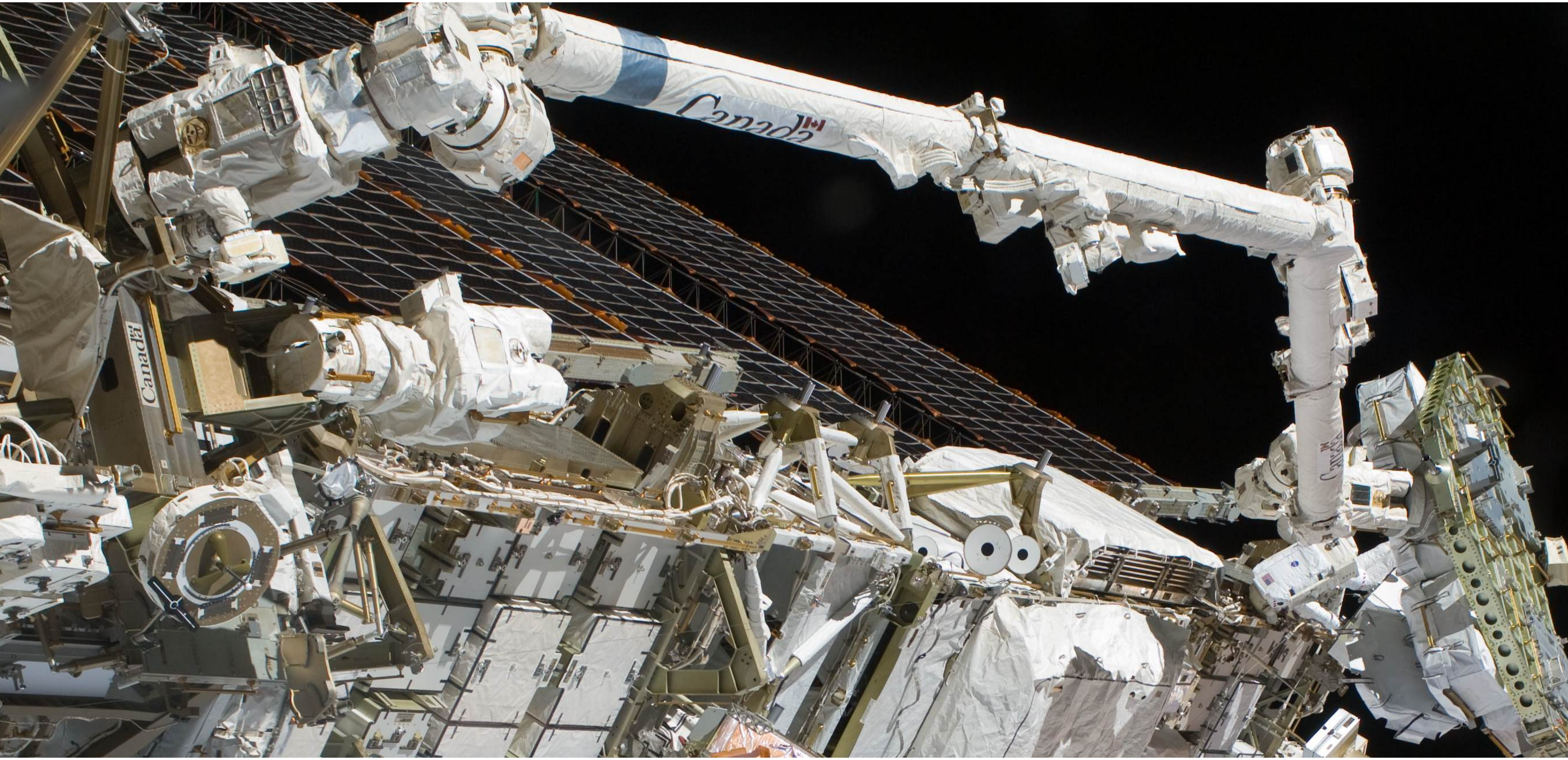

Considerations for Next Generation Space Manipulators

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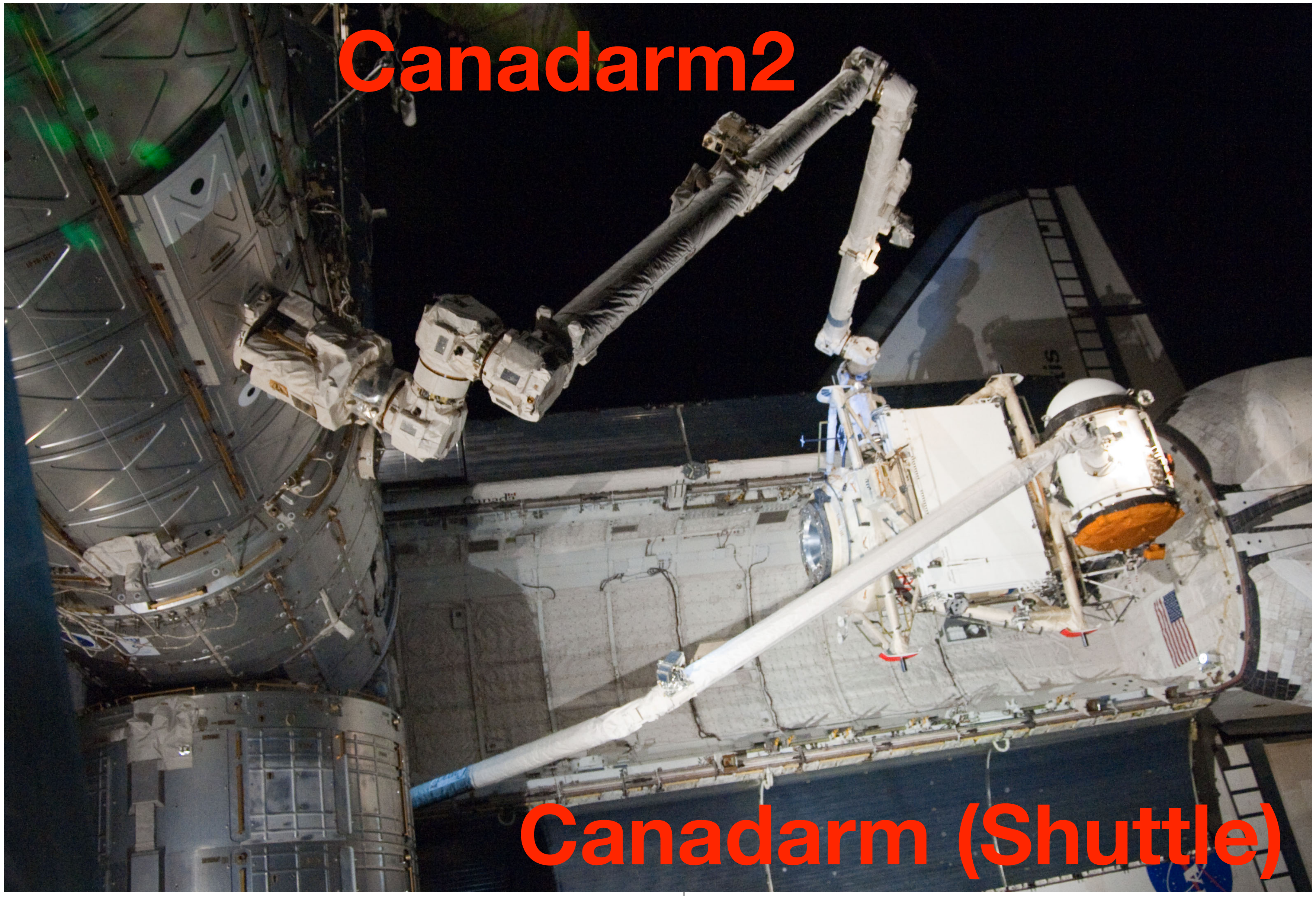
Outline

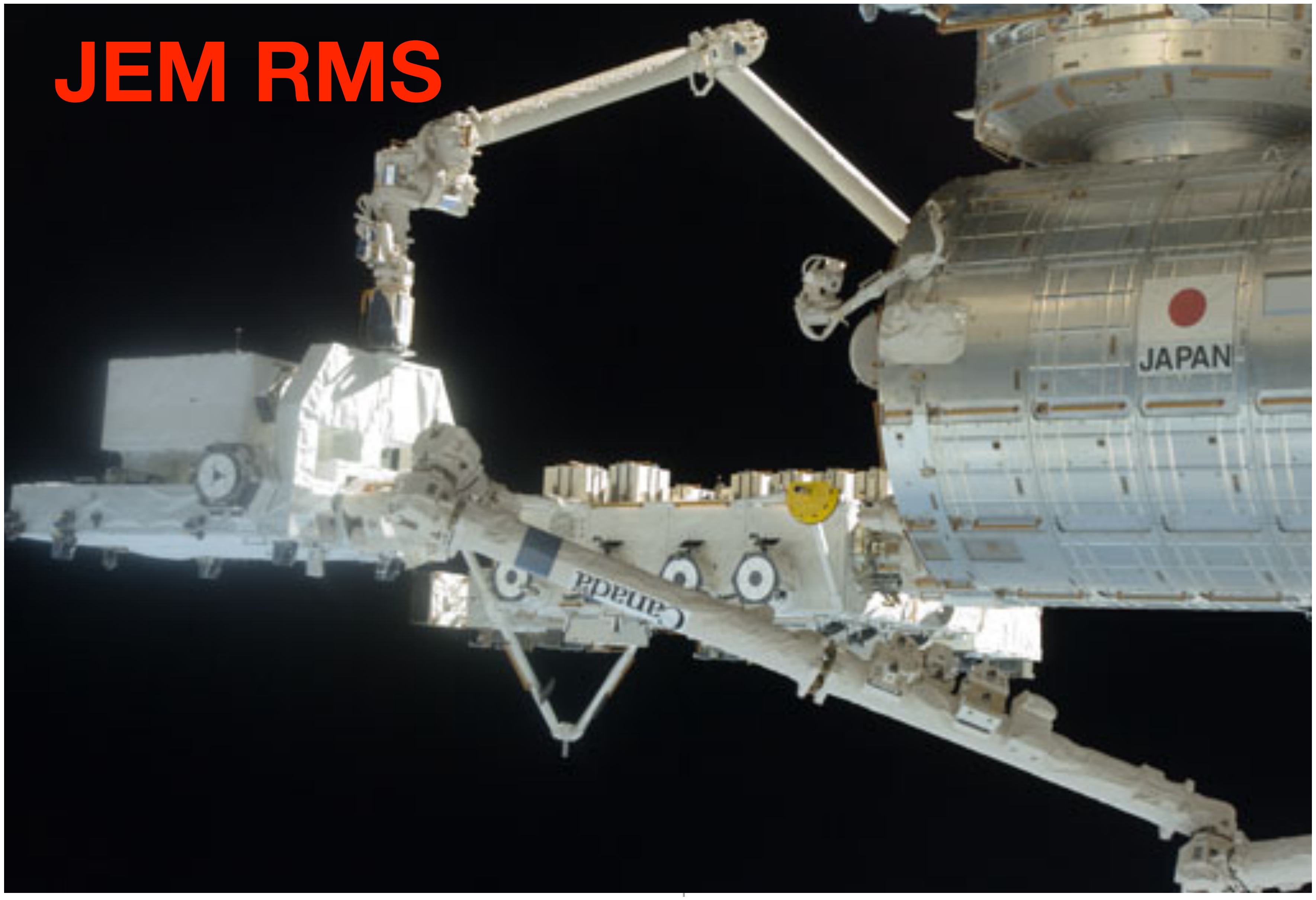
- Robotics on-board the International Space Station
- Objective and motivation of presentation
- Operations Considerations
    - Changing operational environment
    - Integrated nominal and off-nominal ops concept development
- Summary and questions

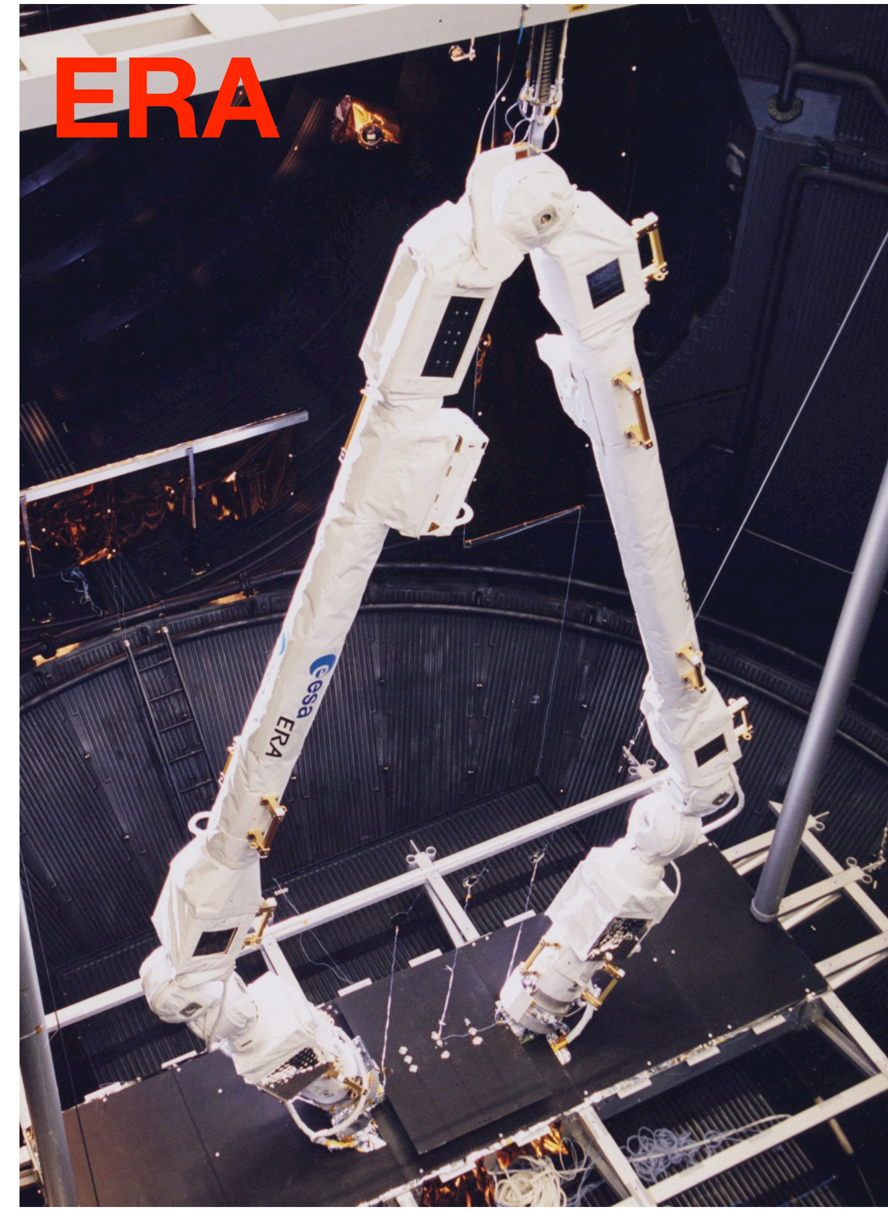
Objective

- Present a different view of how robots are operated in space
- Share some of the lessons learned from robotics operations on-board the ISS for consideration in the design of next generation systems
  - Increase the safety and robustness of new systems
  - Reduce operations costs
- "Get the ops inputs early"
  - Frequently heard complaint from spaceflight operations specialists



ISS Manipulators

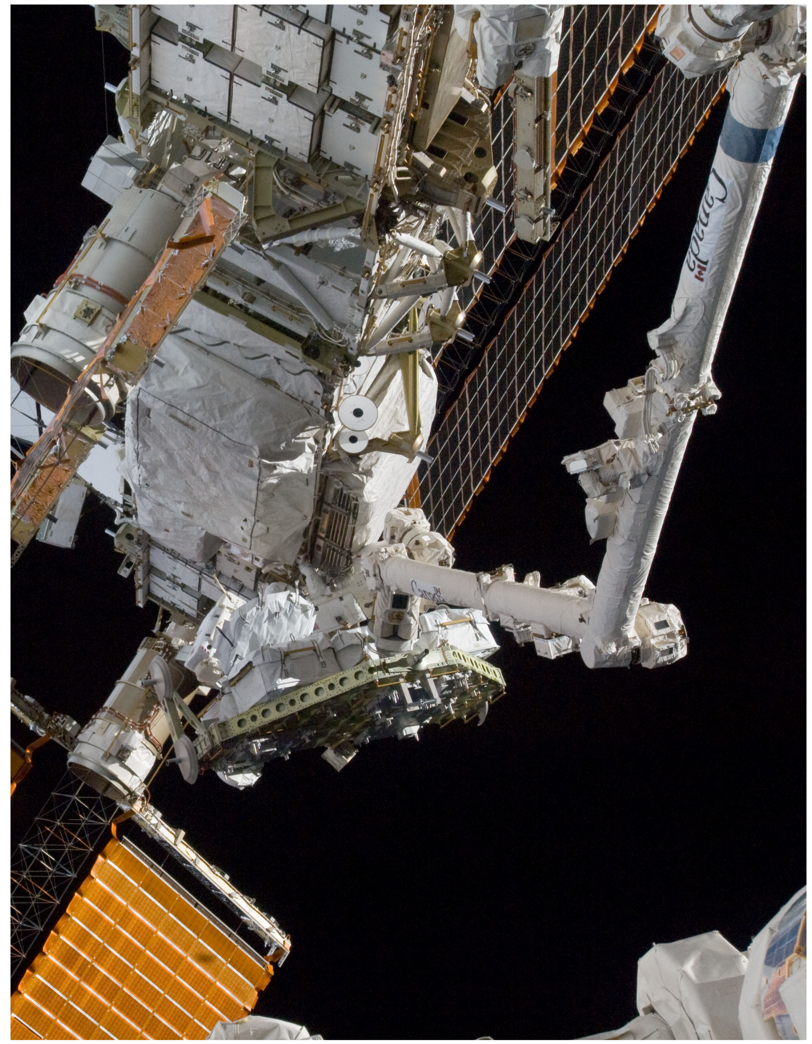




ISS Manipulators

Robotics On-board the International Space Station

- Robotics have played (and continue to play) a major role in the assembly and maintenance of the ISS
- Space-Shuttle and ISS Manipulators have been used to
    - Maneuver and attached space modules (pressurized and unpressurized)
    - Capture free-flying supply vehicles and dock them to the ISS
    - Perform maintenance and replace failed components with spare parts
    - Perform video inspections of ISS and visiting vehicle structures
    - Serve as mobile work platforms for spacewalking astronauts



Robotics On-board the International Space Station

Robotics On-board the International Space Station

- Developers of next generation systems can benefit from the experience gained in over 10 years of robotics operations on-board the ISS
  - New systems planned for the ISS
  - Assembly and maintenance of Lunar or Martian outposts
  - On-orbit servicing of satellites, including telescopes
- The ISS has helped identify additional challenges for space robotics operations that were not previously understood
  - These go beyond the technical and engineering challenges associated with zero-gravity and harsh thermal and EMI environments

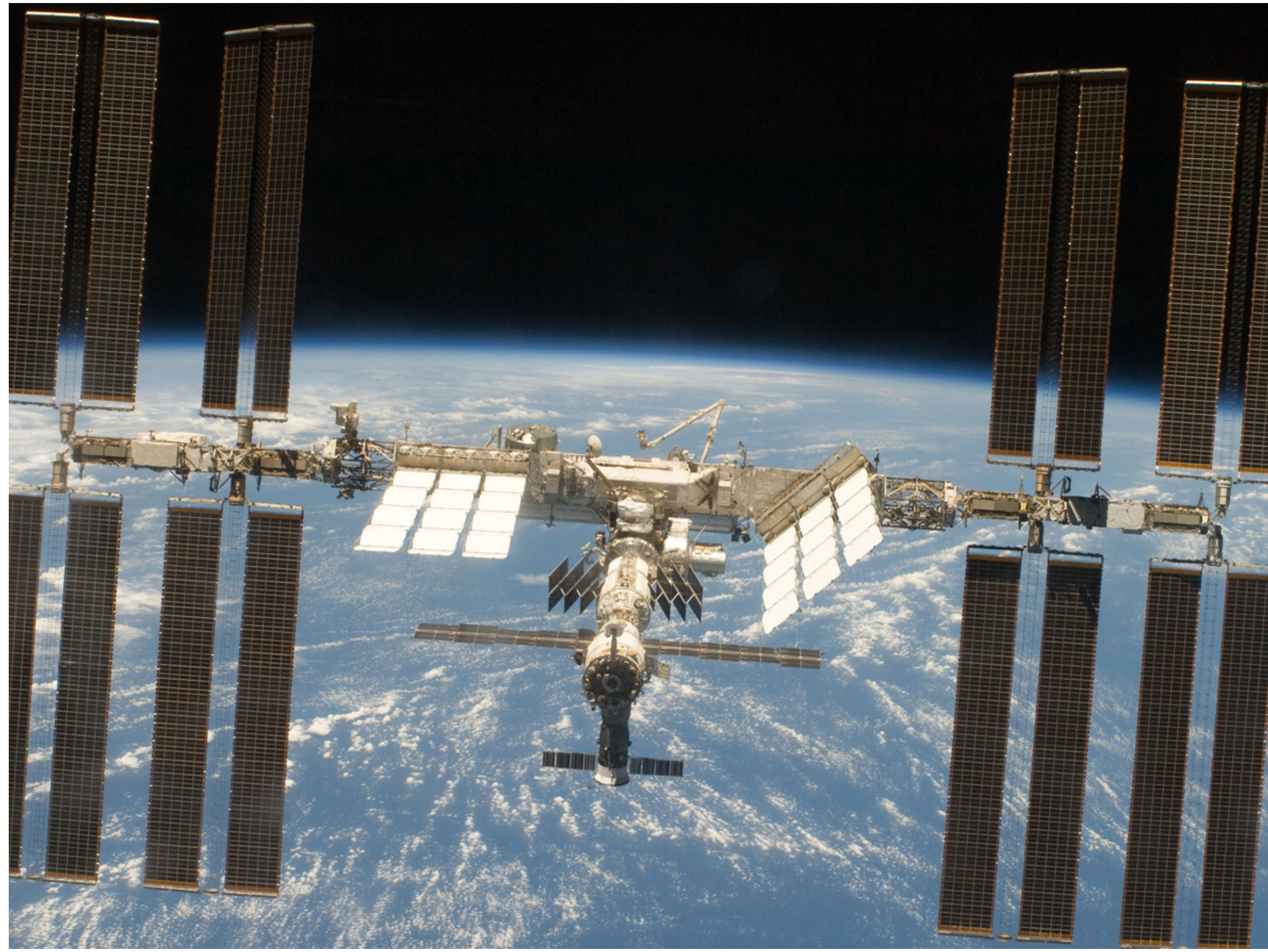
Th Big Picture

- The focus during design and development is on solving the technical challenges
  - Overall system is divided into manageable pieces
  - Top level safety requirements used to derive system and sub-system level failure handling and safing mechanisms
  - Interfaces between subsystems specify how they should interact (timing, communications, force limits...etc.)
- Integrated testing and verification is limited to interfaces
- The integrated end-to-end operational scenario is only considered during mission planning
  - By that time the system has been designed, built, and may have also been launched

Changing Operational Environment

- The operational environment for ISS robots has been different from the ones imagined during the design phases
- New operational requirements have arisen often necessitating changes (sometimes significant) to on-board software and concepts of operations
- Major contributing factors to changing operational environment
  - Growth over time: The physical environments where the manipulators are required to operate has changed over time
  - Increased complexity: Robotics operations are affected by the constraints imposed by/on other systems (operational or due to failures)
    - Sharing resources (such as power, telemetry, and crew time)

The Growth of the ISS



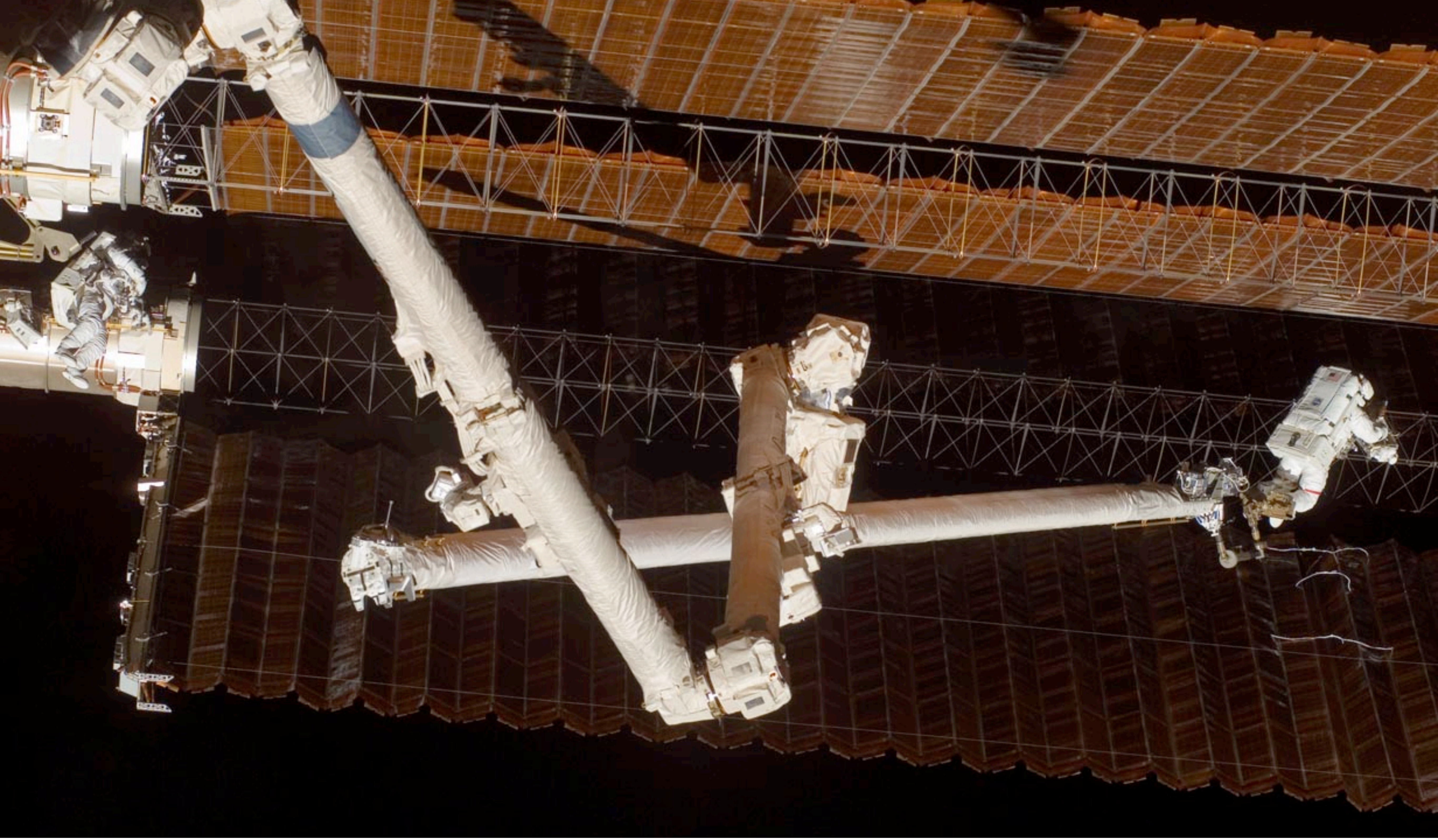
- ISS robots are responsible for changing their own operating environment with each assembly mission
  - New systems bring with them new constraints and new operational demands

Examples - Resource Limitations

- The increased size and complexity of ISS has two major impacts on robotics operations
    - Limited availability of crew time to perform robotics operations
    - Increased demand for robotics operations
- The result was the development of ground based tele-robotics for ISS manipulators
    - A significant shift in the concept of operations requiring new ground tools and operator training programs to be developed
    - On-board software modifications requiring extensive testing and verification

Examples - Resource Limitations

- Limited bandwidth for telemetry downlink must be shared between more systems
- There is limited insight into keep-alive data when the robots are not being operated
  - Not considered during the design of the robotics systems
- Complex on-board autonomous failure detection and recovery in keep-alive mode had to be developed
  - Increased costs
  - Unintended consequences of increased software complexity



P6 Solar Array Repair

Unforeseen new operational requirements driven by failures on other ISS systems

What Can Be Done to Prepare

- Understanding the end-to-end robotic operational scenario is a very important step in the design of the robotic systems
  - Especially important as the complexity of the space vehicle, where the manipulator is based, is expected to change over time
- This requires evaluating the interaction between the robotic systems and other systems on the vehicle
  - Direct interaction such as video system, and payload handling and attachment mechanisms
  - Indirect interaction with other vehicle systems which share the power, telemetry, and operator resources
  - The constraints derived from these interactions will result in design choices that can increase the effectiveness and robustness of the system

Operational Flexibility

- Analysis of the end-to-end scenarios will not eliminate unforeseen changes in operational requirements such as those resulting from changing programmatic requirements, or failures in on-board systems
- Being prepared for the unexpected requires flexibility
  - This means software flexibility in addition to hardware design flexibility
  - Considerations should be given to the following where possible
    - Capability to execute user-built scripts to modify software behaviour without the need for software patches or redesign
    - Context driven telemetry generation
    - Ground based tele-robotics if possible

Handling Failures Within the Manipulator Systems

- Additional Complexity in space systems often results from strict safety requirements
    - Needed to protect the astronauts and the space vehicle
- ISS systems are required to be two fault tolerant against failures causing uncommanded motion or uncommanded payload release
- These requirements result in distributed architectures, multiple failure detection and safing mechanisms running on different control units
- Operational impact
    - Increased exposure to timing issues as the different monitoring systems get out of sync
    - Increased complexity of nominal and failure recovery operations

Ops Workarounds

- Out-of-sync conditions can occur even under “nominal” system behaviour
  - For example as a result of timing variations as the mechanical systems of the manipulator interact with the ISS
- During nominal operations, special commanding sequences are needed to avoid known software and timing issues
  - This results in increased operator workload and exposure to operator error as procedures become more cumbersome and complicated
- During actual failure recovery, additional time is needed to reconfigure all the different sub-systems to resume operations
  - This is especially problematic during time-critical operations such EVAs

Examples - Switching to Backup String

- Canadarm2 is fully electrically redundant to allow critical operations to resume after a failure
    - Each "string" is powered from a different power channel and contains a complete set of computer units and electromechanical drive elements
    - The design intent is for the operator to power-off the string with the failed component, power-up the back-up string, and resume operations
- The operational reality is very different
    - Complex commanding sequences are needed to bring the software in line with the physical configuration of the system before operations can resume
    - Recovery from failure occurring during end-effector operations with the payload in an intermediate capture/release state

Examples - Smart Safing

- Modifications to the Canadarm2 safing architecture were made in preparations for free-flyer capture operations
- “Smart Safing” takes into account the operations taking place at the time of failure to determine the correct safing action
- Major modification to the on-orbit software

What Can Be Done to Avoid These Scenarios

- Failure recovery can be included in the system requirements and software testing/verification campaigns
  - Requirements need to be specific with respect to the maintaining synchronization with the physical state of the system in the event failures
  - Software testing needs to go beyond verifying safing functionality to verifying recovery actions
- The ability to fine-tune health monitoring and safing mechanisms without the need to modify the on-orbit software can be part of the design
  - Having timing and sensor check tolerances as operator settable parameters
  - Having the ability to enable/disable health monitoring checks to simplify operations

Accounting for Integrated Contingency Scenarios

- The complexity of the interaction between the manipulators and other systems on the vehicle increases following unexpected anomalies or failures
- Additional constraints are applied following a failure to protect the astronauts and ISS systems
- Integrated contingency scenarios are identified during operations planning and resulting constraints are applied to the nominal mission plan
  - This is a costly and inefficient process and is repeated for every operation
  - The resulting operational envelope is often very tight and the capabilities of the robots and other systems are not utilized

Examples - Force Fighting

- Most of the ISS attachment mechanisms for external modules are operated independently from the manipulator systems
- A typical attachment scenario using Canadarm2
  - The manipulator position the module/payload with the capture envelope of the mechanism, then
  - The mechanism is actuated to capture payload and secure it to the ISS while the manipulator is in a passive/active compliant mode
  - There is no exchange of information between the systems, and no automated supervisory monitoring of the operation
- Force-fighting occurs if the Canadarm2 brakes were to be applied (as a result of a safing action) while the attachment mechanism continues to operate

Examples - Force Fighting

- To prevent this situation from taking place (within the limitations of the on-orbit systems)
  - Detailed and expensive analysis is performed for each operation to determine the capture envelope of mechanism for the operation
    - Lower misalignments leads to lower interface loads
    - This results in much tighter limits than the design capture envelope
  - Software patches were applied in some cases to provide supervisory control
  - In other cases, tedious and time consuming operational techniques were implements to operate the mechanisms
    - Goal is slow down the load buildup to allow the operator to stop the mechanism

Examples - Part Replacement using Dextre

- Dextre was designed to perform failed part replacement on robotically compatible ISS equipment
- Dextre's systems are not fully redundant
    - Dextre is a maintenance robot that handles failed and spare parts and therefore not considered a critical system
- Problem is that in order to execute an R&R operation on failed power or thermal control system, these systems have to be reconfigured and powered down
    - This places the ISS in a critical configuration which required redundancy to ensure that critical ISS functions continued to operate after a failure
- This places considerable constraints on Dextre operations which require extensive analysis and development

What Can Be Done to Avoid These Scenarios

- Integrated contingency scenarios can be analyzed at an early stage during the requirements development and preliminary design
    - Understanding how robotics systems failures affect other vehicle systems will drive design requirements
    - Understanding the reverse interaction is also important
- Ensuring consistency between the failure management concepts among the different systems will increase the effectiveness of those systems

Summary

- Development of future space manipulators can benefit from the experience gained on-board the ISS
- Incorporating analysis of integrated nominal and off-nominal operational scenarios during the design phase can reduce costs and increase robustness
- Developers can be better prepared for changes in operational environment by providing flexibility in their systems
    - This is especially important for robotic systems that will interact with complex space vehicles