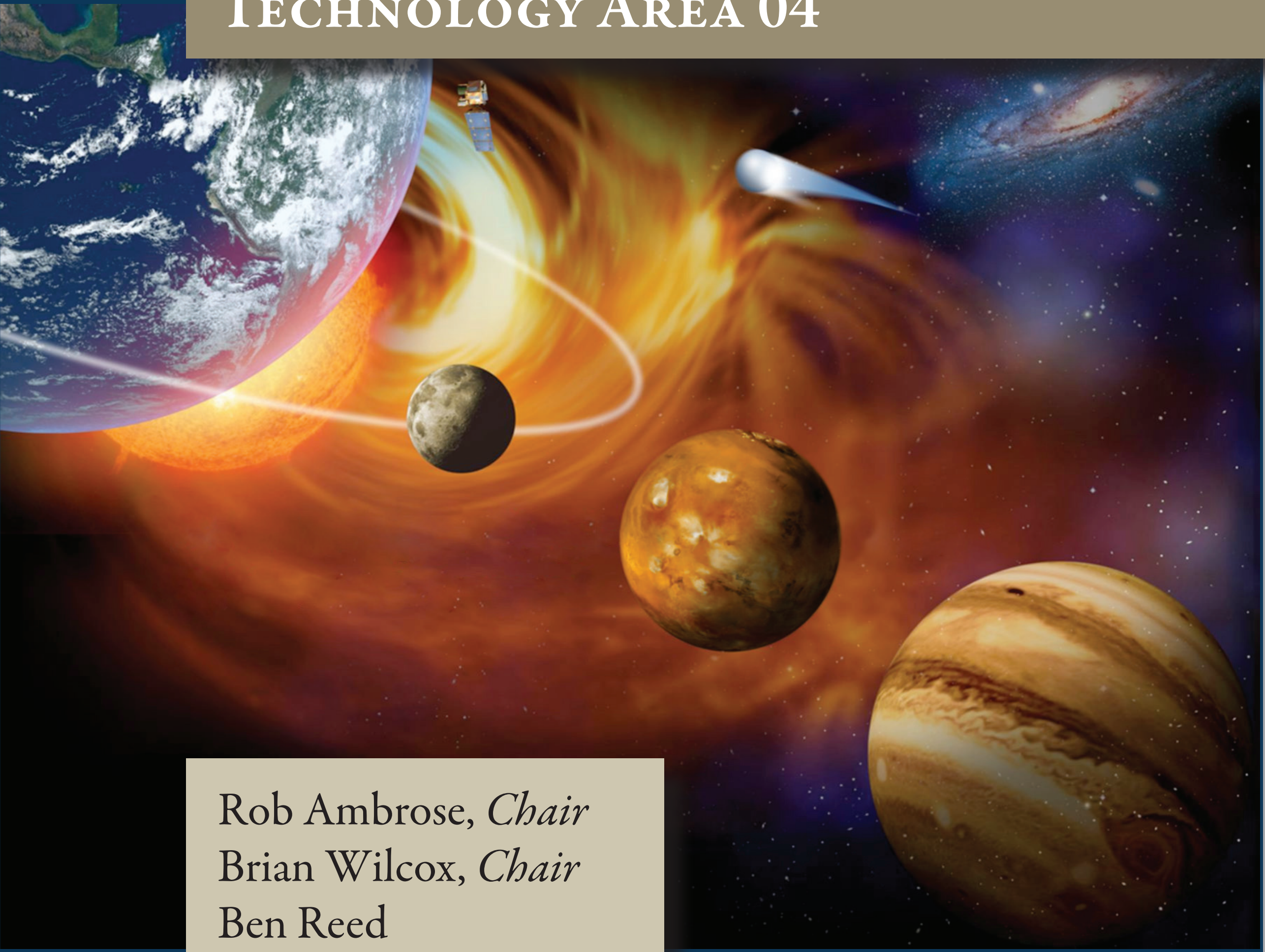
National Aeronautics and Space Administration

ROBOTICS, TELE-ROBOTICS AND AUTONOMOUS SYSTEMS ROADMAP

TECHNOLOGY AREA 04



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FOREWORD

NASA’s integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation’s current capabilities. The present state of this effort is documented in NASA’s Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA’s space technology activities. This document presents the Technology Area 04 input: Robotics, Tele-Robotics and Autonomous Systems. NASA developed this Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

Ongoing human missions to the International Space Station have an integrated mix of crew working with IVA and EVA robots and supporting autonomous systems on-board spacecraft and in mission control. Future exploration missions will further expand these human-robot partnerships. Unmanned science missions are exclusively robotic in flight, but are integrated with Earth-based science and operations teams connected around the globe. Autonomous unmanned aircraft used in military operations are now seeing civilian and science applications, and the line between piloted aircraft cockpits and telerobotic command consoles continues to blur. Robots, telerobots and autonomous systems are already at work in all of NASA's Mission Directorates. NASA will see even more pervasive use of these systems in its future.

The Robotics, Tele-Robotics and Autonomous Systems (RTA) Roadmap effort has focused on the classical areas of sensing & perception, mobility, manipulation, human-systems interfaces, autonomy, and autonomous rendezvous and docking. An additional sub-topic was added for RTA-specific systems engineering such as modularity/commonality and verification and validation of complex adaptive systems. Functional capabilities were identified within each of these sub-topics where advances in processors, communication, batteries and materials have enabled major leaps forward in the past decade.

Sensing and perception research seeks new detectors, instruments, techniques, and algorithms for localization, proprioception, obstacle detection, object recognition and the processing of that data into a system's perception of itself and its environment. Mobility research includes surface, subsurface, aerial and in-space locomotion, from small machines to large pressurized systems that can carry crew for long excursions, using modes of transport that include flying, walking, climbing, rolling, tunneling and thrusting. Contemporary manipulation research is focused on force control, compliance, eye-hand coordination, tactile control, dexterous manipulation, grasping, multiarm control and tool use. RTA human-systems interface research includes classical areas of tele-robotics such as haptics, human-systems interfaces, and augmented reality with newer topics that include human safety, human-robot teams, crew decision support, interaction with the public, and supervision across the time delays of space. Autonomous systems research seeks to improve performance with a reduced burden on crew and ground support personnel, achieving safe and efficient control, and enabling decisions in complex and dynamic environments. Automated rendezvous and docking research has focused on coupled sensing and range measurement systems for vehicle pose estimation across short and long ranges relative navigation sensors for various constraints, autonomous GN&C algorithms and implementation in flight software, integrations and standardization of capabilities, docking mechanisms that mitigate impact loads that can increase allowable spacecraft mass, electrical/fluid/atmospheric transfer across docked interfaces. Systems engineering topics identified for the RTA domain include system-level modular design philosophies that provide for interoperability and support for international standards, verification and validation of complex adaptive systems, and issues related to onboard computing as specifically relate to RTA. Interfaces will exist between the RTA domain and other roadmap domains, including power, destination systems, and information/modeling/simulation, habitation, and communications technology. Sensing and Perception metrics include resolution, accuracy, range, tolerance of environmental conditions, and power. Mobility system metrics include range, payload, speed, life and mass. Manipulation system metrics include strength, reach, mass, power, resolution, minimum force/position, and number of interfaces handled. Human systems interface metrics include efficiency indices such as mean time for a human to intervene in a system. Autonomous system metrics include number of humans per system, mean time between human interventions, and number of functions performed per intervention. Autonomous rendezvous and docking metrics include near and far range, resolution, accuracy, mean docking impact impulse, mean docking alignment error at contact, and capture envelope.

The RTA Technology Area Strategic Roadmap (TASR), shown in Figure R, evaluates dozens of NASA missions of the four Mission Directorates over the next few decades and maps technology push and pull elements from the RTA core disciplines into those missions, identifying ~100 individual technologies that are enabling or strongly enhancing for those missions.

The top technical challenges for sensing and perception are object recognition and pose estimation and fusing visual, tactile and force sensors for manipulation. The top technical challenges for mobility are achieving human-like performance for piloting vehicles and access to extreme terrain in zero, micro and reduced gravity. The top technical challenges for manipulation are grappling and anchoring to asteroids and non-cooperating objects and exceeding human-like dexterous manipulation.

The top technical challenges in human-robot interfaces are full immersion telepresence with haptic, multi sensor feedback, understanding and expressing intent between humans and robots, and supervised autonomy of dynamic/contact tasks across time delay. The top technical challenge in Autonomy is verification of autonomous systems. The top technical challenge for autonomous rendezvous and docking is proximity operations culminating in its successful accomplishment despite the expected extreme conditions of harsh lighting, unknown near-Earth asteroid gravity and other unknown environmental conditions like dust. The benefits to NASA of RTA technology include extending exploration reach beyond human spaceflight limitations, reduced risks and cost in human spaceflight, enabling science, exploration and operation mission performance, increasing capabilities for robotic missions, use of robots and autonomy as a force multiplier (e.g., multiple robots per human operator), and autonomy and safety for surface landing and flying UAV's. The benefits outside NASA include bringing manufacturing back to America; electric vehicles, wind turbine control, smart grids, and other green technology; synergy with other government agency robotics programs; in orbit strategic asset inspection, repair and upgrade; automated mining and agriculture; prosthetics, rehabilitation, surgery, telesurgery, assistive robotics; undersea robotics for exploration and servicing; educational robotics for stimulating Science, Technology, Engineering and Mathematics inspiration; household robotics and automation; emergency response, hazardous materials, bomb disposal; and automated transportation via land, air, and sea.

In summary, NASA's four Mission Directorates are depending on Robotics, Tele-Robotics and Autonomy Technology. Over the next few decades, this technology should aim to exceed human performance in sensing, piloting, driving, manipulating, rendezvous and docking. This technology should target cooperative and safe human interfaces to form human-robot teams. Autonomy should make human crews independent from Earth and robotic missions more capable.

1. GENERAL OVERVIEW

1.1. Technical Approach

Ongoing human missions to the International Space Station have an integrated mix of crew working with Intra Vehicular Activity (IVA) and Extra Vehicular Activity (EVA) robots teamed with supporting autonomous systems on-board spacecraft and in mission control. Future exploration missions will further expand these human-robot partnerships. Unmanned science missions are exclusively robotic in flight, but are integrated with Earth-based science and operations teams connected around the globe. Autonomous unmanned aircraft used in military operations are now seeing civilian and science applications, and the line between piloted aircraft cockpits and telerobotic command consoles continues to blur. Robots, Tele-robots and Autonomous systems (RTAs) are already at work in all of NASA's Mission Directorates. NASA will see even more pervasive use of these systems in its future.

The RTA Roadmap effort has focused on the classical areas of sensing & perception, mobility, manipulation, rendezvous & docking, human-systems interfaces, autonomous rendezvous and docking, and system autonomy. An additional sub-topic was added for RTA systems engineering. Specific functional capabilities were identified within each of these sub-topics where advances in processors, communication, batteries and materials have enabled major leaps forward in the past decade.

Sensing and perception research seeks new sensors and algorithms for 3-D perception, position and velocity estimation, terrain understanding, object recognition, multi-sensor perception in support of sample acquisition and manipulation and onboard analysis of science data.

Mobility research includes surface, subsurface, aerial and in-space locomotion, from small machines to large pressurized systems that can carry crew for long excursions, using modes of transport that include flying, walking, climbing, rolling, tunneling and thrusting.

Contemporary manipulation research is focused on force control, compliance, eye-hand coordination, tactile control, dexterous manipulation, grasping, multi-arm control and tool use.

Human-systems interface research includes classical areas of tele-robotics such as haptics and augmented reality, with newer topics that include human safety, human-robot teams, crew decision support, interaction with the public, and supervision across the time delays of space.

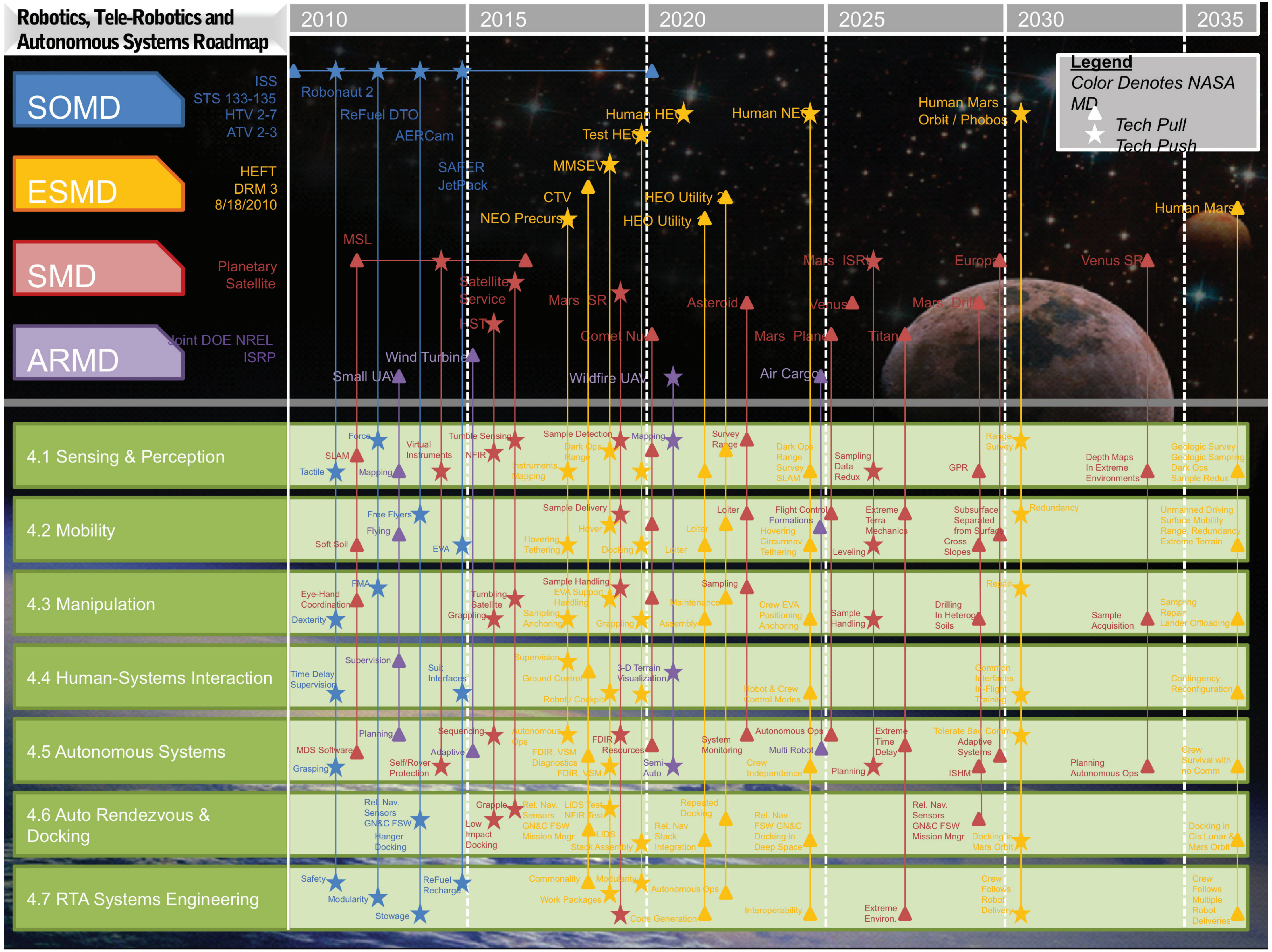

Figure R: *Robotics, Tele-Robotics and Autonomous Systems Technology Area Strategic Roadmap (TASR)*

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Autonomous systems research seeks to improve performance with a reduced burden on crew and ground support personnel, achieving safe and efficient control, and enabling decisions in complex and dynamic environments.

Automated rendezvous and docking research has focused on development, integration, and reuse of several capabilities needed for estimating vehicle relative position and attitude (pose) from several kilometers distance into docking/capture/berthing, including: relative navigation sensors and integrated communications; robust GN&C algorithms and implementation in real-time flight software; docking/capture mechanisms/interfaces that mitigate impact loads that can increase allowable spacecraft structure and mass; and mission/system managers that enable increased autonomy/automation.

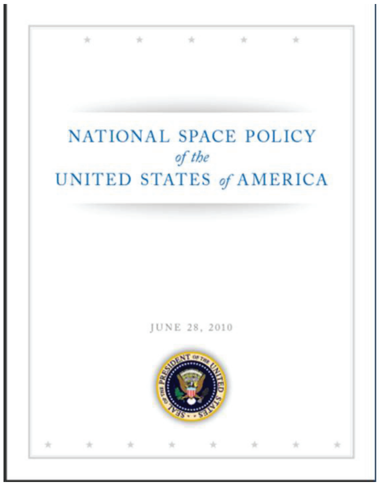
Systems engineering topics identified for the RTA domain include the required tolerance to environmental factors of vacuum, radiation, temperature, dust, and system level modular design philosophies that provide for interoperability and support international standards.

Interfaces will exist between the RTA domain and other roadmap domains, including power, destination systems, and information/modeling/simulation, habitation, and communications technology.

1.2. Benefits

Spaceflight is costly across the development, flight unit production, launch, and operation phases of missions. Spaceflight is also risky to both man and machine. Each of the RTA subtopics is focused on research to reduce cost and risk. An even greater benefit is when new technologies increase capabilities, or add whole new functions that truly "change the game".

So for each subtopic within the RTA domain, we seek to make spaceflight safer and more economical, while looking for improvements and breakthroughs as measured with quantifiable metrics. Sensing and Perception metrics include resolution, accuracy, range, tolerance of environmental conditions, and power. Mobility system metrics include range, payload, speed, life and mass. Manipulation system metrics include strength, reach, mass, power, resolution, minimum force/position, and number of interfaces handled. Human systems interface metrics include efficiency indices, such as mean time to intervene in a system. Autonomous system metrics include number of humans per system, mean time between intervention by humans, and number of functions performed per intervention. Autonomous rendezvous and docking metrics include near and far range, resolution, accuracy, mean docking impact impulse, mean docking alignment error at contact, and capture envelope.



NATIONAL SPACE POLICY
of the
UNITED STATES *of* AMERICA

JUNE 28, 2010

Figure 1. *Cover of the National Space Policy of the United States of America*

1.3. Traceability to NASA Strategic Goals

Robotics, Tele-Robotics and Autonomous Systems are prominently mentioned in the US Space Policy released June 28, 2010 (Figure 1). One of its goals is to "Pursue human and robotic initiatives" to develop innovative technologies (page 4). In the US Space Policy, NASA is directed to "Maintain a sustained robotic presence" in the solar system to conduct science, demonstrate technologies and scout locations for future human missions (page 11).

The Policy also establishes the use of space nuclear power systems to safely enable or significantly enhance space exploration and operational capabilities. The use of nuclear electric and nuclear thermal power will require a significant improvement in autonomous system functions for the management of nuclear power sources providing electrical power, thermal power, and propulsion. The maturation of autonomous systems will require demonstration missions in interplanetary space. This policy directly drives the need for immediate and sustained development and maturation of autonomous system technologies.

1.4. Technology Push

Robotics, Tele-Robotics and Autonomous Systems represent an exploding domain of research with broad investments beyond NASA and the US. This roadmap seeks to identify technologies that can be integrated for flight missions over the next 25 years. The conventional approach to road mapping involves technology pull, where mission needs are used to guide technology investment and development. The following sections use this approach, identifying missions over the next 25 years and proposing technology needs. At the same time the panel recognized the need for technology push, where major breakthroughs enable new missions or potentially change mission planning with new capabilities. Therefore some investment in basic research is encouraged to invent and mature new approaches that are not today seen as credible.

2. DETAILED PORTFOLIO DISCUSSION

2.1. Technical Area Breakdown Structure (TABS) Diagram

Technology Area 4 (TA4), which addresses Robotics, Tele-Robotics and Autonomous Systems (RTAs), is broken down into seven major areas of research as shown in the Technology Area Breakdown Structure (TABS) diagram below (Fig.2). Each of the major research areas is further broken down into three to seven subareas of research. Each of the major research areas and their subareas are discussed in the sections below.

2.1.1. *TA4.1: Sensing & Perception*

This research area includes sensors and algorithms needed to convert sensor data into representations suitable for decision-making. Traditional spacecraft sensing and perception included position, attitude, and velocity estimation in reference frames centered on solar system bodies, plus sensing spacecraft internal degrees of freedom, such as scan-platform angles. Current and future development will expand this to include position, attitude, and velocity estimation relative to local terrain, plus rich perception of characteristics of local terrain—where "terrain" may include the structure of other spacecraft in the vicinity and dynamic events, such as atmospheric phenomena. Enhanced sensing and perception will broadly impact three areas of capability: autonomous naviga-

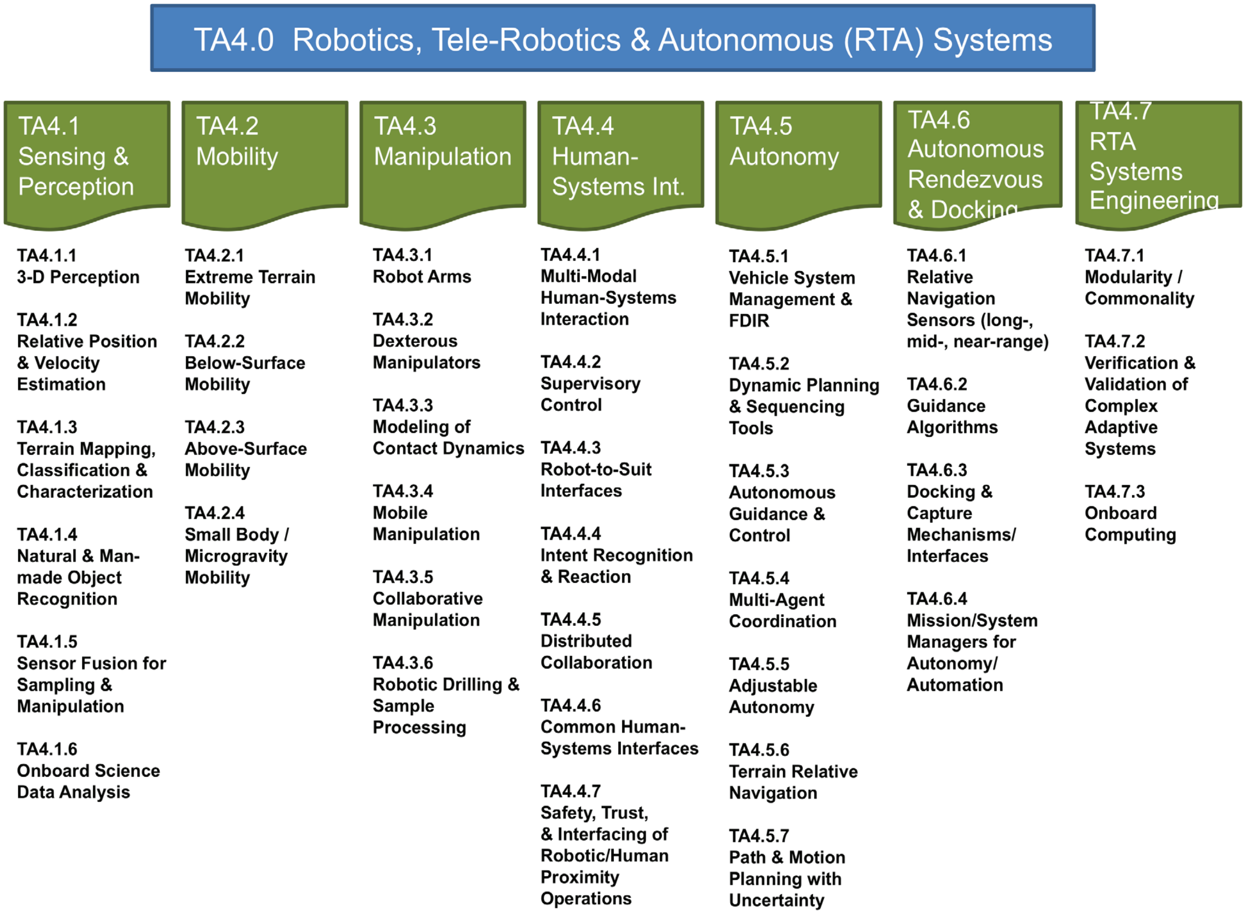


Figure 2. *RTA Technical Area Breakdown Structure (TABS) Diagram*

tion, sampling and manipulation, and interpretation of science data. Perception tends to be very computationally intensive, so progress in this area will be closely linked to progress in high-performance onboard computing.

TA4.1.1 3-D Perception

3-D perception has already been central to autonomous navigation of planetary rovers, using stereoscopic 3-D perception in daylight. Active optical ranging (LIDAR) is commonly used in Earth-based robotic systems and is under development for landing hazard detection in planetary exploration. Progress is necessary in increasing the speed, resolution, and field of regard of 3-D sensors, reducing their size, weight, and power, enabling night operation for rovers, and hardening them for flight. Applications include rovers, landers, rendezvous and docking, and robotic manipulation.

TA4.1.2 Relative Position & Velocity Estimation

Imagery and range data is already in some use for rover and lander position and velocity estimation, though with relatively slow update rates. Real-time, onboard, terrain-relative position and velocity estimation capability is also needed for small-body proximity operation, balloons and airships, micro-inspector spacecraft, and rendezvous and docking.

TA4.1.3 Terrain Mapping, Classification, and Characterization

For surface navigation, sensing and perception must be extended from 3-D perception to accumulating maps to facilitate path planning, distinguishing terrain classes that differ in navigability or science potential, and estimating other terrain properties pertinent to trafficability analysis, such as softness of soil or depth to the load-bearing surface. Many types of sensors may be relevant to this task, including contact and remote sensors onboard rovers and remote sensors on orbiters. These capabilities are also needed for surface and subsurface characterization of small bodies and for near-surface flight and surface sampling by lighter-than-air craft in the atmospheres of Titan and Venus.

TA4.1.4 Natural and Man-Made Object Recognition

Natural objects that are important to recognize include: landmarks that facilitate navigation; obstacles to rovers or landers; and objects that are important to science investigations, such as geologic targets and atmospheric phenomena. Man-made object recognition will be important in retrieving sample caches and in robotic inspection, assembly, servicing, and repair operations in space.

TA4.1.5 Sensor Fusion for Sampling and Manipulation

Sampling generally refers to handling natural materials in scientific exploration; manipulation includes actions needed in sampling and actions to manipulate man-made objects, including sample containers in scientific exploration and handling a variety of tools and structures during robotic assembly and maintenance. 3-D perception, mapping, and relative motion estimation are also relevant here. Non-geometric terrain property estimation is relevant to distinguish where and how to sample, as well as where and how to anchor to surfaces in micro-gravity or to steep slopes on large bodies. Additional needs include recognizing known objects, estimating the position and orientation of those objects, and fusing measurements from force-torque, tactical, and visual sensors to execute grasping operations and mating/de-mating of pairs of objects.

TA4.1.6 Onboard Science Data Analysis

Onboard science data analysis is important in at least two broad situations: (1) where large data sets must be searched to find things of interest, and it is impractical to downlink the entire data set to Earth; and (2) where time-sensitive phenomena must be detected before the phenomena end (e.g., eruptions) or the spacecraft moves beyond range of further observation. Success stories already include onboard detection of dust devils and clouds by Mars rovers. Future examples could include detecting dynamic events on Earth, comets, or Titan and onboard analysis of large, hyperspectral data sets.

2.1.2. TA4.2: Mobility

Mobility is defined as the ability to move between places in the environment, as distinct from intentionally modifying that environment. Examples include moving between places on a planetary surface or in a planetary atmosphere, or to reach a point in the subsurface.

TA4.2.1 Extreme Terrain Mobility

The state of the art in space extreme terrain mobility are the Mars Exploration Rovers (MER) (see Figure 3) and soon the Mars Science Laborato-

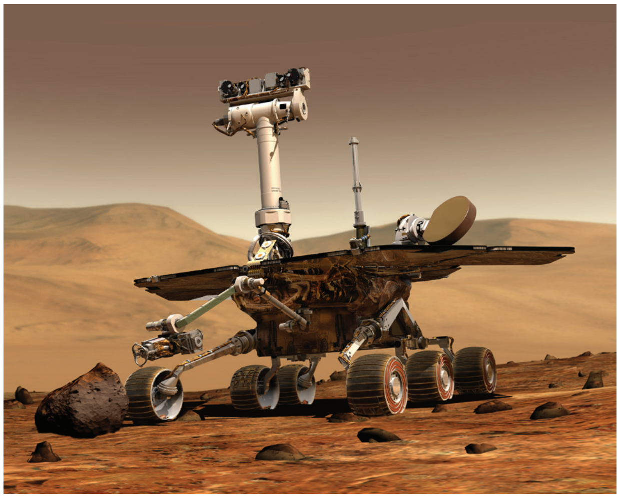


Figure 3. *Mars Exploration Rover*

ry (MSL) rover as examples of "all-robotic" systems, and the Apollo lunar roving vehicle as a crewed system. Earth test-systems planned for future space exploration include the Multi-Mission Space Exploration Vehicle (MMSEV) and many robotic test-beds, including rappelling systems for steep terrain or cliff access. This technology is largely informed by a huge terrestrial analog base in the defense and commercial spheres, and has evolved from 6+ wheels using passively-articulated suspensions to active suspensions to mother-daughter rappelling systems. Challenges include both vertical and lateral mobility on steep or vertical surfaces, overhangs, and access to lava-tubes, skylights, etc.

TA4.2.2 Below-Surface Mobility

The state of the art in space subsurface access are the MER Rock Abrasion Tool and the upcoming MSL rotary-percussive drill. A drill adapted from commercial technology was used to sample up to 3 m deep on the Apollo missions. Again, this technology is informed by a huge base of terrestrial work in the mining and petroleum industries. Challenges include access up to tens of km deep on Mars to the putative liquid water aquifer, by a system whose mass and power are such that it can be credibly proposed for flight to Mars. As a general rule, deep drilling and sampling of pristine samples at depth is considered superior to analysis and sampling of weathered materials on the surface, on the sides of cliffs, etc. But deep subsurface access has been considered so extremely difficult that it has not been seriously considered.

TA4.2.3 Above-Surface Mobility

This includes surface mobility, such as rovers, along with powered and unpowered balloons, gliders, blimps, airplanes, and helicopters. Again the state of the art non-terrestrial surface rovers are MER, soon MSL, and the Apollo lunar roving vehicle. The former Soviet Union successfully deployed two balloons into the atmosphere of Venus in 1985. Assorted balloons and aircraft have been proposed for Mars missions, although none have been accepted for flight. Powered blimps are considered attractive in the relatively dense atmospheres of Venus and Saturn's moon Titan. Solar-heated balloons are frequently considered for Mars or the gas giants (where the atmospheres are mostly hydrogen and helium, so lighter gas can only be achieved by heating). Challenges for surface rovers are mostly in the extreme terrain category above, along with power/thermal. Challenges in atmospheric vehicles include environmental compatibility (hot, cold, sulfuric acid on Venus, etc.), light-weighting of power sources, avionics, communications, instruments, etc. Autonomy for Titan blimps is especially challenging without an expensive relay satellite since the slow rotation of Titan means that the balloon may not have line-of-sight to Earth for a week or more. In all cases, path planning, and modeling with uncertainty (e.g., where the time and energy to get from A to B is a probability distribution) is a key factor not incorporated into many planning systems.

TA4.2.4 Small Body/Microgravity Mobility

The state of the art includes the rendezvous/docking/berthing capabilities of all vehicles that approach the International Space Station (ISS), along with the Manned Maneuvering Unit flown in the 1980s and the SAFER (Figure 4) emergen-

Figure 4. *Existing Simplified Aid For EVA Rescue (SAFER) Jetpack*

cy-recovery jetpack flown on some EVAs since the 1990s. The Aercam-Sprint free-flying inspection camera was flown in the late 1990s. Proximity operations technology has advanced from solutions to Hill's equations for the relative position of two bodies in orbit, developed in the Gemini and Apollo programs, to very elaborate modeling of the 3-D shape of gravity fields around asteroids, such as used to land the NEAR spacecraft (Fig.5) on the asteroid Eros at the end of its mission. Challenges include the large number of perturbing forces of comparable magnitudes on the very small asteroid being considered for possible human exploration, including electrostatic, photon pressure, magnetic, outgassing, etc.

In the next few decades, we can expect that robotic vehicles designed for planetary surfaces will approach or even exceed the performance of the best piloted human vehicles on Earth in traversing extreme terrain and reaching sites of interest, despite severe terrain challenges. Human drivers have a remarkable ability to perceive terrain hazards at long range and to pilot surface vehicles along dynamic trajectories that seem nearly optimal. Despite the limitations of human sensing and cognition, it is generally observed that experienced drivers can pilot their vehicles at speeds near the limits set by physical law (e.g., frictional coefficients, tip-over and other vehicle-terrain kinematic and dynamic failures). This fact is remarkable, given the huge computational throughput requirements needed to quickly assess subtle terrain geometric and non-geometric properties (e.g., visually estimating the properties of soft soil) at long-range fast enough to maintain speeds near the vehicle limits. This ability is lacking in today's best obstacle detection and hazard avoidance systems.

Figure 5. *Near Earth Asteroid Rendezvous (NEAR) mission to Eros 1996-2001*

For free-flying vehicles, either in a microgravity environment or flying through an atmosphere, we can similarly expect that robotic vehicles will become capable of utilizing essentially all available vehicle performance, in terms of acceleration, turn rate, stopping distance, etc., without being limited by the onboard sensors, computational throughput, or appropriate algorithms in making timely decisions. Future missions may be identified for small or nano satellites, where breakthroughs in miniaturization of electronics, cameras and other sensors will allow functions performed by large spacecraft at less than 1% the mass and cost.

NASA in particular has the need to reach sites of scientific interest (e.g., on the sides of cliffs) that are of less interest to other agencies. So NASA needs to focus especially on those aspects of extreme-terrain surface mobility, free-space mobility and landing/attachment that will not be developed by anyone else. Also, NASA has environmental constraints such as thermal extremes and rad-hard computing that may make solutions developed for others in-applicable to NASA. While high-speed operations are of only limited use to NASA, mission success will often depend on reliable, sustained operations, including the ability to move through the environment long distances without consuming too much of the mission timeline.

Mass, and to some degree power, generally need to have a much greater degree of emphasis in the design process for NASA missions than others. As a result, mobility systems that can "brute force" a solution to a difficult problem may need to be accomplished by "finesse" in a NASA context. A good example of this is the use of tank-treads of high-mobility military vehicles. Such systems provide good mobility but tend to entrain debris into the running gear in a way that requires a great deal of mass and power to crush and expel. As a result, NASA has invested in alternatives such as multi-wheel vehicles that have similarly low ground pressures but much lower power requirements. This trend of NASA needing to invest in specialized systems that meet its own unique needs will presumably continue. A mobility system is highly dependent on its power subsystems, especially for long transit, working against friction, or when carrying heavy payloads. In particular the specific power and specific energy metrics will dominate a mobility system's range, speed and payload capacity. Technology Area 3 addresses new technologies for improved space power and energy storage systems.

Other agencies have made significant development and investment in Unmanned Aerial Vehicles (UAVs). These capabilities can be adapted and applied to exploration of planetary surfaces and weather. In particular, NASA will need to develop fully autonomous and automated UAVs for operations on distant planets. Coordination of multiple robotic systems is an active area of research. Combinations of heterogeneous systems, such as flying and roving systems is potentially useful for surface missions, pairing long range sensing on the flyer with higher resolution surface-sensing on the rover.

Mobility applications for human missions are described in Technical Area 7, Human Exploration Destinations Systems. These include rovers, hoppers, docking spacecraft and EVA mobility aids such as exoskeletons and jetpacks.

2.1.3. TA4.3: Manipulation Technology

Manipulation is defined as making an intentional change in the environment. Positioning sensors, handling objects, digging, assembling, grappling, berthing, deploying, sampling, bending, and even positioning the crew on the end of long arms are tasks considered to be forms of manipulation. Arms, cables, fingers, scoops, and combinations of multiple limbs are embodiments of manipulators. Here we look ahead to missions' requirements and chart the evolution of these capabilities that will be needed for space missions. Manipulation applications for human missions can be found in Technology Area 7 as powered exoskeletons, or payload offloading devices that exceed human strength alone.

TA4.3.1 Robot Arms

The state of the art is found in the Robonaut 2, Phoenix arm, Orbital Express, and soon to be MSL arm. Previous arms flown include the Shuttle Remote Manipulator System (SRMS), ROTEX, ETS-VII, MFD, JEM-RMS, MER arm, SSRMS and SPDM (Figure 6). Technology has advanced from position control, to impedance control with end point force sensing, to embedded joint torque control. Autonomy has advanced from line of sight tele-operation to ground supervised control. Challenges include safety near people, handling natural objects (samples), eye-hand coordination, and tool use.

TA4.3.2 Dexterous Manipulators

The state of the art is found in the Robonaut 2 limb, combining a manipulator that has a dexterous workspace with a multi-fingered end-effector able to make compliant grasps on natural objects. Dexterous manipulation includes working with human interfaces, and extends beyond human performance to smaller scale and greater agility. Challenges include integrated tactile perception, force control, grasping reflexes, grasp learning, tool use, and autonomous object manipulation.

TA4.3.3 Modeling of Contact Dynamics

The state of the art is assembly contact modeling for the International Space Station assembly with the SSRMS, and interaction with natural media for the Phoenix arm and MER rock abrasion tool. Challenges include soil terra-mechanics, object mating, tools shifting in a robot's grasp, modeling disconnect mechanisms, and multi point contact problems.

TA4.3.4 Mobile Manipulation

The state of the art is MER arm operations, and soon to be MSL arm and Robonaut 2. Mobile manipulation involves systems that have both the ability to move great distances, but also manipulate once static or while in motion. Coordinated moves allow the manipulation subsystem to aid in management of the center of gravity for mobility, and the mobility function to expand the range of motion for manipulation. Challenges include coordinated motion, force control across the entire system, and fusion of localization with force control.

TA4.3.5 Collaborative Manipulation

The state of the art is in the SSRMS, where a human is positioned by a robot arm. This is only a simplified case of collaborative manipulation, and much research remains. On the ground the start of the art includes robotic handling of large objects, measurement systems positioned by hand, and experiments with Robonaut and HRP hu-

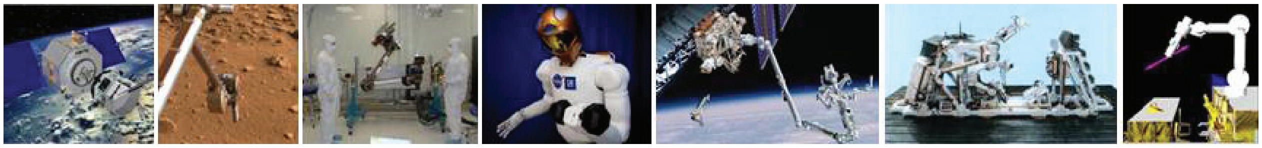


Figure 6. *Orbital Express, Phoenix Arm, MSL Arm, Robonaut 2, SSRMS & SPDM, JAXA MFD, ETS-VII*

manoids. Terrestrial multi-robot handling systems include large/fine combinations and swarm approaches. Challenges include a wide array of human interaction modalities superimposed on a force control problem, multi-point contact problems, and safety.

TA4.3.6 Robotic Drilling & Sample Processing

The state of the art is the Phoenix arm and the MER arm, and soon to be the MSL arm. On the ground, robotic drilling is dominated by down hole tooling for oil and gas exploration, and sample processing is primarily medical or hazardous material handling. Challenges include dry drilling, sample conveyance, and cleanliness/contamination.

2.1.4. TA4.4: Human-Systems Interfaces

The ultimate efficacy of robotic systems depends greatly upon the interfaces that humans use to operate them. As robots and the tasks assigned to them grow more complex, the demands placed on the interfaces used to control them also increase. An excellent human-system interface enables a human to rapidly understand the state of the system under control and effectively direct its actions towards a new desired state. This research area explores advanced technologies for improving situational awareness of a human operator, capturing the operator's intent, and enabling the safe operation of robots in the vicinity of humans and critical systems.

TA4.4.1 Multi-Modal Human-Systems Interaction

Current interfaces rely heavily on visual displays to communicate system state to an operator, with information from external sensors often presented in its native form (for instance, image streams from a camera) and occasionally aggregated into a navigable visual model of the environment that may contain data from multiple sensors. Commands are typically issued using a joystick-like device (as is the case with low time delay systems such as the Shuttle RMS and SSRMS) or via a sequence of typed command directives with arguments (as is the case with the Spirit, Opportunity, and Curiosity Mars Rovers). Challenges in this area include utilizing all of the senses of the operator (visual, auditory, and tactile at a minimum) to communicate system and environmental state and enabling operators to effectively use gestural, speech, EMG / EEG, and other input mechanisms to issue commands. A long-term goal in this space is the creation of "Holodeck"-like virtual environments that can be naturally explored by the human operator with "Avatar"-like telepresence.

TA4.4.2 Supervisory Control

Most robotic systems are controlled using simple, immediate-mode directives that may be issued via joystick-like devices or by playing back preprogrammed actions designed for a tightly-controlled environment like a manufacturing facility. Some systems, including the Sprit, Opportunity, and Curiosity Mars Rovers, K10, ATHLETE, and Robonaut 2 are capable of executing sequences of higher-level directives. As robots grow increasingly autonomous, this research area must provide improved techniques for communicating the "mental state" of robots to the operator. In addition, operators must be allowed to interact with one or many complex robots at a sufficiently high level to enable the operator to attend to his/her own tasks while supervising and cooperating with the robots under control.

TA4.4.3 Robot-to-Suit Interfaces

Nowhere are the safety challenges inherent in human-system interaction more present than when robotic systems must physically interface with the equipment worn by a crew member. The state of the art in this space is the SAFER jetpack, the SSRMS, and the suit-port interfaces found on technology precursors of the MMSEV. Challenges include effective mating / demating of these systems and the suit in vacuum and dusty environments, and effective control of robotic systems attached to the suit by the crew member.

TA4.4.4 Intent Recognition and Reaction

In some situations, it is preferable for a robotic system to be able to recognize and react to the intent of an operator without requiring the operator to issue a formal directive. Challenges in this area include developing systems to recognize gaze direction, gestures, speech, and other elements as indicators of implicit operator intent, behavioral models capable of predicting future operator actions, and planning systems capable of responding appropriately. These techniques are applicable when the operator is interacting with a virtual environment or the real environment that is also occupied by the system under control.

TA4.4.5 Distributed Collaboration

High-value robotic systems such as the Spirit and Opportunity Mars Rovers are controlled through the combined efforts of a geographically distributed operations team. State of the art human-system interfaces in this area enable these teams to collaboratively analyze the data returned from the robot, discuss potential future actions, and then facilitate the shared development of new directives for the system under control. Challenges in this space include developing distributed collaboration tools for the control of robotic systems with short time delay, the sharing of control by operations personnel with varying amounts of time delay to the system under control, the creation of more advanced security solutions to allow convenient, but highly secure access by authorized remote operators, and the utilization of technologies like cloud computing to provide highly elastic collaboration services that scale from a handful of operators to hundreds.

TA4.4.6 Common Human-Systems Interfaces

The present lack of standards or conventions for the control of robotic systems is having a negative impact on usability and limits the leveraging of one robot's interface for another. In addition, significant benefits could be derived through a common standard for robot commanding and telemetry. The state of the art in this space is RAPID (Robot Application Programming Interface Delegate). Challenges include capturing both the common attributes and capabilities of robotic systems while still allowing the control of capabilities specific to a single robot. Usability standards are also needed to bring the control interface of similar robotic systems towards the level of standardization found in aircraft cockpits and automobile dashboards. Finally, delay and disruption tolerant telemetry and command standards must be developed and demonstrated across multiple robotic platforms.

TA4.4.7 Safety, Trust, & Interfacing of Robotic/Human Proximity Operations

As humans interact more closely with robotic systems (in some cases riding on or inside them), increased focus on the need for safe physical interactions between robots and humans is necessary. The state of the art in this space is the compliant manipulation capabilities found in Robonaut 2, the human recognition and avoidance behaviors demonstrated on Centaur, and the procedures followed when positioning a crew member with SSRMS. More advanced sensing and perception is necessary to enable robots to recognize and understand the actions of nearby humans. In addition, autonomous robots must be able to communicate their own immediate plans to nearby humans and react swiftly in a safety-critical situation.

2.1.5. TA4.5: Autonomy

Autonomy, in the context of a system (robotic, spacecraft, or aircraft), is the capability for the system to operate independently from external control. For NASA missions there is a spectrum of autonomy in a system from basic automation (mechanistic execution of action or response to stimuli) through to fully autonomous systems able to act independently in dynamic and uncertain environments.

Two application areas of autonomy are: (i) increased use of autonomy to enable an independent acting system, and (ii) automation as an augmentation of human operation. Autonomy's fundamental benefits are; increasing a system operations capability, cost savings via increased human labor efficiencies and reduced needs, and increased mission assurance or robustness to uncertain environments.

An "autonomous system" is defined as a system that resolves choices on its own. The goals the system is trying to accomplish are provided by another entity; thus, the system is autonomous from the entity on whose behalf the goals are being achieved. The decision-making processes may in fact be simple, but the choices are made locally. In contrast, an "automated system" follows a script, albeit a potentially quite sophisticated one; if it encounters an unplanned-for situation, it stops and waits for human help, e.g., "phones home". The choices have either been made already (and encoded in some way), or will be made externally to the system.

TA4.5.1 Vehicle System Management & FDIR

Vehicle Systems Management (VSM) and autonomous fault detection, isolation, and recovery (FDIR) are critical for overall system autonomy. These real-time health management functions require assessments and decisions in a timeframe of milliseconds to minutes. Representative capabilities include crew escape and abort decisions as well as on-board diagnostics and recovery. The state-of-the-practice in VSM within NASA is the Mars Science Laboratory rovers, the Cassini mission, and the ISS mission systems.

VSM capabilities require unambiguous knowledge of the vehicle states, including location of failures and future states. Intelligent Systems Health

Monitoring (ISHM) provides the state determination, diagnostics, and prognostics of the systems and vehicle. Building upon this state information, on-board mission executive and mission planning autonomy provides the decision making necessary to manage the mission, vehicle, and failure responses. Radiation hardened, high performance processors are essential to enable this level of functionality (see TA 11 for more detail on processing). Different autonomous algorithms may prove to perform different functions better and different vehicle systems (i.e., life support, propulsion, thermal control, electrical power) may require different algorithmic approaches. The integration of different algorithms to provide a consistent management function has not yet been accomplished. Verification and Validation of non-deterministic algorithms (e.g., dynamic neural networks, inference engines, fuzzy logic) will require new methods in order to verify and validate the safe operation of these algorithms in all possible vehicle conditions.

For human missions perhaps four to six crew, the challenge with VSM is availability of crew, and is limited to perhaps 2 crew members managing the entire vehicle at any given time. It is likely that the level of complexity of an interplanetary spacecraft will be similar to that of a U.S. Navy nuclear attack submarine which has 134 crew. Managing a vehicle of this complexity with only 2 crew members will require significant automation of the vehicle management functions. In addition, as the vehicle moves beyond 2 light minutes from Earth, response time becomes a limiting factor. The vehicle will have to respond to unexpected conditions such as solar flares or system failures without input from terrestrial control centers or operators. VSM and automated operation for this level of complexity and crew size has not yet been demonstrated, nor fully understood, and is the focus of ongoing NASA research efforts.

TA4.5.2 Dynamic Planning & Sequencing Tools

Many NASA scientific and exploration systems are highly constrained due to limited time, power, communication and other resources. In order to make the best use of these constrained systems dynamic planning and sequencing tools are necessary. The state-of-the-practice in planning and sequencing tools within NASA are the Hubble Space Telescope (HST), the MER and MSL rovers, and Astronaut Crew time on the ISS. These tools allow the exploration of the trade-space between operational activity versus resource constraints, and the development of mission critical sequences for command and control. The challenges include the computational complexity and ability to rapidly explore the optimization space, repair complex plans, and develop verifiable command sequences with traceability to the initial activity requirements.

TA4.5.3 Autonomous Guidance & Control

The state-of-the-practice in autonomous guidance and control (G&C) is with NASA's F-18 intelligent flight control system and the Mars entry guidance and control system. The F-18 G&C systems can respond to real-time changes in environment and control capabilities, including damage to or failure of control surfaces. The Mars entry G&C systems can respond to real-time changes in the environment. Challenges include: determining control modes during mission phase and the propagation and update of gains as the systems dynamically change in real-time, and the coupling with the vehicle systems management tools during control execution.

TA4.5.4 Multi-Agent Coordination

The state-of-the-practice in multi-agent coordination is with the ISS orbital communication adapter modeling system (OCAMS). This is one of the few multi-agent systems certified for use on an active space system. The OCAMS uses agent systems to represent and model the activities of multiple mission operations systems and tools. These agents coordinate between directed goals, while managing constraints, and executing procedures to move data files between ISS onboard systems and the ground-based mission operations systems. Challenges in multi-agent systems include validation and verification of the complex agent interactions, and the capability and management of agent system group goal direction.

TA4.5.5 Adjustable Autonomy

Key attributes of such autonomy for a robotic system include the ability for complex decision making, including autonomous mission execution and planning, the ability to self-adapt as the environment in which the system is operating changes, and the ability to understand system state and react accordingly. Adjustable (or mixed initiative) autonomy refers to systems in which a user can specify the degree of autonomous control that the system is allowed to take on, and in which this degree of autonomy can be varied from essentially none to near or complete autonomy. For example, in a human-robot system with mixed initiative, the operator may switch levels of autonomy onboard the robot. Controlling levels of autonomy is tantamount to controlling bounds on the robot's authority, response, and operational capabilities.

The Mars Exploration Rovers are the state-of-the-practice for operational adjustable (mixed initiative) autonomy in a space robotic system. Multi-day top-level plans of rover actions are developed on the Earth for execution on-board the Rovers. On-board autonomy enables hazard avoidance while driving, provides limited onboard automation of the acquisition of science data, and provides limited failure mode behaviors and actions when faults occur in the system. The Mars Science Laboratory rover will continue the use of mixed initiative autonomy.

Adjustable levels of autonomous systems can be applied to virtually any NASA system: aircraft (autonomous, remotely-piloted, commercial free-flight systems); spacecraft (robotic systems performing exploration, crewed spacecraft with decision support systems); and ground-based automation to support science discovery, vehicle system management, and mission operations. Greater use of highly adaptable and variable autonomous systems and processes can provide significant time-domain operational advantages to robotic systems or crewed systems that are limited to human planning, decision, and data management speeds. Crew-centered operations is a complex challenge because it means that the crew must be able to track and modify daily activity plans, monitor key systems, isolate anomalies, and select and perform any required recovery procedures. All this requires significant on-board automation and system autonomy to support the crew.

TA4.5.6 Terrain Relative Navigation

A number of Terrain Relative Navigation (TRN) techniques involving passive and active sensors have been developed and tested for Earth-based applications. By comparing images from onboard active or passive sensors to stored reference terrain maps developed from reconnaissance data, TRN can provide in-flight position/attitude updates, support autonomous landings near pre-selected targets (global precision landing), and enable the avoidance of known landing hazards that have been identified and registered in the reference maps. The historical spaceflight experience base for onboard TRN during planetary landings is limited to the crewed Apollo missions and the Mars Phoenix and Mars Science Laboratory robotic missions, through the application of their entry and descent imaging instrumentation. The Smart Impactor on the Deep Impact mission to comet Tempel-1 used passive optical TRN to guide course corrections after separating from the flyby section. The Mars rovers, Spirit and Opportunity, are the source of NASA's experience base for localization, hazard avoidance, and TRN by robotic vehicles on another planet. The primary challenges associated with implementing TRN on spacecraft and rover vehicles include: (1) obtaining and processing the reconnaissance data needed to generate the reference terrain maps; (2) onboard, real-time processing of the TRN sensor information to generate the TRN measurement; (3) integration of the TRN measurement into an autonomous vehicle GN&C system; (4) ambient lighting conditions and constraints for passive sensors; and (5) obscuration of the target terrain by clouds or dust.

TA4.5.7 Path & Motion Planning with Uncertainty

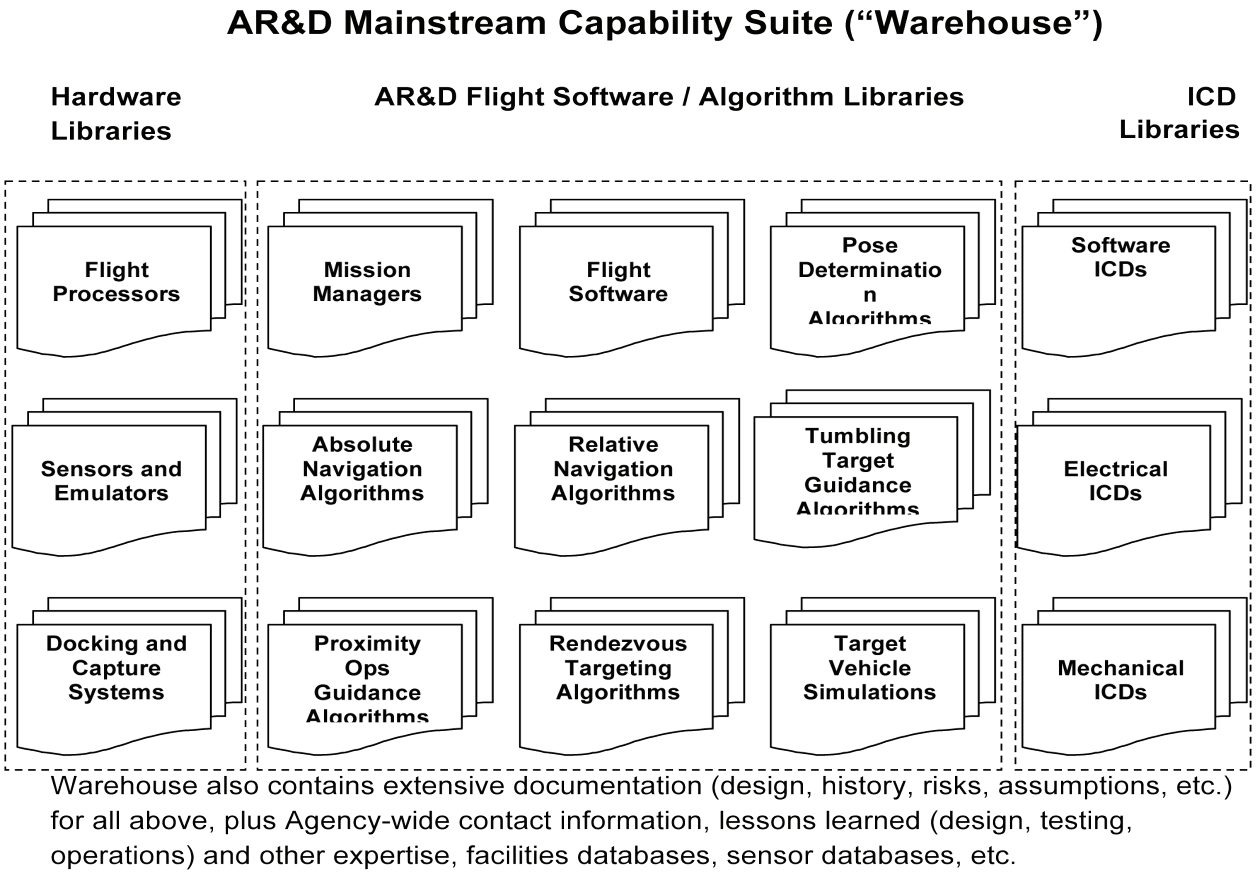
The state-of-the-practice in path and motion planning with uncertainty is with the ISS robotic arm, and the Mars rover. These activities take into account the uncertainty in data, and the dynamic response and requirements of determining the path and motion of the arm and end-effector, and the rover surface motion during traverse. Challenges include time bounding the probabilities and their propagation during the planning and execution of the motion.

Autonomy is a critical area for NASA technology investment and development. These capabilities will enable functional improvements with and without humans in-the-loop during NASA missions. Achieving all these desired gains from use of autonomous systems will require developing new methods to establish “trusted autonomy” through verification and validation (V&V) of the near-infinite state systems that result from high levels of adaptability; state management and system diagnostic/prognostic technologies to enable complex systems to operate across a range of functional capabilities; and for human decision support systems that manage multivariate plans and constraint optimizations.

2.1.6. TA4.6: AR&D

The ability of space assets to rendezvous and dock/capture/berth is a fundamental enabler for numerous classes of NASA’s missions, and is an essential capability for NASA’s future. In spite of a significant track record of successful rendezvous and docking missions to the ISS involving varying degrees of AR&D capability, and other successful demonstration missions of limited AR&D capability, a U.S. mainstream AR&D technology base for a wide spectrum of missions does not exist. Essentially all U.S. programs to-date have generated point-designs with limited future application. Thus, new missions requiring AR&D capabilities continue to incur significant non-recurring engineering (NRE) and development costs related to AR&D component sensors and integrated systems; and each time the systems developed are point designs—even worse, designs that become obsolete after each mission is flown. Currently, programs requiring AR&D capabilities are estimated to be spending up to an order-of-magnitude more than necessary and taking twice as long as necessary to achieve their AR&D capability, "reinventing the wheel" each time. Furthermore, NASA has fallen behind our foreign counterparts in AR&D technology (especially autonomy). These cost and schedule estimates, this history of point-designs, as well as a proposed strategy to overcome our challenges in AR&D, are well documented in a paper released on February 2012 by the NASA AR&D Community of Practice (CoP) entitled *"A Proposed Strategy for the U.S. to Develop and Maintain a Mainstream Capability Suite ('Warehouse') for Automated/Autonomous Rendezvous and Docking in Low Earth Orbit and Beyond"*. (Figure 7) This paper is a joint collaboration among AR&D practitioners at ARC, DFRC, GRC, GSFC, JPL, JSC, LaRC, MSFC, and the NESC. The majority of this section is taken from this paper.

The solution proposed by the AR&D CoP is two-fold. First, the CoP calls for broad Agency support and funding for an evolutionary, stair-step development through a campaign of space-based system demonstrations of an AR&D "warehouse" (see below) that supports the spectrum of Agency exploration missions. As capabilities continue to be developed, it may not always be in the best interest of individual Programs to help advance these capabilities, especially in terms of maintaining the versatility of the system. If upcoming missions simply tailor their systems to fit their specific needs, their contribution to future planned missions will be minimal, as we have seen



Warehouse also contains extensive documentation (design, history, risks, assumptions, etc.) for all above, plus Agency-wide contact information, lessons learned (design, testing, operations) and other expertise, facilities databases, sensor databases, etc.

Figure 7. *AR&D Mainstream Capabilities Suite ("Warehouse")*

in the past. The Agency will actively coordinate AR&D efforts at various centers. The NESC will support all continued efforts to ensure continual Agency support and manage overall integrated Agency AR&D success.

Second, the CoP has proposed and the Agency has begun to develop an AR&D Warehouse (see the Figure 7). The term "warehouse" is used herein to refer to a toolbox or capability suite that has pre-integrated selectable supply-chain hardware and reusable software components that are considered ready-to-fly, low-risk, reliable, versatile, scalable, cost-effective, architecture and destination independent, that can be confidently utilized operationally on human spaceflight and robotic vehicles over a variety of mission classes and design reference missions, especially beyond LEO. Note: This is not a standardization effort and will not provide 100% of what is needed for AR&D; rather, the goal is ~80%.

It is important to clarify that AR&D is not a system and cannot be purchased off the shelf. Rather, AR&D is a distributed capability that requires many vehicle subsystems to operate in concert. Thus, AR&D leverages the complete vehicle capability through the systems engineering and integration of multiple subsystems. For this reason, the proposed strategy does not focus on development of a single complete AR&D package capable of being wired into a spacecraft which supports all mission types ("AR&D-in-a-box"). Instead the strategy focuses on development of this AR&D warehouse, which primarily involves four specific subsystems that can enable AR&D and its required integration for all these missions. These four subsystems are those which are most impacted by adding an AR&D requirement to a vehicle: GN&C, Mission Manager, Sensors, and the Docking System. The AR&D capability suite would be populated with various solutions for each of these four areas, and all solutions would have standardized interfaces (e.g., the recently agreed-to "International Docking System Standard"). Then, each mission would pick-and-choose which solutions in the AR&D suite are most useful for implementing their design. We next focus on the four subsystems that are most impacted for any AR&D mission. Note that none of the subsystems are low TRL by themselves; the immaturity is in their integration.

TA4.6.1 Relative Navigation Sensors (Long-, Mid-, and Near-Range) and Integrated Communications

During the course of RPOD, varying accuracies of bearing, range, and relative attitude are needed for AR&D. Current commercial implementations for optical, laser, and RF systems (and combinations of these) are mid-TRL (Technology Readiness Level) and require flight experience to gain reliability and operational confidence. Moreover, integrated communication capability (at mid-field to near-field range) greatly enhances the responsiveness and robustness of the AR&D GN&C system, along with its portability.

TA4.6.2 Guidance Algorithms

Robust AR&D GN&C & Real-Time Flight Software (FSW) – Space Shuttle, Orbital Express, XSS-11, and other development efforts have raised the maturity of AR&D GN&C algorithms to a very high level for these point designs. However, to develop and refine these point design algorithms into a robust AR&D GN&C system capability, integrated with the high-level Mission/System Managers (TA4.6.4), and implemented into real-time FSW is an enormous challenge. A best practice based implementation of an AR&D GN&C system into real-time FSW needs to be developed and tested.

TA4.6.3 Docking & Capture Mechanisms/Interfaces

NASA is planning for the imminent construction of a new low-impact docking mechanism built to an international standard for human spaceflight missions to ISS. A smaller common docking system for robotic spacecraft is also needed to enable cost-effective robotic spacecraft AR&D. Assembly of the large vehicles and stages used for beyond LEO exploration missions will require new mechanisms with new capture envelopes beyond any docking system currently used or in development. Berthing methods may also be utilized when warranted by mission requirements. Furthermore, for satellite servicing / rescue, development and testing is needed for the application of autonomous robotic capture of non-cooperative target vehicles in which the target does not have capture aids such as grapple fixtures. AR&D capability must be compatible with the capture envelopes of all of these systems.

TA4.6.4 Mission/System Managers for Autonomy/Automation

A scalable spacecraft software executive that can be tailored for various mission applications and various levels of autonomy and automation, as enabled by the robust AR&D GN&C system (TA4.6.2), is needed to ensure safety and operational confidence in AR&D software execution. A scalable and evolvable executive architecture will prevent each mission from reinventing this critical piece of the AR&D software. Numerous spacecraft software executives have been developed, but the necessary piece that is missing is an Agency-wide open interface standard which will minimize the costs of such architectures. Creation of such a standard is also critical to ensure an ability of these architectures to leverage lessons learned and to evolve to higher levels of autonomy/automation over time as trust increases gradually in these capabilities. This evolutionary trait is especially critical to the trust of, and therefore success of, AR&D on crewed vehicles. Advances in fault management techniques must also be made in parallel.

Development of a U.S. AR&D warehouse consists of three elements:

First, initial maturation of the four subsystem technologies already discussed. This can be addressed in relatively short order with the judicious coordination of ongoing Program efforts and new funding. Leveraging the RPOD accomplishments of previous Programs, heritage GN&C algorithms, and software will be utilized to minimize development costs. Existing mission manager software will be used initially as a baseline to create a flexible and configurable system to support future vehicle architectures. NASA has already invested significant resources toward the NRE development costs for pertinent navigation sensors required for AR&D. This first element involves both ground and flight testing, provides NASA with hands-on experience, establishes the architecture for the capability suite, and lays the groundwork for commercial application.

Second, achieve an understanding of the integration and interplay of AR&D with various subsystems, while meeting vehicle and mission requirements and constraints. This is our most significant challenge. The vast majority of the AR&D development effort involves recognizing and dealing with contingencies and unexpected behavior from subsystem interaction and off-nominal conditions. So, in addition to architecting the AR&D GN&C system to maximize robustness (through well-designed FDIR and contingency responses) and minimize such subsystem interaction/dependencies (i.e., keeping clean interfaces by design), we must accumulate operational experience, confidence, and history with these systems and capabilities through ground testing as well as multiple space-based system demonstrations to lower the risk for each mission.

Third, develop supply chains for AR&D hardware. A very large portion of the cost reductions estimated herein is due to use of hardware made available through a stable supply chain. Our history is one of AR&D hardware developed for single-use applications. In the case of standardizing docking mechanisms for larger spacecraft, NASA is already moving forward with changing this paradigm. We have many more opportunities however to ensure that hardware is available for multiple uses. For example, three separate flash LIDAR experiments have flown on the Space Shuttle in recent years. NASA should take steps to ensure that all three continue in development and remain available for selection by programs, "off-the-shelf", as all three have their applications depending on program requirements. But none will ever be selected if the supply is not there. The classes of sensors of use to AR&D can be generally grouped according to: long range RF devices, long range optical devices, medium range optical and laser devices, and short range optical and laser devices.

While landing on planetary bodies is the domain of TA9 (Entry, Descent and Landing Systems) there may be some overlap with Autonomous Rendezvous and Docking when the planetary body is small, as in the case of an asteroid. For very small objects the gravity forces approach zero and the landing approaches docking. Measuring spin rate, matching rates and the use of anchoring devices will likely have much in common with the previously described technologies. Additional challenges will arise with a dusty and heterogeneous landing surface.

As noted above, AR&D is not a system, it is really a distributed capability involving multiple types of guidance algorithms, control algorithms, relative and absolute navigation algorithms, targeting algorithms, sensors, mission managers, flight software, docking systems, not to mention all the other vehicle systems involved. While it would be possible provide a rather lengthy list identifying the state-of-the-art for each of the components listed, such a list would largely not have much meaning, and furthermore would soon be outdat-

ed. For example, there are currently four relative navigation LIDAR sensors with recent flight experience, each of which could be legitimately argued is state-of-the-art for its particular design requirements and constraints. Also, discussion of the component outside of the entire AR&D capability is also relatively meaningless. If we attempt a discussion of the state-of-the-art of AR&D as an integrated vehicle capability, it gets even more difficult. All AR&D capabilities that the U.S. has flown, as discussed, are ultimately point-designs that are not readily extensible to future use. The ultimate goal of the AR&D warehouse and integrated collaborative utilization of that warehouse is to reverse this history of obsolescence; ultimately the AR&D Warehouse will in itself be the state-of-the-art.

NASA has already begun to make the necessary commitments and investments to implement a cohesive cross-Agency strategic direction for AR&D, which is based on evolutionary stair-step development through a campaign of coordinated ground tests and space-based system demonstrations, to achieve a mainstream AR&D capability suite, or “warehouse”, which supports the spectrum of future Agency exploration missions. The Agency will coordinate and integrate all ongoing and future technology and development Programs, including investing additional minimal resources and levying additional strategic AR&D requirements on current Programs, as necessary, such that current Programs are fully integrated into the Agency strategy. The NASA AR&D CoP believes that with this approach, a U.S. mainstream AR&D technology base for a wide spectrum of missions can be developed that is ready-to-fly, low-risk, reliable, versatile, architecture and destination independent, and extremely cost-effective, perhaps reducing AR&D implementation costs by an order-of-magnitude, and cut development time in half. This capability would enable the future missions of the Science and Human Exploration and Operations Mission Directorates, would benefit the DoD and the commercial spaceflight sector, and would re-establish U.S. leadership in the AR&D community.

2.1.7. TA4.7: RTA Systems Engineering

Many advances in robotics and autonomy depend on increased computational power. Therefore, advances in high performance, low power onboard computers are central to more capable space robotics. Current efforts in this direction include exploiting high performance field programmable gate arrays (FPGAs), multi-core processors, and enabling use in space of commercial grade computer components through shielding, hardware redundancy, and fault tolerant software design. Further pushes in these or other directions to achieve greater in-space computing power are needed.

TA4.7.1 Modularity / Commonality

Modular interfaces allow for structural, mechanical, electrical, data, fluid, pneumatic and other interactions across interfaces and form the basis for robotic assembly and servicing. Such interfaces support tool change-out on robotic arms whether for rovers or for in-space robotic assembly and servicing. Tools and end effectors developed in a modular manner need a reduced logistics footprint over dedicated arms for specialized tools. Developing modular robotic interfaces will also allow multiple robots to operate together and will make servicing of the robotic components (either by humans or other robots) easier.

Modular and common interfaces are also the building block for reconfigurable and self-assembling, and perhaps even self-replicating, robotic systems. Such system design allows deployed systems to respond to changing needs and system failures through in-situ reconfiguration of mechanical, electrical, and computing assets.

TA4.7.2 Verification & Validation of Complex Adaptive Systems

System verification will be a new challenge for human-rated spacecraft bound for deep space. New V&V approaches and techniques and in-flight re-verification may be necessary following a repair. Similar approaches will need to be developed to verify a robotic system that was assembled on-orbit using the self-replicating and/or reconfigurable approaches described above.

TA4.7.3 Onboard Computing

The explosive growth in scientific data and the increasing complexity of robotic and autonomous systems are some of the driving needs for higher performance computing systems. There are two approaches to satisfy these growing computing power needs—improvements in the traditional radiation-hardened computer processors (e.g., Rad750) that are “immune” to radiation effects; or use of modern, reconfigurable, computing technology coupled with electronic and software hardening against radiation effects. This new approach uses less expensive commercial components, which results in at least an order of magnitude increase in processing power over a typical Rad750 flight processor. However, this "radiation hardening by software" technique along with the incorporation of radiation-hardened FPGAs should make larger system more immune to single-event upsets. Reconfigurable computing offers the ability to internally reconfigure in response to chip-level failures caused by environmental (i.e., space radiation), life limitations, or fabrication errors.

2.2. Subtopics and Mission Diagram

The subtopics and mission diagram is shown in the Figure R foldout.

2.3. Mission by Mission Assessment

2.3.1. SOMD Missions

2.3.1.1. Robonaut 2 mission to ISS

During FY11 the Robonaut 2 system (Figure 8) was launched on STS-133 and delivered to the ISS in what will became the Permanent Multipurpose Module (PMM). Robonaut 2 (R2) is the latest in a series of dexterous robots built by NASA as technology demonstrations now evolving from Earth to in-space experiments. The main objectives are to explore dexterous manipulation in zero gravity, test human-robot safety systems, test remote supervision techniques for operation across time delays, and experiment with ISS equipment to begin offloading crew of housekeeping and other chores. The R2 was built in a partnership with General Motors, with a shared vision of a capable but safe robot working near people.

The R2 has the state of the art in tactile sensing and perception, as well as depth map sensors, stereo vision, and force sensing. The R2 will be deployed initially on a fixed pedestal with zero mobility, but future upgrades are planned to allow it to climb and reposition itself at different worksites. Robonaut 2's dexterous manipulators are the state of the art, with three levels of force sensing for safety, high strength to weight ratios, compliant and back drivable drive trains, soft and smooth coverings, fine force and position control, dual arm coordination, and kinematic redundancy. Human interfaces for the R2 include direct force interaction where humans can manually position the limbs, use software tools and script engines for trajectory design and sequence generation. R2 is designed to be directly tele-operated, remotely supervised, or run in an automated manner. The modular design can be upgraded over time to extend Robonaut capabilities with new limbs, backpacks, sensors and software.

Figure 8. *Robonaut 2 working inside the ISS*

2.3.1.2. ISS Refueling

The Robotic Refueling Dexterous Demonstration (R2D2) is a multifaceted payload designed for representative tasks required to robotically refuel a spacecraft. Once mounted to the International Space Station, the demonstration will utilize the R2D2 payload complement, the Special Purpose Dexterous Manipulator (SPDM) robotic arms, and 4 customized, interchangeable tools to simulate the tasks needed to refuel a spacecraft using its standard ground fill-and-drain valve. During the mission, operators at JSC will maneuver the SPDM robotic arms which will interact with the R2D2 payload box and complete its robotic tasks. Using SPDM's end effector and interchangeable R2D2 tools, operators will locate and access the fuel valve on the R2D2 payload box, uncap it, open the manual valve, and then transfer a liquid, simulated fuel through the tool interface into the fill-and-drain valve. A "busy board" on the R2D2 payload box will support the demonstration of general robotic operations relevant to space servicing. Four advanced tools were developed for this mission. Each tool is equipped with two integral cameras to help operators guide their maneuvers. The cameras use the OTCM umbilical connector for power and data.

2.3.1.3. Free-flyer Inspection Robot

This proposed technology push mission is based on an ISS utilization proposal titled "ISS Free flyer for Inspection, Remote Viewing, Science and Technology". The small free-flyer would be taken to ISS and flown outside through the JAXA air-

Figure 9. *Mini AERCam Image and Top Level Assembly*

lock, then back inside for refurbishment. The design is based on a mix of results from the AERCam (Figure 9) flight DTO (STS-87), as well as technology work done for Mini-AERCam (JSC), Inspector (JPL), PSA (MIT,ARC) and other free flyer work in universities and other agencies. The free-flyer benefits both current human spaceflight (ISS) and future exploration missions. In near-term operational applications, an external free flyer provides beneficial views of on-orbit maintenance and servicing tasks that cannot be obtained from fixed cameras, cameras on robotic manipulators, or cameras carried by crewmembers during EVA. Similar tasks are anticipated for exploration missions: Inspect descent vehicle thermal protection system before entry and landing; provide alternative to EVA inspection during lunar cruise or interplanetary flight; provide visual inspection cues to aid in developing repair plans and procedures for EVA tasks, including in-space assembly and maintenance.

The free-flyer represents the state of the art in remote sensing instruments, with a 10x reduction in mass and power due to the small scale of the system (<20kg). The mobility requires complete 6 axis motion control using a cold jet system that can be refueled IVA, relative navigation in space, proximity loiter for inspection, obstacle avoidance and trajectory planning. Human interfaces include direct handling, tele-operation, and remote supervision. Autonomous skills for hover, relative trajectories, and autonomous rendezvous and docking with the JAXA airlock are required to retrieve the free-flyer.

2.3.1.4. Astronaut JetPack

As humans extend their reach to asteroids or other in-space destinations, the ability to fly will become essential for human mobility and locomotion. The ISS is designed with handrails and tether points to assist EVA, but asteroids and satellites have no such features. EVA for the Shuttle and ISS missions relies on the SAFER Jetpack for emergency recovery if an astronaut falls off the spacecraft, but the SAFER is single string, and can only be used if the astronaut looses grip and a tether system fails. This technology push mission would develop a multi-string Jetpack able to be used for nominal flight during EVA on ISS, as well be applied to asteroid and high orbit missions where handrails and tether points are not available.

Sensing and perception requirements are minimal, though the jetpack could be augmented with future sensor payloads for specific missions. The mobility system is complete 6 axis motion control, with >10 m/s delta velocity for the combined mass of the crew, suit and jetpack. The base jetpack would have no manipulation, but be modular so that future upgrades are possible. The human interface will provide suit interaction, as well as access to pre recorded waypoints and system data/status. The nominal mode of control will be by the crew member wearing the Jetpack, but remote control will be possible to rescue injured crew. Rendezvous and docking will allow the crew member to return to airlocks, suit ports and worksites with an in-space version of cruise control.

2.3.1.5. ISS DPP

The Dexterous Pointing Payload (DPP) is a demonstration payload that will be installed and subsequently exercised on the ISS. In preparation for servicing missions requiring greater dexterity and tracking capability, the DPP will demonstrate the algorithms and control mechanisms to locate and point at a specific location on Earth or a celestial object. DPP performs attitude determination using a star tracker and an Inertial Measurement Unit (IMU). It will receive target parameters via commands from a ground terminal, and will send rate requests to the ISS Robotic Workstation Software (RWS) to achieve desired instrument pointing. This closed-loop control of Dextre (SPDM) enables real-time pointing and disturbance reduction that is beneficial for a wide range of servicing architectures.

2.3.1.6. Geo Fuel

The mission consists of a servicer spacecraft that can sequentially capture and control several non-cooperative legacy satellites in nearly co-planar geosynchronous orbits, refuel them, or relocate them to a disposal orbit 350 km above the GEO belt. The servicer spacecraft launches into geosynchronous orbit and then executes sorties to multiple customer satellites. At the start of the mission, the customer satellites (near the end of their mission life for refuel or at the end of their life for supersync) are on-orbit waiting for fuel or a boost to a disposal orbit. The servicer spacecraft is equipped with all hardware, algorithms and fuel necessary for supervised autonomous rendezvous and capture (AR&C), and refueling or supersync of the customers. The servicer is launched and inserted directly into GEO in the plane of the first customer satellite. The AR&C sequence puts the servicer onto a safety ellipse about the customer spacecraft during which time it performs pose estimation to accurately determine its position and attitude relative to the customer. The servicer then executes a series of maneuvers to acquire and translate down a capture axis, maneuvers the robotic arms to within approximately 1 meter of the customer (placing the arms in a predefined capture box), and finally autonomously grasping the customer. The servicer then refuels the customer or boosts the stack into a super-synchronous orbit (GEO + 350 km) as per NASA-STD-8719.14 (Process for Limiting Orbital Debris). It then releases the customer satellite and waits until the next customer is ready for refuel or removal.

2.3.1.7. HST

The mission launches a deorbit module into low Earth orbit to rendezvous and berth with the Hubble Space Telescope (HST) at the end of the life of the observatory and deorbits it. The grappling of HST upon approach would require a closed loop autonomous rendezvous and capture system. After capture, the servicing vehicle would perform a series of maneuvers to deorbit the observatory. However, prior to those maneuvers, the servicer could perform servicing technology demonstrations on a well understood serviceable platform before the deorbit occurs. This would reduce risk of future robotic servicing missions in a low risk environment as the telescope is being deorbited anyway.

2.3.2. ESMD Missions

2.3.2.1. Near Earth Asteroid (NEA) Robotic Precursor

At the time of this writing three classes of robotic missions are being proposed as precursors to Near Earth Asteroids. These classes are a survey observatory in space, a rendezvous mission that does not land on the asteroid, and a robotic mission to explore the asteroid's surface. NASA's Wide-field Infrared Survey Explorer (WISE) has observed over 100,000 asteroids, only 90 of which are in the near Earth class, leaving uncertainty that a survey mission can better resolve. A robotic rendezvous with a NEA will position sensors closer to the surface to collect better images, record spin rate, measure magnetic properties, and build a complete 3D surface map. Robotic missions that contact an asteroid's surface will be coupled with standoff imaging, providing the same data as the rendezvous mission but with additional surface data and the ability to study dust/rock ejecta. These missions are unlikely to be before 2015.

The survey mission has little requirement for Robotics, Tele-robotics and Autonomy beyond contemporary spacecraft engineering. The rendezvous mission would benefit from new mapping sensors and can be used as a test demonstration of autonomous rendezvous algorithms and sensors at mid-range.

Relative navigation sensors, GN&C algorithms, and mission manager subsystems can be integrated and demonstrated. An asteroid contact mission that includes controlled landing and sampling, and perhaps anchoring will challenge sensing (depth maps, materials), perception (map sensor fusion), mobility (landing), manipulation (anchoring and sampling), autonomy (remote ops), and be a more complete test of rendezvous at mid and near range down to contact.

2.3.2.2. Crew Transfer Vehicle (CTV)

Design Reference Missions (DRM's) produced by the Human Exploration Framework Team (HEFT) identified a need for a Crew Transfer Ve-

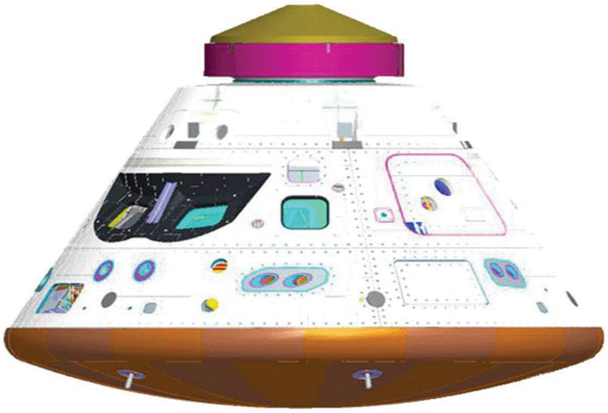


Figure 10. *Concept for a Crew Transfer Vehicle*

hicle (CTV) (Figure 10) for ascent and entry capabilities. This road mapping team studied several of the HEFT DRM's and found roles for either a CTV or commercial capsule in all cases. The CTV is designed to return an exploration crew of up to 4 crew members from an interplanetary trajectory directly to the Earth (water landing). The CTV is based on the Orion crew module design. Active duration is on the order of 36-40 hours. First launch for the CTV varies from 2019 to 2023 across the HEFT DRM's, or never if a commercial capsule option is pursued.

Little or no sensing, perception or manipulation is needed for the CTV. The spacecraft will need to support autonomous rendezvous and docking, where sensor technology will be needed. If missions choose to grapple the CTV, a manipulator grapple fixture can be added. Human interfaces will be minimal, with launch and entry being highly automated functions. The CTV will require onboard autonomous systems in order to achieve the reliability and affordability required by the President and Congress. The CTV will need autonomous systems to manage the spacecraft, requiring ground assistance only when a significant state change has occurred which affects mission success or when a state change has occurred beyond the limits of the onboard systems. Autonomous systems need to be able to minimize the need for operator assistance thereby limiting the size of ground based operations teams and minimizing operations costs. If strong ground operator dependence is required then the CTV will not be able to be transported beyond the cis-lunar system as crew time will not be available to monitor the vehicle. The CTV will need a modular docking interface that is compatible with the MMSEV and other spacecraft.

2.3.2.3. Multi Mission Space Exploration Vehicle

Figure 11. *MMSEV Concept Image*

Designed to compliment capsules used for launch and re entry, the MMSEV (Figure 11) is designed to provide in-space functions such as EVA support, habitation, and exploration of manmade satellites or asteroids. It will be capable of refueling, and could be tested initially with missions to ISS or HEO. The cabin will have commonality with future surface rovers, providing multiple applications and refinement of the technology on a flexible path to Mars. The cabin is design to nominally support 2 crew for 2 weeks, or more crew or duration in contingency or with additional logistics modules. The cabin has suit port interfaces for supporting EVA, a grappling manipulator to dock or anchor on asteroid, dexterous arms for sampling and servicing functions, solar arrays for power generation, an RCS system for local motion control, and iLIDS docking interfaces to mate with other spacecraft.

Sensors include depth mapping radar, LIDAR, and multispectral imagers. Mobility requires a full 6 axis RCS motion control system, but with limited delta Velocity for only local navigation. Manipulation requires grappling that will likely be customized for ISS, Satellites or asteroid missions, and smaller arms for dexterous manipulation like sampling, servicing and carrying objects. Human interfaces include cockpit controls (displays, joysticks, audio), EVA interfaces, and remote interfaces for flying and operating the MMSEV as an unmanned vehicle. Autonomy includes the full range of spacecraft systems automation, as well as support for flying, manipulation, EVA support, and the rendezvous and docking required to mate the hatches with other vehicles. The Multi Mission Space Exploration Vehicle (MMSEV) will require onboard autonomous systems in order to achieve the reliability and affordability required by the President and Congress. The MMSEV will need autonomous systems to manage the spacecraft, requiring ground assistance only when a significant state change has occurred which affects mission success or when a state change has occurred beyond the limits of the onboard systems. Autonomous systems need to be able to minimize the need for operator assistance thereby limiting the size of ground based operations teams and minimizing operations costs.

2.3.2.4. Test HEO

The requirements for Robotics and Autonomy technologies to support near-term High Earth

Orbit (HEO) missions will focus on the autonomous capabilities necessary to operate outside of real-time control and support from the Earth. For missions to Lagrange Points, lunar orbit and near-vicinity NEAs, robotics and autonomous systems work will focus enabling robotic capabilities to perform precursor exploration and autonomous operations in support of the Crew. The evolution in robotics and autonomous systems capability for high earth orbit will focus on crew-system autonomy to support exploration in uncertain and dynamic environments.

2.3.2.5. Human HEO

Low-thrust, solar electric vehicles will travel from low-earth to a High Earth Orbit (HEO) carrying cargo using autonomous guidance, navigation and control to orient the electric propulsion system over the continuous thrusting period. Autonomy will be required to manage the complex spacecraft's system state. To dock with the cargo, autonomous rendezvous and docking will be required at the beginning and end of the HEO transfer.

The Human Rated Autonomy may be essential for Human HEO missions. Limited crew sizes and the need to abort to Earth require proactive autonomous systems to manage the vehicle. These capabilities require unambiguous determination of vehicle states, quick response to vehicle anomalies, and the ability to abort the crew to Earth well in advance of life threatening failures. Autonomous systems will need to implement vehicle state determination, diagnostics, prognostics, mission executives, and mission planning functions. Radiation hardened avionics will be necessary to ensure the vehicle can maintain crew functions during solar radiation events. A variety of intelligent algorithms will need to be integrated to accomplish these functions. New verification and validation methods will also be required for these human rated autonomy and automated functions.

2.3.2.6. HEO Utilization Flight 1 &

2.3.2.7. HEO Utilization Flight 2

For flexible human mission architectures, the crewed vehicle will require several basic on-board capabilities in order to complete the fundamental scientific and technical objectives. As missions explore farther and farther from the Earth, going to Earth-Moon Lagrange points, then Sun-Earth Lagrange points, and onward to Near Earth Objects (NEOs), the crew will need to be increasingly autonomous (see Section 2.3.2.5) from the Earth. The crew and spacecraft systems will need to be operationally autonomous from real-time ground control support due to distance based communications delays. Proximity operations to any targets (space telescopes, or small NEOs) will require autonomous rendezvous and coupling technologies. This would require significant on-board capabilities beyond what has been planned for low-earth orbit or even lunar missions. The crew would need to have the equivalent of flight directors on-board to support real-time operations, EVA, robotic systems, and Proximity Ops. In addition, the crew would be a scientific vanguard to the destination (Lagrange Pts, NEOs, etc), needing all the equipment and tools of any first explorers.

2.3.2.8. Near Earth Asteroid (NEA) Human Mission

The first human mission to an asteroid (Fig.12) will challenge our ability to live and work in deep space, perform EVA in space, rendezvous with distant objects, and support an independent crew working far from Earth. The mission will begin with stack assembly, likely even with heavy launch capability. Trans-rock injection will be followed by a lengthy cruise phase, then insertion and rendezvous with the asteroid's orbit. Depending on the scale of the asteroid, proximity operations may have little in common with orbiting a planet, but more like hovering next to a satellite or other small object. Crew-centered operations will be the norm rather than the exception here. Mission control will be in an advisory function due to light-time communication delays. Onboard automation must exist to support the crew operations for the mission. The crew will perform mapping and survey tasks, and then attempt to make contact with the asteroid surface with either their spacecraft or going EVA. Trans-Earth injection will be followed by a second lengthy cruise phase,

Figure 12. *Concepts for a Human Asteroid Mission*

then Earth capture and re entry.

All mapping and sensing technologies developed for precursors will be reused with refinement; then added to sensors and perception associated with supporting crew. Mobility needs include spacecraft 6 axis motion as well as EVA mobility for crew in a micro gravity environment. The mission will need manipulation technology for stack assembly, grappling and anchoring to an asteroid, EVA crew positioning, and sample handling. The human interfaces will span the spectrum of Earth supervision, cockpit command and control, and EVA suit interfaces. The crew will be required to operate their spacecraft far from Earth, so autonomy will be needed to reduce the system overhead and make the crew independent. The ability to reconfigure vehicle systems to maintain the crew in the event of major system losses will need to be addressed. New verification and validation methods will also be required for these human rated autonomy and automated functions. These abilities build on the requirements for the HEO missions. Multiple autonomous rendezvous and docking steps are likely, from stack assembly to proximity ops, and ranging from near earth locations to deep space docking.

2.3.2.9. Human Mars Orbit/Phobos

For a Human mission to Phobos or Mars Orbit, requirements for robotics and autonomy would involve equipment and techniques supporting remote sensing, deployment/re-deployment of robotic surface experiment packages, and robotic surface sampling. Previous ground-based observations and precursor mission data should have adequately characterized the surface and local space environment to reduce risk to the spacecraft and its assets (i.e., the crew and equipment). Hence, the majority of spacecraft operations should be able to take place in close proximity (~a few to several hundred meters) to the surface of Phobos. Such operations have been found to be challenging for remotely controlled spacecraft due to round trip light delay times of several tens of seconds or minutes, but should be much more tractable for the crew with humans directly in the loop. The crew and spacecraft should be able to match the rotation of Phobos, or hover over its surface, while maintaining a stable attitude from which they can conduct a detailed scientific exploration of the surface. This capability will ideally have been validated during a crewed NEA mission previously. Proximity operations and automated rendezvous technologies will be critical. Additional autonomous systems technology needs become more demanding with missions to Mars orbit, Phobos, Deimos, more remote NEAs and Venus orbit. Automation to support cryogenic fluid management for long-duration transfer and management of liquid hydrogen, other propellants and life support fluids, and ECLSS systems will be needed as well. Autonomy and other functions will build upon capabilities cited as essential for the previous missions to HEO and asteroids.

2.3.2.10. Human Mars Mission

There is much debate about the path to Mars, but general agreement that Mars is the ultimate destination for humans in the inner solar system. Volumes have been written on Mars mission architectures, and our science missions have greatly informed our plans with knowledge of the surface and experience in landing, operating and exploring. Standout differences between a human mission to Mars (Figure 13) and our previous experiences are the long duration of the mission for crew, the combination of zero gravity and reduced gravity, the large scale of entry and descent vehicles, and long surface stay and mobility range required. A human mission to Mars may be preceded by missions to near Mars, its moons or Mars orbit.

Pre-deployed robotic assets could potentially be used to help produce propellant from the massive amounts of sub-surface water ice that are expected to be present. By excavating water ice from the regolith, oxygen and hydrogen propellant can be produced by electrolysis without transporting hydrogen to Mars, as is needed for the production of Methane. Landing pads may be robotically prepared to reduce the risk of a bad landing. Robotic assistants can connect the crew lander to a power plant by deploying and mating a power cable to the power plant before the lander runs out of stored power. The robots will use sunlight energy for solar electric propulsion, and then the humans will use the propellants that are produced by the robotic mining systems. This is a good example of enabling human-robotic exploration.

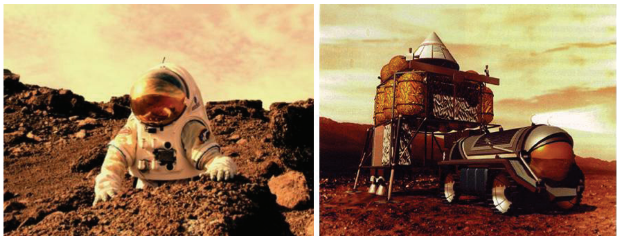


Figure 13. *Human Mars Mission Concepts*

Human missions generate massive amounts of data, and humans augmented with sensors are now the baseline for exploration. Mapping, science instruments, biomedical instruments, and sensors to support navigation and mobility will be required with redundancy in numbers and type. Mobility will include in-space flying, surface roving, and EVA mobility. The crew will be far from Earth and will need interfaces to all systems, and those systems will be highly autonomous to avoid consuming crew time. Autonomous systems will need to integrate across vehicle stages or platforms. The Human Mars vehicle will have a complicated configuration including aerocapture, landers, and ascent stage recovery. The mission will involve complex stack assembly with manipulation, grappling, rendezvous and docking, EVA/robotic assembly, and must be able to conduct those operations either near Earth, in deep space, Mars orbit, or on the surface.

2.3.3. SMD Missions

2.3.3.1. Mars Science Laboratory (MSL)/ Extended

Extended phases of the MSL mission are opportunities for insertion and testing of software upgrades representing technology push items. Examples of potential new onboard capabilities include faster implementations of visual odometry algorithms for slip estimation, onboard visual terrain classification for improved path planning, estimating parameters of soil mechanics models for improved trafficability analysis, automated mid-sol and end-of-sol position estimation using orbital imagery, automated instrument pointing, science operations while driving, and automated site survey and downlink of site maps annotated with science observations. Some functions current performed on the ground could be migrated onboard, including motion planning and collision checking for the sampling arm. Since MSL is powered by RTGs, not solar panels, new operational modes could include driving in the dark through terrain determined in advance to be free of obstacles by examination of onboard and orbital sensor data.

Technology push opportunities exist for uploading new perception software that while utilizing the existing sensors, will expand capabilities and productivity per sol. Software upgrades can also provide for improved mobility and manipulation performance. Autonomy upgrades include more efficient data handling, and fault detection and recovery.

2.3.3.2. Mars Sample Return (MSR) Mission 1

2.3.3.3. Mars Sample Return (MSR) Mission 2

2.3.3.4. Mars Sample Return (MSR) Mission 3

A definitive answer to whether there is or has been life on Mars or, if not, why not, requires return of carefully selected samples from one or more well-characterized, high-priority sites. Analysis of returned samples allows measurements using complex analytical techniques (i.e., occupying large laboratories), provides necessary opportunities for follow-up measurements, and enables subsequent analyses using techniques not yet developed at the time of sample return. Properly interpreting evidence related to life requires multiple approaches, and it is not possible to select discrete and unique criteria ahead of time. Answers will come only through multiple analyses of returned samples. Analysis of returned samples would also contribute to most disciplines at Mars and is necessary for advancing our understanding of many of them, including through comparison with Earth. There is high relevance to topics including planetary formation, geophysical evolution, surface geology, climate and climate history of all the terrestrial planets.

Sample return is also thought to be a necessary step along the path toward potential human missions to Mars, in order to understand the environment prior to human arrival.

The proposed MSR would be a campaign of three missions:

1. 2018: sample caching mission, which would cache rock cores for later retrieval.
2. 2022: MSR Orbiter Mission, which would augment the planetary communications network and return the Orbiting Sample container (OS) to the Earth's surface after 2024.
3. 2024: MSR Lander Mission, which would retrieve the sample and places it in Mars orbit in an OS container.

A fourth component is the Mars Returned Sample Handling element that would include a Sample Receiving Facility (SRF) and a curation facility.

The campaign would entail three launches. The current baseline for the first mission is the Joint NASA/ESA Mars 2018 mission, which would use a Mars Science Laboratory (MSL)-style entry, descent, and landing (EDL) system to land both a NASA Caching Rover and the ESA ExoMars Rover on a single platform. The proposed MSR Orbiter would be sent nominally two opportunities (four years) later. It is projected to launch before the MSR Lander, so that it could provide telecommunications infrastructure for the lander and its fetch rover and Mars Ascent Vehicle (MAV). In the next opportunity (two years later), the MSR Lander would be sent, also using an MSL-style EDL system to get the lander platform, including the MAV, to the surface. The lander would dispatch a fetch rover to retrieve a sample cache previously deposited on the surface by the 2018 NASA Caching Rover. The cache would be augmented by a lander-collected sample and inserted into the OS that would be launched into a 500 km orbit by the MAV. The orbiter—having monitored the launch and release of the OS—would rendezvous and capture the OS. On the orbiter the process of "breaking the chain of contact" with Mars would take place, sealing the OS into an Earth Entry Vehicle (EEV). The orbiter would then return to Earth, release the EEV a few hours before entry, and divert into a non-Earth return trajectory. Because of Planetary Protection requirements, the EEV seals would have to be verified before targeting the Earth. The EEV would hard land on the surface and then be transferred to a secure SRF for quarantine before samples are extracted.

All three MSR missions have a broad set of technology pull opportunities. MSR-1 Has potentially the most complex manipulation and mobility requirements of any mission yet attempted. This robot will need sensing and perception to assist Earth science teams and augment their visualization of the geologic units and transitions. Coupled with a long term mission life, the robot will be responsible for long term cache management. MSR-3 will perform the first Automated Rendezvous and Docking task ever attempted on the surface.

MSR Key Requirements

Numerous science advisory groups have met over the past decade to define proposed science objectives for MSR and to address the balance of objectives and mission difficulty and cost. While the science would be ultimately performed in laboratories here on Earth, the following goals reflect the latest thinking on the MSR missions.

- Return >500 g of sample consisting of:
    - Rock cores from multiple geological units
    - Regolith from a single location, but potentially from multiple locations
    - A compressed atmospheric sample
- Use a suite of in situ instrumentation to carefully select coring targets and document context of the cores
- Minimize organic and inorganic contamination
- Package samples to minimize cross contamination and sample alteration (which might or might not include hermetic sealing)
- Maintain temperature control of samples to <20°C (except potentially higher for a short period after landing at Earth)

2.3.3.5. Comet Surface Sample Return (CSSR)

The fundamental CSSR mission scientific objectives are as follows:

- Acquire and return to Earth for laboratory analysis a macroscopic (at least 500 cc) sample from the surface of the nucleus of any comet.
- Collect the sample using a "soft" technique that preserves complex organics.
- Do not allow aqueous alteration of the sample at any time.
- Characterize the region sampled on the surface of the nucleus to establish its context.
- Analyze the sample using state-of-the-art laboratory techniques to determine the nature and complexity of cometary matter, thereby providing fundamental advances in our understanding of the origin of the solar system and the contribution of comets to the volatile inventory of the Earth.

The baseline CSSR mission scientific objectives will also provide revolutionary advances in cometary science:

- Capture gases evolved from the sample, maintaining their elemental and molecular integrity, and use isotopic abundances of the gases to determine whether comets supplied much of the Earth's volatile inventory, including water.
- Return material from a depth of at least 10 cm (at least 3 diurnal thermal skin depths), if the sampled region has shear strength no greater than 50 kPa, thereby probing compositional variation with depth below the surface.
- Determine whether the sample is from an active region of the nucleus because those areas may differ in composition from inactive areas.

After the mission spacecraft travels to Comet 67P/C-G and collects images to characterize the comet's nucleus, a sample return vehicle (SRV) will return ≥500 cc of material to Earth for laboratory analysis. The payload will collect the samples using 4 drills. Samples will be maintained during the return trip at ≤ –10°C. After SRV recovery, the samples will be transferred to Johnson Space Center astromaterials analytical laboratories that will have been upgraded with capabilities to store, analyze and characterize frozen samples. The reliance on heritage spacecraft design wherever possible is intended to minimize risk. The following critical technologies will require development to Technology Readiness Level (TRL) 6:

- Ballistic-type sample return vehicle (SRV) will require new mobility and control technologies.
- UltraFlex solar array Sample Acquisition System (SAS) will require new sensing technologies.
- Height and Motion System (H&MS) will require manipulation, sensing and control technologies.

2.3.3.6. Comet Nucleus Sample Return (CNSR)

SMD will propose a technological development program to enable a CNSR mission in the subsequent decade (2021–2030). This Technology Development Program will address technology needs for CNSR, mitigate mission development risks, and verify promising technologies and mission concepts via a test and evaluation program.

The overriding objective is to provide assurance that the key CNSR-required technologies can all be raised to at least Technology Readiness Level 5 (TRL 5, full-scale prototype testing) in the coming decade.

It is assumed that by the time a CNSR mission is launched, a Comet Surface Sample Return (CSSR) mission will have been accomplished and will have demonstrated how to obtain a surface sample. The primary interest for the CNSR mission is to obtain a sample at depth(s) from beneath the surface layer and to maintain it cold enough to return material to the Earth in the ice phase.

The following set of top-level science goals is assumed for the mission study with highlighted tech opportunities:

- *Floor:* Return one sample from a single site, with water ice and less volatile organics intact (i.e., no water ice melting or loss of "moderately volatile" species to vacuum). [manipulation and control technology]
- *Baseline:* Return one sample from a single site, with >20% water ice by mass, with water ice, most volatile organics preserved, and stratigraphy intact. (It is noted that the preservation of stratigraphy is highly desired, but it is recognized to be difficult to achieve). [sensing, perception and manipulation technology]
- *Desired:* Return up to several kilograms of samples from multiple sites on the nucleus, with stratigraphy and all ices intact, and no cross-contamination of collected samples. [sensing, perception, manipulation and mobility technology]

2.3.3.7. Venus Mobile Explorer (VME, aka Venus Aerobot)

The Venus Mobile Explorer (VME) mission concept affords unique science opportunities and vantage points not previously attainable at Venus. The ability to characterize the surface composition and mineralogy in two locations within the Venus highlands (or volcanic regions) will provide essential new constraints on the origin of crustal material, the history of water in Venus' past, and the variability of the surface composition within the unexplored Venusian highlands. As the VME floats (~3 km above the surface) between the two surface locations, it offers new, high spatial resolution, views of the surface at near infrared (IR) wavelengths. These data provide insights into the processes that have contributed to the evolution of the Venus surface. The science objectives are achieved by a nominal payload that conducts in situ measurements of noble and trace gases in the atmosphere, conducts elemental chemistry and mineralogy at two surface locations separated by ~8–16 km, images the surface on descent and along the airborne traverse connecting the two surface locations, measures physical attributes of the atmosphere, and detects potential signatures of a crustal dipole magnetic field.

The VME design includes an elegant, volume efficient cylindrical gondola to accommodate the science payload in a thermally controlled environment. An innovative, highly compact design surrounds the gondola with a toroidal pressure tank capped with the bellows, enabling the entire lander system to fit in an aeroshell with heritage geometry. The thermal design uses heat pipes and phase change material that enable the gondola electronics and instruments to survive 5 hours near the Venus surface, thus providing sufficient time for surface chemistry and an aerial traverse >8 km in the current- like winds.

Launched on an Atlas V 551 in either 2021 or 2023, the carrier spacecraft carries the VME probe to Venus on a Type II trajectory. After release from the carrier, the VME probe enters the atmosphere,

descends on a parachute briefly, and then free-falls to the surface. Science is conducted on descent and at the surface. While collecting data at the first site, the bellows are filled with helium and when buoyant, rise with the gondola, leaving the helium pressure tank on the surface. Driven by the ambient winds, the gondola floats with the bellows for ~220 minutes, conducting additional science. At the completion of the 8–16 km aerial traverse, the bellows are jettisoned and the gondola free falls back to the surface, where final surface science measurements are performed. The total mission time in the Venus atmosphere is 6 hours, which includes 5 hours in the near surface environment. The VME probe transmits data to the flyby carrier spacecraft continuously throughout the 6-hour science mission. After losing contact with the VME probe, the carrier spacecraft then relays all data back to Earth.

This mission represents a completely new approach to surface exploration. Technology needs span sensing, perception, mobility, sample manipulation, and spacecraft autonomy.

2.3.3.8. Titan Aerobot

A mission launched in the 2018–2022 timeframe would provide a unique opportunity to measure a seasonal phase complementary to that observed by Voyager and by Cassini, including its extended missions.

Recent discoveries of the complex interactions of Titan's atmosphere with the surface, interior, and space environment demand focused and enduring observation over a range of temporal and spatial scales. The Titan Saturn System Mission (TSSM) two-year orbital mission at Titan would sample the diverse and dynamic conditions in the ionosphere where complex organic chemistry begins, observe seasonal changes in the atmosphere, and make global near-infrared and radar altimetric maps of the surface. This study of Titan from orbit with better instruments has the potential of achieving a 2–3 order-of-magnitude increase in Titan science return over that of the Cassini mission. Chemical processes begin in Titan's upper atmosphere and could be extensively sampled by an orbiting spacecraft alone. However, there is substantial additional benefit of extending the measurements to Titan's lower atmosphere and the surface. Titan's surface may replicate key steps toward the synthesis of prebiotic molecules that may have been present on the early Earth as precursors to life. In situ chemical analysis, both in the atmosphere and on the surface, would enable the assessment of the kinds of chemical species that are present on the surface and of how far such putative reactions have advanced. The rich inventory of complex organic molecules that are known or suspected to be present at the surface makes new astrobiological insights inevitable. In situ elements also enable powerful techniques such as subsurface sounding to be applied to exploring Titan's interior structure. Understanding the forces that shape Titan's diverse landscape benefits from detailed investigations of various terrain types at different locations, a demanding requirement anywhere else, but one that is uniquely straightforward at Titan, using a Montgolfière hot-air balloon. TSSM's Montgolfière could circumnavigate Titan carried by winds, exploring with high resolution cameras and subsurface-probing radar. The combination of orbiting and in situ elements is a powerful and, for Titan, unprecedented opportunity for synergistic investigations— synthesis of data from these carefully selected instrumentation suites is the path to understanding this profoundly complex body.

The flight elements would be launched on an Atlas V 551 launch vehicle in 2020 using a gravity-assist SEP trajectory to achieve a trip time of 9 years to Saturn. Following Saturn orbit insertion, the orbiter would conduct a Saturn system tour, including 7 close Enceladus flybys and 16 Titan flybys. This phase would allow excellent opportunities to observe Saturn, multiple icy moons and the complex interaction between Titan and Saturn's magnetosphere. The Montgolfière would be released on the first Titan flyby, after Saturn orbit insertion, and would use an X-band relay link with the orbiter for communications. The lander would be released on the second Titan flyby and communicate with the orbiter during the flyby only. This 24-month period would also mark the mission phase when all of the Titan in situ data is relayed back to Earth. Following its tour of the Saturn system, the orbiter would enter into a highly elliptical Titan orbit to conduct a two-month concurrent Aerosampling and Aerobraking Phase in Titan's atmosphere, sampling altitudes as low as 600 km. The orbiter would then execute a final periapsis raise burn to achieve a 1500-km circular, 85° polar-mapping orbit. This Circular Orbit Phase would last 20 months.

This mission represents a completely new approach to surface exploration. Technology needs span sensing, perception, mobility, sample manipulation, and spacecraft autonomy.

2.3.3.9. Additional SMD Missions

The RTA panel is continuing to investigate additional missions that will provide both push and pull technology opportunities for robotics, telerobotics and autonomous systems technology.

These include:

- Europa Lander
- Venus Sample Return
- Advanced Technology Large-Aperture Space Telescope (ATLAST)
- 30-meter Space Telescope

2.3.4. ARMD Missions

2.3.4.1. Small UAV

Small Unmanned Aerial Vehicles (UAVs) are aircraft that are either fully- or semi-autonomous (mixed initiative) robotic vehicles. UAVs are fundamentally similar in concept to spacecraft. They are used for NASA science missions in uncertain and rapidly changing environments, and they drive much the same set of autonomy requirements (pilot automated monitoring, diagnosis, planning and execution, reliable software, and advanced controls) that NASA finds in inter-planetary exploration missions. Additionally, they can naturally be used to investigate issues in multi-agent cooperation (e.g., for surveillance by fleets of UAVs, or planetary robots) that NASA will need to solve for various future missions.

2.3.4.2. Wind Turbines

Many challenges exist for the efficient and safe operation of wind turbines due to the difficulty in creating accurate models of their dynamic characteristics and the turbulent conditions in which they operate. A promising new area of wind turbine research is the application of adaptive control techniques, which are well suited to problems where the system model is not well known and the operating conditions are unpredictable.

2.3.4.3. Wildfire UAV

Full automation of the Wildfire UAV system will enable free-flight within the National Airspace. This included the autonomous filing of flight plans and execution of the same, based upon satellite sensor data indicating where fires exist in a geographic area. On-board system health management and adaptive control will enable the UAV to operate in degraded modes. On-board data analysis and science discovery will permit the UAV to report operational fire targets to ground firefighters and to support remote sensing of fire progress.

2.3.4.4. Air Cargo

Advanced adaptive control technologies and system state monitoring and management capabilities will be required to enable real-time feathering, engine control, and system health management of variable speed rotorcraft operations. V&V of the flight critical systems will also be necessary.

3. CONCLUSIONS

3.1. Top Technical Challenges

The RTA panel identified multiple top technical challenges, and these will be described in order of their associated location in the WBS, not a particular priority. Each represents the top priority within its WBS sub topic.

Object Recognition and Pose Estimation

Object recognition requires sensing, often fusing multiple sensing modalities, with a perception function that can associate the sensed object with an object that is understood a priori. Sensing approaches to date have combined machine vision, stereo vision, LIDAR, structured light, and RADAR. Perception approaches often start with CAD models or models created by a scan with the same sensors that will be used to identify the object later. Pose estimation seeks to locate an object relative to a sensor coordinate frame, computing the six axis pose using sensing data. Pose estimation is often preceded by object recognition, or presumes an object so that its pose can be estimated and tracked. There is a special case of identifying humans as objects of interest, tracking human motion, gestures, and doing human recognition. Major challenges include the ability to work with a large “library” of known objects (>100), identifying objects that are partially occluded, sensing in poor (high, low and sharply contrasting) lighting, estimating the pose of quickly tumbling objects, and working with objects at near and far range. This technology is important for object manipulation and in mobility for object following and avoidance. Human tracking is important in manipulation for safely working with human teammates, and in mobility for avoiding collisions with pedestrians.

Fusing vision, tactile and force control for manipulation

The field of mobile robotics has matured with the advance of safe, fast and deterministic motion control. This success has come from fusing many sensors to avoid contacting hazards. Manipulation requires forming contact, so the breadth of sensing will require proximity, then tactile, and ultimately force sensing to reach, grasp and use objects like tools. Vision requires sensors that are not blocked when limbs reach for objects, but that can be pointed and transported for mobile manipulation applications. Major challenges include calibration of highly dissimilar sensors, dissimilar resolution, noise, and first principles of physics in the development of new sensors.

Achieving human-like performance for piloting vehicles

Machine systems have the potential to outperform humans in endurance, response time and number of machines that can be controlled simultaneously. Humans have safety limits on flight or drive-time that do not exist in machines. Human response time, coupled with human machine interfaces, results in significant delays when faced with emergency conditions. Humans are poor at parallel processing the data and command cycles of more than a single system. But machines are currently far behind humans in handling extremely rare cases, improvising solutions to new conditions never anticipated, and learning new skills on the fly.

Access to extreme terrain in zero, micro and reduced gravity

Current crew rovers cannot access extreme Lunar or Martian terrain, requiring humans to park and travel on foot in suits. In micro gravity, locomotion techniques on or near asteroids and comets are undeveloped and untested. Access to complex space structures like the ISS is limited to climbing or positioning with the SSRMS. Challenges include developing robots to travel into these otherwise denied areas, or building crew mobility systems to move humans into these challenging locations.

Grappling and anchoring to asteroids and non cooperating objects

Grappling an object in space requires a manipulator or docking mechanisms that form a bi directional 6 axis grasp. Grappling an asteroid and then anchoring to it is an all-new technology. Grappling approaches attempted on man- made objects may not apply to asteroids, since these techniques count on specific features such as engine bells that will not be available on a natural object. Similarly, grappling an object that is tumbling has not been attempted.

Exceeding human-like dexterous manipulation

The human hand is generally capable. A robotic equivalent, or superior grasping ability, would avoid the added complexity of robot interfaces on objects, and provide a sensate tool change-out capability for specialized tasks. Dexterity can be measured by range of grasp types, scale, strength and reliability. Challenges include fundamental 1st principles of physics in the development of actuation and sensing. Other challenges include 2 point discrimination, contact localization, extrinsic and intrinsic actuation, back-drivability vs. compliance, speed/strength/power, hand/glove coverings that do not attenuate sensors/motion but are rugged when handling rough and sharp objects.

Full immersion, telepresence with haptic and multi modal sensor feedback

Telepresence is the condition of a human feeling they are physically at a remote site where a robot is working. Technologies that can contribute to this condition include fully immersive displays, sound, touch and even smell. Challenges include 1st principles of physics in the development of systems that can apply forces to human fingers, displays that can be endured for long periods of telepresence immersion, and systems that can be used by people while walking or working with equipment concurrently with the telepresence tasks.

Understanding and expressing intent between humans and robots

Autonomous robots have complex logical states, control modes, and conditions. These states are not easily understood or anticipated by humans working with the machines. Lights and sounds are helpful in giving cues as to state, but need to be augmented with socially acceptable behaviors that do not require advanced training to interpret. Likewise, robots have difficulty in understanding human intent through gesture, gaze direction or other expressions of the human's planned behavior.

Verification of Autonomous Systems

Large software projects have such complex software that exhaustive and manual exploration of all possible cases is not feasible. Human rated autonomous systems are particularly challenging. Verification techniques are needed to more fully confirm system behavior in all conditions.

Supervised autonomy of force/contact tasks across time delay

Tasks have time constants that vary greatly, with the shortest time constants involving motions that form contacts with the environment and force controlled actions. These tasks require high speed local control loops. As time delays approach these tasks time constants the ability to tele-operate the machine degrades. Supervision is the management of a robot with autonomous skills, working along a sequence of tasks. Challenges include run time simulation to predict future states, visualization approaches to overlay predicted, committed and commanded states, and the ability to work ahead of real-time.

Rendezvous, proximity operations and docking in extreme conditions

Rendezvous missions include flybys of destinations without landing or docking. Proximity operations require loiters at destinations with zero relative velocity. Docking drives latching mechanisms and electrical/fluid couplings into a mated condition. Major challenges include the ability to rendezvous and dock in all ranges of lighting, work across near to far range, and achieve a docked state in all cases.

Mobile manipulation that is safe for working with and near humans

Merging manipulative capabilities with general mobility is sought to allow robots to go to the work site, rather than require the work be delivered to the robot. Manipulator arms and mobility drives each pose hazards to people. Combined, they present many risks. Challenges include tracking humans in the workspace, responding deterministically to inadvertent contact, compliance, and providing redundant sensor and software systems.

3.2. Overlap with other Technical Areas.

Table 1 summarized overlaps that have been identified with between TA4 and the other technology areas. These have been sorted into the two classes of either being technologies needed by TA4, or technologies from TA4 needed by the other area.

3.3. Summary of Findings for Robotics, Tele-Robotics and Autonomous Systems

1) NASA's four Mission Directorates are depending on Robotics, Tele-Robotics and Autonomy Technology.
2) Technology should aim to exceed human performance in sensing, piloting, driving, manipulating, rendezvous and docking.
3) Technology should target cooperative and safe human interfaces to form human-robot teams.
4) Autonomy should make human crews

Table 1. *Overlap with other Technical Areas showing technologies needed by TA4 and technologies from TA4 needed by the other area.*

Area ID	Area Name	Needed By RTA TA4	Provided By RTA TA4
TA01	Launch Propulsion	RTA System Delivery	Health Management, Abort Systems
TA02	In-Space Propulsion	RTA System Delivery	Controlled Formation and Docking
TA03	Space Power & Energy Storage	High Specific Power and Energy	Offloading, Setup, Maintenance
TA05	Communication & Navigation	High Throughput, Bi-dir comm, RF Nav	(Re)Deployment and Maintenance
TA06	Human Health, Life Support & Habitation		System Health, Automation
TA07	Human Exploration Destination Systems		Robot and Autonomy Applications
TA08	Science Observatories, Instruments & Sensor Systems		Data Mining, Assembly, Servicing
TA09	Entry Descent & Landing	RTA System Delivery	Precision Landing, Hazard Avoidance, Autonomy
TA10	Nanotechnology	Advanced Materials, Sensors, Actuators	
TA11	Modeling, Simulation, IT & Processing	Computing, Physics Based Models	RTA System Design Data, Test Results
TA12	Materials, Structures, Mechanical Systems & Manufacturing	Docking Mechanisms, Mechanical Interfaces	Robotic Manufacturing in Space
TA13	Ground & Launch Systems Processing	RTA System Processing	Robotic Launch Equipment, Mars Ground Processing, Curation
TA14	Thermal Management Systems	RTA System Thermal Control	Deployment, Servicing, Cleaning
TA15	Aeronautics	RTA System Delivery	Robotic Systems, Autonomy

independent from Earth and robotic missions more capable.

4. NATIONAL RESEARCH COUNCIL REPORT

An earlier version of this document was issued publicly in December, 2010. NASA subsequently tasked the Aeronautics and TA04-26 Space Engineering Board of the National Research Council (NRC) of the National Academies to perform the following tasks:

- **Criteria:** Establish a set of criteria to enable prioritization of technologies within each and among all of the technology areas that the NASA technology roadmaps should satisfy;
- **Technologies:** Consider technologies that address the needs of NASA's exploration systems, Earth and space science, and space operations mission areas, as well as those that contribute to critical national and commercial needs in space technology;
- **Integration:** Integrate the outputs to identify key common threads and issues and to summarize findings and recommendations; and
- **Prioritization:** Prioritize the highest-priority technologies from all 14 roadmaps.

In addition to a final report that addressed these tasks, NASA also tasked the NRC/ASEB with providing a brief interim report that "addresses high level issues associated with the roadmaps, such as the advisability of modifying the number or technical focus of the draft NASA roadmaps."

In August, 2011, the NRC/ASEB delivered *"An Interim Report on NASA's Draft Space Technology Roadmaps"* which, among other things, verified the adequacy of the fourteen Technology Areas as a top-level taxonomy, proposed changes in the technology area breakdown structure (TABS) within many of the TA's, and addressed gaps in the draft roadmaps that go beyond the existing technology area breakdown structure.

On February, 1, 2012, the NRC/ASEB delivered the final report entitled *"NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space"*.

The report prioritizes (e.g., high, medium, low) the technologies within each of the 14 Technology Areas, and also prioritizes across all 14 roadmaps [highest of the high technologies].

The remainder of this section summarizes:

- The changes that the NRC recommended to the 2010 TA04 TABS. This 2012 revision of the TA04 roadmap document includes the updated TABS and has been modified to address those updates.
- The NRC prioritization of the technologies in this TA, as well as highlights any of this TA's technologies that the NRC ranked as a 'highest of high' technology.
- Salient comments and context, quoted verbatim, from the NRC report that provide important context for understanding their prioritization, findings, or recommendations.

4.1. NRC Recommended Revisions to the TABS

The NRC observed that the initial draft of the TABS had some entries that prescribed technical solutions, rather than needed capabilities, that the supporting roadmap text was not adequately linked to the level 3 technologies in the TABS, and that there were some gaps in the list of level 3 technologies in the roadmap. The NRC's recommendations have been adopted in this revision. The current TABS closely matches that proposed by the NRC, with a few variations in the level 3 technology lists that are in spirit with the NRC's recommendations but address problems perceived by the NASA TA-04 team. For example, 3-D perception is a critical capability in most robot sensing and perception systems, so much so that this warranted explicit listing among the level 3 technologies. Also, the NRC's suggested "Mobile Feature Tracking and Discrimination" technology described a capability that is already at TRL 9 in the Mars Exploration Rover mission.

The NRC's list of the top six technical challenges includes at least two (Hazard Avoidance, Object Recognition and Manipulation) that require large computational throughput. Figure G.3 on page G-10 of the report lists Onboard Computing as having moderate linkage to Hazard Avoidance and weak to no linkage to Object Recognition and Manipulation. The team believes that the linkage is strong in both cases. The discussion of Onboard Computing on page G-19 of the report ascribes it medium priority for a number of reasons, including that "so many other agencies and commercial entities are working on it that NASA's contribution would be relatively small." The TA-04 team notes that relatively modest investments by NASA in this area can have dramatic and enabling impact on mission capabilities. For example, exploiting high performance, low power, field programmable gate arrays have made a difference of 2 to 3 orders of magnitude in the performance

Table 2. *NRC Prioritization of TA04 Level 3 Technologies*

Section	Title	Comments
4.6.2	Guidance Algorithms	High Priority
4.6.3	Docking and Capture Mechanisms/Interfaces	High Priority
4.5.1	Vehicle System Management & FDIR	High Priority
4.3.2	Dexterous Manipulators (including robot hands)	High Priority
4.4.2	Supervisory Control (including time delay supervision)	High Priority
4.2.1	Extreme Terrain Mobility	High Priority
4.3.6	Robotic Drilling and Sample Handling	High Priority
4.2.4	Small Body / Microgravity Mobility	High Priority (QFD Score Override from Medium Priority)
4.3.5	Collaborative Manipulation	Medium Priority
4.1.5	Multi-Sensor Data Fusion (covered under Sensor Fusion for Sampling & Manipulation)	Medium Priority
4.7.3	Onboard Computing	Medium Priority
4.7.2	V&V of Complex Adaptive Systems	Medium Priority
4.5.5	Adjustable Autonomy	Medium Priority
4.5.3	Autonomous Guidance & Control	Medium Priority
4.4.7	Safety, Trust, and Interfacing of Robotic/Human Proximity Operations	Medium Priority
4.1.1	Vision- Including Active Illumination (covered under 3D Perception)	Medium Priority
4.5.2	Dynamic Planning & Sequencing Tools	Medium Priority
4.4.1	Multi-Modal Human-Systems Interaction	Medium Priority
4.4.5	Distributed Collaboration	Medium Priority
4.7.1	Modularity/Commonality	Medium Priority
4.6.1	Relative Navigation Sensors	Medium Priority
4.5.4	Multi-Agent Coordination	Medium Priority
4.5.6	Terrain Relative Navigation	Medium Priority
4.3.4	Mobile Manipulation	Medium Priority
4.1.2 & 4.1.3	Localization and Mapping (covered under Relative Position & Velocity Estimation as well as Terrain Mapping Classification & Characterization)	Medium Priority
4.1.5	Tactile Sensing (included under Sensor Fusion for Sampling & Manipulation)	Medium Priority
4.2.3	Above-Surface Mobility	Medium Priority
4.1.3	Terrain Classification and Characterization (covered under Terrain Mapping Classification & Characterization)	Medium Priority
4.2.2	Below-Surface Mobility	Low Priority
4.4.6	Common Human-Systems Interfaces	Low Priority
4.5.7	Path & Motion Planning with Uncertainty	Low Priority
4.1.3	Natural Feature Image Recognition (covered under Natural & Man-made Object Recognition)	Low Priority
4.1.2	Mobile Feature Tracking and Discrimination (this is largely a solved problem, but is subsumed by relative position and velocity estimation)	Low Priority
4.3.1	Robot Arms	Low Priority
4.3.3	Modeling of Contact Dynamics	Low Priority
4.4.3	Robot-to-Suit Interfaces	Low Priority
4.1.2	Pose Estimation (covered under Relative Position & Velocity Estimation)	Low Priority
4.4.4	Intent Recognition and Reaction	Low Priority

of vision systems for Mars rovers, compared to existing flight computers. Similarly, exploiting advanced computing architectures is critical to enabling perception systems for precision landing and landing hazard avoidance. In research outside of NASA, on object recognition and manipulation for terrestrial application, high performance computing has been essential to enabling progress.

4.2. NRC Prioritization

The TA04 Roadmap is divided into 37 Level 3 technologies, and, like some other TAs, they typically encompass a variety of systems, subsystems, and components, with multiple potential design solutions. Table 2 lists the overall NRC Panel rankings for the 38 TA04 Level 3 technologies, 8 of which they assessed as “high priority”. Seven of the eight received this designation based on their Quality Function Deployment evaluation scores, which significantly exceeded the scores of lower ranked technologies. The Panel later designated one additional technology as high priority, recognizing the evaluation process alone could not fully assess a given technology’s importance.

4.3. Additional / Salient Comments from the NRC Reports

To place the priorities, findings, and recommendations in context for this TA, the following quotes from the NRC reports are noteworthy:

- "Top Technical Challenges for Technology Objective B (Explore the evolution of the solar system and the potential for life elsewhere)" TA04-28 include "Precision Landing: Increase the ability to land more safely and precisely at a variety of planetary locales and at a variety of times" and "Robotic Maneuvering: Enable mobile robotic systems to autonomously and verifiably navigate and avoid hazards and increase the robustness of landing systems to surface hazards."
- "NASA’s future capabilities would also benefit greatly from new technologies to build robotic vehicles that can maneuver over a wider range of gravitational, environmental, surface, and subsurface conditions with a sufficient degree of autonomy to enhance operation at large distances from Earth."
- "The ability to perform autonomous rendezvous and safe proximity operations and docking/grappling are central to the future of diverse mission concepts. Major challenges include improving the robustness of the rendezvous and capture process to ensure successful capture."
- "Current rovers cannot access extreme lunar or Martian terrain, eliminating the possibility of robotic access and requiring humans to park and travel on foot in suits. Locomotion techniques in microgravity on or near asteroids and comets are undeveloped and untested. Challenges include developing robotics to travel into these otherwise denied areas, developing techniques to grapple and anchor with asteroids and non-cooperative objects, or building crew mobility systems to move humans into these challenging locations."
- "A top astrobiological goal and a fundamental NASA exploration driver is the search for life or signs of previous life in our solar system. A significant planetary science driver exists to obtain unaltered samples (with volatiles intact) for either in situ analysis or return to Earth from planetary bodies. Terrestrial drilling technologies have limited applicability to these missions and robotic planetary drilling and sample handling is a new and different capability."
- "Due to the large computational throughput requirements needed to quickly assess subtle terrain geometric and non-geometric properties fast enough to maintain speeds near vehicle limits, robotic systems lag behind the ability of human drivers to perceive terrain hazards at long range."
- "More effective and safe human interaction with robotic systems has a number of different focuses which range from the potential dangers of proxemic interactions to remote supervision with or without time delays. Remote interactions with robotic systems do not pose the same immediate potential level of danger to humans as close proximity interactions; however, it is often significantly more difficult for a remote human to fully understand the context of the environment in which the robotic system functions and the status of the system."
- "Object recognition requires sensing, and requires a perception function that can associate the sensed object with an object that is understood a priori. Sensing approaches to date have combined machine vision, stereo vision, LIDAR, structured light, and RADAR, while perception approaches often start with CAD models or models created by a scan with the same sensors that will later be used to identify the object. Major challenges include the ability

to work with a large library of known objects, identifying objects that are partially occluded, sensing in poor lighting, estimating the pose of quickly tumbling objects, and working with objects at near and far range. Robotic hands with equivalent or superior grasping ability to human hands would avoid the added complexity of robot interfaces on objects and provide a sensate tool change-out capability for specialized tasks."

- "Relative guidance technologies encompass algorithms that determine the desired trajectories to be followed between vehicles performing rendezvous, proximity operations, and/or docking and capture. These algorithms must anticipate applicable environmental effects, the nature of the trajectory change/attitude control effectors in use, and the inertial and relative navigation state data available to the guidance algorithms. The new Level-3 technologies of interest provide real-time, onboard algorithmic functionality that can calculate and manage spacecraft maneuvers to achieve specific trajectory change objectives. Relative guidance aligns well with NASA's needs because it impacts crewed deep-space exploration, sample return, servicing, and orbital debris mitigation."
- "Docking and capture mechanisms enable the physical capture and attachment as well as subsequent safe release, of two bodies in space that achieve part of their mission objectives when operating while joined. Development of a physical docking and capture interface for AR&D operations would greatly simplify the control demands for a working AR&D system. This technology will improve reliability of AR&D and enable new interfaces that can be employed. Variations of docking and capture mechanisms enable transfer of crew between delivery and destination vehicles, provide means for attachment of added equipment modules, facilitate execution of robotic servicing missions, and potentially enable TA04-30 grapple/capture of inactive, possibly tumbling spacecraft."
- "The panel combined the related and overlapping topics of integrated systems health management (ISHM), fault detection and isolation and recovery (FDIR), and vehicle systems management (VSM), which together provide the crucial capability for an autonomous spacecraft to operate safely and reliably. ISHM/FDIR/VSM will improve the reliability of future missions by providing a diagnostic capability that helps ground or crew failure assessment and an automated capability to fix/overcome faults; increase robotic mission flexibility in response to failures; and increase crew safety in the event of a detected need for crew escape and abort. This technology is highly aligned to NASA's needs because it will impact many missions, such as deep space exploration, robotic science missions, planetary landers and rovers."
- "Dexterous manipulation is a system-level technology that encompasses multiple stand-alone technology areas, and has high relevance for several current and future NASA applications including: servicing and maintenance of the ISS, remote satellite servicing, on-orbit assembly of larger structures, and applications to remote exploration. Since 1997, NASA has focused on the development of Robonaut which is now being evaluated on the ISS and approaches the dexterity of a suited astronaut. Development activities to date have focused primarily on human-in the- loop teleoperation and limitations of this system do exist from high bandwidth, low latency communications requirements. NASA could explore options for extending Robonaut technologies and capabilities for operations in large latency and low bandwidth environments. Additionally, the size and weight of Robonaut preclude its use for exploration activities and NASA could benefit from the development of novel actuation technologies that dramatically increase the strength to weight ratio."
- "Supervisory Control is defined as incorporating the techniques necessary for controlling robotic behaviors using higher-level goals instead of low-level commands, thus requiring robots to have semi-autonomous or autonomous behaviors. This increases the number of robots a single human can simultaneously supervise and also incorporates time-delayed supervision. Key components to be addressed include the development of robust high-level autonomous behaviors and control, multi-sensor fusion, clearly understood and usable presentations of information from multiple robots for human understanding, time-delayed interpretation and presentation of robot provided information, haptic feedback, and means for a supervisory control system to handle communication outages. This technology is highly aligned to

NASA's needs due to the impact of reducing the number of personnel required to supervise robotic missions and the number of science and exploration missions to which the technology can be applied."

- "Robotic Drilling and Sampling Processing technologies (RDSP) will improve the science return of robotic science missions to small bodies, moons, and planets, and will also benefit in situ resource utilization for human spaceflight to the moon and small bodies. The development of new robotic drilling, drill-like, and coring technologies coupled with sample processors will have a major beneficial impact on the quality of planetary science returned by future missions due to the relatively uncontaminated, unaltered, and volatile-rich nature of the samples acquired by the next generation of RDSP technology."
- "Extreme mobility encompasses all ground or surface level mobility. Extremely mobile platforms will be a critical component to both the success and diversity of extraterrestrial body exploration and determining the terrain that will be traversed. In addition, higher degrees of mobility serve to compliment autonomy. This technology provides NASA with the capability to maneuver its surface vehicles in extreme terrain in order to "follow the water" – a high-priority science focus for Mars and lunar science missions, and is applicable to any exploration mission, human or robotic, to a planetary (or lunar) surface."
- "Operating robots in microgravity poses many challenges and is particularly difficult without fixing or tethering to grounded structures. Even simple tasks such as turning a screw can be extreme challenges to mobile platforms that are not attached to other structures. The development of adaptive mobility systems with complimentary perception and autonomy are key elements to performing exploration and sample return missions in tight spaces TA04-31 and microgravity environments. Variable or dynamic CG capabilities can greatly enhance the ability of platforms to move around and perform meaningful work by dynamically shifting the CG in conjunction with the motion of vehicles. This technology is well aligned with NASA's goals related to the exploration of small bodies both robotic and with crew, making this a critical technology for future missions; therefore, the panel designated this as a high-priority technology because the NASA 2010 Authorization Act (P.L. 111-267) has indicated that small body missions (to near-Earth asteroids) should be an objective for NASA human spaceflight beyond Earth orbit. If this goal is pursued as a high NASA priority, it would likely also require precursor robotic missions to small body surfaces with applicable mobility capability."
- "In the case of much longer missions to the Moon than previously attempted, and ultimately Mars, enhanced surface mobility at all levels will improve the science return of exploration missions. A comprehensive program of geological exploration needs access to high slopes, loose and unstable surfaces, and the subsurface access via drilling or excavation. Technology issues such as wheel-soil interactions, optimum mobility platform design, and high-reliability mechanisms with high tolerance for dust and exposure to extreme environments must be addressed."

ACRONYMS

AERCam	Autonomous EVA Robotic Camera
ARC	Ames Research Center
AR&C	Autonomous Rendezvous and Capture
AR&D	Autonomous Rendezvous and Docking
ARMD	Aeronautics Research Mission Directorate
ATHLETE	All Terrain Hex-Limbed Extra Terrestrial Explorer
ATP	Authority to proceed
ATV	Autonomous Transfer Vehicle
ATLAST	Advanced Technology Large-Aperture Space Telescope
CNSR	Comet Nucleus Sample Return
CoP	Community of Practice
CSSR	Comet Surface Sample Return
CTV	Crew Transfer Vehicle
EDL	Entry Descent and Landing
EEG	Electroencephalography
EEV	Earth Entry Vehicle
EMG	Electromyography
ESA	European Space Agency
ESMD	Exploration Systems Mission Directorate
ETS-VII	Engineering Test Satellite 7
EVA	Extra Vehicular Activity – activities performed in space, outside the spacecraft
FSW	Flight Software
DPP	Dexterous Pointing Payload
DRM	Design Reference Mission
FDIR	Fault Detection Isolation and Recovery
FPGA	Field Programmable Gate Array

FSW	Flight Software
G&C	Guidance and Control
GEO	Geosynchronous Earth Orbit
GN&C	Guidance, Navigations and Control
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HEFT	Human Exploration Framework Team
HEO	High Earth Orbit
HRP	Humanoid Robotics Project
HST	Hubble Space Telescope
HTV	H-II Transfer Vehicle
ILIDS	International Low Impact Docking System
IMU	Inertial Measurement Unit
IR	Infrared
ISS	International Space Station
ISHM	Intelligent Systems Health Monitoring
IVA	Intra Vehicular Activity – activities performed inside a spacecraft or vehicle
JEM-RMS	Japanese Experimental Module Remote Manipulator System
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
LIDS	Low Impact Docking System
MAV	Mars Ascent Vehicle
MER	Mars Exploration Rover
MFD	Manipulator Flight Demonstration
MMU	Manned Maneuvering Unit
MSL	Mars Science Laboratory
MSR	Mars Sample Return
MMSEV	Multi Mission Space Exploration Vehicle
MPCV	MultiPurpose Crew Vehicle
NASA	National Aeronautics and Space Administration
NEA	Near Earth Asteroid
NEAR	Near Earth Asteroid Rendezvous
NEO	Near Earth Object
NRE	Non-Recurring Engineering
OCT	NASA's Office of the Chief Technologist
OCAMS	Orbital Communication Adapter Modeling System
ORU	Orbital Replacement Unit
OTCM	ORU Tool Change-out Mechanism
R2	Robonaut 2
R2D2	Robotic Refueling Dexterous Demonstration
RAPID	Robot Application Programming Interface Delegate
RCS	Reaction Control System
RF	Radio Frequency
RMCT	Robotic Micro Conical Tool
RMS	Remote Manipulator System
RPOD	Rendezvous, Proximity Operations, and Docking
ROTEX	Robotics Experiment
RTAs	Robotics, Tele-Robotics and Autonomous systems
RWS	Robotics Workstation Software
SAFER	Simplified Aid For EVA Rescue
SMD	Science Mission Directorate
SOMD	Space Operations Mission Directorate
SPDM	Special Purpose Dexterous Manipulator
SRMS	Shuttle Remote Manipulator System
SRV	Sample Return Vehicle
SSRMS	Space Stations Remote Manipulator System
TA	Technology Area
TABS	Technology Area Breakdown Structure
TASR	Technology Area Strategic Roadmap
TRL	Technology Readiness Level
TRN	Terrain Relative Navigation
TSSM	Titan Saturn System Mission
UAV	Unmanned Aerial Vehicle
V&V	Verification and Validation
VSM	Vehicle System Management
VME	Venus Mobile Explorer
WBS	Work Breakdown Structure

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