AUTONOMY GAP ASSESSMENT REPORT

5/15/2020

International Space Exploration Coordination Group

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The Autonomy Gap Assessment Team would like to acknowledge key contributors to this report. Their assistance as subject matter experts was invaluable in conducting the gap assessment and completing this report.

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***ESA:** Special thanks to Alessandro Bergamasco, who also served as co-chair for the Autonomy Gap Assessment Team.*

EXECUTIVE SUMMARY

Communication gaps and time delays necessitate that capabilities for autonomy enable the crew to interact with the spacecraft and mission support systems/infrastructure in order to conduct operations during nominal and off-nominal conditions, independent of assistance from Earth-based support teams. Capabilities for autonomy must also sense, perceive, reason and act in order to safely and reliably control the spacecraft and mission support systems/infrastructure.

In-space, maturation of decision support tools and computing architectures to enable crew autonomy are progressing within a few space agencies but can be accelerated through collaboration. Advances in electronics, computing architectures and software that enable autonomous systems capabilities which interact with humans in terrestrial applications can be leveraged from commercial markets to support collaborative efforts among space agencies and commercial providers to further develop, integrate and mature capabilities for operations beyond low-Earth orbit. Collaboration among the space industry and defense agencies, as well as partnerships with commercial providers, are needed to:

- develop affordable, radiation-hardened electronics;
- mature capabilities in perception and reasoning in order to recognize and mitigate loss of control; and
- ensure data integrity and security of electronic assets in the extreme environment of space.

Four key recommendations were formulated:

RECOMMENDATION 1: COMMUNICATE GUIDELINES, CONVENTIONS AND STANDARDS

It is recommended that the International Space Exploration Coordination Group (ISECG) ensure communication of guidelines, conventions and standards for autonomous systems among the partner agencies to facilitate integration of hardware and software elements, ensure technical and operational interoperability, and facilitate sustainability.

RECOMMENDATION 2: ENABLE ROUTINE ASSESSMENT OF AUTONOMY TECHNOLOGY GAPS

In order to keep up to date with the identified technology gaps and the proposed actions for closure, it is recommended to support a continuous assessment by the ISECG Autonomy Gap Assessment Team (GAT).

RECOMMENDATION 3: ESTABLISH COMMERCIAL PARTNERSHIPS

Establish strong partnerships with commercial industry to plan technology development and demonstration activities to advance capabilities and meet Global Exploration Roadmap (GER) goals for autonomy.

RECOMMENDATION 4: PLAN AND CONDUCT TECHNOLOGY DEMONSTRATIONS

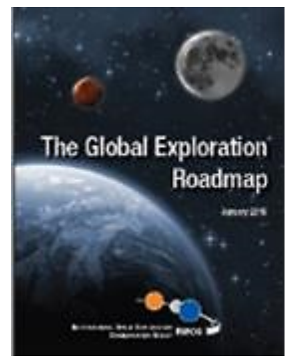
Partners should assess the technology demonstration possibilities identified within this Autonomy Gap Assessment Report and formulate plans to mature, assess and enhance technologies during each stage of the mission scenario.

1. BACKGROUND

The ISECG formed two gap assessment teams to evaluate topic discipline areas that traditionally had not been worked at an international level to date. Accordingly, the ISECG Technology Working Group (TWG) recommended two discipline areas based on Global Exploration Roadmap (GER) critical technologies needs reflected within the GER Technology Development Map (GTDM); the first topic being Telerobotic Operations with Time Delay and the second topic being Autonomy. The ISECG approved the recommended gap assessment teams and tasked the TWG to formulate the new teams using Subject Matter Experts (SME) from the participating agencies.

The ISECG Gap Assessment Team for the topic discipline Autonomy consisted of SMEs from the following participating agencies: The *Centre National d'Etudes Spatiales* (CNES); The Canadian Space Agency (CSA), Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR); The European Space Agency (ESA); The Japan Aerospace Exploration Agency (JAXA); and the National Aeronautics and Space Administration (NASA).

2. GOALS AND OBJECTIVES



In January 2018, ISECG published the third version of the Global Exploration Roadmap document, reaffirming the interest of 14 space agencies in expanding the human presence into the solar system, with the surface of Mars as a common driving goal. The document provides a common view on how, using the International Space Station (ISS) as a starting point, future space exploration missions will aim at extending the human presence in the lunar vicinity, on the lunar surface, and then on Mars.

Each step in expanding the human presence beyond Low-Earth Orbit (LEO) relies on the readiness of new capabilities and technologies.

The TWG identified a number of critical technologies, autonomy being one, related to the missions envisioned in the GER, which are currently not available or need to be developed or matured. The Autonomy GAT will address the identified technology needs and inform the ISECG on technology gaps that must be addressed in order to implement the foreseen missions beyond LEO.

The assessment will provide valuable information to individual space agencies:

- Highlight and substantiate existing gaps
  - Detailed analysis will inform space agencies and support long-term planning
- Create international dialogue among experts
  - Support agency decisions to increase investment in exploration technologies
  - Identify collaboration opportunities

The objectives established for the Autonomy GAT by the ISEGC TWG include:

- Identifying the key tasks/questions to be addressed, in coordination with the International Architecture Working Group (IAWG) and using the GER architecture details and performance metrics
- Reviewing the existing GTDM and portfolio entries and determining what updates are needed, if any, to the current GTDM portfolio of technology development activities to reflect the activities and interests of the respective agencies
- Conducting a gap analysis for the identified critical technologies and capabilities in the GER Technology Portfolio
- Identifying options (e.g., key technology/engineering solutions) for closing the technology gaps
- Identifying key technology development milestones (e.g., technology demonstrations, analogue deployments, cis-lunar space test demonstrations) to close the identified gaps (optional objective)
- Identifying opportunities for international partnership, coordination, and collaboration to close the identified gaps
- Producing an Autonomy Gap Assessment Report
- Delivering a presentation and paper identifying the GER critical technology needs (21, 23, and 49) and summarizing the technology gaps.

3. APPROACH

Initial discussions revealed an overlap between the Autonomy and Telerobotics gap assessment teams in the area of robotic autonomy (e.g., mobility, motion, etc.) and responsibility for the gap assessment in this area was transferred to the Telerobotics GATs.

The Autonomy GAT formulated and executed the following approach to meet the ISECG's gap assessment objectives:

1. Review GER mission scenario
2. Review agency capabilities related to the critical technology needs (GERs 21, 23 and 49)
3. Develop a taxonomy for autonomy
4. Formulate examples of key aspects of autonomy related to the critical technology needs
5. Formulate a methodology for conducting the gap assessment
6. Conduct the gap assessment
7. Identify critical and cross-cutting technology gaps
8. Identify opportunities for partnering and private sector involvement
9. Formulate key findings and recommendations

4. MISSION SCENARIO

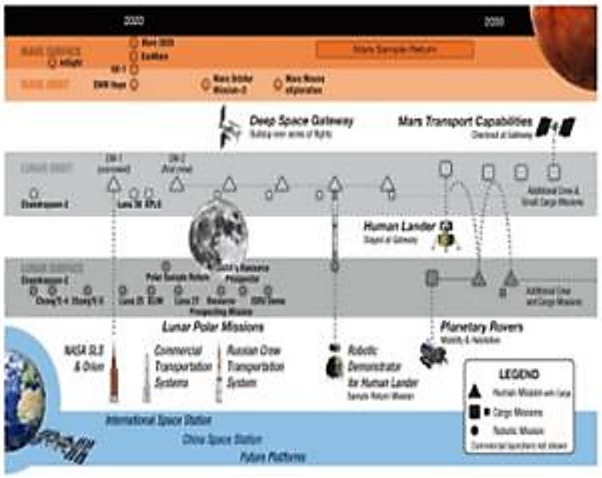


FIGURE 1: GER MISSION SCENARIO

The GER defines mission scenarios (Figure 1) in which human and robotic missions contribute to achieving a sustainable exploration on Mars.

LOW-EARTH ORBIT (LEO)

As a long-duration flight analogue, the ISS is a key element in preparing for the mission beyond LEO. In fact, the ISS provides a variety of equipment and systems to support the mission:

- advanced research (life sciences, physical sciences and materials science research)
- technology development and verification
- systems and subsystems test and maturation (i.e. advanced ECLSS)
- operational concepts validation.

LUNAR VICINITY: THE MOON ORBITS AND SURFACE

The Deep Space Gateway (DSG) is the next element of the architecture that enables a sustainable and affordable future for human space exploration. It is a transit habitat that will primarily reside in a Near-rectilinear Halo Orbit (NRHO) in cis-lunar space (with the exception of planned excursion missions). The DSG is essential to the lunar surface architecture as it will enable lunar surface access and act as a waypoint for ISECG's lunar surface campaign.

- It will be assembled throughout the 2020s by NASA's exploration missions with Orion and the Space Launch System (SLS), using ~10 metric tons modules
- Crew presence: minimum 30 days that may increase as the Gateway evolves and additional transportation systems become available (up to 1 year for a Mars demo missions)

Key autonomy-related considerations for this scenario are:

- in-space assembly of the habitat
- demonstration of the habitat's transit capabilities with orbital transfers
- use of the habitat as a waypoint for planetary body access
- autonomous crew and spacecraft operations (both extended inhabited and uninhabited periods with a crew visit frequency of 1 to 2 years)

ROBOTIC DEMONSTRATOR FOR HUMAN LANDING MISSION

The robotic demonstrator mission (Figure 2) is expected to be launched approximately four years prior to the return of humans to the lunar surface, with the objective to flight-demonstrate critical components of the human campaign (lander and rover).

The robotic demonstrator will take advantage of the DSG presence:

- to validate ascent, approach and Rendezvous & Docking (RvD) operations with the Gateway
- to demonstrate reusability aspects
- to retrieve the lunar samples via DSG robotic means and return them to Earth with the Orion.

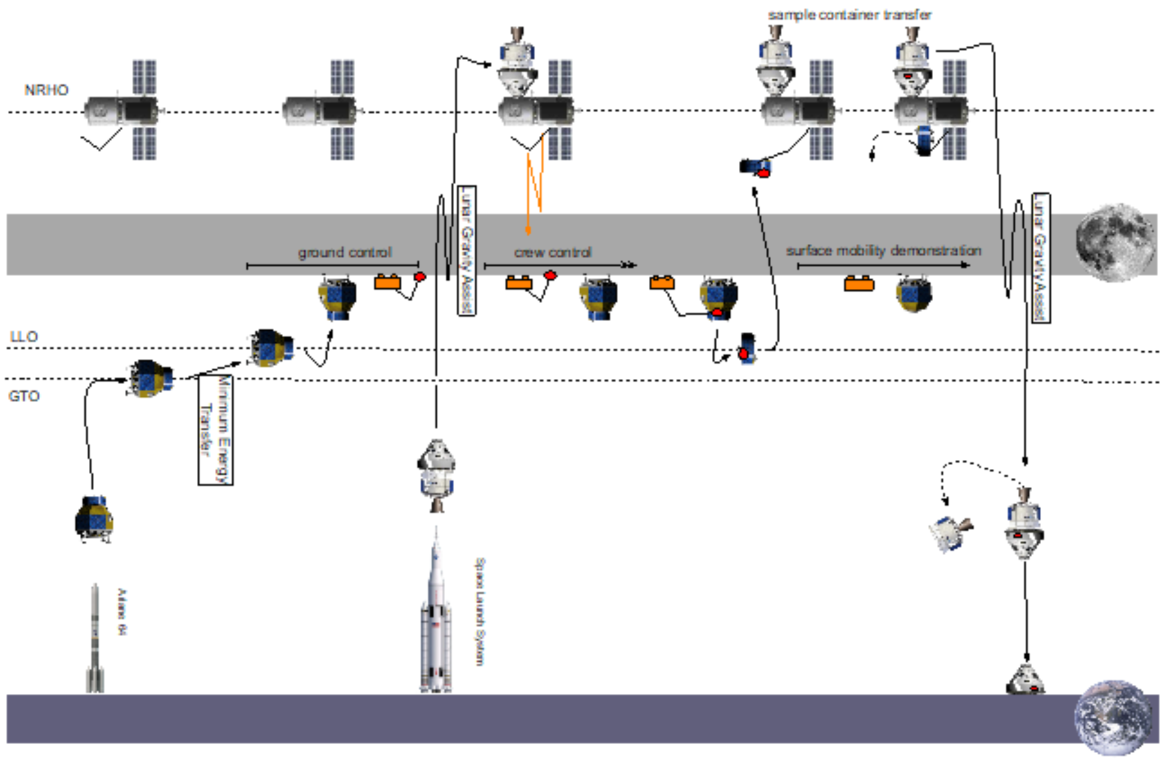


FIGURE 2: ROBOTIC DEMONSTRATOR FOR HUMAN LANDING MISSION

The entire mission comprises a 70 d (TBC) circular path for sample collection and return with Lunar Ascent Element, followed by a one-year rover mission to explore the connection between the interior of the Schrödinger basin and the south polar region.

A high-level concept of operations identifies the requirements for autonomy, as listed in Table 1.

TABLE 1: OPERATIONS REQUIREMENTS FOR AUTONOMY

Operation Type	Requirements for Autonomy
Landing Operations	Autonomous
Ascent Operations	Autonomous, started by a mission control center command
Lunar Departure Orbit Operations and Transfer to Habitat	Supervised and guided by the mission control center
Berthing Operations	Performed by either the mission control center or the crew onboard the DSG
Rover Operations	Three phases 1. operated from Earth 2. teleoperated from NRHO 3. autonomous traverse and sampling

HUMAN LUNAR SURFACE SCENARIO

The envisioned Human Lunar Surface campaign is a DSG-enabled, multiple-mission (5), extended range exploration architecture:

- A SLS Block 1B launcher will be used to inject the partially reusable Human Lunar Lander toward the DSG, where it will autonomously perform the necessary RvD maneuvers.
- Starting from the second mission, the ascent stage will be reused (via refueling and refurbishment) while the descent stage and the fuel for the ascent will be delivered by an SLS Block 1B launcher. In this case, the descent stage will be asked to autonomously perform the RvD maneuvers.
- The crew will arrive at the DSG onboard the Orion vehicle as previously done during the DSG extended duration phase.
- With four crew members aboard, the lander will leave the DSG and perform the descent and landing maneuvers (operated/supervised by the crew).
- On the surface, the astronauts will ingress two pre-deployed pressurized lunar rovers and perform the 42-day mission.
- At the end of the surface mission, the crew will ingress the ascent stage, ascent toward the DSG, and perform/supervise approach and RvD maneuvers with the DSG.
- The two Pressurized Lunar Rovers (PLRs) will then autonomously relocate to the next landing site.

The considerations for autonomy to support this mission scenario are:

- The crew's primary responsibility while onboard the DSG is to prepare for their lunar surface mission (reduced time for DSG-related operations).
- The lunar descent stage should be able to autonomously perform orbital and RvD maneuvers.
- The rover shall be able to autonomously relocate between missions.
- To maximize the Extra Vehicular Activity (EVA) activity (and minimize maintenance), the PLR should ensure autonomous vehicle monitoring.
- The reusable ascent shall guarantee autonomous vehicle monitoring and operation validation (i.e. maintenance, refueling, etc.) between missions.
- Astronauts EVA activity should become more and more independent from Earth ground segment control.

HUMAN MARTIAN SURFACE SCENARIO

Currently, a robotic demonstrator has not been identified for human landing mission on Mars. Space agencies are, however, beginning to develop the different technologies needed to send humans to Mars in the 2030s. Different approaches have been proposed based on a direct mission from Earth, or using in-orbit capabilities, potentially on the Moon, however a mission architecture is not yet fixed.

The considerations for autonomy to support this mission scenario are provided through the following examples:

- Vehicle autonomy: highly automated Guidance, Navigation, and Control (GNC) for the transportation system.
- Crew autonomy: an automated planning system for crew activities.
- Crew health and performance and crew safety and intervention: These aspects become more critical in a deep space mission. As an example, while an ISS astronaut can be brought back to Earth in a matter of hours, a Mars mission might need several months, which makes a timely evacuation effectively impossible and enforces the need of much more complex health/safety capabilities onboard.
- Robotic caretakers: robotic systems used for EVA repairs might play a very important role.
- Food production and stowage management: Due to the early state of the mission concept, logistics such as food provision are not yet properly evaluated. However, a crewed Mars mission represents the perfect study case.

5. CRITICAL TECHNOLOGY NEEDS

Three capability areas were identified as critical for implementing the GER mission scenario.

Autonomous Vehicle Systems Management (GER 21) enables autonomous vehicle management with limited crew effort and little or no ground oversight. This autonomous capability is required to ensure safe vehicle operations and monitoring of complex systems, especially at increased distances from Earth, where communications time delays are present.

Performance Characteristics:

- Enable onboard vehicle systems management for mission critical functions at destinations with > 3-second time delay
- Enable autonomous nominal operations and Fault Detection, Isolation and Recover (FDIR) for crewed and un-crewed systems
- Reduce onboard crew time to sustain and manage vehicle by factor of 2x at destinations with > 6-second time delay (see Crew Autonomy sheet)
- Reduce Earth-based mission ops "back room engineering" requirements for distant mission support delay (see Mission Autonomy sheet)

Crew Autonomy beyond LEO (GER 23) includes autonomous crew operations (planning, commanding, fault recovery, maintenance) in beyond LEO missions and systems and tools to provide the crew with independence from Earth-based ground operations support. Enabling crew autonomy is essential to accommodating ground communication delays and blackouts between Earth and distant locations beyond LEO.

Performance Characteristics:

- Enable crew nominal operation of vehicle or habitat at destinations with > 6-second time delay to ground
- Enable coordinated ground and crew nominal operations at destinations with > 6-second time delay (See Mission Control Automation Sheet)
- Enable crew to detect off nominal situations and put vehicle in safe configuration without ground coordination

Mission Control Automation beyond LEO (GER 49) supports missions beyond LEO in problem solving activities during remote or long-duration exploration missions, where space crew reliance on mission control is critical and dependent upon minimum reaction time. Advanced decision-support systems are needed in Mission Control to reduce operations costs and to maximize mission safety with Earth-based operators.

Performance Characteristics:

- Enable Earth-based nominal operation of vehicle or habitat at destinations with > 6-second round-trip time delay to Earth
- Enable handoffs in Mission Ops between ground and crew for operations in transit and at destinations with > 6-second round-trip time delay
- Enable Tools to help Flight Controllers resolve off nominal situation after detection and initial response
- Enable highly efficient, small staff Earth-based Mission Control for beyond LEO crewed missions

The aspects of autonomy needed to support this mission scenario are the same as those identified for the human Martian surface scenario:

- Vehicle autonomy
- Crew autonomy
- Crew health and performance
- Crew safety
- Robotic caretakers
- Food production and stowage management

6. AUTONOMY TAXONOMY

The Autonomy GAT revised a taxonomy and the definitions originally devised by NASA to use in categorizing and mapping technology gaps. The taxonomy consists of four Level 1 functions and fourteen Level 2 functions that are performed when enabling crew autonomy or implementing system autonomy. Figure 3 is a graphical depiction of the taxonomy.

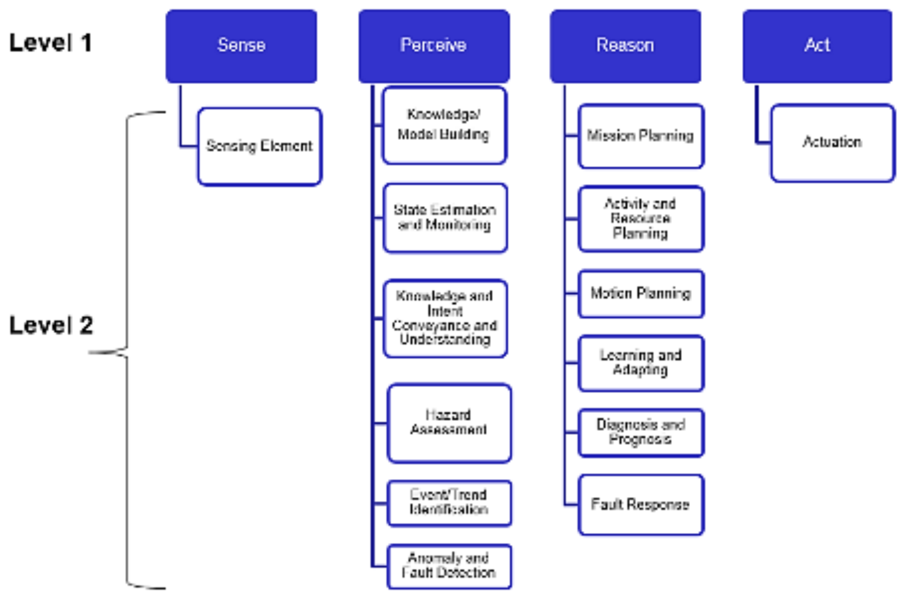


FIGURE 3: TAXONOMY-1 FOR AUTONOMY

Figure 4 provides definitions for the functions in Taxonomy-1.

Sense	**Interrogation, identification, processing, and evaluation of the internal state of a system or its external environment and assessment of its ability to achieve goals and objectives. to a performing defined task, activity, function, requirement, or mission.**
1) Sensing element	1) A function or mechanism that receives and responds to external or internal stimuli.
Perceive	**The ability to identify, process, and evaluate situations that are internal (state) or external (environment) to the system related to a performing defined task, activity, function, requirement, or mission.**
1) Knowledge/Model Building	1) Aggregation information from multiple sources across time to form a model of the system or environment to allow forecasting and planning.
2) State Estimation and Monitoring	2) Estimating internal or external state from multiple raw or processed sensor/instrument input, ascertain, and compare on an on-going basis to the expected state(s).
3) Knowledge and Intent Conveyance and Understanding	3) The collecting, assembly, communication, sharing, and comprehension of information and intent about a domain among entities that can be used to solve problems and plan actions and response.
4) Hazard Assessment	4) Assessment of whether the environment or system state, poses a threat to safety or successful achievement of goals. The ability to assess the environment, internal state, and/or interaction to determine the safety of actions or inactions that are contemplated. The ability to assess the environment, state, and/or interaction and determination is safety or goal success may be compromised by possible responses.
5) Event/Trend Identification	5) The analysis of data sets to identify events and trends that may affect future state, operations, or decision making.
6) Anomaly and Fault Detection	6) The determination that a system or environment is not performing as expected.

Reason	**Formulation of the step(s) or action(s) needed to achieve a defined mission, goal, objective, task, function, or requirement based on the current perceived state and environment.**
1) Mission Planning	1) The ability of a system to employ *strategic decision making* about mission level goals or objectives to plan activities to optimize chances of mission success.
2) Activity and Resource Planning	2) The ability of a system to plan tasks and activities, based on procedures or other knowledge, to be achieved by system components and to manage system resources, subject to constraints, in order to achieve the task or activity.
3) Motion Planning	3) Generation and modification of a path or trajectory within system/environmental constraints to optimize the likelihood of reaching a desired target.
4) Learning and Adapting	4) The ability of a system to learn from past or other systems' experiences and adjust to changing environments and conditions without explicit re-programming.
5) Diagnosis and Prognosis	5) Assessment of the current health state of a system, including the identification of faults, and provide a prediction of its future health state.
6) Fault Response	6) The ability to restore nominal operations after a fault, if possible, or to derive an acceptable alternative goal.
Act	**Execution of the step(s) or action(s) needed to achieve a defined mission, goal, objective, task, function, or requirement.**
1) Actuation	1) The process of moving or controlling a mechanism or system.

FIGURE 4: TAXONOMY-1 DEFINITIONS

A second taxonomy also developed in collaboration with a team of medical experts to assess the unique technology gaps associated with the medical aspects of enabling crew autonomy is shown in Figure 5.

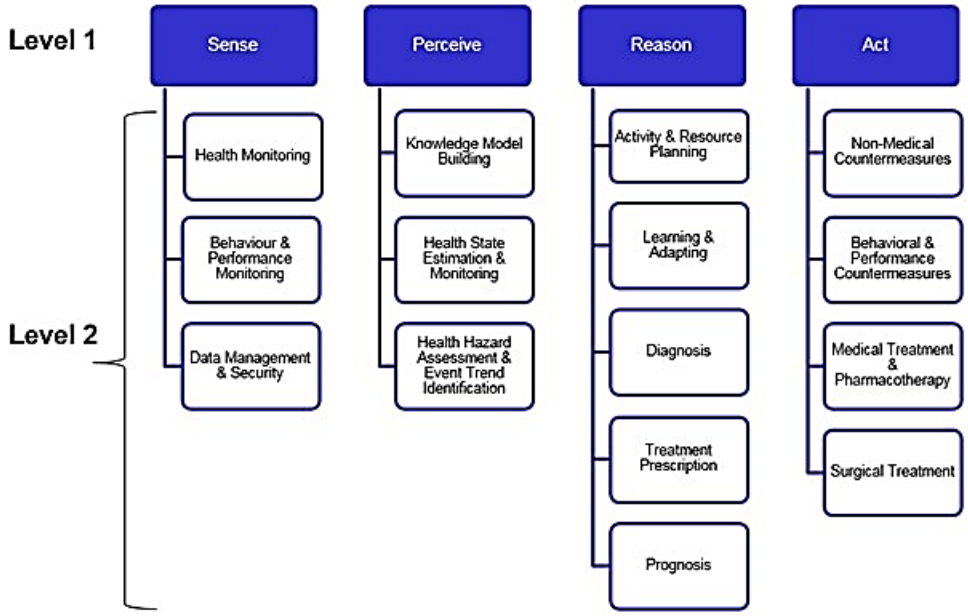


FIGURE 5: TAXONOMY-2 FOR CREW AUTONOMY (MEDICAL ASPECTS)

Figure 6 provides definitions for the functions associated with Taxonomy-2.

Sense	**Data collection on crew health and performance**
1) Health Monitoring	1) Collect data to assess the physical, mental and social health of the crew (via biomonitoring, bio-analysis, clinical examination, including cognitive and psychological aspects, and medical imaging); either directly through wearable technologies, biomarkers, testing, or indirectly through environmental indicators (ex: CO2 levels in surrounding
2) Behavior & Performance Monitoring	2) Collect data to assess the behavior & performance of the crew through task performance indicators (ex: task trainers), functional evaluations (ex: proprioceptive assessments), monitoring of discreet elements (ex: movement in the module, sleep patterns), objective/subjective assessments (ex: questionnaires), and crew feedback (ex: journal entries).
3) Data Management & Security	3) The data collection, conversion, storage and management (synchronization with Mission Control) of crew medical data in a secure manner that maintains crew privacy. This applies to the patient's medical data from initial intervention, screening, diagnosis, through to treatment, recovery, and record keeping.)
Perceive	**Detect, build baseline and identify any deviations from the baseline**
1) Knowledge Model Building	1) Aggregation of health and performance data from multiple sources and across time to form a baseline model of crewmember's nominal state for missions beyond LEO.
2) Health State Estimation & Monitoring	2) Estimation and monitoring of crew health using health, performance, and environment data and comparison with an expected healthy state. This involves the definition of a healthy (acceptable) state, acceptable deviations, and unhealthy (unacceptable) states in a variety of environmental conditions / mission phases.
3) Health Hazard Assessment & Event Trend Identification	3) The analysis of physical, mental, social health, performance and environment data (potentially AI-enabled) to identify patterns/trends in crew health that would provide indications of deviations from a healthy state, and/or events that could negatively affect future crew health and mission success. Data analysis may target high-yield areas and focus on treatable illnesses, or where early intervention is beneficial.
Reason	**Formulation of action(s) needed to achieve a defined objective, task, or requirement based on the current perceived condition / mission environment**
1) Activity & Resource Planning	1) The ability of the system to plan health related procedures/activities (tests, data collection, countermeasures), and to manage medical resource usage. Such a plan should ensure careful resource usage and uptake, and include the aspect of contingency planning. In addition to managing medical resources (e.g.. medications and supplies), this category may include key life-supporting resources/consumables such as oxygen, water, food etc.
2) Learning & Adapting	2) The ability of the system to learn from past medical events and experiences from other integrated systems', use pattern recognition, and the ability to adapt to changing
3) Diagnosis	Identification of the disease, condition or health issue(s) which most likely explains the signs and symptoms, based on the assessment of the current health, performance and environmental data. This process will also include an assessment of severity level and future health course with and without treatment.
4) Treatment Prescription	3) Identification of a health goal and a course of action to reach that goal. The treatment plan should link to onboard procedures and checklists, and should identify time-based measureable outcomes to track health progression throughout the treatment. Illnesses where no treatment is available, should be identified/flagged upfront.
5) Prognosis	4) The determination of treatment & countermeasures for the patient seeks to heal the patient while considering various personal, environmental, and operational factors for an effective and sustainable recovery to good health. This activity should be closely linked with resource planning of consumables (medical and life-supporting resources).
Act	**Execution of action(s) needed to achieve a defined objective, task, or requirement**
1) Non-Medical Countermeasures	1) Non-medical countermeasures are intended to support the mitigation of health risks, especially on long-duration missions. Countermeasures consist of physical activity to assist in physiological conditioning, nutritional or functional food inclusion, and/or other non-medical interventions.
2) Behavioral & Performance Countermeasures	2) Behavioral & performance countermeasures consist of strategies contributing to maintaining mental well-being, social adaptation, and operational performance. These are intended to prevent or reduce the effects of stress, fatigue, isolation, and depression due to the exposure to extreme and confined environments.
3) Medical Treatment & Pharmacotherapy	3) Any medical intervention needed to reduce or eliminate a physiological, mental health or performance issue. Sufficient medication & medical supplies will be required, thus linking medical treatment closely with resource planning activities.
4) Surgical Treatment	4) A medical course of action involving the cutting of patient's tissues or closure of a previously sustained wound. Surgical procedures can be minor procedures (ex: casting, suturing), or more complex (ex: endoscopic, or robotically-assisted surgeries). Surgeries are invasive procedures requiring a sterile environment, anesthetics and specialized tools.

FIGURE 6: TAXONOMY-2 DEFINITIONS

7. GAP ASSESSMENT METHODOLOGY

The current GER mission scenario calls for operations to be guided by Earth-based mission controllers. Under this operations concept, mission operations must be planned in advance and coordinated carefully to overcome time delays and communication outages. For long-duration missions, autonomy must enable operations to continue uninterrupted even when communication with Earth-based resources is not possible. Autonomy is also critical to mitigating, if not eliminating the risk to human crew and mission assets.

The critical technology needs documented in GERs 21, 23, and 49 are necessary to support the concept of operations, which relies on Earth-based mission monitoring and control. As capabilities for machine learning mature and become robust and reliable, the GAT anticipates mission scenarios will evolve to include local mission monitoring, control and decision-making at or near exploration destination points. With this evolution in mind, the GAT adopted the key functions, or aspects, of autonomy as the categories for the gap assessment and identified gaps which much be addressed to ensure control functions can extend beyond mission monitoring and control by Earth-based assets. The aspects formulated for the assessment are:

- Vehicle Autonomy[1]
- Crew Autonomy
- Crew Health and Performance
- Food Production
- Crew Safety and Intervention
- Robotic Caretakers
- Stowage Management

Assessment criteria and evaluation ratings were also formulated and a data collection template was created to capture the assessment results for both taxonomies (non-medical and medical). The evaluation template for gaps associated with the non-medical taxonomy is depicted in Figure 7.

Taxonomy Level 1	SENSE	PERCEIVE						REASON						ACT
Taxonomy Level 2	Sensing Element	Knowledge/Model Building	State Estimation and Monitoring	Knowledge and Intent Conveyance and Understanding	Hazard Assessment	Event/Trend Identification	Anomaly and Fault Detection	Mission Planning	Activity and Resource Planning	Motion Planning	Learning and Adapting	Diagnosis and Prognosis	Fault Response	Actuation
Present Capabilities in Space														
Present Capabilities on Earth														
Identified Gap (Criticality)														
Agencies' Research Activities on-going														
Overall level of Gap Criticality														

FIGURE 7: GAP ASSESSMENT EVALUATION TEMPLATE (NON-MEDICAL ASPECTS)

The evaluation template for gaps associated with the medical taxonomy is depicted in Figure 8.

[1] Assessment related to telerobotics/rovers is addressed in the ISECG Gap Assessment Report, *Telerobotics Control of Systems with Time Delay*

Taxonomy Level 1	SENSE (Monitor Crew = Get Data)			PERCEIVE (Detect & Identify Issues = Parse Data)			REASON (Diagnose & Determine Course of Action = Interpret Data)					ACT (Treat Patient = Act on Data)			
Taxonomy Level 2	Health Monitoring	Behavior and Performance	Data Management & Security	Knowledge Model Building	Health State Estimation &	Health Hazard Assessment and Eve	Activity & Resource Planning	Learning & Adapting	Diagnosis	Treatment Prescription	Prognosis	Non-Medical Countermeasures	Behavioral & Performance	Medical Treatment & Pharmacotherapy	Surgical Treatment
Present Capabilities in Space *(Assumes ISS technology but used in BLEO context)															
Present Capabilities on Earth															
Identified Gap (Criticality)															
Agencies' Research Activities on-going															
Overall level of Gap Criticality															

FIGURE 8: GAP ASSESSMENT EVALUATION TEMPLATE FOR CREW AUTONOMY (MEDICAL ASPECT)

The gap assessment evaluation ratings for each of the assessment criteria are defined in Figure 9.

Present Capabilities in Space
Can be done easily and well
Can be done but needs to improve
Can't be done with current technologies
Not Applicable

Identified Gap	
Not present	No gap identified
Enhancing	Filling the gap is useful for mission success/enhance performances
Enabling	Filling the gap is required for mission success or safety
Critical	Filling the gap is critical to mission success and/or safety
Not Applicable	

Present Capabilities on Earth
Can be done easily and well
Can be done but needs to improve
Can't be done with current technologies
Not Applicable

Research Activities on-going	
Activities are on-going	Space Agencies are investigating the issue
Activities are planned	Space Agencies plan to investigate the issue
No Activities planned/on-going	Space Agencies are not investigating the issue
Not Applicable	
TBD	To Be Determined

Overall level of Gap Criticality	
Low	The gap is not considered critical (i.e. does not put in risk the mission, agencies are investigating the issue, etc.)
Medium	The gap is considered important but not critical (i.e. if filled can augment the mission performances)
High	The gap is considered critical (i.e. puts in risk the mission, no agencies are investigating the issue, etc.)
Not Applicable	

FIGURE 9: GAP ASSESSMENT EVALUATION RATINGS

A template (Figure 10) was developed to map the aspects of autonomy to the functions in the GER mission scenario. The template was also used to identify technology demonstration opportunities.

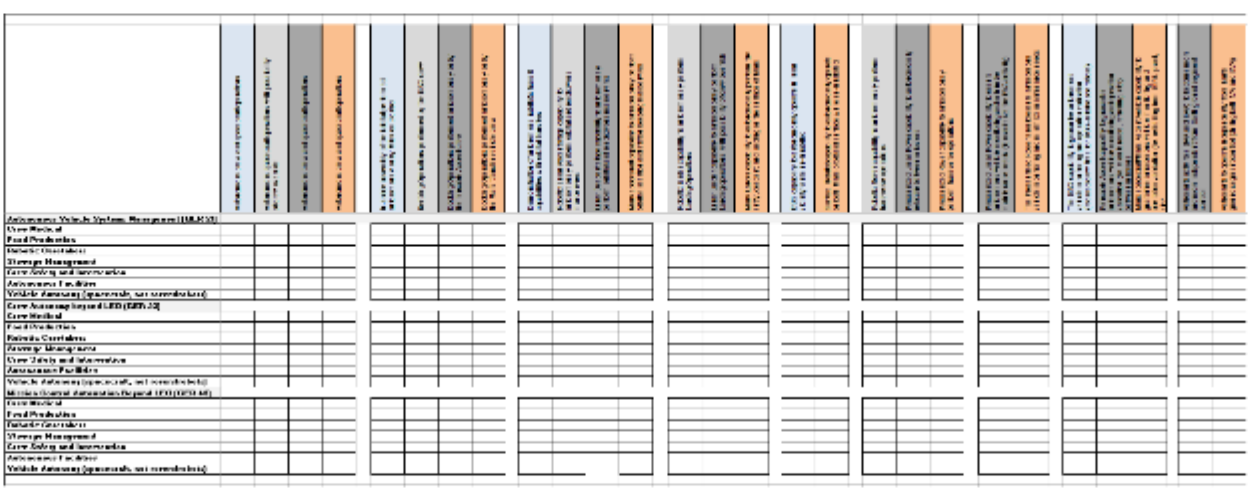


FIGURE 10: TEMPLATE FOR MAPPING ASPECTS OF AUTONOMY TO MISSION SCENARIO

8. GAP ASSESSMENT

A summary of the technology gap assessments and crosscutting gaps are provided in this section.

8.1. VEHICLE AUTONOMY

GER 49 stipulates that "back-room" control center effort should be reduced. "Back room" planning and analysis functions can largely be done much as they are today. The GAT found that "front-room" operations – real-time monitoring, commanding and control – are also targets for automation and autonomy if mission scenarios are to overcome constraints associated with communications outages and delays and evolve to local monitoring, commanding and control for vehicle operations.

Present Capabilities in Space

Missions are becoming more complex in multiple areas: longer durations, longer distances, complex operations, multi-spacecraft collaboration, etc. Vehicles involved in such missions must be supported by new autonomous systems in a way that is proportional to the mission complexity.

In the case of human-rated vehicles, autonomous systems shall be integrated in each of the four functions identified in the Autonomy Taxonomy in three different ways:

- Option 1) - Support crew in the understanding and decision-making process
- Option 2) - Based on sensors and crew inputs (facts and goals respectively), take decisions without humans in the loop
- Option 3) - Given an overall mission objective, auto-generate goals and take decisions based on them without human intervention.

Options 1 and 2 have been applied fundamentally to deterministic, well-defined, low-level vehicle control (individually or in collaborative scenarios), even though it can be expected to be expanded in the future to higher level cognitive tasks related to decision-making. One relevant example is the ISS crew decision support system demonstration done onboard ISS.

Option 3 is focused on single-vehicle control and involves all different spacecraft subsystems: data handling, guidance and navigation, power, thermal, failure management, etc. Guidance, navigation and control /Attitude and Orbit Control System (AOCS) and FDIR can be arguably considered the most challenging for autonomous systems as they must handle a broader problem space. On the other hand, thermal and power traditionally employ more deterministic rule-based systems, used for decades of space exploration.

Multi-vehicle interaction ranges from well-known operations, such as rendezvous, to more sophisticated, such as berthing with a non-cooperative spacecraft. Given the fact that human exploration in the modern era has focused on LEO, the need for such levels of autonomy has been limited to demonstrators, such as the NASA Extreme Environment Mission Operations demonstration.

Critical Gaps

Taxonomy Level 1	SENSE	PERCEIVE						REASON						ACT
Taxonomy Level 2	Sensing Element	Knowledge/Model Building	State Estimation and Monitoring	Knowledge and Intent Conveyance and Understanding	Hazard Assessment	Event/Trend Identification	Anomaly and Fault Detection	Mission Planning	Activity and Resource Planning	Motion Planning	Learning and Adapting	Diagnosis and Prognosis	Fault Response	Actuation
Present Capabilities in Space	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can be done easily and well
Present Capabilities on Earth	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done easily and well	Can be done easily and well	Can be done easily and well	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done easily and well
Identified Gap (Criticality)	Enhancing	Enhancing	Enabling	Critical	Critical	Enhancing	Enabling	Enabling	Enabling	Enabling	Enabling	Enabling	Enhancing	Enhancing
Agencies' Research Activities on-going	Activities are on-going	No Activities planned/on-going	Activities are on-going	No Activities planned/on-going	Activities are on-going	Activities are on-going	Activities are on-going	Activities are on-going	Activities are on-going	Activities are on-going	No Activities planned/on-going	Activities are on-going	Activities are on-going	Activities are on-going
Overall level of Gap Criticality	Low	Medium	Medium	High	High	Medium	Medium	Medium	Medium	High	Medium	Medium	Medium	Low

FIGURE 11: CRITICAL GAPS - VEHICLE AUTONOMY

The assessment illustrates that perception and reason are the Level 1 functions requiring more work in opposition to sense and act functions. This aligns with the trend, explained at the beginning of this section, to provide space systems with higher reasoning capabilities.

More in detail, knowledge modelling and understating, hazard assessment, motion planning and learning are the fields that present bigger gaps. While most of these Level 2 functions are studied at present, further efforts need to be dedicated in order to provide the capabilities required for human exploration scenarios for the Moon and Mars.

It is important to emphasize that, in the frame of the mission scenario described above, it is required not only to (further) develop technologies, but also to define standards to allow autonomous systems from different space agencies to synchronize and collaborate.

Following subsections will provide further details for each function.

<u>Knowledge Model Building/Model Understanding</u>

Model building is used by space agencies to support the determination of the status of spacecraft. However, the incorporation of data fusion techniques, complemented if required by Artificial Intelligence (AI) tools (data mining, pattern matching, etc.) needs to be further developed. In addition, reasoning and understanding the consequences of a given state in support of forecasting and planning present an even bigger gap. In this area, automated reasoning (constraint satisfaction problems, rule engines, model checking, machine learning, etc.) are some of the techniques to be further investigated in the context of space, which is clearly behind its terrestrial counterparts.

<u>Hazard Assessment</u>

Hazard assessment is highly critical when required for human-rated vehicles. While performing this function it is addressed in different ways by FDIR systems, more complex missions and vehicles will require higher levels of abstraction which also will benefit from more advanced model understanding.

Hazard assessment uses similar techniques as those cited above with the addition of online formal verification and validation techniques. Similarly, further developments are required in this area despite current efforts.

Motion Planning

Motion Planning refers to both vehicle (orbital and surface) path planning, and libs (such as robotic arms) trajectory planning, all of them being highly dependent on the underlying platform architecture.

Path Planning

There is a big difference in the level of maturity of motion planning for orbital and surface vehicles. In the case of orbital vehicles, motion planning is highly automated and does not present major challenges for future missions, primarily due to the deterministic environmental behavior. On the other hand, surface vehicles (primarily envisioned for Moon exploration), present a big gap with respect to their terrestrial counterparts and can claim very limited heritage, mostly coming from space (robotic) wheeled vehicles, due to the limitations of the last ones in terms of volume, speed and power.

In terms of orbital vehicles, GNC systems could benefit from intelligent systems such as automated planners and schedulers in order to adapt the vehicle trajectory to changing conditions or goals. Terrestrial vehicles could benefit from further development in Visual Odometry (SLAM), continuous driving and real time hazard avoidance.

Trajectory Planning

Even though there is a gap with respect to terrestrial systems, derived from the limitations imposed by the environment, trajectory planning has been developed in multiple space scenarios, from ISS to Mars rovers. Therefore, its level of maturity is moderately high and doesn’t present major challenges. A different aspect is the part related to grasping and object handling, which is beyond the scope of this report.

Learning and Adapting

Learning might have very limited online applications, but it can be used as an offline tool to further refine the behavior of the different autonomous systems onboard a space vehicle such as obstacle avoidance, automated docking/berthing, etc. Neural networks is one of the most prominent techniques in this field. Space agencies have devoted some scarce efforts to their development, but the gap with respect to terrestrial applications is increasing. Considering the transversal benefit to other areas, it seems an area of big potential for further development in the immediate future.

Plan Execution

Plan execution is highly linked to other autonomous systems, namely: planning (mission, motion), model understanding and FDIR. In consequence, execution systems will need to be further developed in order to cope with the increasing capabilities of the rest. Among other techniques, conditional execution, goal-based hierarchical execution and interlinked planning, execution and repair are some of the areas subject to further development.

8.2. CREW AUTONOMY

Crewed missions beyond LEO, long duration spaceflight, surface operations (Moon base) and any other mission where crew is involved in medium- and long-term permanence (like the Gateway) require an adequate level of mission control automation and proper intelligent habitats to support crew autonomy in nominal activities and emergencies.

The concept of crew autonomy centers on supporting astronauts with planning and completing tasks with limited to no assistance of ground support teams. Moreover, the more future exploration missions will bring humans farther from Earth and for longer durations, the more communication with Earth will be both delayed (from seconds to minutes) and intermittent, making it even more important to provide the crew with increasing levels of autonomy. In fact, crew will only have limited opportunities to ask ground teams for planning, clarifications and guidance on assigned tasks. Furthermore, crew also may have specific, local information about what tasks require planning and on how to execute them.

Enhanced autonomy induces a new repartition of processes between Ground and Space. Mission control capabilities must be enhanced. Ground systems currently used to pre-plan almost every task to be executed on board will evolve as decision-support systems to help the mission controllers in planning only functions the crew cannot currently perform at the destination. But, as systems to support crew autonomy become more reliable, the operations concept and mission scenarios will migrate from ground-based controllers to autonomous control at the destination point, where only long-term strategic planning will be ground-based.

Regardless of the location, to support an adequate level of crew autonomy, facilities also must be sensitive and responsive to the presence of people, and assist, support and protect crew during their time in the facility during nominal, off-nominal and off-duty activities.

Earth-based research on automated reasoning is leading to design and implementation of responsive environments where devices work to support people in carrying out their activities, tasks and rituals in an easy, natural way using information and intelligence that is hidden in the network connecting these devices. Such a growing technology still has no real application in space, even considering that it could provide a valuable contribution to improve habitability and productivity in closed environments (like the ISS or Gateway). However, the more challenging goal of establishing a permanent human presence in space brings a scenario where ambient intelligence has not only been considered as a support to ease the life and to improve productivity, as in Earth based applications, but also as a real need (or enabling technology) to allow and protect life in critical, hazardous environments.

Present Capabilities in Space

Research and deployments of technologies that can relate to crew autonomy and ambient intelligence are currently being investigated by major space agencies. The NASA Space Robotics Challenge aims at funding research on humanoid robotics also operating in human habitats. NASA investigated crew autonomous scheduling for the ISS with the NASA Extreme Environment Mission Operations (NEEMO) project. with technologies that could support ambient intelligence, such as intelligent user interfaces, scheduling and fault management procedures for ISS's crewmembers (as with the Total Organic Carbon Analyzer Autonomous Operations project), and with readers for improved logistics tracking, as with the RFID-Enabled (Radio-Frequency IDentification-Enables) Autonomous Logistics Management project. Use of Hololens to display and assist with maintenance procedures also are being investigated by NASA (ta similar European payload, the Augmented Reality Application for Maintenance, Inventory and Stowage (ARAMIS) is in development).

Critical Gaps

Taxonomy Level 1	SENSE	PERCEIVE						REASON						ACT
Taxonomy Level 2	Sensing Element	Knowledge/Model Building	State Estimation and Monitoring	Knowledge and Intent Conveyance and Understanding	Hazard Assessment	Event/Trend Identification	Anomaly and Fault Detecti	Mission Planning	Activity and Resource Planning	Motion Planning	Learning and Adapting	Diagnosis and Prognosis	Fault Response	Actuation
Present Capabilities in Space	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can't be done with current technologies	Can be done but needs to improve	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Not Applicable	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can be done easily and well
Present Capabilities on Earth	Can be done easily and well	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done easily and well	Can be done easily and well	Not Applicable	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done easily and well
Identified Gap (Criticality)	Enhancing	Enhancing	Enabling	Critical	Critical	Critical	Critical	Enabling	Enhancing	Not Applicable	Critical	Enabling	Enabling	Enhancing
Agencies' Research Activities on-going	Activities are on-going	Activities are on-going	Activities are planned	No Activities planned/on-going	No Activities planned/on-going	Activities are on-going	Activities are on-going	Activities are on-going	Activities are on-going	Not Applicable	Activities are on-going	Activities are on-going	Activities are planned	Activities are on-going
Overall level of Gap Criticality	Low	Medium	High	High	High	High	High	Medium	Medium	Not Applicable	Medium	Medium	Medium	Low

FIGURE 12: CRITICAL GAPS – CREW AUTONOMY

The gap assessment revealed critical gaps mostly concentrated in the area of perception and knowledge deduction:

<u>Knowledge and Intent Conveyance and Understanding, Hazard Assessment</u>

Ambient Intelligence requires technologies to implement reliable situational awareness, to infer temporally contextualized knowledge regarding the state of the user (based on heterogeneous sensor readings and previously inferred knowledge). This appears to be the most critical gap, for the lack of technologies and competences also on terrestrial applications. It is not easy nowadays to provide complex semantics by mixing the information provided by multiple cameras and environmental sensors to bring back what is sensed to a model of a conceptual behavior with a reasonable reliability. For instance, the sensor reading of a human engaged in physical training can be similar to the reading for a human having a heart problem; with current capabilities, the correct context to explain the sensor's reading must be inferred to answer the questions "*What is the human doing?*", "*Is the human in distress?*". Regarding hazard assessment, a criticality can be envisaged on what concern the verification and validation of the technologies embedded in the intelligent ambient is, as well as the need for providing understandable and transparent behavior (explainable AI). In fact, we can suppose, for an intelligent ambient in space, the need is for a more reliable and verifiable behavior than is currently available for similar terrestrial technologies.

<u>Event/Trend Identification, Anomaly Detection</u>

The analysis of big amounts of raw data to identify events and trends that may affect future state, operations, or decision-making, as well as the determination that a system or environment is not performing as expected, is currently being investigated on terrestrial application in the fields of machine learning and anomaly detection. In the space field, these technologies are currently used on ground in mission operations to analyze satellites' telemetry to detect anomalies. Few examples also have been attempted onboard, but in general there is a criticality related to the computational power required by algorithms for machine learning and issues related with the expandability of proposed analysis.

Besides these critical gaps, it also is important to highlight the need for adapting existing operational approaches and workflows. Current "command-oriented" paradigms where remote crew and the flying assets are dependent on direction from the ground segment should evolve into a more "goal-oriented" and collaborative approach where the remote crew and the flying resources cooperate with the ground segment, reasoning more on objectives than on a sequence of commands to achieve them.

Less critical are other enabling technologies:

Sensing

Sensing technologies to support ubiquitous computing and embedding technologies are currently being deployed. Linking information and capabilities to inanimate entities such as tables, doors, areas and displays are not a problem. This includes: embedding technologies into artifacts (devices and environment objects) and embedding sensors to perceive interactions (to acquire information from these actions which enables the inference of the user tasks and needs). Technologies to enable "personal space" are also deployed: portable devices carried by the user and which move around with them, providing context-aware pervasiveness at all times and places. Intelligent User Interfaces (for augmented, virtual and mixed reality), as well as technologies for video recognition (to support inference of intent, decision-making on follow-up actions) also are sufficiently deployed to be applied in ambient intelligence.

Reasoning

Software for planning and execution monitoring (to proactively plan and execute services to provide contextualized assistance) currently appears to be sufficiently deployed on Earth to be used in space. Also, computational requirements of such technologies (for the size and complexity of the problems to be solved to support ambient intelligence) do not appear to be a problem for computational resources we can reasonably suppose will be available in space. A medium level criticality has been identified in Learning and Adapting. In this respect, present technologies are less deployed (there are the same issues identified above for situational awareness), and this would certainly be an important added value for ambient technology. But at the same time, given the nature of the decision-making to be made in an intelligent ambient, it is reasonable to suppose that sufficiently preforming and accurate models can be designed and updated offline, with no unavoidable need for advanced learning techniques.

Learning and Adapting, Diagnosis and Prognosis

Assessment of the current health state of a system and ability to restore nominal operations after a fault are of primary importance on a technology aimed at supporting the human in its living and working environment. In this regard, technologies already are in place on the ISS, but need to be improved for a more stable and long-term permanence. These gaps are considered of medium criticality because primary technologies to guarantee survival are considered out of the scope of ambient intelligence, but gaps still need to be addressed since adding intelligence poses threats to safety and security.

8.3. CREW HEALTH AND PERFORMANCE

An important aspect of Crew Autonomy is to ensure that the crew remain in good health, where health includes physical, mental and social well-being. In order to remain healthy, crew need to be able to autonomously provide preventative and curative (*e.g.*, emergency) health care. This includes executing preventive activities (*e.g.*, use of CounterMeasure (CM) exercise, optimized nutritional practices), monitoring their health, perceiving any deviations from the baseline, analyzing and diagnosing the cause and acting (continue to monitor, apply countermeasure, or treat).

Present Capabilities in Space

The relative locality of ISS to Earth and the resulting ease with which ground-based experts can communicate with crew, and an injured or sick astronaut can be returned to ground for medical care, has resulted in a traditional "doctor (ground-based expert) – patient (astronaut)" approach to preventative medicine and a "scoop and run" concept for emergency medical management. For preventative medicine on ISS, astronauts rely on ground-based experts – not only medical doctors, but also exercise specialists, dietitians and psychologists – to provide them with guidance/support, with these experts making use of the real-time video and audio communication with ISS to provide these capabilities. Likewise, for emergency medical management, should it be required, the crew are trained in advanced first aid and emergency response and the ground-based medical doctor would guide the attending astronaut's response. In all but the simplest medical cases, the default response is to evacuate the patient and the current depth of ISS crew medical training and the medical technologies provided on ISS reflects these medical support concepts.

Critical Gaps

Taxonomy Level 1	SENSE (Monitor Crew = Get Data)			PERCEIVE (Detect & Identify Issues = Parse Data)			REASON (Diagnose & Determine Course of Action = Interpret Data)					ACT (Treat Patient = Act on Data)			
Taxonomy Level 2	Health Monitoring	Behaviour & Performance Monitoring	Data Management & Security	Knowledge Model Building	Health State Estimation & Monitoring	Health Hazard Assessment and Eve Trend Identification	Activity & Resource Planning	Learning & Adapting	Diagnosis	Treatment Prescription	Prognosis	Non-Medical Countermeasures	Behavioural & Performance Countermeasures	Medical Treatment & Pharmacotherapy	Surgical Treatment
Present Capabilities in Space *(Assumes ISS technology but used in BLEO context)	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can't be done with current technologies	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can be done but needs to improve	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies
Present Capabilities on Earth	Can be done easily and well	Can be done easily and well	Can be done easily and well	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can be done easily and well	Can be done easily and well	Can be done but needs to improve	Can be done easily and well
Identified Gap (Criticality)	Critical	Enabling	Enhancin	Critical	Critical	Critical	Enabling	Enabling	Critical	Critical	Enabling	Critical	Critical	Critical	Enabling
Agencies' Research Activities on-going	Activities are on-going	Activities are on-going	Activities are on-going	Activities are on-going	Activities are planned	Activities are planned	Activities are on-going	Activities are planned	Activities are planned	Activities are planned	Activities are planned	Activities are on-going	Activities are on-going	Activities are on-going	No Activities planned /on-going
Overall level of Gap Criticality	Medium	Medium	Low	High	High	High	Medium	Medium	High	High	Medium	High	High	High	Medium

FIGURE 13: CRITICAL GAPS – CREW HEALTH AND PERFORMANCE

Health Monitoring

In order to properly monitor crew on longer missions beyond LEO, and to develop preventative and curative strategies, there needs to be more data collected over longer periods across a genetically diverse group in order to establish a proper baseline and understand which parameters are key for monitoring both the effects of the space flight environment and the effectiveness of interventions/countermeasures. This data is crucial to better understand what countermeasures and treatments will be necessary on eventual missions to Mars and to better understand the effects of isolation, loneliness and depression for missions with small crews far from home. As a preliminary measure, robotic missions could carry organoid samples based on stem cells to see the effects of the cislunar or deep space environments prior to sending humans.

Crewmembers may not always recognize or feel the need to report symptoms. Monitoring systems which can automatically and unobtrusively collect the data and transmit it, securely, periodically, and privately, to the medical diagnostics system for autonomous early detection of health issues will be essential on longer missions. In the case of severely delayed or no communications, such systems must also have the ability to present relevant data (with recommendations) to individual crew members and/or the mission medical doctor in a way which increases crew-self-awareness without increasing health anxiety. Early detection allows for more timely responses, which in turn reduces the consumption rate of limited medical consumables. Autonomous monitoring also is critical for cases where the crew may be busy, impaired and/or unable to recognize an immediate or impending health problem. However, key to successful medical monitoring is crew "buy-in" to its purpose and value, especially when they are far from Earth without direct communication. Without this, medical monitoring risks being viewed by the crew as an unnecessary inconvenience, with likely knock-on effects on their compliance.

Health monitoring also should include monitoring of CM exercise and crew nutrition. On ISS today, exercise and nutrition are good examples of how the crew are still highly reliant on ground-based experts. For CM exercise, ground-based exercise specialists prescribe training, review the results and adjust future exercise sessions accordingly. Likewise, for nutrition, nutritional experts provide guidance as the crew try (as best they can with the technologies provided) to record what and how much they eat. Experts review the recorded data and make recommendations for the next period of the mission. For exploration autonomy, the crew needs reliable tools for accurately capturing data, as without good data, deciding what to do next/what to adjust is highly challenging (see 'Diagnosis Support' section below).

Performance and behavior monitoring of crew allows for early detection of possible mental health issues. Besides the reporting done by behavioral health specialists in journals and at conferences, it is currently still reliant primarily on self-reporting in the absence of robust psychometrics and other psychological measures. Experiencing mental health issues, and by extension reporting them, may be seen as counter to astronaut culture and negatively impacting future flight opportunities. Therefore, crew members may be reluctant to divulge potential issues to crewmates or ground personnel. In these situations, tools are needed that allow for autonomous assessment of the crew's mental health, acquiring patient data in a manner acceptable to the crew, where results and any subsequent treatments are addressed with a sufficient level of confidentiality. Such tools can be combined with tools that provide treatment, such as Virtual Reality (VR) games designed to treat symptoms of depression.

Knowledge Model Building

The most critical gap is the lack of ability to determine if crew health is nominal due to the lack of a comprehensive baseline model for long term (~2 year) missions beyond LEO. Over the years there has been a large amount of data collected on astronauts on long-term ISS missions, and even then, there remains some debate as to what is considered "healthy" for ISS. ISS missions average six months in LEO, where the radiation effects are not as severe, and isolation can be counterbalanced by larger crews and relatively easy communication with friends and family on Earth. In addition, as all ISS crew (and many non-ISS crew before them) perform an intense and regular CM exercise program, it is impossible to separate the effects of the space environment (that induce adaptation) from the effects of exercise (that should attenuate many of the adaptive changes). Despite the relatively constant condition on ISS, large differences exist in the magnitude of physiological changes between individual crew members. The extent to which these differences reflect individual variation in response to the space environment and/or to the CM exercise program is still unknown.

Health state models will need to take into account normal physiological adaptation to different environmental conditions throughout a mission (Earth, microgravity, lunar surface gravity and Mars gravity). There is a need to develop baseline datasets and models for long-duration Beyond LEO (BLEO) missions to build up our capability to detect deviations and forecast future health and performance levels for such long missions. From ISS experience, some health degradation is expected over long missions and may or may not be a concern as some conditions return to normal post-flight.

For longer missions, the data set is extremely limited with only four Russian men and no women having spent more than one year consecutively in space. Only 24 American men have ventured out beyond LEO for missions of six to twelve days. In addition, due to the limited number of subjects, the data collected cannot easily be made anonymous, and so much of it is protected due to privacy concerns and not easily accessible to the international scientific community at large.

Deviation From Baseline Model

Trend analysis is critical to allow early disease onset detection and intervention in order to minimize crew down-time and minimize use of medical consumables. Evaluation of environment, health and performance state and trends also is necessary to determine whether changes in environment may impact crew health, and to predict whether changes in crew health pose a threat to mission success. Improvements in machine learning and pattern recognition can be leveraged as AI technologies develop, to identify health issues while sorting through the constant inflow of collected data points. Trend analysis also serves in the assessment of impact of actions (countermeasures) or inactions on crew health and mission success.

Diagnosis Support

Currently, even ISS crews that do not include a medical doctor can rely on having immediate specialized medical support available from the ground to help diagnose any issues that may arise during a mission. With significant time delays, the ability of ground staff to effectively examine and diagnose a patient is limited. While some of this can be mitigated by having a doctor as part of the crew, not all crews include medical doctors and medical responsibility always lies with the Flight Surgeon on Earth. Certain illnesses that are more treatable and/or those conducive to early intervention can be prioritized for high-yield screening.

Many doctors on Earth today use their extensive professional experience, a patient's family, medical and environmental history, and diagnostic tools and medical databases to help diagnose patients. While terrestrial diagnostic tools exist, the symptomology of patients in zero-G may be significantly different – requiring specialized versions of the tool. For example, a crew member with kidney stones may feel pain but will experience the pain differently than a patient on Earth, which could lead to a misdiagnosis if relying on terrestrially-based diagnostic tools. The interface must be easy for non-medical specialists to use in the case where the Crew Medical Officer (CMO) is incapacitated, or cognition is impaired. Tools can be developed in a wide range of formats, including everything from a basic decision tree to a holographic virtual interface. In many cases, a differential diagnosis may be required, in which several possible diagnoses are compared and contrasted.

In addition to diagnostic tools used in medical examinations, in-situ testing of samples and medical imaging provide critical information for diagnoses and to help determine the most effective treatment while at the same time minimizing the use of medical consumables. While these technologies are widely used on Earth, most are too large or otherwise incompatible with use in space (due to radiation, Electromagnetic Interference (EMI), power). Several technologies have been demonstrated on ISS for use but may require extensive support from the ground. In terms of medical imaging, ultrasound systems are available and used on the ISS for research and crew monitoring (e.g., the Ultrasound 2 System in the Human Research Facility onboard ISS), but much smaller 'hand-held' Commercial-off-the-Shelf (COTS) devices are already available and used in terrestrial medicine, one of which (Butterfly) has already been tested by NASA at ISS astronaut landings. In terms of sample analysis, the Bio-Analyzer is in development and test on the ISS to analyze blood sample composition. This facility could be complemented by the MicroFluidic Sample Preparation (MFSP) system designed to facilitate sample purification (also known as MicroPREP). A portable flow cytometer was tested on the ISS in 2019, and a COTS Point-of-care-Diagnostics (POCD, 1DROP Diagnostics) will be tested in 2020.

Diagnosis should also include evaluation of the effectiveness of preventive medical strategies, including the use of CM exercise and nutrition. For example, did the CM exercise session create the physiological response (e.g., target heart rate) that was expected? Did nutritional intake (e.g., total energy intake in the past period) meet its target? Today on the ISS, ground-based experts make these decisions, but for exploration autonomy, crew should have technologies and/or training that allow them to decide what course of action to take (see 'Treatment' section below).

FIGURE 14: MICROPREP (LEFT) AND THE BIO-ANALYZER (RIGHT) TO BE TESTED ON THE ISS

could potentially improve patient care on Earth. (Credit: NRC, CSA)

Medication

There are several gaps related to the transport, dispensing and use of medication in long-term space missions. Due to the inherent mass and volume limitations, the crew will only be able to take a small selection of medications with them. Limiting the use of these consumables will be critical to ensure that they are available late in the mission, if required. In some cases, it may be necessary to synthesize medicines in-situ, as needed, and to select the medications that are best suited to the crew member (e.g., through the use of pharmacogenetic diagnostics) in order to maximize the likelihood of therapeutic efficacy, minimize the risk of unwanted side-effects and reduce the unnecessary consumption of limited supplies. To maximize crew autonomy, technologies are required that will inform crew which medications to take and in what dose, especially in time-critical medical situations. Due to limited supplies (and re-supply) in the context of crewed deep space exploration, careful resource planning and uptake is critical to mission success. To further promote recovery, virtual counselling and therapy (e.g., with AI tools), social management strategies and operational accommodations could be helpful to supplement the medicinal treatment.

While most medications have a limited shelf life, the effect of radiation on many pharmaceutical ingredients may significantly reduce their effectiveness over the duration of the mission. These effects need to be studied to determine which medications are best suited for use in long missions. Systems also need to be developed which incorporate the best way to store and dispense the appropriate medications, automatically taking into account the specific needs of the patient and the remaining supplies on board. Although it is assumed that the mechanism of action, time course and metabolism of the medication will be the same on Earth, this has not been determined for many medications.

Training

Training is a key component in Crew autonomy. Long term missions will require training of crew in medical intervention for most common issues and for emergency situations, with little to no support from Earth. It is expected, but yet to be confirmed, that early long duration missions will include at least one crew member who is a medical doctor and designated as the CMO. The CMO will need advanced training prior to flight, but no amount of training can cover every potential scenario, and the CMO may be the crew member in need of treatment. Advanced training techniques will be needed to maintain skill sets over the duration of a mission, as well as for the acquisition of new skills. Simulators will be required, allowing the crew to practice complex procedures in-flight prior to performing it on their crewmates. Although medical training and currency is key, training will be of limited value unless a CMO has the technologies/resources required to diagnose and treat medical conditions. As such, the provision of medical training must always be viewed in the context of also providing the correct tools to resolve medical situations.

Treatment

In terms of treatment – most injuries of the type that can be treated with first aid are not an issue. For example, most broken bones can be set by a crew member, a splint or cast can be 3-D printed and painkillers dispensed. Any treatment beyond first aid is currently dealt with by sending the crew member back to Earth as more complicated treatments such as surgery are not currently possible in the space environment.

VR, or augmented reality, simulators could be developed to provide a means to assist in medical examinations or procedures and provide crew with a means to practice a procedure before attempting it on a crewmate. These methods also could be employed to assist in training before and during the mission.

For long missions, surgery in zero-G would only be a last resort as there are significant issues related to environmental contamination leading to infections, the use of anesthetics, and the management of bodily fluids, among other challenges. However, there may eventually be a need for emergency surgery in low gravity environments. To assist with surgical needs, adapted techniques for minimally-invasive, robotically-assisted endoscopic surgeries would need to be investigated, in addition to basic surgical procedures.

Treatment also includes making decisions concerning the ongoing use of preventive medicine strategies such as CM exercise and nutrition. For example, if an exercise session does not produce the expected physiological effect, what adjustment should be made (if any) for the next session? For nutrition, if the nutritional target was missed, what adjustment in the next period should be made to correct this difference without negatively affecting another aspect of nutrition? As with monitoring and diagnosis in the ISS context, these decisions are currently made by ground-based experts. Ideally, systems should be available for exploration astronauts that capture such data, analyze it, decide if a target has/has not been met, and provide a recommendation for the forthcoming phase of the mission.

Countermeasures and Prevention

Non-medical countermeasures are intended to mitigate health risks on long-duration missions through prescribed physical exercises, nutritional supplements, functional food inclusion and/or non-medical interventions. Physical therapy may consist of the treatment of illness, injury or other condition (e.g., deformity) by physical methods such as massage, heat treatment and exercise, rather than by medication or surgery.

Behavioral and performance countermeasures aim to prevent or reduce the effects of stress, fatigue, isolation, and exposure to extreme and confined environments. These countermeasures consist of strategies to support mental well-being, social adaptation and operational performance. It also can support the optimization of various areas, including team and individual training, team selection, operational procedures, operational accommodations (communications, schedule, etc.), environment design, psychological support, etc. Further research into autonomous, confidential, easy-to-use personal devices, along with the development of advanced (e.g., AI-enabled) tools in the area of virtual counselling and therapy will benefit long-duration spaceflight, with societal/health benefits extending to the population on Earth.

In terms of prevention, health optimization is already a pre-op priority for surgery patients here on Earth. Extending to BLEO missions, it is advantageous to increase astronaut resilience and reserve before long missions. Pre-mission phase preparatory objectives can include, for example, increasing Bone Mineral Density (BMD), muscle strength/function and aerobic capacity (VO_{2max}), increased intake on fat-soluble vitamins/minerals, mitigating immune dysfunction, removing the appendix pre-mission, pre-emptive assessment and treatment of coronary artery disease, identifying and protecting against radiation susceptible diseases (e.g., thyroid cancer), etc. In the case of increasing physical and physiological parameters, this might allow CM exercise to be used more sparingly resulting in lower consumption of resources and less wear and tear on exercise devices.

8.4. FOOD PRODUCTION

Food production for crew consumption is essential to expanding and sustaining the human presence beyond LEO. Development and testing of open, partially open, and closed-looped plant growth habitats have shown great progress in Earth-based experiments. Small scale experiments with open- and closed-looped habitats currently are being conducted aboard the ISS. Crews aboard the ISS currently participate in plant growth experiments by manually assisting with planting, watering and harvesting processes. While crew involvement in these activities is believed to have beneficial performance rewards for crew health, limitations on crew time necessitate the development of an autonomous food production capability that can sustain human life. Constraints on volume and power also point to a need for horticultural techniques that enable food to be autonomously produced at maximum quality and quantities within the rigid limitations imposed by microgravity.

Plans to scale up Earth-based and in-space research and development for plant habitats, and to utilize the lunar orbiting Gateway to mature and validate autonomous food production capabilities are in place. For example, the European Union/DLR initiated the EDEN ISS greenhouse experiment in Antarctica to validate and demonstrate techniques for plant cultivation in space during a 12-month analogue mission in Antarctica, and NASA is continuing to demonstrate plant growth in habitats onboard the ISS. Executing these plans will result in a progression of capability from the manual labor space gardening system of today to an automated food production system having significant impact on the nutritional and caloric needs of the flight crews. However, although plant growth capabilities are developing, plants have a low caloric density and require significant resources/space to grow. Depending on body size and excluding the use of CM exercise (which will further increase the caloric requirement) to keep a crew of four in energy balance, something in the region of 8,000–12,000 kcal/d is required. As such, to provide sufficient energy to sustain crew for long-duration exploration missions without being dependent on supply and resupply from Earth, an inflight source of high caloric density food would be highly beneficial. Ongoing terrestrial research already has demonstrated that macronutrients (protein, fat and carbohydrate) can be produced from hydrogen-oxidizing bacteria in the presence of carbon dioxide. Water, electricity (to split the water) and carbon dioxide will all be available either in space vehicles or from planetary surfaces/atmospheres, making such technologies potentially transferable to space missions.

Present Capabilities in Space

Over the past decades, a large number of plant systems have been flown in space to perform scientific investigations. Data from those investigations has enabled the development of the Veggie and Advanced Plant Habitat (APH) flight systems, both of which are actively being used for space life sciences-based experimentation onboard the ISS. The Veggie system is open to the ISS habitation environment and dependent on the ECLSS of ISS for environmental control. It has a controllable Red, Green and Blue (RGB) Light Emitting Diode (LED) lighting system, air circulating fan and single use plant pillows. The APH is a closed-loop environment for conducting controlled plant physiology investigations. It has active temperature, humidity, lighting, watering control, and CO_2 augmentation and trace gas reduction as well as imaging and numerous other sensors and control systems.

Critical Gaps

Taxonomy Level 1	SENSE	PERCEIVE						REASON						ACT
Taxonomy Level 2	Sensing Element	Knowledge/Model Building	State Estimation and Monitoring	Knowledge and Intent Conveyance and Understanding	Hazard Assessment	Event/Trend Identification	Anomaly and Fault Detection	Mission Planning	Activity and Resource Planning	Motion Planning	Learning and Adapting	Diagnosis and Prognosis	Fault Response	Actuation
Present Capabilities in Space	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can be done but needs to improve	Can't be done with current technologies	Can't be done with current technologies	Can't be done with current technologies	Can't be done with current technologies	Can be done but needs to improve
Present Capabilities on Earth	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve	Can be done but needs to improve
Identified Gap (Criticality)	Critical	Enabling	Critical	Enabling	Critical	Enabling	Critical	Enabling	Enhancing	Enhancing	Enabling	Critical	Critical	Critical
Agencies' Research Activities on-going	Activities are on-going	No Activities planned/on-going	Activities are planned	Activities are on-going	Activities are on-going	Activities are on-going	No Activities planned/on-going	Activities are on-going	Activities are on-going	Activities are on-going	Activities are planned	Activities are planned	Activities are planned	Activities are on-going
Overall level of Gap Criticality	High	Low	High	Medium	High	Medium	Medium	Medium	Low	Low	Medium	High	High	High

FIGURE 15: CRITICAL GAPS – FOOD PRODUCTION

The gap assessment revealed gaps in several areas:

Sensing

Techniques must be developed for sensing the presence of plant stress factors, such as wounding and disease. Ethylene, a colorless gas, has considerable influence on plant growth, even at parts per billion concentrations. Current sensor technology cannot detect ethylene at the low resolutions (few parts per billion) expected to be needed for successful and sustained food production. Current sensor technology can monitor and detect the other parameters that are vital for plant growth, such as temperature, moisture, lighting and oxygen. Sensors that can withstand the effects of radiation are needed.

Knowledge/Model Building

To enable autonomous food production, the key factors and indicators relevant to plant growth cycles must be identified and their interrelationships well-defined and understood. The optimum recipe for plant performance, including light levels and wave lengths, humidity, temperature, CO_2, nutrients and trace gases must be developed based on continued ground-based testing and testing in microgravity. The effects of radiation on seeds, plants and produce also must be understood and incorporated in food production models. Research is in progress to gather this knowledge, but the current lack of knowledge in this area represents a critical gap.

The integrated food production cycle (planting, harvesting, processing, food waste management) and support elements (e.g., habitats) must be modeled to provide a baseline that enables autonomous state estimation, monitoring, diagnosis, prognosis and decision-making necessary for sustained food production. For example, the impact of the habitation facility (Heating, Ventilation and Air Conditioning (HVAC), power, heat rejection, etc.) per unit of food produced by the system must be identified. Models also are needed to support automated/autonomous food production planning, analysis and decision-making during testing and full operations in microgravity.

Larger scale systems, or test beds, should be operated in space to produce domain-relevant data to anchor models and data, and refine architecture requirements. Capabilities to automate the development and accreditation of models are needed.

State Estimation and Monitoring; Knowledge and Intent Conveyance and Understanding

Methods, systems and software applications are needed to accurately estimate and monitor the state of seeds, plants, produce and the integrated food production system. Capabilities for extracting knowledge from data collected to correctly identify the presence of indicators that signal a transition to new state and interpreting the effect of those indicators in influencing transitions to new states must be advanced to enable long-term, large-scale food production in space.

Hazard Assessment

Terrestrial and in-space research and development applications largely assume seeds and produce are healthy and safe for human consumption. The ability to assess the effects of radiation and detect the presence of microorganisms that could render seeds or produce inedible or harmful is a critical gap that must be addressed to support exploration beyond LEO.

Anomaly and Fault Detection

Automated capabilities are needed to identify deviations and detect conditions in the components of the growth environment that are counter to maintaining a healthy, viable food production capability.

Mission Planning

Mission planning systems and capabilities existing in numerous domains can be tailored for and applied to in-space food production, however, gaps related to sensing and perception for food production must be addressed to effectively mature mission planning capabilities that can sustain human life beyond LEO.

Motion Planning

Motion planning capabilities factor into automated or autonomous planting, harvesting and processing. Many of the gaps associated with motion planning will be addressed by closing gaps for robotic and telerobotic capabilities for in-space and surface operations.

Learning and Adapting

Machine learning capabilities must be advanced to enable sustained food production without human interaction.

Diagnosis and Prognosis; Fault Response

Automated capabilities are needed to diagnose conditions that are not conducive to desired growth cycles and to take the appropriate action to maintain and sustain a healthy growth environment. Capabilities to accurately predict the end of viability of seeds, produce or the growth ecosystem also are needed.

Actuation

The Veggie system was designed to use passive watering, but due to the challenge of control fluid flow in microgravity, the crew has had to provide the needed water and nutrients via manual application up to this point. A robust food production capability should not be dependent on the availability of human crew members to water crops. Actuation devices and methods for delivery of active or passive watering and nutrient delivery in microgravity must be demonstrated and matured for operational use. Active systems have been demonstrated in space, but more work is needed to improve efficiencies in areas such as power consumption, thermal management and mass requirements.

8.5. CREW SAFETY AND INTERVENTION

Space exploration and surface operations beyond LEO expose humans to harsh environments. Crew safety must be maintained during space travel and mission operations, and it is imperative to provide capabilities to avoid the catastrophic or hazardous condition which may cause personal injury or fatality.

The functions of the crew intervention ensure that the autonomous system can be operated in a safe and effective manner. The autonomous system should operate in any nominal, predefined contingency situation with a satisfactory response and in any off-nominal/critical situation with a safe response. The crew member must "understand" the deliberation process and the steps taken by the autonomous system in executing the "acting" process when the autonomous system intervenes in unpredictable, off-nominal, unsafe behavior. In order to prevent unsafe conditions that may be experienced by crew, the autonomous system must interpret the human's intent (accounting for human error) when performing automated detection and recovery functions.

Present Capabilities in Space

The following aspects are considered for crew safety to address the gap between present capabilities and future need: emergency safing, caution/warning monitoring, hazardous commanding, electrical power shutdown, internal environment control, meteoroid/debris collision and fire protection.

The following aspects are considered for crew intervention: human to machine interfaces regarding commandability and deactivation, safety and fault tolerance of the autonomous system, observability, controllability and testability.

Critical Gaps

Taxonomy Level 1	SENSE	PERCEIVE						REASON						ACT
Taxonomy Level 2	Sensing Element	Knowledge/Model Building	State Estimation and Monitoring	Knowledge and Intent Conveyance and Understanding	Hazard Assessment	Event/Trend Identification	Anomaly and Fault Detection	Mission Planning	Activity and Resource Planning	Motion Planning	Learning and Adapting	Diagnosis and Prognosis	Fault Response	Actuation
Present Capabilities in Space	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can't be done with current technologies	Can be done but needs to improve	Can be done but needs to improve	Can be done easily and well	Not Applicable	Can be done but needs to improve	Not Applicable	Can be done but needs to improve	Can't be done with current technologies	Can't be done with current technologies	Can't be done with current technologies
Present Capabilities on Earth	Can be done but needs to improve	Can be done easily and well	Can be done easily and well	Can be done but needs to improve	Not Applicable	Can be done easily and well	Can be done easily and well	Not Applicable	Can be done easily and well	Not Applicable	Can be done easily and well	Can be done but needs to improve	Can be done but needs to improve	Not Applicable
Identified Gap (Criticality)	Enabling	Enhancing	Enhancing	Critical	Enabling	Enhancing	Not present	Not Applicable	Enhancing	Not Applicable	Enhancing	Enabling	Enabling	Critical
Agencies' Research Activities on-going	Activities are on-going	Activities are on-going	No Activities planned/on-going	Activities are planned	Activities are planned	Activities are planned	Not Applicable	Not Applicable	Activities are planned	Not Applicable	Activities are planned	Activities are planned	Activities are planned	Activities are planned
Overall level of Gap Criticality	Medium	Low	Medium	High	Medium	Low	Not Applicable	Not Applicable	Low	Not Applicable	Low	High	High	High

FIGURE 16: CRITICAL GAPS – CREW SAFETY AND INTERVENTION

The gap assessment revealed critical gaps in several areas:

<u>Sensing Element</u>

To protect the crew from meteoroid or debris impacts during flights and long duration missions, techniques and capabilities must be developed to detect the objects early enough, and at a great enough distance from the vehicle or a crew member to ensure that collision avoidance maneuvers can be performed in time.

State Estimation and Monitoring

Current caution and warning system capabilities need to be advanced to enable accurate estimation of conditions and to ascertain internal or external states using multiple raw or processed data from sensors and instruments.

Knowledge and Intent Conveyance and Understanding

There are necessary technologies which must be matured to ensure transparency in AI or machine learning-based applications and increase crew confidence in the autonomous capabilities by explaining deliberations and decisions made through the collection of data and the generation of knowledge. It is vital to produce and share this information in a comprehensive format that enables the crew to understand the intent of the autonomous system at all times.

Hazard Assessment

Capabilities to assess hazards must be matured. It is expected that in emergency situations, the crew should be provided clearly defined escape routes for emergency egress in the event of hazardous conditions. The ability to perform this function autonomously is required, whether the environment or situation poses a threat to safety or whether the system is enunciating the successful achievement of a goal. If there is an oxygen deficiency that could threaten the crew or an operation, a command to increase oxygen flow should not be issued unless the full impact of issuing the command is known beforehand. Because response time may be critical, it also is necessary to develop capabilities to rapidly assess conditions and command paths and ensure the direction provided to the crew, or the automated or autonomous response that is planned by the system, will not have unintended consequences.

Diagnosis and Prognosis

The ability to diagnose problems and predict the state that would result from continuing in existing conditions or issuing a command in a nominal or hazardous situation must be matured.

Fault Response

To enable the restoration of nominal operation after emergency safing, or to derive an acceptable alternative goal autonomously after the safing, advancement in fault response technologies are required to enable the autonomous system to have a comprehensive view of all data that is needed to understand and respond to the situation safely.

Actuation

Improvement in the balance between autonomous and manual intervention to accomplish mission operations is needed. There are no autonomous techniques for emergency repair or fire extinguishment in low pressure environments to keep the crew safe.

8.6. ROBOTIC CARETAKERS

The GER scenarios include missions in which facilities will be occupied only for short intervals, leaving them uncrewed for the rest of the mission, or long periods between crew arrivals. This includes missions in cislunar space, such as the Deep Space Gateway (DSG), with even longer periods of dormancy for Mars missions. These facilities will be deployed without a crew, using non-human-rated delivery systems. Early assessments show some human subsystems can be throttled to lower settings, but few human spacecraft systems can be completely turned off. In addition, some logistics support may be required in advance of crew arrival. In order to allow remote facilities to function autonomously for long durations, a class of small caretaker robots for the logistical handling, preventive/corrective maintenance and routine inspections is required. As the financial and safety benefits of this new approach are studied, several agencies are investing now in the robotics and autonomous technologies to make it possible.

Present Capabilities in Space

For the ISS, a mix of robots, ground control and astronauts are used for preventive and corrective maintenance, with ground-controlled robotics used for most external tasks and crew or ground control used for most internal tasks. The external robotics consist of the Canadian Mobile Servicing System (MSS) and the Japanese Element Module Remote Manipulator system (JEM RMS). ISS robotic operations all are planned by the ground control team and teleoperated for all inspection and Orbital Replacement Unit (ORU) maintenance tasks. The system is only locally operated by the crew for free-flier capture and EVA support. As the ISS ages and logistics flights have increased, these operations have become more frequent. Presently, robotic operations for maintenance and support take place almost daily. Internal robotics such as NASA's Robonaut have been demonstrated as capable of providing some support but are typically not used for most maintenance and logistics support, as humans tend to be able to accomplish the tasks much more efficiently.

The mix of robots and human crew likely will shift towards robots as missions go deeper into space, with long phases of uncrewed operation. For the cislunar environment where the time delay is fairly short, robots may be teleoperated from Earth. As missions venture deeper into the solar system and time delays increase, caretaker robots will need to become more autonomous. However, the caretaker robots must also be designed to facilitate interaction with crewmembers, since some activities, such as cargo transfer, could be autonomously carried out by the robots while the crew is otherwise occupied. Current safety protocols on the ISS typically call for teleoperated or autonomous robots to be disabled for motion when in close proximity to EVA crewmembers. No capability exists for EVA crew to directly control the external robotics, which can be problematic on small ISS crews of three; two crewmembers are required at the robotic control station (one to control and one to monitor for safety) in addition to the pair of crewmembers outside for the EVA, nominally requiring a total crew of at least four.

Crew training currently is required for robotic operators, and this training needs to be supplemented with occasional practice sessions to maintain proficiency. To facilitate the use of robots by the crew, these robots need to be easy to command. They also need to be able to function around humans, either EVA or Inter-vehicular Activity (IVA), in a manner that is safe and does not interfere with crew activities.

ISS maintenance and inspection tasks performed robotically require extensive planning, which can take a team of engineers on the ground anywhere from two days to six months or more, depending on the complexity of the task. Due to the amount of time, effort and background systems knowledge required for robotic planning, the crew does not plan any robotic operations but follows carefully reviewed, prevalidated procedures. Future crew-operated caretaker systems will need to be able to plan tasks automatically with limited crew inputs.

Critical Gaps

Taxonomy Level 1	SENSE	PERCEIVE						REASON						ACT
Taxonomy Level 2	Sensing Element	Knowledge/Model Building	State Estimation and Monitoring	Knowledge and Intent Conveyance and Understanding	Hazard Assessment	Event/Trend Identification	Anomaly and Fault Detection	Mission Planning	Activity and Resource Planning	Motion Planning	Learning and Adapting	Diagnosis and Prognosis	Fault Response	Actuation
Present Capabilities in Space	with current technologies	done but needs to	done but needs to	done with current	done with current	but needs to improve	done but needs to	done with current	but needs to improve	done with current	done with current	done with current	done with current	done but needs to
Present Capabilities on Earth	with current technologies	done but needs to	done but needs to	done but needs to	done with current	but needs to improve	done but needs to	done but needs to	but needs to improve	but needs to improve	done but needs to	done but needs to	done but needs to	done but needs to
Identified Gap (Criticality)	Critical	Enabling	Critical	Enabling	Critical	Critical	Critical	Enabling	Enhancing	Enhancing	Enabling	Critical	Critical	Critical
Agencies' Research Activities on-going	Activities are on-going	Activities planned/on-	s are planned	are on-going	are on-going	Activities are on-going	Activities planned/on-	are on-going	Activities are on-going	Activities are on-going	Activities are planned	Activities are planned	Activities are planned	are on-going
Overall level of Gap Criticality	High	Low	High	Medium	High	Medium	Medium	Medium	Low	Low	Medium	High	High	High

FIGURE 17: CRITICAL GAPS – ROBOTIC CARETAKERS

Technology gaps related to teleoperated, autonomous robotics are addressed largely in the ISEGC Gap Assessment Report, *Telerobotics Control with Time Delays*. The main technology gaps identified in the Autonomy Gap Assessment Report are:

- High-speed space-qualified processors
- High-speed data buses
- Improved LIDAR
- Verification and Validation (V&V) of autonomous systems in integrated systems

In addition to these gaps, which are described in detail in the referenced report, caretaker robots also will need to be used by the crew, and/or operate autonomously in the presence of crewmembers. In the case of the crew operating and/or interacting with the systems, the biggest gaps lie in the area of planning the operations. Robotic planning currently is a very time-consuming task requiring extensive systems knowledge and coordination with other systems support teams – all of which is managed by the ground. Since the crew will have a limited need to interact with the robots, the training and skills maintenance requirements for robotic planning and operation need to be minimized as much as possible through the use of autonomous planning systems and simplified interfaces.

<u>Improved Autonomous Planning and Coordination</u>

In order to reduce the complexity and time required for crewmembers to plan any robotic activities, as well as reduce the reliance on ground control teams, caretaker systems should be capable of planning tasks given a high-level command, or as a response to an anomaly. For example, to swap an external battery on the ISS takes weeks of planning and command script building and verification. Future systems should be able to autonomously plan all the required subtasks to replace battery A with battery B, including motion accounting for other constraints such as clearances and keep-out zones. The system must be capable of scheduling and task coordination with other autonomous systems, such as verifying power shutdown of the circuit before removing a battery.

Human/Robotic System Interaction – Simplified Commanding

In order to reduce the requirements for training and skills maintenance, the commanding of robotic systems should be simplified. In addition to the current hand controller and computer interfaces, command inputs, such as voice and gesture detection, need to be developed so that the robot can easily assist suited crew members without requiring manual inputs via a keyboard or hand controller. Crew commands should be intuitive and must not require extensive crew training or skills maintenance and must be at a high enough level to not require any extensive planning on the part of the crew.

Human/Robotic System Interaction – Safe Proximity Operations

Currently, teleoperated systems are typically disabled whenever external crewmembers are present in close proximity in order to ensure they do not interfere with crew activities. Autonomous systems will need to be able to safely work around and interact with the crew, whether the crew is suited or in a shirtsleeves environment.

Fully Autonomous Robotic Systems

In some cases, robots may be set to autonomously function for long durations without human interaction, such as for remote In-Situ Resource Utilization (ISRU) system maintenance. For systems which are neither intended to be teleoperated nor crew commanded but are in fact fully autonomous, advanced decision-making capabilities will be required in order to allow the system to adapt and to react to unforeseen events in the correct manner without relying on human input – but still maintain safe operations in the presence of humans and follow human commands when required.

8.7. STOWAGE MANAGEMENT

Once beyond-LEO missions are defined and resource needs evaluated, stowage management – the capability to correctly stow items, trace their positions within the spacecraft, avoid incompatibilities that can harm them (i.e., hard drives stored close to magnets), and validate loading and unloading procedures – becomes a key factor for the success of exploration endeavors. Increasing the level of autonomy in managing items and resources onboard a spacecraft will:

- Increase the overall safety of the mission by assuring planned resources are loaded or present onboard and avoiding mistakes during unloading operations
- Monitor loading operations to assure needed items are not unintentionally returned to Earth, jettisoned or otherwise disposed
- Safeguarding science by ensuring that unique equipment for conducting experiments is not lost and can be located in a timely manner
- Increase onboard operations efficiency by reducing crew time spent in preparing for operations and permitting quick location of needed tools/resources
- Improve onboard operations reliability by combining improved tracking technology and advanced operational concepts
- Free crew time for higher-value tasks by reducing the crew time spent taking inventory and managing stowage logistics
- Increasing packing efficiencies, owing to denser packing methodology that becomes feasible when finding items is not an issue

Present Capabilities in Space

Stowage management has been a significant component of human spaceflight programs since the beginning, with increased levels of accuracy/complexity in response to the different missions' needs and durations. As exploration destinations move further from LEO, resupply missions (when foreseen) will become less frequent and costlier, both in financial resources and time. In such deep space missions, inadequate logistics management (for example, improperly loaded items, insufficient embarked resources, and/or unwanted deterioration of assets), can lead to catastrophic consequences. At the outset of the ISS Program, optical barcode technology was established as the basis for audits and tracking. The handheld barcode reader is used by the crew to read barcodes attached to Cargo Transfer Bags (CTBs), resealable bags, individual items and labels on ISS that denote stowage locations. The reader interfaces wirelessly to a database called the Inventory Management System (IMS). Instances of the IMS database exist on the ground, as well, and the two are synchronized by two delta files each day. While routine audits, based on the barcode reader, were originally planned, they occur very infrequently due to the labor-intensive activity that involves successively pulling items out of stowage location, CTBs and/or resealable bags while keeping other items from floating out.

The IMS database, used by flight controller disciplines and by the entire stowage and inventory community, provides the most recent snapshot of the items on board the ISS. It also is used to generate stowage notes required in the crew's daily activities (i.e., to create a list of supplies and equipment that the crew will need to execute a procedure for an activity) and to monitor consumables to ensure adequate resupply. IMS is managed (updating, data management, etc.) by the flight controllers on the ground (Inventory Stowage Officers, or ISOs), based on the onboard daily activities. Given the complexity of ISS logistics operations and the limited cargo visibility afforded the stowage officers, the IMS and related stowage processes have proven remarkably useful. However, the database accuracy is entirely dependent on rigid adherence to processes involving humans subject to an enormous workload. In addition, the management of the IMS requires a huge effort from operators, depends on crew reporting, introduces a high chance to make mistakes, and decreases the crew's autonomy – all very important aspects in view of long-term exploration missions.

In 2008, NASA began conducting experiments with passive-tag RFID on the ISS to allow for rapid audits during an era when cargo resupply was limited and consumables occasionally became scarce. Since then, the abundance of commercial resupply opportunities alleviated some of the pressure on frequent, accurate inventories. Concurrently, though, more cargo was being unloaded onto the ISS than had ever been planned. Stowage volume became scarce, and on-orbit cargo-packing density increased. These factors contributed to increased crew difficulties in locating items. The handheld RFID functionality has been used occasionally to assist in searching for tagged items, with mixed success.

In 2015, NASA initiated the RFID-Enabled Autonomous Logistics Management (REALM) experiment, the first step toward the development of a fully automated inventory management system. REALM-1 was the first of three experiments designed to address three main challenges:

- Limitations imposed by high Radio-Frequency (RF) scattering
- Difficulties with passive RFID tags becoming obscured
- Limitations imposed by passive-tag RFID's narrow spectrum band

To date, the REALM-1 has been successful in contacting and providing location assistance for a number of lost items since activation in February 2017 (approximately 34 items in 15 months), and it has been shown to be useful in discrepancy reports between IMS and the RFID database, possibly preventing items from becoming lost. Nevertheless, a number of challenges remain to be addressed and evolved. Location accuracy of static items has been steadily improving, and capabilities of machine learning have only begun to be exercised. Accurate tracking of moving items also is important, as the "last seen" location along a trajectory can convey critical information regarding the location of items, perhaps prior to being stowed behind a metal rack. Evolution of the currently ground-based software application called Complex Event Processing (CEP) remains forward work. For very deep-space missions, such as to Mars, a CEP system would likely be space-borne. Strategies on data retention and storage, as well as efficient processing, need to be considered. The CEP engines should have a certain degree of internal health monitoring and autonomous corrections. Methods to efficiently incorporate data context from a mobile free-flyer or so-called "smart drawers," in which the signal from RFID readers is fed to antennas inside the interior of a metallic container, also are in an early stage.

The REALM-2 and REALM-3 systems are designed to build upon the foundation established by the REALM-1 system. In particular, the REALM-2 main objective is to understand the roles of a mobile agent in Autonomous Logistics Management (ALM), and particularly, in locating items. More specific objectives include extending the coverage area and improving the location accuracy of a fixed reader system, such as REALM-1. The REALM-3 system is based on smart drawers. Several such drawers have been tested on ISS, but not connected to the REALM CEP system.

Further out on the ALM technology roadmap are high-accuracy real-time location systems. These are expected to allow for location accuracies at the cm-level, as well as determination of angular degrees of freedom. Such a capability allows for safer and more effective human-machine and machine-machine interactions, and may enable robotic precursor missions in which machines grapple, unpack, arrange and assemble cargo.

Similar to the REALM experiments, the Agenzia Spaziale Italiana (ASI) ARAMIS experiment on the ISS aims to increase accuracy and reliability of the stowage management system and to provide the crew accurate information on items' location and status, improving the efficiency and autonomy of crew operations. ARAMIS aims to demonstrate the use of augmented reality technology to improve efficiency of operations onboard the space station. During the experiment, the astronaut used a simple portable device equipped with software capable of recognizing predeployed markers or standard barcodes and stowage labels (through optical character recognition and barcode reader technology) for triggering the augmented reality response to provide the needed information, to either successfully perform preventive maintenance operations without the intervention of the ground control, and identify, locate and track items exploiting both the information contained in the onboard database and the data collected by the portable device (e.g., reading items' existing barcodes), by exploiting the onboard Wi-Fi connection to the IMS.

Critical Gaps

Taxonomy Level 1	SENSE	PERCEIVE						REASON						ACT
Taxonomy Level 2	Sensing Element	Knowledge/Model Building	State Estimation and Monitor	Knowledge and Intent Conveyance and Understand	Hazard Assessment	Event/Trend Identification	Anomaly and Fault Detection	Mission Planning	Activity and Resource Planni	Motion Planning	Learning and Adapting	Diagnosis and Prognosis	Fault Response	Actuation
Present Capabilities in Space	Can be done but needs to improve	done but	be done with	be done with	be done with	done but needs to	done easily	done but	done but	Applica ble	be done with	be done with	be done with	be done with
Present Capabilities on Earth	Can be done but needs to improve	done easily	done but	done but	done but	done easily and well	done easily	done easily	done easily	Applica ble	be done with	done but	done but	done but
Identified Gap (Criticality)	Critical	Enablin g	Critical	Enablin g	Enhanc ing	Enabling	Not present	Enhanc ing	Critical	Applica ble	Enhanc ing	Enablin g	Enhanc ing	Enhanc ing
Agencies' Research Activities on-going	Activities are on-going	s are on-going	s are on-going	s are on-going	Activitie s	are planned	Activitie s	s are on-going	s are planne	Applica ble	Activitie s	Activitie s	s are planne	s are planne
Overall level of Gap Criticality	High	Mediu m	High	High	Mediu m	Medium	Low	Low	High	Applica ble	Low	High	Mediu m	Mediu m

FIGURE 18: CRITICAL GAPS – STOWAGE MANAGEMENT

The gap assessment revealed critical gaps in several areas:

<u>Sensing Element</u>

Precious crew time onboard the ISS is devoted to maintenance and stowage management operations. During loading/unloading operations or inventory checks, crewmembers can be asked to manually check items contained in flight bags that are frequently stored in multiple layers against spacecraft walls. Techniques should be advanced to automatically sense items within densely packed containers (with high metal or liquid content), and innovative solutions should be developed to permit the tracking of items that are too small to be tagged with current tags, and consumables, such as food and clothing. Complete tracking of food (i.e., what remains vs. what was provided, and comparing what remains at a given time point to what was projected to remain [i.e., the real vs. the projected rate of consumption]), especially when options for resupply do not exist, would facilitate real-time replanning of nutritional strategies as missions progress. Automatic tracking of food "shelf life" also would ensure that items with shorter shelf lives are identified and prioritized for consumption to minimize food waste due to spoiling. The current technology should be advanced to provide a sufficient level of reliability in view of beyond-LEO exploration missions. Significant consideration should be given to requirements for ALM technologies. For example, a mapping of location accuracy and the associated value or capabilities derived should be established as a basis for requirements. Similarly, the granularity requirement for item tracking should be considered carefully. For example, do AA-size batteries need to be tracked at the individual cell level, or rather at a stowage bag-level of a small quantity of batteries? Closely related is the accuracy requirement for different types of assets. A relaxed accuracy requirement for lower criticality assets may still achieve significant operational benefits at a greatly reduced cost and mass by allowing for soft decisions through machine intelligence.

<u>State Estimation and Monitoring</u>

Allowing the crew to quickly locate items and tools within the spacecraft will improve onboard operations' efficiency and reliability. An autonomous system capable of taking trace of items' positions, potential incompatibilities, and elements' states (especially perishable or small items) is not currently available. Research activities tackling some aspects of the overall issue are ongoing onboard the ISS (e.g., REALM and ARAMIS), but the inability to provide a high read accuracy of tags (i.e., readers cannot always detect a huge number of tags having different positions and orientations within a bag), to offer a precise item real-time location, and to identify when incompatible items are collocated or improper tools have been selected for a procedure is considered a gap to be filled in preparation for future missions. The use of innovative solutions (e.g., augmented reality tools, visual recognition algorithms and advanced software applications) should be investigated and validated in space. Fusion of different sensors and data analytics tools should be considered, as sensors that satisfy one requirement often fail at others. For example, battery-powered tags can provide for more robust links to a reader but are usually unsuitable for small items and entail a mass penalty. Firm establishment of requirements and a minimal mass/volume solution will be critical.

<u>Knowledge and Intent Conveyance and Understanding</u>

A reliable stowage management system must be capable of collecting data from different sources, processing them correctly, updating existing databases, autonomously making decisions and planning actions, and communicating them to the correct entities/interfaces. The interaction among multiple devices (e.g., sensors in equipped racks, portable devices and laptops) must be assured; intelligent software should be developed to process the collected data, derive actions and predict items states and needs; and a complete interface between information management systems should be assured (e.g., the onboard IMS and crew procedures databases). Experiments on board are only marginally addressing the gap. For example, ASI ARAMIS interfaced only partially with ISS systems and did not require any connection to telemetry and tele-commanding systems. It did set up a connection to the onboard IMS through the ISS Wi-Fi. This allowed the crew to have the current status of stowage configuration and inventory items. Additional functionality, such as Internet Protocol Version (IPV) connection, can be exploited in a future version. A complete integration of different databases (i.e. planned launch manifests, planned crew operations or IPV) from different agencies also would be beneficial.

<u>Activity and Resource Planning</u>

Activity and resource planning are mainly performed on Earth by flight controllers. Although this task is easily done on Earth, beyond-LEO missions will demand progressively higher levels of planning capabilities onboard the spacecraft. Experiments are ongoing (e.g., ARAMIS attempted at validating systems and procedures to increase the items tracking and crew operational autonomy in order to increase the overall resources availability awareness), but additional actions should be envisioned to move from an Earth-based to a spacecraft-based planning system. An increased interaction between onboard-collected data (i.e., visual recognition and tracking of items ensured by portable devices) and the ground-based database, together with onboard-generated operational concepts, would increase crew autonomy, operations reliability and overall safety of the mission. REALM is moving in the right direction, trying to interface IMS with the onboard CEP software information. A subsequent migration of the ground-based stowage management system onboard the spacecraft, in combination with adequate items-state-estimation and resource-needs-prediction capabilities, is considered crucial.

<u>Diagnosis and Prognosis</u>

Once proven methods and software applications are capable of closing the "*<u>State Estimation and Monitoring</u>*" gaps, predictive software should be developed to forecast the state of items and consumables and anticipate what items are necessary for each mission. Decision-making capabilities, such as the autonomous creation of cargo manifests for resupply missions, should be investigated. In addition, an in-space autonomous software testing, verification and validation is needed.

9. CROSSCUTTING AUTONOMY CHALLENGES

The GAT identified challenges that were relevant for multiple aspects and mission destinations:

<u>Communications</u>

Robust capabilities to enable autonomous operations of complex systems often require persistent and large amounts of health and status data – data which may be generated by physical or simulated means. The GER scenario calls for ground-based controllers to play a key role in the operation and maintenance of mission assets beyond LEO. To accomplish this role, data from mission assets must be communicated to Earth-based command/control and decision support systems. It is therefore reasonable to assume that data transmission rates and bandwidths may require new communications approaches and capabilities. Robust capabilities to enable autonomous operations can often require persistent and large amounts of recent and valid data, which may be generated by physical or simulated systems. This may include communication between assets while operating, as well as communication with ground segments. NASA also continues to enhance capabilities of its space communications network to support exploration to distant destinations. While a critical gap is not identified, the data rate requirements needed to support autonomy in various applications needs to be defined, as well as the evolution from Earth-based mission operations to mission operations based at distant destination (especially for high data rate communications). It is strategically wise to conduct studies to understand performance limitations and establish requirements for mission systems and/or new enabling technologies. Communications capabilities and requirements should continue to be assessed as technologies and systems to support autonomous operations mature.

In order to migrate to local control of mission systems beyond LEO, local communications outages must be minimized or eliminated.

As machine learning and automated reasoning capabilities mature and become reliable, the trust in and acceptance of autonomous capabilities will evolve. As this trust grows and is proven, less and less data will need to be transmitted from destination points to Earth-based assets.

<u>Cybersecurity</u>

Ensuring the security of our cyber resources is vital to ensuring capabilities are not compromised, particularly those which enable autonomy.

<u>Radiation Protection</u>

Critical gaps in the protection of humans, live food sources and electronics from the effects of harmful radiation are well-known and are the focus of numerous studies and investigations within partner agencies.

<u>Trusted Autonomy</u>

Procedural control can provide automation that enables some level of crew, vehicle, station and surface-system infrastructure autonomy, but some level of machine intelligence will be needed to enable the fully-autonomous operation of some systems and functions to support long-term mission operations beyond LEO. Technology solutions are needed to determine when autonomous systems are trending toward or in a loss-of-control state. Methodologies and capabilities to verify the ability of autonomous systems to reason and make decisions that "do no harm" are evolving in the area of self-driving vehicles and unpiloted aerial vehicles, but more work is needed to develop an acceptable level of trust in autonomous systems. Until these gaps are overcome, safeguards should be in place to allow human or automated intervention. Guidelines on when and how to invoke that intervention are also needed.

Verification and Validation

There is a critical gap in automated methods for V&V, which results in a critical gap in the ability to perform low-cost V&V of software that is needed to address critical gaps and ultimately, enable autonomy for exploration beyond LEO. This gap also includes the certification/accreditation of models used to support the Level 1 tasks in the Autonomy for Taxonomy (Figure 3).

The lack of dust mitigation capabilities is recognized as a critical gap that will affect goals for sustainable autonomous operations at destination points and has been addressed by a separate gap assessment team.

10. TECHNOLOGY DEMONSTRATIONS

THE GAT MAPPED THE ASPECTS OF AUTONOMY TO APPLICABLE FUNCTIONS IN THE GER MISSION SCENARIO AND USED THIS MAPPING TO IDENTIFY POSSIBLE TECHNOLOGY DEMONSTRATIONS FOR THE LUNAR VICINITY, ROBOTIC PRECURSOR AND HUMAN MISSIONS TO THE MOON, AND THE HUMAN CAMPAIGN FOR MARS (

Figure 19).

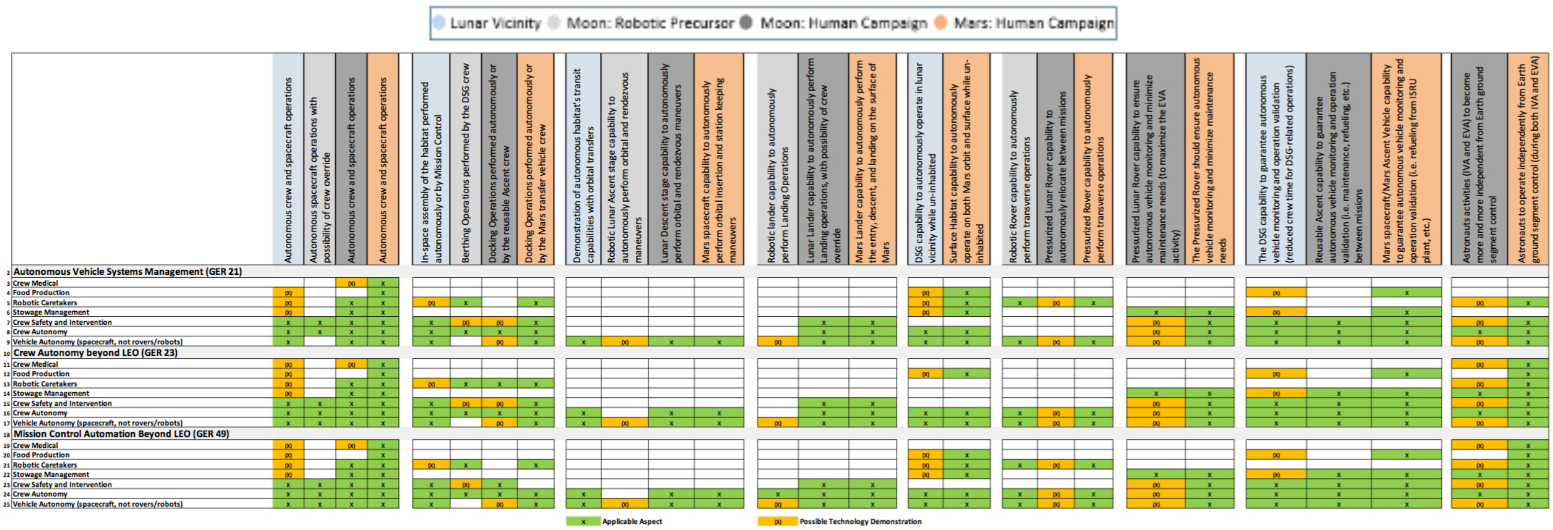


FIGURE 19: TECHNOLOGY DEMONSTRATION OPPORTUNITIES FOR ASPECTS OF AUTONOMY THROUGHOUT MISSION SCENARIOS

The GAT further derived demonstration opportunities for the seven aspects of autonomy for each of the Critical Technology Areas (GER 21, GER 23 and GER 49) in Figure 20, Figure 21 and Figure 22, respectively. A filled circle indicates the capability is needed for exploration at the destination (e.g., lunar vicinity). A red circle surrounding a filled circle indicates the mission destination is the first opportunity to conduct a technology demonstration. The demonstration opportunity applies to all aspects on the same row as the red circle.

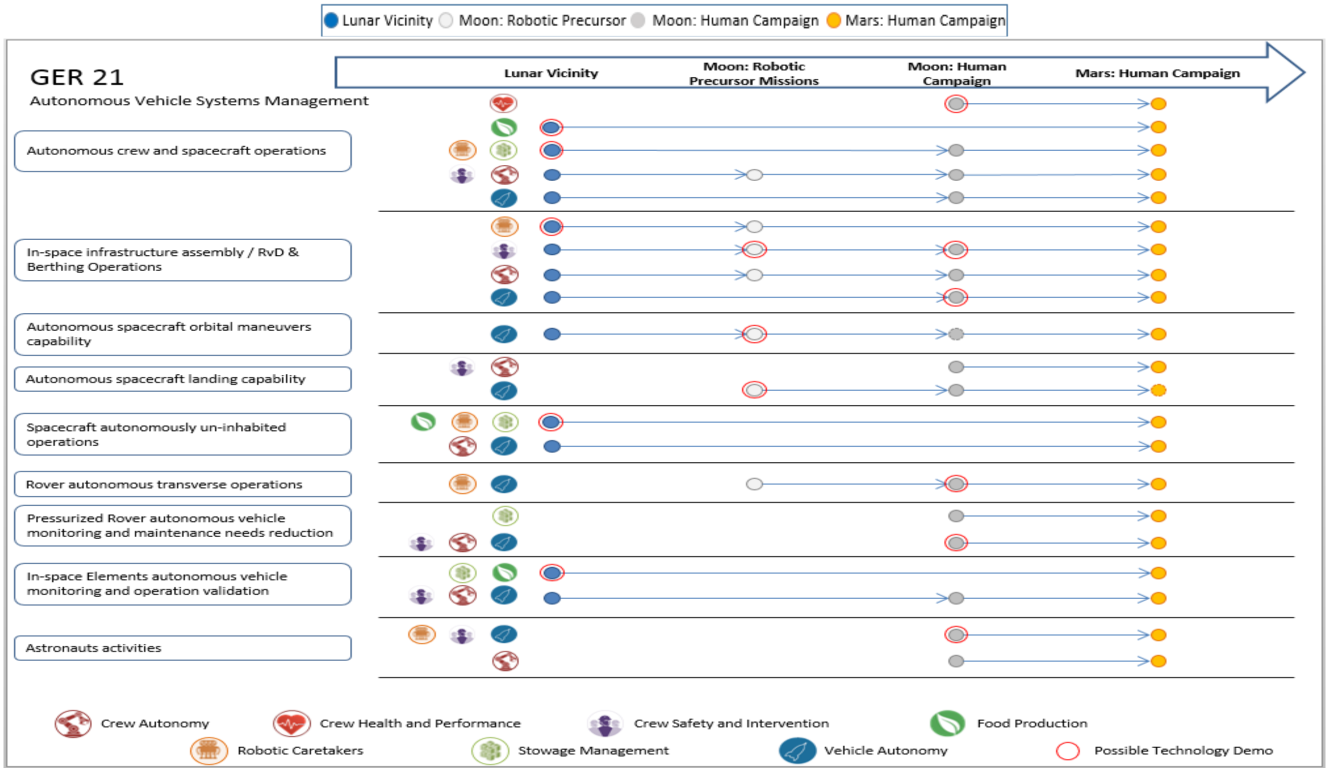


FIGURE 20: POSSIBLE TECHNOLOGY DEMONSTRATIONS FOR GER 21

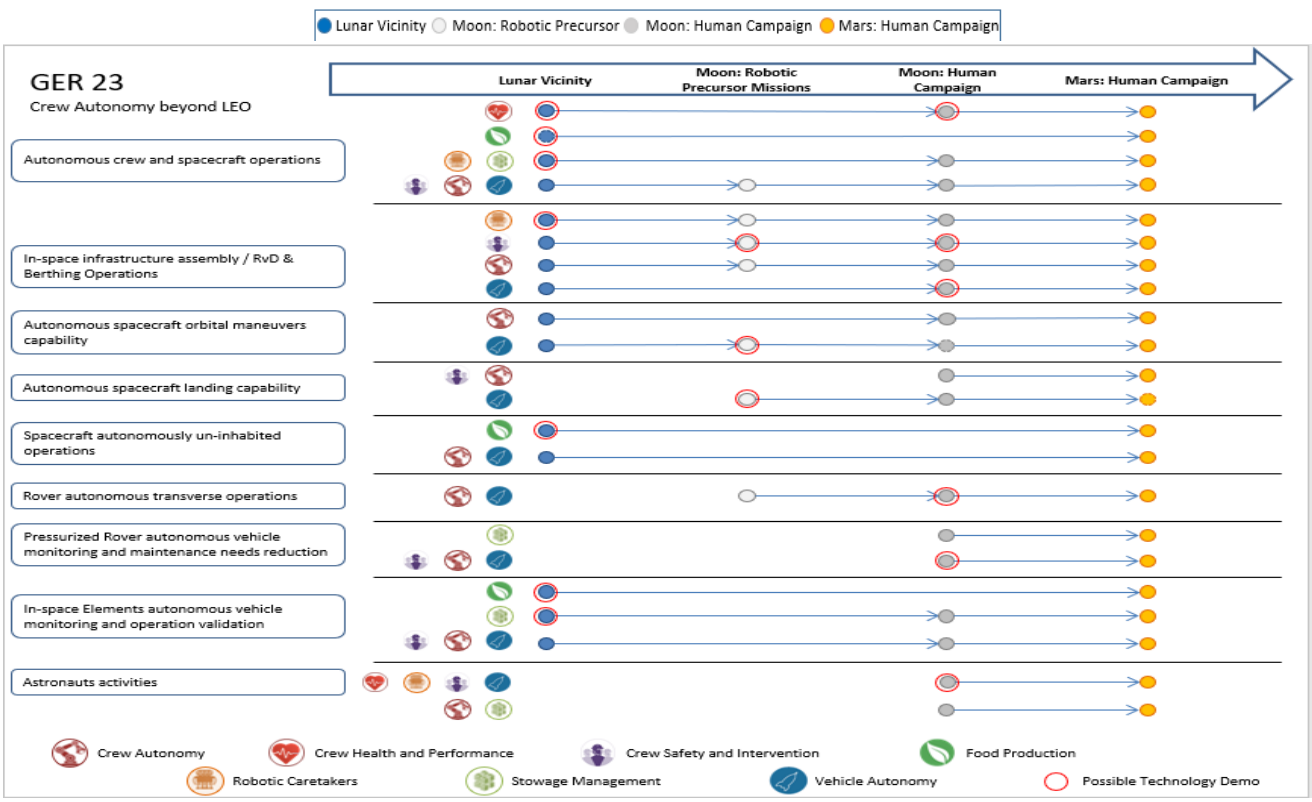


FIGURE 21: POSSIBLE TECHNOLOGY DEMONSTRATIONS FOR GER 23

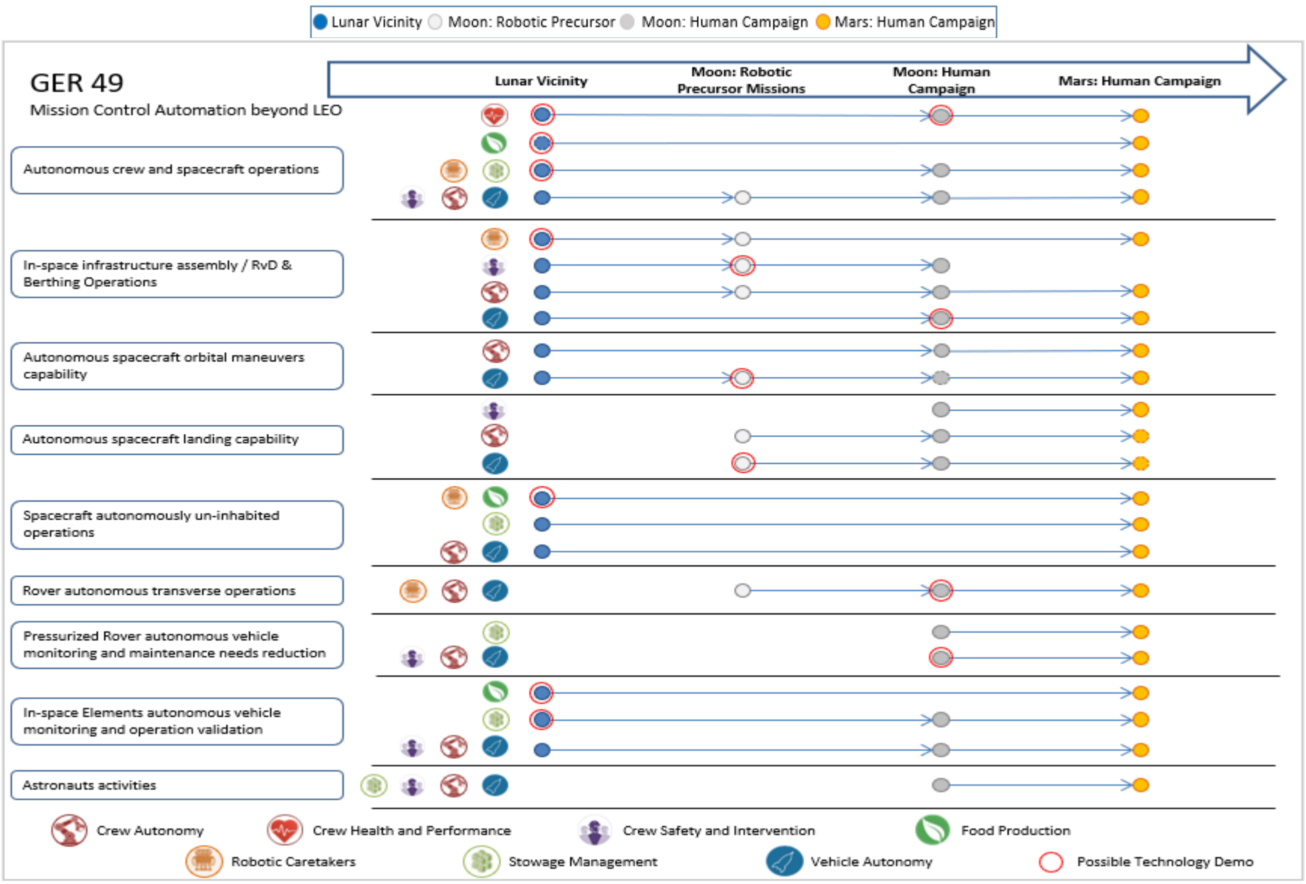


FIGURE 22: POSSIBLE TECHNOLOGY DEMONSTRATIONS FOR GER 49

11. PARTNERSHIP OPPORTUNITIES

The technology demonstration opportunities identified in the previous section (Figure 20 – Figure 22) provide prospects for partner agencies and industry collaborations to mature technologies and advance capabilities that enable autonomy for exploration beyond LEO. Partners can assess these opportunities and formulate plans to collaborate on technology development and demonstration in various ways:

Planning and Coordination

Partner agencies can continue to coordinate on a) monitoring the progress of technology development and demonstrations, b) communicating technology advances and c) updating the mission scenario and concepts of operations as technology gaps related to autonomy are closed.

Data and Information Sharing

Partner agencies can conduct joint conferences and seminars on autonomy and establish a new (or utilize an existing) secure joint repository to share data, papers, reports and lessons learned.

Research and Development

Partner agencies can promote and participate in joint programs/projects, coordinating research objectives, roles/responsibilities and schedules to minimize duplication and maximize progress.

Hardware/Software System and Subsystem Development, Test and Demonstration

Partner agencies can promote and participate in joint programs/projects, coordinating performance and design objectives, roles/responsibilities and schedules to minimize duplication and maximize progress. Partner agencies also can coordinate on the minimum set of standards and the minimum set of data needed to a) enable development and test, b) facilitate integration, c) ensure trades, benchmarks and demonstrations are relevant, d) minimize rework and e) ensure future mission infusion.

12. PRIVATE SECTOR INVOLVEMENT

There are a number of promising technologies, capabilities and applications currently available in the private sector that could have an impact in bridging gaps on autonomy identified in this report:

Communications

Collaborative aerial system consisting of drones with onboard sensors and embedded processing, coordination and networking capabilities currently are being investigated. Multi-drone systems are being considered in disaster assistance, search and rescue, and aerial monitoring. These technologies can be beneficial for bridging communication gaps.

Crew Health and Performance

Currently, few off-the-shelf solutions seem available in the private sector to support autonomous health care. Telepresence, telesurgery and telemedicine rely on remote expertise currently not available for deep-space missions or scenarios with significant communication delay. Some elements, parts and specific technologies are available, mainly in data capture and diagnostics, but no integration on a whole system suitable for significant support in complex medical applications is currently known to be under commercial deployment.

The constraints of exploration bear many similarities to those of professional emergency medical treatment on Earth in difficult environments (e.g., military and remote/mobile civilian), or where potential patients are separated from medical professionals (e.g., commercial aircraft). There are already some examples of commercial terrestrial technologies that integrate multiple medical devices into a compact, mobile device (e.g., RDT Ltd's TEMPUS PRO) and can aid non-expert users in establishing a telemedicine connection and capturing key clinical data for review by expertise off-site (e.g., RDT Ltd's IC2). There is potential interest for the private sector to address closing technology gaps which would enable crew medical care in space – and closing these gaps also would have positive benefits for an aging society and remote communities on Earth. It is necessary for space agencies to encourage investors to devote resources to pursuing these solutions.

Cybersecurity

Currently, technologies of machine learning, planning and human interfaces are being applied in the context of cybersecurity. Security immune systems, which apply automation and machine-learning capabilities to identify malicious behavior in a computer system or network, are considered a key technology in cybersecurity research, and a number of commercial applications on that basis already exist. Of course, this also is relevant in the space context. Another current trend is to improve security by automating more and more system administration and configuration functions. This then reduces the risk of the possible escalation of privileges during a cyberattack. Cloud providers are using this technology. In terms of communication security, a lot of spin-in is happening. For example, space-link security is benefitting from spinning in Internet Protocol Security (IPSec) and other security protocols.

Gaming Technologies

All state-of-the-art gaming consoles offer some form of motion-control technologies, speech recognition capabilities and applied examples of AI. Sophisticated depth-sensing cameras can track movements without a physical controller, combining also gyroscopes, accelerometers and magnetic sensors. These technologies can support autonomy and enable advanced User Interface (UI) based on voice, gesture and eye tracking commands.

Machine Learning

Machine learning can be used on board to automatically identify opportunistic science targets and support autonomy. The most plausible approach is to train machine learning models on the ground and uplink the models for their onboard or remote utilization. Depending on the selected machine learning approach, specialized hardware may be needed (e.g., graphical processing units, or GPUs). Some vendors already provide space-qualified GPUs. The usage of machine learning frameworks is recommended, as they speed up the development and deployment process enormously. Some frameworks are already compatible with GPUs and even with the space-qualified versions of these GPUs. Machine learning is a groundbreaking technology to support a wide spectrum of autonomous capabilities.

Mission Control Automation and Autonomous Facilities

Companies currently are working on fire safety, security, automation, heating, ventilating, air-conditioning and refrigeration systems and services to promote integrated, high-performance buildings that are safer, smarter and sustainable. The whole field of "domotics"[2] is full of solutions and implemented systems that can apply in bridging the gaps identified in providing autonomy for habitats and labs.

Radiation Protection

There are companies with core competence on design of radiation-hardened integrated circuits, more specifically electronic devices that reliably operate in both ionizing and particle radiation environments. Main application areas outside space include particle accelerator centers, medical devices for diagnostics and therapy. These technologies can be beneficial for space-qualified sensors and hardware to support autonomy.

Robotic Caretakers

Robotic systems for search-and-rescue and operations in hard conditions (mines and deep water) already are operational.

Vehicle Autonomy

Almost all the big car producers are working on Level 5 self-driving cars. Of course, technologies applied on sensing, perception, reasoning, decision-making and collision avoidance can be beneficial to cut the gaps identified in vehicle autonomy.

[2] A contraction of the Latin word for home, "domus", combined with robotics, a common synonym for home automation.

<u>Verification And Validation</u>

V&V are concerned with answering two fundamental questions: did we build the right product, and did we build the product right? This issue has been identified as a crosscutting gap and a fundamental building block for trustable autonomy. Quite a number of companies currently are working on formal methods of V&V of embedded systems for avionics/aeronautics, space, transport, automotive, telecommunications, smart cards and consumer electronics. These companies have solutions to lower the cost of model certification/accreditation (for use in decision-making), solution for assembling software "correct by construction" and for increasing the user's trustiness in software (in general and for autonomy in particular).

While there are many advances in the private sector, it was beyond the scope of the GAT to effectively coordinate an approach for leveraging these advances among partner agencies to further goals for autonomy as defined in the GER.

13. KEY FINDINGS AND OBSERVATIONS

KEY FINDINGS

Member agencies, academia and commercial providers have made advances in Earth-based capabilities that provide solutions and options that can be applied or leveraged to meet the goals of the GER mission scenario. Significant gaps in capabilities needed to enable the GER mission scenario were identified, however, and the overall assessment of the criticality of the gaps for each of the aspects of autonomy are captured in Figure 23 and Figure 24.

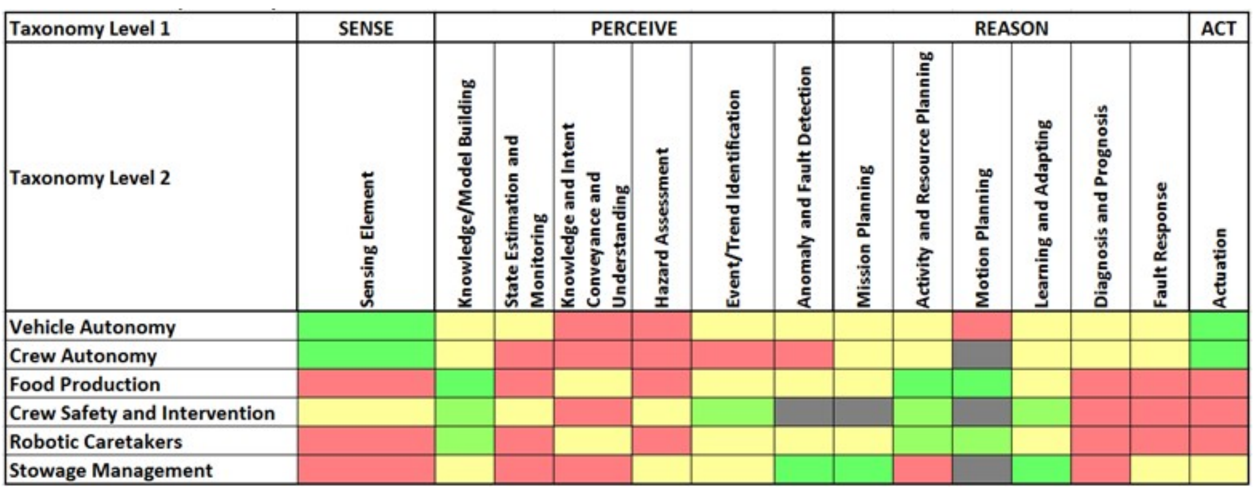


FIGURE 23: OVERALL GAP ASSESSMENT FOR NON-MEDICAL ASPECTS OF AUTONOMY

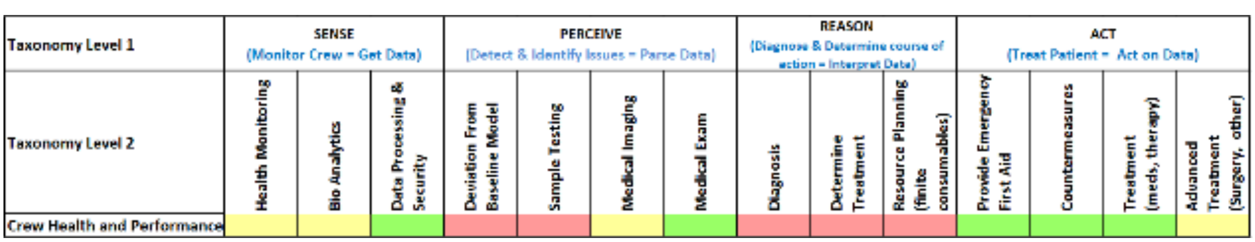


FIGURE 24: OVERALL GAP ASSESSMENT FOR CREW HEALTH & PERFORMANCE

A summary of the gap criticality for each of the seven aspects is provided below.

Vehicle Autonomy

- In the field of autonomy in support of crew decision-making, perception and reasoning are the areas requiring more work.
- In the field of autonomy without humans in the loop, some systems (e.g., Timeliner) have been successfully deployed on the ISS and could be expanded to future Moon and Mars exploration activities.
- While investment in research activities from different space agencies cannot be neglected, the path for autonomous systems to be deployed in vehicles is very complex, even more so for crewed vehicles. As a result, most of these systems do not reach enough Technology Readiness Level (TRL).
- A machine-learning boom in Earth applications might have positive effects in potentially every autonomy function described in the report (e.g., knowledge modelling, motion planning, etc.).

Crew Autonomy

- Mission control capabilities must be enhanced. Ground systems currently used to pre-plan almost every task to be executed on board must evolve to support operations concept and mission scenarios that will migrate from ground-based controllers to autonomous control at the destination point, where only long-term strategic planning will be ground-based.
- The gap assessment revealed critical gaps mostly concentrated in the area of perception and situational awareness. It is currently an issue to infer temporally contextualized knowledge regarding the state of the user (based on heterogeneous sensor readings and previously inferred knowledge). This appears to be the most critical gap, for the lack of technologies and competences also on terrestrial applications.
- A criticality also can be envisaged on what concern the V&V of the technologies embedded in the intelligent ambient, as well as the need of providing understandable and transparent behavior (explainable AI).

Crew Health And Performance

- Substantial investment in Research and Development (R&D) is ongoing for in-situ bio-analysis tools, with further fine-tuning required. Further R&D into systems supporting health monitoring, diagnosis support, resource planning and robotically-assisted surgery are some of the key gaps identified in this report.
- Certain crew autonomy systems will benefit from advanced developments in terrestrial applications, spinning-in technologies matured through application in hospitals, other medical facilities and other industries.

Food Production

- Larger scale terrestrial demonstrations for autonomous food production and demonstrations in LEO are progressing in the area of plant growth and plant habitats, but currently cannot be scaled up to a level to demonstrate sustainable, autonomous production to provide food and nutrition for the crew during operations beyond LEO.
- Critical gaps must be addressed in the areas of sensing, knowledge and intent conveyance and understanding, anomaly and fault detection, diagnosis and prognosis, fault response and actuation to enable food production beyond LEO.

Crew Intervention and Safety

- Due to the complexities associated with automated decision support systems and autonomous operations, it is vital to provide information to the crew in a comprehensive and intuitive format to increase crew confidence in system alerts and actions.
- Technology maturation/demonstration in operational environments is taking place and will help to understand and improve the balance between requirements for autonomous intervention and manual intervention to ensure crew safety.
- Additional research is required to ensure transparency in plans and decisions made and carried out by automated/autonomous systems. Critical gaps must be addressed in knowledge and intent conveyance and understanding, diagnosis and prognosis, fault response and actuation in order to ensure the crew is not put into an unsafe condition or that the crew does not unknowingly create an unsafe condition.

Robotic Caretakers

- For the cislunar environment, where the time delay is fairly short, robots may be teleoperated from Earth. As missions venture deeper into the solar system and time delays from Earth increase, robotic caretaker systems will need to be able to plan tasks automatically with limited crew inputs. These systems also will need to operate in the presence of human crew and as team members with human crew.
- Critical gaps must be addressed in sensing, state estimation and monitoring, hazard assessment, diagnosis and prognosis, fault response and actuation in order to enable crew and mission autonomy beyond LEO.

Stowage Management

- Demonstration and test of cargo and inventory management systems onboard ISS are paving the way for maturation of a capability for robust capabilities to support crew and mission autonomy beyond LEO.
- Critical gaps in sensing, state estimation, knowledge and intent conveyance and understanding, activity and resource planning, diagnosis and prognosis must be addressed to complete the technology maturation process.

OBSERVATIONS

Consider autonomy from the early mission design phase

It is critical to consider the potential capability and needs for autonomy when designing new mission concepts and mission scenarios. Autonomy can definitely provide dramatic increase of science data, both in quality and quantity, or become an enabler element of future missions. Hence, experts in autonomy should be sitting around the ”conceptual” table to raise awareness of what can be done and allow mindset transformations of stakeholders to happen for progressive acceptance of autonomy where it is justified and can provide added value at acceptable risk. This change of mindset is a necessary prerequisite for any technical application of autonomy for operations beyond LEO.

Coordinate design, operation and exploitation of autonomous operations

An approach where autonomy studies and projects should see involvement from a combination of space segment, ground segment and operations experts is required. Operations will be deeply affected by introducing autonomy; and its exploitation, on board, should require strong coordination with SMEs having operations expertise to ensure design requirements are correctly captured and operational design constraints are considered. The applicability of autonomy shall cover all phases of the life cycle, including the design process, the operations and the data exploitation.

Autonomy in space missions raises exciting interest along with opportunities and challenges. A strategy on how to develop, validate and deploy progressive, dependable and secure autonomous operations capability at acceptable risk levels should require contribution of expertise across all domains.

Create a community

A transversal community of experts across organizational boundaries and competences is already happening (with this report, for instance). We should encourage and support such a community within and across the international partners to grow across space industry at large, including research institutes, to make autonomy a new asset for space. This is crucial to ensuring all partners benefit from the advances made and forward progress is sustained in closing gaps.

14. RECOMMENDATIONS

Based on the crosscutting gaps, key findings, and observations, the following recommendations were developed:

RECOMMENDATION 1: COMMUNICATE GUIDELINES, CONVENTIONS AND STANDARDS

It is recommended that the ISECG ensure communication of guidelines, conventions and standards for autonomous systems among the partner agencies to facilitate integration of hardware and software elements, ensure technical and operational interoperability, and facilitate sustainability. Adherence to common guidelines, conventions, nomenclature and standards will help to mitigate the risk associated with integrating software and hardware, which in turn will minimize and/or eliminate the need for costly redesign and delays in achieving timelines for exploration. Guidelines and standards also will help ensure design, test and performance objectives are met. Guidance may evolve as operations and design concepts mature.

One example of an international working group already communicating guidelines, conventions and standards for technical and operational interoperability is the Interagency Operations Advisory Group (IOAG).

RECOMMENDATION 2: ENABLE ROUTINE ASSESSMENT OF AUTONOMY TECHNOLOGY GAPS

In order to keep up to date with the identified technology gaps and the proposed actions for closure, it is recommended to support a continued Autonomy gap assessment effort. The periodicity of this exercise would be defined by the ISECG perceived needs. The intention is for a renewed team to be established at a later point in time and continue coordination among partner agencies and industry. The future Working Group (WG) would need to communicate with groups coordinating international standards (such as the International Deep Space Interoperability Standards and the Consultative Committee for Space Data Systems) to assess if the appropriate standards are being used to facilitate integration of hardware and software elements and ensure interoperability.

The working group would first assess if the previously identified technology gaps have been addressed and continue to review and recommend key technology/engineering solutions that can be leveraged to close identified technology gaps. Experts from existing related working groups could be invited to join future ISECG Autonomy gap assessments in order to bridge specialized knowledge of individual aspects of autonomy for future exploration missions. Some examples are the autonomy team under the Gateway Vehicle System Manager (SVM) WG; and the International Crew Health and Performance (ICHP) WG for Gateway and beyond.

RECOMMENDATION 3: ESTABLISH COMMERCIAL PARTNERSHIPS

Establish strong partnerships with commercial industry to plan technology development and demonstration activities to advance capabilities and meet GER goals for autonomy.

In the scope of the GER and its associated critical technologies (i.e., gaps needing closure), the dissemination of technical information (nationally and agency generated) to the TWG is seen as a very interesting mechanism to raise awareness and focus the discussion on technology needs in view of potential interagency and/or commercial future partnerships. This would increase the synergies related to capability and technology development among stakeholders in the area of lunar and Mars surface exploration. The objective would be to increase the dialogue and coordination with external organizations (i.e., non-space agency organizations, mainly industry) regarding capability development and technology needs to eventually enable comprehensive scientific exploration and sustained human presence on the Moon and, ultimately, on Mars.

Commercial partnerships may provide access to the surface or to orbit for payloads, or for the delivery of CubeSats to both lunar and lunar-vicinity space. Lunar exploration is increasingly emerging as the next global strategic priority in space exploration, and the latest developments are expected to further support highly ambitious government and commercial missions. While space agencies are and will remain the driving force behind space exploration activities, private players' interests and contributions are increasing with more public-private partnerships established thanks to programs such as NASA's Commercial Lunar Payload Services program and ESA's Commercial Partnership Initiative. Partner agencies recognize and embrace this opportunity as is evidenced by JAXA's new program called JAXA Space Innovation Partnership through Co-creation (J-SPARC), which supports the private business through JAXA's technologies and assets. U.S. Space Policy Directive 2 (SPD2) and Canada's Space Strategy both encourage commercial partnerships and are examples of the strong push toward public and private partnerships.

RECOMMENDATION 4: PLAN AND CONDUCT TECHNOLOGY DEMONSTRATIONS

Partners should assess the technology demonstration possibilities identified in Figure 20 through Figure 22 and, where possible, collaborate to share resources (e.g., test facilities, etc.), and formulate plans to mature, assess and enhance technologies for each stage of the mission scenario. Partners should ensure the capture of subsystem and test data to enable trade studies and collaborate on the development and testing of tools, techniques and approaches in terrestrial and space-based environments. Promoting inter-organizational and international collaborations in the early planning and conduct of strategic technology demonstrations will be the key to success in overcoming the challenges of our global Lunar and Mars exploration goals.

APPENDICES

APPENDIX 1: AUTONOMY GAP ASSESSMENT TEAM ROSTER

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APPENDIX 2: ACRONYMS LIST

3D	Three Dimensions
AI	Artificial Intelligence
ALM	Autonomous Logistics Management
AMO	Autonomous Mission Operations
AOCS	Attitude and Orbit Control System
APH	Advanced Plant Habitat
ARAMIS	Augmented Reality Application for Maintenance, Inventory and Stowage
ASI	Agenzia Spaziale Italiana
BLEO	Beyond LEO
BMD	Bone Mineral Density
CEP	Complex Event Processing
CM	CounterMeasure
CMO	Crew Medical Officer
CNES	Centre National d'Etudes Spatiales
CO_2	Carbon Dioxide
COTS	Commercial-off-the-Shelf
CSA	Canadian Space Agency
CTB	Cargo Transfer Bag
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DSG	Deep Space Gateway
ECLSS	Environmental Control and Life Support System
EMI	Electromagnetic Interference
ESA	European Space Agency
EVA	Extra Vehicular Activity
FDIR	Fault Detection, Isolation and Recover
GAT	Gap Assessment Team
GER	Global Exploration Roadmap
GNC	Guidance, Navigation, and Control
GPU	Graphical Processing Units
GTDM	GER Technology Development Map
HVAC	Heating, Ventilation and Air Conditioning
IAWG	International Architecture Working Group
ICHP	International Crew Health and Performance
IMS	Inventory Management System
IOAG	Interagency Operations Advisory Group
IPSec	Internet Protocol Security
IPV	Internet Protocol Version
ISECG	International Space Exploration Coordination Group
ISO	Inventory Stowage Officer
ISRU	In-Situ Resource Utilization
ISS	International Space Station
IVA	Inter-vehicular Activity
JAXA	Japan Aerospace Exploration Agency
JEM RMS	Japanese Element Module Remote Manipulator System
J SPARC	JAXA Space Innovation Partnership through Co-creation

LED	Light Emitting Diode
LEO	Low Earth Orbit
MFSP	MicroFluidic Sample Preparation (MicroPREP)
MSS	Mobile Servicing System
NASA	National Aeronautics and Space Administration
NEEMO	NASA Extreme Environment Mission Operations
NRHO	Near-rectilinear Halo Orbit
ORU	Orbital Replacement Unit
PLR	Pressurized Lunar Rover
POCD	Point-of-care-Diagnostics
R&D	Research and Development
REALM	RFID-Enabled Autonomous Logistics Management
RF	Radio-Frequency
RFID	Radio-Frequency IDentification
RGB	Red, Green, Blue
RvD	Rendezvous & Docking
SLAM	Simultaneous Localization and Mapping
SLS	Space Launch System
SME	Subject Matter Expert
SPD2	U.S. Space Policy Directive 2
TABS	NASA Technology Area Breakdown Structure
TBC	To Be Confirmed
TRL	Technology Readiness Level
TWG	Technology Working Group
UI	User Interface
VEGGIE	Vegetable Production System
VO_{2max}	Maximum Oxygen Uptake
VR	Virtual Reality
VSM	Vehicle System Manager
V&V	Verification and Validation
WG	Working Group