Capability 9.4
Servicing

Presenter:

Rud Moe

- **Inspection and detection of faults, maintenance, repair, resupply, and upgrade of accommodating in-space and extraterrestrial systems.**

  – Maintenance: refurbishment of wear-out items, resupply of consumables, adjustment and realignment, cleaning or recoating of surfaces, exchange of degraded fluids, lubricants, filters, materials

  – Repair: replacement of or substitution for worn, damaged, or failed items at several levels of hierarchical modularity, reconstruction of structures or surfaces with fresh material

  – Upgrade: replacement or supplement of obsolete items with version having higher-performance or increased functionality

- **All servicing operations include reverification of system integrity and functionality**

- **Extended mission life and systems reusability for increased sustainability**
  - Versatile ability for life extension allows efficient use of high-capitalizations systems
  - Extended reuse of heritage systems for new purposes or objectives
- **Increased performance through upgrade improves affordability**
  - Decoupling of systems to accommodate differential rates of technology advancement and obsolescence
  - New capability establishment
  - Exploitation through extended reuse of high-capitalization systems to support unique performance items
- **Mission rescue**
  - Reduction of consequences of failures or unexpected events and situations results in preservation of capital value and continuation of operations
  - Intervention using available items, tools, and materials for temporary (possibly degraded) operation
  - Revisit with design-to-case permanent replacement or supplementary components

Drivers & Assumptions for Servicing

- **Logistics for provisioning of spares and upgrades**
  - Manufacture, inventory, launch, in-space and extra-terrestrial transport and storage of components, modules, spares, materials, tools, test equipment
- **Accommodation of systems to servicing agent abilities**
  - Modularity and separable interfaces, local force/torque reaction, self-alignment, self-protection, available power and data ports, built-in test, configuration databases
- **Accessibility of systems to servicing agents**
  - Affordable access Earth-to-space, in-space or extra-terrestrial transport from operations venue to servicing venue, proximity operations and capture/handling, gross positioning systems
- **Supporting systems for servicing operations**
  - Handling and temporary stowage, inventory controls, environmental protection, clean workspace, information and communication systems, general-purpose tools and test equipment, in-situ fabrication and feedstock
- **Servicing agent availability**
  - Robotics and/or human presence in-space and extra-terrestrial sites with supporting logistics and utilities, medicine and life support, transport, information and communication systems
- **Servicing agent abilities**
  - Mobility, sensing, handling and dexterous manipulation, positioning, aligning, connecting, disconnecting, advanced controls, on-board databases, autonomy, team coordination
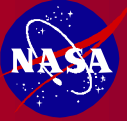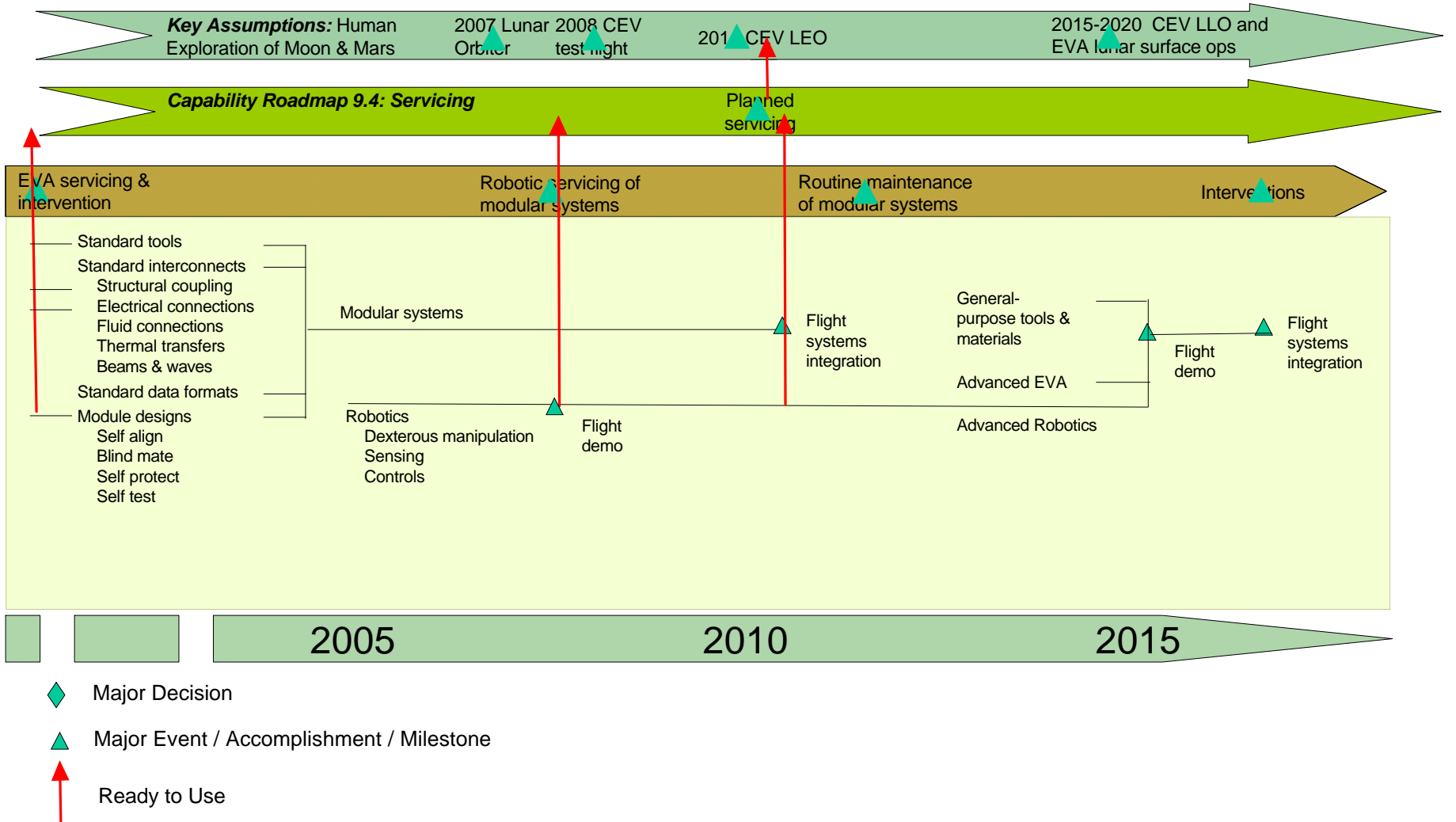
Capability Breakdown Structure
9.4 Servicing

9.4.1   **Inspect & survey (monitoring)**

9.4.2   **Detect & isolate faults (diagnostics)**

9.4.3   **Perform planned maintenance**

  9.4.3.1   Replace modular component

  9.4.3.2   Replenish supplies

9.4.4   **Perform unplanned repair**

  9.4.4.1   Assess repair options and available materials

  9.4.4.2   Repair/replace component

9.4.5   **Install upgrades**

9.4.6   **Planning, logistics, training, etc.**

Key Assumptions: Human Exploration of Moon & Mars
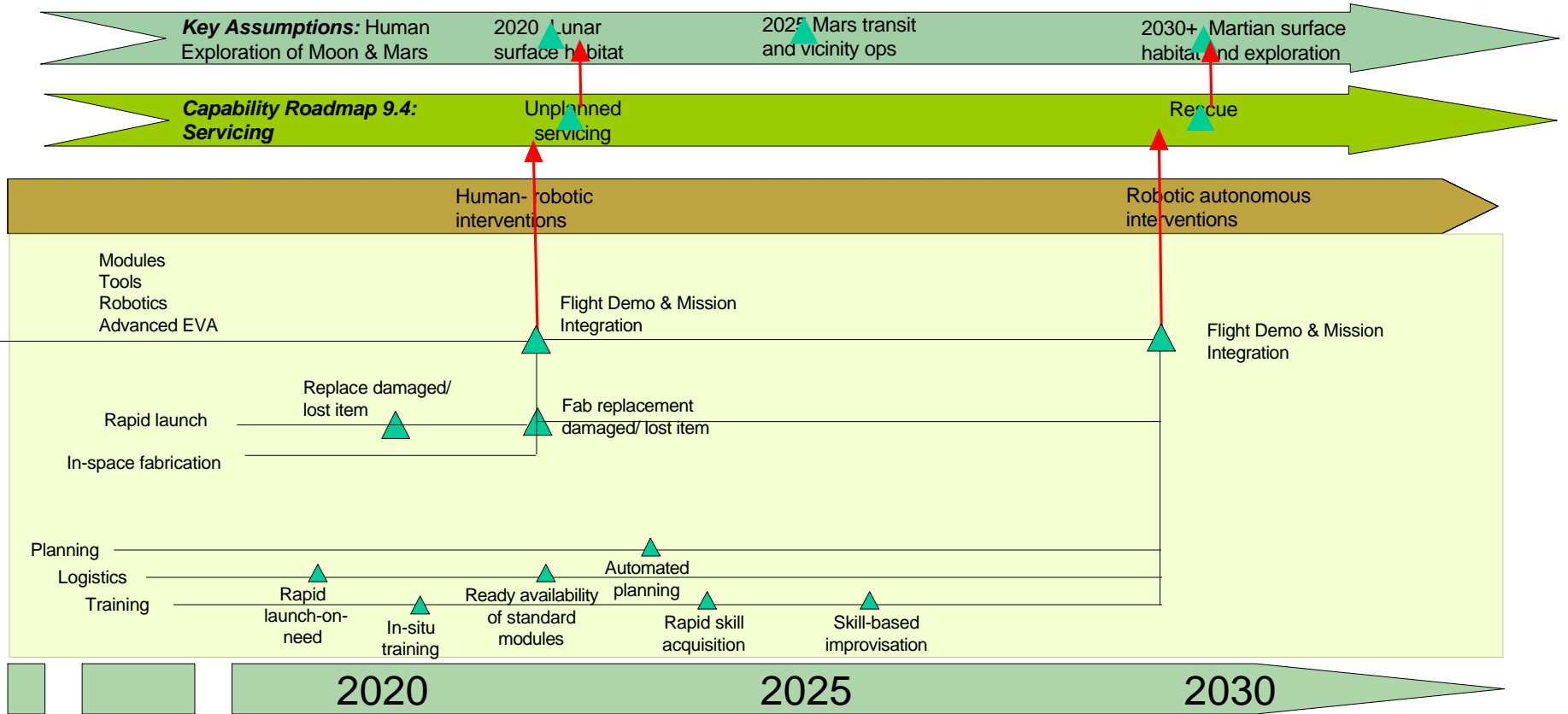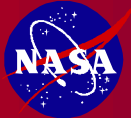
2007 Lunar Orbiter

2008 CEV test flight

2010 CEV LEO

2015-2020 CEV LLO and EVA lunar surface ops

Capability Roadmap 9.4: Servicing

Planned servicing

EVA servicing & intervention

Robotic servicing of modular systems

Routine maintenance of modular systems

Interventions

Standard tools
Standard interconnects
  Structural coupling
  Electrical connections
  Fluid connections
  Thermal transfers
  Beams & waves
Standard data formats
Module designs
  Self align
  Blind mate
  Self protect
  Self test

Modular systems

Robotics
  Dexterous manipulation
  Sensing
  Controls

Flight demo

Flight systems integration

General-purpose tools & materials

Advanced EVA

Advanced Robotics

Flight demo

Flight systems integration

2005

2010

2015

◆ Major Decision

▲ Major Event / Accomplishment / Milestone

↑ Ready to Use

Roadmap for Servicing

Advanced Planning & Integration Office

Key Assumptions: Human Exploration of Moon & Mars

2020 Lunar surface habitat

2025 Mars transit and vicinity ops

2030+ Martian surface habitat and exploration

Capability Roadmap 9.4: Servicing

Unplanned servicing

Rescue

Human- robotic interventions

Robotic autonomous interventions

Modules
Tools
Robotics
Advanced EVA

Flight Demo & Mission Integration

Flight Demo & Mission Integration

Replace damaged/ lost item

Fab replacement damaged/ lost item

Rapid launch

In-space fabrication

Planning
Logistics
Training

Rapid launch-on-need

In-situ training

Ready availability of standard modules

Automated planning

Rapid skill acquisition

Skill-based improvisation

2020

2025

2030

◆ Major Decision

▲ Major Event / Accomplishment / Milestone

↑ Ready to Use

- TBD

Appendix with SOA details by WBS

w.chun_Feb_22_2005

- **Description:**
  - Tools and operations for inspecting systems, components, structures, etc. to determine status, operating condition, physical characteristics
  - Passive inspection techniques, active sensing approaches, combination
  - High degree of autonomy needed
- **Benefits**
  - Allow determination of system configuration or status with human intervention providing interpretation of non-autonomous cases.
  - Effective inspection systems can lower risk of repairs
- **Figures of Merit**
  - Amount of human supervision required, coverage of system, resolution and bandwidth, availability of inspection capability, complexity of inspections system, versatility of inspection system
- **General Assessment**
  - Current SOA is human intensive, reliant in-situ crew. External inspection tools are limited and lack autonomy. Many inspection approaches available, not well integrated with servicing systems.
- **Development Needed: Medium**

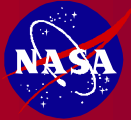| Capabilities	State-of-the-Art	TRL	Needs	Need TRL 6	Capability Date	CRL
9.4.1 Inspection					2015	5
9.4.1.1 Passive sensors: cameras (resolution, positioning, lighting, focus, iris, É), nonvisual sensors (proximity, haptic, acoustic conduction)	Shuttle, ISS, HST Robotic Servicing (HRSDM), AerCam	9	Multispectral sensing Hi Def resolution Coverage & positioning	2012		
9.4.1.2 Active sensors & scanners	LIDAR	6	Interferometry	2012		
9.4.1.3 Built-in	Telemetry	9				

- **Description:**
  - Interpretation of inspection surveys and instrumentation data analysis and projection into the mission performance context
- **Benefits:**
  - Provides systems assessments of extant and impending degradations; provides specifics for servicing mission planning content and timing, design-to-case repair components and operations development
- **Figures of Merit:**
  - Percent coverage of possible failures/degradations
  - Percent of manual vs. automated assessment and planning
  - Time to failure/degradation identification
  - Impact to operations of reconfiguration for test
  - Amount of system resources required (MIPS, bytes, etc.)
- **General Assessment:**
  - Built-in instrumentation trend analysis is best current capability; in-situ assessment of overall configuration is reliant upon human interpretation; no autonomous capability to characterize and project system performance
- **Development Needed: High**
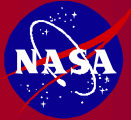
State-of-the-Art /Maturity Level /Capabilities for 9.4.2 Diagnostics

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
Built-in test equipment	Boeing aircraft	9	Broader		2010	7
Integrated computational diagnostics and prognostics	Livingstone (L2)	4	Continued development; testing/demo under operational conditions	2008	2010	5
Diagnostic test planning and execution during operations	Livingstone (L2)	4	Continued development; testing/demo under operational conditions	2008	2010	5
Maintenance/repair planning and execution monitoring	Livingstone (L2)	4	Continued development; testing/demo under operational conditions	2008	2010	5

- **Description:**
  - Installs replacement modular components or consumable materials having standardized interfaces and procedure accommodations
- **Benefits:**
  - Versatile ability for life extension and efficient use of high-capitalizations systems
  - Extended life and reuse of heritage systems for new purposes or objectives
  - Reduced impact on mission times, costs, and risks relative to unplanned servicing
- **Figures of Merit:**
  - Compliance of modular systems with standard or generic interface connectors and formats
  - Number of disassembly steps needed for access
  - Robustness of modules designs for self-protection in space environment
  - Completeness of modules self-test functions
  - Type and complexity of agents required;
  - Type and complexity of infrastructure required
- **General Assessment:**
  - Depends strongly on modular systems design, human and robotic capabilities, logistics, and supporting systems; limited in size and mass of modular systems and sub-systems that have been replaced
- **Development Needed: Medium**

Advanced Planning & Integration Office

| Capabilities	State-of-the-Art	TRL	Needs	Need TRL 6	Capability Date	CRL
4.3 Perform planned maintenance					2010	5
4.3.1 Replace modular component						
EVA s upported	ISS, HST	9				
Robotic	HRSDM	5	Robotic	2008		
		5	Task Autonomy			
4.3.2 Replenish supplies	Flight demo hardware	7	Mission integration	2010		

- **Description:**
  - Address mission unplanned events and situations during operations using available components, materials, tools, procedures, skills, and creativity; preserve valuable assets for continued operation
- **Benefits: Mission rescue**
  - Reduce consequences of failures or unexpected events and situations for preservation of capital value and continuation of operations
  - Intervention using available items, tools, and materials for temporary (possibly degraded) operation
  - Revisit with design-to-case replacement or supplementary components
- **Figures of Merit:**
  - Number of types of intervention possible
- **General Assessment:**
  - Highly advanced capabilities needed for robotic implementation; general-purpose tools and materials provide limited intervention capability even for human agents in-situ; rapid launch capability and in-space fabrication capability have potential for greatly reducing loss-of-mission risk
- **Development Needed: High**

Capabilities	State-of-the-Art	TRL	Needs	Need TRL 6	Capability Date	CRL
Perform unplanned repair					2015	2
Intervention kit, EVA s upported	Shuttle, ISS, HST	9	Robust capability			
Intervention kit, robotic supported	HRSDM	4	Robust capability	2015		
Improvisation skills, human supported	ISS, HST	6	Rescue capability	2020		
Improvisation skills, robotic autonomy	none	0	Auto-rescue capability	2030		
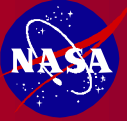
- **Description**
  - Many components and subsystems have technology advancement rates significantly shorter than the systems they are incorporated into and as a result become obsolete long before the system's intended duration of useful life is over.
  - As technology improves, replace or augment original hardware and software with higher performance, increased functionality, or new capbility.
  - Examples: HST servicing, nuclear reactor robotics, spacecraft software uploads
  - Upgrade potential is dependent on degree of interface standardization.
- **Benefits**
  - Enable adaptation to new circumstances and evolve faster than the systems-of-systems rate
  - Increase Functional Capability/Performance
  - Increase Reliability (MTBF) and Safety
  - Increase Maintainability/Supportability
  - Allow space systems to be entered into service more quickly (initial capability) and upgrade capability at a later time

- **Figures of Merit**
  - Time to Upgrade
  - Supporting Infrastructure Required
  - Cost of Use of Human and/or Robotic Agents

- **General Assessment**
  - SOA is advanced for upgrade by humans in space environment, but unproven for robotics in space environment. Need to significantly increase robotic capability.

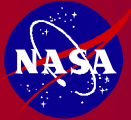- **Development Needed: Medium**

HST Servicing Mission

Nuclear Power Plant Telerobot

Robonaut Space Telerobot

State-of-the-Art /Maturity Level /Capabilities for 9.4.5 Install Upgrade

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
EVA upgrade of science instruments and components	HST servicing missions; ISS	9	Beyond LEO; control of harsh environmental	2012	2015	5
IVA upgrade of components	ISS	9	Cleanliness	2012	2015	5
Upgrade of spacecraft software	Upload to various spacecraft	9	Increased reliability	2008	2010	5
Autonomous upgrade of components	DARPA Orbital Express Advanced Technology Demo	5	Continued development. Launch of demo scheduled for 2006.	2015	2020	2
Teleoperated upgrade of components	HST robotic servicing mission; operational nuclear reactors; Robonaut	4-5	Continued development; testing/demo under operational conditions	2015	2020	2

- **Description:**
  - These are broad capabilities that span the entire sequence. Planning is defined as the ordering of steps required to complete a task or maneuver. Logistics is all of the support and movement planning of assemblies, parts, tools, equipment, and supplies necessary to meet the objectives of the servicing task. Training is the teaching and practicing of a skill or maneuver to be able to perform as expected.

- **Benefits:**
  - Planning, logistics, and training are integral to each other, and necessary to complete all servicing operations. Pre-planning and contingencies will increase the probability of success of the servicing operations. Logistics determines the whereabouts and timing of all the tools, consumables, and parts required. Training is necessary to insure that the task of servicing will occur as planned by man or robot.
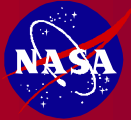
- **Figures of Merit:**
  - Number of steps in the plan, Completeness of plan, including acceptable contingencies, Timeline for logistics, Transport Manifest, Skills Training Plan and competency test, Number of skills in training, Realistic Simulation based on update rate, fractal & polygon count, field-of-view

- **General Assessment:**
  - Planning, Logistics, and Training are commonplace today in NASA type missions, typically in a manual mode with some automated tools. Fully automated planning tools exist, but with less maturity at the mission level. Logistic tools are mature and verifiable through comprehensive checklists. Training exist, but could benefit from better tools and technologies to insure a higher level of preparedness.

- **Development Need: Low,** with room for technological improvements as available except for human-robot training

w.chun_Feb_22_2005

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
1. Planning						
Mission Planning	Apollo, Soyuz, Shuttle	6	Auto	-	2010	
Strategic Planning	Shuttle	7	Auto	-	2010	
Vehicle Planning	Shuttle	8	Integ.	-	2010	6
Trajectory Planning	Shuttle, Soyuz	9	Auto	-	2010	
Collision Avoidance	Manual Visualization	3	Dev.	2006	2008	
Dynamic Replanning	XSS-11	4	Real-Time	2006	2008	
2. Scheduling						
Automated	Shuttle	6	Real-Time	2010	2012	7
3. Logistics						
Logistics Planning	Shuttle PIC	9	Auto	-	2010	
Resource Allocation	New Millennium	6	Auto	2008	2010	6
Automated Tracking	Shuttle GSE	8	Common	-	2010	
Inventory Control	NASA Pre-Flight	8	Implement	-	2010	
4. Training						
Competency Program	Astronaut Program	9	Update	2008	2012	
Skill-based	Astronaut Program	9	w/ robot	2008	2012	
Knowledge-Based	Astronaut Program	4	experts	2006	2008	6
Simulation	Shuttle Training	6	hi-res	2006	2008	
Immersion	Laboratory	4	mature	2008	2012	
Testing & Checkout	Conventional	9	Auto	-	2012	

Sub-Capabilities	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
1. Planning Auto Mission Planning	Apollo, Soyuz, Shuttle	5	Auto	2008	2008	
Auto Strategic Planning	Shuttle	7	-	-	2008	
Auto Vehicle Planning	Shuttle	8	-.	-	2008	6
Smooth Trajectory Planning	Shuttle, Soyuz	9	-	-	2008	
Auto Collision Avoidance	Manual Visualization	3	Dev.	2006	2008	
Auto Dynamic Replanning	XSS-11	4	Real-Time	2006	2008	
2. Scheduling Ground	Shuttle	8	-	-	2008	7
On-board	Shuttle	6	Real-Time	2008	2010	
3. Logistics Real-time Log. Planning	Shuttle PIC	5	Auto	2008	2010	
Off board Log. Plan	Shuttle	9	-	-	2008	
Resource Allocation	New Millennium	6	Auto	2008	2010	
Real-time Tracking	Shuttle GSE	8	Common	-	2008	6
Auto Inventory Mgt	NASA Pre-Flight	8	Implement	-	2008	
Real-Time Traffic Model	Shuttle	8	Auto	-	2008	
Spares Planning	ISS	9	-	-	2008	

Sub-Capabilities	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
4. Training						
General Comprehension	Astronaut Program	9	Update	-	2008	
Situation-based	Military	6	infusion	-	2010	
Skill-based	Astronaut Program	9	w/ robot	-	2012	
Knowledge-Based	Astronaut Program	4	experts	2008	2010	6
Computer Sim.	Shuttle Training	6	hi-res	2008	2010	
Hardware-In-Loop Sim	Ground	4	custom	2008	2010	
Immersion Room	Laboratory	4	facility	2010	2012	
Immersion Desk	Laboratory	4	models	2010	2012	
Testing & Checkout	Conventional	9	Auto	-	2008	

Technologies	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
1. Planning Auto Mission Software Auto Strategic Software Auto Vehicle Software Trajectory Algorithm Col. Avoid Sensor Col. Avoid Behavior Auto Replanning	COTS-Grease 4D-RCS, Mapgen Remote Agent A*, D* Manual Visualization Potential Field, Occupancy-Grid State Machine Re-Planning	6 7 8 9 3 4 4	Auto Auto Integ. Auto Dev. Mature Real-Time	2010 2010 2008 - 2006 2006 2006	2012 2012 2010 2008 2008 2008 2008	6
2. Scheduling Ground On-board	COTS Remote Agent	9 6	- Optimization	- 2008	2005 2010	7
3. Logistics Real-time Log. Planning Off board Log. Plan Resource Allocation Real-time Tracking Auto Inventory Mgt Real-Time Traffic Model Spares Planning	Shuttle PIC COTS New Millennium Shuttle GSE NASA Pre-Flight COTS NASA Std	9 9 6 8 8 9 9	Auto - Auto Common Implement Contingency Contingency	- - 2008 - - - -	2010 2005 2010 2010 2010 2005 2005	6