Advanced Technologies for Robotic Exploration Leading to Human Exploration: Results from the SpaceOps 2015 Workshop

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This paper will provide a summary and analysis of the SpaceOps 2015 Workshop all-day session on "Advanced Technologies for Robotic Exploration, Leading to Human Exploration", held at Fucino Space Center, Italy on June 12th, 2015. The session was primarily intended to explore how robotic missions and robotics technologies more generally can help lead to human exploration missions. The session included a wide range of presentations that were roughly grouped into (1) broader background, conceptual, and high-level operations concepts presentations such as the International Space Exploration Coordination Group Roadmap, followed by (2) more detailed narrower presentations such as rover autonomy and communications. The broader presentations helped to provide context and specific technical hooks, and helped lay a foundation for the narrower presentations on more specific challenges and technologies, as well as for the discussion that followed.

The discussion that followed the presentations touched on key questions, themes, actions and potential international collaboration opportunities. Some of the themes that were touched on were (1) multi-agent systems, (2) decentralized command and control, (3) autonomy, (4) low-latency teleoperations, (5) science operations, (6) communications, (7) technology pull vs. technology push, and (8) the roles and challenges of operations in early human architecture and mission concept formulation. A number of potential action items resulted from the workshop session, including: (1) using CCSDS as a further collaboration mechanism for human mission operations, (2) making further contact with subject matter experts, (3) initiating informal collaborative efforts to allow for rapid and efficient implementation, and (4) exploring how SpaceOps can support collaboration and information exchange with human exploration efforts. This paper will summarize the session and provide an overview of the above subjects as they emerged from the SpaceOps 2015 Workshop session.

I.   Introduction

THE SpaceOps 2015 Workshop session on "Advnaced Technologies for Robotic Exploration Leading to Human Exploration" was held at Fucion Space Center and was structured to have the first three presentations provide a broader overview, with the remaining three presentations covering details of narrower areas of interest. Table 1 below shows the paper order, authors, and organizations. The SpaceOps Workshop sessions are held biannually during the off-year of the larger SpaceOps international conference. The workshop is intended to be a small group of experts that focuses on specific themes of international interest, providing a forum for in-depth technical interchange as well as assessments of potential areas of cooperation and any other future areas or next steps that may be warranted.

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Table 1. Session presentations in session order, authors, and organizations

Presentations	Presenter	Organization
Introduction: Session Overview and Global Exploration Roadmap as Context for Robotic and Human Exploration	Mark Lupisella & Thomas Mueller	NASA & DLR
Operations Concepts Considered in Space Exploration Roadmaps	Giovanni Martucci & Ivano Musso	ALTEC
Various concepts for Robotic Exploration Concepts foreseen for Human Exploration Missions	Kim Nergaard	ESA/ESOC
On-ground Planning for Autonomous Rover Operations	Robin Steel	Telespazio VEGA
Low-Latency Teleoperations for Human Exploration	Mark Lupisella	NASA GSFC
Human Space Flight to Moon and Beyond - Communication Challenges	Joe Statman	NASA JPL

II.   Presentation Summaries

This section will provide brief summaries of the individual presentations.

A. Session Overview and Global Exploration Roadmap as Context for Robotic and Human Exploration, Mark Lupisella and Thomas Mueller, NASA and DLR

The session overview suggested the following potential themes to focus on:

- Distributed/Multi-asset Ops – including distributed control authority
- Interoperability of increasing number of international assets
- Communications that appear to be insufficiently architected in international efforts
- How to avoid robots possibly increasing crew workload?
- Common user interfaces
- Service-oriented architectures
- Crew Science Ops (e.g. real-time crew science decisions)
- Wearable technology
- Lunar quiet zone regulations

The session overview also suggested the following possible discussion areas/questions:

1. *What are key questions, challenges, and advanced technologies* requiring further attention for robotics leadingto human exploration? What could we collaborate on and/or prioritize?
2. *Autonomy*: How do we strike the right balance between crew, robots, systems, e.g. how do we enable effective crew science ops?
3. *Distributed/Multi-asset Ops*: How could this be best addressed and architected?
4. *Service-oriented architectures*: Should we pursue and if so, how?
5. *Big Data*: What big data challenges are envisioned for human exploration? E.g. can/should we make all human knowledge or human internet available at Mars?
6. *Cubesats*: How can they enhance human exploration?
7. *Process/Organizational Question*: Should SpaceOps put additional focus on human exploration? If so, how? E.g. more involvement in human exploration operations assessments or operations concept modifications and development? Timing may be good given GER and emerging agency visions (e.g. NASA "Evolvable Mars Campaign"). Any extra activities at SpaceOps 2016?
8. *Other*?

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Mark Lupisella presented an overview of the International Space Exploration Coordination Group (ISECG) Global Exploration Roadmap (GER) to help provide context for understanding how robotic missions and robotic assets can enable future human exploration of multiple destinations. The presentation focused on key robotic missions and robotic assets that can provide enabling technology advancements and that also raise interesting operational challenges in both the near-term and long-term, ranging from: (1) leveraging the International Space Station, (2) planetary science robotic missions to potential human destinations, (3) micro-g body proximity operations (e.g. asteroids), (4) autonomous operations, (5) high and low-latency telerobotics, (6) human assisted sample return, and (7) contamination control. The presentation highlighted operational and technology challenges in these areas that have feed forward implications for human exploration.

B. Operations Concepts Considered in Space Exploration Roadmaps, Giovanni Martucci & Ivano Musso, ALTEC

This presentation gave an overview of ALTEC's projects and initiatives to develop scenarios for Ground Operations for monitoring and support of future exploration missions including Mars, Moon and NEO. Areas of interest covered were (a) communications, including DTN, (b) procedures and instruments including supporting technologies for procedures execution, (c) analog field testing for addressing how to reproduce mission opeations on Earth in order to better specify and prepare for the expected crew operations, and (d) virtual reality and virtual presence technologies to support operations from ground.

Long distance communication combined with short coverage times impose several constraints. The communications setup must be flexible to allow for maximized coverage by using different setups, and communications planning requires a high flexibility to answer crew needs. The crew will likely require a high level of autonomy for longer duration missions which will require a high degree of training and long-term activity planning. The crew composition requires a balancing of scientists to reach good science results by a high autonomy of the crew and experienced astronauts to gain high mission autonomy. Virtual environments can help address a number of operational challenges, including psychological needs of the crew.

C. Various Concepts for Robotic Exploration Concepts Foreseen for Human Exploration Missions, Kim Nergaard, ESA/ESOC

This presentation covered system operations, data systems for operations, and robotics operations for the different types of robotic operations that would be foreseen for future human exploration missions, ranging from traditional sequence-based operations to direct real-time human-robotic interaction potentially using haptic telerobotic devices. Distributed multi-asset operations, present current and planned activities in the area of preparation for such operations with a particular focus on the METERON experiments, and advances in the area of robotic operations planning and scheduling were highlighted.

ESA is currently conducting research and development in (1) interoperability between systems (e.g. the interface between rover systems and system operations systems), (2) standardisation (e.g. within the context of the CCSDS Telerobotics Working Group), (3) end-to-end mission control (e.g. sufficient situational awareness at all stations; Point of Control (PoC) handling, and (4) CCSDS Mission Operation services (much already demonstrated/validated in METERON). Service-oriented architectures, goal-based operations, as well as more specific efforts such as the Advanced Planning and Scheduling Initiative, Goal-Oriented Autonomous Controller, and IRONCAP were touched on. It was noted that there has been no real-time rover operations in space missions since the 1970s and no truly international rover mission ever, which highlight the need to establish interface standardizations to guarantee interoperability.

D. On-Ground Planning for Autonomous Rover Operations, Robin Steele, Telespazio VEGA

This presentation focused on the autonomous rover operations in the context of results of the Innovative Rover Operations Concepts – Autonomous Planning (IRONCAP) study project. While automation of spacecraft has increased significantly, future rover missions that interact with an unpredictable environment would benefit from significantly higher levels of autonomy which would allow ensuring safety of remote systems, increasing the complexity of the missions requiring more powerful systems capable of adapting to a wider range of inputs and situations, and improving mission return in an opportunistic manner.

The presentation covered concepts, techniques, interactions, different levels of on-board autonomy, and the tools that would be needed to support assets with increased autonomy. The on-ground issues covered were the support to the situational (science and engineering) assessment of the last activity period of the rover, the definition of science and engineering goals, the operations planning in-line with the level of autonomy of the rover, plan validation, and

plan refinement. To allow flexible and high-degree autonomous rover operations, the development of operations into smaller discrete activities is required, which can then be composed into new or modified operational sequences. However, many operational sequences can be complex enough to require extensive planning beforehand, and the planning requires verification by simulation (on-ground) with powerful simulation facilities. Goal-based operations was stressed and it was noted that IRONCAP can be used for both kinds of paradigms – normal command plans or goal-oriented input.

E. Low-Latency Teleoperations for Human Exploration, Mark Lupisella, NASA/GSFC

    This presentation highlighted the potential roles for low-latency telerobotic (LLT) operations in the context of a number of NASA mission concepts and activities being considered in the context human exploration architecture work presently underway. Some mission concepts covered were "Crew-Assisted Sample Return" which involves the crew acquiring samples that have already been delivered to space and /or acquiring samples via LLT from orbit to a planetary surface and then launching the samples to space to be captured in space and then returned to the earth with the crew. Both versions have key roles for low-latency teleoperations.

    More broadly, the NASA Evolvable Mars Campaign is exploring a number of other activities that may involve LLT, such as: (a) human asteroid missions, (b) Phobos/Deimos missions, (c) Mars human landing site reconnaissance and site preparation, and (d) Mars sample handling and analysis. Much of these activities could be conducted from Mars orbit and also with the crew on the Mars surface remotely operating assets elsewhere on the surface, e.g. for exploring Mars "special regions" and/or teleoperating a sample analysis laboratory – both of which may help address planetary protection concerns. The operational and technology implications of low-latency teleoperations were explored, including the idea that previously deployed robotic assets from any source could subsequently be used by astronauts via LLT.

F. Human Spaceflight to Moon and Beyond: Communication Challenges, Joe Statman, NASA/JPL

    The focus of this presentation was on autonomous crew operations for human missions to Mars. Today, robotic and human mission near Earth assume "joy stick" operations are possible (at least in an emergency), where ground controllers can tightly adjust even minor aspects of operations. To Mars, round-trip-light-time is ~40 minutes, so "joy-stick" operations from earth are impractical. Technologies for on-board intelligence and decision-makers are accepted for robotic missions. The presentation focused on the technical and management challenges of applying these, and similar technologies, to human missions to Mars. For example, it was suggested the ISS cannot really serve as a test bed for long distance human missions.

An emerging change in the social acceptance of the risks to astronauts during missions could have a direct influence on mission designs, technologic requirements, etc. For example, can/should we accept lack of communication coverage for human Mars missions? The usability of video and audio conferences was called into question due to the long communications delay (e.g. ~ 20 minute max for one-way to Mars) and yet the psychological benefits of video transmissions was emphasized, suggesting the need for bandwidth and creative developments in dealing with communications delays. Redundancy and good FDIR (Fault Detection, Identification, Repair) can help with risk postures, but will increased mass and development costs price us out of the mission? Do we want to consider reducing automation? How we assess the ROI for human missions can help drive assess risk posture and cost commitments regarding automated systems. Approaches were suggested such as acknowledging human space flight is high-risk and that we accept the risk level of high-performance military aircraft. Nevertheless, the presentation concluded that in the meantime technology development (comm, automation) must continue, getting to near-flight-readiness.

III. Presentation Themes, Questions, Observations

    This section briefly captures key themes, questions and observations that emerged from the workshop session.

1. If/how should operations communities provide operations input for such a wide variety of relatively immature architectures and mission concepts?   On the one hand operations could be proactive and provide specific early input to concept formulation. On the other hand, ops also has to be reactive and flexible. This tension might be addressed by having robust operations considerations early in concept formulation as well as through flexible "operations systems engineering" that can address many mission development outcomes.

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2. Advanced technology should generally be pulled and is often a long-lead item. However, flexible operations systems engineering may require technology push in some circumstances.

3. Multi-agent and distributed operations can provide significant flexibility and ROI, but operations challenges need to be further researched.

4. Autonomy and goal-based operations could significantly enhance, and perhaps in some cases, critically enable, human exploration missions – particularly deep space long duration missions.

5. First human Mars missions are likely to be limited to demonstrate fundamental human exploration systems and operations, with reduced attention to science. However, science operations readiness should still be pursued and crew composition, systems, and training should reflect a balance to achieve other returns such as science.

6. High quality video links for human Mars exploration missions will be important, and perhaps necessary for public engagement and support.

7. Requirements are generally driven by budget, and while operations needs to be extremely sensitive to cost constraints, there are near- and long-term tensions when developing the right systems and operational approaches for uniquely challenging human missions such as a long duration deep space missions to the surface of Mars.

IV. Discussion Summary

The approach adopted for the discussion was to briefly discuss high-level ideas for potential collaboration without discussing many technical details – except when critical and/or able to do so in a quick fashion. The discussion ranged a bit beyond the session theme and as a result captured a few thoughts relevant to the other two workshop sessions as well which explored topics in Big Data and Cubesats.

1. CSDS can be utilized to stipulate collaboration via the generation of working groups and standards:
   • Definition of standards for human mission operations
   • The CCSDS working group for Telerobotics is looking for more participants
   • The newly founded group for Mission Planning is looking for members as well as is still open for new fields, e.g. mission planning for human operations.

2. Increase contact with centers of expertise:
   • One example noted was interacting more with JPL for low-latency telerobotics. During the discussion it was recognized that there is an important differences between low-latency teleops and high-latency teleops that JPL specializes in.
   • How can SpaceOps help to support or establish these contacts with centers of excellence around the world?

3. There is a strong recommendation to have non-formal collaborations:
   • Set-up of formal collaborations often takes much time and has many challenges:
     - Requires a clear definition of collaboration
     - Exchange of information is complicated (ITAR, etc.)
     - Can often leads to inefficiencies

4. Proposal to provide a summary of this workshop to the SpaceOps community:
   • In a summary article in the SpaceOps Journal
   • In a summary presentation(s) during SpaceOps 2016 (e.g. human spaceflight operations session)

5. Proposal to do a market survey and get more in touch with commercial space companies:
   • For example, areas of interest and collaboration with an emphasis on the emerging areas of cubesats and big data

6. Some presenters asked for expertise and collaboration in their areas:
   • Are there studies about what is to be gained from haptics/force-feedback in telerobotics?

- Are there studies about what is to be gained from full-immersion vs. partial immersion? (e.g. virtual reality vs. augmented reality)
- Experience existing for mission ops teams controlling different and decentralized assets and sharing data among different facilities

7. How can SpaceOps support collaboration and information exchange on Human Space Flight?
   - SpaceOps could emphasize Human Space Exploration more:
     - To provide a forum for presenting new programs
     - At plenary sessions to be held?

8. The ISS redesign decided to reduce development costs and increase crew responsibility, but:
   - There are undesirable consequences ranging from unfavorable crew time implications to crew safety
   - Future operations analyses and systems should attempt to reduce unfavorable crew time and safety implications for deep space long duration missions when those kinds of consequences will be more critical

9. High bandwidth and reliable connections will be important for video for the crew – psychologically and for many operations.
   - Disruption tolerant networking (DTN) is important for long-range comm reliability
   - Weekly sessions with psychologists is standard

10. There is a strong need to design for human health and embed human factors in operations concepts and test well on ground

11. Collaboration could be pursued regarding research and operational tests of multiple rovers from different providers, which can also relate to collaboration on distributed systems and distributed control:
    - Potential autonomous or semi-autonomous collaboration among assets where different rover activities could inform each other's activitie
    - Classify data for every ground ops team to find data that can be shared – e.g. a web platform

12. Testing low-latency teleoperations from ISS should continue to be explored to find value-added test activities – e.g. testing force-feedback in micro-gravity and low-latency science operations.

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