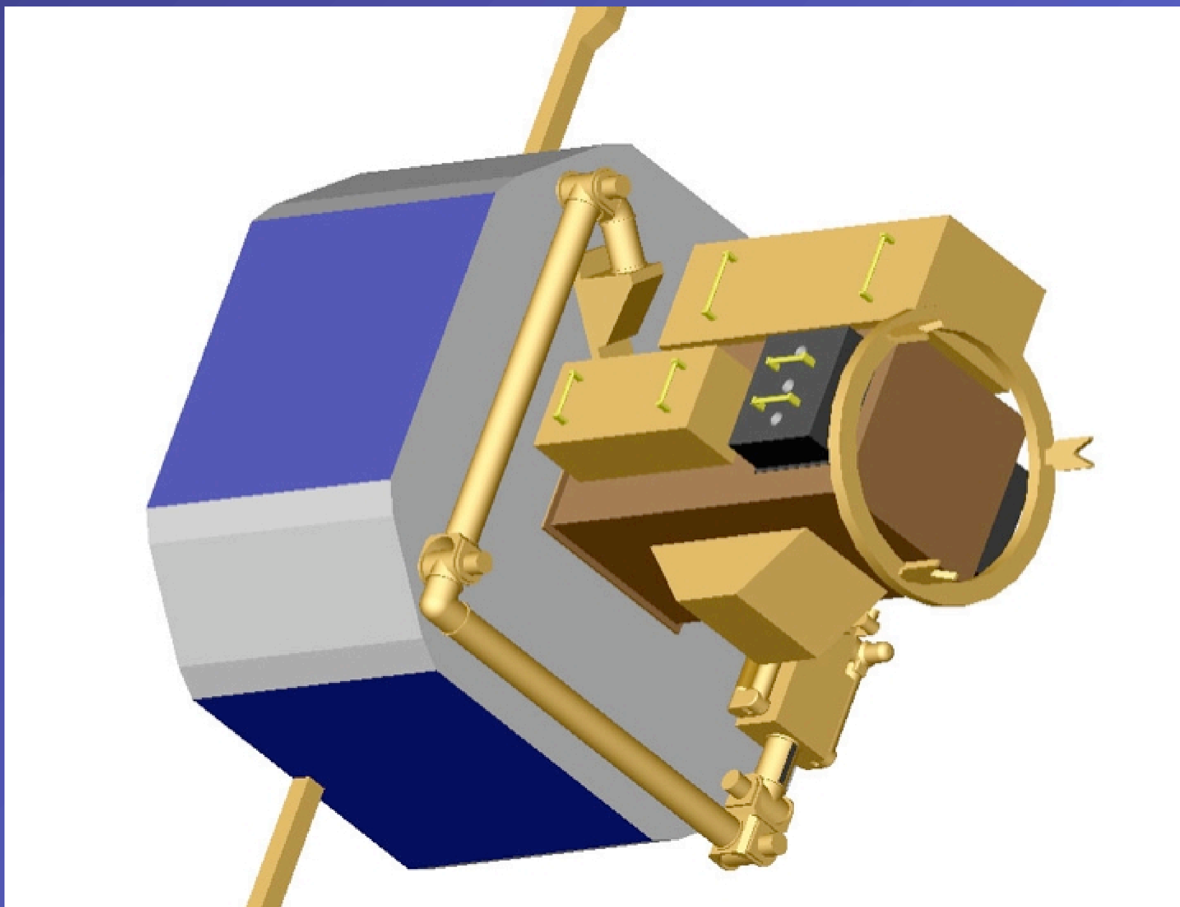
- Developed by University of Maryland for NASA as low-cost flight demonstration of dexterous telerobotics
- Designed to be capable of using EVA interfaces and performing EVA tasks
- System passed through NASA Phase 0/1/2 PSRP safety reviews for shuttle flight
- High-fidelity qualification arms in extended tests at UMd SSL
- 70% of flight dexterous manipulator components in bonded storage at UMd

Servicing Option 1



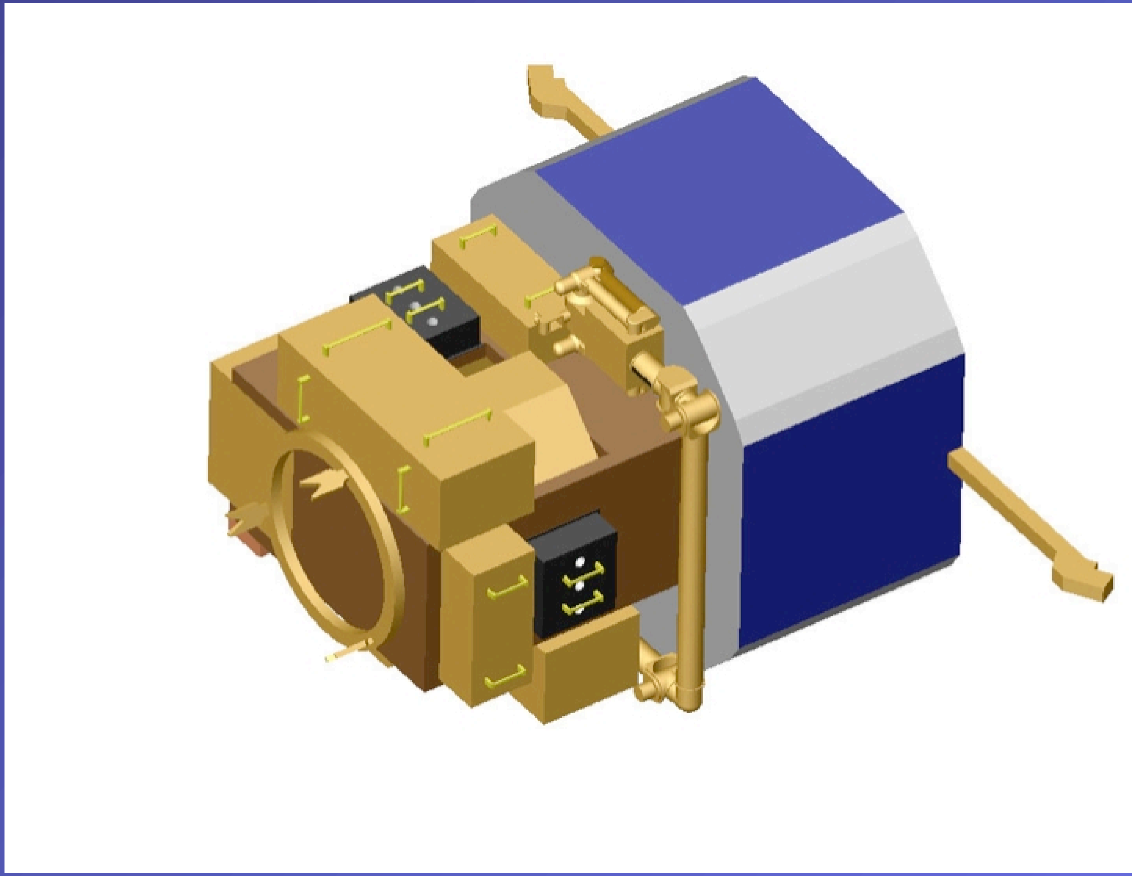
- Limited to critical servicing options
  - Batteries
  - Rate sensor units
  - Battery carrier plates, SOPE, COPE
- HST payload mass 3194 lbs
- Total ICM payload 4454 lbs
- Servicer empty mass 11,065 lb

Servicing Option 2



- Limited to critical servicing options
  - Batteries
  - Rate sensor units
  - Battery carrier plates, SOPE, COPE
- HST payload mass 3194 lbs
- Total ICM payload 4454 lbs
- Servicer empty mass 11,065 lb

Servicing Option 3



- All SM4 ORUs and launch protective enclosures
- HST payload mass 9574 lbs
- Total ICM payload 10,834 lbs
- Servicer empty mass 17,445 lb

Modifications to Existing Hardware

- ICM
  - Addition of TDRSS Ku-band command data links
  - Mounting interfaces for robotic hardware, HST servicing hardware, MMS berthing ring
  - Attachment to EELV payload adapter
- Ranger
  - Addition of longer strut elements to provide needed reach for positioning leg
  - Completion of flight manipulator units
  - Development of required end effectors for servicing tasks
  - Implementation of launch restraints for robot on ICM deck
  - Development of control station for teleoperated/supervisory control
- HST servicing hardware
  - Modification of shuttle launch restraints to ICM deck
  - Verification of thermal environment for ORUs

SM4R Mission Scenario

- Launch on EELV, rendezvous and dock to HST at aft bulkhead MMS fittings (high level supervisory control)
- Perform high-priority servicing (batteries/gyros), other targets of opportunity (e.g., SM4 instrument changeouts), boost HST to multi-decade stable altitude
- Separate ICM and move into coorbital location to allow HST to perform nominal science data collection (no impact to HST pointing or stability) - ICM can be used as robotics testbed during this time
- ICM can redock and service multiple times if needed (e.g., periodic gyro replacements)
- ICM is based on design with proven flight duration of 6 years on-station
- At end of HST science mission, ICM redocks and performs deorbit/disposal boost mission

Launch Vehicle Considerations

- Due to size of ICM and servicing hardware, an EELV with a 5-meter payload fairing is required
  - Delta IV Medium+ (5,2)
  - Atlas V 501
- Also considered next larger size EELV for heavier mission cases
  - Delta IV Medium+ (5,4)
  - Atlas V 521

ICM Propellant Loads

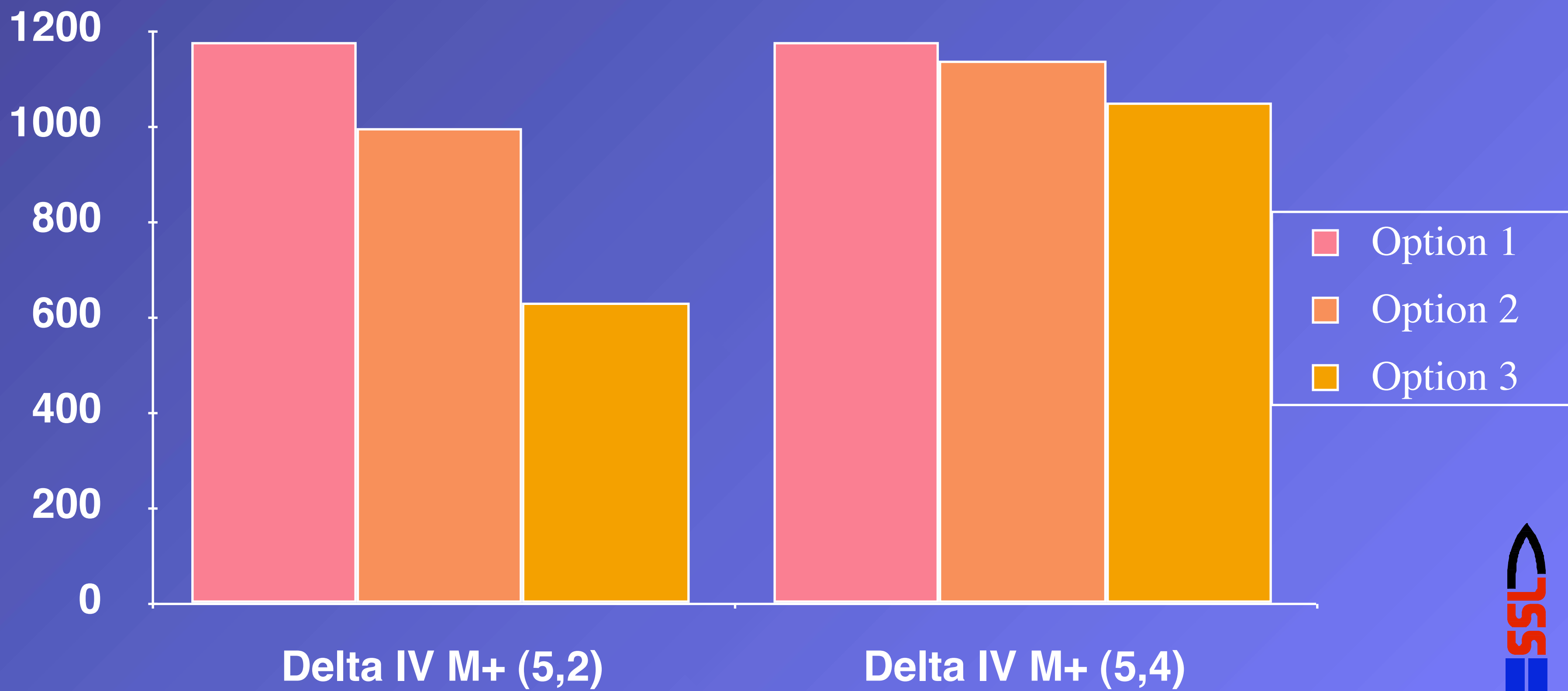
	Option 1	Option 2	Option 3
Delta IV M+(5,2) Atlas V 501	11,700	11,040	7,515
Delta IV M+(5,4) Atlas V 521	11,700	11,700	11,700

Propellant Mass in lbs

Achievable Boost Altitude

Assumptions:

- 300 m/sec deltaV reserve for rendezvous and docking
- Remaining propellant used to raise orbit from 330 NMi to new circular altitude, then deorbit from that altitude



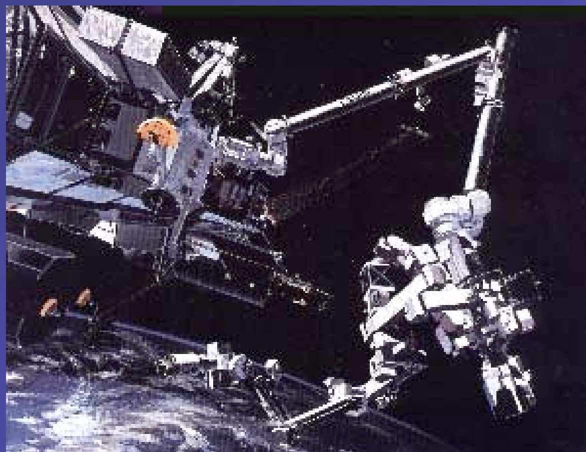
Mission Assurance

- Use existing hardware to initiate comprehensive testing program
  - Hubble SM4 EVA neutral buoyancy training hardware
  - Ranger neutral buoyancy robot
  - UMd Neutral Buoyancy Research Facility
- Three keys to success:
  - Test
  - Test
  - Test
- Evaluate every SM4 task in first 6-9 months and decide on whether or not to perform it on-orbit
- Aim for 25-30 hours of end-to-end simulation for every hour of on-orbit operations

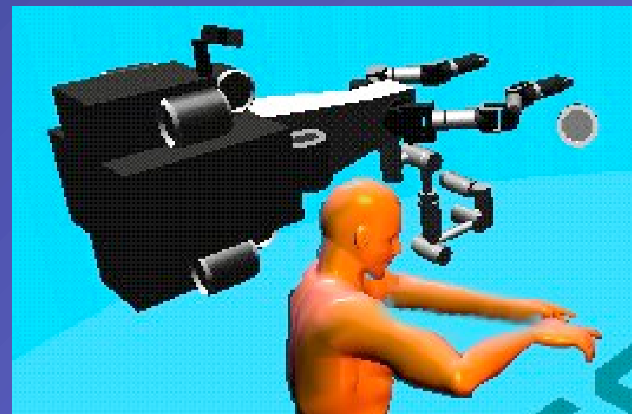
Why SM4R?

- No other options come close to matching technology readiness:
  - ICM based on “black” spacecraft with flight heritage, currently ready to fly
  - Ranger manipulators developed and tested; 70% of dexterous manipulator flight components already procured
- No other options come close to matching the proven capabilities
  - Long on-orbit endurance and high maneuvering capacity provide assurance of successful deorbit at Hubble end-of-life
  - Ranger manipulators designed for EVA-equivalent servicing, building on 20-year heritage of HST robotic servicing operations
- No other options come close to matching the flexibility
  - Interchangeable end effectors provide unlimited interfaces
  - Ranger arm design parameters (force, speed, clean kinematics) unrivaled among flight-qualified manipulators

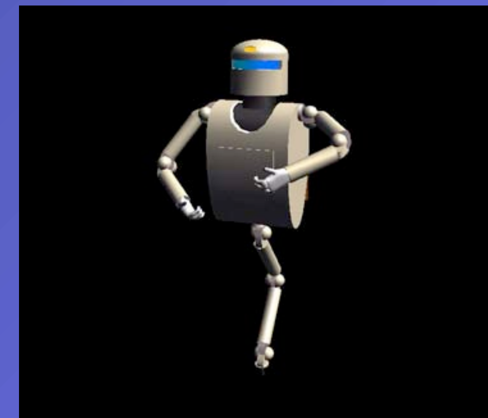
Results of a Successful SM4R Mission



Demonstration of Dexterous Robotic Capabilities

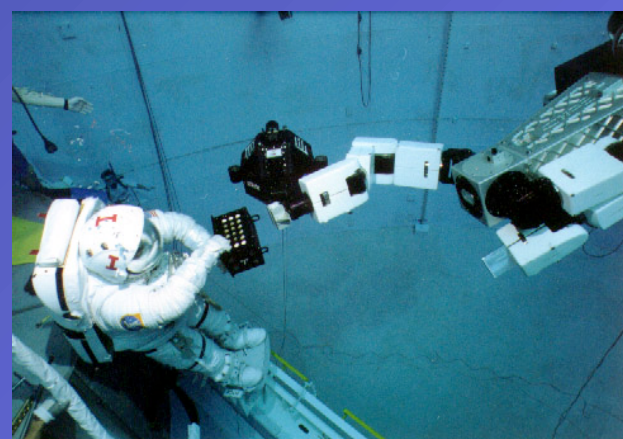


Understanding of Human Factors of Complex Telerobot Control

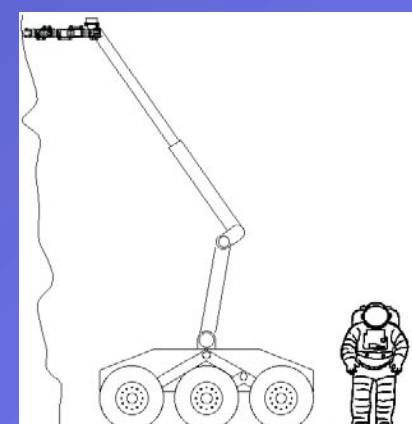


Pathfinder for Flight Testing of Advanced Robotics

Precursor for Low-Cost Free-Flying Servicing Vehicles

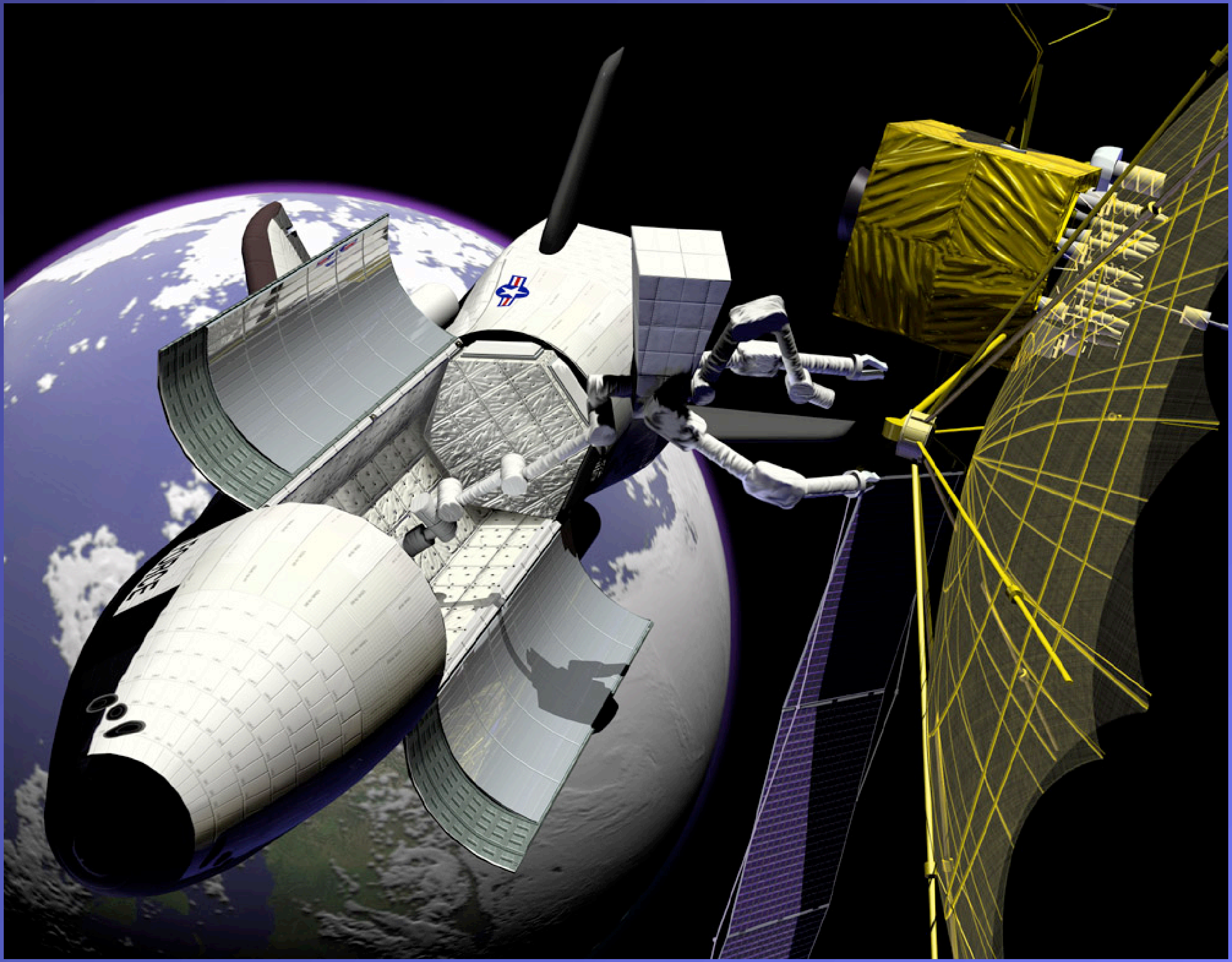


Lead-in to Cooperative EVA/Robotic Work Sites



Dexterous Robotics for Advanced Space Science

Ranger on SMV



For More Information

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