

HERRO: A Science-Oriented Strategy for Crewed Missions Beyond LEO

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This paper presents an exploration strategy for human missions beyond Low Earth Orbit (LEO) and the Moon that combines the best features of human and robotic spaceflight. This “Human Exploration using Real-time Robotic Operations” (HERRO) strategy refrains from placing humans on the surfaces of the Moon and Mars in the near-term. Rather, it focuses on sending piloted spacecraft and crews into orbit around exploration targets of interest, such as Mars, and conducting astronaut exploration of the surfaces using telerobots and remotely controlled systems. By eliminating the significant communications delay with Earth due to the speed of light limit, teleoperation provides scientists real-time control of rovers and other sophisticated instruments, in effect giving them a “virtual presence” on planetary surfaces, and thus expanding the scientific return at these destinations. It also eliminates development of the numerous man-rated landers, ascent vehicles and surface systems that are required to land humans on planetary surfaces. The propulsive requirements to travel from LEO to many destinations with shallow gravity-wells in the inner solar system are quite similar. Thus, a single spacecraft design could perform a variety of missions, including orbit-based surface exploration of the Moon, Mars and Venus, and rendezvous with Near Earth Asteroids (NEAs), as well as Phobos and Deimos. Although HERRO bypasses many of the initial steps that have been historically associated with human space exploration, it opens the door to many new destinations that are candidates for future resource utilization and settlement. HERRO is a first step that takes humans to exciting destinations beyond LEO, while expanding the ability to conduct science within the inner solar system.

I. Introduction

PRIOR to the end of the Apollo program, NASA’s approach to space exploration took two distinct paths, and a debate over their comparative merits has persisted ever since. One path sees the extension of human presence into the solar system – regardless of whether it is done for science, economic development, national prestige or sheer destiny – as the overarching goal of the space program. The German rocketeer Wernher von Braun aggressively promoted this view, and it has been the long-term goal for human spaceflight ever since, most recently with President Bush’s 2004 “Vision for Space Exploration.”

The other path embraces robotic, unmanned missions as a more practical, cost-effective way of exploring space. This view has been bolstered by the

tremendous successes of robotic missions, such as Voyager, Galileo, Cassini, MER and many others, and their unprecedented contributions to our understanding of the universe. Although many advocates of this path recognize the potential value of hands-on field research on the surfaces of other worlds, they see human spaceflight as being too difficult, and more importantly, as too expensive for scientific exploration.

This paper describes a new strategy for exploration that combines the best features of both human and robotic spaceflight. This approach – Human Exploration using Real-time Robotic Operations” (HERRO) – achieves the dual benefits of advancing the ability to conduct planetary science, while facilitating crewed voyages to exciting destinations within the inner solar system. It does this by refraining from placing humans on the Moon,

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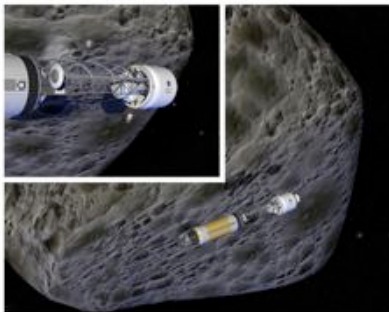
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Mars and planetary surfaces at the bottom of large gravity wells. As shown in Fig. 1, it instead concentrates on sending piloted spacecraft to in-space locations and to the surfaces of small planetary bodies.



Planets and Large Planetary Bodies



Small Planetary Bodies

Figure 1: HERRO approach to exploration (Telerobotic concepts by Carter Emmart)

Potential near-term destinations include lunar orbit, which is quite within the capability of systems currently under development. With more sophisticated systems, it is possible to send human explorers to many Near Earth Asteroids (NEAs), Mars orbit, Mars' two moons Phobos and Deimos, and conceivably Venus orbit. Although Venus has not been associated with human exploration in the past, it is an appealing candidate for orbital-based exploration, and is of great interest to the space science community.

For small planetary bodies (asteroids, the moons of Mars) and in-space locations, the spacecraft could rendezvous directly with the object of study. Operations could be conducted immediately from the spacecraft, without the need for dedicated landers and ascent vehicles. For orbital destinations, the crew

would explore via teleoperation of robotic vehicles and systems pre-deployed on the surface. This closely approximates the cognitive and decision-making advantages of having humans at the site of study, and unlike today's autonomous space robotic missions, provides real-time command and control of operations and experiments.

This approach is very similar to how scientists, commercial explorers and operators use telerobotic submersibles to work in inaccessible areas in the ocean. Good examples of this are the Remotely Operated Vehicles (ROVs) used in oceanography, undersea construction and oil exploration/recovery. ROVs, such as the one in Fig. 2, are operated by a person onboard a sea-going vessel, and are comparable to a scuba diver in terms of maneuverability and dexterity. These devices have become a mainstay for work in the ocean, and the philosophy for their use is extensible to space.

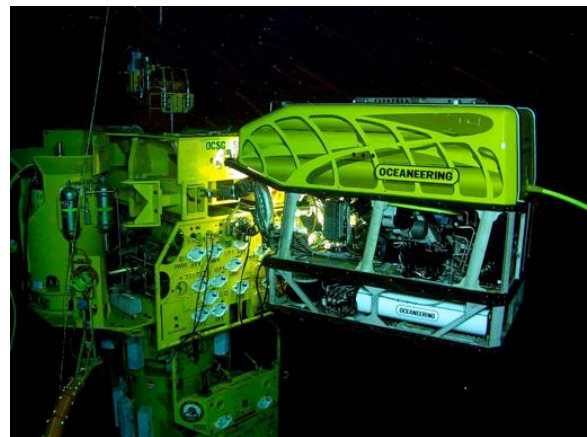


Figure 2: ROV at work in an underwater oil and gas field. (Courtesy of Oceaneering, Inc.)

Telerobotics for in-space operations, to potentially reduce the burden of astronaut extravehicular activity (EVA), is also a significant research activity at NASA. Figure 3 shows the "Robonaut," a telerobotic platform being developed at NASA's Johnson Space Center. The Robonaut platform has highly-capable manipulators, including robotic hands, that can be used to perform external activities on the International Space Station (ISS). Variants of robonaut have also been proposed for use in exploration.



Figure 3: “Robonaut,” a human-equivalent telerobot being developed for EVA at NASA Johnson Space Center

In summary, HERRO offers some major advantages to human exploration over the more conventional approaches of the past. These include:

- Broadening the range and variety of potential destinations that can be considered for near-term human missions;
- Reducing cost and risk by requiring fewer man-rated elements and less overall system complexity;
- Facilitating opportunities for international collaboration through contribution of robotic systems with straightforward command, communication and control interfaces.

HERRO also expands the ability to perform space science by offering the following benefits:

- Providing human-equivalent presence on planetary surfaces through real-time control and operation of robotic elements;
- Offering advantages of in-situ cognition, decision-making, and field-work on other planetary bodies;

- Providing, with crew-assisted retrieval, a simpler approach to sample-return missions from the Mars and Venus surface.

II. Description of Concept

HERRO is a departure from the conventional view of human exploration, which has actually changed very little over the last 50 years. The conventional view could be described as the “Lilly Pad” approach, in which humankind moves out into the solar system in a methodical series of “jumps” (Fig. 4). It starts out with the return of humans to the Moon, and then uses the Moon as a site for proving out new technologies or as a permanent outpost for settlement and expansion. The next major jump is Mars, starting with long-duration surface missions, followed eventually by establishment of a base and permanent settlement. Missions to other destinations, such as Lagrange Points and NEAs, have been considered, but only in the context of being steps on a path leading to the Moon and Mars.

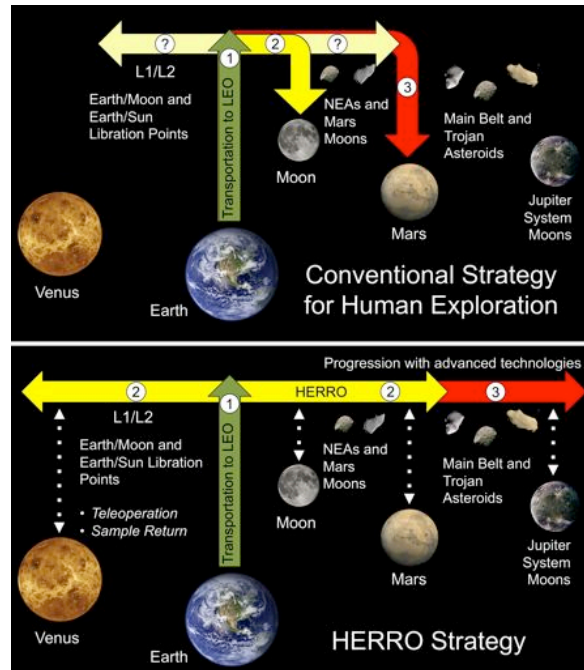


Figure 4: Comparison of strategies for human exploration

The problem with this view is that sending human crews to the surface of any planetary object with a deep gravity well not only increases the total energy expenditure for the mission, but it also opens a whole new dimension of complexity, systems development and ultimately cost.

Most scientists acknowledge the superiority of doing hands-on work in the field. For example, Dr. Steve Squyres, Principal Investigator of the Mars Exploration Rover mission, stated: “What Spirit and Opportunity have done in 5-1/2 years on Mars, you and I could have done in a good week. Humans have a way to deal with surprises, to improvise, to change their plans on the spot.”

However, human geological fieldwork on another planet is difficult to justify for the science return, due to the high costs involved. A large number of complex (and hence expensive) systems must be developed to land humans on the surface of another planet. These include, at a minimum: man-rated entry descent and landing systems for large, heavy vehicles; a surface habitat capable of reliable operation for a long term (typically over 500 days) in a complex and hostile environment; airlocks and seals that are unaffected by dust and other degradation factors for similar long durations; surface suits capable of operating in an extreme environment for periods hundreds of times longer than existing spacesuits have ever operated without refurbishment; pressurized rovers and human-support systems to allow humans to reach scientific sites of interest from the (necessarily flat and rock-free) human-safe landing sites; and a man-rated ascent vehicle capable of reliably launching into orbit after several years of inactivity on the surface of Mars.

There is also an argument for delaying landing people on the surfaces of planets on which there are yet unresolved questions about the possible existence of life, since human presence could contaminate the environment with earth-originating microbes and compromise future scientific studies.

HERRO (Fig. 4) capitalizes on the fact that the energy requirements for travel between LEO and in-space locations beyond LEO are very similar. Although mission times can vary significantly, it is possible to use a single spacecraft configuration to perform missions to several different destinations.

Figure 5 shows the ΔV requirements to travel from LEO to destinations within the inner solar system. The values in light blue connote orbital and in-space destinations. The quantities in red represent the additional ΔV requirements to go to the surfaces of the Moon, Mars and Venus. These are additionally portrayed as projections to highlight the need for dedicated, high-thrust propulsion systems using space-storable propellants for these maneuvers.

Several in-space destinations fall within a modest ΔV range of 3.5 to 4.0 km/s. These include Earth Geosynchronous Orbit (GEO), major Lagrange Points (L1, L2, L4 and L5) for Earth-Moon and Sun-Earth orbits, lunar orbit, and several asteroids. Beyond 4.0 km/s and up to 6.8 km/s, many more

destinations become possible. These include Mars Orbit and rendezvous with its moons, Phobos and Deimos, and Venus orbit. In addition, 2,276 of the 6,014 cataloged NEAs are accessible within the range of 3.5 to 6.8 km/s, although many of these may be too small to be of major interest.

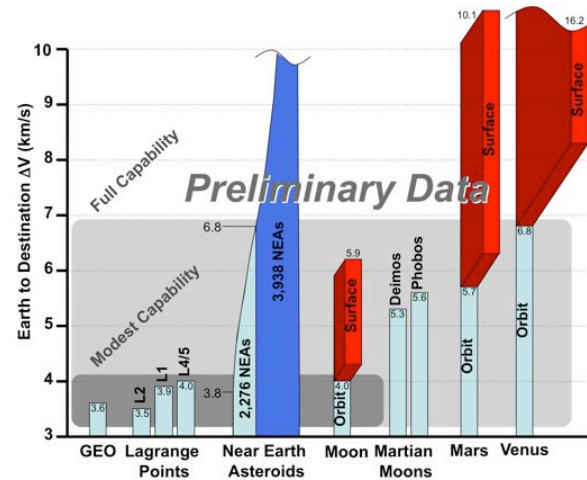


Figure 5: Approximate ΔV requirements for various destinations

The ΔV required to reach the surface of other planets, on the other hand (right-most columns of Fig. 5, shown in red), is significantly greater, and adding in the ΔV required to return from the surface increases the difficulty further. Since mission mass is an exponential function of the ΔV , landing humans on planetary surfaces is a vastly more difficult problem than exploring from orbit.

By eliminating the significant communications delay with Earth due to the speed of light limit, teleoperation provides scientists real-time control of rovers, aerobots and other sophisticated instruments, thus expanding the scientific return at these destinations. Table 1 illustrates the communications latency stemming from the speed of light limit for potential HERRO destinations.

The effect is very pronounced for communications between Earth and interplanetary targets (NEAs, Mars and Venus). The delay can range up to 42 minutes in the case of Mars. Placing astronauts and controllers in close proximity to these destinations greatly improves the prospects of performing tasks and operations of a short-turnaround nature.

Table 1: Round-trip communications delay for Earth communication to various destinations

Location		Approximate Latency
GEO		0.2 sec
EM	L1 & L2	~2.5 sec
	L4 & L5	2.5 sec
Moon		2.5 sec
SE	L1 & L2	10.0 sec
	L4 & L5	8.3 min
		Min Max
NEAs		<0.5 sec 38 min
Mars		8.6 min 42 min
Venus		4.6 min 28 min

HERRO also provides a path to more ambitious human exploration missions. Venus, with a surface pressure of 92 bars and a temperature of 450°C, is not credible as a target for exploration using the conventional strategy of landing humans on the surface. However, technologies have been proposed for developing mobile robots for Venus surface exploration, utilizing high-temperature electronic components and high-temperature motors and actuators that have been developed at NASA’s Glenn Research Center. Using these, or similar technologies, it is reasonable to seriously consider exploring the surface of Venus using human telepresence.

In the longer term, HERRO could be of use for exploration of many targets beyond the inner solar system. With incorporation of new propulsion and life support technologies, the in-space approach could be extended to destinations in the Main Asteroid Belt and possibly even some of the more accessible outer planets. Although HERRO bypasses many of the initial steps that have been historically associated with human space exploration, it opens the door to many new destinations that may be better candidates for future resource utilization and settlement.

III. Architecture

Operations for Planetary Surfaces

Although the mission architectures for large and small planetary bodies are different, both feature use of a Piloted Transfer Vehicle (PTV) as the basis for crew operations. For missions to planetary bodies (Fig. 6), a majority of the surface systems would be

deployed onto the planet’s surface prior to the PTV’s departure from LEO.

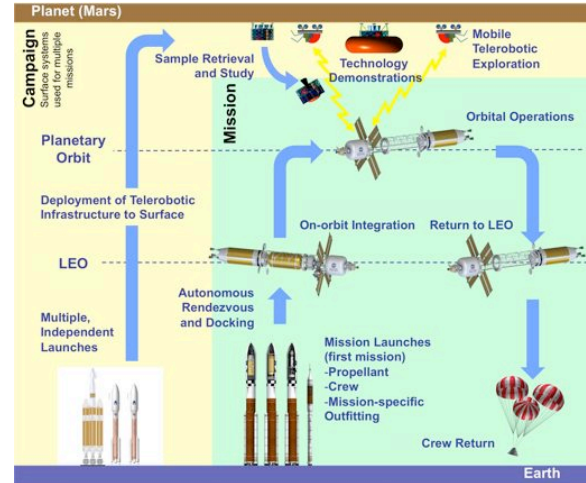


Figure 6: Exploration of large planetary bodies

This pre-deployment could occur up to several years in advance of the piloted mission, depending on trajectories and planetary alignments. These systems would include mobile telerobots, sample storage and return systems, deep-drilling stations and in-situ resource technology demonstration payloads. Figure 7 shows one possible conceptual design for such a robotic explorer, integrating a telerobot incorporating stereo-vision and robotic “hand” manipulators, onto a highly-mobile “body” section which incorporates support systems and scientific instrumentation, using wheel-legs or “whegs” technology for mobility.

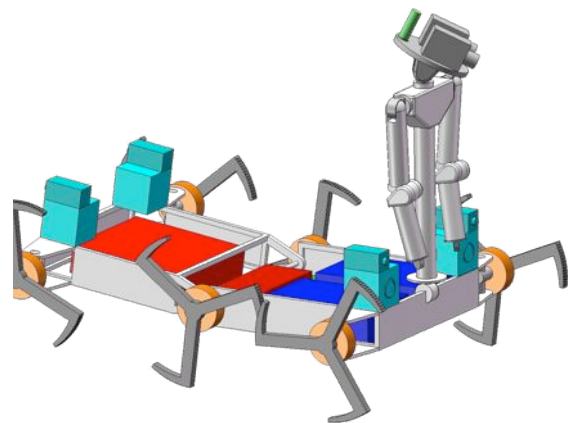


Figure 7: Telerobot concept for exploration of planetary surfaces

Transporting this infrastructure from Earth to orbit could involve a number of different launch vehicle options, depending on the payload’s size,

launch vehicle requirements and national origin. The PTV would likely require the launch of several heavy lift vehicles for the crew payload elements, propulsion and propellant. The architecture shown in Fig. 6 is for a Mars orbital mission using nuclear thermal propulsion. Once the PTV is integrated, the crew would travel to orbit on an Orion and dock with the PTV for final boarding.

The PTV would travel to the destination, perform a flyby or inject into orbit, and eventually return to Earth. While in proximity to the planet, the crew would directly control the robotic elements that had been deployed on the surface. Once the operations were completed and the return window had opened, the crew would return to Earth and use the Orion's Crew Module for return to the surface.

Operations for Small Bodies

The architecture for missions to small bodies and in-space locations (Fig. 8) differs by not requiring the pre-deployment of assets on the surface. In fact, the low gravitational fields of these destinations would allow the PTV to rendezvous and “dock” with the body under study. Extravehicular Activities (EVAs) of the surface by the crew could be conducted directly from the spacecraft, possibly using the already-developed Manned Maneuvering Unit (MMU) technology, although a significant portion of the mission could still be conducted via telerobotic operation from the PTV.

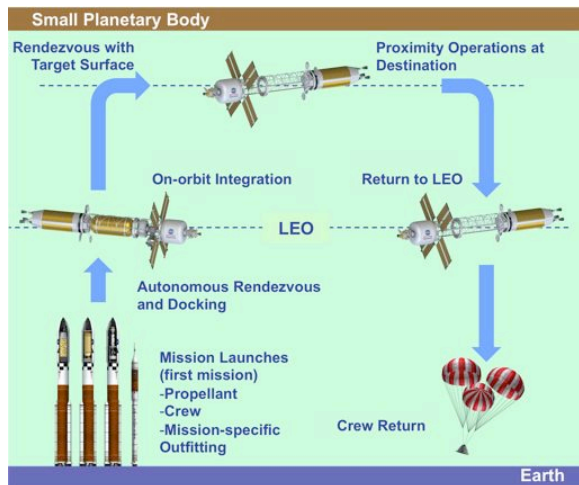


Figure 8: Exploration of small planetary bodies

Crew Vehicles for Human Exploration

The split in ΔV requirements in Fig. 5 suggests that the implementation of HERRO could begin with a PTV of modest capability and then evolve to a

more sophisticated system in the future. Near-term missions could probably be accomplished with a PTV configuration consisting of an Orion and single upper stage, as shown in Fig. 9.

The upper stage would provide the propulsion required for Earth departure. A man-rated Centaur Upper Stage may be adequate for lunar orbital missions and other in-space targets. More ambitious missions to accessible NEAs would require a larger stage, something on the order of an Ares V Earth Departure Stage (EDS). Longer duration missions in this class could range from weeks to months, and would probably require additional habitable volume. This extension in living space could range from an ISS-derived airlock or node to a full-scale module derivative.



Figure 9: Modest capability PTV configuration

The PTV used for more ambitious missions would be much larger (Fig. 10). As before, it would employ an Orion for crew access and Earth return, but would require several heavy lift launches to assemble. Recent Mars Architecture studies pointed to three Ares V-equivalent launches to integrate the propulsion, drop tank and crew habitat/payload elements of the PTV.

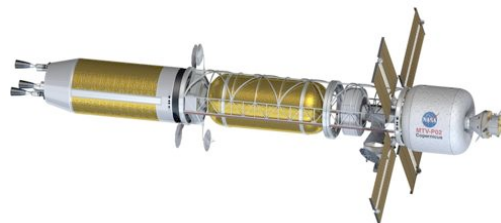


Figure 10: Full capability PTV configuration

A major consideration with the full capability PTV is the extent of its reusability. Although reusability increases the vehicle's overall propulsion and propellant requirements, it reduces the number of heavy lift launches per mission. This is especially important for a spacecraft of this size and scale of investment. The extent of space-basing for a reusable PTV is an issue that should be evaluated more thoroughly in future studies.

IV. Comparison of Exploration Strategies

Comparison Matrix

Figure 11 shows a matrix that compares HERRO with robotic space flight (traditional space science) and human space flight (current human exploration strategy) against seven different criteria. These criteria attempt to capture the most important features associated with the different exploration approaches. They include: (1) cognition (rapid recognition, response to unexpected findings, and rapid pattern recognition); (2) dexterity (ability to perform a multitude of different manipulative tasks); (3) adaptability (ability to react in real time to new unexpected situations); (4) efficiency (sample and equipment manipulation and problem solving); (5) robustness (ability to tolerate extreme and hazardous environments); (6) cost (total resources required to conduct mission); and (7) risk (potential for loss of mission, valuable hardware assets and/or human life). A three-color grading scheme is used to assess the criteria for each strategy, where green, yellow and red signify strength, weakness and major weakness, respectively.

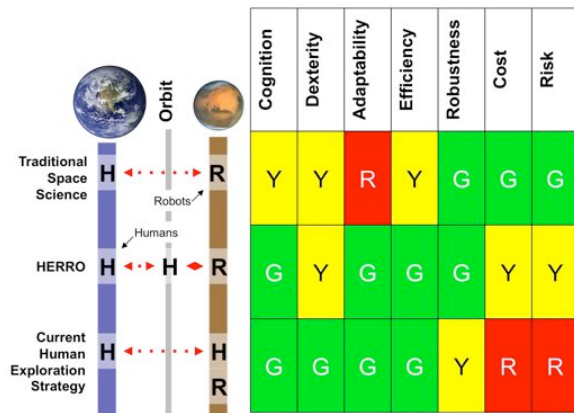


Figure 11: Comparison between robotic, human and HERRO exploration strategies

The first four criteria (i.e., cognition, dexterity, adaptability and efficiency) are ordinarily viewed as the unique strengths of human space flight. These are best demonstrated when scientists conduct research directly in the field, but crewed missions are constrained by the hazards of the space environment, hence the lower rating for robustness. In the long run, however, it is cost and risk that truly limit human space flight, and are the factors that have historically restricted the ability to conduct missions beyond LEO.

Alternatively, space science missions are much less expensive and risky than human space flight, and can certainly venture into a much broader range of hazardous environments (e.g., Venus surface, Jovian orbit). However, these missions are incapable of achieving the high levels of cognition, dexterity, adaptability and efficiency possible with humans at the site. The main advantage of robotic missions is their relative robustness, low cost and low risk compared to crewed missions.

The middle row in Fig. 11 shows how HERRO offsets the main weaknesses of the other two approaches. HERRO is certainly not superior in all respects. Its cost and risk will undoubtedly be greater than autonomous robotic missions. Furthermore, the dexterity of telerobotic operation may not be on a par with that of an astronaut. But overall, HERRO compensates for the marked weaknesses of the other two approaches, provides real time cognition, adaptability, and response, and creates a human-machine environment that will enable completely new ways to perform planetary science

Advantages to Human Exploration

HERRO represents a much more affordable, nearer-term approach to human exploration that enables crewed missions to multiple destinations beyond Earth orbit. It avoids locking in on one destination for many decades, and adopts a methodology that enables a more parallel development. It also leverages much infrastructure that has already been developed by maximizing use of ISS as a critical element for system design, operations and technology development.

HERRO embodies a much simpler architecture, because it avoids the development of man-rated landers, ascent vehicles and surface systems. This should lead to lower cost and a more affordable human space flight program. It also reduces the risk to crew operations and exploration in potentially dangerous environments. It requires fewer crew transfers between spacecraft, eliminates high-powered crew ascents/descents within large gravitational wells, and keeps people away from planetary surfaces that could be fraught with many unknowns and uncertainties.

The HERRO concept provides human-equivalent operational capacity on the surface with greatly reduced cost and risk. Ideally, the operational experience will be equivalent to being on the surface, however, HERRO will allow much more surface capability. According to Abeles and Schaefer, a maximum of 19.5 hours of EVA productive work per astronaut can be achieved in a week without stressing human capabilities in terms of work/rest cycles. A

significant portion of the workload is involved in simply putting on the suits, checking the systems, and operating the airlocks. A higher level of risk can be tolerated, and hence more challenging (and more scientifically interesting) terrain can be accessed, since a human life is not at stake in the case of an accident. In addition, it is no longer necessary to restrict the science areas of interest to be within a “walk-back” radius in case of a vehicle failure.

Finally, HERRO would probably relate better to a new generation of technology savvy scientists and engineers, who recognize robots as important tools and extensions of human presence. This flexible nature appeals to a culture that values multitasking and more immediate results. Robots are also more resilient to harsh conditions.

Advantages for Space Science

Figure 12 shows how HERRO could increase the rate of performing certain types of operations for Venus and Mars orbit missions.

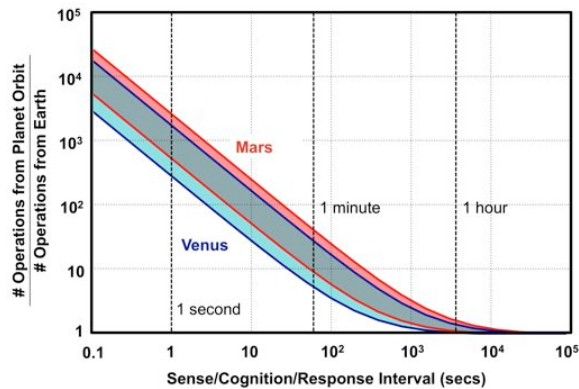


Figure 12: Command and control effectiveness versus operation interval

The X-axis represents the type of task in terms of the time between receiving information and responding to the condition. The lower range of 0.1 to 1 seconds reflects relatively rapid quick-response operations, such as driving at high speeds while negotiating rough terrain. On the upper end are tasks of a more deliberative nature, taking on the order of hours to days. This reflects the rate of human controller decision-making found in current robotic missions, where instruction sets are uploaded about once per day.

The Y-axis shows the effectiveness of HERRO relative to autonomous/Earth-controlled operations. This is expressed as the ratio between the number of operations per unit time with HERRO (i.e., human decision-making in orbit) and that with autonomous

robotic operations (i.e., decision-making on Earth). As expected, the payoff with HERRO occurs with the short-response time tasks. Here the communications delay predominates the total roundtrip communications time between human operator and robot, but this decreases as the time interval between receipt and response increases.

For decisions that entail considerable deliberation, such as mission planning and strategizing, the advantage of having humans in close proximity still exists although the actions may not be carried out immediately. On the spot planning and strategizing by the local humans will become the norm, enabled by quick robotic trials of different options to inform a final decision.

The benefit of reduced latency could be exploited in two ways. First, it would allow offloading of short response operations to a human operator. This would reduce the autonomy and complexity of the robot, and ultimately decrease the cost and risk of the robot design. Additionally, reduced latency could be applied to enable much faster operations on the surface, particularly with mobility and driving. Current operation of the Mars Exploration Rovers, for instance, is exceedingly slow. The vehicles are in effect crawlers traveling at a rate of 1 cm/sec. This is done to keep the vehicle’s position and operational state within a safe and manageable range of variation. The level of conservatism obviously increases with uncertainty and response time. Regardless of the approach, reducing communications delay will provide new opportunities for space science and change the nature of surface exploration.

A second major benefit to space science is the opportunity to facilitate the return of surface samples from the Moon, Mars, Venus and NEOs. These types of missions are considered to be the most challenging for robotic space science, mainly because they rely on the precise coordination and integrated operation of several autonomous flight elements. These mission concepts typically consist of an orbiter, lander/ascent vehicle, sample retrieval system and a return system within the orbiter element. In addition, there is the added complexity of having several challenging autonomous operations, such as landing, sample acquisition, loading within the launcher, launch and staging, orbital rendezvous and docking, sample transfer, and Earth entry and recovery.

Although HERRO does not allow direct crew retrieval of samples, as in Apollo, it does facilitate the recovery of samples by eliminating the systems needed to autonomously return samples to Earth. Sample return, in a HERRO context, would entail independent launch of a robotic/lander spacecraft to the surface of Mars or another planetary body. A

separate rover could search for and acquire samples, with the human operator determining which samples are actually collected for further analysis. Once the capsule is full, the ascent vehicle would launch and deploy the sample package into orbit. From this point on, an operator aboard the PTV could either control the sample package directly or maneuver a small robotic spacecraft to collect the package. The crew would be in orbit for a year or more, and would have adequate time to recover the sample using a low-thrust but very high performance electric propulsion system. The only unique hardware for this mission would be a small ascent vehicle that could take samples from the Mars surface to the orbiting HERRO spacecraft, where the material could be evaluated, discarded or kept for further study on Earth.

A third benefit of HERRO is its ability to facilitate the exploration of Venus. The biggest challenge for Venus exploration is the difficulty of developing systems that could last for meaningful lengths of time in Venus' high temperatures and crushing atmosphere. The most sensitive components are sensors and electronics for high-order computation. In the context of a HERRO mission to Venus, the high-order electronic functions would be offloaded to crew in the PTV, and the surface robots would employ much simpler high-temperature electronics.

HERRO also facilitates planetary protection by preventing forward and backward contamination between Earth and the planetary environment. Avoiding crew presence on the surface, at least until the environment has been thoroughly evaluated by a series of HERRO missions, protects the planetary environment from contamination by hearty Earth-originating microbes, and prevents human exposure to potential alien pathogens. The use of robotic elements, even for potential sample return packages, greatly improves the quarantine of potential Mars microbes from contaminating the crew systems. All the elements sent to the surface would have no contact with human crew prior to their arrival. Thus, one would expect a long period of ramped up exploration where the surface of Mars was kept sterile for biological study – a key issue when one of the main goals is searching for indigenous life.

Other Advantages

HERRO provides many opportunities for participation by international and non-NASA entities. The surface and robotic systems are developed and deployed separately, but all adhere to a common communication and control architecture. There are no complex mechanical interfaces to develop, and

this facilitates participation by crewmembers from international and non-NASA organizations, in a manner similar to operations aboard the ISS.

HERRO also takes advantage of the significant investment made in ISS, which will become particularly important as a testbed for developing crew zero-g countermeasures. It could also be used as a vehicle support center and safe haven for vehicle assembly and integration. In addition, derivatives of the habitable volumes used on ISS may be used as part of the early PTV configuration.

In general, HERRO provides a more flexible first step in determining where to concentrate future human surface missions and settlement. Teleoperations could be used for extensive exploration, site preparation and construction prior to a future phase of exploration involving crew surface missions.

V. Technology Challenges

There are several technologies that are important in enabling implementation of HERRO missions. The main one is the area of Life Support and Human Health. HERRO missions will place tremendous demands on the ability to sustain the crew over long multi-year missions, and will require the development of improved environmental control and life support systems to minimize the amount of water, oxygen and other life support fluids that have to be brought from Earth.

The PTV will also be exposed to large cumulative amounts of radiation stemming from cosmic rays and other sources. Countermeasures will have to be developed to mitigate these effects. For radiation, these include lightweight radiation shields and the use of multifunctional materials and structures. Examples include use of hydrogen propellant to shield astronaut crew quarters or construction of shields using stored water.

Another health concern is the deleterious effects of long-term exposure to microgravity. Work aboard the ISS over the last decade has improved our understanding of how to mitigate these effects. However, these countermeasures have been validated only to a year or so, and depend on individual physiology. For long multi-year missions, it is likely that methods of subjecting the crew to artificial gravity using a rotating structure and centrifugal acceleration will be necessary. This will require testing in a zero-g environment. It also places additional challenges on the overall spacecraft configuration and integration of its functions with the rest of the spacecraft.

A second major technology area is Robotic Systems. Most of NASA's work in this area has been

aimed at highly autonomous systems and telerobots to support Shuttle, ISS and human operations in space. For HERRO, the emphasis will expand to include methods of providing high power, which will be necessary to effect faster mobility and real-time operations. Candidates will include high-performance solar photovoltaics, advanced radioisotope generators and possibly fission power supplies.

Advanced sensors and improved mechanical dexterity will also be important. The reduced communications latency and possibility of employing high-bandwidth communications between orbiting crew and surface systems will push technology forward on telepresence and facilitate crew control.

HERRO missions do not require high thrust human-rated propulsion for landers and surface ascent. However, new in-space propulsion technologies could facilitate the implementation of HERRO missions by reducing propellant mass, trip times and overall costs. For modest capability missions (*e.g.*, to the Moon and Lagrange Points), chemical propulsion will be adequate. Full capability missions (*e.g.*, to more distant NEAs, and Mars and Venus orbit) could benefit through use of advanced technologies.

Nuclear thermal propulsion (NTP) is one technology that could double the propulsion performance for these missions. The U.S. had conducted an ambitious technology program in this area, called NERVA, over 40 years ago. Several studies over the years have evaluated resumption of NTP development. Most of these have pointed to the need for new infrastructure and testing methodologies to reduce environmental impact, but there are no apparent showstoppers in moving forward with this work. There are also other forms of high performance propulsion, such as plasma propulsion, that could provide another route to faster and more cost effective missions to Mars, Venus and beyond. These include the Variable Specific Impulse Magnetoplasmadynamic Rocket (VASIMR) and high power electrodynamic thrusters.

Finally, HERRO missions will employ crewed EVA to the surfaces of NEAs, Phobos and Deimos. These will require the advancement of mobility systems that are safe and allow astronauts to make direct visits to these destinations. An example NASA technology that could play a role for this is the Manned Maneuvering Unit (MMU), which was demonstrated in use on the Shuttle prior to the Challenger accident in 1986. More advanced versions of the MMU would complement missions to small planetary bodies, along with new technologies for space suits and astronaut work performance.

The technologies discussed here are only a portion of the total number that would be suitable to HERRO-type missions. Other technologies, such as cryogenic fluid management, communications, advanced materials and structures will also be important.

VI. Stepping Stone to Future Human Landings

It is important to emphasize that the HERRO concept does not preclude a path toward crewed landings on the Moon and Mars. The HERRO concept is, in fact, a logical stepping-stone to more advanced exploration. Just as the preparation for Apollo-11's landing on the Moon included the Apollo-8 mission, which orbited the moon but did not land, it is reasonable to assume that missions to Mars should also proceed in smaller steps. Each step would bring the technology and the experience incrementally forward, so that when the actual human landing occurs, all the components have already been demonstrated. It avoids the rather unrealistic expectation that the first mission to Mars not be flown until all of the required systems – high-capability PTV, entry descent and landing vehicle, surface habitats, EVA suits for exploration, ascent vehicle – are ready.

Rather, the HERRO concept allows missions to begin as soon as a PTV is ready. HERRO allows significant science return, as well as public engagement, in the process of flight demonstrating the intermediate stages. Development of the landing, deployment, and surface mobility systems of the HERRO surface-exploration telerobots will also be directly applicable to eventual human landing systems. Before the first human landing, we will have significant confidence in our surface systems and have gained considerable experience in landing large, complex systems on the surface of Mars.

Pre-deployed telerobotic systems could perform, in addition to scientific exploration, most of the site construction and preparation prior to sending humans to the surface. In essence, the first humans to walk on Mars would have the “red carpet” waiting for them, with all the habitation and operational infrastructure already in place.

VII. Conclusions

Although HERRO bypasses many of the initial steps that have been historically associated with human space exploration, it opens the door to many new destinations that may be better candidates for future resource utilization and human settlement. HERRO should be viewed as a first step, one that

takes humans to exciting destinations beyond LEO while solidly expanding our ability to conduct science within the inner solar system. In fact with appropriate advancements in propulsion and life support technology, it is reasonable to consider extending the HERRO approach to missions into the main asteroid belt and destinations in the outer solar system.

Finally, advocates for human exploration should understand that HERRO does not replace eventual human missions to the surfaces of other worlds. The technologies developed for HERRO are directly relevant to later human surface missions. When the nation decides to develop the systems needed to send crews to the surfaces of the Moon and Mars, a good portion of the technological infrastructure will already be in place.

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