

Multi-Level Autonomy Robot Telesupervision

Gregg Podnar, John Dolan, Alberto Elfes, and Marcel Bergerman

Abstract — This paper focuses on the development of an advanced telesupervision system architecture that supports a highly efficient approach to human-robot interaction while allowing heterogeneous robotic assets to be deployed. The described multi-level framework not only supports human monitoring and control of existing state-of-the-art autonomous agents, but also allows new autonomous agents to be incorporated at each level as they become available.

Our philosophy of maximizing the efficiency and safety of humans through telesupervision of autonomous robotic systems is applicable in extreme environments on Earth, and across space including telesupervising Lunar and Martian robots when humans are nearby.

We describe two applications of our Multilevel-Autonomy Robot Telesupervision Architecture: for planetary mineral prospecting using multiple semi-autonomous rovers conducted under a past project funded by the NASA Exploration Systems Mission Directorate; and for Harmful Algal Bloom detection and characterization by multiple semi-autonomous ocean vessels conducted under an ongoing project funded by the NASA Earth Science Technology Office.

I. INTRODUCTION

HUMAN control of robots has typically involved teams of humans controlling one robot. As robotic systems are employed to more applications and with greater levels of autonomy, significant improvements in human safety and efficiency can be gained, especially when the ratio of robots to humans increases. Long-term wide-area terrestrial tasks, such as monitoring coastlines for harmful algal blooms, are ideal for the application of teams of autonomous robots. For extraterrestrial tasks, greater human safety and efficiency are paramount to successful exploration.

In January 2004, NASA established a long-term program to extend human presence across the solar system. It encompasses a broad range of human and robotic missions. The key goal of this policy and strategic direction is that

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future space exploration activities will be enabled by combining human and robotic capabilities in order to achieve a long-term and well-orchestrated campaign of space exploration [1].

Lunar and planetary surfaces are the most hostile working environments into which humans can be sent. The protective spacesuit is massive and cumbersome, with EVA mission time limited by both the suit’s resources and the astronaut’s stamina. To maintain human presence on the Moon and to expand it to Mars requires enormous investments in transportation and life support for each human. Therefore, successful and sustainable space exploration and operations must maximize the efficiency of every astronaut and keep them “as safe as reasonably achievable”.

Towards this goal, tasks for which current robotic autonomy technologies are effective should be offloaded from the astronauts. However, whenever the limits of autonomy are reached, a human must directly intervene, preferably by teleoperating the robotic assets (thus reducing EVAs). This completely changes the risk profile of a mission, and allows astronauts to perform substantial amounts of hazardous work from a well-supplied operations base, such as an orbital station, a Crew Exploration Vehicle, or a Lunar or Martian habitat. This results in a manifold increase in the human’s performance and a significant improvement in safety.

To effectively support the human telesupervisor interacting from very high supervisory levels, all the way down to taking direct teleoperation of an asset, we have defined, designed, and are continuing to develop an advanced telesupervision system architecture that supports highly efficient human-robot interaction while allowing heterogeneous robotic assets to be deployed. This flexible architecture, proven by real-world tests, becomes the operational framework for a wide variety of tasks where teams of autonomous robots are telesupervised by fewer humans. Demonstrating the architecture’s flexibility, we have applied these concepts to two very different real-world task domains: adaptive investigation of harmful algal blooms (HABs) in Earth’s oceans; and planetary mineral prospecting for *in situ* resource utilization.

II. TELESUPERVISION ARCHITECTURE

Our flexible Multilevel-Autonomy Robot Telesupervision Architecture (MARTA) is designed as a general architecture for telesupervision of teams of robots. It supports human telesupervision of robotic assets with a range of autonomy capabilities. Implemented as a multilevel, multi-robot

control and coordination architecture, it can accommodate different configurations of stationary and mobile robotic assets. Here, “multilevel” means that robot system control is performed at multiple levels of resolution and abstraction.

The lower-level robot-specific functions of MARTA operate under typical Perception – Decision-Making – Actuation sequences. While the higher-level functions are for multi-robot control and monitoring. These follow a similar paradigm, also having Perception – Decision-Making – Actuation sequences but at a higher level of abstraction. For example, stationary robotic assets have low-level modules for operational autonomy, and mobile assets (e.g., rovers and boats) each have a low-level Autonomous Navigation System. These robot-specific functions are abstracted at a higher level in MARTA for team coordination, monitoring, decision-making, and when required, handover to the telesupervisor. A diagram showing the modules and levels of MARTA is presented in Figure 1 with each of the subsystems explained below.

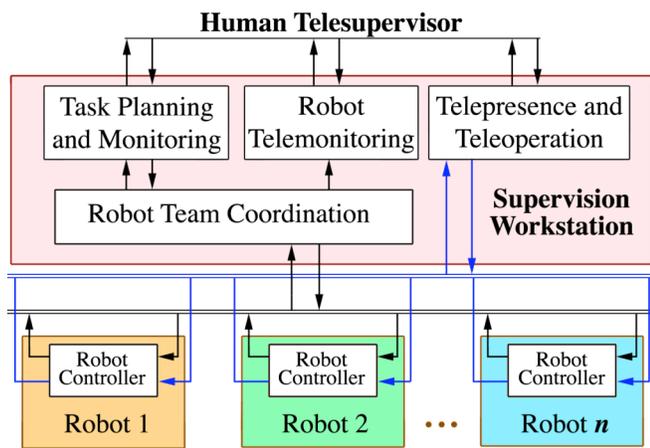


Figure 1. Multilevel-Autonomy Robot Telesupervision Architecture (MARTA) block diagram.

A. Human Telesupervisor

A human telesupervisor oversees the entire mission planning and execution, being able to assume a wide range of roles – from “pure” supervision at the highest system level while monitoring autonomous progression of accomplishing the overall *task*; to monitoring the performance of the team of autonomous *robots*; to “pure” teleoperation at the lowest level of any *individual* robot. The telesupervisor devises the high-level mission plans and assigns them to the Robot Team Coordination module for further task decomposition and assignment to the individual robots. The telesupervisor may also drive the robots directly via the Telepresence and Teleoperation subsystem. All results, in the form of images and sensor data, science data, and other task-specific information are provided at the Telesupervisor Workstation, one conception of which is shown in Figure 2.

B. Task Planning and Monitoring

To the left in Figure 2 are high-level task planning and monitoring. Functionally, this is represented by the Task Planning and Monitoring module in Figure 1. Maps representing different aspects of the area of operation are displayed and overlaid with navigation information such as planned paths, waypoints achieved, current locations, and other robot and team specific data. These graphical interfaces provide for mission task design, which for HAB ocean sensing may include a marine navigational chart and areas of interest, while for the mission of wide-area mineral prospecting it may include terrain map and a list of prospecting sites. This high-level mission monitoring also provides the feedback needed for successful replanning as a mission progresses.



Figure 2. Tele-Science Workstation

Where a priori and sensor data are integrated, Inference Grid [2] representations are used. Inference Grids (IG) are a multi-property lattice-based Markov-Random-Field (MRF) model where sensor information is stored in spatially and temporally registered form, and are used for both scientific inferences and for vehicle mission planning. The information in Inference Grid cells is represented as a stochastic vector, and metrics such as entropy are used to encode the uncertainty in the IG. Measured data fields such as mineral concentrations can be manipulated together with generated maps such as terrain roughness.

These high-level functions are adapted to the task domain: the methods for coordinating prospecting rovers are instantiated for the prospecting task; and the methods for sensor-based adaptive fleet control are instantiated for the marine platforms investigating Harmful Algal Blooms. The Monitoring level also includes Perception — Decision-Making — Actuation sequences to monitor multi-robot operations as a system, and to analyze it for high-level hazard and assistance detection.

C. Robot Team Coordination

The Robot Team Coordination module (Figure 1) decomposes high-level commands and generates robot-specific commands. This provides a separation from the high-level planning that adds flexibility to the system by supporting coordination of robotic assets with very different

physical characteristics and even different command protocols.

D. Robot Telemonitoring

The team of robotic assets is constantly monitored at low bandwidth by the human telesupervisor with imagery and data updated regularly from each robot. The Robot Telemonitoring module manages the image and telemetry archives for each robot and presents these data both for human, and for automatic monitoring and analysis. As shown at the right in Figure 2, each robot has a “dashboard” that includes a regularly-updated image from one of the robot’s cameras, and engineering data such as battery charge, attitude, motor temperatures, and other telemetry provided to the operator in both tabular and graphical form. The archive function allows for later mission analysis, but also allows for a *replay* to give the telesupervisor a quick review the robot’s recent activities, thus providing the context leading up to its current situation. This attention to human factors allows the telemonitor to rapidly assess conditions when a hazardous situation is detected or assistance is required.

E. Telepresence and Teleoperation

We make a distinction between monitoring the operation of a team of robots, and telepresently taking control of an individual robot. Whereas monitoring is supported by simultaneous low-bandwidth data streams from each of the robots, telepresence is supported by high-bandwidth imagery and other telesensory modalities for one robot at a time, such as stereoscopic video, aural, and attitude proprioceptive feedback that allows for more immersive telepresence.

Teleoperation involves direct human control of a single robot when a vehicle must be remotely controlled rather than operating under its Autonomous Navigation System; and when its task-specific tools must be operated manually. Appropriate joystick, keyboard, and task-specific human interface devices support this. Robot actions and sensor data continue to be reported through the Robot Controller up to the Robot Team Coordination Module for maintaining a model of the robot’s state which is necessary when the robot is returned to autonomous control.

This subsystem is ideally implemented over a dual-path data communication infrastructure, where the low-bandwidth path is used for communication of commands and telemetry data, and the high-bandwidth path is used for telepresence, such as geometrically-correct stereoscopic video [3][4]. This is represented by the parallel data path of Figure 1 (blue).

F. Robot Controller

As depicted in Figure 1, the Robot Controller subsystem on each robot receives a collection of lower-level task commands from the Robot Team Coordination module and monitors its execution on that robot. When a robot is a relatively complex combination of mobility, manipulation, and other engineering or science subsystems, the

corresponding Robot Controller may be implemented as a collection of modules responsible for each one of them. For example, in addition to a navigation module, a vehicle *health* module can be monitoring at a low level — battery charge and temperature, vehicle attitude, motor currents — and when an out-of-range condition occurs, appropriate immediate action is taken locally, and a message is sent to the Telesupervision Workstation where higher-level Hazard and Assistance Detection agents are monitoring.

III. APPLICATION EXAMPLES

The Multilevel-Autonomy Robot Telesupervision Architecture has been applied to two very different real-world tasks: investigation of marine-borne Harmful Algal Blooms; and Planetary Prospecting for exploration and *in situ* resource utilization (ISRU). Each of these task application areas is described in the following subsections.

A. Harmful Algal Bloom Investigation

Interest in Harmful Algal Bloom (HAB) detection has grown in recent years for scientific, commercial and public health reasons. Ocean sensing is typically done with satellites, buoys, airborne assets and research vessels. Satellites and airplanes are limited by resolution, cloud cover, and temporal and geographical coverage; while research vessels are expensive and take time to deploy, and buoys cannot self-deploy to specific areas of interest.

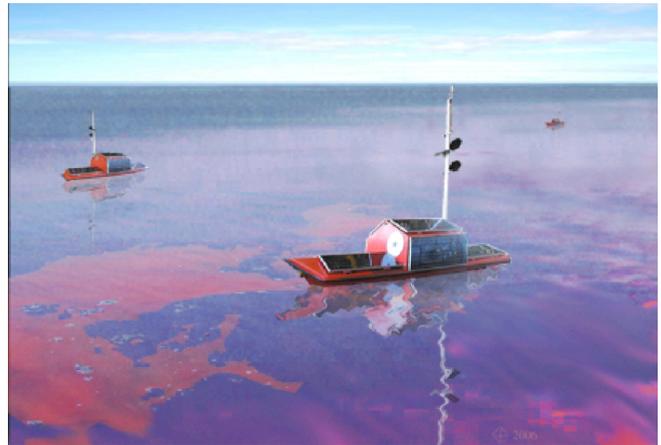


Figure 3. OASIS investigating an HAB (concept).

The National Oceanic and Atmospheric Administration (NOAA) is addressing some of these constraints through the development of robotic ocean vessels for weather-related ocean monitoring. The OASIS (Ocean-Atmosphere Sensor Integration System) vessels are long-duration solar-powered autonomous surface vehicles (ASVs) designed for global open-ocean operations (Figure 3). Using our Multilevel-Autonomy Robot Telesupervision Architecture to investigate HABs enhances the science value of the OASIS sensing assets by coordinating their operation, and adapting their activities in response to sensor observations. MARTA supports a human telesupervisor monitoring these and other



sensing assets such as Earth observing satellites [5].

Our HAB investigation system is called: Telesupervised Adaptive Ocean Sensor Fleet (TAOSF). This instantiation of the MARTA architecture supports the following features:

- Multilevel autonomy, allowing an operator to control the vehicles by setting high-level goals, such as specifying an area to monitor, or by taking direct control of the vehicles via teleoperation, or at other autonomy levels in between.
- Adaptive replanning of the activities of the OASIS vessels based on sensor inputs (“smart” sensing) and sensorial coordination between multiple assets, thereby increasing data-gathering effectiveness while reducing the effort required for tasking, control, and monitoring of the vehicles.
- Web-based communications permitting control and communications, and the sharing of data with widely-dispersed remote experts for higher-level scientific analysis and mission planning.
- Autonomous hazard and assistance detection, allowing automatic identification of hazards that require human intervention to ensure the safety and integrity of the robotic vehicles, or of science data that require human interpretation and response.
- Science analysis of the acquired data in order to perform an initial onboard assessment of the presence of specific science signatures of immediate interest.

2. A task-specific Robot Team Coordination module, named the Adaptive Sensor Fleet (ASF) and developed by NASA’s Goddard Space Flight Center, provides platform assignment and automated path planning for area coverage, as well as monitoring of mission progress. Command protocols and collected data are conformed and passed here.
3. The Task Planning and Monitoring module, developed by Carnegie-Mellon University, provides high-level planning, monitoring, and telesupervision, as well as analysis of science data from both the OASIS platforms and external sources such as satellite imagery and fixed sensors. These data are used in planning of vessel navigational trajectories for data gathering.
4. The Robot Telemonitoring module provides an operator interface for those occasions when a scientist desires to exert direct monitoring and control of individual platforms and their instruments. Both the Task Planning and the Robot Telemonitoring module are presented to the telesupervisor through an instantiation of the Multi-Robot Operator Control Unit (Figure 4) developed by SPAWAR Systems Center San Diego [6].

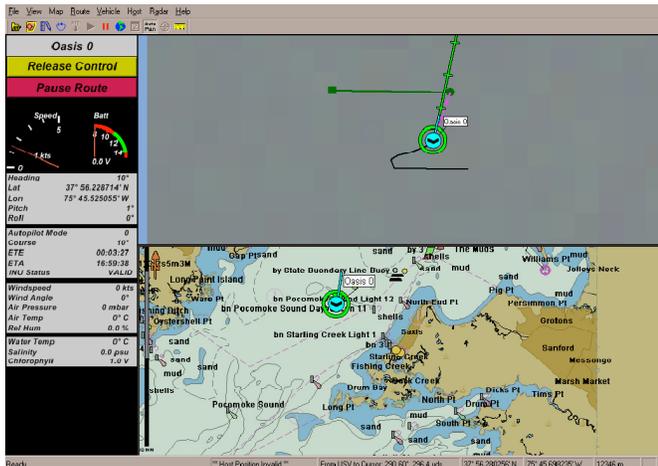


Figure 4. Multi-robot Operator Control Unit.

Within the MARTA architecture subsystems previously-developed by the participating institutions are effectively integrated. The major TAOSF subsystems are:

1. The OASIS Autonomous Surface Vehicle (ASV) system, (developed jointly by NOAA, NASA Goddard’s Wallops Flight Facility, and Emergent Space Technologies, Inc.) includes the vessels themselves, their on-board control systems, and the land-based control and communications infrastructure developed for them. Each OASIS Robot Controller module directly controls the hardware of its platform (sensors, actuators, etc.), and also provides a low-level waypoint navigation capability.



Figure 5. OASIS platform about to enter a simulated Harmful Algal Bloom.



Figure 6. OASIS Platform, Chase Boat, and Aerostat far overhead (in header).

Real-world field tests involve mapping of a simulated Harmful Algal Bloom. Rhodamine water-tracing dye is deployed into the ocean and sensed with fluorometers on the OASIS platforms. Figure 5 shows an OASIS platform about to enter a dye patch. The second vessel is a chase boat that also has an aerostat tethered to it. The image was taken from

the video down-linked from the areostat's avionics package. Figure 6 shows a view from the shore of the OASIS platform, and the Chase Boat. The tether controlling the Aerostat cannot be seen in this image, but the aerostat can be seen (but one must look above the column of text to find it).

B. Planetary Mineral Prospecting

Space exploration is one of the costliest and riskiest activities human beings pursue. It is estimated that, for each astronaut who walks on the surface of Mars, it will be necessary to lift some 500,000 tons of cargo, at a cost of several hundred billion dollars. Because these missions require extended stays, the use of *in situ* resources is compulsory to provide building materials, breathable atmosphere, and even fuel. For experiences both on orbit and on the Moon it is commonly reported that after about five hours of work in a space suit, astronauts must return to their base habitat, exhausted by the intensive effort required.

Robots, on the other hand, have been proven to work very well in extraterrestrial environments, being able to travel autonomously, explore, photograph, collect samples, and even perform limited scientific analysis of materials. The Spirit and Opportunity Mars Exploration Rovers, for example, combined have logged more than 2,900 Martian days, and over 19 km, and are still operating. However, human interaction with the Mars Exploration Rovers is restricted by round-trip communication delays ranging from six to forty-five minutes.

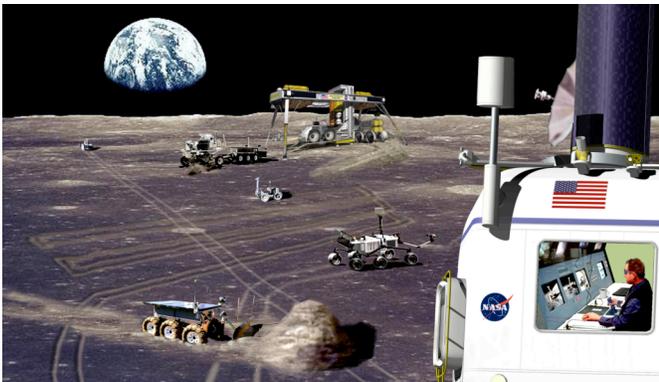


Figure 7. Telesupervision of a very heterogeneous team of ISRU robots.

When humans and robots are near each other the communication delays become less significant, and a human telesupervisor can take more direct control of a robot when necessary as if the human were immediately present. By exploiting this scenario of human-supervised robotic exploration and work, we can optimize the human's time by deploying a fleet of robots that operate *as autonomously as possible*, and have the human supervisor provide direct control only when necessary. This paradigm has significant benefits: the robot fleet multiplies the effectiveness of one human; the human supervisor remains in a relatively safe, shirtsleeve environment (Figure 7); and the weight lifted from Earth can be reduced by orders of magnitude.

We modified a K-10 robot developed by NASA Ames Research Center to adapt it for the surface prospecting including an articulated geometrically-correct stereoscopic telepresence camera with both a high view for teleoperation and a low view for close-up inspection of surface minerals; and a laser scanner for tight-quarters navigation (Figure 8).

The Prospecting [7] instantiation of MARTA follows the same framework as outlined in *Section II. Telesupervision Architecture*, and has subsystems analogous to the TAOSF subsystems while being applied to a very different task domain. The major Prospecting subsystems are:

1. The Autonomous Prospecting Vehicles included testing with two different physical platforms: the CMU-augmented NASA Ames K-10, and the JPL Sample Return Rover (SRR). While we were unable to conduct tests on the Moon, we did remotely telesupervise a K-10 at Moffett Field, California (Figure 8), and the SRR in Pasadena, California, both from CMU in Pittsburgh, Pennsylvania (Figure 9.)



Figure 8. K-10 rover modified for surface prospecting.

2. A task-specific Robot Team Coordination module supported efficient multi-robot area coverage algorithms. The prospecting task required that each robot autonomously traverse to the next prospecting site and then request assistance, where the human telesupervisor would perform the actual prospecting task. This is part of the high-level Hazard and Assistance Detection monitoring.
3. The Task Planning and Monitoring module included functionality for generating high-resolution maps by building up robot-acquired imagery on top of satellite imagery as the prospecting robots traversed the terrain. This was provided using Inference Grid technology. As part of this module's development, significant scheduling for efficiency work was also done [8][9].
4. The Robot Telemonitoring module included a graphical Dashboard which relayed vehicle telemetry (Figure 9).

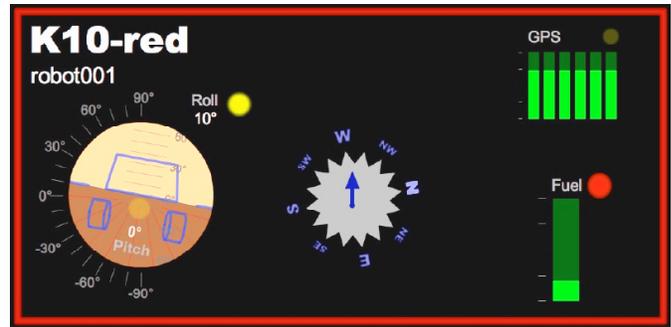


Figure 10. Prospecting vehicle “Dashboard”.

The Telesupervisor Workstation provided a live video display for teleoperation. This was demonstrated by setting up bullseye targets at NASA Ames’ “Moonscape” lab, and teleoperating their K-10 with a telepresence camera and a long pointing tool (Figure 8). These same experiments using CMU’s K-10 with a geometrically-correct stereoscopic camera allowed the teleoperator to approach the targets with much greater accuracy and then to just barely touch them (Figure 11).



Figure 8. Teleoperation from CMU of a K-10 at NASA Ames “Moonscape”.



Figure 11. Teleoperating Prospecting robot using geometrically-correct stereoscopic system.

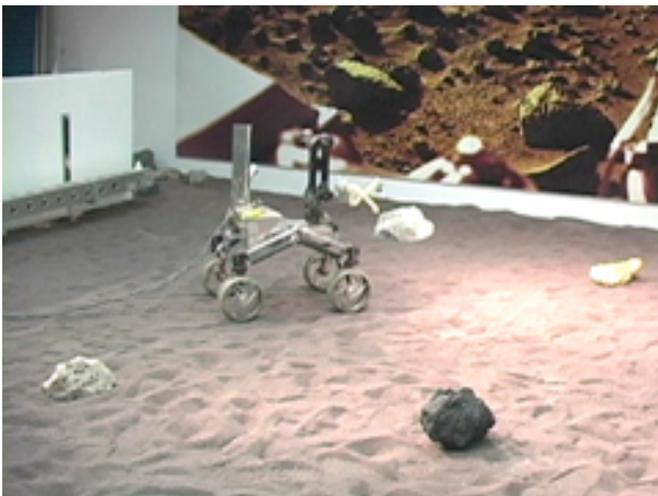


Figure 9. Teleoperation from CMU of NASA JPL Sample Return Rover (SRR).

For a task such as prospecting, being able to autonomously navigate to a prospecting site, then turn control over to the telesupervisor allows the human to make decisions for precise placement of the sampling tool and to closely monitor delicate operations such as core boring and retrieval.

IV. TELESUPERVISION OF PLANETARY ROBOT TEAMS

The summaries of these two multi-robot telesupervision tasks, HAB investigation and Planetary Prospecting, demonstrate the flexibility of MARTA working within these very different domains. While the ongoing program for the Telesupervised Adaptive Ocean Sensor Fleet is focused on this planet, NASA Goddard Space Flight Center’s

Innovative Partnerships Program [10] recognizes that:

Within the context of the Vision for Space Exploration, this system will have applications for lunar, orbital, or planetary construction and inspection; lunar and planetary *in situ* resource utilization; and prospecting, mining, transport, and construction.

Telesupervision of robot teams using MARTA, with its support for multiple levels of autonomy, is significantly different than exploration programs that have been conducted on the Moon and Mars to date: our human exploration of the Moon was conducted by humans primarily out on the surface in space suits; and our remote exploration of Mars is being conducted from the Earth with a roomful of people dedicated to each rover, with each rover communicating for short periods twice per Martian sol to download science data and to upload the next sol's program.

A. Human and Robot Teams

The Human and Robotic Technology Formulation Plan¹ envisioned intelligent multi-agent systems of human and robot teams "...working in close proximity". Working together in *close proximity* deserves very great attention now precisely because the plans are to "extend human presence across the solar system". Humans *will* be in close proximity to robotic assets, unlike most of our previous experiences. However, the concern is over how one defines "close".

While the goal is certainly to develop reliable fully-autonomous systems eventually, their modest abilities now do not preclude taking full advantage of the current state of the art. This has led to our pragmatic approach of combining the strengths of autonomous systems with the ingenuity of a *nearby* human supervisor. Augmenting a human's expertise with teams of autonomous robots will result in efficient use of the human's reasoning ability and attention while simultaneously keeping the human in the safest possible environment

B. Robot Teams with a Human Nearby

We suggest that "nearby" means the communication time delay is relatively short and, depending on distance, interactions can be relatively quick or practically immediate. A human in a space station telesupervising robot teams just "outside" in the same orbit is "nearby", as is a human in a habitat telesupervising robot teams out on the surface.

Pursuing a further definition of "nearby" begins with the distances depicted in Figure 12. Anywhere within geostationary Earth orbit is technically nearby the Earth's surface with less than a 250 millisecond round-trip communications delay. These nearby scenarios allow the best of telesupervision, where the robots operate as autonomously as possible, but when one is in need of direct human assistance, the human can efficiently teleoperate the robot through a high-fidelity, low-temporal-delay telepresence system.

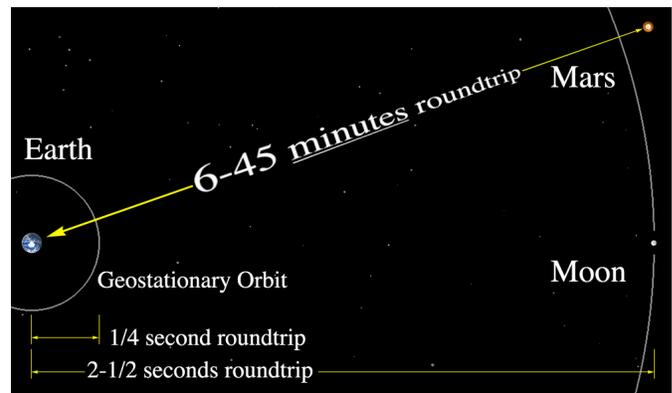


Figure 12. Roundtrip communications delays.

Telesupervision of robotic assets on the Moon from the Earth becomes far less efficient with its order-of-magnitude increase in communications delay. And the long communication delays between the Earth and Mars (which cannot be considered *nearby*) require that human intervention take the form of teleprogramming.

C. Practically Mars

Taking the approach of developing robotic technology for humans working on the Moon in preparation for sending humans to Mars is an excellent way to prove these technologies (where backup systems can be available) before taking them so far away that we must be able to depend on them unequivocally. By employing telesupervised-autonomy and high-fidelity telepresence technologies we will be able to mount a telerobotic precursor mission to Mars that puts humans *nearby* Mars without landing them on the surface of the planet. Interestingly, the roundtrip communications delay between a Mars geostationary orbit and the surface is only about one-eighth of a second (Figure 13). This is *closer* than geostationary orbit above Earth.

Geologists on an orbital station might actually have a better experience through telepresence than if working on the surface in bulky spacesuits. Samples can be lifted on small rockets for direct analysis by scientists, and only the best and most varied samples need be returned to Earth for further study, dramatically increasing the potential science return.

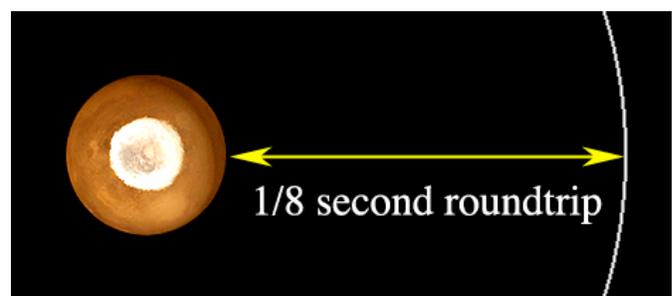


Figure 13. Mars geostationary orbit — very *nearby*.

By postponing the need to build a launching center and heavy-lift rockets down in the gravity well of Mars, the amount of hardware needed to be transported is reduced by orders of magnitude, and the probability of a safe return is dramatically increased.

D. Heterogeneous Robot Teams

An example of terrestrial testing of a very heterogeneous group of robots is being conducted in the Arizona high desert [11]. These tests by the Desert Research and Technology Studies (RATS) team are investigating human and robotic interaction with a collection of potential extraterrestrial equipment.

A homogeneous team of two K-10 robots in the Haughton Crater Site Survey Field Test [12] conducted detailed surveys in the high Canadian Arctic of a kind that will be needed at a variety of sites on the Moon and Mars to lay out infrastructure locations, prospect for resources, and plan astronaut excursions. This NASA Ames Intelligent Robotics Group investigation was carried out this year.

These are excellent efforts by dedicated teams braving inhospitable terrestrial conditions to test a wide variety of discrete robotic systems for future space explorations. However, the ratio of humans-to-robots for these tests is large. This ratio must be inverted to practically realize a sustained exploration program.

By integrating these and nascent robotic technologies using our Multilevel-Autonomy Robot Telesupervision Architecture, a few astronauts will be able to efficiently telesupervise these very heterogeneous assets.

V. CONCLUSION

For efficient exploration and monitoring of Earth, and for a sustained human presence on the Moon, and human exploration of Mars, substantial and sustained operations must be largely conducted with autonomous systems. The flexibility of our multilevel architecture supports integration of higher levels of autonomy and efficient coordination of varied robot teams. As more intelligent agents are developed they can be directly integrated, thus further reducing the demand on the humans' attention, and making these systems-of-systems more efficient, and safer. For space exploration, applying this telesupervision architecture will save thousands of hours of astronaut time, as well as thousands of tons of mass due to fewer astronauts needing support to achieve Lunar and Martian exploration objectives.

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