Activities of the NASA Exploration Team Human-Robotics Working Group

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Abstract

This paper summarizes some of the work performed by the NASA Exploration Team (NEXT) Human-Robotics Working Group. The team had representation from across NASA and performed a number of key studies and experiments between 2001 and early 2003.

1.0 Introduction

The NASA Space Architecture Team (formerly the NASA Exploration Team; NEXT) at NASA HQ is charged with determining NASA's exploration priorities and the technologies needed to attain them. A key area of interest is the role of humans and robots in future exploration activities. Robotic systems have been used since the beginning of space exploration (Surveyor, Lunakhod, Voyager, Sojourner), expanding human presence throughout the solar system and providing stunning visual and scientific observations. At the same time, human missions have fired the imagination of the whole world and accomplished amazing feats (Apollo, Skylab, Mir, the Space Shuttle, and the International Space Station). The notion of heterogeneous teams of human and robot pioneers is central to the NASA Exploration Team's strategic vision for space exploration. Both humans and robots have already proven themselves in this role, but opportunities for teaming have been limited. Whether testing scientific theories, surveying life-sustaining resources or building infrastructure to support space development, people and machines exercise different, but often complementary, sets of capabilities. How can these capabilities be leveraged to reduce mission risk and cost while increasing flexibility and productivity? What kinds of machines will humans need to support future missions? Should these machines be restricted to dumb tools or should they function largely autonomously?

Reviewing these questions and finding answers was the charter of the Human-Robot Working Group, charted by the NASA Exploration Team. The Working Group was chaired by Mary DiJoseph and Brenda Ward and had representation from throughout NASA. This paper summarizes some of the key studies and experiments performed by the working group between 2001 and early 2003.

2.0 State of the Art Study

Knowing the current technological state-of-the-art and predicting near term technology advances is vital to planning missions and guiding the requisite technology development. Dr. David Kortenkamp working at the Johnson Space Center, and Dr. Liam Pedersen working at the Ames Research Center were charged by the Human-Robotic Working Group

(HRWG) to complete a study on the current and future state-of-the-art of space robotics. The study explicitly addressed what robots and robotic systems can currently do, what the major space-related challenges are, and what can plausibly be expected in 10 years, under both nominal conditions and with intense effort. The study also attempted to determine those capabilities requiring technological breakthroughs, which by their very nature are unpredictable. A broad range of space robotics functionalities were considered, spanning planetary surface exploration and in-space operations. Inputs were received from researchers and experts at NASA centers and universities, through site visits, interviews, and a web-based questionnaire through which the community consensus on space robotics technologies was assessed. A short summary of this study follows.

2.1 Planetary Surface Exploration Robots

The current state of the art for deployed planetary surface exploration robots is the Sojourner robot [1] (Figure 1), which visited Mars in July 1997, and the Mars Exploration Rovers (MER) launched earlier this year. They are both autonomous within small local segments, with images sent back from Mars each day and a rigid sequence of robot motions uploaded for the following day. Scientists dealt with Sojourner only through robot specialists and even simple operations such as placing an instrument against a rock took command cycles, each one being a full Martian day. MER will be more capable due to a larger size, greater science instruments, and a better communications infrastructure, but otherwise will be operated in a similar manner.

In contrast, terrestrially demonstrated planetary exploration robots have significantly greater capabilities. Autonomous robotic vehicles have performed multi-kilometer traverses in the Arctic (Hyperion, [2]) and searched Antarctica to identify meteorites (Nomad, [3]). Other robots [4][5] can autonomously approach targets and place instruments in contact with them. Taken together these demonstrate the ability to traverse long distances between sites, intensively investigate them and perform some autonomous science in less time and with less human supervision than is currently the norm for flight rovers.

In the next ten to twenty years navigation and mobility will be less of a constraining factor in planetary exploration – long traverses and access, with specialized robots, to most locations on a planetary surface will be possible. Ground based planning and visualization tools will enable mission scientists to interact directly with the robots. However, robotic performance at the level of a space suited human scientist in the field is and will continue to be a major challenge. Without significant breakthroughs, robot systems will perform only within narrowly defined areas of expertise and will lack the general cognitive and perceptual abilities of a field scientist.

Figure 1 The sojourner robot on Mars

2.2 In-Space Operations Robots

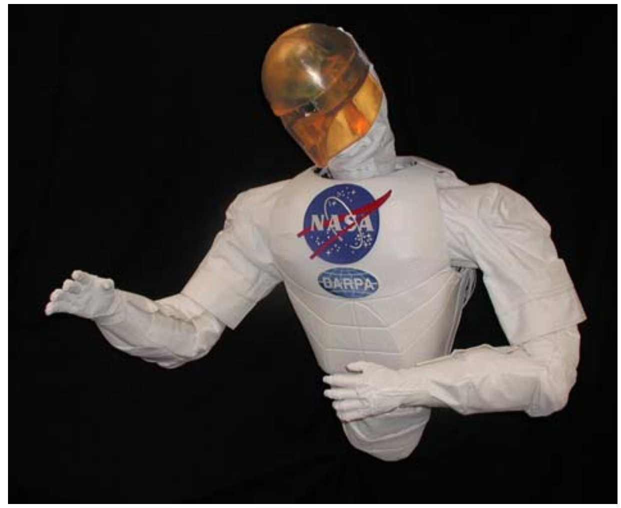

Figure 2 Robonaut at NASA Johnson Space Center

In-space operations focus on component assembly, inspection and replacement. Currently deployed in-space robots are confined to the Shuttle and Space Station Remote Manipulator Systems, which are teleoperated and perform only gross component assembly tasks [8]. Ground testbeds such as Ranger [6] and Robonaut [7] (Figure 2) as well as in-space experiments like ROTEX have demonstrated more dexterous operations, including connecting cables and opening panels, but still under teleoperation. Other ground testbeds such as Skyworker [9] and ASAL (NASA Langley) have demonstrated autonomous assembly of carefully designed components. In-space flight experiments such as AERCam Sprint [10] have demonstrated the potential of teleoperated robots for remote inspection tasks. In the next ten to twenty years the mechanical dexterity of assembly and maintenance robots should approach or exceed that of a *space-suited* human (achieving the dexterity of a human hand unhampered by pressurized gloves is considerably more difficult). This capability is likely to be fully realized only under teleoperation, which requires high-bandwidth, low-latency communication between the human and the robot. Autonomous assembly and maintenance in space will likely require careful systems engineering and constant monitoring from the ground. Automated inspection, on the other hand, seems well within near-term robotic capability.

2.3 Challenges

The information gathered in the report paints a very optimistic picture of the potential of space robotics from those working most closely on the problems. Very little of the necessary future robotic capabilities require fundamental breakthroughs; most require only a sustained engineering effort focused on developing methodologies and gaining experience in the role of robots in space exploration. Such a sustained effort will bear fruit in increasing the capability for a human virtual presence in space and pushing the boundaries of exploration. For this picture to be realized NASA needs to invest in infrastructure and experiments that will advance the state of the art. Nevertheless, significant challenges remain. Robustness and interacting with robots at the mission level are two of several crosscutting significant challenges that emerge in space robotics.

2.3.1 Robustness

Robustness is a challenge because robots must interact with complex environments, which may not be amenable to standard approaches to verification and validation. Furthermore, human level adaptability remains beyond the technological grasp of robotics. Robots that are autonomous and self-reliant-- able to address any fault through self-diagnosis and repair/recovery, and long-lived (years of operation) against the physical challenges of power, temperature, wear, and stability-- will remain a technological challenge.

Careful system design is key to the success and robustness of any robotic mission. Robots cannot work in isolation, nor are they effective if added to a system that was not designed for robots. One cannot place a robot in a situation crafted for humans and expect even adequate performance. The entire system, including the robot, supporting infrastructure (such as power, communications, navigation and maintenance), including the human component, must be considered when designing a mission. This is far more important to the success of robotics than any robot-specific technology such as mobility, dexterity or intelligence. All of these are routinely considered (at great expense) for manned space missions; the same considerations apply for robotic ones. Appropriate system engineering can greatly increase the robustness of robot operations. For in-space operations this might mean the design of components and attachment mechanisms. For surface operations, this might mean centralized power generation or a GPS-like infrastructure.

Robustness is also achieved by bringing to bear human intelligence and flexibility where appropriate. This can be done via direct teleoperation or advice giving when the robot encounters a problem it cannot deal with itself. Space robotic systems entails significant difficulties over and above the usual obstacles to space qualification. Autonomous systems with complex behaviors are hard to characterize to guarantee that minimal performance criteria are met under all reasonable circumstances. Robotics is essentially an experimental science. Few capable robots have been flown in space. There is no statistical basis for validation and characterization of the interaction between the robot and its environment. Without this characterization, robustness will not be fully satisfied.

2.3.2 Mission Level Human-Robot Interactions

Humans will always be in loop of any space robotic system, whether as consumers of the data gathered by the robot or as directors of robot activities. As such, there is no such thing as a fully autonomous robot (if there was it would be on the beach in Miami drinking motor oil instead of working for us!).

The challenge is to shift the human from directing the minute-to-minute activities of the robot and allow the human to concentrate on the mission-level objectives and scientific strategies, while at the same time allowing for direct control when necessary. Currently robots work on goals that are very low-level, e.g., “go to this exact location” or “put your manipulator in this configuration.” Humans string together these low-level goals to accomplish mission objectives. This is tedious and inefficient. Interacting with robots at the mission level implies interpreting ambiguous instructions that the robot can only resolve through intimate knowledge of both the task and humans with which it has to interact.

A long-range goal of space robotics is to allow for human cognitive presence in space or on a planetary surface without human physical presence. Imagine a planetary geologist roaming Mars, picking up rocks, feeling them, even tasting them, without leaving her laboratory. Or imagine a worker putting together a component for a complex space telescope and then troubleshooting it while sitting in a comfortable chair. Some of the technologies required to make this happen fall outside of robots (e.g., high-bandwidth, low-latency communications). However, replicating the dexterity and sensing modalities of a human are challenges for robotics and it is unlikely that even if the communication issues are solved that a complete virtual presence will be possible in the next ten to twenty years. However, robots such as Robonaut at NASA JSC demonstrate the future potential for virtual presence.

In addition to remote interaction, we also envision human-robot teams working together on the same tasks. This will require technology leaps in the areas of natural language processing and human intention recognition. Future acceptance of robotics will be dependent on the ability to give robots mission-level objectives such as “explore that area over there and report anything interesting” or “put together these components to create a truss.” This will require significant advances in robot cognitive abilities including planning, diagnosis and adaptation.

2.4 State-of-the-art Study Conclusions

Most useful space robotic capabilities are well within reach in the next ten to twenty years, although sustained investment is needed to attain many of these. Long traverses and access to, with specialized robots, most locations on a planetary surface will be possible. Sample measurements can be obtained autonomously. Ground based planning and visualization tools will enable users to interact more directly with the robots. Automated inspection of orbiting structures by free flying robots is feasible. Other tasks, such as autonomous assembly and maintenance in space will likely require careful systems engineering and constant monitoring from the ground to be feasible. Robotic performance at the level of a space suited human onsite is and will continue to be a major challenge. Breakthroughs are required if robot systems are to perform beyond narrowly defined areas of expertise and attain the general cognitive and perceptual abilities of a human. Robustness and Mission Level Interaction are cross-cutting challenges that emerge across space robotics. Developing robust robots will require careful systems engineering of both the robot and the infrastructure within which it operates. Sustained investment and significant experimentation is needed to build and verify robust robotic systems. This includes building the needed infrastructure, as well as re-usable robot hardware and software components [11].

3. 0 Human-Robot Teaming Experiments

In addition to the state-of-the-art study, the Human-Robot Working Group sponsored a series of 1G hardware tests to study Extra-Vehicular Activity (EVA) human-robot teams combining the information-gathering and problem-solving skills of human astronauts with the survivability and physical capabilities of space robots. Research topics include developing task analysis and performance evaluation techniques, identifying key mission-enabling technologies, and demonstrating new capabilities through field trials. The results will be used to construct balanced human-robot teams targeting specific tasks and to predict the performance of such teams based on established benchmarks. The hardware tests described should be repeated and re-evaluated periodically to keep NASA abreast of new technology and to maintain relevance as mission plans mature.

3.1 Single Agent activities

In FY01, testing activities featured two categories of exploration-related EVA tasks. The first category, on-orbit assembly, was represented by an umbilical cable deployment task (Fig. 3). Equipment for this task included a rotating spacecraft mockup with EVA handrails and a dummy umbilical cable with EVA electrical connectors at either end. The complete task involved mating one connector to a socket mounted on the mockup, translating to a second socket at the far edge of the mockup while deploying the cable and, finally, mating the remaining connector.

Figure 3 FY01 Umbilical cable deployment task

The second category, planetary surface science, was represented by a rock sample collection task (Fig. 4). Equipment for this task included a simulated planetary surface and a rock-cracking tool. The complete task involved digging through regolith with a shovel to retrieve a suitable specimen, cracking it to expose a fresh surface and then depositing the sample in a beaker for safekeeping.

Figure 4 FY01 Rock sample collection task

Both tasks were scalable with three Levels Of Complexity (LOC) based on subtask inclusion. Two task agents, a human wearing an experimental spacesuit and a teleoperated humanoid robot, worked independently to complete each task three times at each LOC. A total of 36 task trials (2 agents x 2 tasks x 3 LOCs x 3 repetitions) were performed and videotaped. Performance metrics included task success and task/subtask completion times. Both agents were able to complete all tasks at all LOCs successfully, though not necessarily with a 100% success rate. As expected, the robot took more time to complete each subtask than the human but this must be weighed against the reduced risk, cost and complexity of a robotic mission. A more detailed account of the test can be found in [12].

3.2 Multi-agent Activities

Although the FY01 tests accomplished several important objectives, the metrics were mainly comparative in nature because the human and robot completed the task separately (neither task agent could be relocated in a cost-effective manner). In FY03, two experiments were conducted to investigate how a human-robot team consisting of two collocated agents could work cooperatively to complete a simplified on-orbit assembly task. In these experiments, teaming parameters were varied between task trials but the task, itself, remained the same. Each team was required to grasp and maneuver a long structural beam, too awkward for one agent to handle alone, into a fixed socket and pin it in place (see Fig. 5).

First, a teaming configuration experiment (see Fig. 3) was conducted to compare the performance of 8 teams with different combinations of 2 task agent roles and 3 degrees of robot automation. A total of 24 task trials (8 teams x 3 repetitions) were performed and videotaped. Certain restrictions were imposed to preserve the EVA relevance of the task despite the unavailability of a spacesuit. Performance metrics included task success, task completion time, socket forces/torques and robot wrist forces/torques. As the robot played a progressively greater role in the team and the humans suffered more sensory deprivation, task completion time increased monotonically but maximum beam-socket contact force remained constant. Accordingly, the team should be constructed and the task planned to balance the team members' roles against their limitations with the knowledge that some performance objectives may be traded off against others. A more detailed account of the experiment can be found in [13].

Figure 5 FY03 Teaming configuration experiment

The second FY03 experiment examined a different dimension of the cooperative assembly task by measuring the effect of agent interaction on task performance (see Fig. 6). Three independent Interaction Mechanisms (IMs: force, voice and gesture) were controlled in a total of 54 task trials (6 teams x 3 IMs x 3 repetitions) while the task agents completed the simplified assembly task from the first FY03 experiment. Performance metrics included task success, task completion time, socket forces/torques, robot wrist forces/torques and beam forces/torques. For two of the teams, the cumulative addition of progressively more sophisticated modes of interaction (force => force + voice => force + voice + gesture) significantly reduced the components of beam force required to align the beam with the socket but also slightly increased task completion times. For the remaining teams, forces, torques and completion times remained comparable with no clear trends emerging. Nevertheless, the results demonstrate the localized effect of a targeted strategy for improving human-robot team performance. A more detailed account of the experiment can be found in [14].

Figure 6 FY03 Agent interaction experiment

4.0 A Method to Compare the Performance of Humans, Robots and Integrated Human-Robot Systems

Also sponsored by the HRWG was a study developed at the Jet Propulsion Laboratory [15]. There is currently a tendency to evaluate human and robot teams in a qualitative way or by using thought experiments, however this research presented a new analytical method to quantitatively evaluate performance of human and robot agents over a variety of tasks. The overall goal is to allocate tasks intelligently to humans and robots. At present, the performance analysis is in its most general form and does not presuppose a particular type of robotic system. It also allows for a variety of robot control modes including full-immersion teleoperation, supervisory control and automation.

Several classifications of new contributions to human-robot evaluations were looked at. The first is the principal that a unified analytical framework for quantitatively evaluating human and robotic performance can be described and implemented for various mission scenarios. The second contribution presumes that overall/integrated mission tasks can be divided into independent functional primitives. Independence in this case signifies that performance on a particular sub-task is independent of performance on another sub-task. This assumption also drives which sub-tasks are chosen for analysis. These sub-tasks should each elicit distinct sensing, actuation and cognitive system capabilities. A third contribution is the introduction of uniform units and scales to quantify the variables and parameters used for evaluation. Information theory can be applied to the analysis in this case. A common unit is used to measure the degree of difficulty of a task, the aptitude of a given system with respect to any other system (or with respect to a standard reference system) and the relative amount of mass, power and other resources necessary to operate the system.

Another contribution is the ability of the analytical method to operate independent of the scale (i.e., astronomical, global, regional, regional, local, system, sub-system, and component). The example sited in this study is a comparison of relative performance in going to Mars versus Venus, or alternatively the comparison between performance of two particular computer chips for robot vision applications. Comparisons can also be done using combined scales for multi-scale comparisons. Composite scores can be combined across scales using a ratio-based base-2 logarithm operation. Resolution levels are also affected here as the greater the number of primitives used in the comparison, the greater the resolution.

An X-Y planar representation of the comparison results demonstrates the relationship between the resources needed to implement a given system on the X-axis and the composite performance of the system doing a variety of tasks on the Y-axis. Subtracting the X composite resources coordinate from the Y multi-primitive performance coordinate yields the value-added. If this subtraction results in a negative number for value-added, it would be called value-subtracted in using one particular system over another. Finally, the concept of a standard reference is introduced as the reference system characteristics that performance and resources of all other systems are measured with respect to.

The study describes four phases of the analytical comparison method:

1) Decompose the scenario into primitive subtasks
2) Quantify parameters for each primitive
3) Determine aptitudes for each primitive subtask
4) Compute composite scores to obtain the total composite values for tasks requiring the use of two or more primitives for their execution

Consider as an example, a surface exploration scenario. Primitive subtasks might include: Traverse path, navigate (including localization and task planning), detect and identify samples, grasp and handle samples, analyze, store or discard samples and survive the extreme temperature environment. Phase two involves creating an index of a degree of difficulty (a relative measure) of each primitive as compared to a reference value. An example given here involves the difficulty traversing various distances as compared to a one-meter traverse. The Index of Difficulty (ID) is defined as the log to the base-2 of the actual distance over the reference distance. Recall that the base-2 logarithm is used for its generality in combining the effects of difficulty from sources other than simply distance. It also relies on the bit as a well-understood unit by which to compare the level of difficulty. Note that complexity in calculating the ID can arise as it is dependent on the nature of the traverse, the terrain slope, and the curvature or roughness, in addition to the distance.

Phase three determines the aptitude or performance of the various systems under evaluation in completing the primitive. For each level of difficulty, the time (T) that a particular system or agent takes to complete the task is recorded and compared to the standard record (SR). The performance score (S) becomes the ration (SR/T) *1000. Note that not all primitives lend themelves to having a standard reference, and therefore they are not required to complete the calculations. A versatility factor is introduced to measure the degree of versatility (of a given system or agent) with respect to a set of specific tasks. It is defined as the total performance score that a given subject achieves in a set of events measured against the "best" in each event.

Phase four computes the composite scores. Here a matrix is formed with the primitives (k) as the rows (each row has its own unit, but not all rows must have the same unit), and the system type (m) as the columns. The performance of system **m** for primitive **k** is denoted ***p*(k,m)**. A performance ratio can be calculated using a standard reference (**m** = 1) such that the performance ratio **p(k,m) = *p*(k,m)/p(k,1)**. A multi-primitive growth factor is computed by taking the absolute values of **p(k,m)**'s and multiplying across k's for a given m. This performance score **s(m)** reflects the aggregated performance of system **m** with respect to the reference standard, and when the analogous resource score **r(m)** is subtracted from the performance score, the value added is the result. Recall that these multiplication and division calculations are actually computed by using logarithmic additions and subtractions. A visual representation of the value added for a given system can be obtained by plotting a 2-D chart with X-axis representing system resources and system performance plotted along the Y-axis.

The study concludes with an example of how to apply this method to a sample mission. The mission is a field geology and sample collection case with the primitives outlined above, and the system options as follows: Two humans walk, two robots rove, two humans ride a rover, robot aids two walking humans and two robots commanded from earth. Composite log scores, multi-parameter scores, relative mass and power resource comparisons and value added scores are computed for each of the five system types. The resultant graph of performance versus resource reveals that the two robots commanded from a base yields the best performance for the least amount of resources. For comparison, the scenario with two humans riding the rover yields higher performance, but at a greater resource expense. This visualization of the analytical comparison can aid in determining which tasks are allocated to which systems (combination of agents).

In summary, the study introduces and demonstrates an analytical evaluation for a sample mission. The team would like to expand on this work to encompass more low-level task comparisons, as well as replace the logarithmic sums used to calculate multi-primitive scores with a more general, but well-defined mathematical operation.

5.0 Overall Conclusion

The work of the NEXT Human-Robotic Working Group provided a strong framework for a better understanding of how humans and robots can more productively work together. Future space activities are going to need to make use of a wide variety of systems and tools. While humans and robots each have their unique niches, the combination is likely to lead to more effective use of resources, enhanced safety, and reduced costs.

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