Capability 9.3
Assembly and Deployment

Presenter:

John Dorsey

Assembly and Deployment Description

- Large space systems are required for a range of operational, commercial and scientific missions objectives—however, current launch vehicle capacities substantially limit the size of space systems (on-orbit or planetary)
- **Assembly & Deployment** is the process of constructing a spacecraft or system from modules which may in turn have been constructed from sub-modules in a hierarchical fashion.
- In-situ assembly of space exploration vehicles and systems will require a broad range of operational capabilities, including:
  - Component transfer and storage, fluid handling, construction and assembly, test and verification
- Efficient execution of these functions will require supporting infrastructure, that can:
  - Receive, store and protect (materials, components, etc.); hold and secure; position, align and control; deploy; connect/disconnect; construct; join; assemble/disassemble; dock/undock; and mate/de-mate.

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An Example Scenario for Assembly & Deployment

First launch: a crew habitat

Second launch: **Staging** and **Storage** of a payload container, after it rendezvous with & *docks* to the habitat; it contains truss segments, a power system, a *robot* assistant & a *crane*

Preparation For Assembly is completed & the truss is **Constructed** out from the habitat using the robot assistant; the crane is installed, including a mobile base that allows **Local Transport** along the truss, & then used for **Positioning and Alignment** of the power system, enabling it to be **Joined** to the truss

The third launch, with additional truss segments, is **berthed** to the truss using the crane & the truss is extended to provide space for additional storage & the spacecraft under construction

Subsequent launches bring storage containers with parts/modules/etc for the spacecraft that is under construction & are **berthed** to the truss

When assembly of the spacecraft is complete, **Verification** is performed, the spacecraft is undocked & transported to its operating location leaving the facility, including it's agents and infrastructure, available to assemble the next spacecraft.

Benefits of Assembly and Deployment

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- The ability to construct, assemble, deploy components to create a larger device/instrument/structure will enable much more complex missions
  - Allows the construction of large spacecraft without requiring a single launch vehicle that is large enough for the complete system.
  - Allows the construction of spacecraft so large that deployment after launch is not practical.
- In-situ assembly and deployment will allow more ambitious science activities
- Enables affordability through modularity & standardization of spacecraft components, interfaces, agent operations & capabilities & infrastructure.
- Systems designed for in-situ assembly and deployment using a modular system approach are likely to be more easily maintained and serviced
- A versatile Assembly & Deployment infrastructure can be applied to many missions & spacecraft, increasing affordability of Exploration.
- Reduced spacecraft mass - designed for space, not launch environments.

Drivers & Assumptions for Assembly and Deployment

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Payload size and mass will not significantly change over the next 20 – 25 years. In other words, we won't have a 100 metric ton lift vehicle with significantly larger shroud size than today's launch options.

This will lead to the need to assemble larger, more complex systems in-situ

- Spacecraft designed for efficient, in-space construction & servicing. Assume design for modularity, assembly and maintenance will be used and standards developed for broad application and commonality
- Long life systems; years to 10's of years
- Location of assembly facility may vary depending on the choice of missions, but would be at a location from which the spacecraft can "easily move" to its "operating location"
  - For a Mars exploration spacecraft, assembly would be done either in LEO or at the Earth-Moon L1 point
  - For a large telescope, assembly would be done at the Earth-Moon L1 point
  - For surface assembly, it would be local to human exploration activities, a central site where human sorties originate

Capability Breakdown Structure
9.3 Assembly and Deployment

Advanced Planning & Integration Office

9.3.1 Staging (capture, docking & berthing)

9.3.2 Storage (environmental protection, just-in-time component availability)

9.3.3 Preparation for Assembly (unpack, inventory, prepare worksite & worksystem)

9.3.4 Construction (erect, inflate, fabricate)

9.3.5 Local Transport (ref. 9.2.0)

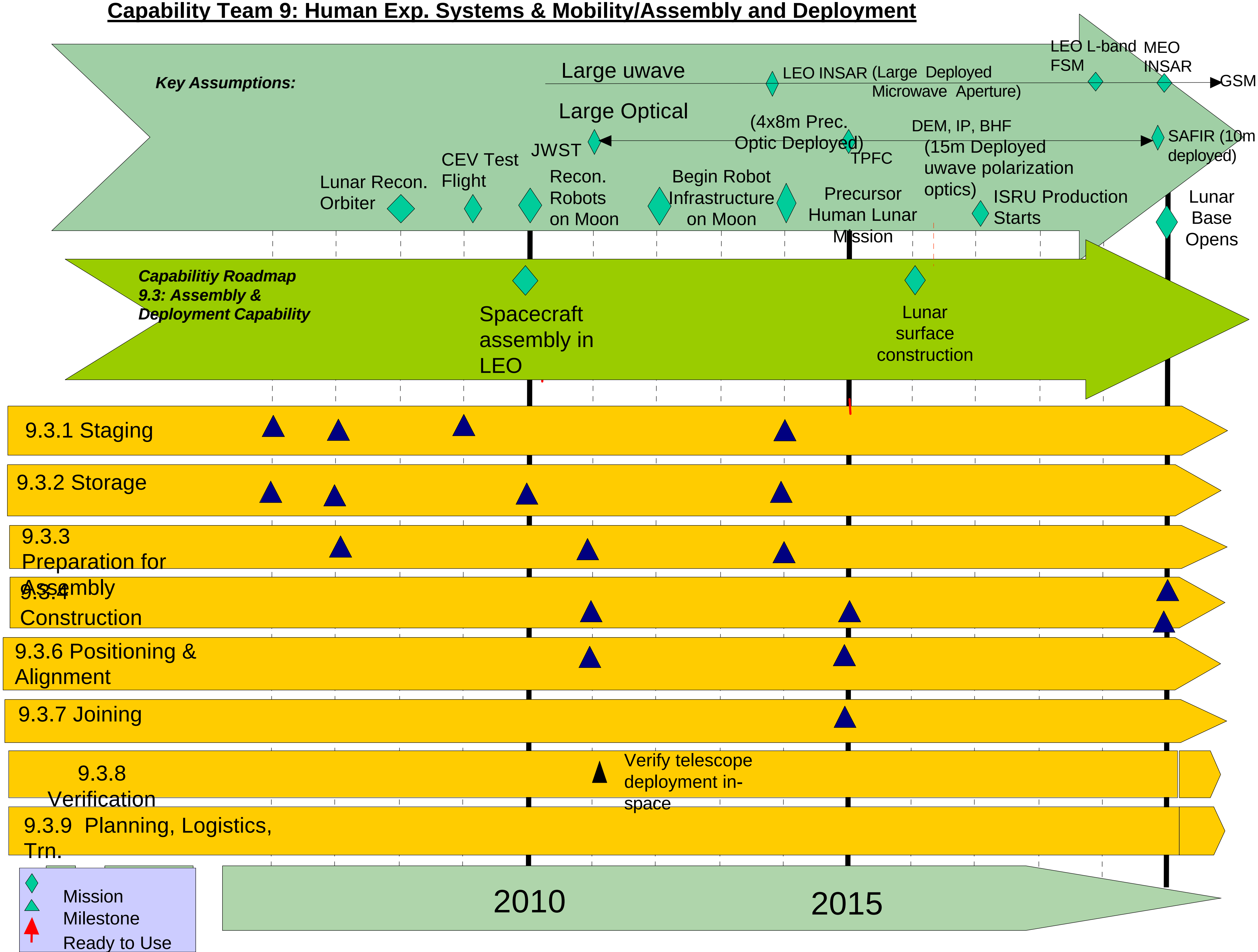
9.3.6 Positioning and Alignment (final assembly)

9.3.7 Joining

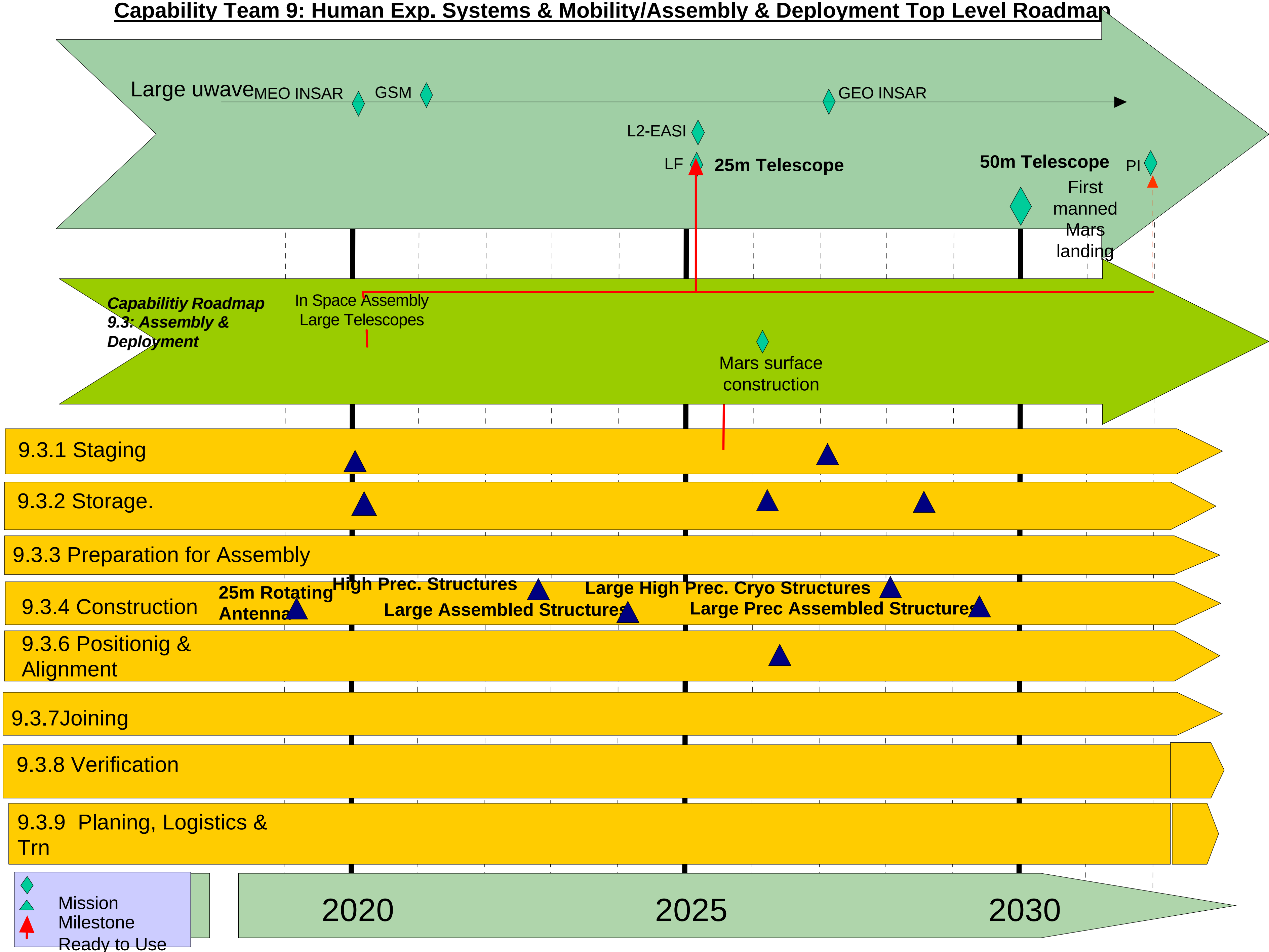
9.3.8 Verification (inspect, test, as-built documentation)

9.3.9 Planning, Logistics, Training, etc. (common across all the above)

Capability Team 9: Human Exp. Systems & Mobility/Assembly and Deployment



Capability Team 9: Human Exp. Systems & Mobility/Assembly & Deployment Top Level Roadmap



9.3 Assembly and Deployment Critical Gaps

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- System level verification of large spacecraft assembled / deployed in-space
- Skill training for human / robot teams who will assemble / deploy large spacecraft in-space
- In-space assembly / deployment that supports the precision required of large telescopes
- Architectures & components that provide standard interfaces & modularity
- Fluid transfer technology

Appendix with SOA details by WBS

Capability 9.3.1
Staging

Contributor:

Wendell Chun

Capability 9.3.1 Staging

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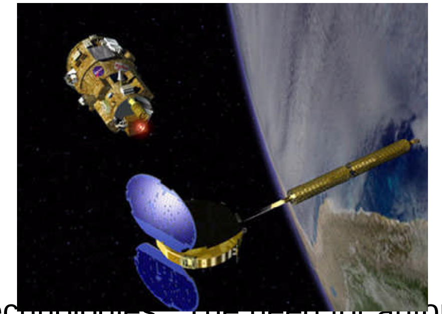
Description: Staging is the first step in assembly, having two or more vehicles working in close proximity to each other\attaching two vehicles together to establish a common coordinate frame. This also includes a payload from a launch vehicle that rendezvous & docks at an assembly facility that represents a permanent in-space infrastructure. In addition to proximity operations, the joining of two platforms includes capture, docking / berthing in 6 DOF for in-space & 3 DOF for surface operations. Staging continues with logistics, unpacking, & inventory planning, leading to storage.

Benefits: By joining two platforms together, a common reference frame is established to enable work to be accomplished, such as manipulation from one vehicle to the other. The remainder of the capabilities are required sequentially to proceed into storage. This capability is necessary for all assembly, servicing, and maintenance operations.

Figure of Merit:

- Zero collisions when multiple vehicles are operating in close proximity
- Pass/Fail criteria for berthing or docking
- Maneuverability & pose sensing to satisfy the capture specifications of the attaching mechanism
- Capability to counteract moments & forces imparted
- Stiffness of attachment interface
- Efficient Logistics Plan (minimum number of steps)
- Minimum lost time in the schedule
- Unpacking efficiency (based on time)
- Number of human inputs into the inventory control system
- Space utilization (in preparation for storage)



General Assessment: Rendezvous and Proximity Operations are mature technologies. The need for automated berthing is driven by communication latencies bandwidth limitations, if the assembly facility is entirely robotic; otherwise, it is an efficiency for the crew who could contnue construction when a new cargo vehicle arrives. This capability requires major development & demonstration. While there is some experience with logistics, unpacking, inventory control, & pre-storage in space, the construction of large telescopes will use many more parts than have been used in Shuttle experiments or ISS construction & servicing.

Development Needed: **High (Soft Docking not demonstrated by NASA) and staging initiates entire capability.**

Capability Breakdown Structure
9.3.1 Staging

Advanced Planning & Integration Office

- 9.3.1 Staging
  - 9.3.1.1 Rendezvous
  - 9.3.1.2 Proximity Operations
  - 9.3.1.3 Capture
  - 9.3.1.4 Berthing
  - 9.3.1.5 Docking
  - 9.3.1.6 Mated Operations
  - 9.3.1.7 Logistics
  - 9.3.1.8 Unpacking
  - 9.3.1.9 Inventory Control
  - 9.3.1.10 Pre-Storage

State-of-the-Art/Maturity Level / Sub - Capabilities for 9.3.1 Staging

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Sub-Capabilities	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
• Rendezvous						7
• Ground Control	Apollo, Soyuz	9	-	-	-	
• Automated	Shuttle	8	-	-	-	
• Proximity Operations						6
• Situation Awareness	Visual Cues	5	Efficient Info Disp.	2007	2012	
• Teaming	Laboratory – ground	4	Rel. Env.	2010	2012	
• Capture						5
• Cooperative	ETS-VII	7	No targets	2007	2010	
• Un-cooperative	Hubble Servicing	3	Pose Est.	2007	2010	
• Tumbling	Hubble Servicing	2	3-Axis	2007	2012	
• Berthing						5
• Formation Control	Station Keep	8	-	2007	2012	
• Grappling	Shuttle RMS	7	-	2007	2012	
• Docking						5
• Hard	Probe & Cone/KURS	9	-	-	2012	
• Soft	ETS-VII latches & towel bars	7	Lidar	2007	2010	
• Mated Operations						6
• Master Active/Slave Passive	Shuttle-active/ISS-passive	8	-	-	-	
• Shared	Not demonstrated	2	Impedance	2010	2012	

State-of-the-Art/Maturity Level / Sub - Capabilities for 9.3.1 Staging

Advanced Planning & Integration Office

Sub-Capabilities	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
• Logistics					5	
• Planning	Apollo, Soyuz, ISS	9	-	-	-	
• Just-in-time	Shuttle	8	-	-	-	
• Unpacking						3
• Pre-assembly Preparation	ISS	5	Robotic	2012	2012	
• Opening	EVA-ISS	6	Robotic .	2012	2012	
• Sorting	EVA-ISS	6	Robotic	2012	2012	
• Inventory Control						6
• Identification	Electronic Tags	4	Rel. Env.	2012	2012	
• Checkout	Electronic Checklist	6	Short. Slev	2010	2010	
• Grouping	Re-Palleting	4	Robotic	2012	2012	
• Pre-storage					4	
• Staging	Mobility to Storage Facility	6	Smaller	2012	2012	

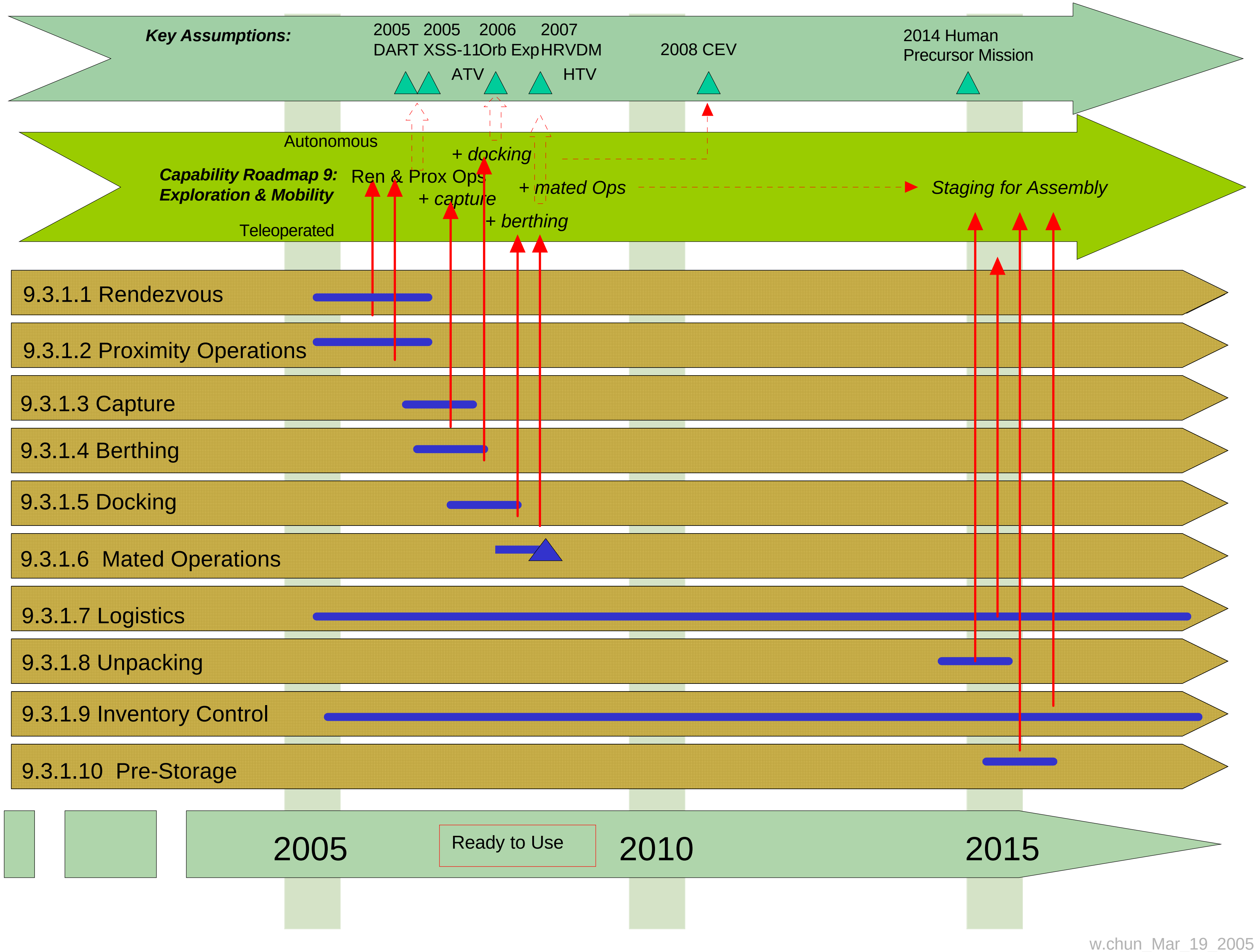
State-of-the-Art/Maturity Level / Technologies for 9.3.1 Staging

Technologies	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
9.3.1.1 Rendezvous						7
• Hills Equations	Apollo, Soyuz, Shuttle	9	-	-	2012	
• Clohsey-Wilshire	Shuttle	9	-	-	2012	
9.3.1.2 Proximity Operations						6
• Collision Avoidance	Range Sensing	5	Real-time 3D Model	2010	2012	
• Circumnavigation	Football Orbits	5	3D	2010	2012	
• Collaborative Planning	Swarm Behaviors	4	Rel. Env.	2010	2012	
9.3.1.3 Capture						5
• RMS Snare EE	Shuttle, SRMS	9	No Grapple	2008	2007	
• Latches	ETS-VII, TPDM	3	Stiffness	2006	2007	
• Magnetic EE	STS-62	2	EMI	2008	2012	
9.3.1.4 Berthing						5
• Auto Manipulation	Factory	7	Closed L	2012	-	
• Auto Tracking	Vision, Sensor Fusion	6	Obscur.	2008	2012	
• Teleoperation	HST, Spartan Retrieval	9	Backup	-	2012	
9.3.1.5 Docking						5
• Sensors	RF, Machine Vision, Lidar	7	Full Range	-	2012	
• Algorithms	RPOP, DART	7	All Axes	2008	2012	
9.3.1.6 Mated Operations						6
• Control Authority	Shuttle-active/ISS-passive	9	-	-	2012	
• Shared Control	Laboratory Demo (JPL)	2	Rel. Environ	2010	2010	

State-of-the-Art/Maturity Level / Technologies for 9.3.1 Staging

Technologies	State-of-the-Art	TRL	Needs	TRL 6 Date	Need Date / Capability	CRL
• Logistics						5
• Planning	Auto. Planning Software	7	-	2010	2012	
• Just-in-time	Scheduling Software	7	-	2010	2012	
• Unpacking						4
• Pre-assembly Preparation	Centralized	5	A Priori	2010	2012	
	Distributed	4	Coordin	2010	2012	
• Opening	EVA	7	Re-usable.	2010	2012	
	Robotic	3	Tools	2010	2012	
• Sorting/Palletizing	Access Experiment	7	-	2010	2012	
	Robotic	3	I/F	2010	2012	
• Waste Disposal	Waste Container (in-space)	7	-	2010	2012	
	In-situ Stacking	4				
• Inventory Control						6
• Electronic Tags	RFID	6	Sp Qual	2008	2010	
• Electronic Checklist	Electronic Checklist	7	Reconfig	2007	2009	
• Grouping	Pick & Place Manipulation	6	Mob Man	2010	2012	
• Pre-storage						
• Mobility to Storage Facility	See Construction & Assembly section for Details					

9.3.1 Staging Top Level Capability Roadmap



Capability 9.3.2
Storage

Contributor:

Kenneth Baker

Capability 9.3.2 Storage

Advanced Planning & Integration Office

Description:

- The process of storing in-space, until preparation for assembly begins, the "parts" needed to build modules/complete spacecraft
  - Storage pre-berthing as launch packages floating nearby or controlled/sustained by upper stage
  - Storage post-berthing is for items unpacked & prepped, awaiting use, in need of keep-alive & protection
- Provide *environmental protection*, including keep-alive utilities, from launch until the parts reach the *assembly point*; say, LEO for a Mars spacecraft or an Earth-Moon libration point for a large telescope..

Benefits

- Removes the size/weight limit that a single launch imposes, enablng larger spacecraft.
- Uncouples assembly & launch, allowing them to proceed at different rates by providing a buffer on-orbit
- Provides environmental protection for parts until preparation for assembly begins.
- Provides access to equipment in the order needed for construction

Figures of Merit

- Probability that equipment will be in *working order* at the start of assembly
- Maximum *number of storage containers* needed on-orbit at one time for assembly
- Maximum *keep-alive power* required at one time.

General Assessment

- Required technology exists, need to integrate it into a standard set of launch package utilities, such as: truss to rendezvous & dock/berth parts containers with, as-shipped parts inventory, crew/robots to unpack, inventory & re-store/assemble as needed, parts marked (barcode?) to enable recording the as-built configuration of the spacecraft, .

Development Needed: Low

9.3.2 Storage

9.3.2.1 **Rendezvous & Docking/Berthing** (see 9.3.1) will be required to attach each launch package to the assembly facility

9.3.2.2 **Utility Joining** (see 9.3.7) will be required to connect utilities, such as power, fluid & communication lines to the launch package after it is attached to the assembly facility

9.3.2.3 **Inventory Control** (see 9.3.9) will be required to keep track of the parts as-shipped in each launch package & to create an al-build record of where each part was used in the assembly process. Bar-coding of parts could facilitate this process.

9.3.2.4 **Assembly Planning** (see 9.3.9) will be required to:

- Determine the overall spacecraft assembly sequence
- Select the parts to be included in each launch package & determine their arrangement so as to provide parts in the order needed for assembly, consistent with protection from the launch environment

Capability 9.3.3
Preparation for Assembly

Contributor:

Jud Hedgecock

Capability 9.3.3 Preparation for Assembly

Advanced Planning & Integration Office

Description:

Preparation for Assembly entails checking that all the *antecedents* for the planned assembly have been completed, such as:

Preparing the *work-site*; if a sub-assembly is to be constructed and added to a previous one as part of a module, is there room for both & is the assembly location convenient to the parts supply.

Preparing the *work-system*; are the agents (*robot & human*) that will do the work on-hand & ready, are their tools in working order and conveniently located for the job

Preparing the *components* to be assembled; have they *arrived*, are they *in good condition* & *conveniently located* with respect to the work-site.

Benefits:

Efficiency, since the work-site has been temporarily optimized for the new subassembly task while still allowing construction of the complete spacecraft.

Figures of Merit:

Number of agent moves required to get the components being assembled & the tools needed

General Assessment:

This task combines a number of the sub-capabilities needed in other areas, such as: inspection of parts & work-site; unpacking & inventorying parts as needed; re-arranging the worksite, for example, moving a completed module to its final location if it was not built there; checking to be sure that all the antecedents of the current assembly task are complete is part of planning.

- **Development Needed**: **Low??**

Capability 9.3.4
Construction

Contributor:

John Dorsey

Capability 9.3.4 Construction

Advanced Planning & Integration Office

Description:

- The process of positioning, holding and joining small to intermediate elements to build a larger spacecraft sub-module or module. Also includes in-space fabrication and manufacturing.
- Will involve many more (smaller, less massive) parts than assembly, & a larger number of repetitive operations.
- For truss structures, examples include: erection, mechanical deployment & inflation deployment.

Benefits

- Increased payload mass & volume efficiency for transportation to orbit; choice of launch vehicles.
- Assembled sub-modules are designed for in-space loads, not launch or 1-g loads.
- Construction capability naturally lends itself to servicing.

Figures of Merit

- For construction agents: reach, stiffness, stability, mass capability, positioning accuracy, contamination.
- Construction operations: time/speed, complexity, versatility, adaptability, autonomy.
- Hardware: modularity, commonality, reconfigurability. standardization.

General Assessment

- EVA is well developed capability, construction robots being developed in ground laboratories. Hardware limited to erectable and mechanical deployable trusses, some operations & infrastructure.

Development Needed: **Medium**

Capability Breakdown Structure
9.3.4 Construction

Advanced Planning & Integration Office

- 9.3.4 Construction
  - 9.3.4.1 Positioning
    - 9.3.4.1.1 Humans - EVA
    - 9.3.4.1.2 Humans - IVA
    - 9.3.4.1.3 Robotic Manipulators
    - 9.3.4.1.4 Turntables
  - 9.3.4.2 Holding and Aligning
    - 9.3.4.2.1 Holding Fixture
    - 9.3.4.2.2 Alignment Jig
    - 9.3.4.2.3 Robotic end Effectors
    - 9.3.4.2.4 Tools (clamps, etc.)
  - 9.3.4.3 Modular Hardware
    - 9.3.4.3.1 Erectable Trusses
    - 9.3.4.3.2 Mechanical Deploy. Trusses
    - 9.3.4.3.3 Inflation Deploy. Trusses
    - 9.3.4.3.4 Pressure vessels
    - 9.3.4.3.5 Other Functional Elements
  - 9.3.4.4 Scenarios, Sequencing

Maturity Level – Technologies for Capability 9.3.4 Construction

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.4.1 Positioning						3
9.3.4.1.1 Humans - EVA	HST Repair/Service ISS Construction Ops.	9 9	Reduced contamination levels	2010	2013	
9.3.4.1.2 Humans - IVA (Teleoperate)	Shuttle ISS	9 9				
9.3.4.1.3 Robotic Manipulators	Robonaut Ranger Industrial type arms	4 5 5	Increased autonomy compatability with space & planetary surface environs.	2010	2013	
9.3.4.1.5 Turntable	ACCESS - manually operated	9	Modularity, versatility, reconfigurability	2010	2013	
9.3.4.2 Holding and Aligning						3
9.3.4.2.1 Holding Fixtures	LaRC SSF, PSR construction experiments	5	Modularity, versatile, adaptable, Reconfigurable	2010	2013	

Maturity Level – Technologies for Capability 9.3.4 Construction (Continued)

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.4.2.2 Alignment Jigs	LaRC SSF, PSR construction experiments	5	Modularity, versatile, adaptable, Reconfigurable	2010	2013	
9.3.4.2.3 Robotic End Effectors	LaRC ASAL truss & hex-panels	5	Versatile, adaptable	2010	2013	
9.3.4.2.4 Tools (Clamps, supports, ..)	HST Servicing	9	Commonality, versatility, standardization	2010	2013	
9.3.4.2.5 Robotic & Astronaut Teaming	1-g test with robonaut, suited astronaut	4	Robot speed, versatility, adapt-ability, autonomy	2010	2013	
9.3.4.3 Modular Hardware						3
9.3.4.3.1 Erectable Trusses	LaRC Erectable SSF, PSR trusses	5	Modularity wrt. Sub-system integration	2010	2013	
9.3.4.3.2 Mechanical Deployable Trusses	Astromasts, ABLEmasts, Stem, Bi-Stem, etc	9	Load, modularity, damping, stiffness reconfigurability	2010	2013	

Maturity Level – Technologies for Capability 9.3.4 Construction (Concluded)

Advanced Planning & Integration Office

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.4.3.3 Inflation Deployable Trusses	LaRC/DARPA - Watson, et. al.	3	Load, modularity, damping, stiffness reconfigurability	2020	2023	
9.3.4.3.4 Pressure Vessels	Shuttle, ISS	9	Modularity, commonality, reconfigurability	2010	2013	
9.3.4.3.5 Other ISS Functional Elements	Solar arrays Other Items	9	Modularity, commonality, reconfigurability	2010	2013	3
9.3.4.3.6 Telescope Mirror Segments	Keck - Grnd. Based JWST - Space	9 6	Modularity, commonality	2010	2013	
9.3.4.4 Scenarios, Sequencing						4
9.3.4.4 Scenarios, sequencing	LaRC SSF, PSR LaRC ASAL LaRC ACCESS ISS HST Servicing	6 6 9 9 9	Reduced time and complexity	2010	2013	

Capability 9.3.6
Positioning and Alignment

Contributor:

John Dorsey

Capability 9.3.6 Positioning and Alignment

Advanced Planning & Integration Office

Description:

- Positioning and alignment are two critical capabilities enabling assembly, where assembly pertains to building the final spacecraft or system from large modules.
- Individual modules must be positioned, aligned and then moved relative to each other so that they can be joined.
- Requires infrastructure hardware to transport, slew, manipulate, hold and position modules.

Benefits

- Allows assembly of modular spacecraft, which will enable affordable and sustainable exploration architectures.
- Versatile, reusable and standardized infrastructure reduces cost and development time for space systems.
- Reduces the cost and complexity of spacecraft modules and sub-modules: capabilities reside in infrastructure and agents.

Figures of Merit

- For all infrastructure and devices (platforms, scaffolding, jigs, etc.): adaptable geometry, scalability, reconfigurability, versatility, low maintenance.
- For arms/cranes: stiffness, damping, mass capability, slew rates, controllability, work volume, accuracy.
- For operations: assembly time, assembly complexity, induced contamination, standardization.

General Assessment

- Arms (SRMS, SSRMS) are in service but are limited to 0-g, limited in: rates, reach, damping. Crane concepts, that are modular, and can be configured for surface operations, have limited development.

Development Needed: **Medium**

Capability Breakdown Structure
9.3.6 Positioning and Alignment

- 9.3.6 Positioning & Alignment
  - 9.3.6.1 Grab, Attach, manipulate
    - 9.3.6.1.1 Manipulators
    - 9.3.6.1.2 End Effectors
    - 9.3.6.1.3 Grippers
  - 9.3.6.2 Slewing (large disp. & angles
    - 9.3.6.2.1 Large Arms
    - 9.3.6.2.2 Space Cranes
    - 9.3.6.2.3 ISS Devices
  - 9.3.6.3 Translation
    - 9.3.6.3.1 Transporters
    - 9.3.6.3.2 Mobile Bases
  - 9.3.6.4 Holding & Aligning
    - 9.3.6.4.1 Platforms & Scaffolding
    - 9.3.6.4.2 Holding Fixtures
    - 9.3.6.4.3 Alignment Jigs

Maturity Level – Technologies for Capability 9.3.6 Positioning & Alignment

Advanced Planning & Integration Office

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.6.1 Grab, Attach, Manipulate						2
9.3.6.1.1 Manipulators	Robonaut Ranger Industrial type arms SPDM	4 5 5 5	Increased autonomy compatibility with space & planetary surface environs.	2010	2013	
9.3.6.1.2 End Effectors	SRMS/SSRMS - snares.	9	Mass capability, stiffness	2010	2013	
9.3.6.1.3 Grippers	Robonaut (hands) Ranger (parallel jaw) SPDM (parallel jaw)	4 5 5	Low maintenance, space and planetary surface qualification	2010	2013	
9.3.6.2 Slewing - Large Displacement, Angles						2
9.3.6.2.1 Large Arms	SRMS, SSRMS	9	Adaptable, damping, reconfigurability, stiffness, mass capability, work volume, slew rate	2010	2013	

Maturity Level – Technologies for Capability 9.3. 6 Positioning & Alignment (Continued)

Advanced Planning & Integration Office

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.6.2.2 Space Cranes	LaRC Erectable crane	4	Engineering development	2010	2013	
9.3.6.2.3 ISS Devices	ORU Transfer Device, Strella	9	Mass capability, work volume, adaptable geometry, reconfigurability			
9.3.6.3 Translation						2
9.3.6.3.1 Transporters	ISS - CETA cart Spiderbots	9 3	Mass capability, versatility, work volume, adaptable geometry	2010	2013	
9.3.6.3.2 Mobile Bases	LaRC Mobile Transporter - SSF	5	Adaptable geometry scalability	2010	2013	
9.3.6.4 Holding and Aligning						3
9.3.6.4.1 Platforms and Scaffolding	LaRC Erectable Truss	5	Modularity wrt. Sub-system integ.	2010	2013	

Maturity Level – Technologies for Capability 9.3. 6 Positioning & Alignment (Concluded)

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Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.6.4.2 Holding Fixtures	HST Servicing	9	Scalability, versatility, reconfigurability	2010	2013	
9.3.6.4.3 Alignment Jigs	HST Servicing	9	Scalability, versatility, reconfigurability	2010	2013	

Capability 9.3.7
Joining

Contributor:

John Dorsey

Capability 9.3.7 Joining

Advanced Planning & Integration Office

Description:

- Joining (and unjoining) is used during operations that perform assembly, construction, replacement, repair & refurbishment. Processes include mechanical connection, welding & bonding.
- Types of potential joining operations include single-point discrete, multi-point discrete & continuous (line-type), & can be either permanent or reversible.
- Completed joints must provide a variety of functions including:load transfer, maintaining structural stiffness & linearity, & transferring utilities (power, data, fluids, etc.).

Benefits

- Enables construction & assembly of systems on orbit or on planetary surfaces.
- Enables reconfiguration, replacement, servicing & repair of systems on orbit or on planetary surfaces.
- Standardization will significantly reduce spacecraft development time, cost & risk.

Figures of Merit

- Degree of standardization, time to join, complexity of joining process & operations, type & complexity of supporting infrastructure required, compatibility with standard agents.

General Assessment

- Limited development of mechanical fastening/joining, electrical, fluid & data connectors for ISS & HST (servicing & repair). Orbital Express developing some capability for servicing (fluid) connections. Limited development of processes that apply to in-space welding (electron beam, laser). Little standardization that applies across missions.

Development Needed: **Medium**

Capability Breakdown Structure
9.3.7 Joining

Advanced Planning & Integration Office

- 9.3.7 Joining
  - 9.3.7.1 Structural Joining
    - 9.3.7.1.1 Mechanical
    - 9.3.7.1.2 Welded
    - 9.3.7.1.3 Bonded
  - 9.3.7.2 Utility Joining
    - 9.3.7.2.1 Power
    - 9.3.7.2.2 Fluids
    - 9.3.7.2.3 Thermal
    - 9.3.7.2.4 Data and Other
  - 9.3.7.3 Specialized Tools, End Effect
    - 9.3.7.3.1 Mechanical Joining
    - 9.3.7.3.2 Welded Joining
    - 9.3.7.3.3 Bonded Joining
  - 9.3.7.4 Fixtures and Jigs
    - 9.3.7.4.1 Alignment
    - 9.3.7.4.2 Holding
    - 9.3.7.4.3 Positioning

Maturity Level – Technologies for Capability 9.3.7 Joining

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Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.7.1 Structural Joining						3
9.3.7.1.1 Mechanical	ISS: latches, bolts HST: over-center clamps LaRC: erectable truss joints	9 9 5	Standardization, reduced time to join, agent compatibility Robot agent compatibility	2010	2013	
9.3.7.1.2 Welded	Terrestrial-based only?	4 - 5	Standardization, process develop., supporting infrastr.	2012	2015	
9.3.7.1.3 Bonded	Terrestrial-based only?	4 - 5	Standardization, process develop., supporting infrastr.	2015	2018	
9.3.7.2 Utility Joining						6
9.3.7.2.1 Power	ISS	9	Standardization, agent compatibility, reduced time and complexity	2010	2013	

Maturity Level – Technologies for Capability 9.3.7 Joining (Continued)

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.7.2.2 Fluids	ISS	9	Standardization, agent compatibility, reduced time and complexity	2010	2012	
9.3.7.2.3 Thermal	ISS	9	Standardization, agent compatibility, reduced time and complexity	2010	2012	
9.3.7.2.4 Data and Other	ISS	9	Standardization, agent compatibility, reduced time and complexity	2010	2012	
9.3.7.3 Specialized tools and end effectors						2
9.3.7.3.1 Mechanical Joining	EVA: ISS, HST Robotic: Robonaut, Ranger	9 4 - 5	Standardization, agent compatibility	2010	2012	

Maturity Level – Technologies for Capability 9.3.4 Construction (Concluded)

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.4.3.2 Welded Joining	Terrestrial based only?	4 - 5	Standardization, agent compatibility	2012	2015	
9.3.7.3.4 Bonded Joining	Terrestrial based only?	4 - 5	Standardization, agent compatibility	2015	2018	
9.3.7.4 Fixtures and Jigs						3
9.3.7.4.1 Alignment	ISS, HST Servicing	9	Standardization, agent compatibility, reduced set-up time & complexity	2010	2013	
9.3.7.4.2 Holding	ISS, HST Servicing	9	Standardization, agent compatibility, reduced set-up time & complexity	2010	2013	
9.3.7.4.3 Positioning	ISS, HST Servicing	9	Standardization, agent compatibility, reduced set-up time & complexity	2010	2013	

Capability 9.3.8 Verification

Contributor:

Chris Culbert

Capability 9.3.8 Verification

Description:

- The process of determining that an assembled (or serviced) item/component is working properly or is in the right configuration or is assembled correctly.
- Usually involves applying active stimulation, lighting, irradiation, mechanical pinging, loading pressurizing, followed by data collection & analysis for characterization
- Frequently, this activity will be closely coordinated with the ground.

Benefits

- Verifying a system prior to use greatly increases the probability of mission success and helps to ensure mission safety.
- Verification allows developers and users to understand any limitations of a system.
- Reuse of equipment unloads customer, accumulated capability at facility

Figures of Merit

- Number of corrected faults, amount of specialized test equipment, time to conduct verification tests, amount of human involvement, raw materials required

General Assessment

- Current SOA is fairly effective, but does not find a high enough percentage of failures during testing and requires too much overhead.

Development Needed: Low

Capability Breakdown Structure
9.3.8 Verification

Advanced Planning & Integration Office

- 9.3.8 Verification
  - 9.3.8.1 Visual Inspection
    - 9.3.8.1.1 Alignment Markers
    - 9.3.8.1.2 Close Out Photos
  - 9.3.8.2 Pressure Testing
    - 9.3.8.2.1 Leak Checks
    - 9.3.8.2.2 Pressure Cycling
  - 9.3.8.3 Functional Testing
    - 9.3.8.3.1 Checklists
    - 9.3.8.3.2 Built in Architecture Testing
  - 9.3.8.4 Continuity Testing
    - 9.3.8.4.1 Indicator Lights
    - 9.3.8.4.2 Voltage/Curerrent Levels
    - 9.3.8.4.3 Fluid Flow Monitors
  - 9.3.8.5 Structural Integrity
    - 9.3.8.4.1 Metrology
    - 9.3.8.4.2 Vibration Analysis
    - 9.3.8.4.3 Latching Mechanisms
    - 9.3.8.4.4 Welding Bond Certification
    - 9.3.8.4.5 Joint Bond Certification

Maturity Level – Technologies for Capability 9.3.8 Verification

Capability/Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.8.1 Visual Inspection						7
9.3.8.1.1 Alignment Markers	Permanent marks, lines, indicators placed on components prior to flight	9		-	2012	
9.3.8.1.2 Close-out photos	Digital close-out photos routinely used on-orbit	9	In-situ access	-	2012	
9.3.8.2 Pressure Testing						5
9.3.8.2.1 Leak checks	External sniffers, pressure sensors	7?	Mobile, external devices that can sense a variety of gasses	2010	2012	
9.3.8.2.2 Pressure Cycles	Cycling pressure higher and lower	8?	Embedded, autonomous systems	2010	2012	

Maturity Level – Technologies for Capability 9.3.8 Verification

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Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.8.3 Functional Testing						7
9.3.8.3.1 Checklists	Electronic checklists in routine use	9	Integrate with fault management tools	2010	2012	
9.3.8.3.2 Built-in test architecture	ISS uses multiple test subsystems	9	Integrate with monitoring and diagnosis tools	2012	2015	
9.3.8.4 Continuity testing						6
9.3.8.4.1 Indicator lights	Routine use in all systems	9		-	2008	
9.3.8.4.2 Voltage or current levels	Routine use in all systems	9		-	2008	
9.3.8.4.3 Fluid flow monitors	Routine use in all systems	7	Improvements for use in low gravity and micro gravity	2010	2012	

Maturity Level – Technologies for Capability 9.3.8 Verification

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.8.5 Structural Integrity						4
9.3.8.5.1 Metrology	Laser alignment systems	6?	Space qualification?	2015	2020	
9.3.8.5.2 Vibration analysis	Space Station	5?	Space qualification, small packaging	2010	2012	
9.3.8.5.3 Latching mechanisms	Space Station	9		-	2012	
9.3.8.5.4 Welding bond certification	X-ray for ground based	3	Space qualification, small packaging	2010	2012	
9.3.8.5.5 Joint bond certification	X-ray for ground based	5	Space qualification	2010	2012	

Capability 9.3.9
Planning, Logistics, Training, etc.

Contributor:
Wendell Chun

Capability 9.3.9 Planning, Logistics, & Training

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Description: These are broad capabilities that span the entire assembly sequence. Planning is defined as the ordering of steps required to complete a task or maneuver. It includes time estimates, resource management & decision reiteria. Logistics is all of the support & movement planning of assemblies, parts, tools, equipment & supplies necessary to meet the objectives of the task. Training uses documentation, models & simulators to teach / practice a skill or maneuver so as to be able to perform it as expected.

Benefits: Planning, logistics, & training are integral to each other & necessary to complete assembly & deployment. Pre-planning & contingencies will increase the probability of success of the assembly operations. Logistics determines the whereabouts & timing of all the sub-assemblies & parts required. Training is necessary to insure that the task of assembly & deployment will occur as planned. A key benefit is reduced cost & time to perform construction, assembly and joining operations. This will increase the probability of success of the assembly operations, *thus reducing risk to mission success.*

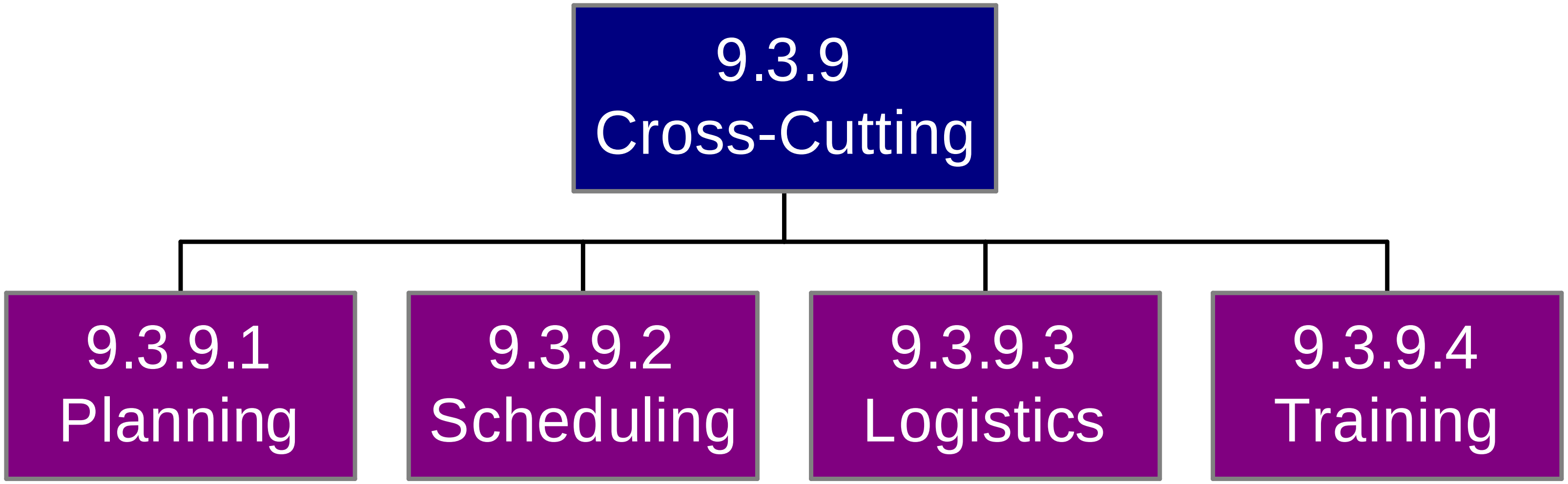
Metrics:

- Number of steps in the plan
- Completeness of plan, including acceptable contingencies
- Percentage of Distributed vs. Centralized Operations
- Timeline for logistics
- Transport Manifest
- Skills, *as opposed to task specific,* training
- Training Plan, competency test & number of skills in training
- Realistic Simulation based on update rate, fractal & polygon count, field-of-view
- Versatility & adaptability of methods

General Assessment: Planning, Logistics, & Training are common today in NASA 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 & verified through comprehensive checklists. Training exist, but could benefit from better tools & technologies to insure a higher level of preparedness.

Development Need: **Low**, with room for technological improvements as available, except for **human-robot training where the need is high.**

Capability Breakdown Structure
9.3.9 Planning, Logistics, & Training



State-of-the-Art/Maturity Level/Capabilities for 9.3.9 Planning, Logistics, & Training

Capabilities	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
• Planning					6	
• Mission Planning	Apollo, Soyuz, Shuttle	6	Auto	-	2010	
• Strategic Planning	Shuttle	7	Auto	-	2010	
• Vehicle Planning	Shuttle	8	Integ.	-	2010	
• Trajectory Planning	Shuttle, Soyuz	9	Auto	-	2010	
• Collision Avoidance	Manual Visualization	3	Dev.	2006	2008	
• Dynamic Replanning	XSS-11	4	Real-Time	2006	2008	
• Scheduling					7	
• Automated	Shuttle	6	Real-Time	2010	2012	
• Logistics					6	
• Logistics Planning	Shuttle PIC	9	Auto	-	2010	
• Resource Allocation	New Millennium	6	Auto	2008	2010	
• Automated Tracking	Shuttle GSE	8	Common	-	2010	
• Inventory Control	NASA Pre-Flight	8	Implement	-	2010	
• Training					6	
• 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	
• Simulation	Shuttle Training	6	hi-res	2006	2008	
• Immersion	Laboratory	4	mature	2008	2012	
• Testing & Checkout	Conventional	9	Auto	-	2012	

State-of-the-Art/Maturity Level/Sub-Capabilities for 9.3.9 Planning, Logistics, & Training

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Sub-Capabilities	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
• Planning						6
• Auto Mission Planner	Apollo, Soyuz , Shuttle	5	Auto	2008	2008	
• Auto Strategic Planning 2008	Shuttle	7	-		-	
• Auto Vehicle Planning	Shuttle	8	-.	-	2008	
• Smooth Trajectory	Shuttle, Soyuz	9	-	-	2008	
• Auto Col. Avoid System	Manual Visualization	3	Dev.	2006	2008	
• Auto Replanning	XSS-11	4	Real-Time	2006	2008	
• Scheduling						7
• Ground	Shuttle	8	-	-	2008	
• On-board	Shuttle	6	Real-Time	2008	2010	
• Logistics						6
• 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	
• Auto Inventory Mgt	NASA Pre-Flight	8	Implement	-	2008	
• Real-Time traffic model	Shuttle	8	Auto	-	2008	
• Spares Planning	ISS	9	-	-	2008	

State-of-the-Art/Maturity Level/Sub-Capabilities for 9.3.9 Planning, Logistics, & Training

Sub-Capabilities	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
• Training					6	
• 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	
• Computer Sims.	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	

State-of-the-Art/Maturity Level/ Technologies for 9.3.9 Planning, Logistics, & Training

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

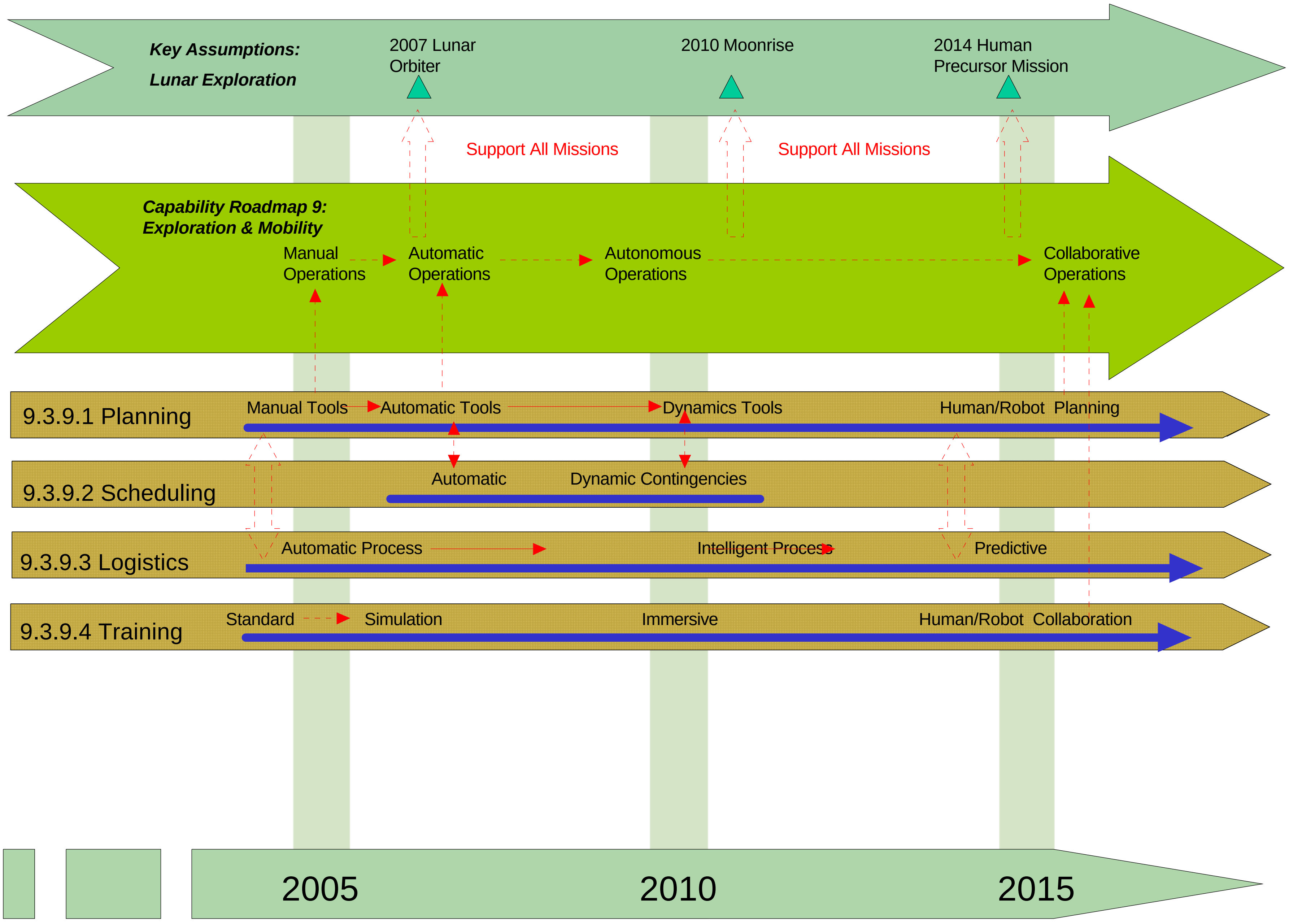
State-of-the-Art/Maturity Level/ Technologies for 9.3.9 Planning, Logistics, & Training

Advanced Planning & Integration Office

Sub-Capabilities	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability CRL
• Training					6
• Tops Down Training	Scenario Role Playing	6	Update	2008	2010
• Bottoms Up Training	Human-skills Development	9	-	-	2010
• Hi-Res Comp. Sim.	Sony, Boston-Dyn, Evans-Suth.	4	Cost	2006	2010
• Low-Res Comp. Sim	COTS	8	-	-	2006
• Pc_based Comp. Sim	COTS	8	-	-	2006
• Man-In-the-Loop Sim.	Univ. Washington, Media Lab	6	Human Fac	2008	2010
• Motion Base	NRL, MSFC, JSC	6	Full Scale	2008	2010
• Virtual Reality	ARC, NC State, Media Lab	3	Maturity	2010	2012
• CAVE-based Virtual	U. of Illinois, U. of Colo.	4	Dev.	2008	2010
• Augmented Reality	HRL, Microsoft, Media Lab	4	Dev.	2008	2010
• Gestures, Gaze	CMU, GM	2	Research	2010	2012
• Human/Robot Training	Commercial Robot Manufac.	2	Dev.	2010	2012

Human-Robot Training is a Gap that requires filling.

9.3.9 Assembly & Deployment Cross-Cutting Top Level Capability Roadmap



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