

IAC-07-A5.2.03

ROBOTIC ASSISTANCE, MOBILITY & VISION SYSTEMS – ENABLING TECHNOLOGY FOR EARLY HUMAN-ROBOTIC LUNAR EXPLORATION

Nadeem Ghafoor
MDA
nadeem.ghafoor@mdacorporation.com

Eric Choi
MDA
eric.choi@mdacorporation.com

Gita Ravindran
MDA
gita.ravindran@mdacorporation.com

Joseph Bakambu
MDA
joseph.bakambu@mdacorporation.com

Tim Barfoot
University of Toronto
tim.barfoot@utoronto.ca

Robert Richards
Optech Incorporated
robertr@optech.ca

Christian Sallaberger
MDA
christian.sallaberger@mdacorporation.com

ABSTRACT

In the 21st Century, space exploration will focus on surface exploration, with human-robotic collaboration allowing extended-duration stays at challenging lunar and planetary sites. This paper focuses on three early phases of lunar exploration: (i) *in-situ* characterisation and site survey for science, prospecting and reconnaissance in advance of human sorties (ii) *in-situ* human sortie field assistance, and (iii) transport of samples, equipment and small-scale infrastructure. In particular two technologies relevant to these phases are examined: surface mobility and advanced vision. For surface mobility, three areas of MDA technology development are discussed: (i) rover chassis simulation and evaluation, (ii) chassis prototype construction and field testing, and (iii) autonomous rover navigation systems for localisation, motion estimation and path planning. An overview of recent activities is given, including the development of a prototype chassis in preparation for the ESA ExoMars mission, and field tests of camera- and lidar-based navigation technologies in partnership with Optech, NASA and the Canadian Space Agency (CSA). The application of vision systems for navigation, science, prospecting and site survey is discussed. The merits of camera- and lidar-based systems are summarized, along with their applicability to the Moon in rover-mounted and astronaut handheld scenarios.

INTRODUCTION

The 21st Century space exploration frontier is markedly different from its predecessor. Whereas human and robotic exploration over the past 50 years featured exploration and development of the Earth-orbit environment, single-shot robotic missions to the major Solar System bodies, and short-duration human sorties to the lunar nearside equatorial region, exploration in the 21st Century will be increasingly surface-based, human-robotic collaborative, extended-duration in nature and targeted at more challenging regions of lunar and planetary surfaces.

For almost three decades now critical robotic systems have been flown in space to develop and support a sustainable human space exploration infrastructure. Applications have spanned astronaut and cargo transport, astronaut assistance, assembly and servicing, safety inspection and human-robotic collaborative repair of critical infrastructure elements.

Fig. 1: Human-Robotic partnership has increasingly characterised the past 25 yrs of space exploration
Credit: NASA

The capability, versatility and reliability of these robotic systems have been well demonstrated throughout the shuttle and ISS programs. Ultra-reliable robotics have provided a safe and cost-effective solution to the challenges of human infrastructure assembly and configuration for 25 years and in this time have been relied upon to deal with a wide variety of contingency, off-nominal and emergency situations.

This specific expertise and heritage will be crucial to space exploration as it enters its third era, that of sustainable planetary surface infrastructure, and the unforgiving extended-duration lunar surface frontier tests human-robotic capabilities to new limits.

This paper focuses on three early phases of human-robotic lunar exploration, namely: (i) *in-situ* characterisation and site survey for lunar science, prospecting and reconnaissance in advance of human sorties, (ii) *in-situ* human sortie field assistance, and (iii) transport of surface samples, astronaut equipment and potentially small-scale infrastructure. Specifically Two areas of robotic technology that support these three phases are discussed, (i) surface mobility and (ii) advanced vision, both for autonomous navigation and situational awareness.

Recent activities at MDA, the Canadian space prime, are described including the development of full-scale prototype rover chassis systems in preparation for Moon and Mars missions such as ESA's ExoMars, and field tested camera- and lidar-based autonomous vision systems for scene modelling and rover navigation, conducted in partnership with lidar partner Optech, NASA and the Canadian Space Agency (CSA).

Several of the systems, with heritage and applications spanning orbital and surface regimes, are already deployed in the terrestrial sector, including mining, survey and security. Vision system technology developments span camera- and laser-based regimes, and the merits of both technologies are discussed.

The utility of these robotic technologies to the lunar endeavour is explored through consideration of a number of rover-mounted and astronaut-deployed scenarios. Finally the importance of the past 30 years experience in successful orbital human-robotic partnerships for space exploration is underlined.

NEXT GENERATION EXPLORATION: SURFACE MOBILITY

Over the next two decades surface mobility will be a key element of lunar and planetary exploration, with upcoming missions, both human and robotic, being highly dependent on surface vehicles for exploration, characterization, transport and deployment. Mobile robotics is a key area of expertise and technology development for MDA, within which three areas of recent activity have been:

- Rapid design, simulation and performance evaluation of rover chassis designs and locomotion characteristics

- Prototype chassis system construction and field-testing

- Autonomous rover navigation development for vehicle localisation, motion estimation and short- and long-range path planning

Rover Locomotion Simulation & Performance Evaluation

The Rover Chassis Analysis and Simulation Tool (RCAST) is a *MATLAB Simulink/SimMechanics*-based tool developed at MDA for modelling rover wheel-terrain interaction and multi-body dynamics. RCAST utilizes a sophisticated wheel-soil interaction model and multi-body dynamics to create simulations for rover mobility assessment and control scheme development, as well design verification and sensitivity studies for a range of terrain cases.

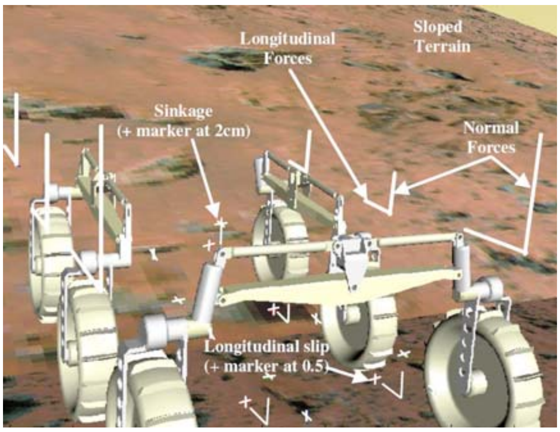

Fig. 1: Sample Screenshot of 3-D Visualization
Credit: MDA

The use of *Simulink* allows for the coupling of control elements to the mechanical systems to study closed-loop actuator performance and to allow for the integration of advanced control techniques such as slip optimization. *SimMechanics* also directly imports models from *SolidWorks* to allow CAD-level designs, including representative mass distributions, to be included in the simulations. This can also be coupled to a virtual reality model for 3-D visualization purposes (Fig. 1) through the *Simulink Virtual Reality Toolbox*.

Prototype Rover Chassis Systems

MDA recently developed a full-scale prototype rover chassis representative of systems applicable to lunar and planetary surface mobility. MDA is also now executing design activity for Phase B1 of ESA's ExoMars rover program, including the design and build of a full-scale ExoMars rover breadboard model.

The original MDA Rover Chassis Prototype (RCP) platform was a six-wheeled, 21 degree-of-freedom (18 active DOFs + 3 passive DOFs) prototype providing accurate full-scale kinematic and dynamic representation of a rover chassis (Fig. 2).

Fig. 2: MDA RCP during tests at CSA MarsYard
Credit: MDA

In addition to the six wheel drives, the RCP has six steering joints/drives and six walking joints/drives. Every drive is equipped with an encoder. Inclinometers measure the angular displacements of the three modules of the chassis, and an on-board video camera monitors wheel sinkage. In addition, the RCP is equipped with six force/moment sensors below each steering axis.

RCP was built to reduce the risks related to chassis design and mobility. Additionally, the prototype was developed to collect experimental data for the validation of the complex simulations in RCAST and to create a representative platform for field testing autonomous navigation. RCP mobility testing and data collection for RCAST validation was completed in 2006. Rigorous testing was carried out at the University of Toronto Institute for Aerospace Studies' (UTIAS) MarsDome and CSA MarsYard (Figs. 3 and 4, respectively).

Fig. 3: MarsDome Rover Mobility Test Facility
Credit: UTIAS

Fig. 4: RCP 2006 Testing at CSA's MarsYard
Credit: MDA

MDA's ESA ExoMars Rover Phase B1 Chassis & Locomotion System (CLS) design activity commenced in May 2007 and MDA's ExoMars rover CLS breadboard model is due for delivery to the program in early 2008.

Fig. 5: MDA is providing a chassis breadboard for the ESA ExoMars program
Credit: ESA

<u>Rover Autonomous Navigation: Localisation, Motion Estimation and Path Planning</u>

Techniques for visual-based localization, motion estimation and path planning are also being developed to increase the autonomy of future rovers. These techniques will allow them to travel greater distances with limited human-in-the-loop control.

Previous rovers have relied on odometric sensors such as wheel encoders and inertial measurement units for on-board motion estimation, which while simple to implement are prone to severe errors from wheel slip and drift of biases. Absolute localization techniques such as radiolocation and horizon feature matching to elevation data do not provide updates frequently enough to be useful.

Navigation techniques developed at MDA employ stereo cameras to identify visual landmarks both near-field and on the horizon. Features from these landmarks are extracted, stored in a database and matched to compute the three-dimensional motion of the stereo camera and thereby localize the vehicle.

To achieve this, the MDA technique employs an approach called simultaneous localization and mapping (SLAM) that first predicts the camera motion using odometric sensors, then corrects the estimated motion using the observations and matching of extracted features, and finally updates the features in the database using the final camera motion.

Visual odometry has been demonstrated on a rover traversing over 40 m during a field test at Valley of Fire State Park in Nevada, USA. Fig. 4a shows an image from a sequence captured by the rover, Fig. 4b shows the reconstructed 3D terrain model with a virtual rover inserted for visualization and Fig. 4c shows the recovered camera trajectory without using wheel odometry. These trials have shown that it is possible to reduce localization errors to a few percent of the distance travelled. This is a major improvement over conventional odometric sensors that can produce position estimation errors in excess of 20% of the distance travelled.

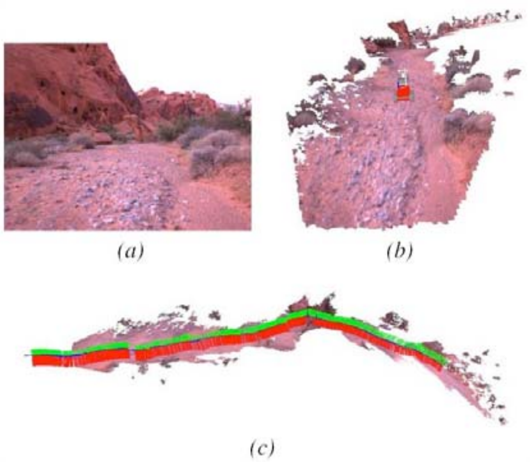

Fig. 4: Demonstration of Visual Odometry
Credit: MDA

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NEXT GENERATION EXPLORATION: ADVANCED VISION SYSTEMS

Advanced vision systems have a number of applications including autonomous navigation (as described in the previous section), scene modelling for science, advance prospecting, site survey and general situational awareness. The ability to instantly generate *in-situ* photo-realistic 3-D models without requiring continuous transmission back to Earth for post-processing, enables rapid reconnaissance of the immediate locale for advance identification of sites with high science, resource and mission operations potential in advance of human EVA. Systems at MDA and Optech are already deployed in terrestrial sectors such as mining, survey and security, with technology solutions spanning laser- and camera-based regimes.

Laser-Based Vision Systems

The key ingredients of short- and long-range navigation are terrain modelling and localization, path planning, and guidance abilities. CSA has used ILRIS lidar for 3D terrain reconstruction and localization through scans and terrain model matching. The acquired terrain was then used to plan short- and long-range paths. The results presented in Dupuis et al (2004 and 2006) demonstrated that lidar-based vision systems provide a reliable and precise guidance and is a potential solution for GN&C. However, 3D lidar data processing presents a challenge due to large data sets (each view has almost 500,000 3D points), sparsity of the point cloud and the non-uniform density and resolution of the data set. Fig. 5 shows the ILRIS lidar from Optech and Fig. 6 illustrates a 3D terrain reconstructed from ILIRIS data.

Fig. 5: ILRIS Lidar
Credit: Optech

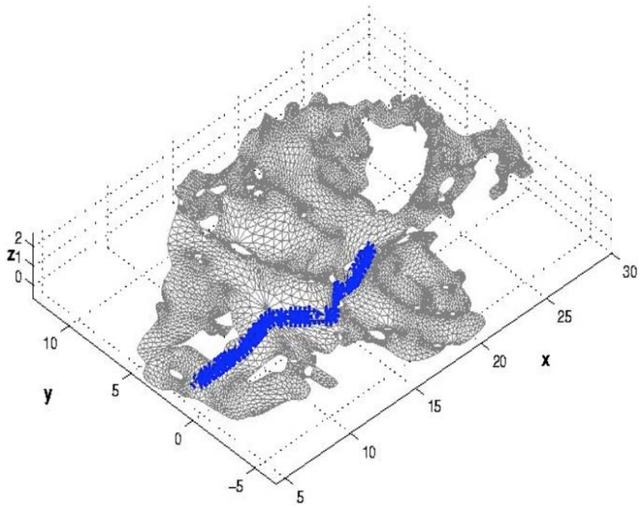

Fig. 6: Terrain Reconstruction and Path Planning
Credit: CSA

Optech has also worked with the University of New Brunswick on evaluating lidar technology as a classification tool for lunar geology. Laboratory testing with an ILRIS (Intelligent Laser Ranging and Imaging System), originally developed to inspect the Space Shuttle's heat shield tiles, has shown that using lidar to differentiate between mafic and felsic samples is feasible provided proper characterization and calibration are done. Characterisation must also address the effects of specular and diffuse reflection. Further development will be required to improve reproducibility, resolution and speed.

Fig. 7 shows a lidar test image of a sample of vesiculated basalt. Field trials at analogue sites with tripod- or rover-mounted lidars are a logical extension to the laboratory testing.

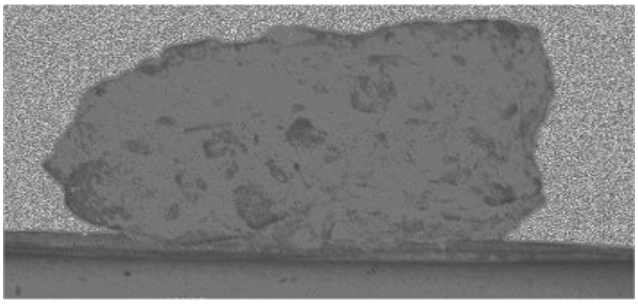

Fig. 7: Lidar Image of Vesiculated Basalt
Credit: Optech, University of New Brunswick

Camera-Based Vision Systems

A vision system developed by MDA called Instant Scene Modeller (iSM) uses images from a hand-held or vehicle-mounted camera to produce photorealistic 3D images. The user moves the camera across a scene, and the system recovers the structure of the environment and the camera motion by tracking and matching features detected in successive frames. A photo-realistic 3D model can be created within minutes of acquisition, and surface texture from the input images can be mapped onto objects. These fully calibrated models are stored in VRML format, in which the user can navigate and view the imagery from any direction and determine distances between objects.

This system has been demonstrated in terrestrial mining applications. Fig. 8a and Fig. 8b are two input images of an underground mine cavity, and Fig. 8c and Fig. 8d are two views of the resultant 3D model. For lunar exploration applications, iSM can be astronaut hand-held or rover-mounted. The technology is ideal for photo-documentation of activities at work sites. Digital recreation or "playback" of scenes of surface activities could be used for direct support during EVAs or planning future sorties.

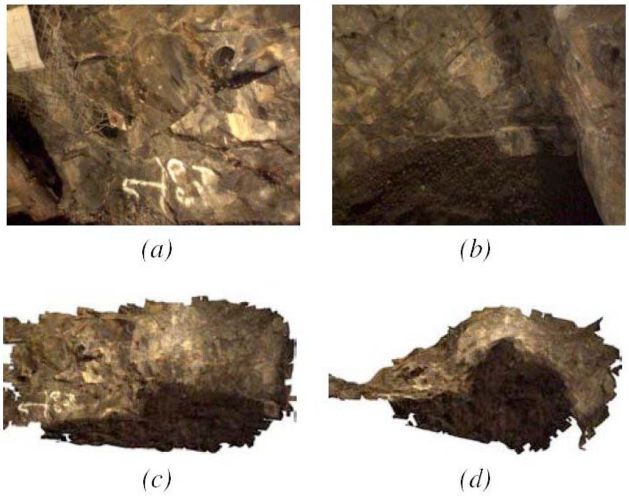

Fig. 8: iSM Modelling of a Terrestrial Mine
Credit: MDA

FIELD TRIALS

MDA's vision-based localization technology has been tested in different representative terrains as well as the CSA's Mars Yard and the Mojave Desert (California, USA). The field trial results in the CSA's Mars Yard are reported here.

The primary testbed for experimental validation of the vision-based localization technique is an iRobot ATRVJr mobile robot with a custom vision system (Fig. 9). The stereo camera was constructed using a pair of Sony DFW-X700 cameras, mounted on a rigid aluminium bar, affixed to a pan-tilt unit. The images used are 8-bit 1024x768 resolution., and the camera field of view is approximately 45° horizontal and 35° vertical. Currently two on-board computers are employed for localisation and vision processing including hardware accelerated image processing, and MDA's implementation of SIFT feature extraction. Several other sensors are housed onboard for performance evaluation: sonar rangefinders, SICK laser rangefinder, DGPS, compass, inertial measurement unit and inclinometer. Fig. 10 shows the testbed in action, avoiding obstacles at the CSA MarsYard facility.

Fig. 9: Testbed Rover Equipped with Vision System
Credit: MDA

Figure 11 shows a typical plot of the localization performance. The robot begins in the bottom-right of the plot and moves towards the top-left. Three different estimates of the robot's position are shown: wheel encoders only (blue), Differential Global Positioning System (DPGS – red), and MDA's vision-based localization (green). All three estimates start in the same place in the bottom-right but it can be seen that the blue line quickly diverges from the red and green, which closely compare. This clearly exposes the impact of wheels slip in the loose soil on localization. The vision-based localization is very similar to the DGPS, which serves as ground truth in this case.

Fig. 10: Testbed in Action at the CSA MarsYard
Credit: MDA

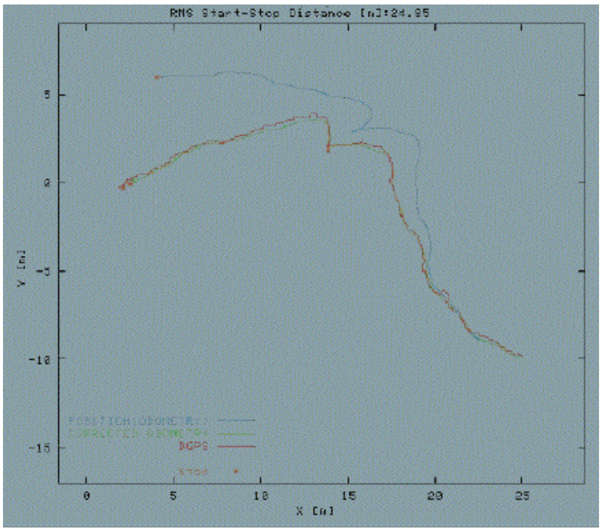

Fig. 11: Localization Result
of Obstacles Avoidance Path
Credit: MDA

Over many sets of experiments and field trials at the CSA's MarsYard, in Valley of Fire State Park (Nevada, USA), and in the Mojave Desert (California, USA), the errors from vision-based localization have been found to be on the order of just a few per cent of distance travelled for traverses over 100m. Orientation accuracy typically remains within 1° over this range.

During the summer of 2007 the NASA Ames Intelligent Robotics Group, dedicated to enabling humans and robots to explore extreme environments, remote locations, and uncharted worlds, conducted robotic field tests in Haughton Crater (Devon Island, Canada) utilising Optech lidar technology. These tests were performed as part of the Human-Robot Site Survey Project, the goal of which is to develop robots that can perform systematic and long duration mapping and surveying tasks over wide geographic areas. These robotic systems will allow NASA to offload the time and cost of tedious site assessment activities from EVA sorties during future lunar surface missions.

Fig. 12: NASA Ames K10 Rover Equipped with Optech ILRIS Lidar
Credit: NASA

For the Haughton Crater Site Survey Field Test, two NASA Ames K10 rovers were used to perform robotic surveys of a 700 m by 700 m region at an analogue lunar site, “Drill Hill”, of Haughton Crater. Each K10 was equipped with two non-contact survey instruments: a CRUX ground-penetrating radar and Optech’s ILRIS-3D scanning lidar, as shown in Figure 12. The ILRIS lidar was used to provide high-resolution topographic mapping. During the three week field test, the two rovers drove over 30 km, collecting more than 25 GB of data.

APPLICATION TO LUNAR EXPLORATION

The surface mobility and advanced vision technologies described in the previous section have direct applicability to the early phases of human-robotic lunar exploration:

- Characterisation and site survey for lunar science, prospecting and reconnaissance in advance of human sorties.
- Human sortie field assistance, including transport of samples, samples, astronaut equipment and small-scale infrastructure.
- Assembly and configuration of larger-scale infrastructure on the lunar surface.

Characterisation and Site Survey

An ability to remotely characterise and survey a site on the lunar surface using systems such as lidar and iSM, which are capable of accuracy and resolution superior to that obtained from orbital imagery, could be a significant advantage in lunar field exploration by reducing time and risk. For example, one could envision a robotic “field assistant” equipped with remote sensing instrumentation to evaluate rocks and provide terrain data to an augmented reality display inside an astronaut’s visor. This *in-situ* data, in conjunction with remote sensing data from orbiters, could then be used by mission control and the crew prior to vehicle egress to determine whether it is scientifically valuable and safe to venture into an unknown region.

Sample site documentation is another valuable task that could be performed by a robotic field assistant. A site could be photographed by the robot via astronaut command, based on established documentation protocols (ie. gnomon, pre- and post-collection photography from various angles, etc.). The documentation of sites was found to be a very time consuming and repetitive task during Apollo EVAs.

Finally, a robotic field assistant could also independently scout ahead for prospecting, mapping and resource assessment. Candidate science instruments could include lidar, a Raman spectrometer, infrared and ultraviolet sensors, a visible stereo imager, APXS or ground penetrating radar (GPR). Volatiles in the lunar regolith (H, He, H_2O) will likely be in low concentrations and will require both active and passive sensing to detect and map. Trenching and coring of the regolith at grid intervals will be needed to verify and calibrate concentrations of volatiles identified by remote sensing. Fig. 13 shows a concept for a GPR-equipped rover.

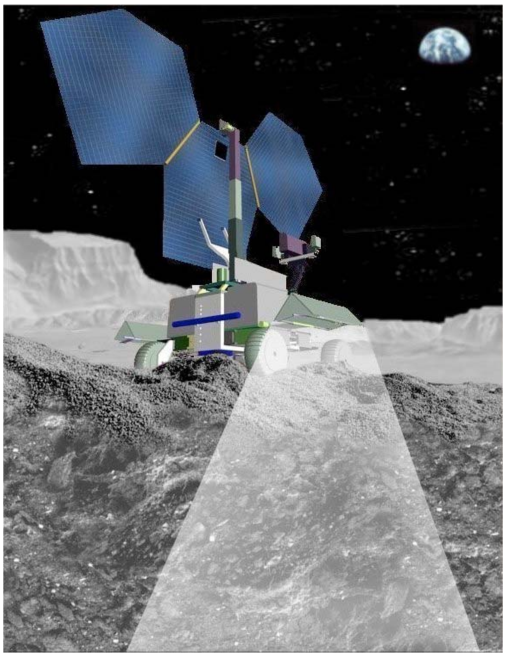

Fig. 13: GPR-Equipped Rover
Credit: MDA

Human Sortie Field Assistance

A small robotic vehicle could directly assist astronauts on field sorties by carrying their tools, equipment and samples. Such a conceptual M.U.L.E. (Mobile Utility platform for Lunar Exploration) could maximize EVA efficiency by doing mundane, repetitive or potentially hazardous tasks, as well as those that require strength, dexterity and mobility outside the range of that possible by a spacesuited astronaut. Such tasks could include:

- Astronaut "Caddie" – Carry tools, equipment and collected samples for astronauts during EVAs. Based on the Apollo experience, a baseline payload should include a hammer, a scoop, tongs, a corer, sample containers, vision systems (on-board and crew-operated), localisation equipment, dust cleaning gear and crew-emplaced science instruments (Fig. 14).

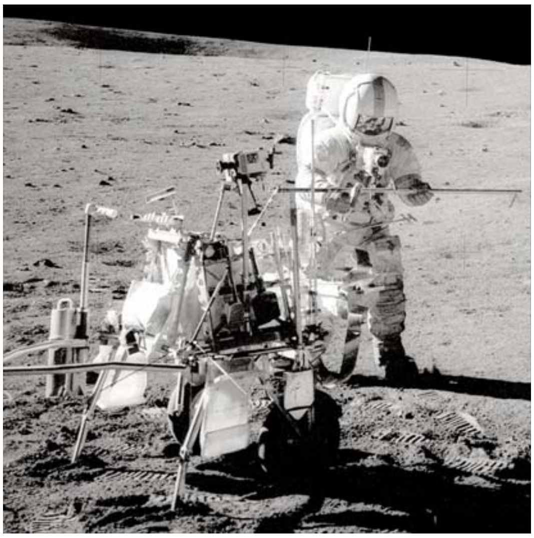

Fig. 14: Apollo Modular Equipment Transporter.
Credit: NASA

- Payload Deployment – Deploy and set up potentially hazardous science instruments such as alpha particle x-ray spectrometers (APXS), RTG-powered ALSEP-type packages or active seismometers with explosive charges.

Infrastructure Assembly and Configuration

For the human return to the Moon, success will rely heavily on exploiting the invaluable lessons learned from the nearly three decades of human spaceflight experience in low-Earth orbit. Throughout the history of the Space Shuttle and International Space Station (ISS) programs, robotics has provided a cost-effective, flexible solution for addressing the challenges of infrastructure assembly and configuration, as well as dealing with a wide variety of contingency or off-nominal situations.

The assembly and configuration of surface infrastructure will be key activities in the early- to medium-range. Mobility for the deployment, re-deployment, transportation and transfer of surface assets will be an implicit requirement for almost every phase of lunar surface exploration.

Surface assets that address these lunar activities span multiple areas of current space robotics capability and heritage (Ghafoor & Sallaberger, 2006) including mobility, science instrumentation (remote and *in-situ*), sensors and vision systems, robotic surface tools (arms, drills, shovels, etc.), lifting / deployment / assembly robotics (arms, cranes, elevators, etc.) and construction equipment (regolith transfer, beam building, etc.).

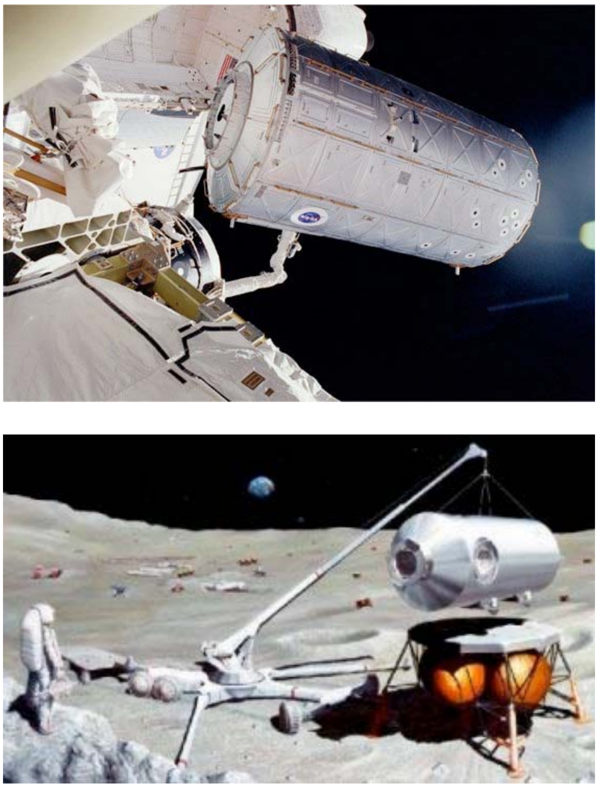

Fig. 15: ISS and Moon Base Robotic Assembly
Credit: NASA

The need for the inclusion of robotic elements becomes apparent when considering the following features of a lunar outpost:

- The long duration of surface operations.
- The number of infrastructure, cargo and payload elements required for the base.
- The diversity and quantity of deployable mechanisms (solar arrays, radiators, antennae, etc.).
- The large size of the surface infrastructure, cargo and payload elements.

As discussed in the introduction, there is surely no clearer demonstration of the versatilityoffered by human-robotic partnership within space exploration than with the hugely successful robotic manipulators used for assembly and servicing on both the Mir and ISS Space Stations. Since the installation of a docking module on Mir in 1995 and the laying of the cornerstone of the ISS in 1998 with the joining of the Russian Zarya and American Unity modules, robotics have played a crucial role in the assembly of complex structures in space.

During the development phase of the ISS, the possibilities offered by combined human-robotic capabilities also allowed engineers to consider space station designs and assembly techniques that would otherwise not be feasible. Robotics would provide a similar flexibility to pursue and develop different configuration options for a lunar base, and the ISS assembly experience could additionally be drawn upon as a vast database of knowledge for performing similar tasks on the Moon (Fig. 15).

Finally, one of the most important lessons learned on the Shuttle and ISS programs is that robotics enable the crew and the mission management team to deal with off-nominal or contingency scenarios. For example, it is expected that lunar surface infrastructure and payloads will have their share of rotating and folding mechanisms such as antennae and solar arrays. Robotic manipulators could be used to directly exert forces to release these types of mechanisms should they become stuck. The ability by the crew to robotically inspect and quantify potential anomalies from the safety of a pressurized module also allows the mission management team to quickly assess a situation and reduce the need for inspection EVAs.

CONCLUSION

Space exploration in the 21st Century will focus on surface exploration conducted by both humans and robots working in collaboration. The capability, versatility and reliability of robotic systems have clearly demonstrated throughout the shuttle and ISS programs. Ultra-reliable robotics have provided a safe and cost-effective solution to the challenges of sustainable human infrastructure assembly and configuration for 25 years. This specific expertise and heritage will be crucial to space exploration as it enters its third era, that of sustainable planetary surface infrastructure, and the unforgiving extended-duration lunar surface frontier tests human-robotic capabilities to new limits. Two key technologies that will enable the new era of exploration right from the outset are autonomous surface mobility and advanced vision. MDA's research, in partnership with Optech, the CSA and NASA, has focused on the design and construction of chassis platforms and their deployment in the field for testing, and the development of autonomous systems for localisation, motion estimation and path planning. Vision systems, both lidar- and camera-based, can be applied for navigation, science, prospecting and site survey, both rover mounter and astronaut deployed. The development of these robotic technologies will be key to the successful and safe execution of the human lunar endeavour, as well as the robotic exploration that paves the way for subsequent expansion of the human frontier towards Mars and beyond.

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