Autonomous Systems, Robotics, and Computing Systems Capability Roadmap

NRC Dialogue

NASA Chair: Steve Zornetzer, ARC
External Chair: Douglas Gage, DARPA (ret.)

March 30, 2005

Overview

- **Introduction (Steve Zornetzer)**
- Process, Mission Drivers, Deliverables, and Interfaces (James Crawford)
- Autonomy (James Crawford)
  - Crew-Centered and Remote Operations
  - Integrated Systems Health Management
  - Autonomous Vehicle Control
  - Autonomous Process Control
- Robotics (Paul Schenker)
  - Robotics for Solar System Exploration
  - Robotics for Lunar and Planetary Habitation
  - Robotics for In-Space Operations
- Computing Systems (Mike Lowry)
- Conclusion

Capability Roadmap Teams

Capability	NASA chair	External chair
High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Capability Roadmap Team

<u>**Co-Chairs**</u>
NASA: Steve Zornetzer, NASA/Ames Research Center
External: Douglas Gage , DARPA (ret.)
NASA Deputy: James Crawford , NASA/Ames Research Center
NASA Deputy: Paul Schenker, JPL

<u>**NASA**</u>
Steve Chien, JPL
Michael Lowry, ARC
Ron Diftler, JSC
Dave Lavery, NASA HQ
Illah Nourbakhsh, ARC
Julia Loftis, GSFC
Michel Ingham, JPL
Serdar Uckun, ARC

<u>**Industry**</u>
Chris Leslie, USA
Dan Clancy, Google (ex-NASA)
Additional reviews underway:
- Barry Fox, Boeing
- Kerry Fisherkeller, NG

<u>**Academia**</u>
Dave Akin, Univ. of Maryland
Red Whittaker, CMU
Reid Simmons, CMU
Bob Full, UC Berkeley
Brian Williams, MIT
James Allen, IHMC
Michael Evangelist, CMU

<u>**Coordinators**</u>
Directorate: Harley Thronson, SMD
APIO: Jan Aikins, ARC

Capability Description

- **The Autonomous Systems, Robotics, and Computing Systems (AR&C) capability roadmap details the information technology and robust hardware and computing technology required for NASA spacecraft, robots, and human/robotic teams to explore harsh dynamic environments safely and affordably.**

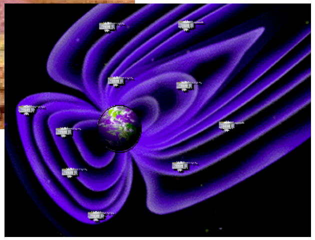
- AR&C capabilities include:
  - 10.1 Autonomous Operations
  - 10.2 Integrated Systems Health Management
  - 10.3 Vehicle Control
  - 10.4 Process Control
  - 10.5 Robotics for Solar System Exp.
  - 10.6 Robotics for Lunar and Planetary Hab.
  - 10.7 Robotics for In-Space Operations
  - 10.8 Software Validation and Verification
  - 10.9 Avionic Systems (incomplete)

- AR&C does NOT include (by charge from APIO):
  - Supercomputing
  - Data archiving and analysis
  - Computer networks and grid computing
  - Robotic hardware (except as required to develop and benchmark software)
  - Much of “classic” Computer Science – compilers, programming languages, databases, etc. (except in limited cases as driven by the capabilities above)

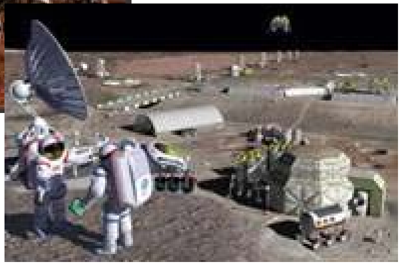
Driving Requirements

- Exploration is a contact sport. To understand our universe and to search for life, NASA robots and spacecraft will be:
  - On and under the surface of Mars, on cliffs and in caves
  - On asteroids and taking samples on comets
  - On the surface and in the clouds of Venus
  - Under the clouds of Titan, and under the ice on Europa
  - On the moon searching for resources and preparing for a long-term human presence

- NASA manned and unmanned missions will be carrying out increasingly challenging tasks far from Earth:
  - Habitat construction and long term habitation
  - In-space construction of spacecraft and observatories
  - Mining and in-situ resource utilization
  - Deep drilling (lunar, Mars, Europa, etc.)
  - Spacecraft constellations (interferometry, gravity wave detection, Earth-Sun connection, etc.)
  - Scientific laboratory tests currently done only on earth
  - Biological and habitability analysis





These missions create pacing NASA challenges in Autonomy, Robotics, and Computing

Capability Breakdown Structure

10.0 Autonomous Systems, Robotics, and Computing Systems

Co-Chair: Steve Zornetzer, NASA/ARC
Co-Chair: Douglas Gage, DARPA (ret.)
Deputy: James Crawford, NASA/ARC
Deputy: Paul Schenker, JPL

- **10.1 Crew-Centered and Remote Operations** — Chair: Julia Loftis / GSFC
  - 10.1.1 Crew-Centered Planning
  - 10.1.2 Autonomous Mission Operations
  - 10.1.3 Multi-System Coordination & Collaboration
  - 10.1.4 Human-Automation Interaction
  - 10.1.5 Multi-Modal Interfaces for Collaborative Execution
- **10.2 Integrated Systems Health Management** — Chair: Serdar Uckun / ARC; Co-Chair: Brian Williams / MIT
  - 10.2.1 Design of Health Management Systems
  - 10.2.2 Real-Time System Health Management
  - 10.2.3 Informed Logistics
- **10.3 Autonomous Vehicle Control** — Chair: Michel Ingham / JPL; Co-Chair: Lorraine Fesq / JPL
  - 10.3.1 Rendezvous and Docking
  - 10.3.2 Orbit Insertion
  - 10.3.3 Entry, Descent, and Landing
  - 10.3.4 Launch Systems
  - 10.3.5 UAV Control
- **10.4 Autonomous Process Control** — Chair: James Crawford / ARC
  - 10.4.1 Life Support
  - 10.4.2 ISRU Process Control
  - 10.4.3 Nuclear Reactors
  - 10.4.4 Deep Drilling
  - 10.4.5 Plug & Play Controllers
  - 10.4.6 Smart Systems
- **10.5 Robotics for Solar System Exploration** — Chair: Reid Simmons / CMU; Co-Chair: Doug Gage / DARPA (ret.)
  - 10.5.1 Mobility and Access
  - 10.5.2 Instrument Deployment
  - 10.5.3 Onboard Autonomous Science
  - 10.5.4 Human-Robotic Field Science
  - 10.5.5 Human-Robot Interaction
- **10.6 Robotics for Lunar and Planetary Habitation** — Chair: Illah Nourbakhsh / ARC
  - 10.6.1 Site Development
  - 10.6.2 Site Maintenance
  - 10.6.3 ISRU
  - 10.6.4 Field Logistics and Support
  - 10.6.5 Human-Robot Interaction
- **10.7 Robotics for In-Space Operations** — Chair: Ron Diftler / JSC
  - 10.7.1 Assembly
  - 10.7.2 Inspection
  - 10.7.3 Maintenance
  - 10.7.4 Human-Robot Interaction
- **10.8 Computing Systems** — Chair: Mike Lowry / ARC; Co-Chair: Mike Evangelist / CMU
  - 10.8.1 Automated Testing
  - 10.8.2 Analytic Assurance
  - 10.8.3 Fault tolerance
  - 10.8.4 Certified, automated SW generation
  - 10.8.3 Maintainability & Reusability

Autonomy | Robotics | Computing

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Approach and Process

- Roadmapping has been based on a series of workshops with presentations by experts on mission classes and by technologists, and a series of follow-up meetings between workshops (process detailed below).

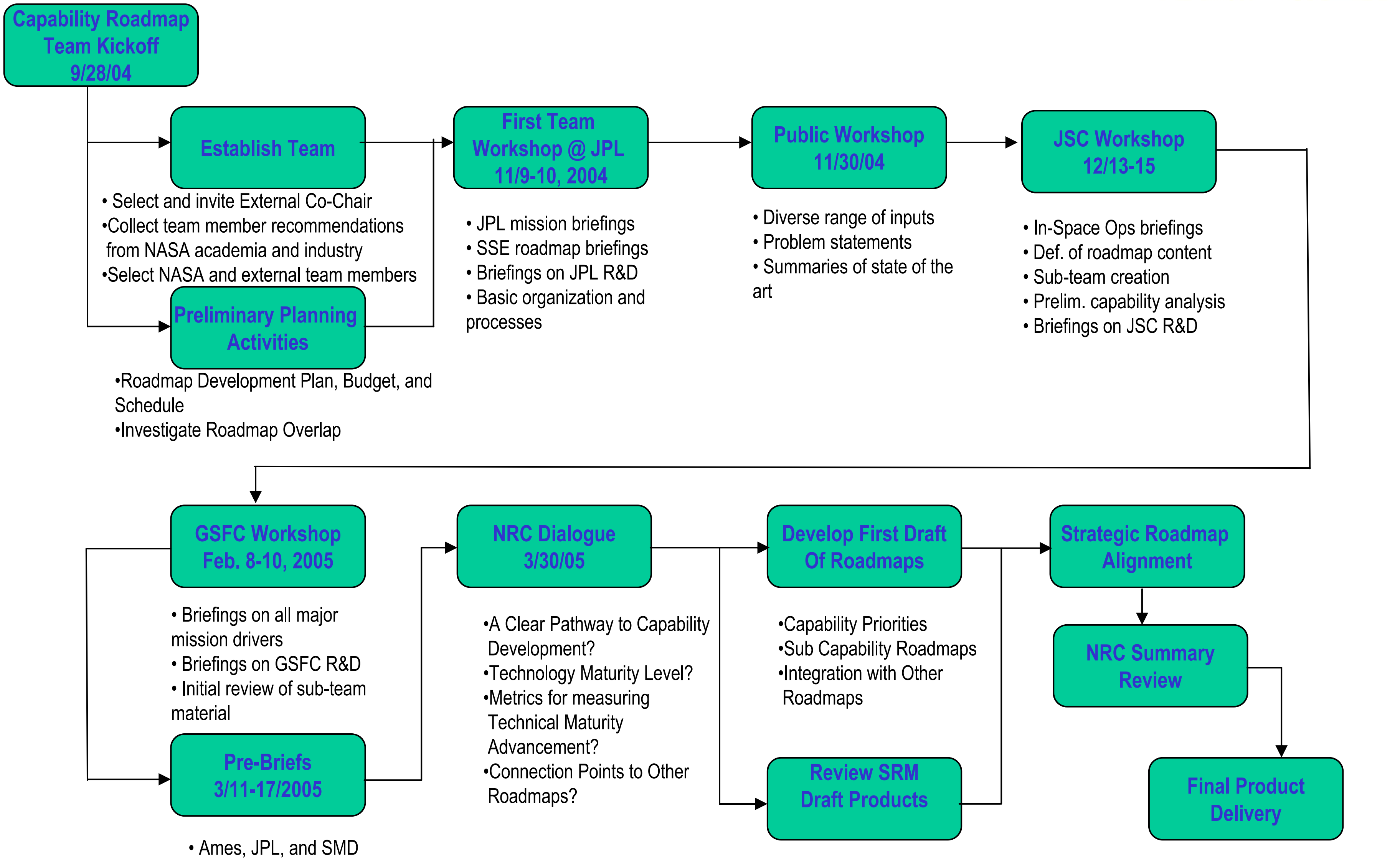
- The capability sub-teams have also studied the relevant NASA-level, directorate-level, and theme-level strategic plans (and other documents detailed below).

- The primary output of the process is a set of deliverables
  - 5-8 per sub-capability
  - Each deliverable linked to one or more mission drivers
  - Sub-Capability deliverables will be prioritized by the degree to which they enable missions and mission classes, and by the degree to which the enhance missions and mission classes (as measured increased science return and decreased cost).
  - This prioritization has been done only roughly since it requires further input from the Strategic Roadmaps.

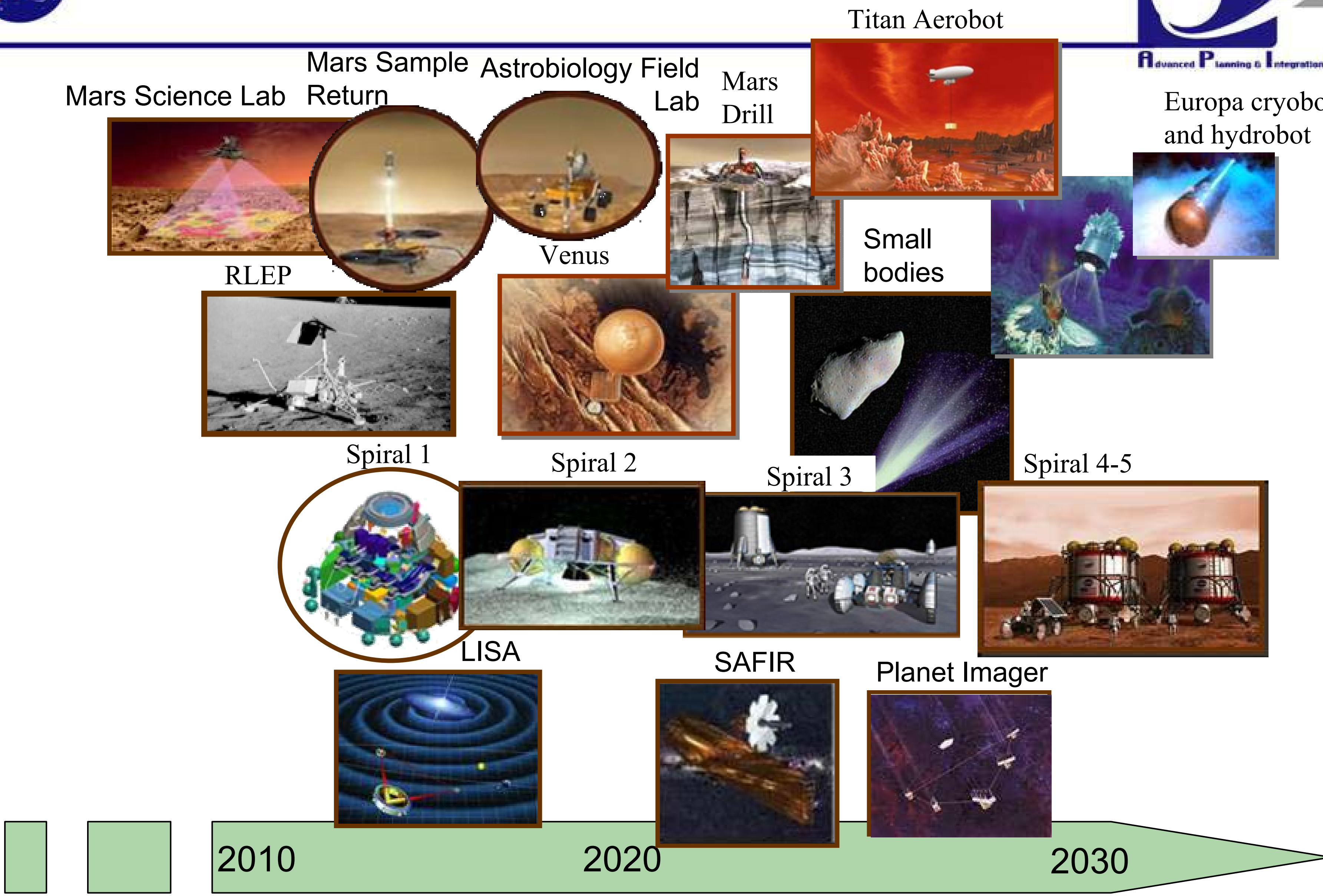
Top Level Assumptions

- Autonomy, Robotics, and Computing requirements will be driven primarily by the following mission sets:
  - Exploration Mission Directorate
    - The Exploration Initiative Mission Spirals
    - Robotic Lunar Exploration (RLEP)
  - Science Mission Directorate
    - Mars Exploration
    - Solar System Exploration
    - Earth Science
    - Structure and Evolution, and Origins
    - Sun-Earth Connection
  - Aeronautics
    - High Altitude Long Endurance Remotely Operated Aircraft (HALE ROA)
- Timelines for these mission classes will be available in April from the Strategic Roadmap Teams. For this package we have used available information and, where necessary, made assumptions about mission dates.
- Roadmap deliverables are shown on the timeline ~5 years before mission launch.
- NASA's investments will focus on NASA pacing challenges. NASA will avoid investing in capabilities that will be independently developed by industry. NASA will pursue partnerships with DARPA, and other federal agencies, where priorities align.
- Since this is a strategic exercise (not program formulation), the following is out of scope:
  - Where R&D will be done (industry, academics, NASA centers)
  - How R&D will be managed to maximize mission impact (integration frameworks, partnerships, etc.)
  - Scope, budgets, and time lines for programs

Roadmapping Process



Mission Drivers



MEP: A Strategy of Exploration & Discovery

A science-driven effort to characterize and understand Mars as a dynamic system, including its present and past environment, climate cycles, geology, and biological potential.

“Following the Water”

This decade we set the context for the Search for Life as we characterize and understand Mars and its environments.

“Following the Carbon”

Towards the end of the decade, the search focus’ on “Following the Carbon”, the basic building blocks of life, and life itself.

“Robots, to Human Precursors, to Humans”

The knowledge and understanding being developed today paves the way…

Mars Potential Next-Decade Pathways

Advanced Planning & Integration Office

Pathway	Lines of Scientific Inquiry
Search for Evidence of Past Life	**Science from First Decade missions plus early next-decade missions confirms ancient Mars was wet and warm** • **Locating and analyzing water-lain sedimentary rock is primary goal.** • **Pathway includes search for evidence of past life.**
Explore Hydrothermal Habitats	**Exploration in First Decade discovers hydrothermal deposits (active or fossil)** • **Probability of hydrothermal regions being discovered is potentially high.** • **Hydrothermal habitats are focus of second decade of Mars exploration.** • **Potential for discovery of evidence of past and present life is greatly improved.**
Search for Present Life	**Commits to search for present life at sites determined to be modern habitats by First Decade missions** • **Search for life at active hydrothermal deposits or polar margins.** • **Path would be taken only following a discovery that revolutionizes our understanding of the potential of Mars to harbor present life.** • **MSR with mobility is included as the most reliable, validatible means of detecting life.**
Explore Evolution of Mars	**Science of First Decade of Mars exploration does not find evidence of past or present liquid water environments** • **Determine the loss mechanisms and sinks for water and CO_2 over time.** • **Determine why the terrestrial planets evolved differently, much more so than we had thought.** • **Determining whether the initial conditions on Venus, Earth and Mars were similar or very different.**

Mars Exploration & Agency Roadmaps

1. Undertake robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations. (Agency Objective 4)

2. **Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (Obj 5)**

   Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions, and after successfully demonstrating sustained human exploration missions to the Moon. (Obj 6)

3. Conduct robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration. (Obj 7)

4. Search for Earth-like planets and habitable environments around other stars. (Obj 8)

5. Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. (Obj 10)

6. Focus research and use of the International Space Station on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (Obj 12)

7. Return the Space Shuttle to flight, complete assembly of the International Space Station, and transition from the Space Shuttle to a new exploration-focused transportation system. (Obj 11)

8. Explore our Universe to understand its origin, structure, evolution, and destiny. (Obj 9)

9. ... erstand ... quences ... for life

10. ... nd the ... tem, and ... ill be experienced by human explorers. (Obj 2)

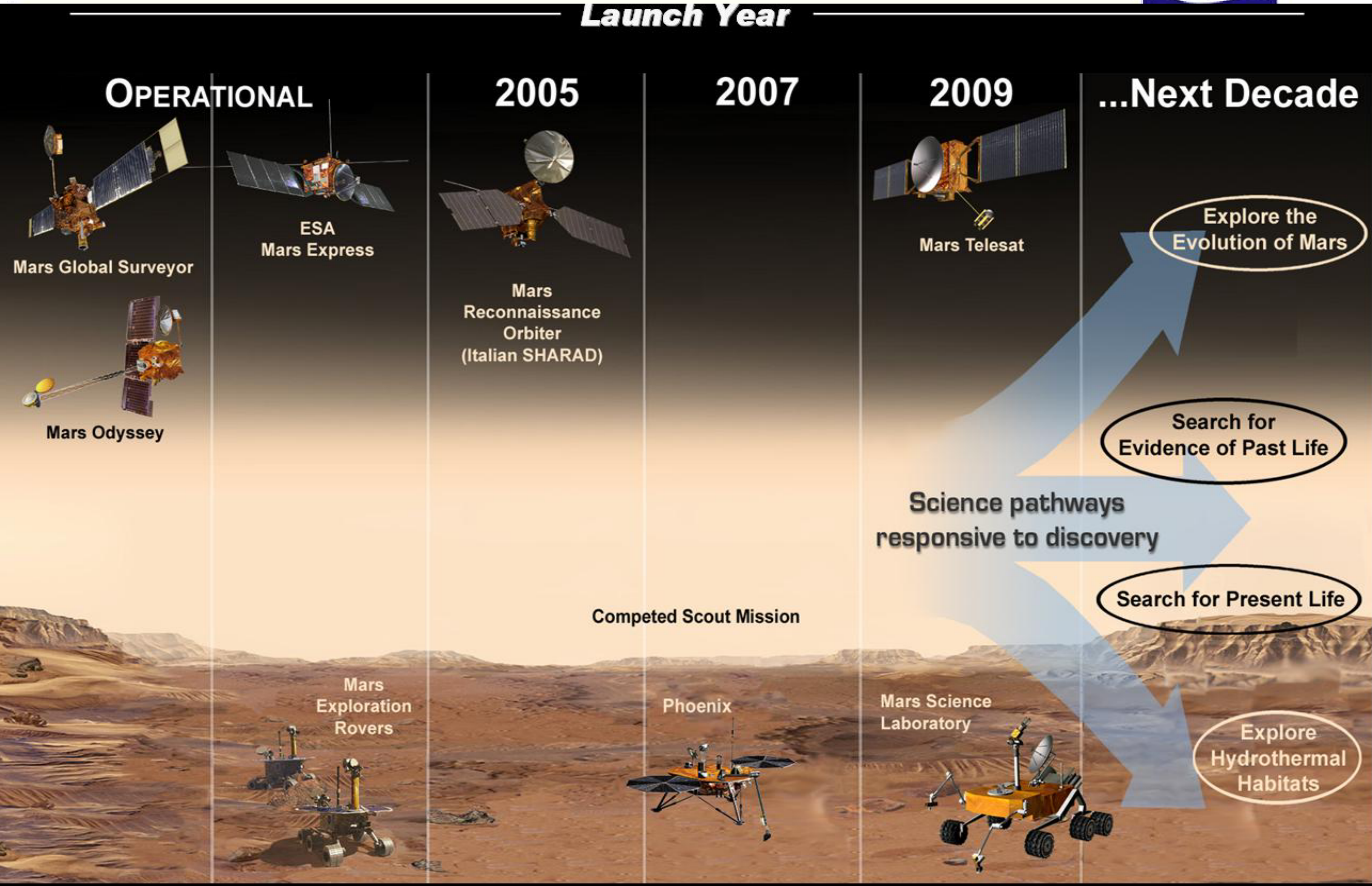
11. Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (Obj 3)

12. Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (Obj 14)

13. Develop a comprehensive national plan for utilization of nuclear systems for the advancement of space science and exploration. (No Agency Obj)

Mars Robotic *and* Human Exploration Requirements

This Decade's Discoveries Leads to the Next Decade's Pathway



...and Potential Pathway Mission Sequences

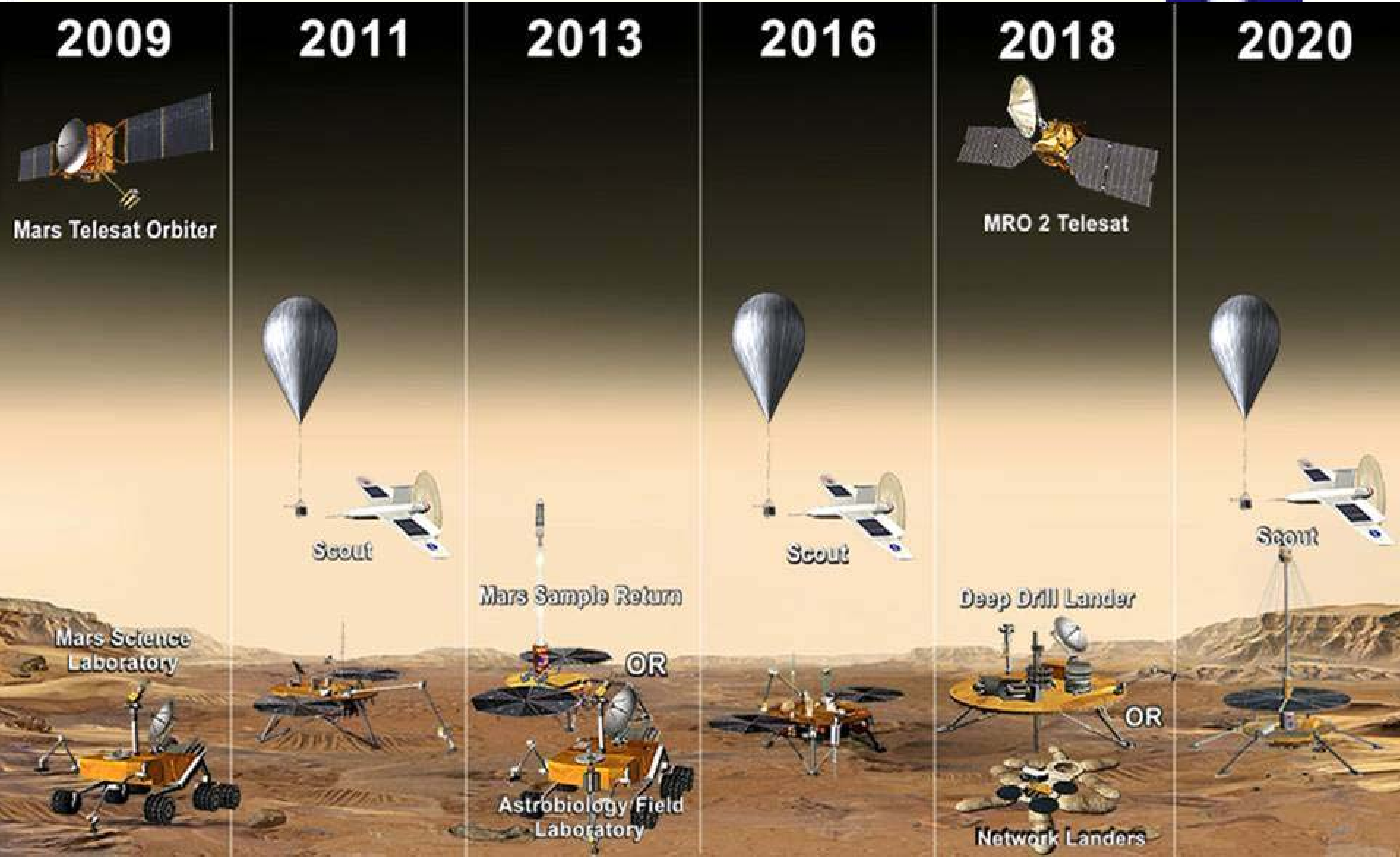
Pathway	2009	2011	2013	2016	2018	2020	Notes
Search for Evidence of Past Life	MSL to Moderate Latitude	Scout	MSR	Scout	Astrobiology Field Lab or Deep Drill	Scout	Missions to high-probability past habitat. Mission in '18 influenced by MSL results.
Explore Hydrothermal Habitats	MSL to Hydrothermal Deposit	Scout	Astrobiology Field Laboratory	Scout	Deep Drill	Scout	All core missions sent to active or extinct hydrothermal deposits.
Search for Present Life	MSL to High Latitude or Active Vent	Scout	Scout	MSR	Scout	Deep Drill	Missions to modern habitat. Path has highest risk.
Explore Evolution of Mars	MSL to Moderate Latitude	Scout	MSR	Aeronomy	Network	Scout	Path rests on proof that Mars was never wet.

2005 President's Budget Augmentation		Scout & Mars Testbed		Mars Testbed		Mars Testbed	

MTO → Replacement Telecom* →

Note: The pathway followed will depend on knowledge and technologies developed this decade.

"Search for Past Life" Pathway Example



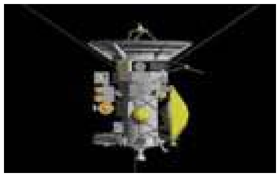
***Mars Testbeds are human exploration pathfinders**

Candidate Solar System Exploration Missions

Advanced Planning & Integration Office

2010

Cassini Huygens

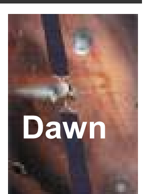


New Frontiers

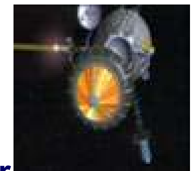
Moonrise

Juno

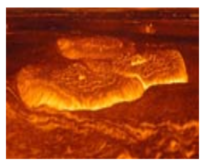
Discovery



Europa Orbiter Or Titan Explorer



New Frontiers Candidates



Venus SAGE

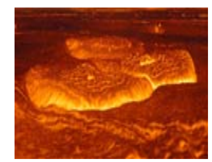
Comet Clipper

2015

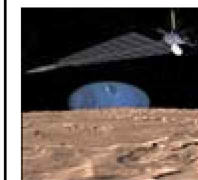
Prometheus Enabled Missions

New Frontiers Candidates

Venus Geophysical Network or rover



2020



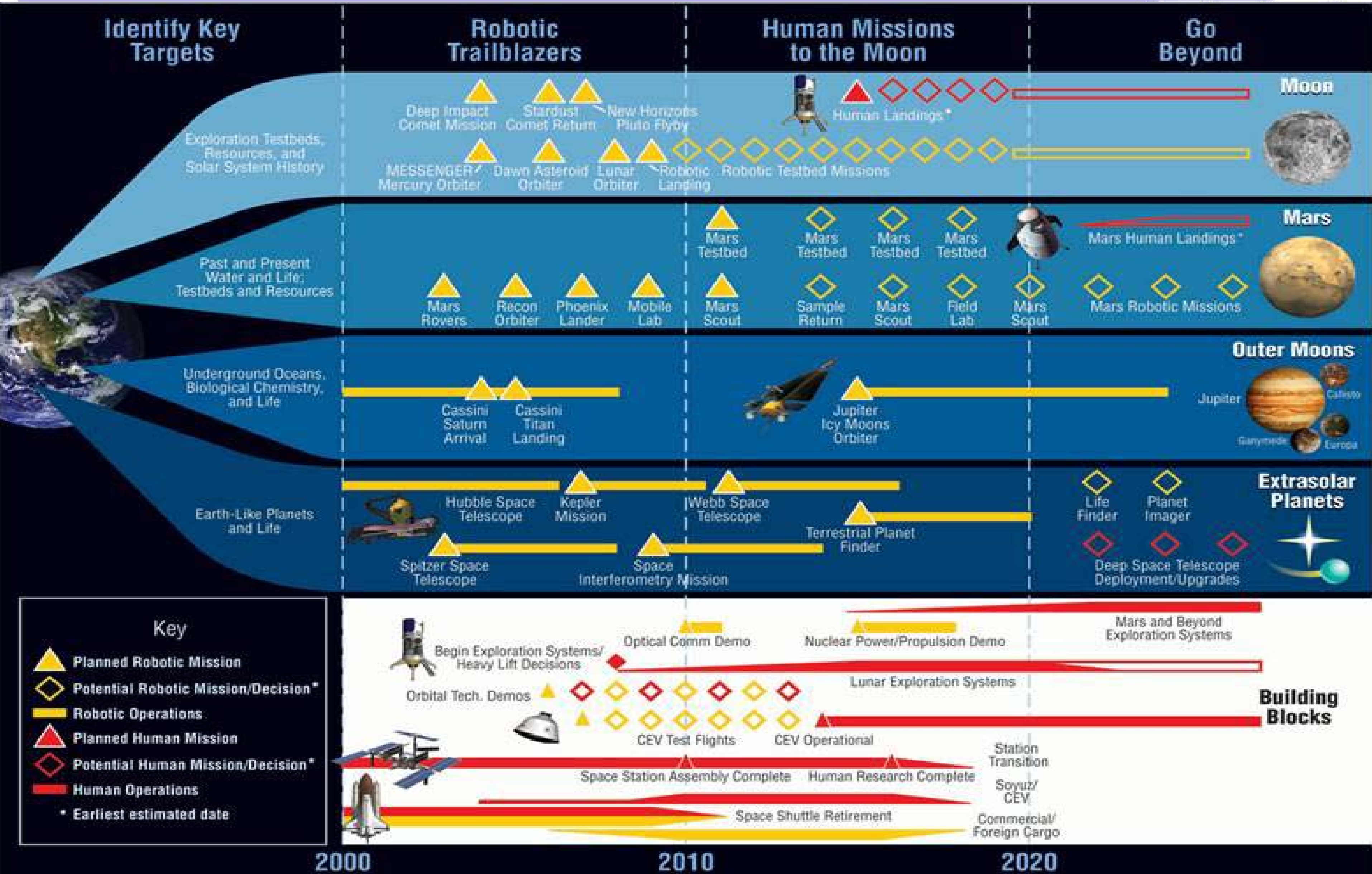
Neptune Triton Orbital Tour

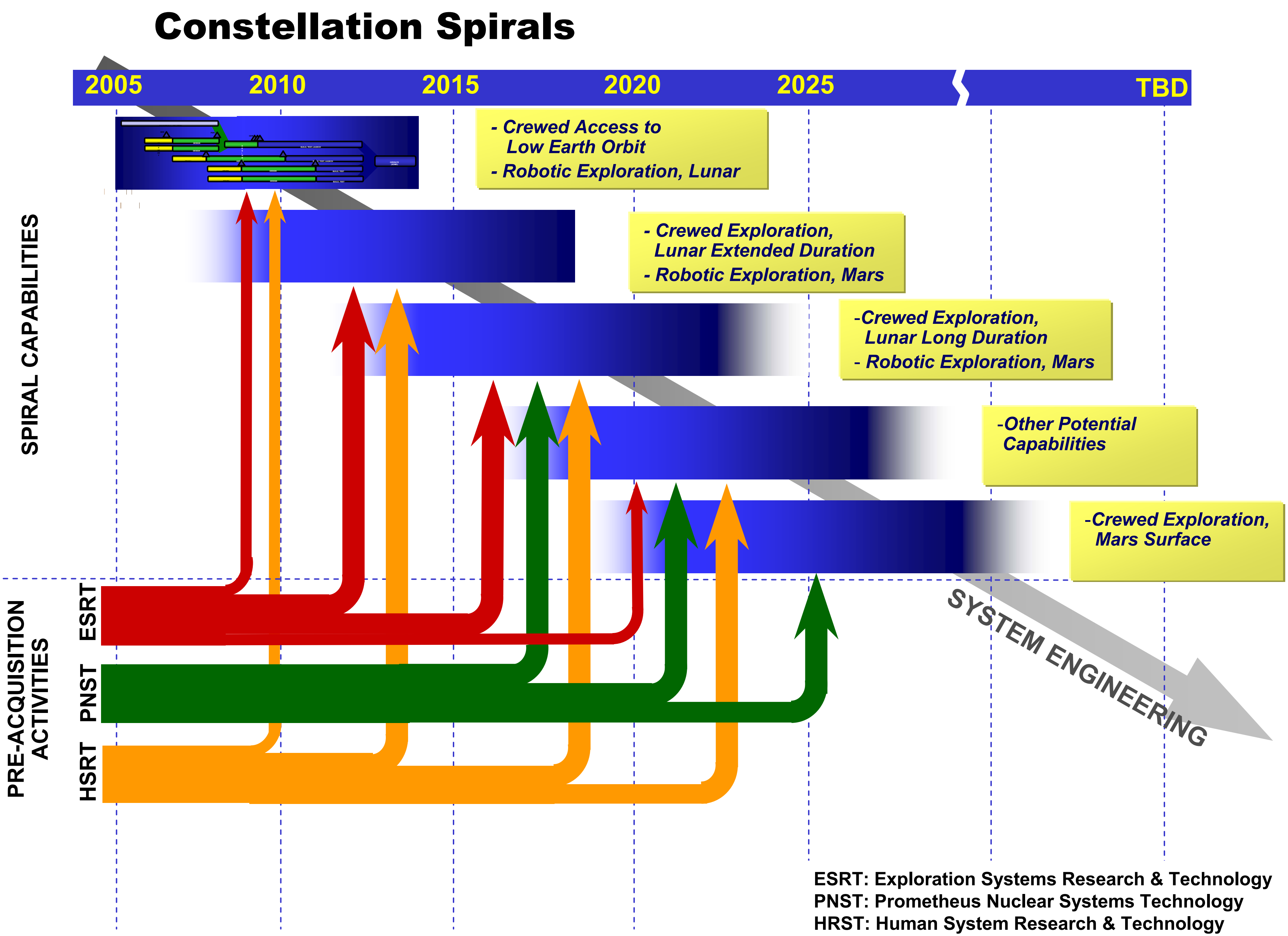
New Frontiers

Comet Cryogenic sample return

Pre-Decisional Draft: Illustrative Only

Exploration Roadmap

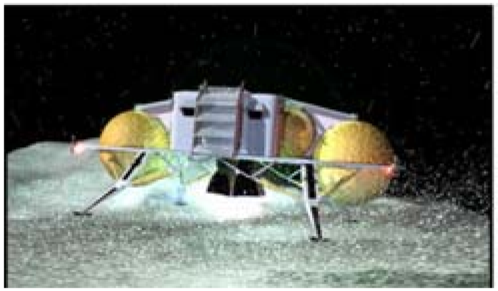


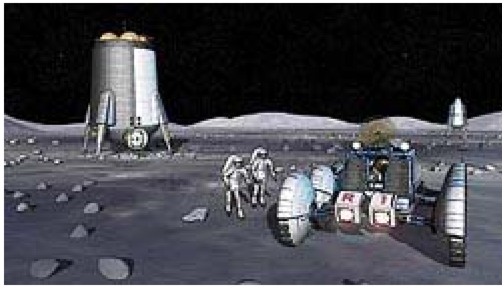


Constellation Spirals
2005
2010
2015
2020
2025
TBD
- Crewed Access to Low Earth Orbit
- Robotic Exploration, Lunar
- Crewed Exploration, Lunar Extended Duration
- Robotic Exploration, Mars
-Crewed Exploration, Lunar Long Duration
- Robotic Exploration, Mars
-Other Potential Capabilities
-Crewed Exploration, Mars Surface
SPIRAL CAPABILITIES
PRE-ACQUISITION ACTIVITIES
ESRT
PNST
HSRT
SYSTEM ENGINEERING
ESRT: Exploration Systems Research & Technology
PNST: Prometheus Nuclear Systems Technology
HRST: Human System Research & Technology

Spirals Definition

- **Spiral 1: 4-6 crew to Low Earth Orbit (2014)**
  - Crew Exploration Vehicle (CEV)
    - Launch environment
    - LEO environment
    - Earth entry, water (or land) recovery
- **Spiral 2: 4-6 crew to lunar surface for extended-duration stay (2015-2020)**
  - Crew Exploration Vehicle (CEV)
    - Earth-moon cruise - 4 days
    - Low lunar orbit (LLO) operations – 1 day
    - Untended Lunar Orbit operations – 4-14 days
    - Low lunar orbit operations – 1 day
    - Moon-Earth cruise – 4 days
  - Lunar Lander
    - Surface operations with EVA 4-14 days
- **Spiral 3: 4-6 crew to lunar surface for long-duration stay (2020-TBD)**
  - Lunar habitat
    - Lunar surface operations 60-90 days
- **Spiral 4: Crew to Mars vicinity (2025+)**
  - Transit vehicle
    - Earth-Mars cruise – 6-9 months
    - Mars vicinity operations – 30-90 days
    - Mars-Earth cruise – 9-12 months
- **Spiral 5: Crew to Mars surface (2030+)**
  - Surface habitat and exploration





Requirements and Deliverables: Observations

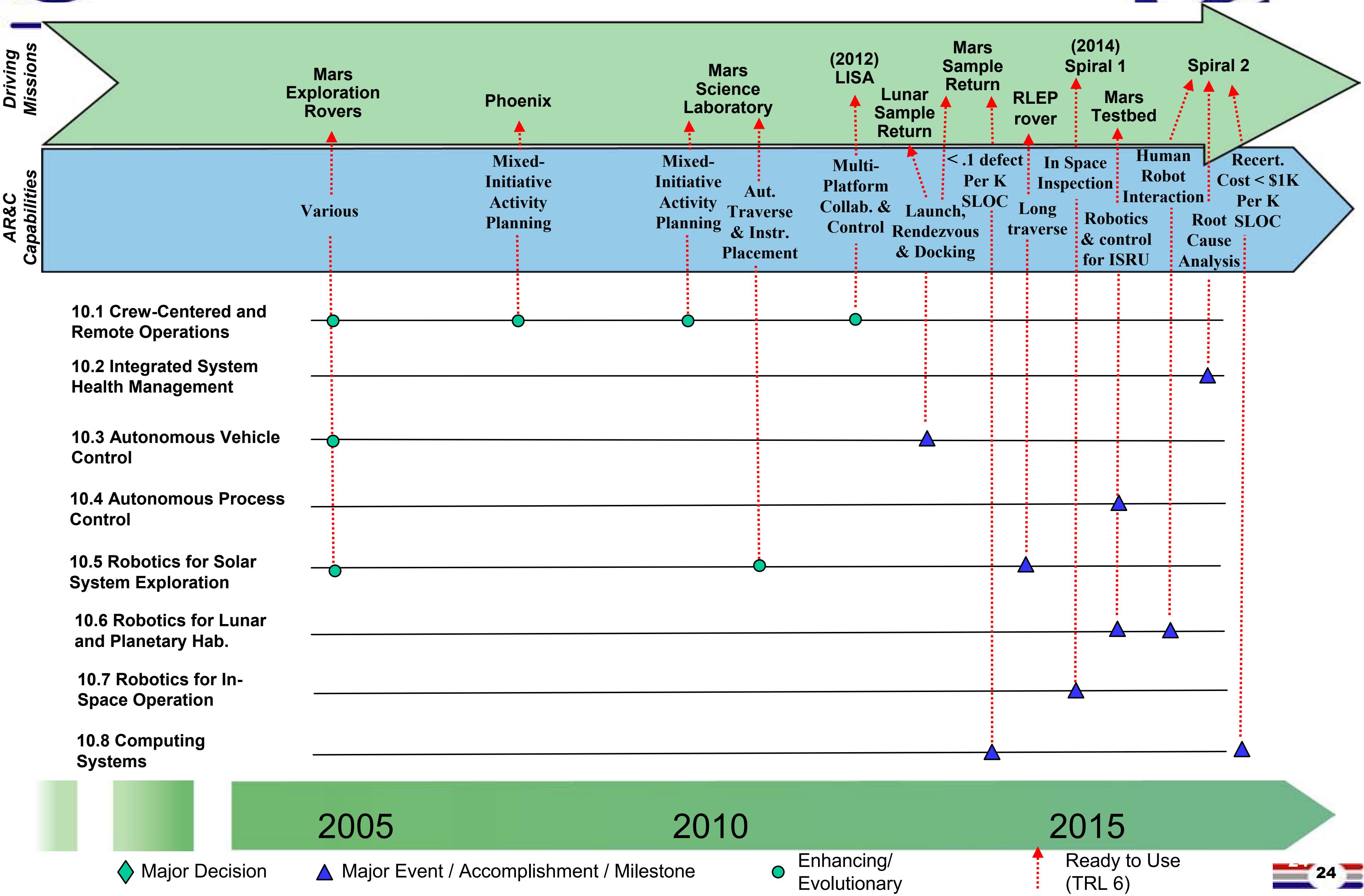
1. AR&C is heavily cross-cutting. Most capabilities are relevant to multiple missions and mission classes. For purposes of the roadmap we have listed the first major driver.

2. In many cases AR&C is providing control and execution software for hardware developed by other capability roadmaps (e.g., drilling, EDL, nuclear reactors, life support, etc.). Conversations with these capability roadmap teams have begun and will increase once all teams have full packages.

3. Numerous AR&C capabilities have applications in superficially very different missions (e.g., control and execution software shared between rovers, drilling, life support, and interferometry). Such sharing can reduce costs, shorten schedules, and reduce risks. This is an important lesson of agency-level analysis.

4. Common themes:
    1. Communication latencies create pacing NASA challenges
    2. Surface exploration drives autonomy and robotics
    3. The other driver is challenging manipulative tasks (construction, drilling, ISRU, constellations, science experiments, etc.)

Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



MER Capabilities (10.1)

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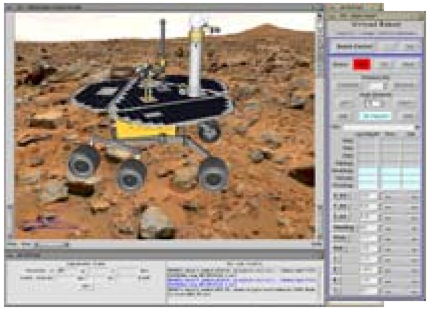
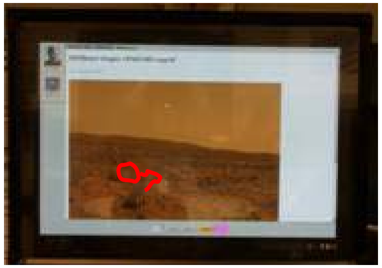
MAPGEN: Activity plan development and analysis

MER science and uplink team members have estimated that overall science return increased by 20 to 50%.



Viz: High fidelity terrain modeling and analysis

CIP: Customizable data navigation, search, and information management



MERBoard: Collaborative information analysis and sharing

HCC & Fatigue Countermeasures: Improved data understanding and Enhanced situational awareness

MER Capabilities (10.3, & 10.5)

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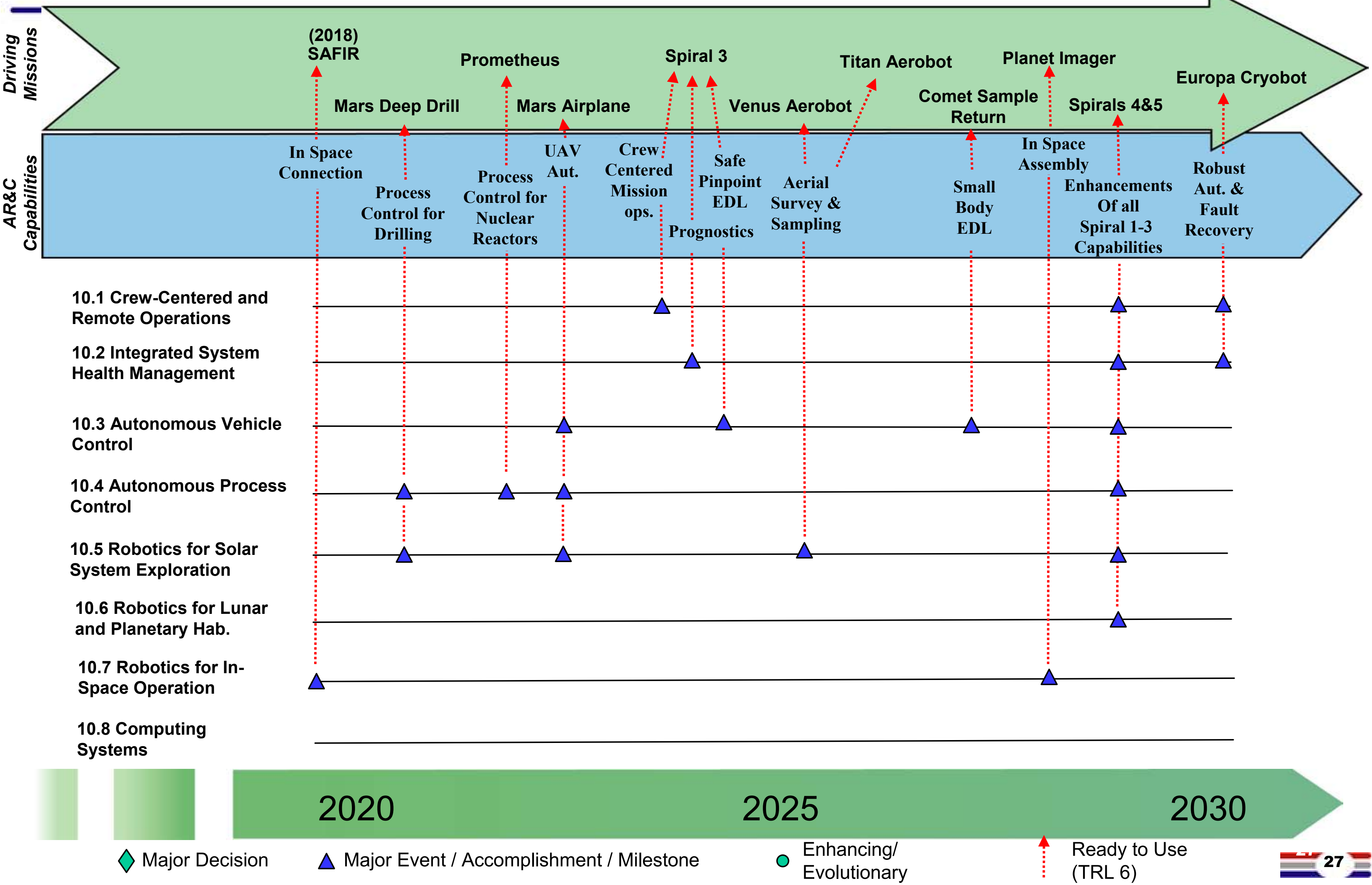
	Technology	Funding Source	Description	PI/Technologist
1	Long Range Science Rover	NASA (Code R and MTP)	Provides increased traverse range of rover operations, improved traverse acuracy, landerless and distributed ground operations with a large reduction in mass	Samad Hayati Richard Volpe
2	Science Activity Planner	NASA (Code R and MTP)	Provides downlink data visualization, science activity planning, merging of science plans from multiple scientists	Paul Backes Jeff Norris
3	FIDO: Field Integrated Design and Operations Rover	NASA (MTP)	Developed TRL 4-6 rover system designs, advancing NASA capabilities for Mars exploration; demonstrated this in full-scale terrestrial field trials, Integrated/operated miniaturized science payloads of mission interest, coupling terrestrial field trials to	Paul Schenker Eric Baumgartner
4	Manipulator Collision Prevention Software	NASA (MTP)	Computationally efficient algorithm for predicting and preventing collisions between manipulator and rover/terrain.	Eric Baumgartner Chris Leger
5	Descent Image Motion Estimation System (DIMES)	NASA (Code R and MTP)	Software and hardware system for measuring horizontal velocity during descent, Algorithm combines image feature correlation with gyroscope attitude and radar altitude measurements.	Andrew Johnson Yang Cheng et al.
6	Parallel Telemetry Processor (PTeP)	NASA (Code R and MTP)	Data cataloging system from PTeP is used in the MER mission to catalog database files for the Science Activity Planner science operations tool	Mark Powell Paul Backes
7	Visual Odometry	NASA (MTP)	Onboard rover motion estimation by feature tracking with stereo imagery, enables rover motion estimation with error < 2% of distance traveled	Larry Matthies Yang Cheng
8	Rover Localization and Mapping	NASA (MTP)	An image network is formed by finding correspondences within and between stereo image pairs, then bundle adjustment (a geometrical optimization technique) is used to determine camera and landmark positions, resulting in localization accuracy good for trav	Ron Li Clark Olson et. al.
9	Grid-based Estimation of Surface Traversability Applied to Local Terrain (GESTALT)	NASA (Code R and MTP)	Performs traversability analysis on 3-D range data to predict vehicle safety at all nearby locations; robust to partial sensor data and imprecise position estimation. Configurable for avoiding obstacle during long traverse or for driving toward rocks for	Mark Maimone

Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Summary of Key Deliverables

Advanced Planning & Integration Office

	Mars	Solar Sys.	Lunar	Obs.	Earth Sci.	Sun-Earth	Spiral 1	Spiral 2	Spiral 3
10.1 Autonomous mission ops	Enhancing	Enabling	Enhancing	Enhancing	Enhancing	Enabling ✸	Enhancing	Enhancing	Enabling ✸
10.1 Multi-platform collaboration				Enabling ✸	Enabling	Enabling ✸		Enhancing	Enhancing
10.2 Root-cause analysis	Enhancing	Enabling	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling ✸
10.2 Prognostics	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling ✸
10.3 Rendezvous and Docking	Enabling ✸		Enhancing	Enhancing				Enhancing	Enabling
10.3 Entry, descent, & landing	Enabling ✸	Enhancing	Enhancing					Enhancing	Enabling
10.4 Nuclear reactor control		Enabling ✸	Enhancing						Enabling ✸
10.4 Sub-surface drilling	Enabling ✸	Enabling	Enabling ✸		Enhancing			Enhancing	Enhancing
10.5 Long traverse	Enabling ✸	Enhancing	Enabling ✸		Enhancing			Enhancing	Enhancing
10.5 Aerial survey and sampling	Enhancing	Enabling ✸			Enabling				Enhancing
10.6 Human-robot interaction					Enhancing			Enhancing	Enabling ✸
10.6 ISRU	Enabling ✸		Enabling ✸					Enhancing	Enabling
10.7 In-space inspection				Enhancing	Enhancing		Enhancing	Enhancing	Enabling ✸
10.7 In-space connecting				Enabling ✸				Enhancing	Enabling ✸
10.8 <.1 defect per K SLOC	Enabling ✸	Enabling	Enabling	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling
10.8 Recert. < $1K per K SLOC	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling ✸	Enabling

SMD (Mars – Sun-Earth) ESMD (Spiral 1 – Spiral 3)

Notes:
- Spiral 4 is similar to spiral 3.
- In most case AR&C is developing software to control hardware developed by other capabilities.

✸ First driver

Enabling

Enhancing

Breakthrough Capability Rollup

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Capability	Enables
Autonomy and control for deep drilling (10.4, 10.3, 10.5, and 10.2)	Sub-surface search for evidence of life on Mars and Europa
Dependable, and affordable robotic in-orbit maintenance (10.7 and 10.3)	Instrument change-out and long term operation of observatories
Dependable and affordable robotic in-orbit assembly (10.7 and 10.3)	Large aperture telescopes, affordable human exploration beyond earth-moon neighborhood.
Dependable autonomy for aerobots and sub-surface (10.4, 10.1, and 10.5)	Aerial Mars survey. Surface access on Titan. Search for evidence of life on Europa.
Surface mobility to cliffs and other current inaccessible sites (10.5).	Search for evidence of life on Mars in areas showing possible recent fluid flow
Largely automated CEV and habitat operations (10.1 and 10.2)	Human exploration of Mars.
Autonomous robotic surface construction and ISRU (10.6 and 10.4). Safe, dependable, pinpoint landing (10.3).	Affordable human habitation on Moon and Mars. Robotic site preparation in advance of manned surface missions

Exploration/Science Traceability

- AR&C requirements can be traced back to the following documentation:
  - Major recent vision documents:
    - "The Vision for Space Exploration", 2004, (Doc NP-2004-01-334-HQ)
    - "Exploration Systems Interim Strategy", 2004
    - "A Journey to Inspire, Innovate, and Discover", President's Commission Report
    - "The New Age of Exploration: NASA's Direction for 2005 and Beyond"
  - NASA Enterprise Strategy Documents
    - "The Future of Solar System Exploration, 2003-2013", NRC Planetary Decadal Report, 2002
    - "Assessment of Mars Science and Mission Priorities", National Research Council, 2003
    - "Scientific Goals, Objectives, Investigations, and Priorities" – MEPAG report on priorities for Mars exploration
    - "Mars Exploration Strategy", Mars Science Program Synthesis Group, 2003
    - Solar System Exploration Roadmap, 2003, (Doc JPL 400-1077 5/03)
  - Design Reference Missions
    - Lunar Surface Reference Missions: A Description of Human and Robotic Surface Activities (NASA/TP 2003-212053)
    - The Mars Surface Reference Missions: A Description of Human and Robotic Surface Activities (NASA/TP 2001-209271)
    - Solar System <update from Cutts>
  - ESMD preliminary requirements documents: ESS Technology Requirements RevB, CTS Spirals 1-3 RevB, RLEP Requirements (Sept '04), CEV ConOps (Sept '04)

- Sub-team materials include tracing from each deliverable to the first driving mission (and our assumptions about the timing of that mission)

Interfaces:
Leveraging non-NASA Robotic Developments

- Other players
  - DOD, DOE: well-defined relevant development thrusts (next slides)
  - Industrial: principally manipulators (pick and place, painting, etc)
  - Commercial/consumer: hard to predict, especially the future
    - Roomba vacuum, Aibo dog
  - Diversity of national focus
    - USA: UAVs, UGVs, military
    - Japan: humanoids, care for aging ("silver society")
    - Korea: robotic workers
- Commonality of technologies limited by diversity of applications
  - Perception, navigation, behaviors, planning, HRI
  - Different tasks, environments require different knowledge bases
    - Sensors, effectors must be appropriate to each application
    - May require qualitatively different software approaches
- Space-based computational resources extremely limited
  - Need for rad-hard operation precludes effective exploitation of Moore's law price/performance gains

DoD Robotics Efforts

- DoD Robotics/UXV Service Thrust Areas
  - Army: Future Combat System (FCS): UGVs, UAVs, crew enhancement
  - Navy: UUVs, UAVs
  - Air Force: UAVs
- DARPA Office Robotics-related Themes
  - TTO: UGVs & UAVs (system level), innovative mobility
  - IPTO: software (perception, behavior, learning, HRI)
  - DSO: biological inspired approaches
  - MTO: sensors, actuators, "micro-robots"
  - IXO: sensor systems
  - ATO: ad hoc communications networks
- DARPA Grand Challenge
  - On-road/trail, following dense GPS waypoints, with perception-based corrections for obstacle negotiation
  - Has successfully generated awareness, enthusiasm, and constituency for attacking the autonomous UGV navigation problem
- NASA Participation in IPTO MARS Program
  - Mobile Autonomous Robot Software (1999-2004)
  - JSC (R. Ambrose): perception-based autonomous manipulation and mobility base for Robonaut
  - JPL (L. Matthies): perception for UGV navigation

Comparison—Inter-Agency Robotics Requirements

	NASA	DoD	DoE
Robot Physical Characteristics	**Light, Mass & Volume Constrained**	**Sturdier; Re-Usable; Can Resist Wear and Tear**	**Sturdier; Re-Usable; Can Resist Wear and Tear**
Robot Environment	**Unexplored Terrain; Extreme Cold/Heat**	**Earth Terrain; On-Road & Off-Road**	**Radiation Rich Sites**
Distance from Control and Command Station	**Up to Millions of Kilometers**	**Few Kilometers**	**Up to 1 Kilometer**
Robot Level of Autonomy	**Semi-Autonomous (long time-delay)**	**Teleoperation/Semi-Autonomous (short time delay)**	**Teleoperation/Semi-Autonomous (short time delay)**
Robot Manipulators	**Pick-Up and Handle Small Objects (e.g. rocks); Low-Gravity Manipulation of Human-Made Objects**	**Lift and Handle Heavy Loads**	**Lift and Handle Heavy Loads**
Robot Vision	**Discover Interesting Science Samples; Detect Natural Hazards**	**Detect & Track Human Objects (walking soldier; moving lead vehicle)**	**Inspect Hazardous Sites; Cluttered Environment**

Leveraging non-NASA Robotic Developments

- NASA is well aware of non-NASA efforts
  - Some joint work with non-NASA sponsors
- Commonalities in technology needs are limited by:
  - Differences in application requirements
    - Differences in environments (e.g., no vegetation)
    - Differences in tasks to be performed
  - Differences in resources available
    - Communications latency and bandwidth
    - Limited opportunity to exploit human support
    - Limited computing power and memory due to rad-hard requirement
- Bottom Line: we can't wait for someone else to do what we need to have done

Capability Roadmap Crosswalk

	Capability Roadmap	Crosswalk Status to Date
Yellow	2. High-energy power and propulsion	
Yellow	3. In-space transportation	Initial discussion with leads. Exchange of material. Results incorporated.
Yellow	4. Advanced telescopes and observatories	Exchange of material.
Yellow	5.Communication & Navigation	Exchange of material.
Red	6. Robotic access to planetary surfaces	Presentations to team workshops. Exchange of materials and multiple ongoing discussions.
Yellow	7. Human planetary landing systems	Discussions with team. Attendance at workshop.
Yellow	8. Human health and support systems	Initial discussions with leads.
Red	9. Human exploration systems and mobility	Close working relationship with lead.
Green	11. Transformational spaceport/range technologies	
Yellow	12. Sensors and instruments	Minimal discussions. Have draft of material.
Yellow	13. *In situ* resource utilization	
Green	14. Advanced modeling, simulation, analysis	
Green	15. Systems engineering cost/risk analysis	
Green	16. Nanotechnology	

Green	Limited relationship (or relationship at sub-capability level)
Red	Critical Relationship
Yellow	Moderate Relationship

Strategic Roadmap Crosswalk

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	Strategic Roadmap	Crosswalk Status to Date
Red	1. Lunar: Robotic and Human Exploration	Jim Watzin presentation at workshop.
Red	2. Mars: Robotic and Human Exploration	Dave Lavery representing Mars program.
Red	3. Solar System Exploration	Design Reference Missions and strategic guidance documentation. Discussions with Jim Cutts and Scott Hubbard.
Yellow	4. Search for Earth-Like Planets	Design Reference Missions and strategic guidance documentation.
Green	6. International Space Station	
Green	7. Space Shuttle	
Yellow	8. Universe Exploration	Design Reference Missions and strategic guidance documentation.
Yellow	9. Earth Science and Applications from Space	Design Reference Missions and strategic guidance documentation.
Yellow	10. Sun-Solar System Connection	Design Reference Missions and strategic guidance documentation.
Yellow	11. Aeronautical Technologies	
Yellow	12. Education	
Yellow	13. Nuclear Systems	
Green	Limited Relationship	
Red	Critical Relationship	
Yellow	Moderate Relationship	

Capability Readiness Levels

7. Capability Operational Readiness
6. Integrated Capability Demonstrated in an Operational Environment
5. Integrated Capability Demonstrated in a Relevant Environment
4. Integrated Capability Demonstrated in a Laboratory Environment
3. Sub-Capabilities* Demonstrated in a Relevant Environment
2. Sub-Capabilities* Demonstrated in a Laboratory Environment
1. Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

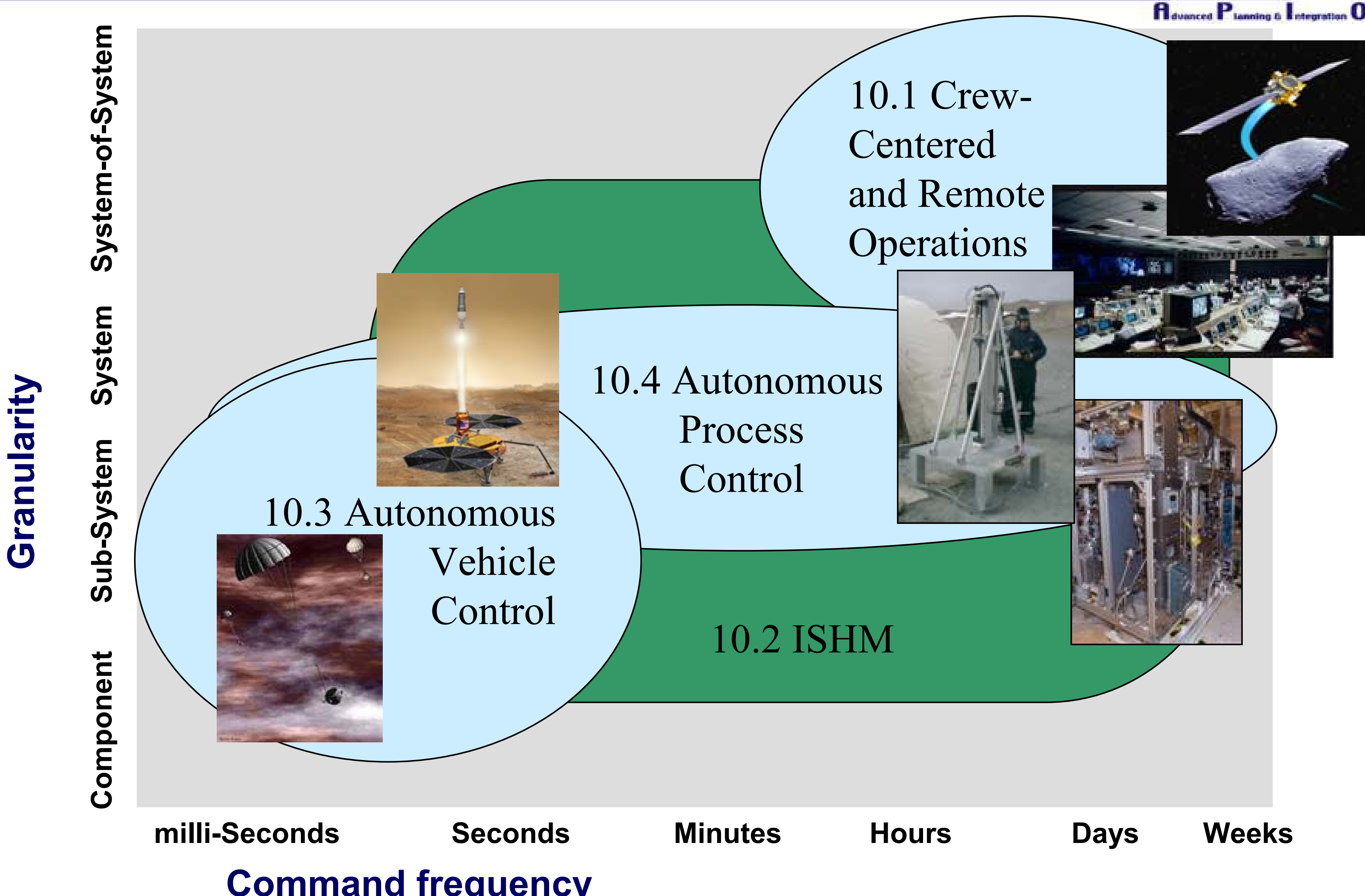
The Four Questions (again)

1. Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?
2. Are technology maturity levels accurately conveyed and used?
3. Are proper metrics for measuring advancement of technical maturity included?
4. Do the Capability Roadmaps have connection points to each other when appropriate?

Overview

- Introduction (Steve Zornetzer)
- Process, Mission Drivers, Deliverables, and Interfaces (James Crawford)
- **Autonomy (James Crawford)**
  - **Crew-Centered and Remote Operations**
  - **Integrated Systems Health Management**
  - **Autonomous Vehicle Control**
  - **Autonomous Process Control**
- Robotics (Paul Schenker)
  - Robotics for Solar System Exploration
  - Robotics for Lunar and Planetary Habitation
  - Robotics for In-Space Operations
- Computing Systems (Mike Lowry)
- Conclusion

Autonomous Systems – 10.1-10.4



Capability 10.1
Crew-Centered and Autonomous Operations

Sub-Team Chair: Julia Loftis, NASA/GSFC
Presenter: James Crawford, NASA/ARC

Capability 10.1
Crew-Centered and Autonomous Operations

- **This capability area defines the evolution of command and control for both manned and unmanned science and exploration missions. This includes:**
  - Crew-Centered Planning (activity sequences created by crew rather than ground personnel)
  - Autonomous Mission Operations
    - Health and Safety Monitoring, Analysis and Anomaly Recovery
    - Science Analysis and Optimization
    - Dynamic Planning
    - Onboard Robust Execution
    - Logistics and Inventory
  - Multi-system Coordination and Collaboration
  - Human Automation Interaction
  - Multi-modal Interfaces for Collaborative Execution

Benefits of Capability 10.1
Crew-Centered and Autonomous Operations

- **Crew-centered** operation is *enabling* for Martian exploration due to both the latency of light speed communication, and the potential loss of communication.
- **Autonomous** operation is *enabling* for some classes of planetary surface exploration and remote in-situ science.
- Additional benefits
  - Reduced operations costs
  - Ability to react to unforeseen circumstances without reliance on ground → increased safety
  - Ability to take advantage of schedule gaps → increased efficiency

Summary Status for Capability 10.1 Crew-Centered and Autonomous Operations

- Operation of crewed missions (Station and Shuttle) is presently a manually intensive process:
  - Station flight controllers uplink ~500,000 individual commands per year to fly and maintain the craft
  - A team of 50 Station mission planners manually develops a timeline for each crew member, which takes 2 weeks for each day's activities; safety and feasibility constraint checking is not automated, but is handled through the knowledge of these experts
  - The Russians (who do not have constant communication via TDRSS as we do) upload some automated procedures.
- Operation of unmanned vehicles is done via ground based sequence generation with some low level task automation and automated constraint checking; onboard automated safety procedures are routinely implemented
- The state of the art in this area includes technology demonstrations for autonomous operation
  - EO-1 ('03-'05): technology demonstration of autonomous tracking of science events, onboard mission planning, smart task execution, and model-based diagnosis; autonomous formation maneuver planning and execution
  - DS-1 ('99): technology experiment demonstrating autonomous planning, diagnosis, and execution

Detailed Status for Capability 10.1 Crew-Centered and Autonomous Operations

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- Crew Centered Planning
  - Constraint-based activity planning (MER)
  - Ground-based automated scheduling (Shuttle ground processing)

- Autonomous Mission Operations
  - Health and Safety Monitoring, Analysis & Anomaly Recovery
    - NASA: largely manual (except critical onboard sequences)
    - Fail-operational autonomous on-board control (DS-1)
    - On-board model-based diagnosis (EO-1/DS-1)
    - DOD/DARPA? External? (JSF,777)
  - Science Analysis and Optimization
    - Autonomous tracking and reaction to science events (EO-1)
  - Dynamic Planning
    - DS-1 and EO-1 technology demonstrations cited above
    - MER (MAPGEN ground planner)
  - Onboard Robust Execution
    - DS-1/ESL, EO-1/SCL
    - Terrestrial robotic demonstrations (LITA, PSA, K-9)
  - Logistics and Inventory
    - NASA: time-consuming, manual process to maintain database
    - External: barcode, RFID (powered & passive)

Current Status for Capability 10.1 Crew-Centered and Autonomous Operations

- Multi-platform Coordination and Collaboration
  - “String of pearls” constellation control (Terra,Aqua,Aura,EO-1)
  - Technology demonstration of cooperation between two spacecraft: leading spacecraft perceives a phenomena and trailing spacecraft reacts to it. (EO-1)
- Human Automation Interaction
  - Tele-operation with sequential command, execution; during execution, some subtasks (such as alignment) are automated
  - Mixed initiative activity planning used for MER (MAPGEN)
- Multi-modal Interfaces for Collaborative Execution
  - In-situ Crew Training
    - Written procedure list; simple assistance for problem diagnosis
    - Task demonstration as human simulation
    - Free-Flying Mobile Robot with LCD/Pointer/Sensors (PSA)
  - EVA Support
    - Basic informational displays within helmet
    - AERCam in testing
  - Voice-based intelligent procedure access (Clarissa)

Summary of Deliverables for Capability 10.1 Crew-Centered and Autonomous Operations

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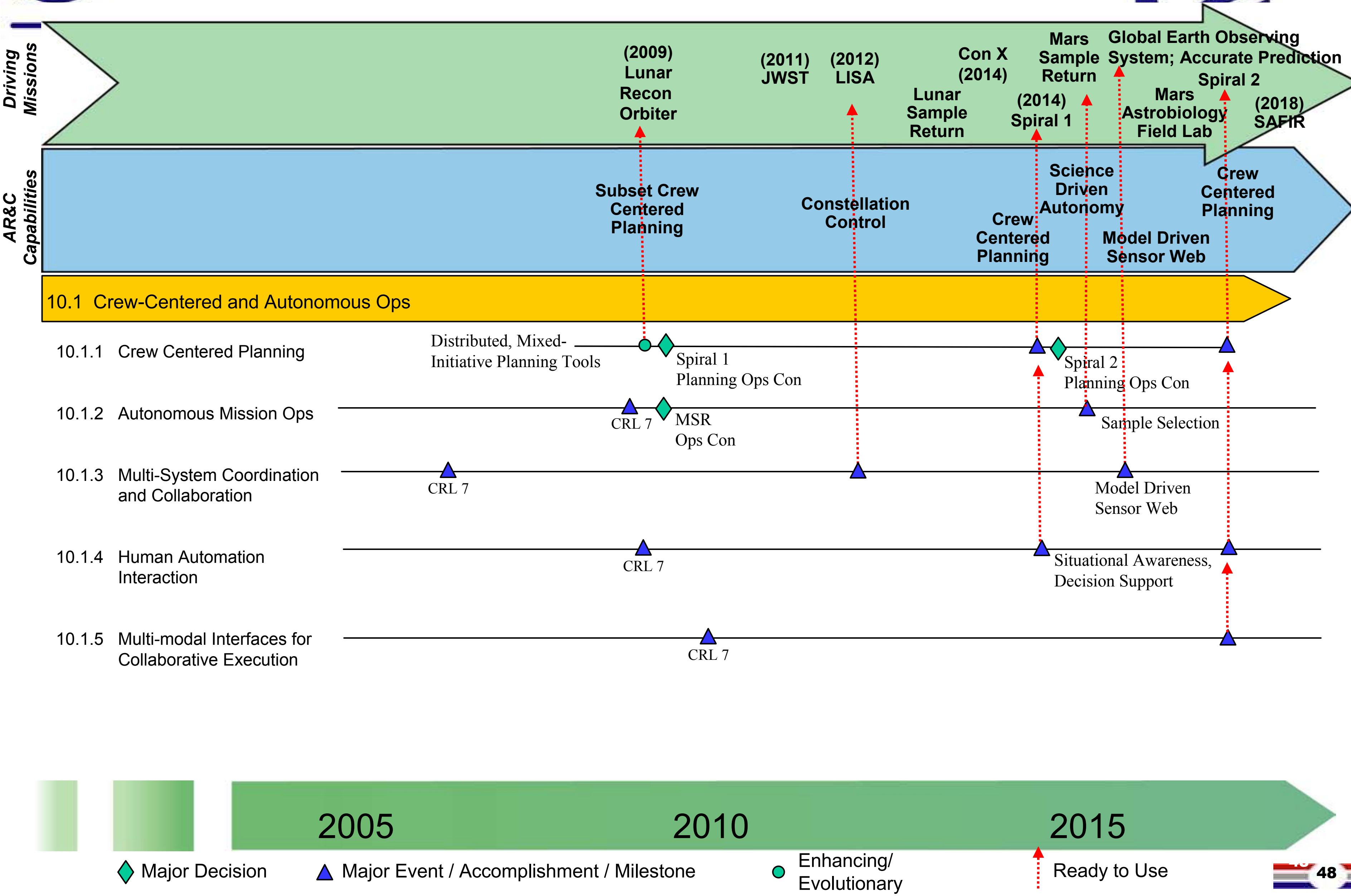
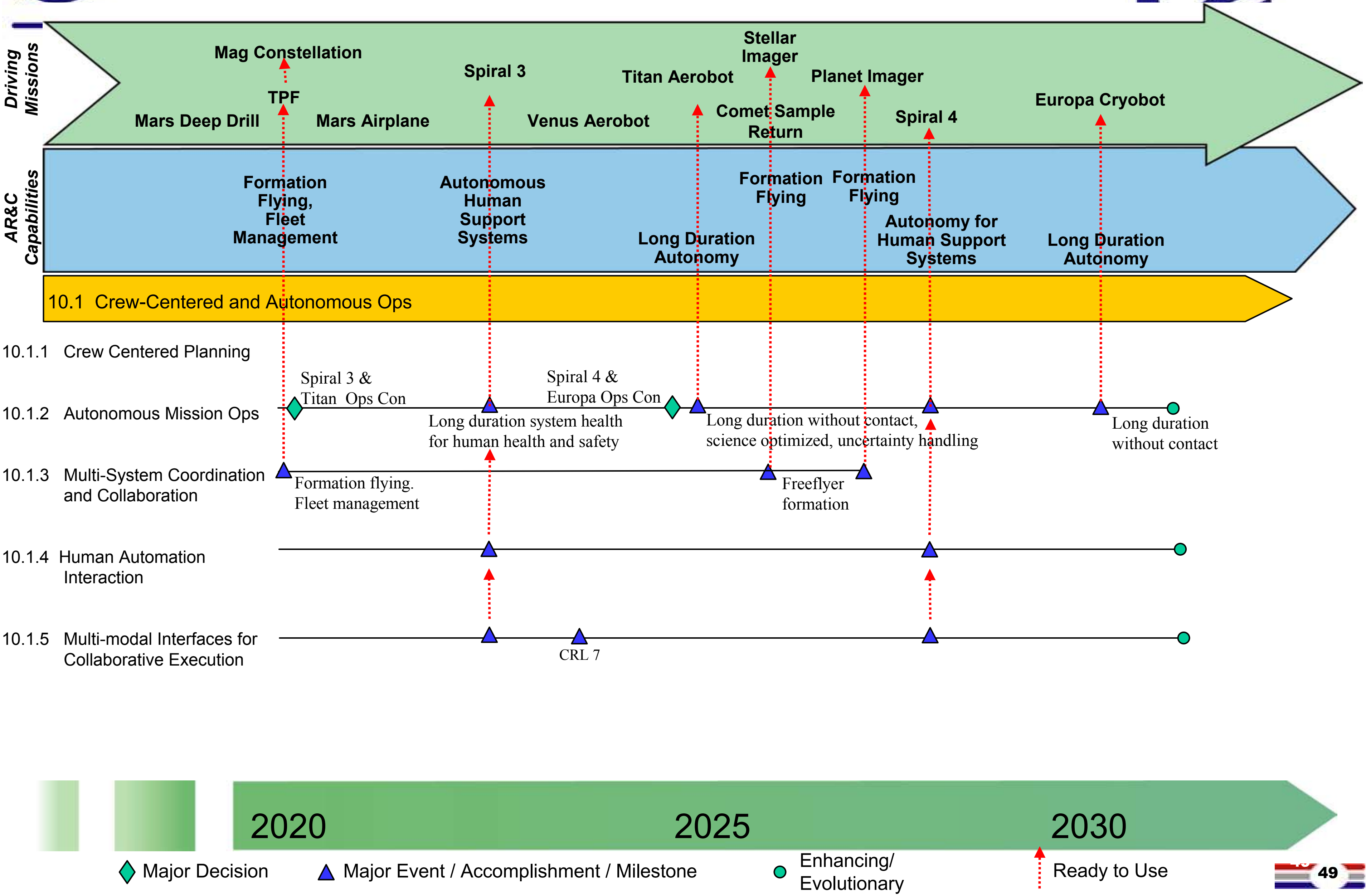
- Human Automation Interaction: Rapid Situational Awareness, Data Analysis, and Decision Support Tools
  - ESMD: Spiral 1 : TRL 6 by 2009
- Crew Centered Planning: Distributed, Constraint-based, Mixed-initiative, Mission Ops Planning Tools
  - ESMD: Spiral 2: TRL 6 by 2010
- Multi-modal Interfaces for Collaborative Execution (e.g., voice for EVA)
  - ESMD: Spiral 2: TRL 6 by 2010
- Multi-platform Coordination and Collaboration
  - SMD: LISA-3, MMS-4, GEC-4, MagCon-50 2012-2014, Stellar Imager-25 2015, Black Hole Imager Pathfinder-several 2018, Earth Science Sensor Web
  - ESMD: Spiral 2: TRL 6 by 2010
- Autonomous Mission Operations: Health and Safety Monitoring, Analysis & Anomaly Recovery; Science Analysis and Optimization; Dynamic Planning; Logistics and Inventory
  - SMD: MSL 2009, MSR 2013, Earth Science Sensor Web, Titan / Europa missions (weeks out of contact), LISA 2012
  - ESMD: Spiral 3: TRL 6 by 2015

Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Deliverables for Capability 10.1 Crew-Centered and Autonomous Operations

- Human Automation Interaction: Rapid Situational Awareness, Data Analysis, and Decision Support Tools
  - ESMD Driver: Spiral 1, CEV (2014)
  - TRL 6 date: 2009
  - Interfaces: HESM
  - Decision points: Technology demonstrations

- Crew Centered Planning: Distributed, Constraint-based, Mixed-initiative, Mission Ops Planning Tools
  - ESMD Driver: Spiral 2, lunar surface habitat (2015)
  - TRL 6 date: 2010
  - Interfaces: HESM
  - Decision points: Technology demonstrations in spirals 1 & 2

Deliverables for Capability 10.1 Crew-Centered and Autonomous Operations

- Multi-modal Interfaces for Collaborative Execution: Voice interfaces between flight crew and automated tools and robots, mixed GUI-voice interfaces for ground crew. (Some risk)
  - ESMD Driver: Spiral 2, surface ops with EVA (2015)
  - TRL 6 date: 2010
  - Interfaces: HESM, HHS
  - Decision points: Technology demonstrations in spirals 1 & 2

- Multi-platform Coordination and Collaboration: Command and control for coordinated observation, sensor web, interferometery, etc.
  - ESMD Driver: Spiral 2, CEV and Lunar Lander (2015)
  - SMD Drivers: LISA-3 (2012), MMS-4 (2012), GEC-4 (2014), MagCon-50 (2013), Stellar Imager-25 2015, Black Hole Imager Pathfinder-several (2018), Earth Science Sensor Web
  - TRL 6 date: 2007
  - Interfaces: HESM. SIS, ATO
  - Decision points: Technology demonstrations in spirals 1 & 2

Deliverables for Capability 10.1 Crew-Centered and Autonomous Operations

- Autonomous Mission Operations: Health and Safety Monitoring, Analysis & Anomaly Recovery; Science Analysis and Optimization; Dynamic Planning; Logistics and Inventory
  - ESMD Driver: Spiral 3, lunar surface habitat (2020)
  - SMD Drivers: MSR sample selection (2013), Earth Science Sensor Web, Titan / Europa missions (weeks out of contact), LISA (2012)
  - TRL 6 date: 2004
  - Interfaces: HESM, SIS, AMSA
  - Decision points: Technology demonstrations in spirals 1 & 2

Maturity Level – Capabilities for 10.1 Crew-Centered and Autonomous Operations

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Crew Centered Planning	Distributed, mixed-initiative constraint-based planning tools (ground and onboard)	2 (crewed missions)	6	ESMD Spiral2	2010
	Graphical interfaces to support plan creation and modification	2 (crewed missions)	6	ESMD Spiral2	2010
Autonomous Health & Safety Monitoring, Analysis and Anomaly Resolution	On-board tools to support diagnosis and recovery by crew	2	6	ESMD Spiral2	2010
	Automated uncertainty handling – autonomous information gathering for resolution	2	6	SMD MSR ESMD Spiral3	2008 2015
	Rapid creation of ad-hoc teams	2?	6	ESMD Spiral1	2009

Maturity Level – Capabilities for 10.1 Crew-Centered and Autonomous Operations

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Autonomous Science Analysis, Predictive Modeling, and Optimization	Science goal driven autonomous systems	2	6	SMD LISA, MSR	2007
Autonomous, Dynamic Planning	Embedded, continuous planning integrated with execution decision theoretic planning	2	6	SMD Titan Aerobot, Europa Cryobot	2010
Onboard, Robust Execution	Reactive task decomposition, health management with goal-achieving recovery	4	6	LISA, MSR	2007
Automated Logistics and Inventory	Inventory / supply chain management	2	6	ESMD Spiral2	2010
Multi-Platform Coordination and Collaboration	Formation flying	2	6	SMD LISA, MMS	2007
	Inter-satellite communication and networking	2	6	TBD	
	Fleet Management (centralized and decentralized)	2	6	SMD MagCon	2008
	Model-driven sensor web	2	6	SMD ES Sensor Web	?

Maturity Level – Capabilities for 10.1 Crew-Centered and Autonomous Operations

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Human Automation Interaction	Rapid situational awareness (visualization of complex information and actions of autonomous systems)	2	6	ESMD Spiral1	2009
	Decision support systems	2	6	ESMD Spiral1	2009
	Trusted autonomy	2	6	SMD MSR ESMD Spiral3	2008 2015
Multi-modal Interfaces for Collaborative Execution	Multi-media interfaces (presentation and reception)	2	6	ESMD Spiral2	2010
	Crew observation, analysis, and assistance	2	6	ESMD Spiral2	2010

Maturity Level – Technologies for 10.1 Crew-Centered and Autonomous Operations

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Distributed, mixed-initiative constraint-based planning tools (ground and onboard)	Planning engine and logic; prioritization scheme	MAPGEN, ASPEN, PASSAT	7	Crew centered mission planning and control	2010
Graphical interfaces to support plan creation and modification	Plan presentation, editing, and explanation of automation	MAPGEN, SAP	7		2010
On-board tools to support diagnosis and recovery by crew	Presentation of fault diagnosis and supporting information	SERS	3	Advanced approaches to communication of complex context, history information	2008
Automated spacecraft health management with uncertainty handling	Probabilistic fault diagnosis and resolution; autonomous information gathering for resolution	PSA Agent, DAPRA Prognosis Program, Army F135 engine health management			
Rapid creation of ad-hoc teams with critical skills for anomaly resolution		SERS	3		2009

Maturity Level – Technologies for 10.1 Crew-Centered and Autonomous Operations

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Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Science goal driven autonomous systems	Goal Capture, Real-time Data and Information Fusion and Analysis	SGM, Domain specific algorithms and models, SWIFT TOO and FOM	6	Performance of key algorithms; data interoperability	2007
Embedded, continuous planning integrated with execution decision theoretic planning	Constraint network, heuristic set, goal set, uncertainty specs	ASPEN / CASPER, Livingstone, EUROPA	6	Performance, verification	2010
Robust Execution Technology	State estimation, task decomposition, goal assessment, recovery, adjustable autonomy	Remote Agent, IDEA, 3T/RAPS, APEX, ESL, TDL, SCL	7 5 6 6	Verification	2007
Inventory / supply chain management	Tag (RFID/Barcode), detector	Autonomous Detector (PSA)	5	Currently manual.	2010
Formation Flying	Formation Control, Relative Navigation	SPHERES, PSA Agent, Autocon, Decentralized Formation Control	5	Operational infusion	2007
Inter-satellite communication and networking		API Crosslink Transceivers (CLT)			

Maturity Level – Technologies for 10.1 Crew-Centered and Autonomous Operations

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Fleet Management (centralized and decentralized)	Path planning and optimization, collision avoidance, collaboration, distributed architectures	ASF	4	Spacecraft application	2008
Model driven sensor web	Data fusion, realtime analysis, sensor collaboration		4	Performance, interoperability	2007
Rapid situational awareness	Visualization of complex information and actions of autonomous systems		3	Communication of complex information	2009
Decision support systems	Knowledge management and presentation		4		2009
Trusted autonomy			4	Reliability, predictability	2008
Multi-media interfaces	Presentation and perception	Clarissa	4	Ease of use	2010
Crew support	Observation, analysis, and assistance		3	Ease of use	2010

Metrics for 10.1
Crew-Centered and Autonomous Operations

Metric	Technology / Sub-Capability	Current Value	Target Value*	Need Date
Number of CEV (or other major) system commands issued weekly by ground crew	Crew centered operations	10,000	1000 100	Spiral 2 (2018) Spiral 3 (2023)
Hours per week of flight crew time required for spacecraft operations	Onboard automation	1 (done by ground)	10	Spiral 3 (2023)
Planned and actual average percent of days of onboard autonomous operation	Onboard automation	0 (except for DS1, EO1)	90%	TBD
Size of ground crew for regular and extended missions. Percent of ground crew that must be physically co-located.	Autonomous mission operations	Varies by mission	Cut by 75%	TBD
Percent of science decisions (e.g., target selection, download prioritization, etc.) that can be done onboard	Autonomous science analysis and optimization	0% (except EO1)	75%	TBD
Hours per week of flight and ground crew time spent tracking inventory (for CEV, lunar base or other facility)	Automated logistics and inventory	TBD	Cut by 90%	TBD
Size of ground team required for coordinated operation of spacecraft fleets	Multi-platform coordination and collaboration	TBD	Cut by 75%	TBD
Minutes required for human ground crew to understand status of remote autonomous craft they were not previously monitoring	Situational Awareness	NA (no current craft are autonomous)	10 min.	TBD

*Target values are an educated guess until mission requirements are finalized.

Technology Candidates

APEX - Architecture for Procedure Execution (ARC)
ASF – Adaptive Sensor Fleet (GSFC)
ASPEN - Automated Scheduling and Planning ENvironment (JPL)
Autocon – Automated On-board Maneuver Planning (GSFC)
CASPER - Continuous Activity Scheduling Planning Execution and Replanning (JPL)
Clarissa – Spoken-Language Dialogue System (ARC)
CLT – Crosslink Transcievers (APL)
ESL – Execution Support Language (JPL)
EUROPA – Extensible Universal Remote Operations Planning Architecture (ARC)
Livingstone – (ARC)
IDEA – Intelligent Distributed Execution Architecture (ARC)
MAPGEN - Mixed-Initiative Activity Planning GENerator (ARC/JPL)
PSA Agent- Personal Satellite Assistant Agent (ARC)
Remote Agent – (ARC)
SAP – Science Activity Planner (JPL)
SHAC – Shared Hierarchical Activity Coordination (SHAC)
SCL – Spacecraft Command Language (ICS)
SGM – Science Goal Monitor (GSFC)
SPHERES - Synchronized Position Hold Engage and Reorient Experimental Satellites (MIT/ARC)
TDL – Task Description Language (CMU)
3T/RAPS – Three-tier Agent/Reactive Action Packages (JSC)

Capability 10.2
Integrated Systems Health Management (ISHM)

Sub-Team Chair: Serdar Uckun, NASA/ARC

Sub-Team Co-Chair: Brian Williams, MIT

Presenter: Serdar Uckun, NASA/ARC

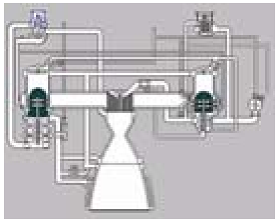
Summary for Capability 10. 2
Integrated Systems Health Management

- Today's state-of-the-art in spacecraft health is fault detection, isolation, and recovery (FDIR).
  - Based on fixed detection/isolation logic and recovery procedures.
  - Verified and validated using exhaustive testing.
  - Fragile (limited modeling of interactions with outside world or across subsystems, anomalous behavior depending on rule orderings).
  - Not scalable (verification and validation complexity increases dramatically with number of inputs/outputs/state variables).
- ISHM is the next frontier in systems health.
  - Highly desirable for complex exploration missions in ill-understood environments.
  - Based on scalable, flexible, model-based detection, isolation, and recovery methods.
  - Integrated into spacecraft at design stage and not as an afterthought.
  - Critical investment for safety, reliability, and mission assurance.

Capability 10.2
Integrated Systems Health Management

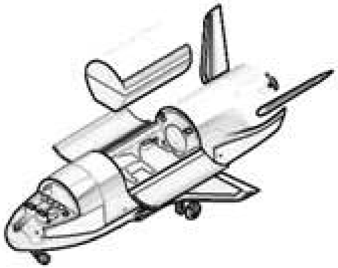
This capability area defines capabilities for robust mission operations throughout the system lifecycle.

- **Design of Health Management Systems**
  - Testability
  - Maintainability
  - Recoverability
  - Verification and validation of ISHM capabilities
  - Verification and validation of software under failure



- **Real-Time Systems Health Management**
  - Distributed sensing for structural health
  - Fault detection, isolation, and recovery
  - Failure prediction and mitigation
  - Robust control under failure
  - Crew and operator interfaces

- **Informed Logistics**
  - Modeling of failure mechanisms
  - Prognostics
  - Troubleshooting assistance
  - Maintenance planning
  - End-of-life decisions



Benefits of Capability 10. 2
Integrated Systems Health Management

- **ISHM *enables*:**
  - Mitigation of failures with short time to criticality,
  - Robust execution of critical maneuvers,
  - Self-sufficient, crew-centered operations, and
  - Missions in harsh environments.
- **ISHM *enhances*:**
  - Long duration missions, and
  - Ground operations (e.g., logistics).
- **Additional benefits:**
  - Increased crew and payload safety,
  - Reduced maintenance costs through adoption of condition-based maintenance policies, and
  - Faster turnaround of reusable systems.

State-of-the-Art for Capability 10. 2 Integrated Systems Health Management

- **Design of Health Management Systems:**
  - ISHM functions often designed *after* initial design of the system.
  - Joint Strike Fighter incorporated prognostics requirements into design.
  - Qualitative failure analysis methods commonly used by NASA (FMEA).
  - Quantitative criticality assessment methods favored by DoD (FMECA).
- **Real-Time Systems Health Management:**
  - Limited sensing capability (weight and power concerns).
  - Caution and warning events require human expertise to resolve.
  - Inflexible recovery schemes (typically scripted failover to backups).
  - Model-based diagnosis and recovery demonstrated on two NASA spacecraft, EO-1 and DS-1.
- **Informed Logistics:**
  - Limited built-in troubleshooting aids in components and subsystems.
  - Trends in industry beyond fixed scheduled maintenance (e.g., condition-based and informed maintenance practices).
  - Prognostics becoming a key driver for systems health (notably JSF and Boeing 777).

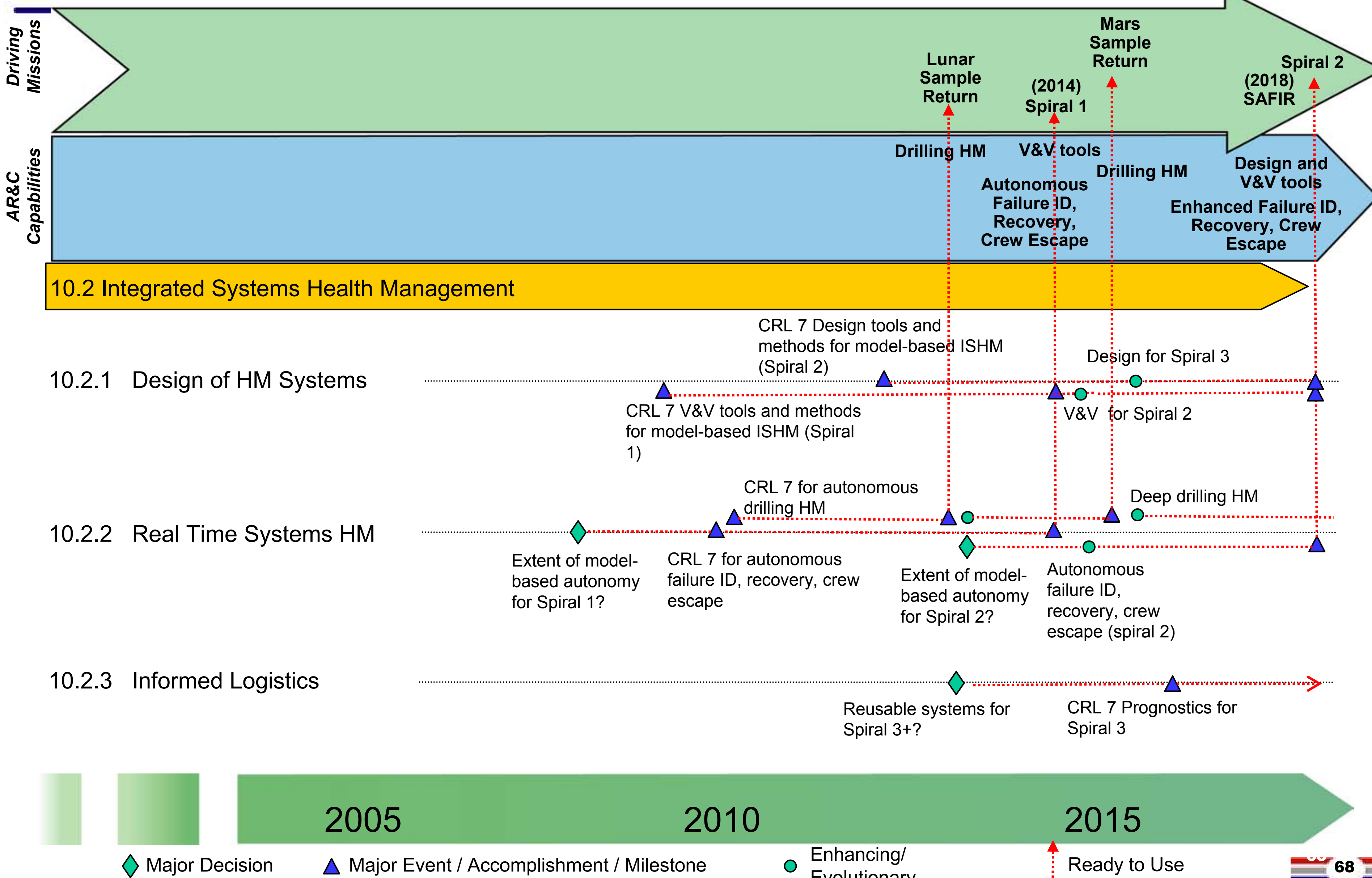
Requirements /Assumptions for Capability 10. 2 Integrated Systems Health Management

- **Crewed Missions**
  - Spiral 1: 2014 Crew Transportation System (CTS) (per ESMD-RQ-0011)
    - *Detection and annunciation of conditions which could result in loss of human life, loss of vehicle, loss of mission, or significantly impact mission capability.*
    - *Autonomous (preferably automated) isolation and recovery from conditions which could result in loss of human life or loss of vehicle.*
    - *Anytime autonomous (preferably automated) abort and crew escape capability.*
    - *Autonomous (preferably automated) rendezvous and docking capability.*
  - Spiral 2: 2015-2020 CTS and extended-duration lunar surface ops
    - *Technology demonstration of ISHM for life support subsystems (anticipated).*
  - Spiral 3: 2020+ Long-duration lunar surface missions
    - *Prognostics and remaining life estimation for critical subsystems and components.*
  - Spiral 4: 2025 Mars transit and vicinity ops
    - *Robust, automated process control and ISHM of all major subsystems on the CTS.*
  - Spiral 5: 2030+ Martian surface habitat and exploration
    - *Above plus ISHM of all major subsystems on the Mars habitat.*

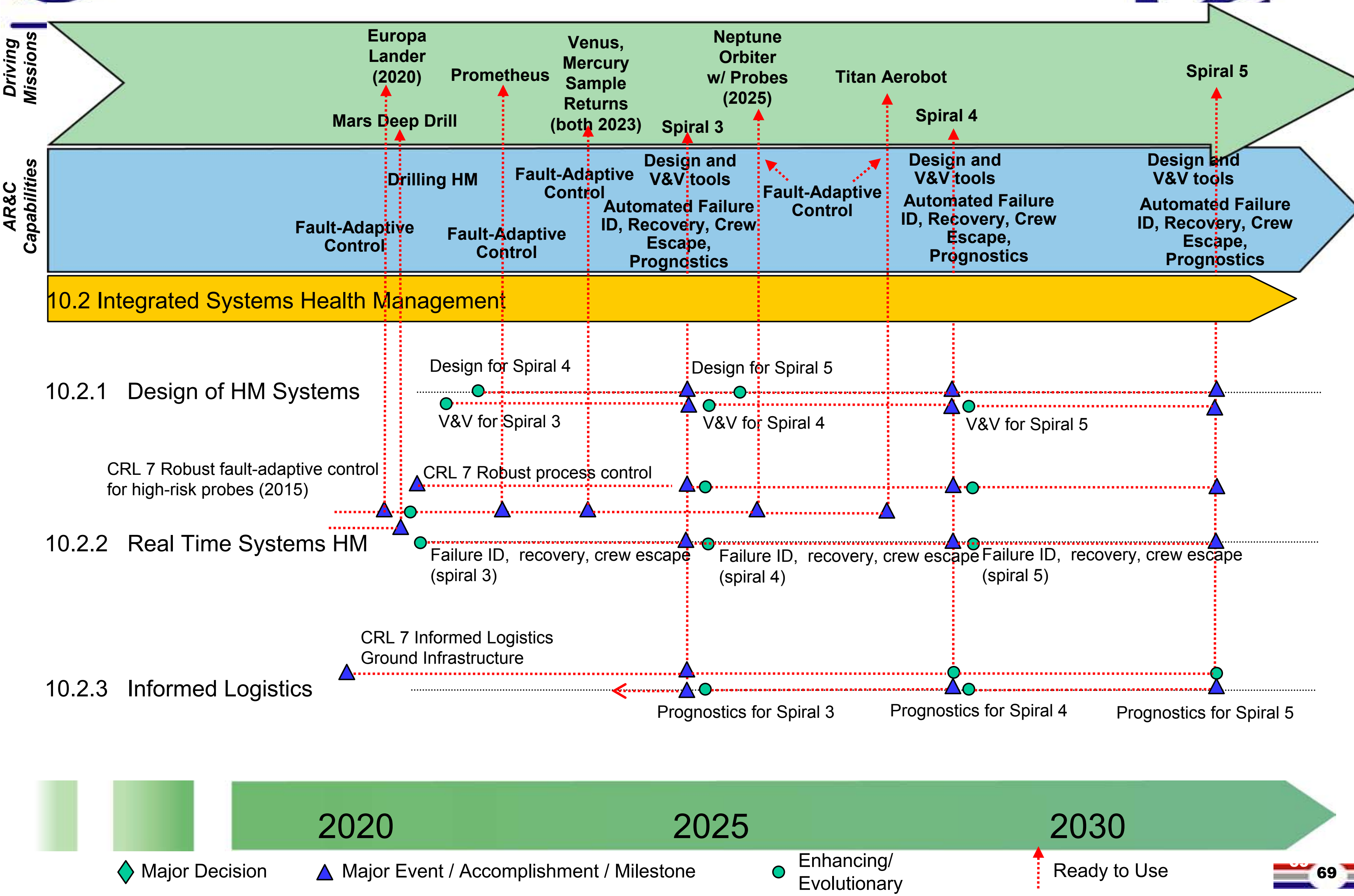
Requirements /Assumptions for Capability 10. 2 Integrated Systems Health Management

- **Robotic Exploration and Science Missions**
  - Robotic Lunar Exploration Program (2009+)
    - *Automated, robust control and recovery of sensor systems during long-duration reconnaissance missions.*
    - *ISHM and recovery for surface ops (ISRU, drilling).*
  - Mars (2011+)
    - *Evolutionary enhancements to increase efficiency and science return, e.g., fault-adaptive control for surface ops (ISRU, drilling, rover mobility).*
  - Solar System (2014+)
    - *Robust, fault-adaptive control for nuclear reactors.*
    - *Robust, fault-adaptive control for autonomous high-risk expeditions (Venus surface, Titan, Europa, etc.).*
  - Observatories (2020+)
    - *Robust coordination of multi-spacecraft constellations (e.g., interferometers).*

Capability Roadmap for Capability 10. 2 Integrated Systems Health Management



Capability Roadmap for Capability 10. 2
Integrated Systems Health Management



Deliverables for Capability 10. 2
Integrated Systems Health Management

- Verification and validation methods for model-based ISHM (some risk)
  - Driver: ESMD Spiral 1
  - CRL 7: 2009+
  - Interfaces: System Engineering Cost/Risk Analysis CRT
- Autonomous failure identification and recovery for CTS (some risk)
  - Driver: ESMD Spiral 1
  - CRL 7: 2009
  - Interfaces: In-Space Transportation CRT; System Engineering Cost/Risk Analysis CRT
- Autonomous anytime abort and crew escape decision capabilities for CTS (some risk)
  - Driver: ESMD Spiral 1
  - CRL 7: 2009
  - Interfaces: In-Space Transportation CRT; System Engineering Cost/Risk Analysis CRT
- ISHM for ISRU, remote drilling, surface mobility, and surface assembly tasks
  - Driver: RLEP, MTP, ESMD Spiral 3
  - CRL 7: 2011
  - Interfaces: Robotic Access to Planetary Surfaces CRT; ISRU CRT

Deliverables for Capability 10. 2 Integrated Systems Health Management

- Tools and methods for codesign of function and ISHM
  - Driver: ESMD Spiral 2
  - CRL 7: 2012
  - Interfaces: System Engineering Cost/Risk Analysis CRT
- Robust autonomous monitoring, control, and recovery for life support and other subsystems (some risk)
  - Driver: ESMD Spiral 2
  - CRL 7: 2012+
  - Interfaces: In-Space Transportation CRT; Human Health and Support Systems CRT
- Robust fault-adaptive control for autonomous probes in harsh environments
  - Driver: SMD Solar System Exploration, Prometheus
  - CRL 7: 2012+
  - Interfaces: High Energy Power & Propulsion CRT
- Prognostics for spacecraft and habitation systems
  - Driver: ESMD Spiral 3
  - CRL 7: 2016+
  - Interfaces: In-Space Transportation CRT; Human Health and Support Systems CRT
- Informed Logistics ground infrastructure
  - Driver: ESMD Spiral 3 (assuming reusable systems)
  - CRL 7: 2020
  - Interfaces: Transformational Spaceport CRT; Exploration Transportation System SRT

Maturity Level – Technologies for Design of Health Management Systems

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Tools/methods for testability	Function and Behavior Modeling Standards	RMPL, TEAMS, FACT Modelica	6-7 3-5 6-7	Established standards No failure models	2009
	Model-based diagnosis and recovery engines	Livingstone, Titan, HyDE, TEAMS, BEAM FACT	5-7 3-5	Certification of engines; V&V methods for models; engine scalability	2009
Function-based failure analysis and design methods	Component function models and failure libraries	FFDT	3-4	Comprehensive failure datasets	2012
	Function-based reasoning engines				
Systems analysis and optimization for ISHM	Sensor placement optimization Figures-of-merit tradeoff analyses	TEAMS	6-7	Cost/benefit trade studies for spacecraft sensor systems	2008
	Sensor selection	DTOOL	4-5	Limited to causal diagnosis	

Maturity Level – Technologies for Real-Time Systems Health Management

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Distributed sensing	Misc. physical and chemical sensors	Misc.	6-7	Sensor durability and reliability	All missions
	Sensor power and data communications	Wired (multiple architectures) or wireless sensor networks	9 (wired); 5-6 (wireless data); 3-4 (wireless power)	Long-term power for wireless sensors; scalable wired architectures	2008+
Situational awareness tools	Data mining and data fusion tools	Misc. commercial and R&D tools (e.g., BEAM, IMS)	3-7	Visualization of very large data sets; effective data reduction	2018
	Integrated vehicle capability and impact assessment	N/A	2	No current investment	2012
Diagnosis and Recovery	Model-based diagnosis	Titan, Livingstone, HyDE, HME, CME, etc.	5-7	V&V; response time; HW/SW and subsystem interactions; hybrid systems; model acquisition	2009
	Model-based recovery	Titan, Livingstone	4-5	V&V; flight validation; coverage of continuous problem domains	2009
	Rule- or dependency-based diagnosis	SHINE, TEAMS, etc.	9	N/A	Available today
ISHM User Interfaces	Displays for crew and ground	Misc.	4-9	Multimodal interfaces	2009
	Recovery procedures	Computer-based procedure manuals	9 (written); 6 (computer-based)	On-demand procedure generation and verification	2009

Maturity Level – Technologies for Informed Logistics

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Prognostic models	Life remaining estimates	Custom models	3-4	Gold standard datasets and testbeds	2015+
	Short-term predictions of functional degradation and failure	Custom models	3-4	Modeling and analysis of across-subsystem interactions	2009
Physics of failure models	Mechanical systems; propulsion systems; structures; electronics	Custom models	3-4	Understanding and quantifying effects of operational environments	2015+
Maintenance Informatics	Planning and scheduling tools	CMMD (USC/ISI, VU/ISIS and DARPA); Autonomic Logistics (JSF)	4-5	Condition-based and informed maintenance practices	2015
	Distributed logistics databases and data analysis tools	Autonomic Logistics (JSF)	4-5	Conflict between access and data security needs	2015
	Integrated logistics architectures	Boeing Sustainment Data System	6-7		2015

Metrics for Design of Health Management Systems

Metric	Technology / Sub-Capability	Target Value	Need Date
% testability of critical failures on a Critical Items List (CIL)	*Tools/methods for testability; System Analysis and Optimization*	100%	2009
Sensor redundancy (alternative means of confirming the validity of data from a particular sensor)	*System Analysis and Optimization*	>2	2009

Metrics for Real-Time Systems Health Management

Metric	Technology / Sub-Capability	Target Value	Need Date
Ambiguity group size	*Diagnosis*	1 for CIL items; 2 for non-critical items	2009
Latency	*Diagnosis and Recovery*	< 2 plant time constants	2009
Sensitivity (% false negatives)	*Diagnosis and Recovery*	Low-very low (tradeoff on the ROC curve with specificity)	2009
Specificity (% false positives)	*Diagnosis and Recovery*	Low-very low (tradeoff on the ROC curve with sensitivity)	2009
Sensor durability (years)	*Sensors*	Order of magnitude longer than the nominal mission	2015
Sensor power consumption (watt/hours)	*Sensors; Sensor Networks*	Low or none (e.g., energy harvesting)	2015
Caution-warning information access (milliseconds)	*User interfaces*	<500 msec.	2009

Metrics for Informed Logistics

Metric	Technology / Sub-Capability	Target Value	Need Date
Prognostic accuracy (+/- % estimated life remaining)	*Prognostics*	+/- 10% for CIL items	2015
Predictive lead time (seconds-hours)	*Prognostics and Prediction*	At least one order of magnitude longer than plant time constant	2009
Short-term predictive sensitivity (% false negatives for failure predictions)	*Prognostics and Prediction*	Low-very low (tradeoff on the ROC curve with specificity)	2009
Short-term predictive specificity (% false positives for failure predictions)	*Prognostics and Prediction*	Low-very low (tradeoff on the ROC curve with sensitivity)	2009
Turnaround time improvements for reusable assets	*Maintenance*	> 30% time savings	2015

Acronyms for Capability 10. 2 Integrated Systems Health Management

- BEAM: Beacon-Based Exception Analysis for Multimissions (NASA JPL product)
- CIL: Critical Items List
- CME: Compiled Mode Estimation (MIT product)
- CMMD: Coordinated Multisource Maintenance on Demand (USC/ISI, NASA ARC, Vanderbilt University product)
- CRL: Capability Readiness Level
- CRT: Capability Roadmap Team
- DARPA: Defense Advanced Research Projects Agency
- DoD: Department of Defense
- DS-1: Deep Space One
- DTOOL: Diagnosability Analysis Tool (Vanderbilt University product)
- EO-1: Earth Observing One
- ESMD: (NASA) Exploration Systems Mission Directorate
- FFDT: Function-Failure Design Tool
- FMEA: Failure Modes and Effects Analysis
- FMECA: Failure Modes, Effects, and Criticality Analysis
- HME: Hybrid Mode Estimation (MIT product)
- HyDE: Hybrid Diagnosis Engine (NASA ARC product)
- IMS: Inductive Monitoring System (NASA ARC product)
- ISRU: In-Situ Resource Utilization
- JSF: Joint Strike Fighter
- RMPL: Reactive Model-Based Programming Language (MIT product)
- ROC: Receiver Operating Characteristics
- RQ: (NASA ESMD) Requirements Division
- SHINE: Spacecraft Healt Inference Engine (NASA JPL product)
- TEAMS: Testability and Engineering Maintenance System (QSI, Inc. product)
- USC/ISI: University of Southern California/Information Sciences Institute
- VU/ISIS: Vanderbilt University/Institute for Software Integrated Systems
- V&V: Verification and validation

Capability 10.3
Autonomous Vehicle Control

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Presenter: Michel Ingham, JPL

Capability 10.3
Autonomous Vehicle Control

- Autonomous vehicle control capabilities are necessary to perform critical mission activities where time-sequenced or ground-in-the-loop control is impossible or impractical.
- Specific sub-capabilities include:
  - Autonomous Rendezvous and Docking
  - Autonomous Orbital Insertion, Maintenance and Modification
  - Autonomous Entry Descent and Landing
  - Autonomous Launch Systems
  - Autonomous Control of Unmanned Air Vehicles

NOTE: we adopt the ESMD definition of "autonomy", i.e., activities performed by manned or unmanned vehicles without Earth-based operators in-the-loop. That is, "autonomous" implies "remote closed-loop", but does not necessarily imply "fully-automated".

Benefits of Capability 10.3 Autonomous Vehicle Control

Advanced Planning & Integration Office

- **Autonomous Rendezvous and Docking:**
  - Mating of separate spacecraft (manned or unmanned) is *enabled* in remote orbits (e.g., at Mars, Lagrange points, in deep space).
  - Return to Earth of samples collected on remote planetary surfaces is *enabled* (assuming no direct-to-Earth transfer of sample from surface).
  - Human safety and operational efficiency is *enhanced* by allowing autonomous (but human-supervised) mating of separate spacecraft in Earth or lunar orbit.
- **Autonomous Orbital Insertion, Maintenance and Modification:**
  - Robust delivery of manned and unmanned spacecraft into orbit around other bodies is *enabled* (for the purposes of remote sensing and/or eventual delivery to the surface).
  - Delivery of manned and unmanned spacecraft into orbit around the Earth or the Moon is *enhanced* through autonomous (but human-supervised) control of the insertion maneuver.
  - Operations are *enhanced* (and operations costs are reduced) through autonomous orbit maintenance and modification.
- **Autonomous Entry, Descent and Landing:**
  - Robust delivery of robotic vehicles and cargo from orbital trajectories down to remote planetary surfaces is *enabled*.
  - Safe transportation of humans from orbital trajectories down to remote planetary surfaces is *enabled* by high-precision autonomous entry, descent and landing.
  - Robust/safe transportation of robotic vehicles, cargo and humans from Earth orbit back to Earth, and from lunar orbit down to the lunar surface, is *enhanced*.
- **Autonomous Launch Systems:**
  - Safe return of humans and samples from remote planetary surfaces back to Earth is *enabled*.
  - Safe return of humans and samples from the lunar surface back to Earth is *enhanced*, by reducing the complexity of, or even the need for, ground-in-the-loop involvement in launches from the lunar surface.
- **Autonomous Control of Unmanned Air Vehicles:**
  - Control of agile vehicles with aerodynamics and highly dynamic flight paths is *enabled.*
  - Control of aerobot vehicles in extreme environments is *enabled*.

Summary State-of-the-Art for Capability 10.3 Autonomous Vehicle Control

Sub-capability 10.3.1: Autonomous Rendezvous and Docking

- Significant ground demonstrations and simulations
- On-orbit, unmanned:
  - Visual acquisition and tracking (AFRL XSS-10)
  - Proximity operations, manipulator-assisted docking, relative GPS (Japanese NASDA ETS-VII RV&D technology demonstration mission)
  - Autonomous RV&D with ground planning (Progress re-supply of ISS)
  - Under development: Autonomous proximity operations, collision avoidance (NASA DART, ~5m), docking (DARPA Orbital Express), onboard planning & resource management (AFRL XSS-11), identification and capture of non-participatory/tumbling s/c (Hubble Robotic Servicing and Deorbit Mission)
- On-orbit, manned:
  - Manned control for final docking (Gemini, Apollo)
  - Significant ground supervision (Soyuz/Progress/Shuttle with MIR/ISS)
  - Shuttle payload operations (Hubble Space Telescope, SPAS, etc)
- Other related or relevant capabilities:
  - Optical-based autonav (DS-1, Deep Impact’s Impactor spacecraft)

Summary State-of-the-Art for Capability 10.3 Autonomous Vehicle Control

Sub-capability 10.3.2: Autonomous Orbital Insertion, Maintenance and Modification

- Orbital insertion demonstrated with unmanned vehicles:
  - Onboard GNC computations based on delta-energy (not delta-V) for optimal arc trajectory burn; event-driven, statechart-based fault protection with burn restart capability (Cassini at Saturn)
  - Small-body orbit insertion (NEAR at Asteroid Eros)
  - State-of-the-art in unmanned orbital insertion control has not advanced significantly since early lunar, Mars & Venus missions
- Lunar orbit insertion demonstrated with manned vehicles in Apollo Program
- Aerobraking for orbit modification of unmanned spacecraft with ground-in-the-loop (Magellan at Venus, Mars Odyssey, Mars Global Surveyor, ESA Mars Express)
- Aerocapture demonstrated in ground simulations (LaRC, JSC/Draper, NASA ST-9 concept study)

Summary State-of-the-Art for Capability 10.3 Autonomous Vehicle Control

Sub-capability 10.3.3: Autonomous Entry, Descent and Landing

- Approach navigation: ground-in-the-loop navigation updates (MER)
- Entry: aeroentry control from Mars orbit (Viking 1 & 2); direct entry control (Pioneer 2 Multiprobes at Venus, Mars Pathfinder, MER); guided entry control (Apollo at Earth); X-38 Crew Return Vehicle demonstrator autonomous landing tests
- Parachute descent: unguided for all space applications to date; Earth-based guided parachute systems (Sherpa, Precision Air Drop System, etc)
- Terminal descent: powered, guided gravity turn maneuver control (Viking 1 & 2 at Mars); feature tracking, lateral velocity estimation based on descent images (MER DIMES); pilot-in-the-loop hazard avoidance (Apollo at Moon)
- System capabilities: precision landing (MER landing ellipse ~80km x 25km); event-driven sequencing (MER, Huygens, etc)

Summary State-of-the-Art for Capability 10.3 Autonomous Vehicle Control

Sub-capability 10.3.4: Autonomous Launch Systems

- Launches currently require significant ground-in-the-loop preparation & process control
- EELV lower-cost, simplified launch operations (Boeing Delta IV, Lockheed-Martin Atlas V)
- Astronaut-in-the-loop launch sequencing (Apollo lunar ascent module)
- Ballistic missiles, ICBMs (e.g., submarine-launched Trident missile)
- “Fire and forget” autonomous missile guidance
- Autonomous launch preparation, planning, initiation, and abort determination not yet demonstrated

Summary State-of-the-Art for Capability 10.3 Autonomous Vehicle Control

Sub-capability 10.3.5: Autonomous Control of Unmanned Air Vehicles

- Remotely piloted with auto-pilot for nominal flight paths: Predator (General Atomics Aero. Systems), Global Hawk (Northrop-Grumman)
- Ground-based coordination of multiple UAVs: J-UCAS (Boeing X-45 & Northrop-Grumman X-47), other UCAV programs
- NASA- & DARPA-funded aeronautics research:
  - High Altitude Long Endurance aircraft (DFRC remotely-piloted Helios)
  - Reconfigurable flight controls research (accommodation of control surface failures – DFRC Intelligent Flight Control System)
  - Adaptive/morphing wing control research (DFRC Active Aeroelastic Wing, DARPA Morphing Aircraft Structures program)
  - Earth-based flight demonstrations of single and multiple UAV/rotorcraft autonomy, micro UAVs (DFRC, Berkeley, MIT, Stanford, etc)
- Simulations & Earth-based demos for Mars Airplane (ARES, KittyHawk, MATADOR, MAGE, etc)
- Aerobot autonomy research (JPL): vehicle management system for failure detection/recovery, GPS-assisted horizontal flight control, Image-based vehicle motion estimation

Requirements/Assumptions for Capability 10.3
Autonomous Vehicle Control

Advanced Planning & Integration Office

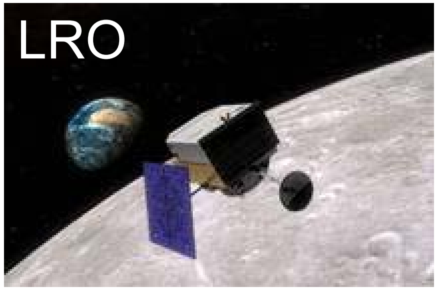
Manned Missions

- **Spiral 1: 2008-2015**
  - Routine Earth entry, descent & landing
- **Spiral 2: 2015-2020**
  - Routine orbital insertion of manned & unmanned lunar orbiting spacecraft
  - High-precision delivery of manned & unmanned lunar landers
  - Ascent from lunar surface, rendezvous & docking in lunar orbit of manned & unmanned spacecraft
  - Routine delivery of robotic precursor Mars orbiters and landers
- **Spiral 3: 2020-2025**
  - High-precision delivery of massive manned & unmanned lunar landers
- **Spiral 4: 2025+**
  - Mars transit and orbital insertion of manned spacecraft
- **Spiral 5: 2030+**
  - Safe pinpoint delivery of manned & unmanned Mars landers
  - Ascent from Mars surface, rendezvous & docking in Mars orbit of manned & unmanned spacecraft

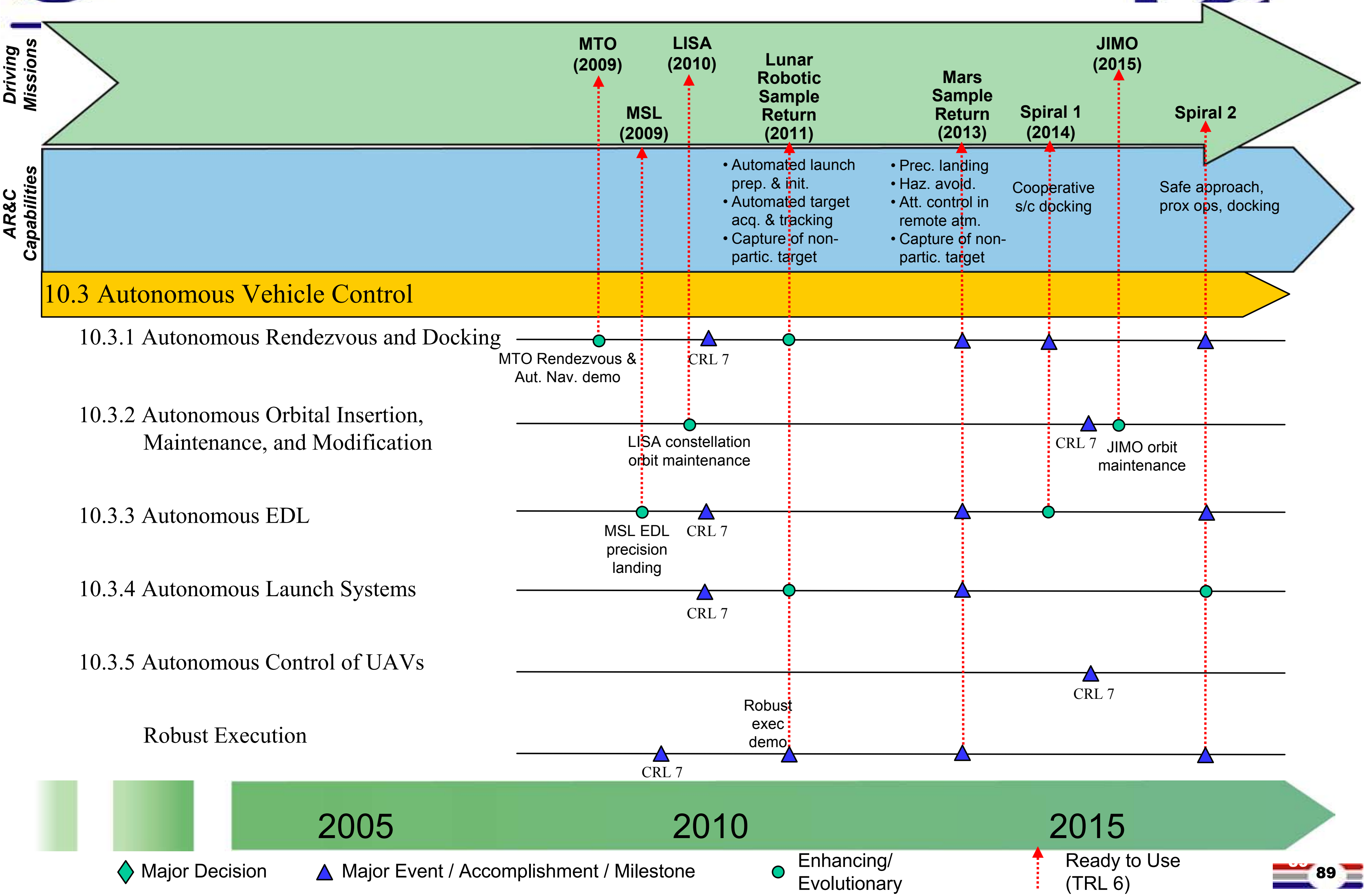
Requirements/Assumptions for Capability 10.3 Autonomous Vehicle Control

Un-manned Missions

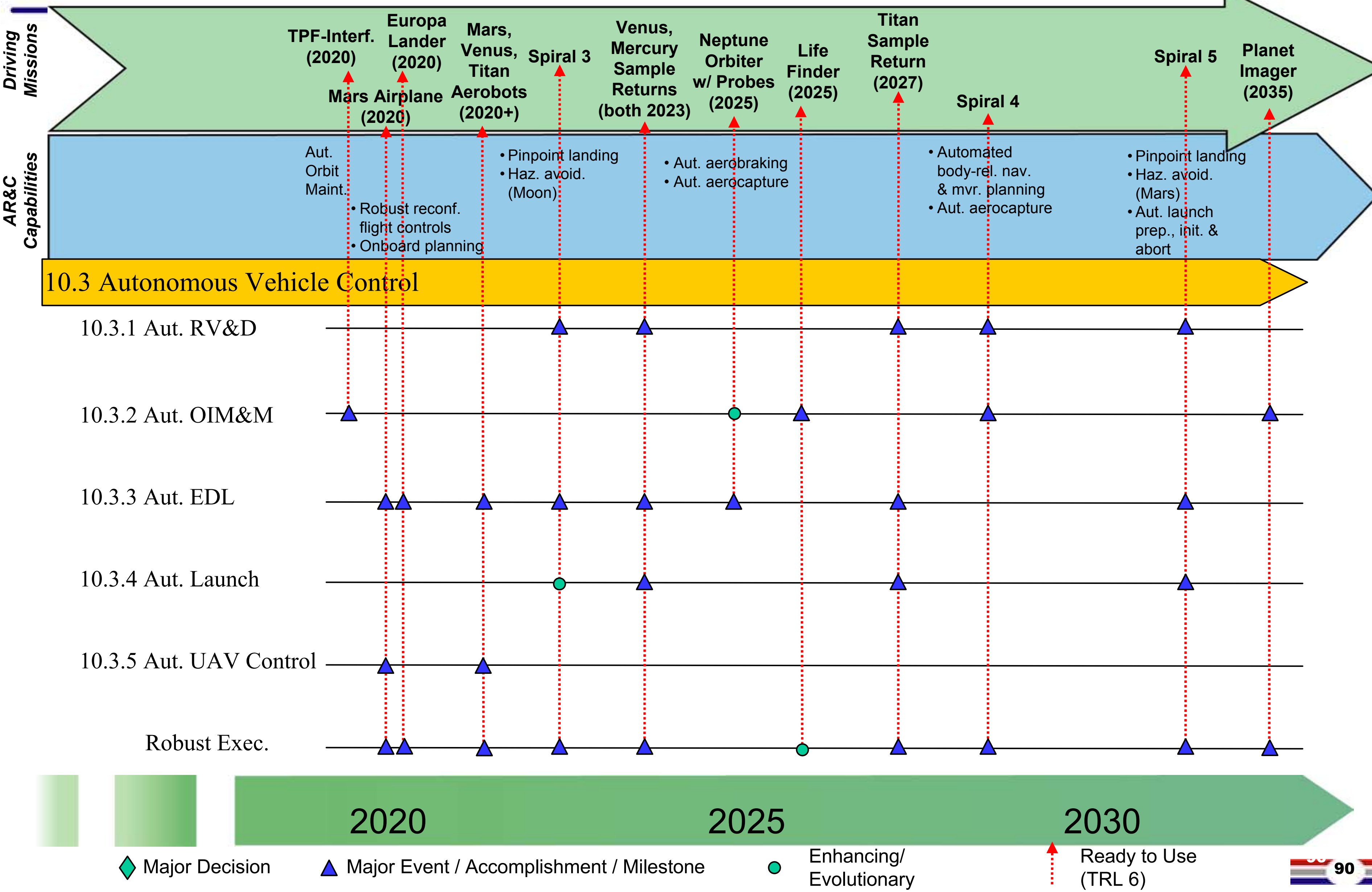
- Orbital Express advanced technology demonstration 2006
- Hubble Robotic Vehicle Deorbit Module ~2008
- Lunar Reconnaissance Orbiter (LRO) 2008
- HALE Remotely Operated Aircraft in the National Air Space 2008
- Mars Science Lab 2009 or 2011
- Lunar robotic sample return ~2011
- Mars Sample Return (MSR) ~2013
- Jupiter Icy Moons Orbiter ~2015
- Terrestrial Planet Finder Interferometer ~2020
- Mars airplane ~2020
- Europa astrobiology lander ~2020
- Mars, Venus, Titan aerobots ~2020+
- Mercury sample return ~2023
- Venus sample return ~2023
- Neptune orbiter with probes ~2025
- Titan sample return ~2027



Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Deliverables for Capability 10.3 Autonomous Vehicle Control

- **Autonomous Rendezvous and Docking: automated target acquisition, target orbit/trajectory determination, target approach, safe proximity operations, docking of cooperative spacecraft, capture of non-participating targets (Moderate risk)**
  - Drivers: Mars Sample Return, ~2013; Spiral 1, CEV docking, ~2014; Spiral 2, Crewed Lunar surface missions, ~2015+
  - CRL 7 date: 2010
  - Interfaces: 9: HES&M, 10.8: AR&C/CS, 12: SI&S, 14: AMSA
- **Autonomous Orbital Insertion, Maintenance and Modification: automated body-relative navigation & maneuver planning, aerobraking & aerocapture (Significant risk for aerocapture)**
  - Drivers: Terrestrial Planet Finder, ~2020; Spiral 4, Crewed Mars orbital missions, ~2025
  - CRL 7 date: 2015
  - Interfaces: 10.8: AR&C/CS, 14: AMSA
- **Autonomous Entry, Descent and Landing: pinpoint landing with <100m (3 sigma) accuracy, hazard avoidance (Significant risk)**
  - Drivers: Mars Sample Return, ~2013; Spiral 2, Crewed Lunar surface missions, ~2015+; Spiral 3, Long Duration Crewed Lunar surface missions, ~2020+; Spiral 5+, Crewed Mars surface missions, 2030+
  - CRL 7 date: 2010
  - Interfaces: 6.3: RAPS/EDL, 7: HPLS, 10.8: AR&C/CS, 12: SI&S, 14: AMSA

Deliverables for Capability 10.3
Autonomous Vehicle Control

- **Autonomous Launch Systems: automated launch preparation (fueling, ignition, etc), initiation and abort, attitude control in remote planetary atmosphere (Moderate risk)**
  - Drivers: Mars Sample Return, ~2013; Spiral 5+, Crewed Mars surface missions, 2030+
  - CRL 7 date: 2010
  - Interfaces: 13: ISRU, 2: HEPP, 10.8: AR&C/CS, 14: AMSA
- **Autonomous Control of UAVs: robust reconfigurable flight controls, onboard mission planning/replanning, coordination of multiple UAVs, adaptive/morphing wing control**
  - Drivers: HALE ROA in the NAS, 2008; Mars airplane, ~2020; Mars/Venus/Titan aerobots, ~2020+
  - CRL 7 date: 2015
  - Interfaces: 6.4: RAPS/AS, 10.8: AR&C/CS, 14: AMSA
- **Cross-cutting capability: robust execution**
  - Drivers: Lunar robotic sample return, 2011; all other complex science & exploration missions
  - CRL 7 date: 2009
  - Interfaces: 10.2: AR&C/ISHM, 10.4: AR&C/APC&EA, 10.8: AR&C/CS, 15: SECRA

Breakthrough Capabilities for 10.3 Autonomous Vehicle Control

Safe, autonomous, pinpoint landing

- To enable a sustained exploration campaign, teams of humans, robots and their supplies must be delivered with tremendously high precision and reliability to the surface of the Moon, Mars, and other remote planetary bodies. The current state-of-the-art atmospheric entry, descent and landing system (e.g., MER) provides sub-100km landing ellipse with a "rough" airbag landing. A capability breakthrough is needed in order to achieve two orders of magnitude improvement in landing precision, while improving reliability to meet safety-critical standards. This will require a return to the propulsive terminal descent control systems of the types used for the Apollo lunar landings and the Viking Mars landers, coupled with significant advanced autonomy technology to assure the necessary reliability and robustness for safe human exploration. In particular, this capability will require advances in robust execution, autonomous GN&C algorithms, sensor fusion, machine vision, and feature recognition/classification.

Autonomous rendezvous and orbital maintenance

- Launch mass/cost constraints will drive the development of breakthrough robotic in-orbit maintenance and assembly capabilities, including autonomous vehicle control for rendezvous and docking. These capabilities will require significant technological advances including robust execution, autonomous GN&C algorithms, and maneuver planning.
- Similar technological advancements will enable successful and affordable operation of future space-based observatories and remote planetary networks consisting of multiple coordinated spacecraft. A breakthrough in autonomous control will be required in order to operate such systems with reasonably-sized ground operations teams and to address the complex coordination and resource management challenges associated with such missions.

Maturity Level – Capability 10.3 Autonomous Vehicle Control

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Autonomous Rendezvous and Docking	• Automated target acquisition & tracking algorithms, • GNC algorithms for safe approach, proximity ops, and capture of cooperative and non-participating spacecraft	4	6-7	MSR, Crewed Lunar Surface Missions	~2010
Autonomous Orbital Insertion, Maintenance & Modification	• Automated body-relative nav & maneuver planning, • Algorithms for automated aerobraking & aerocapture • Libration halo orbit maintenance	3-4	7	Crewed Mars Orbital Missions, Large Space Telescopes	~2015
Autonomous EDL	• Nav algorithms for pinpoint landing, • Guided entry control algorithms, • Optimal-fuel guidance algorithms, • Feature tracking, hazard recognition & avoidance algorithms	3-4 (100m accuracy, 1m haz)	6-7	MSR, Crewed Mars Surface Missions	~2010

Maturity Level – Capability 10.3 Autonomous Vehicle Control

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Autonomous Launch Systems	• Automated launch preparation (fueling, ignition, etc) & initiation, • Attitude control in remote planetary atmosphere	3	6	MSR	~2010
Autonomous Control of UAVs	• Robust reconfigurable flight control algorithms, • Onboard mission activity and path planning, • Algorithms for coordination of multiple UAVs, • Adaptive/morphing wing control algorithms	3-4	6	Mars Airplane	~2015
All	Robust execution	3-4	6	Lunar Robotic Sample Return	~2009

Maturity Level – Technologies for Capability 10.3 Autonomous Vehicle Control

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Robust execution software	State/model-based execution with integral fault management, procedural & rule-based execution	MDS (JPL), RMPL (MIT), TDL (CMU), ESL (JPL/ARC), SCL (ICS)	4-5 7 8	Large-scale system demo	2009
Automated target acquisition & tracking algorithms, feature tracking algorithms	Vision-based target/feature recognition, target/feature tracking	Extensions to Deep Impact impactor targeting & guidance, machine vision research	6	Demo in space application	2010
GNC algorithms for safe approach, proximity ops, and capture of cooperative and non-participating spacecraft	Manipulator-assisted docking, Trajectory planning	ETS-VII, SSRMS Kirk-MILP (MIT, etc), D* (CMU etc), RRT (U of I), RL (Stanford, etc.)	6 5	Fully-automated end-to-end demo in space application	2010

Maturity Level – Technologies for Capability 10.3 Autonomous Vehicle Control

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Automated body-relative nav & maneuver planning		Evolution of DS-1 Autonav, Deep Impact impactor guidance	4	Autonav-maneuver control loop closure	2009
Algorithms for automated aerobraking & aerocapture		Automation of current aerobraking ops process, ST-9 aerocapture study	3	Robust fault protection (deflection maneuver execution)	2015
Navigation algorithms for pinpoint landing	Relative GPS-based nav	Evolution of MSL EDL GN&C	4	Sufficient accuracy & precision	2010
Guided entry control algorithms, optimal-fuel guidance algorithms		Modified Apollo Guided Entry, Evolution of MSL Entry GN&C	5	Algorithm speed (computation speed)	2010
Hazard recognition & avoidance algorithms	Vision-based target/feature recognition, classification	Modified MER DIMES algorithm, machine vision research	2	Hazard recognition from descent images	2010

Maturity Level – Technologies for Capability 10.3 Autonomous Vehicle Control

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Automated launch preparation (fueling, ignition, etc) & initiation		Modified ELV, missile launch process control	3	Adequate observability into process, sensor fusion	2010
Attitude control in remote planetary atmosphere		Modified ELV, missile control systems	3	Atmospheric model fidelity	2010
Robust reconfigurable flight controls		Research for X-33, X-36	4	Flight demo	2018
Onboard mission planning/replanning	Deliberative goal-based planning	CASPER, MDS (JPL), PLASMA (ARC), Kirk (MIT)	7-8	Large-scale system demo, algorithm speed	2018
Coordination of multiple UAVs	Distributed planning	Kirk-MILP (MIT), Maneuver automata (U of I, MIT, Stanford)	3	Large-scale system demo, algorithm speed	2018

Metrics for Capability 10.3 Autonomous Vehicle Control

Metric	Technology / Sub-Capability	Target Value Fig of Merit	Need Date
Time to react to events and faults	Robust execution, Onboard mission replanning (for UAVs)	O(microsecs) for execution, O(seconds) for replanning	2011 for execution, 2020 for replanning
Cost of critical sequence development & validation	Autonomous RV&D, OI, EDL, Launch	Factor of 10 improvement	2015
Error in target trajectory estimate	Autonomous Rendezvous & Docking	3-sigma < X meters	2013
Likelihood of successful docking	Autonomous Rendezvous & Docking	99.99%	2015
Error in achieved orbit	Autonomous Orbital Insertion	3-sigma error < X for each orbital param.	2015
Cost of operations	Autonomous Orbital Maintenance, Autonomous Control of UAVs	Factor of 10 improvement	2015
Pinpoint landing accuracy	Autonomous EDL	3-sigma error < 100m	2015
Likelihood of hazard-free touchdown	Autonomous EDL	99.99%	2030
Mean error in launch trajectory vs. intended profile	Autonomous Launch	3-sigma < X meters	2013

Capability 10.4 Autonomous Process Control and Embedded Autonomy

Presenter: James Crawford, NASA/ARC

Team Lead: James Crawford, NASA/ARC

Capability 10.4 Process Control and Embedded Autonomy

- Autonomous process control encompasses the automation of mission-critical systems that, in terrestrial analog applications, require continuous human monitoring and intervention.

- Example applications include:
  - Process control for closed-loop life support
  - Process control for ISRU
  - Process control for nuclear reactors
  - Process control for deep drilling
  - System-level automation and intelligence for power, propulsion, thermal, communication, GN&C (guidance, navigation, and control), C&DH (command and data handling), and other systems

Benefits of 10.4 Process Control and Embedded Autonomy

- Increased system robustness
- Rapid reaction to off-nominal events
- Increased crew autonomy (for manned missions)
- Decreased operations costs
- Enables complex remote operations (e.g., closed-loop life support, ISRU, Brayton-cycle nuclear reactors, deep drilling, etc.)
- Reduction in (material) buffers (and thus mass) through more effective control

Current State-of-the-Art for 10.4 Process Control and Embedded Autonomy

- The Space Station is manually controlled from earth. Ground controllers issue roughly 500,000 commands per year.
  - Flight crew can, at least in theory, handle emergencies without ground support (for some period of time)
- For unmanned missions, some critical sequences (e.g., entry, descent, and landing) are automated but most systems are monitored and controlled from earth
  - Outside of critical sequences, the state of the art is for the craft to go into a quiescent "safe" mode
- Limited technology demonstrations (e.g., DS1 and EO1) of onboard autonomy have been performed.
- No full demonstrations of automated process control for closed-loop life support, nuclear reactors, ISRU, or other systems.

Requirements /Assumptions for Capability 10.4
Process Control and Embedded Autonomy

Advanced Planning & Integration Office

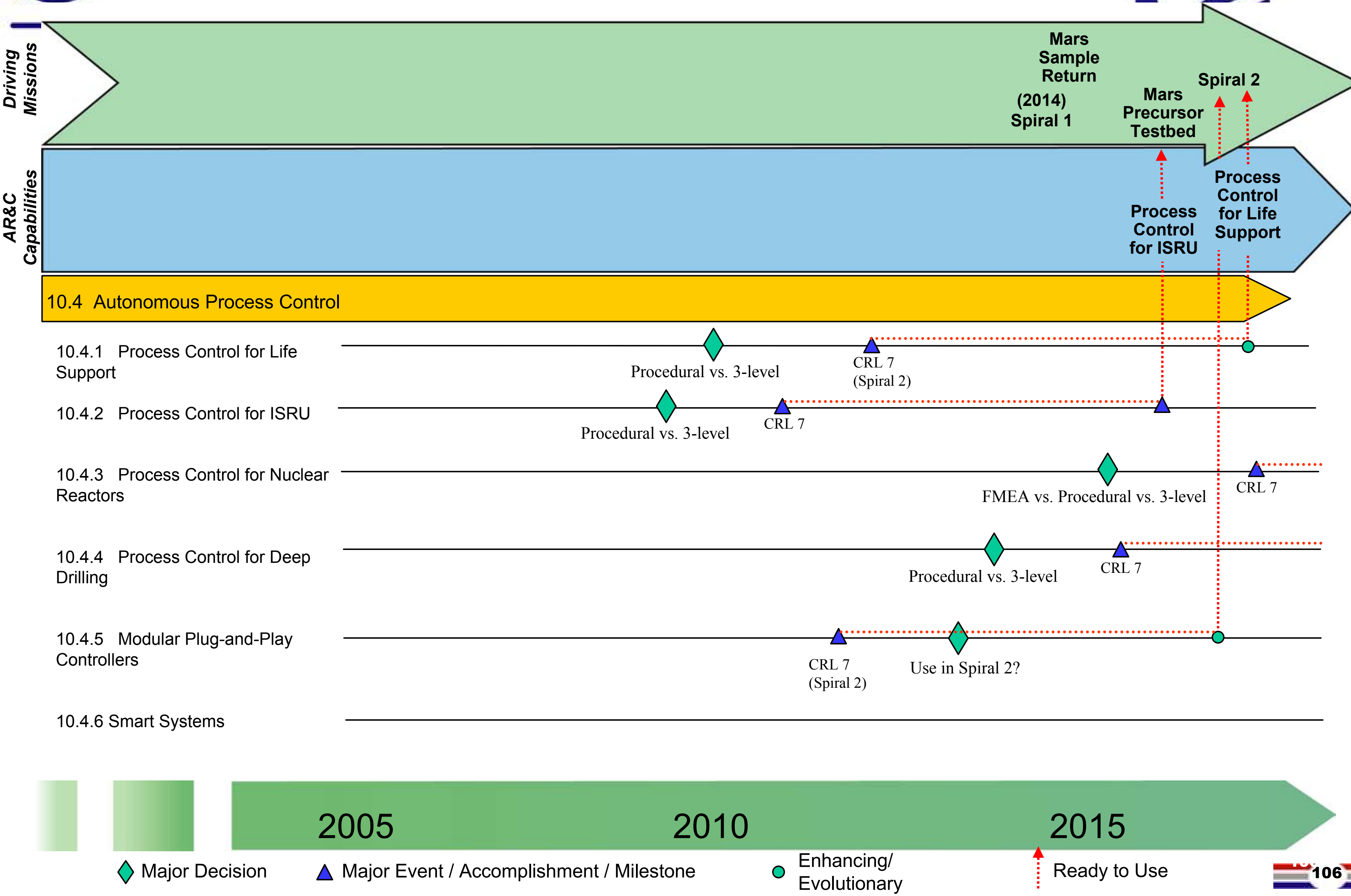
Manned Missions

- Spiral 1: 2014 CEV LEO
- Spiral 2: 2015-2020 CEV LLO and EVA lunar surface ops
  - Technology demonstration of process control for life support
- Spiral 3: 2020 Lunar surface habitat
  - Automated process control of all major systems (CEV, habitat, and vehicles) during nominal operations (under Mars latency). Process control for nuclear reactors?
- Spiral 4: 2025 Mars transit and vicinity ops
  - Automated process control of all major systems during nominal operations and fault recovery, ground as advisor
- Spiral 5: 2030+ Martian surface habitat and exploration
  - Above plus process control for ISRU and surface vehicles

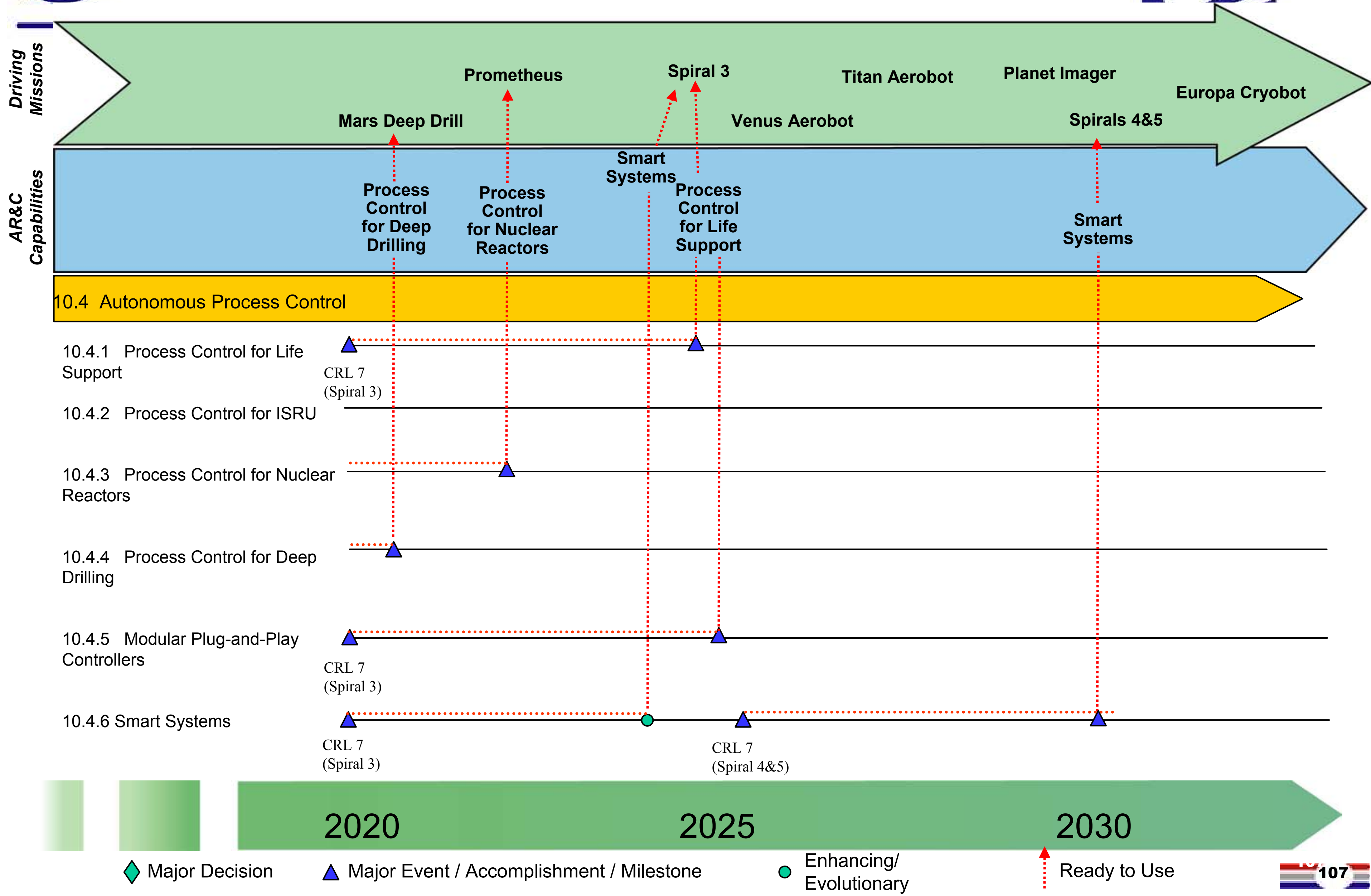
Requirements /Assumptions for Capability 10.4
Process Control and Embedded Autonomy

- Un-manned Missions
  - Mars
    - Process control for ISRU
    - Process control for drilling and sample handling
    - Process control for complex in-situ scientific analysis
  - Planetary
    - Process control for nuclear reactors
    - Process control for complex in-situ scientific analysis
    - Autonomous systems for cases where communications is limited (Venus surface, Titan, Europa, etc.)
  - Observatories
    - Control for interferometry
  - Lunar
    - Process control for ISRU
    - Process control for drilling
    - Process control for in-situ science,
    - Process control for nuclear reactors?

Autonomous Process Control: Capability Roadmap



Autonomous Process Control: Capability Roadmap



Deliverables for Capability 10.4 Process Control and Embedded Autonomy

- Process control for life support: management of material buffers, automation of routine operations, management of system consisting of multiple chemical and biological life support devices, monitoring and fault recovery (joint with ISHM) (Some risk for fault recovery)
  - Driver: ESMD spirals 2-3
  - CRL 7: 2015
  - Interfaces: human environment capability team
- Process control for ISRU: management of flows and processes, automation of routine operations, monitoring, and fault recovery (joint with ISHM) (Some risk)
  - Driver: Mars and lunar precursor missions
  - CRL 7: 2011
  - Interfaces: ISRU capability team
- Process control for nuclear reactors: management of flows and processes, automation of routine operations, monitoring and fault recovery (joint with ISHM) (Moderate risk)
  - Driver: Prometheus reactor deployment
  - CRL 7: 2015 (estimate)
  - Interfaces: HEPP (2.0), "Nuclear Systems" strategic roadmap
- Process control for drilling: management of drilling process, automation of routine operations, monitoring and fault recovery (joint with ISHM) (Some risk)
  - Driver: Mars and lunar programs
  - TRL 6: 10M in 2013, 100M in 2025
  - Interfaces: HESM (9.0), RAPS (6.0)

Maturity Level – Capabilities for 10.4. Process Control

Sub-Capability	Technologies	Current CRL	Required CRL	Driver	Need Date
Process Control for Life Support	• Process-control software architectures • Monitoring and state estimation • Robust execution • Planning and replanning (including fault recovery) • Multi-variant optimal control (including off-nominal) • Model estimation	2	6	ESMD spirals 2-3	2015
Process Control for In-Situ Resource Utilization	• Process-control software architectures • Monitoring and state estimation • Robust execution • Planning and replanning (including fault recovery) • Multi-variant optimal control (including off-nominal) • Model estimation	2	6	Mars and Lunar precursors	2011
Process Control for Nuclear Reactors	• Process-control software architectures • Monitoring and state estimation • Robust execution • Planning and replanning (including fault recovery) • Model estimation	1-2	6	Prometheus	2015?

Maturity Level – Capabilities for 10.4. Process Control

Sub-Capability	Technologies	Current CRL	Required CRL	Driver	Need Date
Process Control for Deep Drilling	• Process-control software architectures • Monitoring and state estimation • Robust execution • Planning and replanning (including fault recovery) • Model estimation	5 (2M) 1 (10M+)	6	Mars and Lunar programs	2013 (to 10M) 2025 (to 100M+)
Modular Plug-and-Play Controllers	• Process-control software architectures • Monitoring and state estimation • Multi-variant optimal control (including off-nominal) • Model estimation	2-3	6	ESMD spirals 1-2	2009
Smart systems (power, thermal, comm., C&DH, etc.)	• Process-control software architectures • Monitoring and state estimation • Robust execution • Planning and replanning (including fault recovery) • Multi-variant optimal control (including off-nominal) • Model estimation	1-5 (varies by sub-system)	6	ESMD spirals 1-2 Mars and SSE programs (enhancing)	2009 – 2020 (varies by sub-system)

Maturity Level – Technologies for 10.4. Process Control

Technology	Components	Candidates	Current TRL*	Key Gaps	Need Date
Process-control architectures		• Three-level architectures • Procedural systems	2-6	• Validation techniques for complex systems	2011 - 2025
Monitoring and state estimation		• Model-based monitoring • Statistical analysis • Expert systems	2-7	• Elimination of false-positives in complex hybrid systems	2011-2025
Robust execution		• Model-based execution • Procedural execution	2-9	• Recovery from unexpected anomalies • Validation	2011-2025
Planning and replanning		• Generative planning • Local repair	3-9	• Mixed-initiative planning • Validation of onboard planners	2011-2025
Multi-variant optimal control			2-6		2011-2025
Model estimation		• Inductive learning	2-4	• Validation	2011-2025

* For many of these technologies the TRL level varies widely by application domain. For example, robust execution for shallow drilling (~2M) is TRL 6 because demonstrations have been done in relevant environments. However, for process control of Nuclear Reactors the same technology is TRL 2 because demonstrations have not yet been attempted.

Metrics for 10.4

Advanced Planning & Integration Office

Metric	Technology / Sub-Capability	Target Value	Need Date
Flight crew hours per week required for process control of life support (assuming Mars-like communication with ground)	Process Control of Life Support	5	2015
Interventions per week by ground team to correct anomalies in ISRU plant	Process Control of ISRU	1 (none mission critical)	2011
Interventions per week by ground team to correct anomalies in Nuclear Reactor	Process Control for Nuclear Reactor	1 (none mission critical)	2010
Depth of autonomous drilling in a variety or rock types	Process Control for Drilling	10M 100M	2013 2025
Number of spacecraft systems that can be controlled by standard controller	Modular Plug-and-Play Controller	Most systems	2015
Flight crew hours per week required for control of major flight systems (assuming Mars-like communication with ground)	"Smart" systems	Less than 1 hour for most systems	2015

Overview

- Introduction (Steve Zornetzer)
- Process, Mission Drivers, Deliverables, and Interfaces (James Crawford)
- Autonomy (James Crawford)
  - Crew-Centered and Remote Operations
  - Integrated Systems Health Management
  - Autonomous Vehicle Control
  - Autonomous Process Control
- **Robotics (Paul Schenker)**
  - **Robotics for Solar System Exploration**
  - **Robotics for Lunar and Planetary Habitation**
  - **Robotics for In-Space Operations**
- Computing Systems (Mike Lowry)
- Conclusion

Introduction to sub-capabilities 10.5-10.7

Robotics

Presenter: Paul Schenker, JPL

Robotic and Human-Robotic Systems

Exploration Systems:

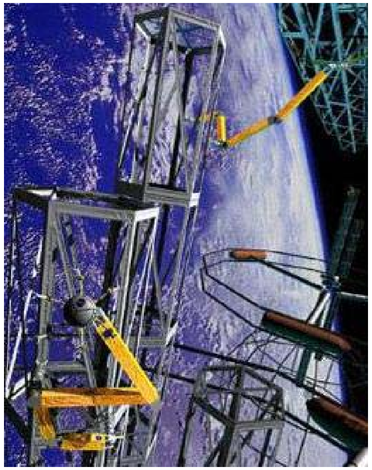
- **Expeditions on-or-near solar system bodies, including sustained robotic access to very rugged and adverse environments (lunar, planetary, and related small bodies). Robotic capabilities will evolve to human-robotic.**
- **In-space assembly, inspection, and maintenance of instruments or facilities, with extension to surface habitat development and servicing**

Required Capabilities:

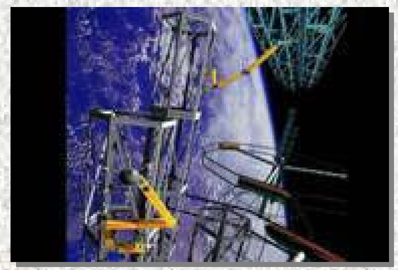
- **Dexterous human/robotic work systems; agile aerial, surface, and sub-surface autonomous explorers**

  … "***go where we currently can't—survive—do breakthrough science***"
- **Advanced mobility, manipulation, and on-board intelligence technologies, enabling efficient human/robotic task inter-actions and multi-robot cooperation for larger tasks**

  … "***autonomy—an integrative bridge for large scale systems***"

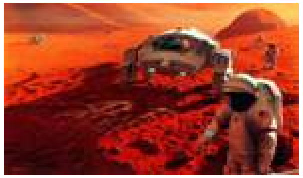


Diverse Mission Applications



Robotics Capability Breakdown

- **Robotics for Solar System Exploration (CRM 10.5)**
  - Autonomous mobility and access (surface, aerial, and sub-surface)
  - Autonomous instrument deployment (from landed and mobile platforms)
  - On-board autonomous science
  - Human-robotic field science (robotic scouts, assistants, telepresence, multi-robot cooperation)
  - Human-robot interaction (remote and on-site C^4I for mission planning, operations, monitoring)



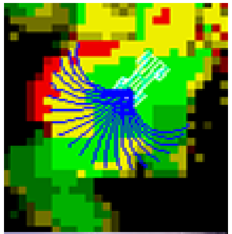
- **Robotics for Lunar and Planetary Habitation (CRM 10.6)**
  - Site development (survey, excavation, initial construction, resource deployments)
  - Site maintenance (inspection, repair, assembly, materials transport & warehousing)
  - In situ resource production (robotic support to extraction, transport, manufacturing)
  - Field logistics and operations support (materials & equipment transport & warehousing)
  - Human-robot interaction (H/R task allocation, teleoperation, remote supervisory control, etc.

- **Robotics for In Space Operations (CRM 10.7)**
  - Assembly (manipulation, preparation, connecting, self-deployment)
  - Inspection (structural, access, component/system failure detection)
  - Maintenance (staging, H/R interface rated manipulation, grapple dexterity)
  - Human-robot interaction (multi-agent teams, communication of intent, time delay compensation)

Science Exploration Examples & Requirements

(Reference: NExT Study on Space Robotic Capabilities)

Surface Mobility



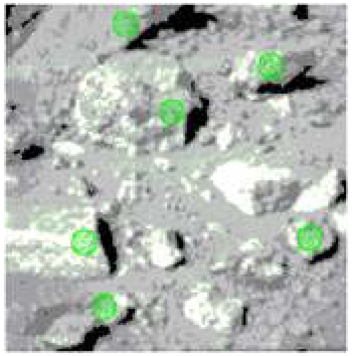
(Mobile Autonomy)

Terrain assessment, path planning, visual servoing

(Mobility Mechanization)

Extreme terrain access, energy efficiency

Science Perception, Planning & Execution



On-board and ground tools; data analysis, target selection, operations planning and execution

Human-Robot EVA Interactions

Tele-operation and human supervision of robotic explorers

Robotic work crews

Instrument Placement and Sample Manipulation

Position sensors, collect and process samples

May include sample containerization and return-rendezvous phases

In-Space Operation Examples & Requirements

(Reference: NExT Study on Space Robotic Capabilities)

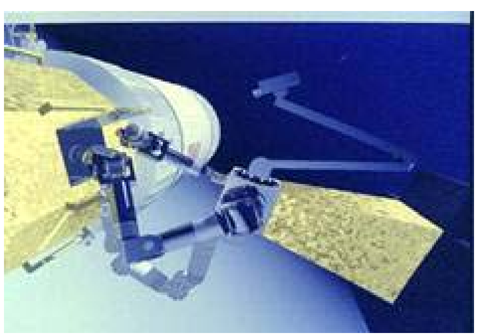
Assembly

Transporting and mating of components; making connections; assembly sequence planning and execution; assembling small structures

Inspection

Visual inspection of exterior spacecraft surfaces; path planning and coverage planning; automated anomaly detection

Maintenance



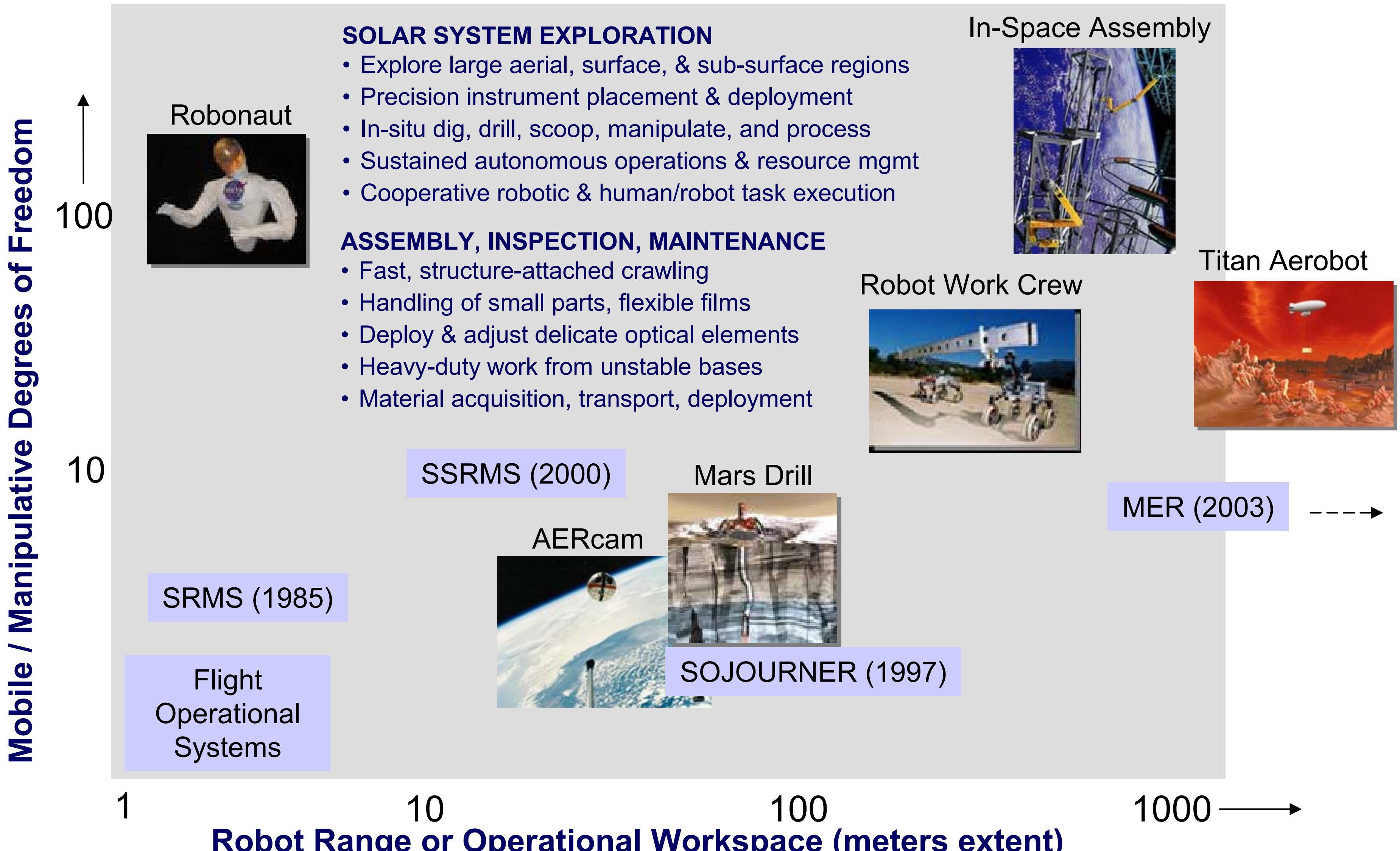
Change-out of components; accessing obstructed components; robotic refueling

Human EVA Interaction

Monitoring and documenting EVA tasks; preparing a worksite; interacting with astronauts; human-robot teaming

Mission Enablement & System Trends

(Space operations will grow in scale—robotic systems will grow in complexity)

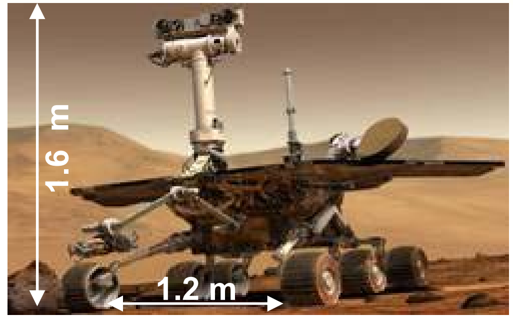


Inter-Agency Robotics Drivers

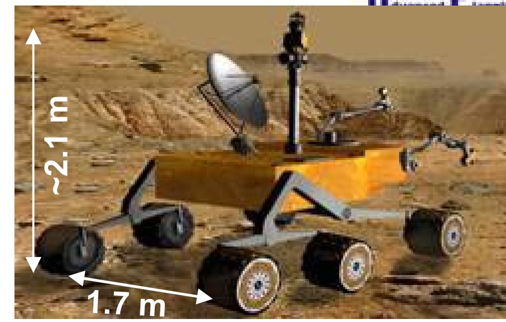
(space imposes unique requirements and constraints)

	NASA	DoD	DoE
Robot Physical Characteristics	Light, Mass & Volume Constrained	Sturdier; Re-Usable; Can Resist Wear and Tear	Sturdier; Re-Usable; Can Resist Wear and Tear
Robot Environment	Unexplored Terrain; Extreme Cold/Heat	Earth Terrain; On-Road & Off-Road	Radiation Rich Sites
Distance from Control and Command Station	Up to Millions of Kilometers	Few Kilometers	Up to 1 Kilometer
Robot Level of Autonomy	Semi-Autonomous (long time-delay)	Teleoperation/Semi-Autonomous (short time delay)	Teleoperation/Semi-Autonomous (short time delay)
Robot Manipulators	Pick-Up and Handle Small Objects (e.g. rocks); Low-Gravity Manipulation of Human-Made Objects	Lift and Handle Heavy Loads	Lift and Handle Heavy Loads
Robot Vision	Discover Interesting Science Samples; Detect Natural Hazards	Detect & Track Human Objects (walking soldier; moving lead vehicle)	Inspect Hazardous Sites; Cluttered Environment

Capability Benchmarks: From MER to MSL



Mars Exploration Rover



Mars Science Laboratory

	Mars Exploration Rover	Mars Science Laboratory
Landed Mass	**174 kg**	**~600 kg**
Designed Driving Distance	**600 m**	**5000-10,000 m**
Mission Duration	**90 sols**	**687 sols**
Power/Sol	**400 - 950 w/hr**	**~2400 w/hr**
Instruments (#/mass)	**7/5.44 kg**	**6-9/65 kg**
Data Return	**50-150 Mb/sol**	**100-400 Mb/sol** **500-1000 Mb/sol** (with MTO)
EDL	**Ballistic Entry**	**Guided/Precision Entry**

**images not to scale*

Two Fundamentally Different Approaches, or a Capability Convergence?

- **Teleoperation**
  - Structured, often well-modeled, sometimes cooperative environment
  - Low latency or none, but past 250 msec, a new operational regime
  - Global viewing is limited, can be obscured, low fidelity is an issue
  - Sensory feedback often multi-modal and non-intuitive to operator
  - Secondary workload is an issue, may require multiple operators
  - Dexterity, haptics, human-rated performance of interest (metrics?)
  - Evolution of teleoperation to *telerobotic* shared and traded control
  - Signal-Sign-Symbol, "Visually Servoed-Guided-Designated", etc.

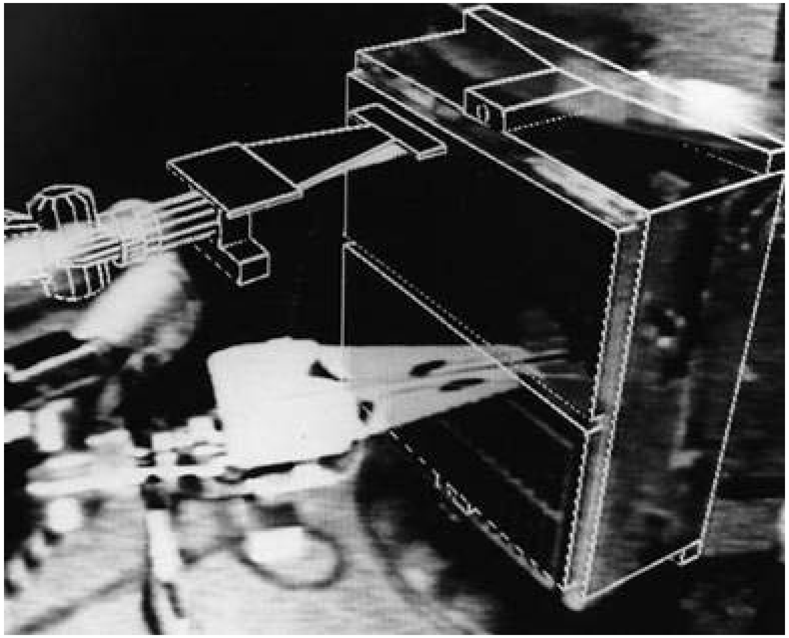
- **Supervised Autonomy**
  - Unstructured, partially-modeled, rarely a "cooperative" environment
  - High latency, structured planning/CDH, limited contingency handling
  - Limited mass, volume, power, and communication; compute bound
  - Localized perception and situational awareness primary to s/c safety
  - Mid-range localization/servoing and analog planning key to efficiency
  - Long range localization and global coordination a key to networking
  - Operator may enter planning, monitoring, and control at multiple levels

EXAMPLE: Teleoperation Task

JPL-GSFC Satellite Servicing under Variable Communications Latency

ORU Change-Out Task with Predictive Graphics and Compliance Control

JPL Operations Site



GSFC Servicing Site

6-to-15 seconds asynchronous communications delay

Robotic Sub-Capabilities (10.5-10.7)

Commonality of Architectures and Components

On-and-Near SSE Bodies

Enabling Technologies

On-Board Intelligence

Manipulation

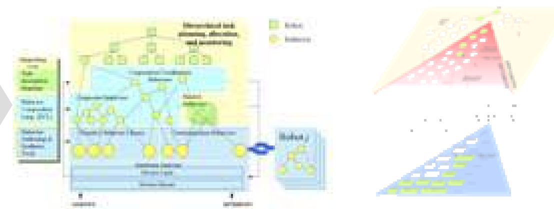
Mobility

Human/Robot System Architectures

- Distributed & cooperative agents
- Reconfigurable, redeployable robots
- Telerobotic & teleprogrammed control
- Visualization & designation interfaces
- Sequencing & contingent planning
- Reactive, reflexive system GN&C
- Sensory fused global perception
- Multi-modal operations interfaces
- Teleoperation with latency

Unified Human/Robot Operations

- Cooperative H/R work on orbit and surfaces
- Surface preparations for human explorers
- Instrument deployments for mission crew
- Robot assistance to EVA exploration
- Robotic risk mitigation to spacecraft and crew safety (inspection & intervention)



Needed Capabilities

Manipulative instrument placement

Sample processing and handling

Navigational long range traverse

Rough terrain mobility & safety

Multi-sensory state estimation

Visual tracking, localization

Local area mobility planning

Cooperation of multiple robots

Activity sequencing / visualization

In-Space

Needed Capabilities

Manipulation of parts / assemblies

Traverse of large space structures

Grapple dexterity on trusses, etc.

Transport, docking, and deployment

Multi-sensor modeling / recognition

Visual tracking, localization

Local structure mobility planning

Cooperation of multiple robots

Activity sequencing / visualization

Draft

EXAMPLE: Capability Trends (1)

Required Capability	Current TRL	Now (TRL varies)	Figure of Merit In 2008 (TRL 6)	Long Term
Surface Mobility				
Command Cycles per Operation for Surface Mobile Exploration	3-9	Mobility: 10+ meters per command (MER) Manipulation: 3-4 sols per instrument placement (MER)	Mobility: 1 Kilometer per command Manipulation: 1 science measurement per command	Automated planning and sequencing of local area activities (science scripts, maintenance & logistics functions). Multi-target science sorties in one command.
Range of Operations (Planetary Surface)	3-9	> 1 kilometer linear path (MER)	>1000 Km^2 incl. use of aerial or multi-agent systems	Global coverage of science bodies through networked science assets
Access to Adverse and Rugged Terrain	4	VL 1 terrains, recent MER post-baseline ops on 30 deg. slopes	> VL2 terrains, vertical cliffs, cratered walls	Rove at will into densely featured and highly variable terrains at lunar and Mars gravity
Networked Robotic Systems (Surface)	2-4	Concept demos of shared payload transport (TRL 4)	Full scale terrestrial demo of power station / habitat deployment	Mix and match modularized hardware-software robotic assets for all basic surface H/R support and logistical functions
In-Space Mobile Dexterity				
Level of Dexterity	4-9	Teleoperatively Grapple Large (>1 m^3) ORUs (STS)	Human "bare hand" dexterity	Full body emulation of human assembly and repair skills by robotic anthropmorph
Range of Operations (In-Space Systems)	2-9	Fixed base (SRMS, SSRMS) operations; 100 meter linear track (MSS/SPDM)	1 Km^3 coverage by coordinated mobile manipulative systems	Robotically traverse complex space structures to perform planned and spontaneous inspection and servicing functions
Networked Robotic Systems (In-Space)	2-3	Cooperative transport and docking by free-flyers, air-table demo (TRL 3)	Dockable, modular multi-robot elements for assembly, servicing	Robots and crew freely and safely interact both physical-cooperative and symbolic command i/f levels

EXAMPLE: Capability Trends (2)

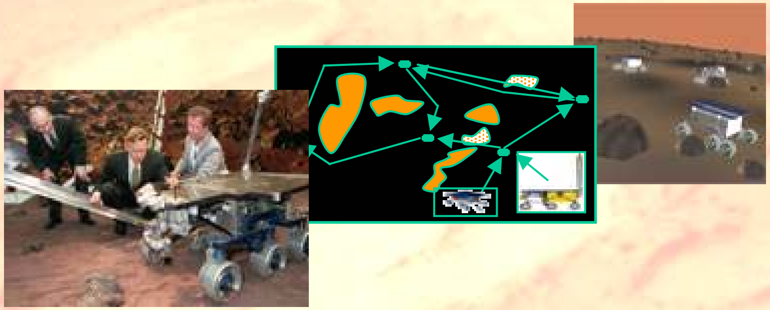
Subsurface & Aerial Access				
Autonomous Drilling/ Coring	3-6	Drilling 10-100's cm in penetrable rock, sand media; novel arm-mounted core extraction devices (TRL 3-4)	Drilling 10-20 meters in Mars analogs. Automated detection and mitigation of slip-stick conditions	Drilling 50-100 meters at Mars, drilling for resources as needed at Earth moon.
Icy Melt Exploration	2-5	Cryobotic access to uniform icy media (TRL 5)	Self powered and science instrumented cryobot earth analog experiment	Cryobotic exploration of Europan ice fields. Deep icy soil exploration of Mars high latitudes.
Aerial Access to Small Bodies	2-4	Powered aerobotic flight over terrain of interest (TRL 3-4)	Titan aerobot scenario demonstrated in full scale earth analog demo	Titan aerial exploration and possible drop-sonde and sampling.
Robotic Intelligence & H/R Interaction				
Planning & Monitoring Systems	3-5	Contingent Resources Planners; Local Spatial Planners (TRL 4-5)	Deliberative task planners for well structured assembly tasks; automated sequencing of basic science routines; integrated spatial-resource planners for long ranging traverse	Integrated planning and sequencing tools for ground operations of SSE robotic missions. High fidelity simulation of all aspects of planetary surface exploration.
Time Delay Control of Telerobotic Tasks (ground to orbit, from orbit to surface)	3-5	Teleoperative preview-predictive displays; shared compliance controls (TRL 3-5)	Teleprogrammed modes of remote control—the robot autonomously sequences local task behaviors / primitives	High dexterity operations over variable time delay from earth, orbit, and at field sites.

EXAMPLE: Field Trials and Analog Missions

Demonstrate New Capabilities and Provide Integrated V&V for Component Technologies

Testbed Use

- Component technology integration and test
- Intelligent Systems (IS) and other initiatives technology product infusion/leverage
- Development and verification of human/robot operation interfaces, planning/visualization
- Quantitative system-level performance evaluation & characterization
- Ground truth, field validation, and science community tie-ins for relevant experiments
- Advances in synergistic science operations and on-board science analysis



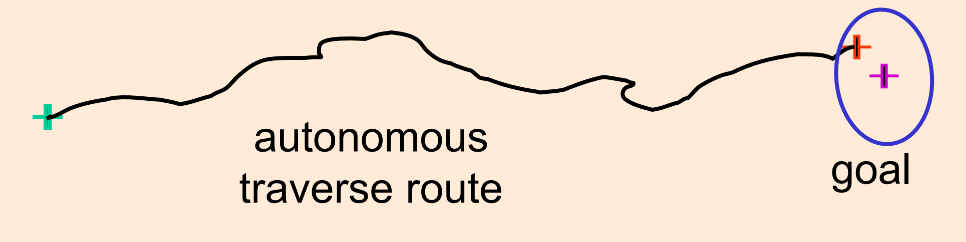
P. S. Schenker, et al., "Planetary Rover Developments Supporting Mars Exploration, Sample Return and Future Human-Robotic Colonization," *Autonomous Robots*, No. 2/3, March/May, Vol. 14, pp. 103-126, 2003 (Special Issue on Robots in Space)

FIDO and K9 Rover Used in MER Analog Missions

Supporting Technology Development

- Comprehensive control architectures for multiple, interacting, instrumented planetary and on-orbit robotic systems
- On-board intelligence for automated science sequence planning, error handling and recovery; visually referenced mobility and manipulation
- High-fidelity simulations for concept development
- End-to-end capability to emulate science-relevant remote operations, including critical program elements of human/robot interaction & cooperation

EXAMPLE: Challenges to Mobile Autonomy



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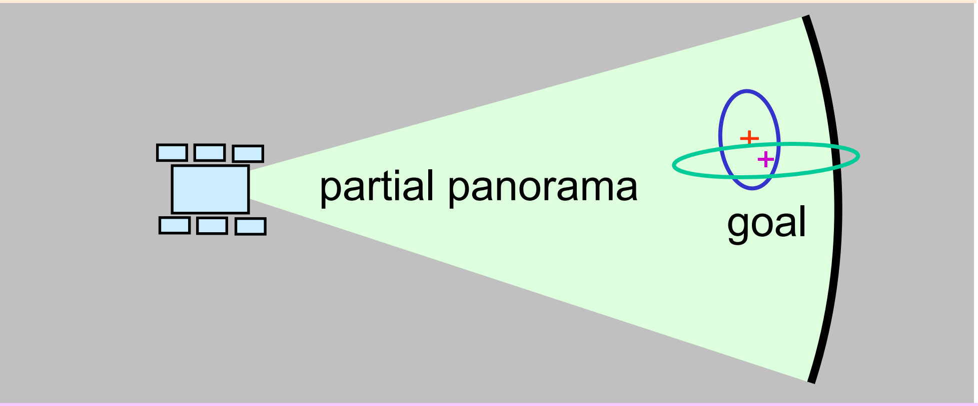

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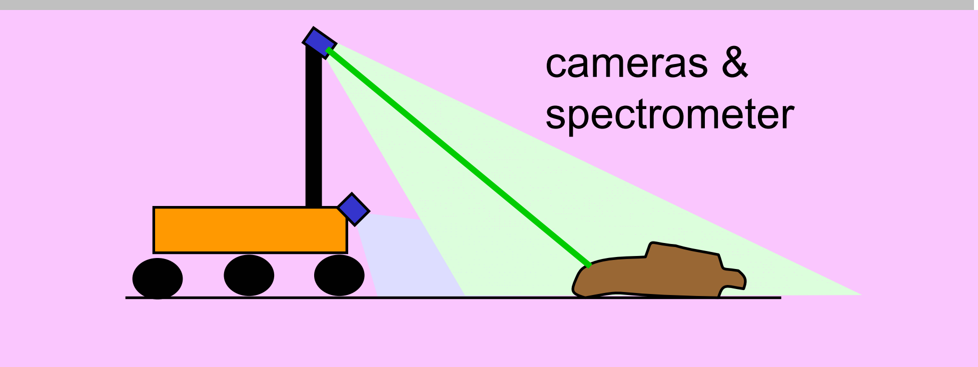

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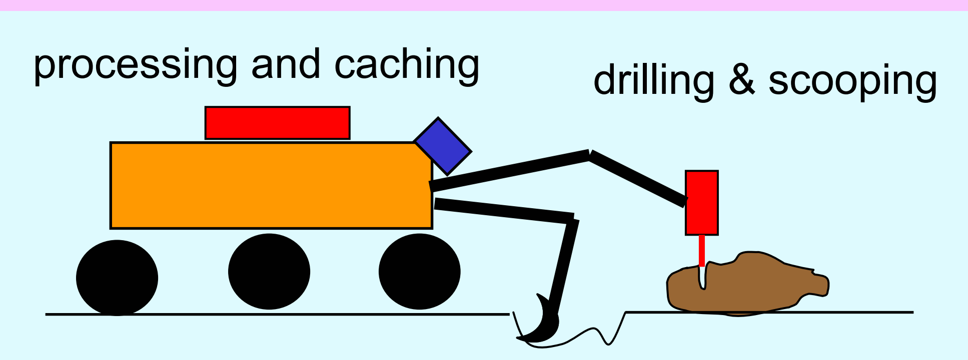

SAMPLING:
Sampling, sample processing, and sample caching through development of controls for new system components.

EXAMPLE: Technology Infusion to MER

(from Mars Technology Program and Predecessors)

Advanced Planning & Integration Office

	Technology	Funding Source	Description	PI/Technologist
1	Long Range Science Rover	NASA (Code R and MTP)	Provides increased traverse range of rover operations, improved traverse acuracy, landerless and distributed ground operations with a large reduction in mass	Samad Hayati Richard Volpe
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Capability 10.5
Robotics for Solar System Exploration

Sub-Team Chair: Reid Simmons, CMU

Presenter: Paul Schenker, JPL

Capability 10.5
Robotics for Solar System Exploration

- This capability area defines the robotic capabilities needed for both unmanned and manned science and exploration missions throughout the solar system. They include:
  - Autonomous mobility and access (surface, aerial, and sub-surface)
    - Exploration of large regions
    - Sub-surface access (shallow, deep, ice-melt probes)
    - Access to high-risk/high-payoff sites (cliffs, canyons, craters)
    - Navigation on small bodies
    - Aerial survey
  - Autonomous instrument deployment (from landed and mobile platforms)
    - Target selection
    - Precision instrument placement
    - Data collection and validation
  - On-board autonomous science
    - Perception
    - Analysis
    - Planning
    - Execution
  - Human-robotic field science
    - Site mapping/survey
    - Site characterization
    - Sample acquisition (digging, drilling, scooping, trenching, etc.)
    - Sample processing (grinding, crushing, etc.)
    - Sample handling (containment)
  - Human-robot interaction
    - Ground based teleoperation
    - Proximate telepresence
    - Shoulder-to-shoulder interaction
    - Robot assistants

Benefits of Capability 10.5
Robotics for Solar System Exploration

- Robotic mobility, instrument deployment, and sample access are ***enabling*** for unmanned planetary surface, aerial, and sub-surface exploration by providing access to places where human access is impossible, or would be too dangerous or expensive
  - ***go where we currently can't—survive—do breakthrough science***
- Robotics and on-board autonomous science capabilities are ***enabling*** for long-endurance remote in-situ science operations at multiple sites, permitting synoptic sampling and increasing science productivity
- Robotic scouts and astronaut assistants are ***enhancing*** for manned planetary surface exploration by replacing humans on some tasks and working with them on others
  - Reduction/elimination of "dirty, dull, and dangerous" tasks for humans
  - Reduction in the workloads of humans
  - Consequent reductions in mission manning levels and, therefore, in the resources required to support them

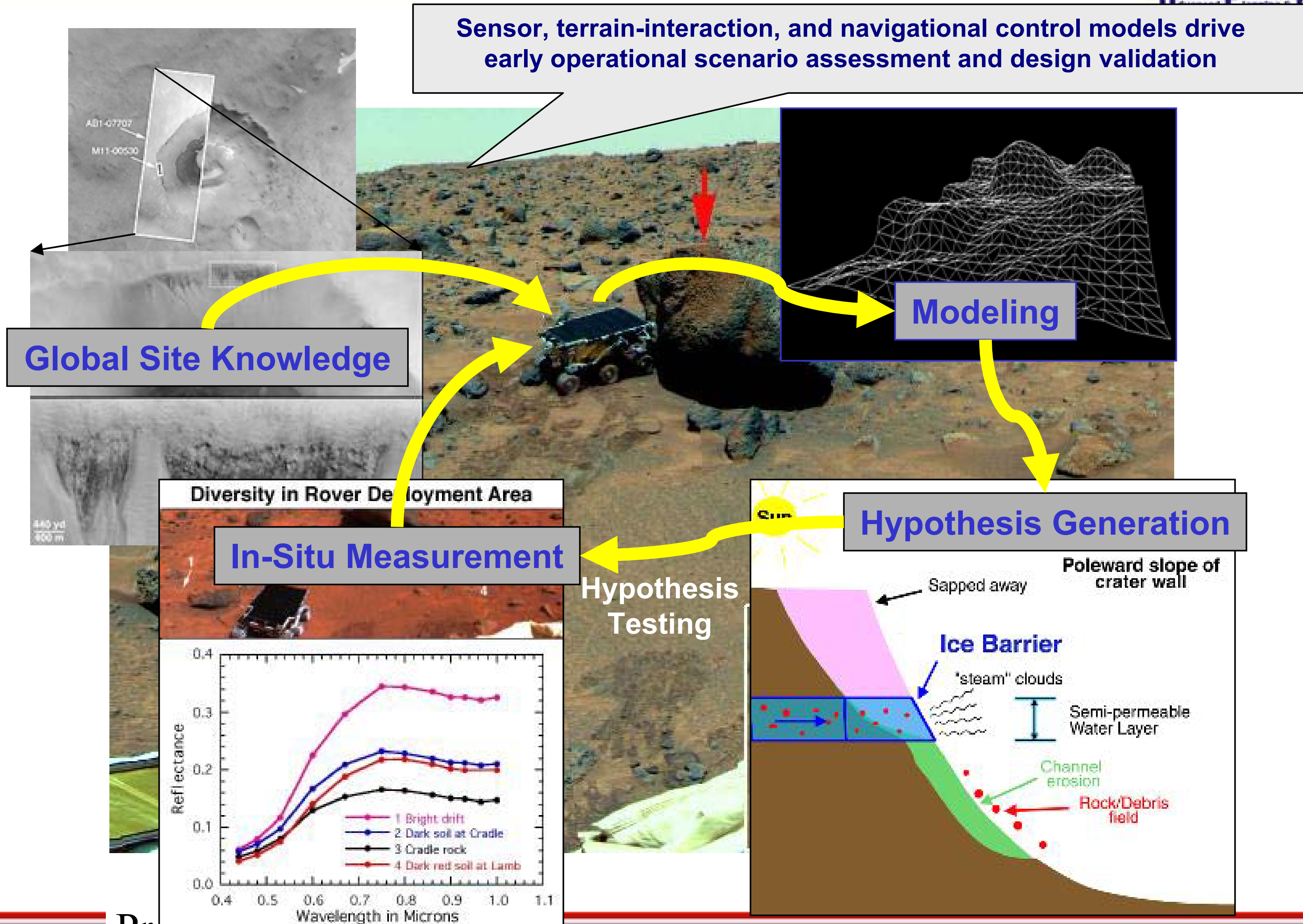
Current State-of-the-Art for Capability 10.5 Robotics for Solar System Exploration

- **Autonomous mobility and sample access**
  - MER mobility: 10-120 m/sol to commanded point with > 90% success, < 20 degree slopes, sparse obstacle field
  - MER visual odometry: ~2% accuracy over distance traveled
  - MER sample access: RAT, wheel scuffing of soil
  - Deep Space 2: Small, sub-surface micro probe, ~50cm access
- **Autonomous instrument deployment**
  - MPL arm: ~2 m reach, 4 DOF, operated from fixed platform
  - MER arm: 90 cm reach, 4 DOF, operated from mobile base
- **On-board autonomous science**
  - Human-commanded on per-sol basis
  - Fixed sequences
- **Human-robotic field science**
  - No operational experience
- **Human-robot interaction**
  - Sojourner/MER: Ground teleoperation
  - MER: Commanded on per-sol basis

=> *Laboratory, and some field, demonstrations of long-range navigation (< km per command cycle), 7DOF arms, meter-deep drilling, single instrument placement, autonomous science planning and execution, robotic assistants, etc.*

Robotic Autonomy, Science & Simulation

… and the potential of "on-board (autonomous) science" …



Requirements /Assumptions for Capability 10.5
Robotics for Solar System Exploration

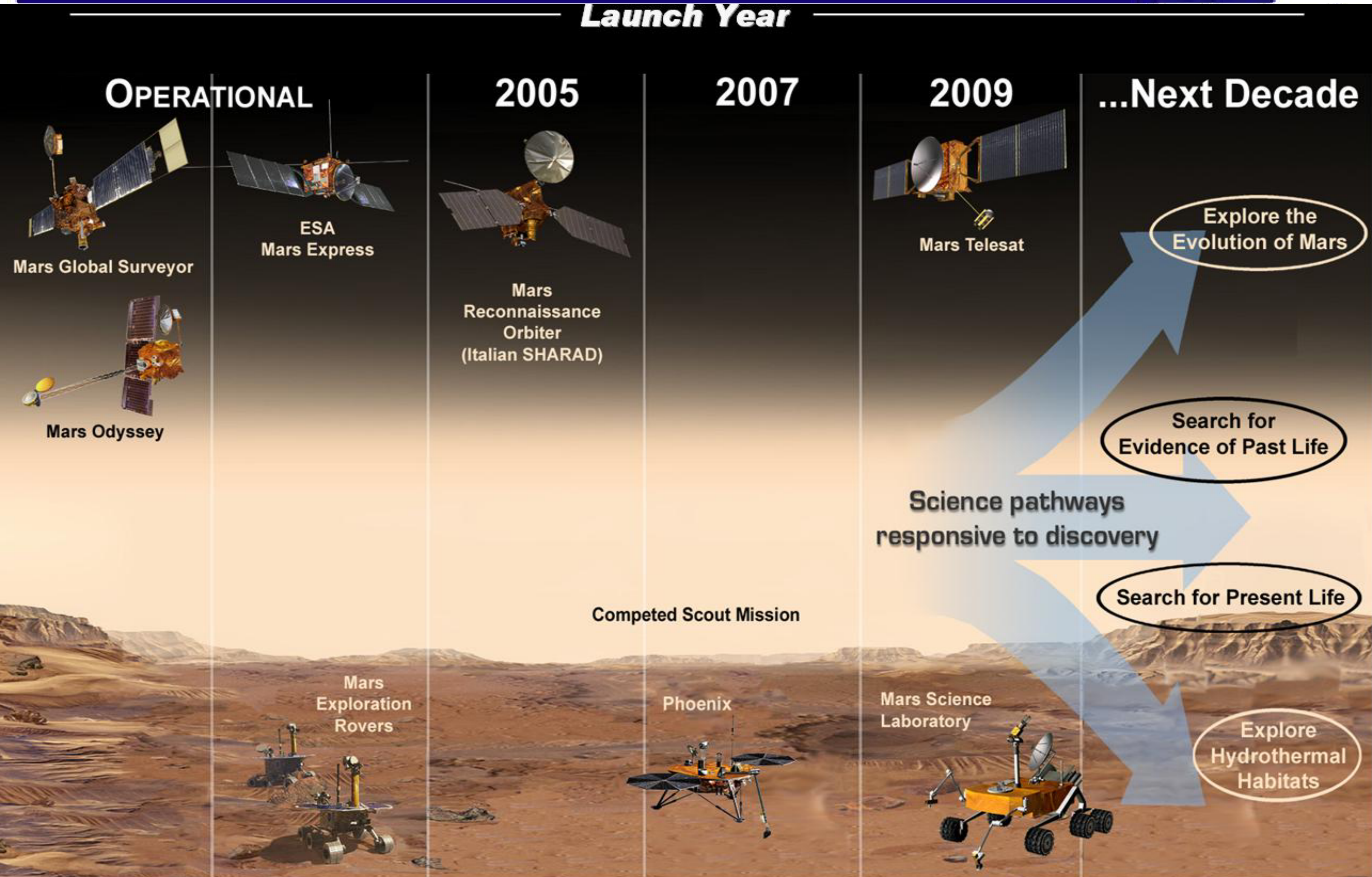
- **Robotics for Solar System Exploration in Support of Manned Missions**
  - **Spiral 1: 2014** Robotic Lunar Exploration
    - Ground-based teleoperation of rovers or landers
    - Exploration of large regions
  - **Spiral 2: 2015-2020** Lunar Surface Ops
    - Human-robot field science from Earth and Lunar surface
    - Sample acquisition and processing
    - Semi-autonomous site mapping / survey
  - **Spiral 3: 2020** Lunar Habitat and Mars Human Precursor
    - Proximate telepresence from lunar habitats
    - Sample acquisition, processing, and analysis
    - Autonomous site characterization
  - **Spiral 4: 2025** Mars Vicinity Ops
    - Human-robot field science from orbiting craft
    - Proximate telepresence from orbiting craft of multiple rovers and landers
  - **Spiral 5: 2030+** Martian Surface Exploration
    - Shoulder-to-shoulder interaction
    - Robot assistants for exploration

Requirements /Assumptions for Capability 10.5 Robotics for Solar System Exploration

- **Robotics for Solar System Exploration in Support of Unmanned Missions**
  - **Lunar Surface**
    - Moonrise
  - **Mars Surface**
    - Astrobiology Field Lab
    - Mars Science Lab
    - Mars Sample Return
  - **Non-Planetary Surface (small body)**
    - Comet Sample Return
    - Asteroid Rover Sample Return
  - **Mars Sub-Surface**
    - Deep Drill
  - **Planetary Sub-Surface**
    - Europa Astrobiology Lander
  - **Planetary Aerial**
    - Titan Explorer
    - Venus Mobile

Mars Exploration Program

This Decade's Discoveries Leads to the Next Decade's Pathway



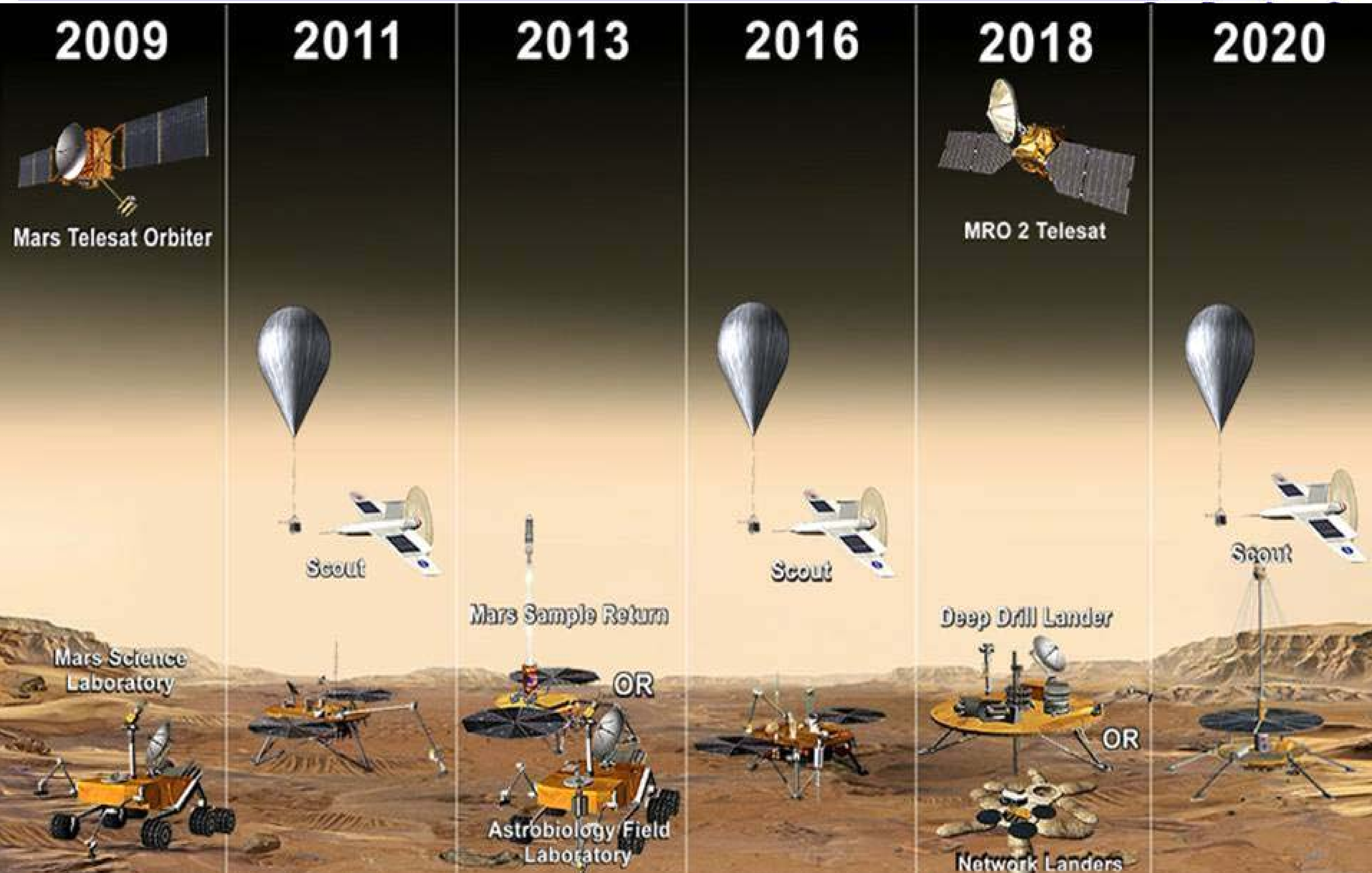
Potential Pathway Mission Sequences

Advanced Planning & Integration Office

Pathway	2009	2011	2013	2016	2018	2020	Notes
Search for Evidence of Past Life	MSL to Moderate Latitude	Scout	MSR	Scout	Astrobiology Field Lab or Deep Drill	Scout	Missions to high-probability past habitat. Mission in '18 influenced by MSL results.
Explore Hydrothermal Habitats	MSL to Hydrothermal Deposit	Scout	Astrobiology Field Laboratory	Scout	Deep Drill	Scout	All core missions sent to active or extinct hydrothermal deposits.
Search for Present Life	MSL to High Latitude or Active Vent	Scout	Scout	MSR	Scout	Deep Drill	Missions to modern habitat. Path has highest risk.
Explore Evolution of Mars	MSL to Moderate Latitude	Scout	MSR	Aeronomy	Network	Scout	Path rests on proof that Mars was never wet.

2005 President's Budget Augmentation		Scout & Mars Testbed		Mars Testbed		Mars Testbed	
	MTO →	→	→	→	Replacement Telecom* →		

“Search for Past Life” Pathway Example



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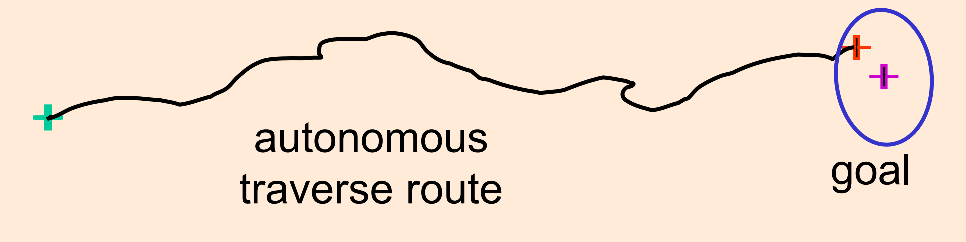

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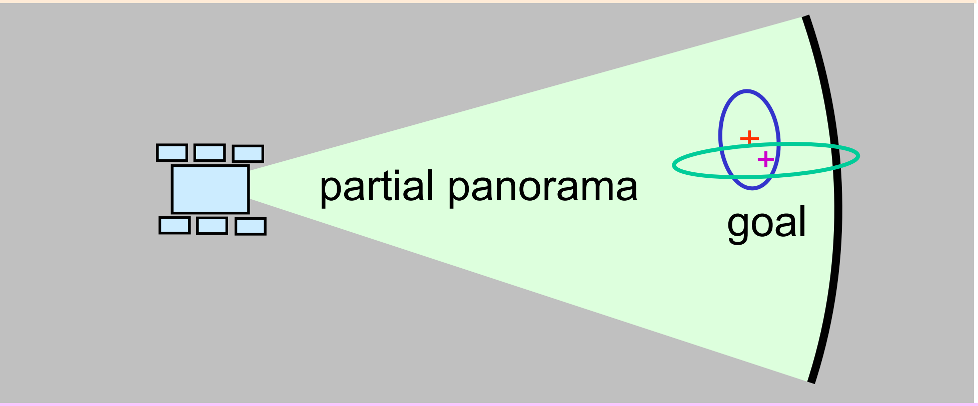

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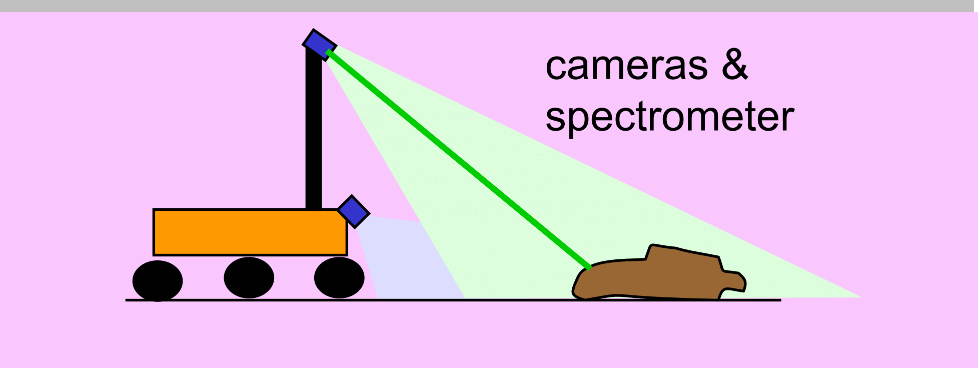

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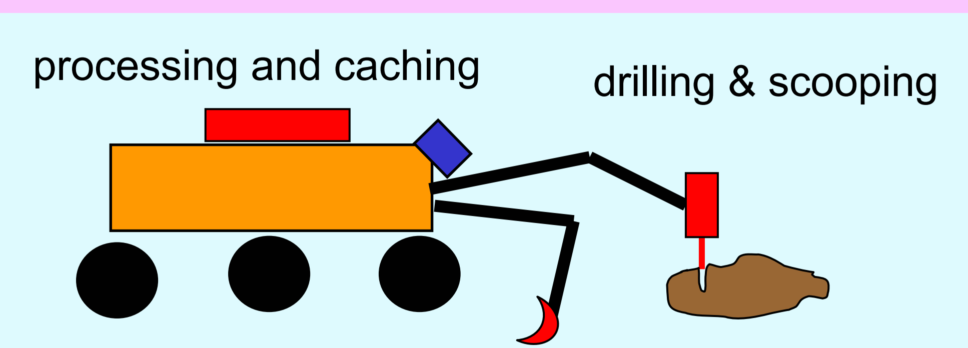

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Technologies Infusion Example: MER

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SSE SRM: Design Reference Mission Set

Mission Class	Time Frame	Small Missions Discovery Class	Medium Mission New Frontiers Class	Intermediate Mission Intermediate Class	Large Missions Flagship Class
Frequency		6 to 7 per decade	4 per decade	TBD per decade	1 per decade
FIRST DECADE	2003 to 2013	***Competitive All solar system targets except for Mars***	*Kuiper Belt- Pluto Explorer* *South Pole-Aitken Basin Sample Return* *Jupiter Polar Orbiter* ***with probes*** *Venus In Situ Explorer* ***- VSSR techval*** *Comet Surface Sample Return*		*Europa Geophysical Observer* ***Jupiter Icy Moons Orbiter(2015)***
SECOND DECADE	2014 to 2023	***Same***			
Primitive Bodies			*Asteroid Rover Sample Return*		*Comet Cryogenic Sample Return*
			Trojan Centaur Reconnaissance Flyby		
Inner Solar System			***Geophysical Network -Venus*** →	***Geophysical Network Venus***	
				Venus Mobile Mission	*Venus Sample Return*
			Geophysical Network - Mercury		*Mercury Sample Return*
Giant Planets			***Neptune Flyby*** ←	***Neptune Flyby with Probes*** ←	*Neptune Orbiter with Probes*
				Neptune Triton Orbital Tour ←	*Neptune Orbiter/Triton Explorer*
			Uranus Flyby ←	***Uranus Flyby with Probes*** ←	*Uranus Orbiter with Probes*
				Saturn Flyby with Probes ←	*Saturn Ring Observer*
			Jupiter Flyby with probes		
Large Satellites			*Io Observer*		*Europa Lander*
			Ganymede Observer	***Titan Explorer (no orbiter)***	*Titan Explorer (with Titan orbiter)*
Third Decade	2024 to 2035		*Overflow from Second Decade*		*Overflow from Second Decade*
			New science driven opportunities		*New science driven opportunities*

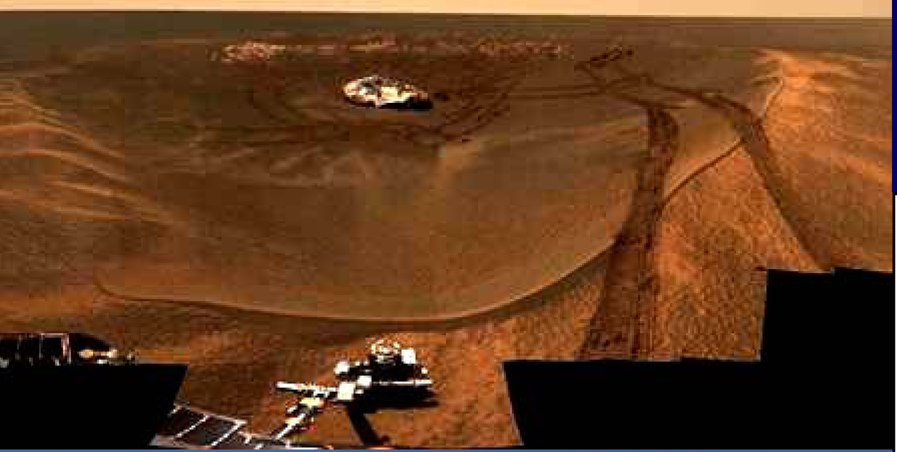
Notes:

Missions in *black italics* are the Decadal Survey missions.

Missions in ***red bold italics*** **are Decadal Survey missions or parts of missions that are now known to be incompatible with this mission class**

Missions ***in blue bold italics*** **are New Missions that have been identified to address some of Major Mission objectives at affordable cost**

Planetary Mobility: Today



Mars

- Ability to traverse moderately rocky surfaces at <500m/sol
- Vulnerable to low bearing strength deposits (sand and dust, particularly on slopes.
- ***Many important science targets including craters and rock outcrops involve a significant risk of the rover getting immobilized .***

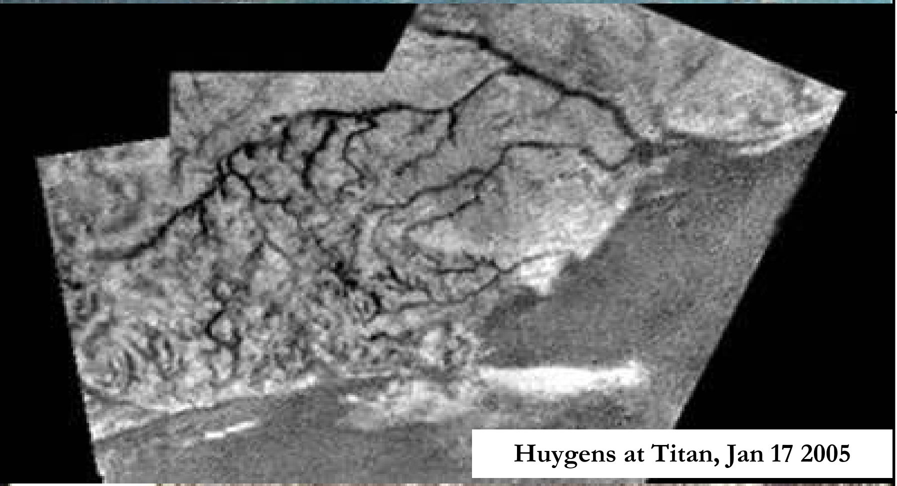
Titan

- Demonstration of key technologies to survive in the cold environment of Titan (FY03-05 R&TD).
- Initial test bed investigations of autonomy for Titan.
- ***Not yet at a point that NASA could commit to a Titan in situ mission.***

Venus

- Capability to circumnavigate Venus by high latitude balloon (e.g. JPL VALOR proposal to the 2004 Discovery call)
- Near surface metal bellows balloon demonstrated in R&TD topic proposal in 2004
- ***No other current NASA work on mobile near surface exploration of Venus.***

Planetary Mobility: Vision



Huygens at Titan, Jan 17 2005

Venera 13, Mar 3, 1982

Mars Surface Mobility

- ***Increase speed of travel*** by a factor of 20 and cover 100 km in three months
- **Reduce power** needed for locomotion by a factor of three.
- **Traverse** dunes, dust deposits, large boulders and steep slopes with equal facility
- ***Access rock outcrops above talus slopes at the angle of repose***.

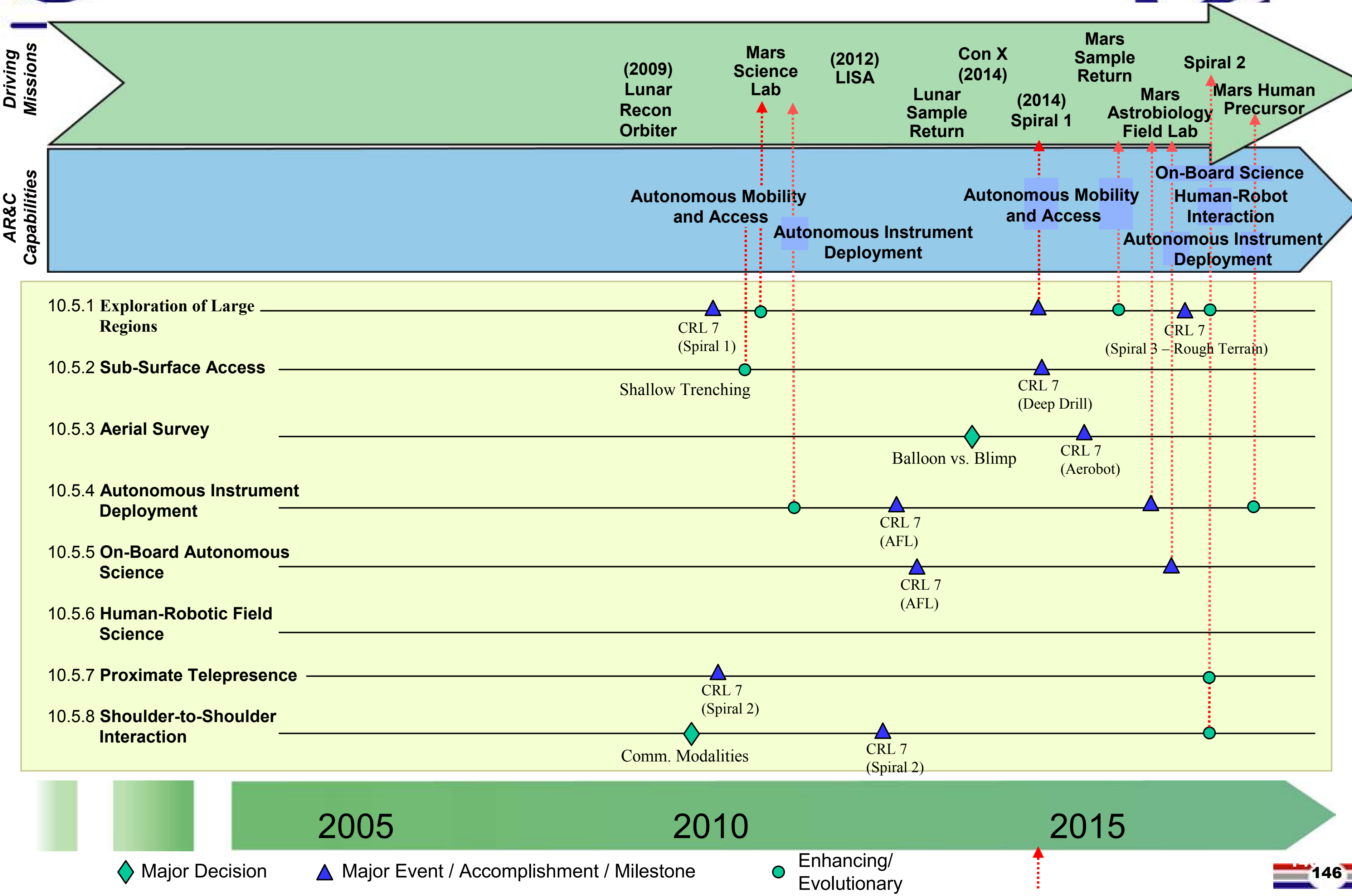
Titan Aerial Exploration

- ***Circumnavigate*** Titan and acquire 1000X the image data obtained by Huygens at high S/N
- ***Descend*** repeatedly to the surface of Titan to image fluvial and cryovolcanic features up close
- **Acquire touch and go samples** from selected targets on the Titan surface and perform in situ analysis.

Venus Aerial Exploration

- ***Circumnavigate*** Venus and acquire 10,000 times the image data obtained by Venera 9-14
- ***Descend*** repeatedly to the surface of Venus and perform in situ analysis.
- ***Survive*** for several months in the Venus **near surface environment** .

Deliverables for Capability 10.5
Robotics for Solar System Exploration



Deliverables for Capability 10.5
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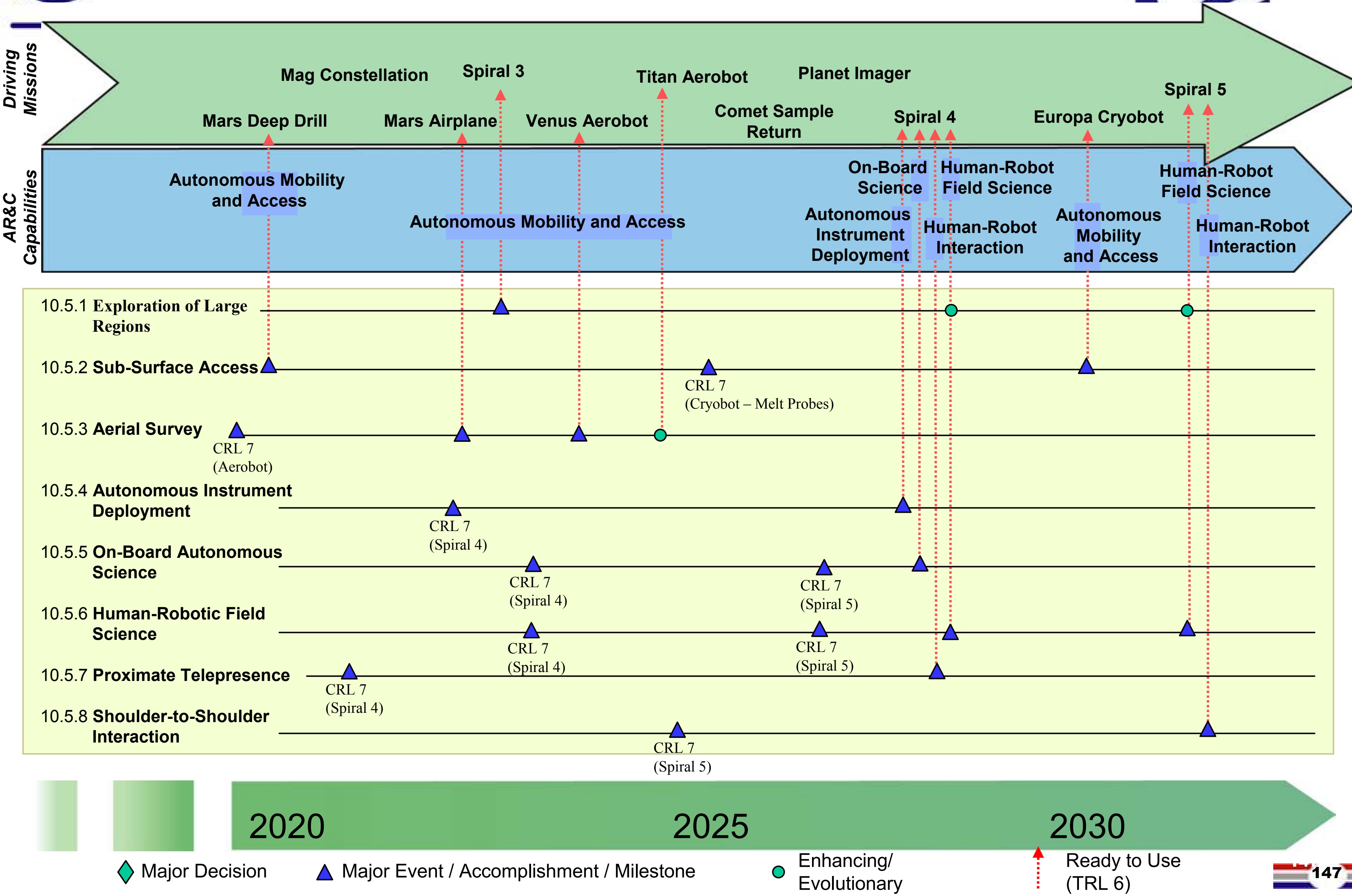


Deliverables for Capability 10.5 Robotics for Solar System Exploration

- **Exploration of large regions**
  - Driver: Spiral 1 (Lunar); Spiral 3 (Mars)
  - CRL 7 date: 2009
  - Interfaces: 6-RAPS, 9-HESM
- **Sub-surface access**
  - Drivers: Deep Drill, Europa Astrobiology Lander
  - CRL 7 date: 2013
  - Interfaces: 6-RAPS
- **Aerial survey**
  - Drivers: Titan Explorer, Venus Mobile
  - CRL 7 date: 2015
  - Interfaces: RAPS
- **Autonomous instrument deployment**
  - Driver: Astrobiology Field Lab, Mars Human Precursor
  - SMD - TRL 6 - 2013
  - Interfaces: 12-SI/S

Deliverables for Capability 10.5 Robotics for Solar System Exploration

- **On-board autonomous science**
  - Driver: Astrobiology Field Lab
  - CRL 7 date: 2013
  - Interfaces: 12-SI/S, 6-RAPS
- **Human-robotic field science**
  - Driver: Spiral 4 and 5 (Mars)
  - CRL 7 date: 2020
  - Interfaces: 6-RAPS,12-SI/S, 9-HES&M
- **Proximate telepresence**
  - Driver: Spiral 2 (Lunar); Spiral 4 (Mars)
  - CRL 7 date: 2010
  - Interfaces: 9-HES&M, 8-HH&SS
- **Shoulder-to-shoulder interaction**
  - Driver: Spiral 5
  - CRL 7 date: 2025
  - Interfaces: 9-HESM, 8-HH&SS

Maturity Level – Capabilities for 10.5 Robotics for Solar System Exploration

Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Exploration of Large Regions	Autonomous Navigation Localization Path Planning Rough-Terrain Navigation (hills, cliffs, craters, etc.)	3-5	6	Spiral 1 – Lunar Exploration Spiral 3 – Mars Exploration	2009
Sub-Surface Access	Shallow Trenching Deep Drilling Melt Probes	2-5	6	Deep Drill Europa Astrobiology Lander	2013
Aerial Survey	Real-Time Adaptive Control Real-Time Control in 3D Path Planning in 3D	2-4	6	Titan Explorer Venus Mobile	2015
Autonomous Instrument Deployment	Target Detection Precision Placement Dexterous Robotic Arms Data Collection & Validation	3-5	6	Astrobiology Field Lab Mars Human Precursor	2013

Maturity Level – Capabilities for 10.5 Robotics for Solar System Exploration

Capability	Technology	Current CRL	Required CRL	Driver	Need Date
On-Board Autonomous Science	Target Detection On-Board Classification Robust State Estimation Task Planning	2-4	6	Astrobiology Field Lab	2013
Human-Robotic Field Science	Autonomous Navigation Target Detection On-Board Classification Sample Acquisition & Processing	2-4	6	Spirals 4 & 5 – Mars Exploration	2020
Proximate Telepresence	Remote Teleoperation Dexterous Robots Safeguarding Sliding Autonomy	3-5	6	Spiral 2 – Lunar Exploration Spiral 4 – Mars Exploration	2010
Shoulder-to-Shoulder Interaction	Multi-Modal Communication Behavior Recognition Safeguarding Task Management	2-3	6	Spiral 5 – Mars Exploration	2025

Maturity Level – Technologies for 10.5 Robotics for Solar System Exploration

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Autonomous Navigation	Long Range Navigation Localization Path Planning Rough Terrain Navigation	Stereo-based local obstacle avoidance Visual odometry Heuristic, resource-cognizant search Dynamics-based planning	6-9 6-9 4-6 2-4	Obstacle density Computational complexity Complexity, modeling	2009
Perception of Geologic Features	Target Detection On-Board Classification	SIFT, PCA-SIFT Neural net, Bayesian classifier	3-5 2-4	Robustness Data volume, scalability	2013
Sample Acquisition	Precision Placement Dexterous Robotic Arms Scooping Coring	Visual Servoing Robonaut, Ranger 5 DOF Arm ?	5-7 4-6 6-9 4-7	Robustness Reliability	2013
Sample Processing	Crushing Containment	? ?	3-5 2-3	Power Validation	2013

Maturity Level – Technologies for 10.5 Robotics for Solar System Exploration

Advanced Planning & Integration Office

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Real-Time Adaptive Control		Non-linear control Fuzzy control	3-6 3-4	Modeling	2015
Robust State Estimation		Kalman Filters Particle Filters	6-9 3-5	Accuracy, modeling	2013
Task Planning		Planning/scheduling Contingent planning Decision-theoretic planning	5-7 4-6 2-4	Complexity, modeling	2013
3D Planning and Control		Probabilistic roadmaps Non-linear control, fuzzy control, memory-based learning	3-5 3-6	Complexity, modeling	2015
Teleoperation		Direct teleop Teleop with local behaviors	6-9 5-6	Validation, scalability	2010
Behavior Recognition	Tracking Interpretation	SIFT, PCA-SIFT HMMs, Cognitive models	3-5 2-3	Robustness	2020
Task Management	Executive	Procedural decomposition Planning/scheduling	4-6 5-7	Validation Modeling	2020
Multi-Modal Communication	Speech Gesture	HMMs, Natural language HMMs	5-7 2-4	Robustness	2025

All-Planetary Vehicle

- Current rovers are limited to exploring small sections of relatively benign terrain. However, the most interesting science sites lie in relatively inaccessible and inhospitable locations (on the sides of cliffs/craters, up in the mountains, in deep valleys). It would be a breakthrough in robotic exploration to have rovers that could go essentially anywhere on a planet that the scientists want to go. Besides the obvious need for advances in mobility, this capability would require significant advances in perception, planning, control, and monitoring and safeguarding.

Self-Aware, Self-Correcting Robots

- By its very nature, exploration involves dealing with the unknown and unexpected. Current robots have limited capabilities for understanding when they are outside their limits and, if they are, how to get back to nominal mode of operations. This is especially apparent when things go wrong internal to the robot (such as sensors or actuators malfunctioning). It would be a breakthrough in robotic exploration to have a capability that monitors the robot at all times for these situations, recovers (or compensates for) such failures, and learns from past mistakes to avoid making them in the future.

Metrics for 10.5
Robotics for Solar System Exploration

Advanced Planning & Integration Office

Metric	Technology / Sub-Capability	SOA	Target Value	Need Date
Distance traveled per day	Autonomous Navigation Aerial Traverse	100m 1km	1km 10km	2009 2015
Difficulty of terrain that is accessible	Autonomous Navigation	VL1	>VL2, cliffs, craters	2015
Drilling depth	Sub-Surface Access	10's cms	10-20 ms	2013
Autonomously controlled manipulator degrees of freedom	Instrument Placement, Human-Robot Interaction	7	10's	2020
Command cycles per sample acquired	Instrument Placement, Field Science	3-6	1	2009
Command cycles per sample processed	Field Science	Dozens	1-2	2013
Command cycles to survey/characterize site	Field Science	>100	<20	2020
Percent of interactions interpreted correctly by robot	Multi-modal communication Behavior tracking	80% 70%	95% 95%	2020
# robots supervised per human	Human-Robot Field Science Co-located Interaction	<<1	3-5	2020

EXAMPLE: Rover System Capability Metrics

Background image:
MER 2 with Sojourner model

Backup slides follow

Deliverable Descriptions for Capability 10.5 Robotics for Solar System Exploration

Exploration of Large Regions

- Effective robotic exploration will require autonomous navigation over wide areas (10’s of kms) with diverse features (hills, craters, dense obstacles). Rover plans to distant goals, executes those plans, and keeps itself safe by knowing where it can, and cannot, go. (Some risk in rough terrain)

Sub-Surface Access

- Direct evidence of water and past life is likely to be found beneath the surface. Access and sample acquisition will be required at shallow depths (10’s of cms), deep depths (10’s of ms) and through thick ice layers (100’s of ms). (Risk for deep drilling)

Aerial Survey

- For some missions, aerial vehicles (balloons, blimps, airplanes) are enabling because either surface access is impossible or access is required to a much larger area than can be covered by ground vehicles. Control for aerial vehicles is much more complex than for ground vehicles, due to the dynamic effects of the (poorly understood) atmosphere and the need to navigate in three dimensions. (Some risk)

Deliverable Descriptions for Capability 10.5 Robotics for Solar System Exploration

Autonomous Instrument Deployment

- Current missions require multi-day, highly complex command cycles to approach and place instruments on targets of interest. Handling this autonomously is extremely enhancing, especially for remote, long-duration missions. This requires advanced sensor-guided dexterous manipulation for precision placement and advanced techniques for autonomously collecting and validating instrument data.

On-Board Autonomous Science

- This capability considers larger scientific goals, such as what in an area is of scientific interest, which experiments are most relevant to characterize that site, and how to carry out those autonomously experiments. Dealing with high levels of uncertainty in state estimation and task planning is critical, as is having highly flexible, contingent plans to deal with the unexpected.

Human-Robotic Field Science

- Field science includes site survey, site characterization, science data collection, and sample acquisition and processing. For complex, remote missions, automating many of these activities will be highly enhancing. To perform such tasks autonomously, robot systems will need a basic understanding of the methods and goals of scientific investigation, as well as the capabilities to perceive, plan, and execute such plans. Advanced manipulation capabilities for sample acquisition and processing will be critical. (Some risk)

Proximate Telepresence

- In many missions, the humans will be near the robots but will be supervising them from a safe distance (e.g., in a habitat or on orbit). To facilitate the interaction, the robots should have capabilities similar to humans (especially in terms of manipulation) and the level of control between robots and humans should be highly flexible ("sliding autonomy"). Situational awareness of the supervisor needs to be high, which can be facilitated with both multi-modal feedback and high-level interpretation (by the robot) of sensor data. Safeguarding to prevent harm to the robots is critical.

Shoulder-to-Shoulder Interaction

- In some missions, humans and robots will be co-located on site, working together. At a basic level, the robots will need to understand and communicate with the astronauts using both speech and gesture. In addition, in many cases they will need to infer (without communication) the behaviors and intentions of the astronauts and alter their activities accordingly to support the astronauts' goals. Safeguarding to prevent harm to the humans is critical. (Some risk)

Capability 10.6
Robotics for Lunar and Planetary Habitation

Sub-Team Chair: Illah Nourbakhsh, NASA/ARC
Presenter: Paul Schenker, JPL

Capability 10.6
Robotics for Lunar and Planetary Habitation

- Robotic capabilities are instrumental to preparing for human habitation, maintaining surface habitats, providing support for human surface operations both in-habitat and in the field, and aiding in the collection of in-situ resources for human habitation.
- Robotic capabilities in lunar and planetary habitation make long-term habitation feasible by greatly reducing risk and cost.
- Specific sub-capabilities include:
  - Site development (survey, excavation, initial construction, resource deployments)
  - Site maintenance (inspection, repair, assembly, materials transport & warehousing)
  - In situ resource production (robotic support to extraction, transport, manufacturing)
  - Field logistics and operations support (materials & equipment transport & warehousing)
  - Human-robot interaction (H/R task allocation, teleoperation, remote supervisory control, etc.)

Benefits of Capability 10.6
Robotics for Lunar and Planetary Habitation

- Robotic ISRU, robotic precursor preparation and ongoing robotic mission support are *enabling* for length of stay targets and operational cost targets due to impact on sustainability and affordability.

- Human safety is *enhanced* through precursor robotic site preparation.

- Field operations productivity is *enhanced* through robotic “mule” support and robotic mobile communication networking.

- Astronaut productivity is *enhanced* by lowering maintenance and inspection overhead assigned to human crew.

- Ground-crew interaction productivity is *enhanced* by improved human-robot interfaces.

Summary State-of-the-Art for Capability 10.6 Robotics for Lunar and Planetary Habitation

- **Robotics has not been used for lunar or planetary habitation. Related state-of-art capabilities demonstrated in flight are:**
  - **MER Long-range navigation, 10M+ navigation**

- **State-of-art can be indirectly measured from sub-capabilities with terrestrial deployment, TRL6 and below:**
  - **Site development: Autonomous robotic excavation and site shaping has been demonstrate by joint CMU – Caterpillar front loader system.**
  - **Site development: Communication infrastructure deployment by various university research groups in the DARPA *Centibots* program has set up networks using robot teams in unexplored urban areas.**
  - **Site maintenance: Dexterous manipulation under teleoperation has been demonstrated in analog environments by both Ranger and Robonaut research teams with astronaut glove-level dexterity and 6x slowdown.**
  - **Field logistics and operations support: Long-distance autonomous navigation has been demonstrated on the order of 100km total distance traveled.**
  - **Field logistics and operations support: Architectures for perception, planning and control have demonstrated efficacy in Mars-analog tests at JPL and Ames.**
  - **Human-robot interaction: No identified sub-capability has demonstrated significant present-day success.**

Requirements /Assumptions for Capability 10.6 Robotics for Lunar and Planetary Habitation

Manned Missions

- Spiral 2: 2015-2020 CEV LLO and EVA lunar surface ops
  - Robotic precursor surface operations
- Spiral 3: 2020 Lunar surface habitat
  - Human/Robotic habitat preparation, maintenance and repair
  - Human/Robot field operations and ISRU experiments
- Spiral 5: 2030+ Martian surface habitat and exploration
  - Human/Robotic habitat preparation, maintenance and repair
  - Human/Robot field operations and ISRU

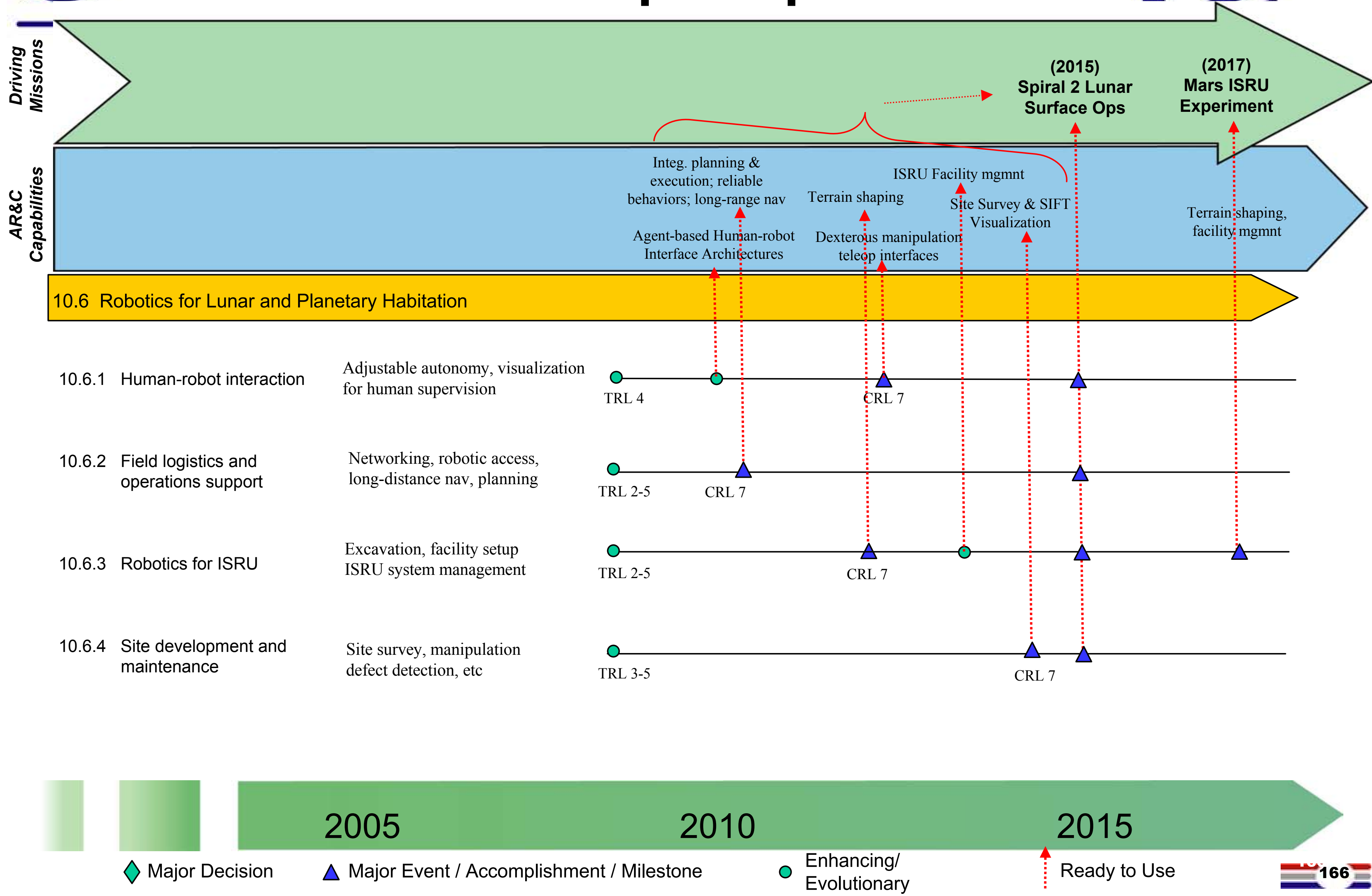
Un-manned Missions

- Lunar robotic missions 2016
- Mars ISRU experiment: 2017
- Mars precursor missions for habitat construction 2025+

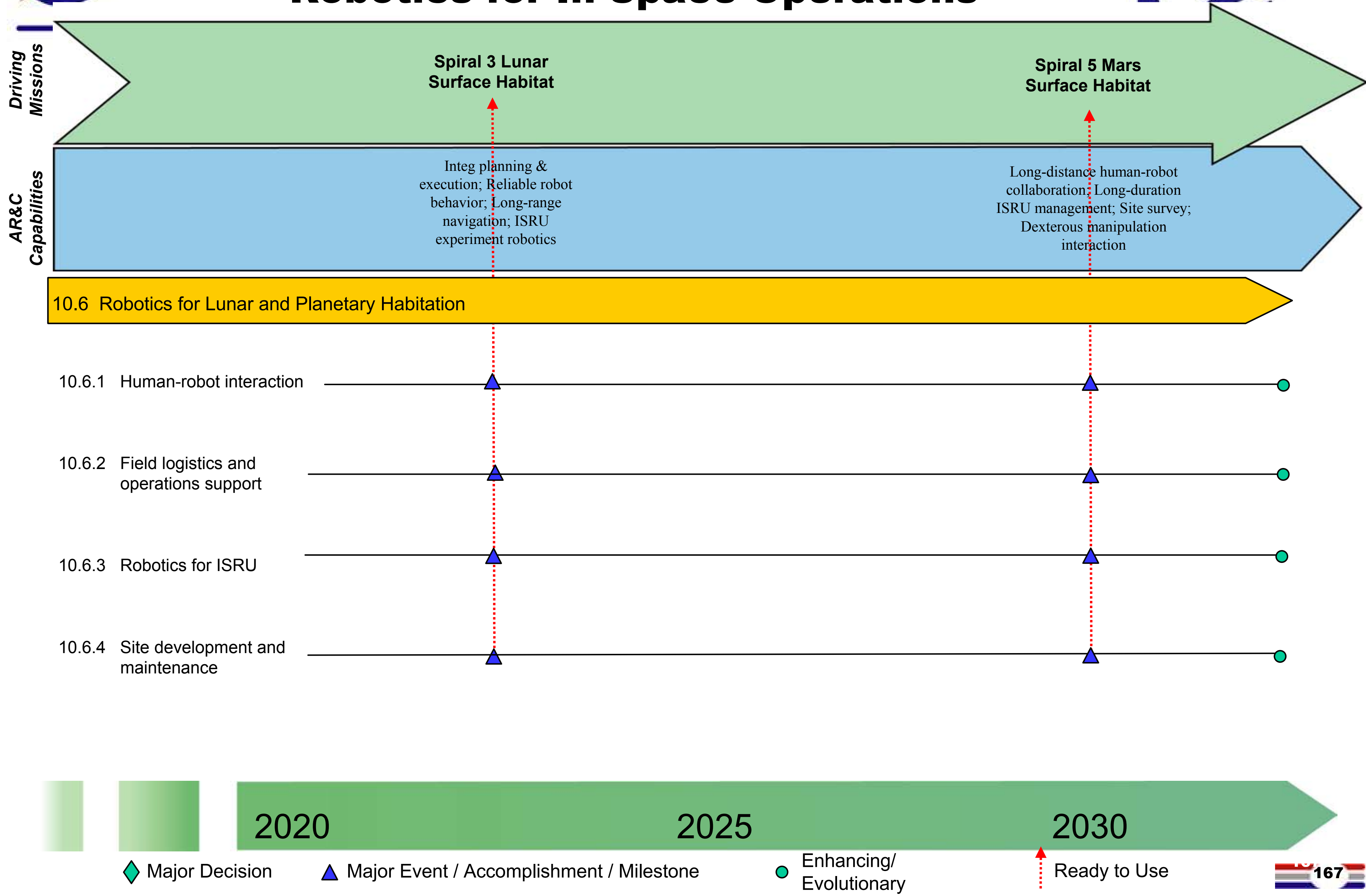
Assumptions

- Human habitation drives primary ISRU need due to requirement for sustainable presence
- Cost and safety arguments will necessitate human-robot teaming and thus human habitation suggests human-robot joint efforts
- Habitation is long-term, not for 6 hours only but days and weeks

Deliverables for Capability 10.6
Robotics for In-Space Operations



Deliverables for Capability 10.6
Robotics for In-Space Operations



Deliverables for Capability 10.6
Robotics for Lunar and Planetary Habitation

- Human-robot interaction, including adjustable autonomy and visualization for human supervision
  - Driver: Spiral 2 (Lunar Lander, Surface Ops), 2015
  - CRL 7 date: 2008
  - Interfaces: 6-RASP
- Field logistics and operations support, including networking, robotic access, long-distance navigation and planning, etc.
  - Driver: Spiral 2 (2015) and Spiral 3, Lunar surface habitat
  - CRL 7 date: 2010
  - Interfaces: 6-RASP and 5-Communication and Navigation
- Robotics for ISRU, including excavation, facility setup, and ISRU system management
  - Driver: Spiral 2 (Lunar Lander), 2015; Mars ISRU Experiment, 2017
  - CRL 7 date: 2012
  - Interfaces: 13-ISRU
- Site development & maintenance, including site survey, manipulation, defect detection, etc.
  - Driver: Spiral 2, Surface Ops and Spiral 3, Lunar/Mars surface habitat (2020)
  - CRL 7 date: 2015
  - Interfaces: 9-HES&M

Deliverable Definitions

- Human-robot interaction, including adjustable autonomy and visualization for human supervision
  - Humans must operate and supervise robotic and human-robot team systems, from direct robot teleoperation in close quarters and over long distance to remote supervisory strategic commanding and guidance, including human/robot task allocation, flexible multi-team member task allocation, adjustable autonomy, and supervision of work crews.
- Field logistics and operations support, including networking, robotic access, long-distance navigation and planning, etc.
  - In order to enable material transport, refueling, equipment transport, long-distance exploration, field science and other activities, technology must enable mobile networking, remote telepresence for mixed local-remote exploration and science teams; robotic access to otherwise inaccessible extreme terrain, autonomous planning, execution and control for long-distance and long-term operations and intelligent energy management for hybrid power systems. (Moderate risk)
- Robotics for ISRU, including excavation, facility setup, and ISRU system management
  - Robotics will play a critical role in supporting both precursor and ongoing activities for ISRU, including facility setup (piping setup, tracking assembly, site preparation); site terrain shaping and excavation for both teleoperated and autonomous robotic team large-scale excavation / terrain shaping; and system-level ISRU feedback, maintenance, inspection, adjustment and control. (High risk)
- Site development & maintenance, including site survey, manipulation, defect detection, etc.
  - From initial site survey, initial construction and resource deployments and collection to ongoing inspection, repair and regular maintenance operations, robotics will provide support for site development and long-term maintenance. Robotic technologies will include dexterous manipulation, perception, resource collection and warehousing control, site clean-up, site survey and visualization and visualization, parts collection and preparation for construction, communication and navigation infrastructure deployment. (High risk)

Visual learning and recognition

- Although advances in vision are consistent and of great practical use, especially recent object recognition work in the vein of spatially invariant feature detection, breakthrough advances in the areas of visual recognition of human-made and natural objects across extreme environmental variation, coupled with *learning*, enabling fielded humans to explain and identify what characteristics to look for and how to categorize what is seen for interpreted perception, would significantly lower the cost and risk associated with robotic inspection and robotic manipulation of structures. This capability has the potentially to trigger one to rethink the costs of long-duration stays on the moon and on Mars.

Robotic tactile dexterity

- Best forecasts will project that robotic dexterity will approach that of a EVA-suited human in the near future. If revolutionary advances in robotic tactile, feedback-based manipulation enable human naked hand-level dexterity and specific energy with human-level tactile feedback, this would completely change the regime of tasks that will be performed by robots during surface habitation activities. This revolutionary progress, requiring both changes in muscle motor technology and surface sensing technology, would dramatically lower the cost of in-space and surface assembly and maintenance activities by more than an order of magnitude.

Maturity Level – Capability 10.6
Robotics for Lunar and Planetary Habitation

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Site development & maintenance	Site Survey & Visualization	3-5	6	Spiral 2	2015
	SIFT-based Visual detection	3-5	6	Spiral 2	2015
Site maintenance	SIFT-based Visual defect detection	3-5	6	Spiral 2	2015
Field logistics & operations support	Integrated planning & execution systems	2-4	6	Spiral 2,3	2010
	Reliable Atomic Robot Behaviors	2-5	6	Spiral 2,3	2010
	MER long-range rover navigation	[+]	6	Spiral 3	2025

Maturity Level – Capability 10.6
Robotics for Lunar and Planetary Habitation

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Human-robot interaction	Agent-based Human-Robot Interface Arch.'s	4	6	Spiral 2	2008
	Dexterous manipulation teleop interfaces	4-5	6	Spiral 2	2008/2012
Robotics for ISRU	Terrain Shaping	2-5	6	Spiral 2, Mars ISRU exp	2010/2010 +
	Facility setup, ISRU management	2-3	6	Spiral 2, Mars ISRU exp	2012

Maturity Level – Technologies for Capability 10.6 Robotics for Lunar and Planetary Habitation

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Integrated Planning & Execution Systems		Three-tiered planning, sequencing and executive systems	2-5	Flexibility, Scale	2010
Agent-based Human-Robot Interface Architecture	Architecture, Dialogue handling, Comm. Network	KQML message-passing semantic protocols for agent interoperation	4-5	Field trialing	2008
Reliable atomic robot behaviors	Sensor and actuator logic	Numerous in research	2-5	Robustness, Predictability	2010
Terrain shaping	Excavation, soil planning, handling	Scanner-based topology modeling and scanning plus force-controlled 2 DOF excavation	4-5	Robustness, field trialing	2010/ 2020
Site Survey and Visualization	Safe approach, tracking, planning	Single cycle instrument placement	5-6	Remote site broad survey	2015
Vision-based defect detection and Object recognition	Object modeling, training, tracking	Spatially invariant visual feature tracking	3-5	Robustness, illumination	2015
Dexterous manipulation teleoperation interfaces		Human-level high DOF teleoperation robots	4-6	Control lag, robustness, cost	2012
Long-range autonomous navigation		Visual odometry-based closed loop navigation	5-6	Workload	2020

Metrics for Capability 10.6
Robotics for Lunar and Planetary Habitation

Metric	Technology / Sub-Capability	SOA	Target Value Fig of Merit	Need Date
# human interventions per task	Site development & maintenance	> 10	< 3	2012
Structural connections per hour	Site development	< 10	> 30	2015
Average distance navigated per human intervention	Field logistics and operations support	<100m	1000m+	2020
Proportion of navigation goals achieved	Field logistics and operations support	96% (MER)	99%	2020
% reduction of human cognitive load	Human-robot interaction	<< 10%	25%	2008 (OASIS)
Maximum parallel human-robot supervisions	Human-robot interaction	~ 1	3+	2020 (Mars)
Cubic meters excavation per hour	Robotics for ISRU	?	?	2015

Capability 10.7
Robotics for In-Space Operations

Sub-Team Chair: Ron Diftler, NASA/JSC

Presenter: Paul Schenker, JPL

Capability 10.7
Robotics for In-Space Operations

- **This capability area defines the robotic systems needed for assembly, inspection and maintenance, and human-robot interaction in space. This includes:**
- **Assembly**
  - Mass Manipulation (large, medium, small, fragile)
  - Preparation (Unpack, Identify, Order, …)
  - Connecting (Align, mate, verify)
  - Self Assembly (deployment, docking, etc..)
- **Inspection**
  - Structural (Mechanical Damage, Air Leaks, Deterioration)
  - Access (Under Thermal Blankets, Delicate Surfaces, Confined Space locations)
  - Component/System Failure Detection (Fault Detection, Non- Destructive Eval)
- **Maintenance**
  - Mass Manipulation (Medium, Small)
  - Locomotion (moving to points along fragile structures)
  - Staging, (Protection Removal, Temporary Stowage, Connector removal, etc…)
  - Human Rated Interface Manipulation (Crew and Robots use same interface to manipulate objects)
  - Dexterous Manipulation
- **Human-robot interaction**
  - Multi-agent teams (Assistants, Surrogates)
  - Intent Communication (Feedback, Task Verification, …)
  - Time Delay Compensation

Benefits of Capability 10.7
Robotics for In-Space Operations

- **In-Space Robotics assembly** is *enabling* for building exploration systems too large for single launch – solar tugs, large telescopes, space stations, etc…
- **In-Space Robotic Inspection** is *enabling* for reducing crew workload, thereby reserving crew time for science and exploration and for providing more precise results.
- **In-Space Robotic Maintenance** is *enabling* for reducing crew workload, thereby reserving crew time for science and exploration.
- Additional benefits:
  – Reduced EVAs → Increased Safety, Reduced crew Health issues
  – Enhancing the option for nuclear operations
  – More options from an operations standpoint, i.e., Minuteman
  – Support unmanned CEV, Ground control operations

Current State-of-the-Art for Capability 10.7 Robotics for In-Space Operations

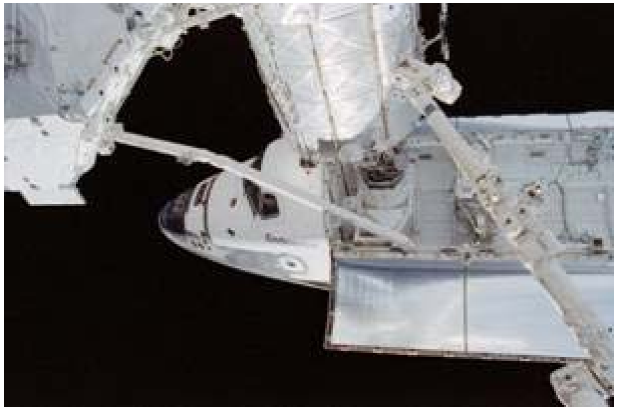
Advanced Planning & Integration Office

- **The state of the art for robotics for In-Space Operations includes the Shuttle Arm, Station Arm, Japanese ETS VII arm, ROTEX, MFD, Inspector, XSS-10, AERCam/Sprint, Charlotte.**
  - Simple end-effectors requiring dedicated robotic interface
  - Operational target based vision systems
  - Experimental force sensing.
- **The state of the art for In-Space Robotic Control Operations:**
  - SRMS release and capture of satellites – Bread and Butter
  - Teleoperation and ground control,
  - Stored sequences for control mode.
  - Single Arm manipulation
  - Limited time delay compensation for USA
  - ROTEX – autonomous capture of ball via ground control – IVA Experimental Flight
  - Supervised Autonomy work performed by Japanese: ETS-VII – Experimental flight
    - Worked with Significant time delay

Current State-of-the-Art for Capability 10.7 Robotics for In-Space Operations

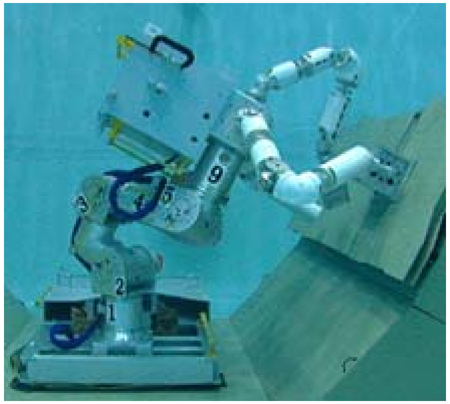
- The state of the art for In-Space Robotic Assembly:
  - SRMS and SSRMS work horses – Manual Control
  - Proven Large Mass Manipulation - ISS
- The state of the art for In-Space Robotic Inspection:
  - Surface Inspection Only
  - Human visual inspection through robotic cameras
  - Japanese MFD/Shuttle experiment - surface flaw detection
  - AERCam/Sprint Experiment – visual data
  - Ground Control starting for SSRMS
- The state of the art for In-Space Robotic Maintenance:
  - All experimental – task board – ETS VII
- The state of the art for Human/Robot Teams:
  - Crew Positioning using Shuttle, Station arms
  - Release and re-capture of free flyer AERCam/Sprint
  - Human finalizing mating after arms dock large payloads

Current State-of-the-Art for Capability 10.7 Robotics for In-Space Operations



Above: flight

Below: R&D



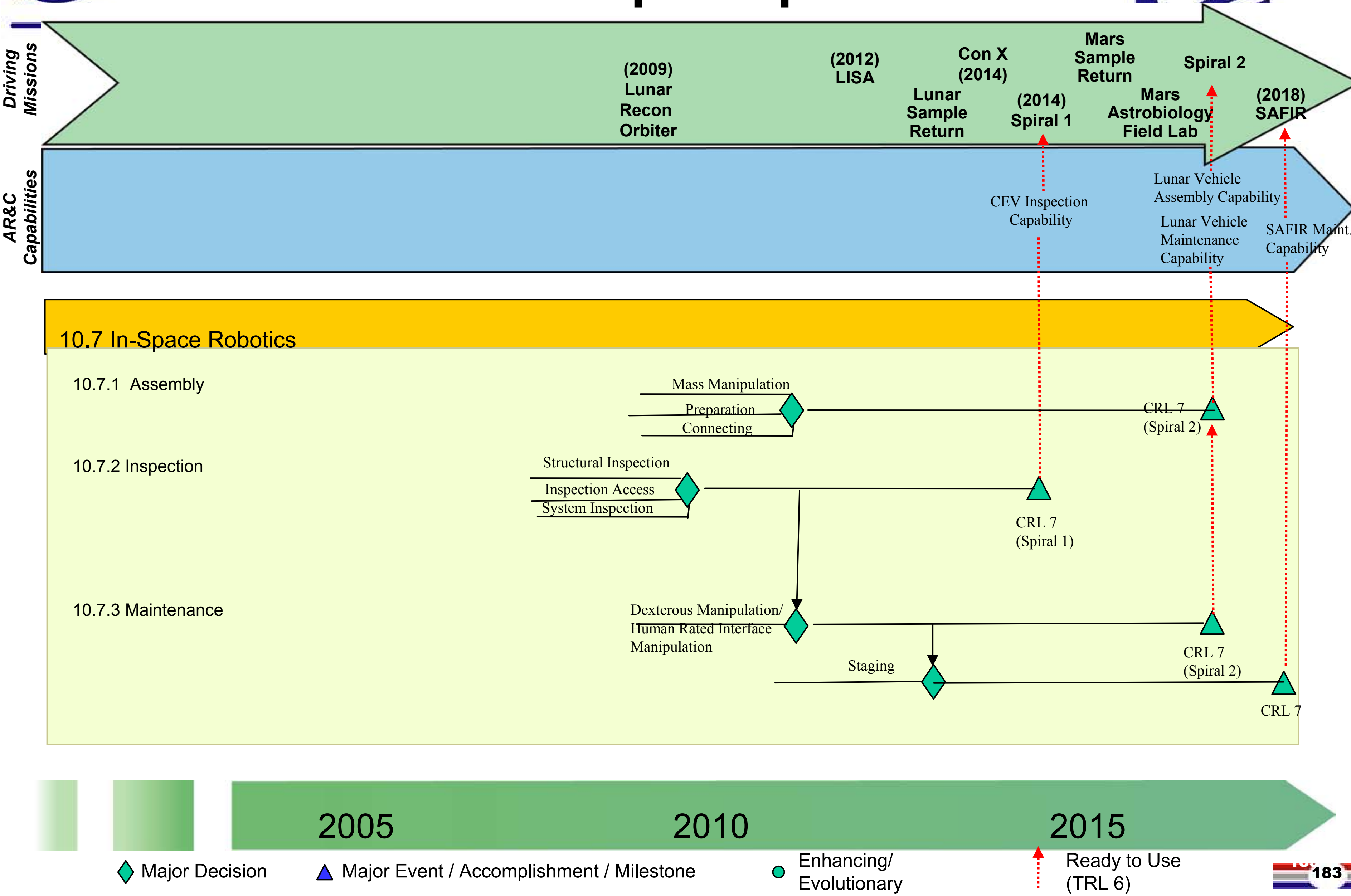
In-Space Robotics in Support of Manned Missions

- **Spiral 1: 2014** CEV LEO
  - Robotic Inspection
  - Robotic Maintenance
- **Spiral 2: 2015-2020** CEV LLO and EVA lunar surface ops
  - Robotic Assembly of Lunar Vehicles
  - Robotic Inspection and Maintenance of Lunar vehicles
  - Multi-Agent Teams
- **Spiral 3: 2020** Lunar surface habitat
  - Robotic Maintenance of In-Orbit Systems
    - Space Solar Power Plant
- **Spiral 4: 2025** Mars transit and vicinity ops
  - Robotic Assembly of Mars Vehicles
  - Robotic Inspection and Maintenance of Mars vehicles
- **Spiral 5: 2030+** Martian surface habitat and exploration
  - Robotic Maintenance of In-Orbit Systems
    - Space Solar Power Plant

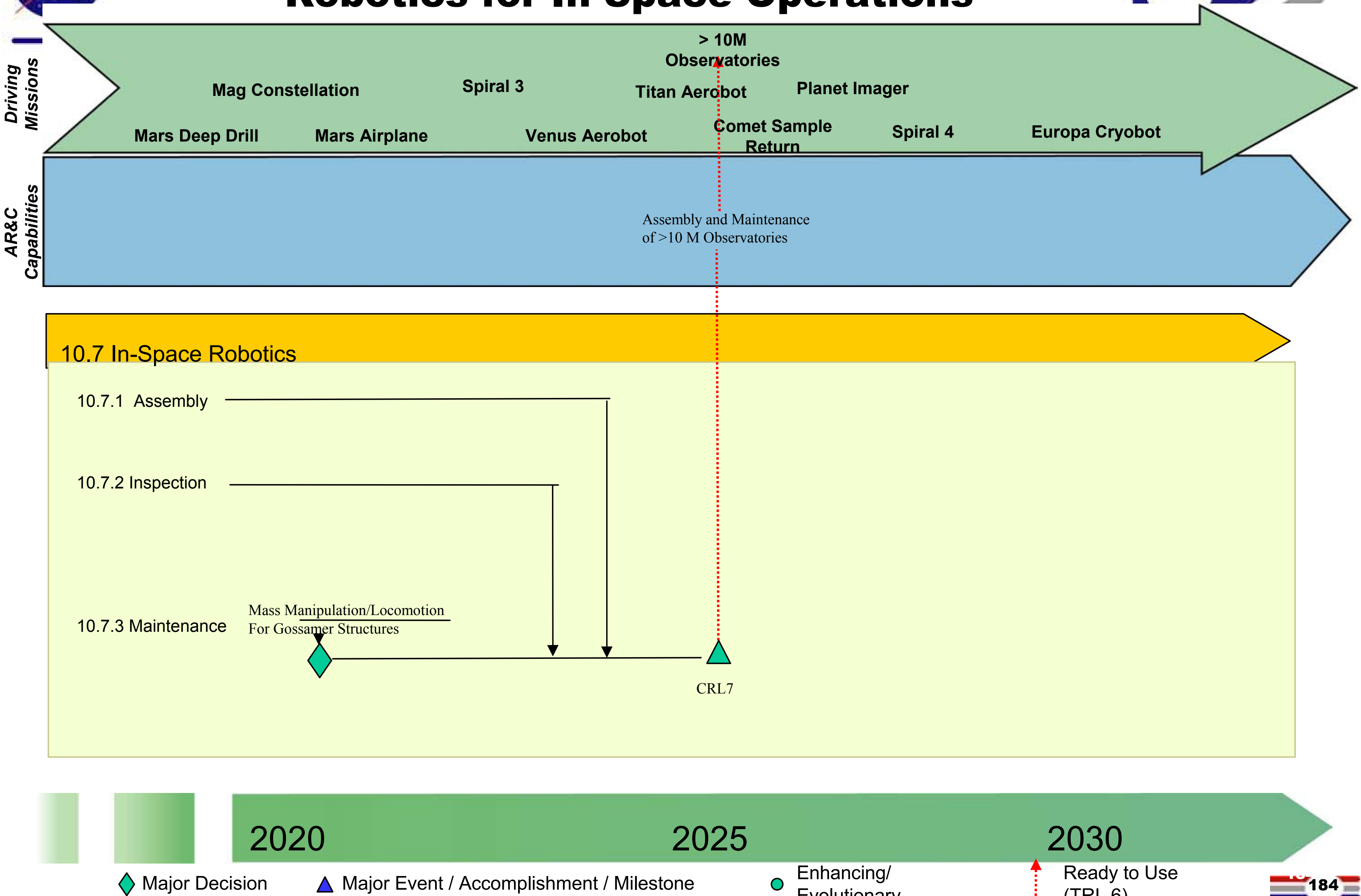
Requirements /Assumptions for Capability 10.7 Robotics for In-Space Operations

- In-Space Robotics in Support of Unmanned Missions
  - **Observatories**
    - Robotic Inspection and Maintenance for Telescopes
      - LEO -
      - GEO -
      - L1 -
      - L2 – SAFIR -2016, Observatories > 10 Meters - 2020

Deliverables for Capability 10.7
Robotics for In-Space Operations



Deliverables for Capability 10.7 Robotics for In-Space Operations



Deliverables for Capability 10.7 Robotics for In-Space Operations

- Inspection (internal, external, automated, sniffers)
  - Driver - CEV
  - Spiral 1 – TRL6 - 2009
  - IST, ATO
- Access for Inspection
  - Driver – CEV (Nozzles, panels, bays, radiators)
  - Spiral 1 – TRL6 - 2009
  - IST, ATO
- Connecting (Align, mate, verify, all power, fluid systems not just docking)
  - Driver – Assembly of Lunar Vehicles
  - Spiral 2 – TRL6 - 2010
  - IST, ATO

Deliverables for Capability 10.7 Robotics for In-Space Operations

- Dexterous Manipulation/Human Rated Interface Manipulation
  - Driver – Maintenance of Lunar Vehicles
  - Spiral 2 – TRL6 - 2010
  - IST, ATO, HESM
- Staging (Protection Removal, Temporary Stowage, Connector removal, etc…)
  - Driver – SAFIR Telescope Maintenance
  - Other– TRL6 - 2016
  - IST, ATO
- Mass Manipulation/Locomotion (Gossamer structures, multi-segmented reflectors)
  - Driver – Advanced Observatories > 10 Meters
  - other– TRL6 - 2020
  - IST, ATO

Deliverable Descriptions for Capability 10.7 Robotics for In-Space Operations

- Inspection (internal and external)
  - Visual and non-visual inspection through cameras, laser range images, hydrazine sniffers, leak detectors, etc.. on free flyers, manipulator end effectors, climbing robots. Looking for micrometeoroid damage, launch damage. Part of this done manually from the ground and on orbit. Need to increase precision and automation. (some risk)
- Access for Inspection
  - The ability to remove protective coverings to gain entry for inspection: panels, blankets. The ability to inspect in hard to reach areas: inside nozzles, along radiators. (moderate risk)
- Connecting (Align, mate, verify, all power, fluid systems not just docking)
  - Currently crew goes out and makes a significant portion of power, fluid, communication connections after arms dock modules. Future robots/vehicles should provide this capability for unmanned assembly prior to crew arrival. (some risk)

Deliverables Descriptions for Capability 10.7 Robotics for In-Space Operations

- Dexterous Manipulation/Human Interface Manipulation
  - Future vehicles for the moon will be complex modular, reconfigurable systems. A high level of dexterity in both manipulator arms and hands will be needed to efficiently work with these vehicles. (moderate risk)
  - All lunar vehicles that require maintenance will require human interfaces or special tooling to interface with robotic interfaces. Human rated interface manipulation would eliminate the need for both robot and human interfaces and special tooling to make robotic interfaces compatible with EVA gloves. (high risk)
- Staging (Protection Removal, Temporary Stowage, Connector removal, etc…)
  - Space Station planned robotic maintenance is limited to removal and replacement of boxes with robotic interfaces. A future capability will incorporate removal of numerous parts, ordering, temporary stowage, part preparation for removal and insertion, etc…. Robots need this capability to off-load crew. (high risk)
- Mass Manipulation/Locomotion (Gossamer structures, multi-segmented reflectors)
  - Observatories with large than 10 meter mirrors can not be launched in a single vehicle. A manipulation system that will apply minimal loads during assembly and maintenace is required for these unmanned systems. (high risk)

Breakthrough Capabilities for 10.7 Robotics for In-Space Operations

Mass Manipulation/Locomotion for Gossamer Structures Activities

- Future observatories will employ gossamer structures to achieve maximum aperture size for minimum weight. To achieve this goal a new class of robots is needed that can move across light and fragile structures while imparting minimal loads that may need to be significantly less than those an EVA astronaut would apply during climbing. This breakthrough class of robots will transport the materials for construction, and provide assembly and maintenance capabilities. Multi-legged systems that can distribute loads widely over a structure and minimize forces during motion are a prime candidate for achieving this capability. Efficient free fliers are a secondary candidate.

Space Suit Level Human Dexterity

- Removing the barrier between tasks performed by suited crew and robots will provide an immense cost savings by eliminating the need to provide a separate set of tooling for both robots and suited humans. In-Space operations will change dramatically as robots with human level dexterity “earn their stripes” by performing as assistants during EVA in-space operations. The percentage of robotic maintenance tasks currently limited to 50% on space station will grow substantially allowing crew to spend more time exploring and performing science. Human level dexterity will be achieved through a system level approach that combines multi-fingered hands integrated with a manipulator system constructed to provide the dexterous envelope than an astronaut can achieve through entire body motion. In addition, sensing used by both the robot’s automated control routines and tele-operators will provide the necessary feedback to maintain proper force levels during dexterous operations.

Maturity Level – Capabilities for 10.7 Robotics for In-Space Operations

Advanced Planning & Integration Office

Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Structural Inspection (Needs More Automation)	Free Flyers Climbers/Crawlers Machine Vision Manipulators	3-7	6	Spiral 1 – CEV LEO	2009
Inspection Access	Dexterous Robotic Arms Dexterous End Effectors Specialized End Effectors Robotic Bore Scopes	3	6	Spiral 1 – CEV LEO	2009
System Failure Inspection/Detection (cross cutting but included for discussion)	Machine Vision/imagine analysis Fluid Detection: Oxygen Hydrazine, Ammonia Radiation Detection Plasma Detection	2-3	6	Spiral 1 – CEV LEO	2009
Robotic Connecting	Specialized End effectors Multi-fingered Hands Force Control	4-5	6	Spiral 2 – CEV LLO and EVA lunar surface	2010
Dexterous Manipulation	Small high DOF arms Multi-fingered Hands Force Control Proximity/Tactile Sensing	4-6	6	Spiral 2 – CEV LLO and EVA lunar surface	2010

Maturity Level – Capabilities for 10.7 Robotics for In-Space Operations

Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Staging – maintenance	Small High DOF arms RF ID-Tags Machine Vision End Effectors/Hands	4-6	6	SAFIR Telescope	2016
Human Rated Interface Manipulation	Small high DOF arms Multi-fingered Hands Force Control Proximity/Tactile Sensing	4-5	6	Spiral 2 – CEV LLO and EVA lunar surface	2010
Mass Manipulation (Large) (SSRMS Proven)	Large Robotic Arms Free Flyers for Moving Mass	2-7	6	Spiral 3/4 – LLO/ Mars Transit vehicles	2010
Mass Manipulation (Gossamer Structures)	Low Reaction Force Crawlers	2	6	Observatories > 10 meters	2020

Maturity Level – Technologies for 10.7 Robotics for In-Space Operations

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Free Flyers for Inspection	Propulsion System Miniaturized Sensors	Rechargeable Propulsion, Docking System MEMS gyros	4-6 5-6	Integrated Ground/Flight Test	2009
Machine Vision beyond targets	Camera Calibration Object Recognition Pose Estimation	Patterns Templates Templates	5 4 3	Environmental Speed/Memory Robustness	2009
Climbers/Crawlers	Low Backlash Actuators	Harmonic Drives	4-9	Packaging	2009
Small, Medium Sized Manipulators	High Power Density Motors Miniature Motor Drivers Miniature Sensors	Rare Earth Hybrids Optical	6-9 4-9	Packaging Packaging Packaging	2010
Force Control	Load Cells	6- Axis load cells	4-7	Temperature Compensation, Size	2010

Maturity Level – Technologies for 10.7 Robotics for In-Space Operations

Advanced Planning & Integration Office

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Multi-Fingered Hands	Miniature High Output Actuators	Brushless DC Magnetic Shape Memory	7-9 2-3	Size Packaging	2010
	Miniature Sensors	Hall Effect	4-6	Reliability	
Proximity/Tactile Sensing	Proximity Sensors	LEDs	4	Environmental	2010
Large Robotic Arms	Low Backlash Gearbox	Large Harmonic Drives	4-6 (9- smaller ones)	scale	2015
Free Flyers for Moving Large Mass	Propulsion system	Stored Gas	0	efficiency	2015
Low Reaction Force Crawlers	Force Control	Damping Control	4-7	Computational Capability Sensor Environmental Issues	2020

Metrics for 10.7
Robotics for In-Space Operations

Advanced Planning & Integration Office

Metric	Technology / Sub-Capability	Target Value	Need Date
Time to Inspect CEV for external structural damage	Autonomous Free Flyer/ Structural Inspection	2 hours	2009
Time to Inspect CEV engine Nozzle	Tendril Robot/Inspection Access	1 hour	2009
Percentage of Robotic connector Mating for Lunar Vehicle	Specialized End Effector/ Assembly Connecting	80%	2010
Percentage of Robotic Maintenance on Lunar Vehicle	Multi-fingered Hands/Dexterous Manipulation	90%	2010
Percentage of tools used by Robot and EVA	Multi-fingered Hands/ Human-Robot Interface Commonality	95%	2010
Successful Robotic Telescope Repair	Dexterous Manipulators/ Maintenance Staging-Connecting	1	2016
Force Level while transversing a Gossamer structure	Crawler robots/ Mass manipulation on Gossamer Structure	< 2 N	2020

Overview

- Introduction (Steve Zornetzer)
- Process, Mission Drivers, Deliverables, and Interfaces (James Crawford)
- Autonomy (James Crawford)
  - Crew-Centered and Remote Operations
  - Integrated Systems Health Management
  - Autonomous Vehicle Control
  - Autonomous Process Control
- Robotics (Paul Schenker)
  - Robotics for Solar System Exploration
  - Robotics for Lunar and Planetary Habitation
  - Robotics for In-Space Operations
- **Computing Systems (Mike Lowry)**
- Conclusion

Autonomy and Robotics Capability 10.8 Computing Systems (Robust Software)

NASA Co-Chair: Michael Lowry, Ames
External Co-Chair: Michael Evangelist, CMU

March 30, 2005

Capability

Capability Summary

Robust computing software that provides high assurance for space-based system-level capabilities including command and control, science data handling, vehicle health management, and fault protection functions envisioned over the next 20 years. The purpose of the capability is to provide software mission assurance and cost-effective robust computing for the autonomy and robotic capabilities of the future.

Benefits

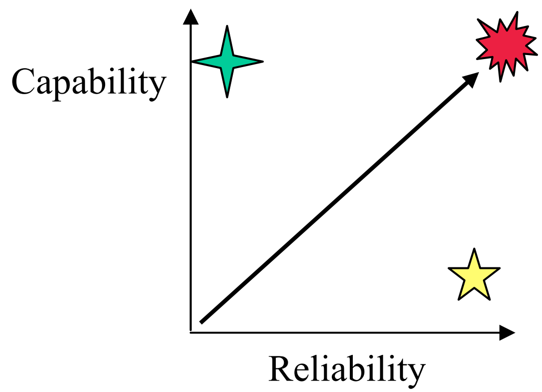
- **High assurance:** Enable reliability of software-based capabilities for NASA missions, particularly advanced autonomy and robotic capabilities. Residual design defects will be minimized, and computing systems will have the capability of recovering from hardware faults and software faults. Many error classes will be eliminated.
- **Cost-Effectiveness:** methods for development and validation of aerospace software that minimize human labor. Architectures that facilitate adoption of commercial components where compatible with mission-critical assurance.
- **Sustainability:** software systems that are maintainable over a mission lifecycle. Reuse of components across missions. Migration of software to new flight processors and avionics architectures as hardware technology improves.
- **Predictable Software Engineering:** Software development for NASA space systems will be matured into an engineering discipline with a well-understood trade-space and trusted products. As early as mission trade studies, the trade-space of different software solutions on system-level functions will be capable of being analyzed.

Capabilities

1. **Advanced testing and analytic tools** that provide assurance better than hardware-in-the-loop (HIL) high-fidelity testbeds alone.
   - Advanced testing enables covering an order of magnitude more scenarios without increasing cost and human labor.
   - Analytic tools provide guaranteed assurance of absence of many error classes.
2. **V&V for Autonomy and Adaptive Systems**
   - Methods that enable reliability for capability 10.
3. **Fault Tolerance** for computing faults.
   - Smart redundancy, micro-rebooting, software-enabled radiation tolerance, fault containment, software fault recovery.
4. **Model-based software development**.
   - Certifiable and automated software generation from engineering design models and requirement specifications.
   - Cost-effective maintenance, upgrade, and recertification.
5. **Predictive Models of software engineering** components, methods, and technologies.

State of Art

Commercial sector historically stresses time-to-market and capability over assurance. Many commercial software products are mature with only incremental feature upgrades. Large product distribution to amortize development costs. Assurance: statement coverage considered adequate for testing. Size: XP is about 40MSLOC



Traditionally aerospace has stressed assurance over cost. Many aerospace systems have limited distribution over which to amortize development costs. Productivity has held nearly constant - rising from 7 to 10 SLOC per person per day over last 20 years. Assurance: extensive branch/statement coverage, MC/DC required for commercial aerospace. Size: ISS is about 2MSLOC

NASA has pacing needs in aerospace computing due to mission length, light-time delays, radiation, lower tolerance for risk. Autonomy and robotics will exceed the limits of traditional aerospace capabilities, but reliability cannot be compromised - it will need to be enhanced. Many NASA systems are one-offs. Size and other risk factors for the software implementing these capabilities is not known, part of the general problem of calibrating software and determining trade-space of solutions.

Benefits

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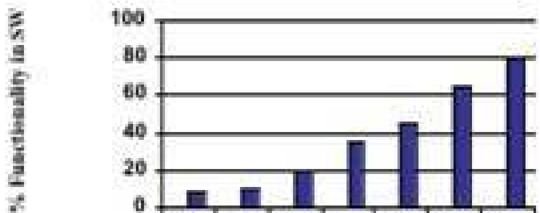
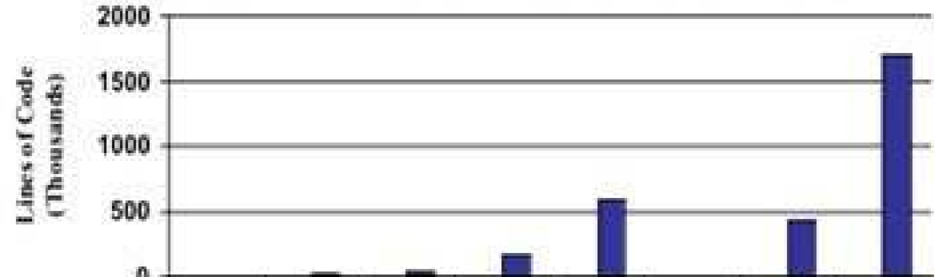
Computing systems are the most cost-effective means of implementing a broad spectrum of mission capabilities. Hence over time, an increasing percentage and number of aerospace mission functions reside in computing systems. New capabilities for autonomy and robotics will accelerate this trend. *(Data from military aerospace)*



	1960	1964	1970	1975	1982	1990	2000
System	F4	A7	F11	F15	F16	B2	F22
%SW Funct	8	10	20	35	45	65	80

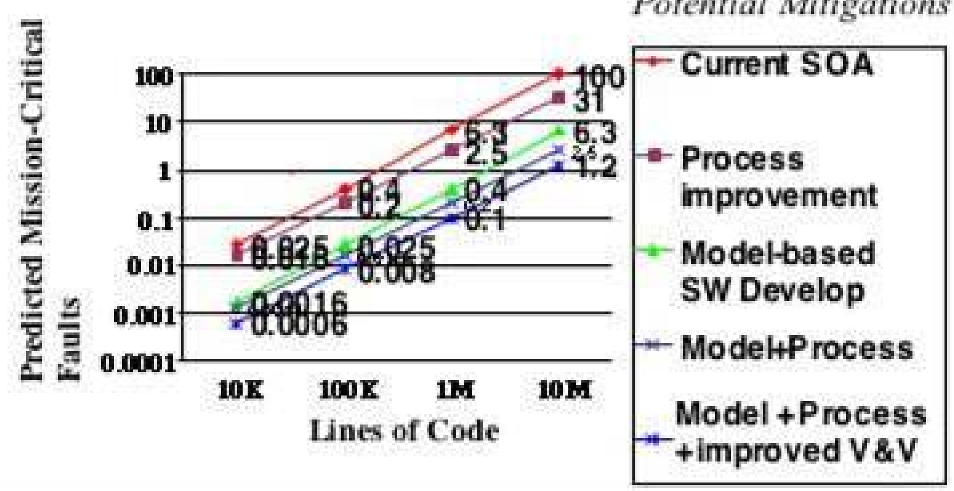
The result is analogous to Moore's law: an exponentially increasing size of flight software systems as the capabilities embedded in aerospace computing systems are increased. *(Data is from NASA robotic and manned mission flight software, by mission date. Progression is by start date of mission development.)*



	1977	1989	1997	1997	2004		2000	2000
Mission	Voyager	Galileo	Cassini	MPF	MER	Manned	Shuttle	ISS
KSLOC	3	8	32	160	580	Missions	430	1700

However, without advances in software engineering for flight systems, these increasing capabilities come at a significant reliability risk, as well as increasing cost and schedule. Residual software defects increase faster than proportional to exponentially increasing size of code (due to supra-linear growth of module-module interactions.) Mission assurance is risked unless better mitigations are developed. New capabilities for autonomy and robotics especially require advances in high-assurance computing. *(Data is extrapolated from COCOMO-based model calibrated to Mars missions SLOC and mission failures.)*
Cost and schedule for flight computing system development follow similar curves and are bottlenecks in mission projects.

Potential Mitigations



State of the Art

• Verification and validation of mission software is labor-intensive and expensive, typically accounting for 60% to 80% of overall development costs in mission-critical aerospace software. Validation bottleneck is scarcity of high-fidelity HIL test-stands.

• Computing faults are pervasive in unmanned missions and space station. These are often of little consequence during non-critical mission phases, and typically fixed through reboot. However, there is no known method of finding only those types of errors that are mission-critical. Bleed-through of faults from non-mission critical components to critical components have caused mission failures.

• Aerospace software development is expensive and labor-intensive to meet process-based assurance.

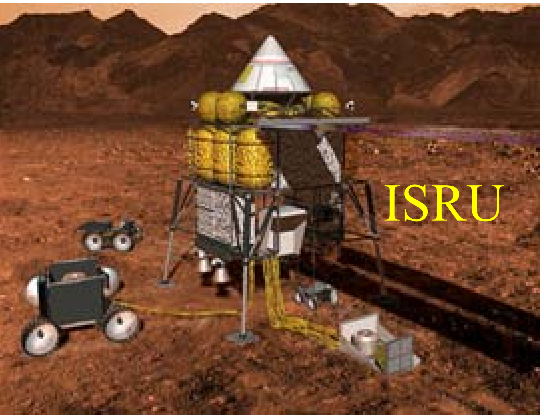
• The superficial malleability of computing systems for implementing changing system requirements leads to addressing computing solutions late in the mission lifecycle - leading to assurance, cost, and schedule problems.

• The tradespace for computing systems solutions - from radiation tolerance through software validation methods through architectures for real-time control - is not well understood.

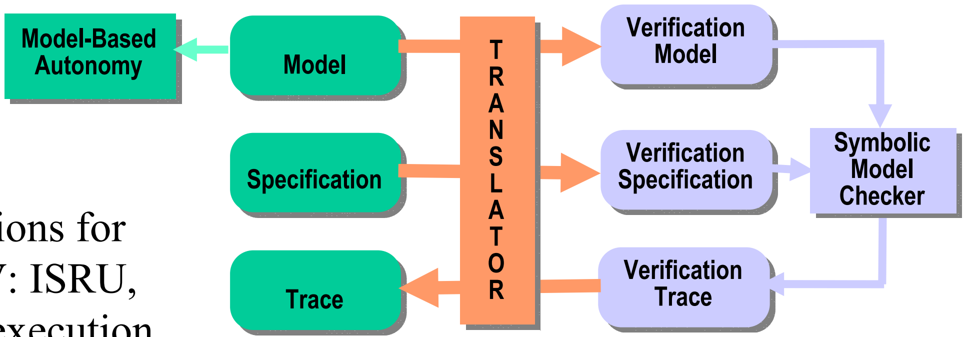
10.8.1: Advanced testing & Analytic Assurance

- **Advanced testing and analytic V&V** methods that provide assurance better than hardware-in-the-loop (HIL) high-fidelity testbeds alone.
  - Calibrated hierarchy of testbeds with accelerated, model-based testing. Massive simulations of critical mission phases such as precision EDL on accelerated software testbeds.
  - Measurement and characterization of false negatives/false positives between HIL and software simulators& analysis tools to optimize use of HIL testbeds.
  - Analytic tools that provide guaranteed assurance for specific error classes (memory out-of-bounds, race conditions, runtime errors, non-compliance with flight rules, etc.)
  - Early lifecycle detection of errors through tool-based analysis at requirements and design level.

10.8.2: V&V for Autonomy and Adaptive Systems

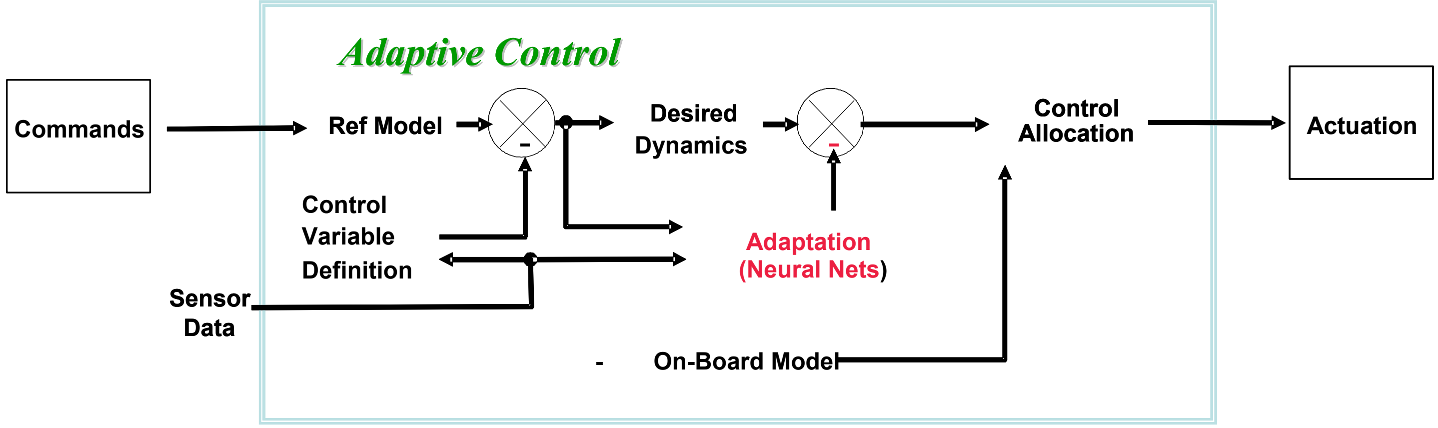


Pacing applications for autonomy V&V: ISRU, ISHM, robust execution, planning and scheduling, etc.



Lyuponov stability analsysis, white-box monitoring of neural net during adaptation scenario simulation, monitoring of adaptation stability during run-time.

Pacing applications for adaptive systems V&V:Mars airplane, aerobots, process control.



10.8.3 Fault Tolerance

- New approaches to fault handling for both hardware (e.g., radiation) and software faults
  - Smart redundancy (pool of reconfigurable redundant computing resources) for effectiveness and weight/power.
  - Smart software failure detection
  - Software architectures for robust radiation tolerance.
  - In-situ diagnosis of computing faults
  - Firewalls between software at different levels of criticality
  - Recovery through micro-rebooting, automated work-arounds, automated synthesis of component replacements

10.8.4 : Model-Based Software Development

- NASA flight systems will be crossing the threshold where unaided labor-intensive development processes are not effective to achieve the capability and reliability required within constrained cost and schedule.
  - Capture of machine-analyzable and testable requirements.
  - Design models close to engineering models used by sub-system, system, and SOS engineers.
  - Largely automated code generation from design models and requirements with precise traceability to both.
  - Increasing automation of verification, validation, and certification.
  - Support for iterative development, with human effort no greater than scope of changes to requirements and design models. Automation of back-end of ‘V’.

10.8.5: Predictive Models of Software Eng.

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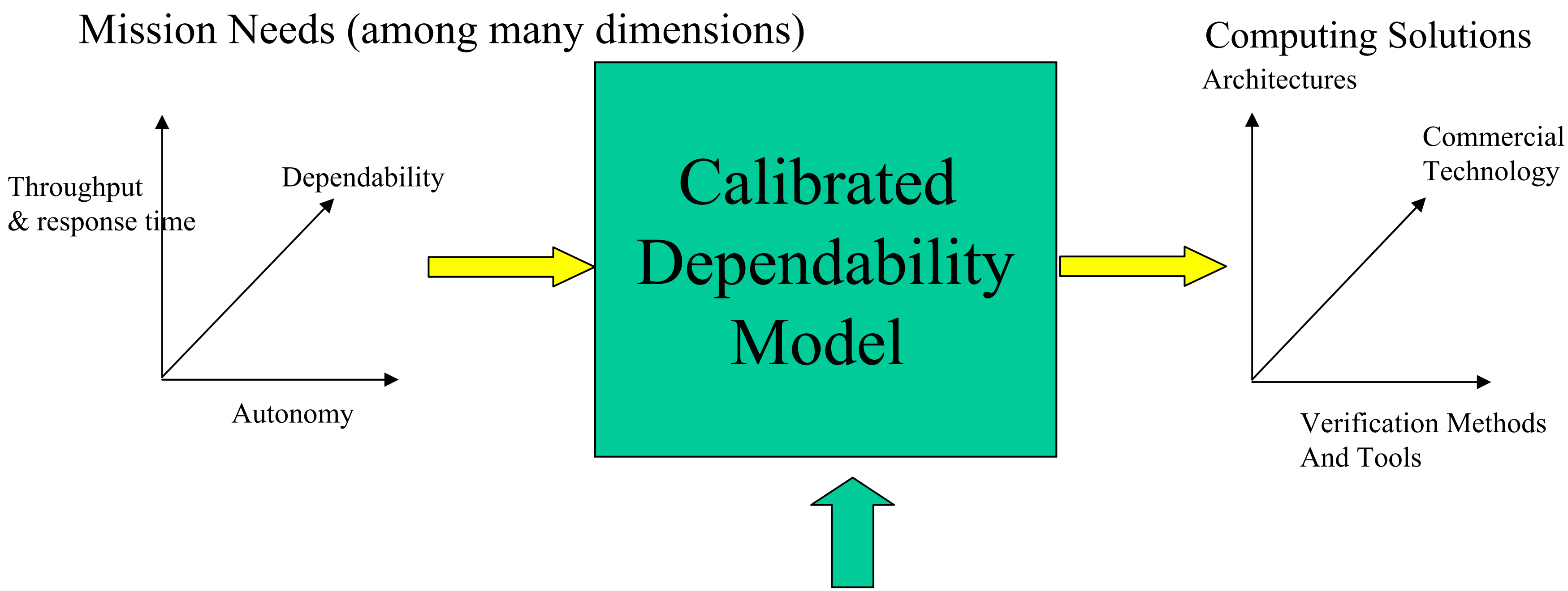


RT OS
Architectures
V&V methods
Etc.

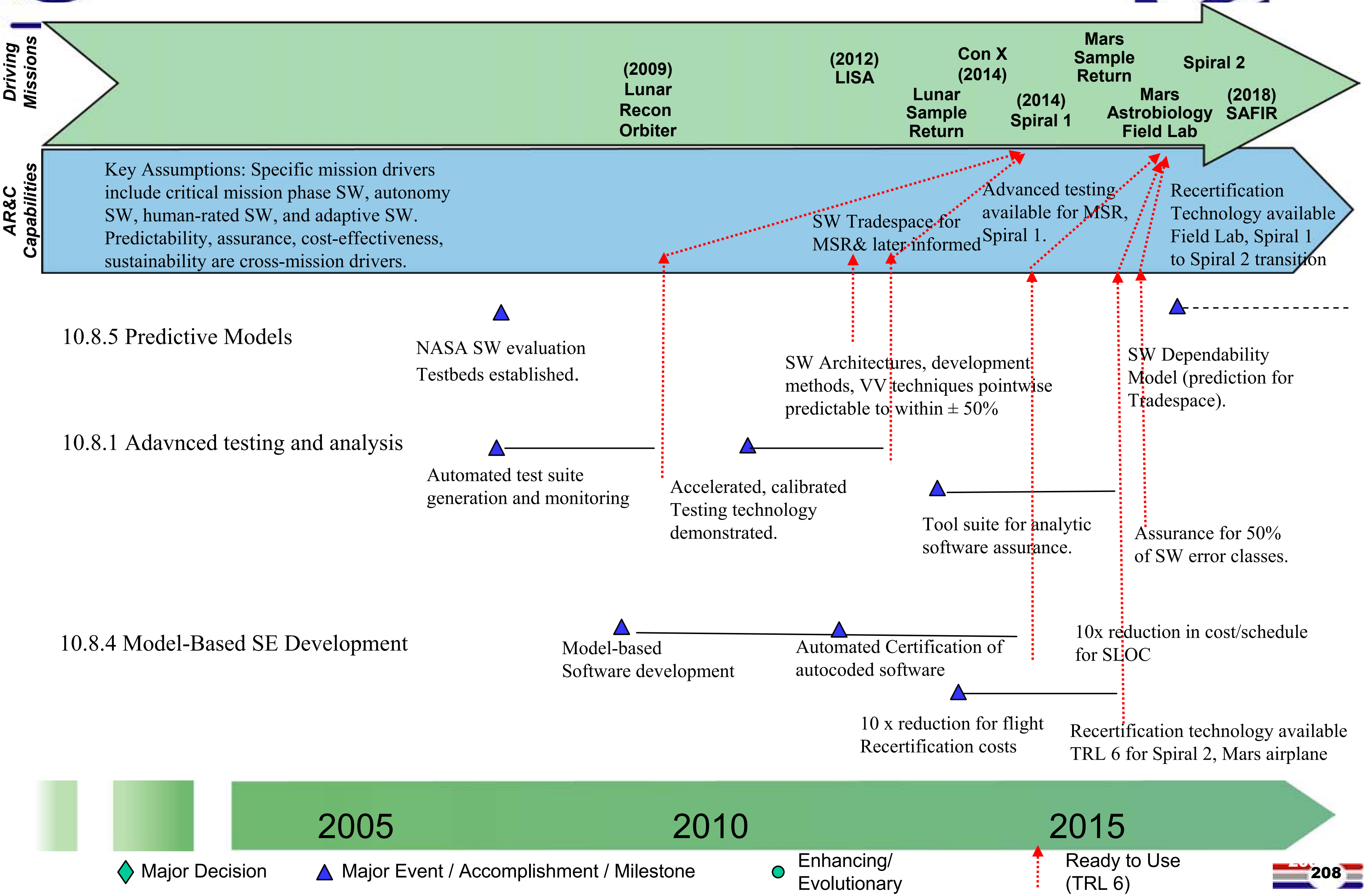
Computing Technology Evaluation Testbeds

Calibration and Validation against NASA needs

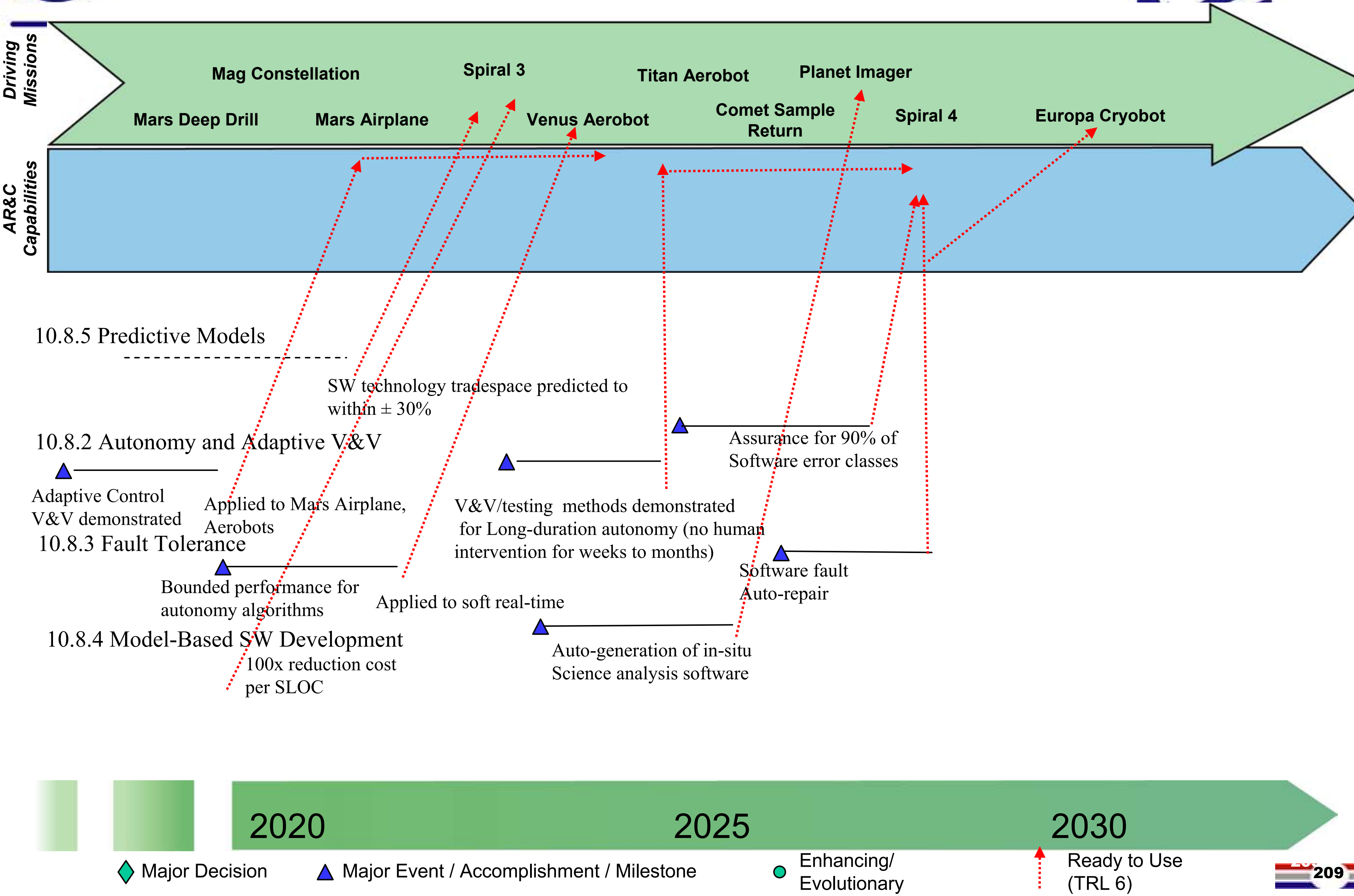
Requirements/Assumptions

- Computing system capability benefits cut across NASA space missions, but technology advances are unlikely to be funded for specific missions.
- The primary driver is safety and mission assurance.
- Secondary drivers are development cost required to support previous and new mission functions, and computing throughput/storage.
- Capability development needs to be designed from the beginning to be used across many different missions to increase safety and decrease cost.
- Barriers to adoption of capabilities need to be addressed:
  - Capabilities need to be validated and evaluated against trade-space for mission design to reduce barrier to mission adoption.
  - Capabilities should be packaged as separably adoptable parts.

Capability 10.8 Computing Systems (Software) Roadmap



Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Deliverables

- **10.8.1 Advanced Testing and Analytical Tools**
  - 10x number of scenarios that can be tested to same level of assurance as high-fidelity testbed at same cost. Example: 10,000 scenarios tested for Mars Sample Return Martian launch at cost of 1,000 scenarios on high-fidelity testbed. (Moderate risk)
  - Residual errors less than .1 per thousands source lines of code (KSLOC) (Moderate risk)
    - Driver: Mars Sample Return
    - CRL 7 date: 2010
    - Interfaces: 15-SEC/RA
- **10.8.2 V&V for Autonomy and Adaptive Systems**
  - V&V methods for robust execution (slight risk).
    - Driver: Lunar robotic sample return, 2011; all other complex science and exploration missions
    - CRL 7 date: 2009
    - Interfaces: 10.2 AR&C/ISHM, 10.3 AR&C/AVC, 10.4 AR&C/APC&EA
  - V&V methods for model-based diagnosis. (Moderate risk)
    - Driver:ESMD Spiral 1
    - CRL 7 date: 2009+
    - Interfaces: 10.2 AR&C/ISHM, 10.3 AR&C/AVC, 10.4 AR&C/APC&EA, System Engineering
  - V&V methods for adaptive control, with on-board monitoring. (Moderate risk)
    - Driver: Mars Airplane, Aerobots, Process Control
    - CRL 7 date: 2015+
    - Interfaces: 10.3 AR&C/AVC, 10.4 AR&C/APC&EA

Deliverables

- **10.8.3 Fault Tolerance**
  - Software Fault Containment, Robustness for Computer Hardware Faults (Slight risk)
    - Driver: Spiral2&3, MSR
    - CRL 7 date: 2010
    - Interfaces: 15-SEC/RA, System Engineering, 10.x
  - Software Fault Recovery (Extensive risk)
    - Driver: Spiral 3&4, Europa Cryobot
    - CRL 7 date: 2015
    - Interfaces: 10.2 AR&C/ISHM
- **10.8.4 Model-Based SW Development**
  - Recertification costs reduced to $1000 per thousand source lines of code (KSLOC) (Moderate risk)
    - Driver: Spiral2&3
    - CRL 7 date: 2010
    - Interfaces: 15-SEC/RA
- **10.8.5 Predictive Models of SW Engineering**
  - Software costs and schedules predictable to within 20% error in 90% of missions (Moderate risk)
    - Driver: Spirals 2&3
    - CRL 7 date: 2010
    - Interfaces: 15-SEC/RA

Maturity Level

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Automated/accelerated/ calibrated testing technology Analytic assurance	Test suite generation/monitoring Calibration to HIL	4 3	6	MSR, Spiral 2 Spiral 1/2	2010
Software Engineering Technology Evaluation Testbeds	JIT testbed, instrumentation	4-5	6	Spiral 2	2009
Fault Tolerant hardware and software	Comp. Architect,	3-5	6	MSR, Spiral 2	2012
Certified automated SW generation	Integrated generation and V&V	4-5	6	Spiral 2	2009
Maintainability& reusability	Iterated develop. Environments/tools	3	5	Spiral 2	2009
Precision recertification	Dependency analysis, targeted Testing	3	6	Spiral 2	2012

Capability Need/Gap Assessment

Sub Capability			
Predictive Models of Software Engineering	Variance between predicted metrics and actual metrics (parameterized by mission phase from trade studies through deployment).	Software engineering architectures/methods/technologies are not considered until late in mission lifecycle. Familiarity of design team with past mission software engineering practices.	Evaluation testbeds for software engineering technologies, to enable transition of new SW technologies to missions.
Advanced Testing and Analysis tools **Fault Tolerance** **V&V Autonomy and Adaptive Systems**	Residual defects Measurable assurance Computing fault tolerance Assurance for advanced autonomy, robotics, adaptive control	Expensive and exhaustive testing on high-fidelity testbeds Human review with limited tool support (e.g., code scanners). Expensive low-level hardware redundancy. Coarse methods of fault tolerance. Demonstrations of model compliance for model-based autonomy, model-checking for robust execution, black-box monitoring of adaptive systems.	Calibrated hierarchy of testbeds with accelerated, model-based testing. Analytic, tool-based approaches. Assurance based on solid engineering principles, validated by space-flight. Smart redundancy . New approaches to fault handling for both hardware (e.g., radiation) and software faults. Model-validation, automated checking of robust execution systems, envelope and white box monitoring of adaptive systems

Capability Need/Gap Assessment

Sub Capability			
Model-Based SW Development	Development cost per LOC/function Develop time (i.e., time elapsed from design to code)	Custom programming. 7loc/developer/day	Product families Certified software generation from engineering models
Model-Based SW Development	Maintainability Reusability Recertification	V&V are bottlenecks in maintenance Š even bug fixes are seen as risky. Estimated 25% reuse of MPF on MER. Full-up revalidation testing.	Tools and methods for iterated development that address V&V Lightweight architectures Targeted recertification testing through dependency analysis

Metrics

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Metric	Benefit / Sub-Capability	SOA	Target Value	Need Date
Predictable performance of Software Engineering Technologies and Methods	High Assurance/ Cost-effectiveness	Anecdotal/ Qualitative	± 30%	2014
Residual defects per KSLOC for flight software	High Assurance	0.5 to 2	< 0.01	2012
Measurable Assurance - % Error classes excluded	High Assurance	< 15%	> 90%	2016
SLOC /person/day	Cost-effectiveness/ High Assurance	7	>100	2012
Recertification cost per KSLOC of system	Sustainability	$10K (ISS)	< $1K	2012
Maintenance cost - KSLOC maintained per person	Sustainability	<1.2 (Shuttle)	> 100	2014

Capability 10.9
Flight Avionics

Sub-Team Chair: Leon Alkalai, JPL
Presenter: Leon Alkalai?, JPL

Capability 10.9
Flight Avionics

- **This capability** is to provide NASA missions with a standard set of hardware components that can be adapted and customized to fit mission-specific needs.
  - Flight Computers
  - Data Storage
    - Volatile
    - Nonvolatile
  - Interface/Buses (I/O)
  - Engineering Sensors
  - GN&C Sensors
  - Power management and distribution
- **Which of these sub-capabilities should be considered within AR&C?**

Overview

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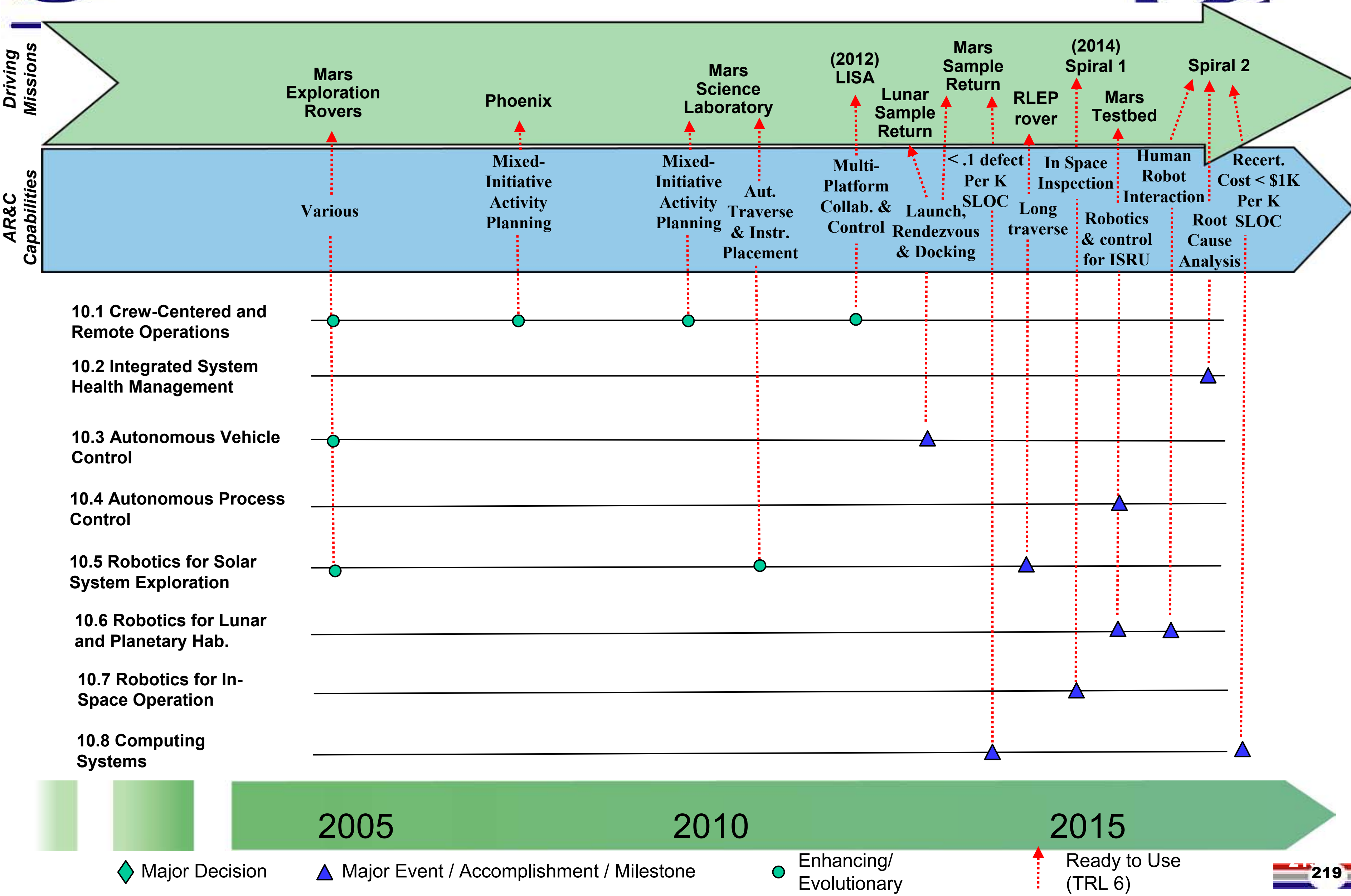
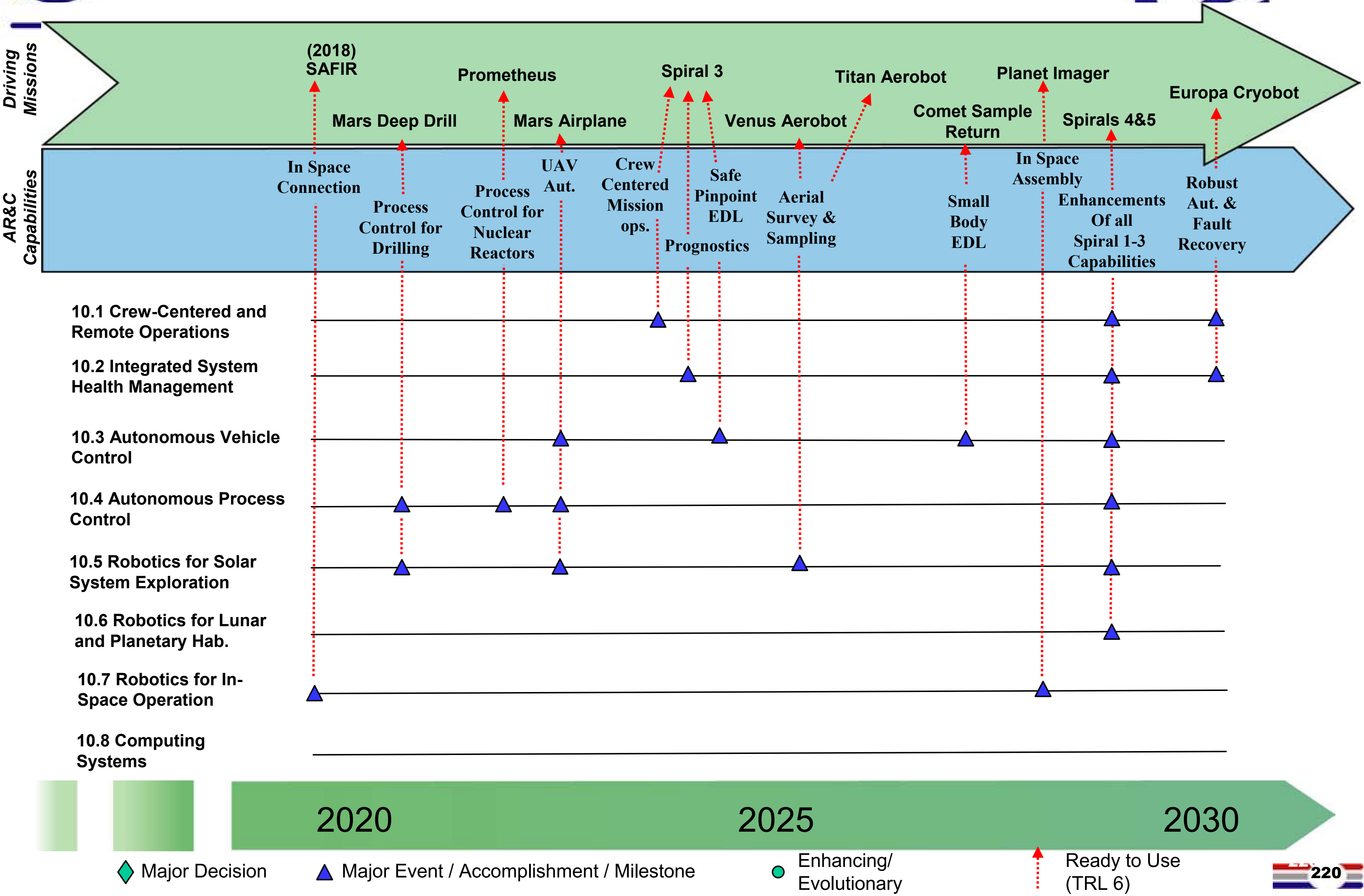
- Introduction (Steve Zornetzer)
- Process, Mission Drivers, Deliverables, and Interfaces (James Crawford)
- Autonomy (James Crawford)
  - Crew-Centered and Remote Operations
  - Integrated Systems Health Management
  - Autonomous Vehicle Control
  - Autonomous Process Control
- Robotics (Paul Schenker)
  - Robotics for Solar System Exploration
  - Robotics for Lunar and Planetary Habitation
  - Robotics for In-Space Operations
- Computing Systems (Mike Lowry)
- **Conclusion**

Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Breakthrough Capability Rollup

Capability	Enables
Autonomy and control for deep drilling (10.4, 10.3, 10.5, and 10.2)	Sub-surface search for evidence of life on Mars and Europa
Dependable, and affordable robotic in-orbit maintenance (10.7 and 10.3)	Instrument change-out and long term operation of observatories
Dependable and affordable robotic in-orbit assembly (10.7 and 10.3)	Large aperture telescopes, affordable human exploration beyond earth-moon neighborhood.
Dependable autonomy for aerobots and sub-surface (10.4, 10.1, and 10.5)	Aerial Mars survey. Surface access on Titan. Search for evidence of life on Europa.
Surface mobility to cliffs and other current inaccessible sites (10.5).	Search for evidence of life on Mars in areas showing possible recent fluid flow
Largely automated CEV and habitat operations (10.1 and 10.2)	Human exploration of Mars.
Autonomous robotic surface construction and ISRU (10.6 and 10.4). Safe, dependable, pinpoint landing (10.3).	Affordable human habitation on Moon and Mars. Robotic site preparation in advance of manned surface missions

Summary of Key Deliverables

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	Mars	Solar Sys.	Lunar	Obs.	Earth Sci.	Sun-Earth	Spiral 1	Spiral 2	Spiral 3
10.1 Autonomous mission ops	Enhancing	Enabling	Enhancing	Enhancing	Enhancing	Enabling *	Enhancing	Enhancing	Enabling *
10.1 Multi-platform collaboration				Enabling *	Enabling	Enabling *		Enhancing	Enhancing
10.2 Root-cause analysis	Enhancing	Enabling	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling *
10.2 Prognostics	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling *
10.3 Rendezvous and Docking	Enabling *		Enhancing	Enhancing				Enhancing	Enabling
10.3 Entry, descent, & landing	Enabling *	Enhancing	Enhancing					Enhancing	Enabling
10.4 Nuclear reactor control		Enabling *	Enhancing						Enabling *
10.4 Sub-surface drilling	Enabling *	Enabling	Enabling *		Enhancing			Enhancing	Enhancing
10.5 Long traverse	Enabling *	Enhancing	Enabling *		Enhancing			Enhancing	Enhancing
10.5 Aerial survey and sampling	Enhancing	Enabling *			Enabling				Enhancing
10.6 Human-robot interaction					Enhancing			Enhancing	Enabling *
10.6 ISRU	Enabling *		Enabling *					Enhancing	Enabling
10.7 In-space inspection				Enhancing	Enhancing		Enhancing	Enhancing	Enabling *
10.7 In-space connecting				Enabling *				Enhancing	Enabling *
10.8 <.1 defect per K SLOC	Enabling *	Enabling	Enabling	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling
10.8 Recert. < $1K per K SLOC	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling *	Enabling

SMD (Mars through Sun-Earth) ESMD (Spiral 1 through Spiral 3)

* First driver

Enabling

Enhancing

Conclusions

– AR&C is heavily cross-cutting. Most capabilities are relevant to multiple missions and mission classes. In several cases, AR&C results will change theme roadmaps.

– In many cases AR&C is providing common control and execution software for hardware developed by other capability roadmaps. Close programmatic and technical collaboration is essential.

– Strategic needs differ from other areas:
  – Infrastructure needs for AR&C are modest.
  – Creating a talented and motivated workforce focused on NASA's unique challenges is essential (and difficult when NASA's R&D funding is unstable).
  – Additional focus on validation and verification of Autonomous and Robotic systems is also essential in order to enable mission infusion.

– Other government agencies (and private enterprise) have similar but distinct requirements.
  – Industry advances can be leveraged opportunistically but not assumed.
  – DoD advances should be leveraged in areas of overlap (e.g. machine vision and tele-robotics).

– NASA pacing challenges trace to three sources:
  – Extremely high dependability requirements for one-of-a kind systems
  – Communication latencies
  – Surface exploration of unknown and dynamic environments
  – Challenging manipulative tasks (in the presence of communications latencies)

BACKUP

Capability Roadmap Teams

Capability	NASA chair	External chair
High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)