NEW PARADIGMS FOR HUMAN-ROBOTIC COLLABORATION DURING HUMAN PLANETARY EXPLORATION. Joseph C. Parrish\textsuperscript{1}, David W. Beaty\textsuperscript{2}, and Jacob E. Bleacher\textsuperscript{3}, \textsuperscript{1}NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena CA 91109, joseph.c.parrish@jpl.nasa.gov, \textsuperscript{2}NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena CA 91109, david.w.beaty@jpl.nasa.gov, \textsuperscript{3}NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, jacob.e.bleacher@nasa.gov.

Introduction: Human exploration missions to other planetary bodies offer new paradigms for collaboration between humans and robots beyond the methods currently used to control robots from Earth (e.g., Mars rovers) and robots in Earth orbit (e.g., ISS Mobile Servicing System, ISS Dexter). Additionally, certain science objectives may lend themselves better to human operation or robotic operation, or a hybrid of the two. In terms of resource availability, EVA crew time is expected to be a dominant factor, but other factors such as communication bandwidth, command time delay, power, and robotic system availability may also affect decisions regarding the application human and/or robotic resources. Furthermore, the next several decades promise enormous advances in particular technologies affecting the human-robotic interface (e.g., autonomy, sensing) and these technology advances will almost certainly change the paradigms of human-robot collaboration.

In 2015, the Human Science Operations-Science Analysis Group (HSO-SAG) of the Mars Exploration Program Analysis Group (MEPAG) studied this issue for the case of human exploration of Mars and published its findings\cite{1}. This paper describes the relevant findings from the MEPAG HSO-SAG report, focusing on: (1) the range of potential styles of interaction between humans and robots, and (2) the range of potential styles of control of robotic systems by humans at varying levels of separation.

Human/Robot Interactions: A human exploration mission could possibly utilize robots to more efficiently achieve some of its science objectives while other science objectives would be best accomplished by humans alone. One example might be the use of sterilized robots to explore special regions in order to minimize forward and backward contamination.

High latency rover operations on Mars (where humans are operating from Earth) are well understood (e.g., Mars Pathfinder, Mars Exploration Rovers, Mars Science Laboratory), but the types of robots that would be utilized and the model of human/robot operation for human planetary exploration missions are not as clearly defined.

There are several existing models of human-robot interaction that could be useful, including (1) International Space Station, (2) subsea oil rig repair, (3) tele-operated, minimally invasive surgical techniques. These models offer significant insight into potential applications of interaction and control, but the overall concept of operations for the human planetary exploration application needs more development, including: (1) interaction during field work, (2) exploration of special regions, and (3) reconnaissance.

Style of Crew Control and Interaction with Robots: The crew and robots would have several styles of interaction during a crewed mission (Fig.1). These include: (1) crew and robots cooperating on tasks both inside and outside of a pressurized habitat, (2) crew and robots operating independently and handing off tasks between each other when appropriate, and (3) robots operating independently of crew.

![Figure 1. Range of Styles of Human/Robot Control/Interaction.](image)

Furthermore, there is a range of styles of control of the robots by humans, including: (1) directly from an EVA suit over a few to tens of meters, with no time delay, (2) from a pressurized rover over tens to hundreds of meters, with no time delay but potentially limited line of sight, (3) from a fixed habitat over kilometers, with 1-10 second time delay, (4) from Earth over millions of kilometers, with 1-10 minute time delay. It should be noted that the current ISS robotic operations fall largely into the second class, while
Mars rover operations fall into the fourth class. The first and third classes have relatively little precedent in space operations, but other operations environments such as subsea oil well repair do offer relevant analogs.

The science objectives to be addressed during a crewed mission are influenced by robot involvement, the style of crew control and the style of crew/robot interaction that are supported by the mission architecture. Some objectives are better met by different combinations of robot involvement, crew control and crew/robot interaction.

**Finding (HSO-SAG #4):** The range of possible science objectives to be addressed during a crewed mission would be broader if crewed mission architecture supports the development of and an ability to routinely switch between styles of robot involvement, crew control and crew/robot interaction to achieve tasks.

**Telepresence Beyond an Exploration Zone:** Robots operating beyond line of sight of crew could extend the human presence beyond the edge of the Exploration Zone via telepresence. Furthermore, telepresence could be the only permissible way to explore in protected areas on Mars. Objectives to be met by telepresence operations should be identified as those that: (1) benefit from crew operation in the Mars system, and (2) support the overall science objectives of the human mission.

**Finding (HSO-SAG #5):** Operation of robots out of the line of sight of crew could be used to extend the human presence beyond the Exploration Zone or into protected areas.

**EVA Time as a Critical Resource:** Crew time during a crewed mission is a limited resource; only a fraction of the total crew time would be available for dedicated science operations. A main rationale for a crewed mission is to enable EVA time; as such, EVA time must be used to conduct tasks that require a crew presence. A critical role filled by the use of robots is an ability to ensure that crew time is dedicated to tasks that most benefit from a human presence. A useful paradigm used on ISS is for EVA worksite setup and teardown by robotic systems that “let the robot prep the patient, then have the human enter for the surgical procedure”.

**Finding (HSO-SAG #6):** Use of robots to support EVA-related activities could increase the number of or degree of satisfaction of a science objective(s) be enabling crew to focus on tasks that benefit from a human presence.

**Summary:** The style of human/robot interaction may have implications for Exploration Zone selection. In particular, remote operations outside of the Exploration Zone may expand the scope of science investigations. In this case, it is worthwhile to ask which tasks could be accomplished by robots, and how could these be integrated into the human mission to enable the completion of the broadest range of high intrinsic value science objectives.

One potential example is robotic deployment of science packages by autonomous robots inside or outside the Exploration Zone. Robots could complete tasks such as deployment of science packages to accomplish high value goals while humans complete tasks that most beneficially involve their participation (sampling, lab work field analyses). It is important that these robot-only activities support the overall science objectives of the human mission.

**Finding (HSO-SAG #7):** Preparation for a potential Mars surface mission requires more focus on the development and testing of operations concepts that include human-robotic interaction. This also requires development and testing of supporting technologies and systems.

**References:**
