CO-OPERATIVE HUMAN-ROBOTIC EXPLORATION OF LUNAR ANALOGUE SITES.

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Introduction: Past planetary exploration missions have used either humans or robotic assets to explore planetary surfaces. A series of analogue missions led by the Centre for Planetary Science and Exploration (CPSX) and funded by the Canadian Space Agency [1] tested three scenarios: a robotic-only sample-return mission with a single rover, a human mission with a crew of two astronauts, and co-operative mission with two astronauts joined by a robotic field assistant. A comparison between the operational results of the three scenarios reveals potential benefits of co-operative human-robotic exploration in future missions.

Mission architecture: The robot-only mission took place over ten days at the Sudbury impact structure in Ontario, Canada, in June 2011 while the astronaut-only and joint human-robotic scenarios took place at the Mistastin Lake (Kamestastin) impact structure in Labrador, Canada, in August-September 2011, with each scenario lasting four days (the rover portion of the joint scenario was realized on only three days due to inclement weather). For all three scenarios, a remote Mission Control facility was operated at the University of Western Ontario, in London, Ontario, Canada.

A ROC6-type six-wheeled rover was used both for the robotic-only mission and as the robotic field assistant to the astronauts in the co-operative exploration scenario [2]. The rover was equipped with a vision-based autonomous navigation system [3]. In the robotic-only mission, this allowed it to autonomously plan paths when given a destination by Mission Control. The system also allowed the rover to be commanded to return to any point it had previously occupied; these capabilities greatly reduced the amount of detailed mobility planning required in Mission Control compared to what would have been required in the absence of the navigation system.

These capabilities were used differently in the joint human-robotic scenario. In this case, the greater mobility, judgment, and visibility of the astronauts was used to augment the system by having an astronaut direct the rover to sites of interest, thus building up a network of safe paths. Once taught a path by the astronaut, the rover's autonomous-return capability allowed it to return along that path to the site of the lander, or to revisit the same or another site, as desired.

To make use of this capability, EVAs were scheduled to begin with a period of robotic operations, in which one astronaut would direct the rover to a new site of interest, while the second would conduct parallel work at a nearby site. Once the rover's destination was reached, both astronauts would move away to work at a separate site, with the rover left to explore the outcrop of interest with its suite of instruments, under the direction of Mission Control.

Range of operations: Both the robotic-only and the joint scenario made significant use of the rover's mobility capability. In the robotic-only case, however, Mission Control was able to judge the feasibility of desired traverses only based on data products previously requested from the rover. Expanding the area explored required sending the rover to destinations outside the areas seen by its visual navigation system, and this could only safely be done in steps of 75 metres or less. Traverses longer than this required several command cycles to complete, and these competed for slots in the time and data budgets with direct scientific observation requests for sites of interest within the network already explored.

Conversely, with an astronaut directing the rover, the relative merits of sites within and beyond the explored area could be quickly assessed, and continuous roving into unexplored areas was possible. The astronaut could choose a destination – often in co-ordination with Mission Control – and direct the rover there in a single traverse, pausing to assess terrain or conduct scientific work if needed.

As a result, the rover aided by the astronaut was able to cover much more ground than when controlled remotely. The longest single trip achieved in the rover-only scenario totalled 168 metres, and took 9 hours of operations time over two days and 6 command cycles to achieve. By comparison, the longest single trip under astronaut control reached a distance of 381 metres, conducted in a single EVA using 86 minutes of astronaut time.

Another comparison is the amount of time required to reach a newly-discovered site of interest and sample it. In the rover-only scenario, 3 to 4 command cycles were needed to reach a visible outcrop, position the rover, acquire imagery, choose sampling locations, and sample. With the rover delivered to the outcrop by the astronaut, this process could be achieved in 1 to 2 command cycles.

Costs and benefits of time: While the assistance of the astronaut greatly enhances the performance of the robotic exploration, it comes at a cost of astronaut EVA time, which is of great value during a landed mission. However, the key question for assessing value obtained from a mission is the performance of the mission as a whole – considering the value delivered by the human and robotic assets together.

During the joint exploration scenario, the astronauts spent 1615 working minutes on EVA. Of these, 212 minutes (13.1%) were spent on robotic work (including 60 minutes scheduled, but not realised on the first day due to inclement weather). At this cost, 546 minutes of robotic operations during the EVA period were enabled, along with the capability to conduct further rover activities outside of the EVA period. Additionally, the rover could be used for follow-on exploration after the return of the astronauts to Earth; the simulation included four days of such activities, during which the amount of imagery and instrument data collected at the sites of interest was significantly expanded and the rover's travel network was further extended to new sites, both under the direction of Mission Control.

As a comparison, during the subsequent human-only scenario, the astronauts spent 1730 working minutes on EVA, again over four days. While lacking the robotic field assistant, the astronauts were equipped with wheeled vehicles to carry them to the sites of investigation (to the extent the terrain allowed). The speed achievable and the layout of the analogue site resulted in significant use of time in driving. A total of 640 working minutes was used in driving from the landing craft to the first site of interest on each EVA, and from the final site of interest back to the lander.

The use of these vehicles enabled the astronauts to reach more distant sites than on foot, to save energy for other work, and to carry more equipment and samples, but these benefits came at a cost of 37.0% of the working time available on EVA. Unlike the robotic assistant, they brought no benefit of operational time outside the EVA period, or after the astronauts returned to Earth. They further could not complete instrument, imaging, or sampling tasks at outcrops in parallel to astronaut work elsewhere, as the robotic assistant did.

The percentages quoted above for time spent driving the rover and vehicles will vary significantly for other missions, depending on the layout of the site of exploration, the speeds achievable and the particulars of the equipment available. Nonetheless, they do suggest that the cost in astronaut time of using the robotic assistant may be reasonable, in comparison to the other demands on the schedule, and that the benefits may justify this cost.

Other benefits: In addition to the potential for extending the operations time available through parallel work, work outside of EVA time, and follow-on work after the astronauts' departure, the robotic assistant contributes in off-loading particular tasks from the astronauts. Tedious or precise instrument work is better assigned to the robot, leaving the astronauts to spend the EVA time on other activities best suited to humans. There is a safety implication as well; instruments whose operation might be hazardous to an astronaut – perhaps x-ray sources or drills – can be operated when the astronauts are safely away from the rover. As well, the rover's navigation system, with its ability to return to the lander precisely and on command, presents the possibility of a safe route home for a disoriented astronaut.

Finally, the astronaut operator provides benefits to the rover beyond better terrain judgment and swifter operation. The astronaut can not only judge terrain more quickly than the remote operators, but can also modify it, removing small obstacles to open up new areas to the rover. This was done on several occasions in the scenario, enabling the rover to move into areas it otherwise could not have reached.

Conclusion: The employment of a robotic field assistant for joint human-robotic exploration of a lunar analogue site proved useful and allowed significant additional data collection at a small cost of astronaut time. The working time spent was, in this case, significantly less than that used on non-science mobility work in a comparable scenario without the robotic assistant. The benefits realized were enabled by the robot's highly capable autonomous visual navigation system, and by the support of a remote Mission Control centre to control the robot in parallel with astronaut EVA work. The employment of such robot-human co-operation in planetary missions shows promise, and should be further tested.

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