HUMAN-ROBOT TEAMING IN A MULTI-AGENT SPACE ASSEMBLY TASK

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ABSTRACT

NASA's Human Space Flight program depends heavily on spacewalks performed by pairs of suited human astronauts. These Extra-Vehicular Activities (EVAs) are severely restricted in both duration and scope by consumables and available manpower. An expanded multi-agent EVA team combining the information-gathering and problem-solving skills of humans with the survivability and physical capabilities of robots is proposed and illustrated by example. Such teams are useful for large-scale, complex missions requiring dispersed manipulation, locomotion and sensing capabilities. To study collaboration modalities within a multi-agent EVA team, a 1-g test is conducted with humans and robots working together in various supporting roles.

KEYWORDS: Robonaut, Mini-AERCam, FAIR, multi-agent, EVA, NASA, DARPA

1. INTRODUCTION

The Hubble Space Telescope (HST) was carried into orbit in 1990 aboard the Space Shuttle Discovery (STS-31). Newer, high focal length designs are too large to fit in the Orbiter payload bay as a single unit. Instead, components of these space telescopes could launch separately and rendezvous in Low Earth Orbit (LEO) for assembly and final repositioning. These and other larger, lighter, more extendable space structures will require greatly expanded EVA and Extra-Vehicular Robotic (EVR) capabilities as well as new and innovative structural systems.

The recent emergence of highly dexterous space robots dramatically increases the opportunities for humans and robots working together in space. These machines can help conserve EVA hours by relieving human astronauts of many routine chores and assisting them in more complex tasks. Robots can take risks unacceptable to humans, perform contingency EVA operations in minutes, instead of hours, and setup worksites in preparation for the arrival of human astronauts.

2. THE FAIR TELESCOPE: A MULTI-AGENT CASE STUDY

The proposed Filled-Aperture Infra-Red (FAIR) telescope is one example of the new generation of space science platforms requiring expanded EVA/EVR capabilities. Boasting an extremely long focal length, the FAIR design is too large and flimsy to be carried into orbit as a single pre-integrated assembly. Instead, the spacecraft subassembly and components of the telescope truss are launched aboard the Space Shuttle while the propulsion stage is launched separately on an expendable vehicle.

After executing a Low Earth Orbit (LEO) rendezvous with the propulsion stage, the EVA assembly team builds telescope truss segments from individual struts, ranging in length from 6 m to 13.6 m, which are stored side-by-side in the Shuttle payload bay. The resulting truss segments, up to 25 m in length, are, in turn, mated at both ends to attachment nodes on the partially-

requested ER to make clear that these 1) robots are not yet a reality in space, and 2) that case-study is hypothetical
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assembled telescope truss. Once complete, the telescope truss is attached to the spacecraft subassembly using the Shuttle Remote Manipulator System (RMS). Next, the Shuttle approaches and berths the propulsion stage, to which the spacecraft is mated (Fig. 1). After final testing and inspection, the propulsion stage boosts the FAIR telescope from LEO to its final position at the L1 libration point.

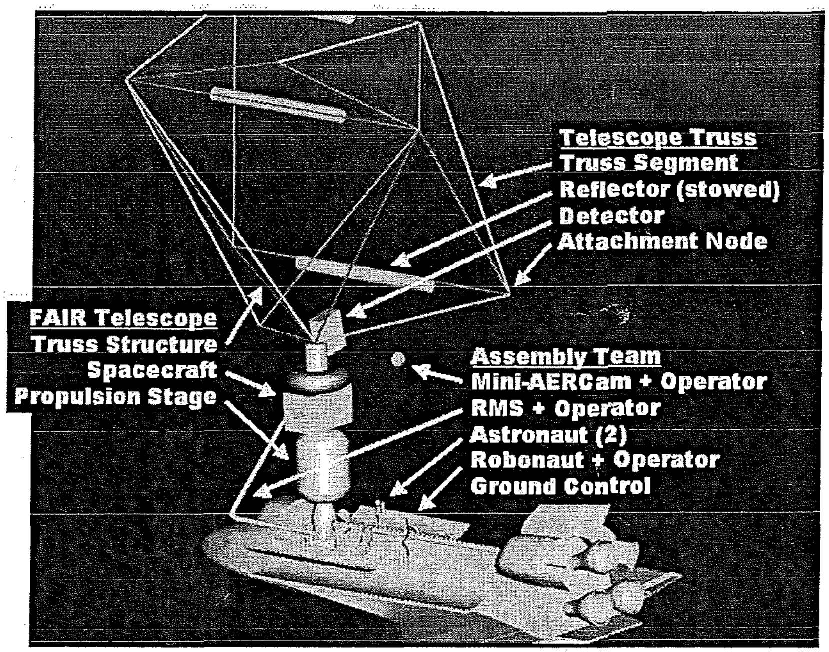

Figure 1. Fully-assembled FAIR telescope in Space Shuttle payload bay (adapted from [1]).

The FAIR assembly concept [1] serves to illustrate the need for multi-agent teaming. The telescope truss consists of struts and nodes based on a modular EVA construction system developed at NASA's Langley Research Center and tested on STS-49 in the ASEM (Assembly of Station by EVA Methods) flight experiment. The FAIR telescope strut lengths and truss geometry naturally disperse the mechanical interfaces and EVA worksites across a huge volumetric workspace growing out of the Shuttle payload bay. In order to reduce point-to-point translation requirements between these worksites and simplify the handling of long, unwieldy structural components, the conventional EVA team consisting of two astronauts and an RMS is expanded to include the NASA/DARPA Robonaut [2] (a highly dexterous space robot) and the NASA Mini-AERCam [3] (a free-flying inspection nanosatellite) (Fig. 2).

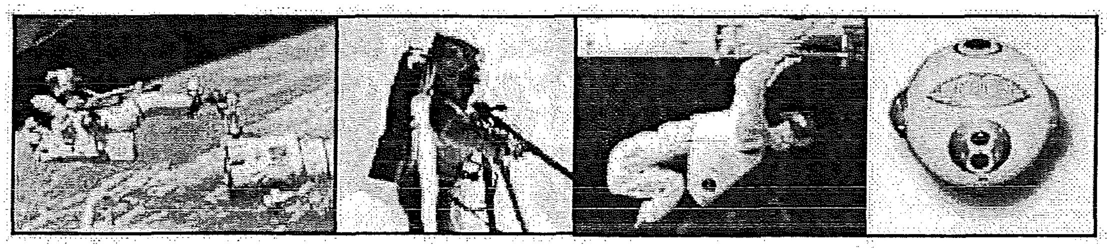

Figure 2. Members of the expanded multi-agent team (left to right): astronaut riding RMS, astronaut at ASEM node, Robonaut climbing along EVA handrail, Mini-AERCam free-flyer.

As part of the truss assembly sequence, the Robonaut system (RV1) is positioned in the payload bay, unstowing and feeding struts up to an astronaut (EV1) positioned at a central node. Together, these two agents integrate the struts into truss segments, which are then mated to the central node (Fig. 3). The second astronaut (EV2) rides the RMS between peripheral nodes on the telescope truss and mates them to free ends of truss segments. The Mini-AERCam robot (RV2), meanwhile, provides critical teleoperation and diagnostic views while improving overall situational awareness.

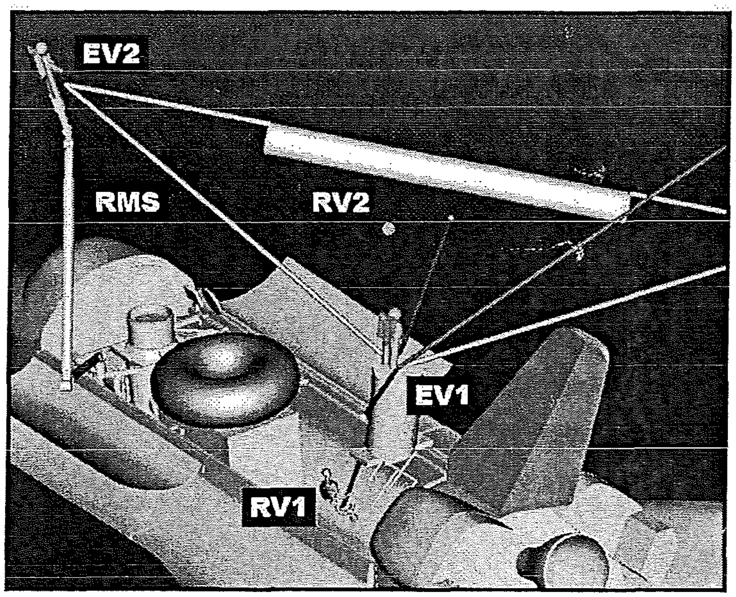

Figure 3. Dispersed assembly agents, remote team members not shown (adapted from [1]).

Over the course of multi-day EVA operations like the FAIR assembly procedure, robotic agents can continue working even after all humans have left the worksite. Robonaut could reconfigure worksites in preparation for the next EVA workday and perform other single-agent tasks. In the meantime, Mini-AERCam could visually inspect truss joints and verify critical alignments.

Coordinating heterogeneous teams of humans and robots is not a trivial undertaking. The astronauts direct the robotic agents through physical interaction, indirectly via appropriate human-machine interfaces or by communicating with their remote human operators. The most flexible architecture allows for each agent to have multiple command paths and degrees of automation. For example, an astronaut teamed with a large-scale manipulator might want to fly it using hand controllers and spoken commands while riding the end-effector and then allow a remote human to take control when faced with a task that requires two hands. Similarly, control of the Mini-AERCam and its roving view could be passed between team members as required by the task.

3. ONE-G MULTI-AGENT TESTING ACTIVITIES

A 1-g hardware test based on the STS-61B ACCESS flight experiment [4] is conducted to evaluate human-robot teaming strategies in the context of a simulated EVA assembly task. Four human test participants assume prescribed roles as members of a multi-agent team featuring two NASA/DARPA Robonaut systems working side-by-side with a suited human subject to build an erectable truss on a rotating assembly fixture. Integrating some of the latest technology advances in high-mobility spacesuits, dexterous robots and modular structural systems, the Multi-agent

Truss Assembly Test demonstrates new EVA capabilities enabling orbital assembly of large space structures.

3.1 Objectives

Key test objectives include:

- Demonstrate supporting capabilities applicable to in-space assembly using existing technology prototypes and 1-g test beds.
- Develop teaming strategies for EVA astronauts working side-by-side with highly dexterous, teleoperated robots.
- Study the operational trade-offs inherent in human and robot teaming in a space assembly context.

The Multi-agent Test was conducted to exercise collaboration modalities within a multi-agent team, not to assess the feasibility of a particular EVA task. The focus of the activity was to economically learn as much as possible about how heterogeneous teams of collocated and remote humans and robots can work together in space using available 1-g hardware and test beds.

3.2 Description

The Multi-agent Test is based on the STS-61B ACCESS flight experiment in which two EVA crewmembers built an erectable truss on an assembly fixture in the Space Shuttle payload bay. It features two Robonaut systems working side-by-side with astronaut Nancy Currie, wearing the experimental I-Suit, to build the Langley Cubic Truss in 1-g (Figure 4). Robonaut is an anthropomorphic robotic system capable of using tools and handling mechanical interfaces designed for humans. The I-Suit is a high field of view, high mobility, lightweight prototype soft suit developed by ILC-Dover. The Langley Cubic Truss is a stiff, lightweight structural system designed for EVA assembly. Truss assembly is facilitated with a low-fidelity, rotating assembly fixture and other supporting equipment.

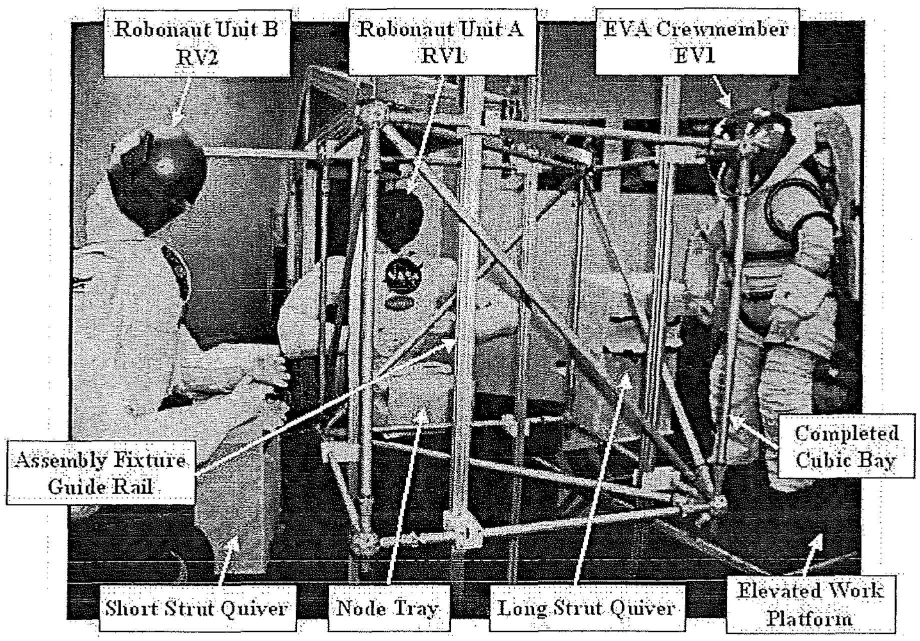

Figure 4. Multi-agent Test initial configuration, as seen by Ground Controller via Mini-AERCam

Working together, the two humanoid class robots (RV1 and RV2), controlled by remote human teleoperators, serve in various roles supporting the astronaut (EV1), who operates as team leader. A ground controller (IV1), stationed at a simulated mission console, is tasked with directing the EVA over a wireless communication system and dictates the procedural details to each of the assembly agents. An emulation of the Mini-AERCam (Autonomous Extravehicular Robotic Camera), a free-flying nanosatellite outfitted with video cameras, is positioned adjacent to the worksite, providing the ground controller with a "bird's eye" view of the worksite and assembly team during the course of construction.

Initially, the truss consists of a single cubic bay, which is translated up along the assembly fixture to make room for the addition of a second bay beneath it. The struts forming the truss are housed in two quivers located near EV1 and RV1 while the nodes are contained in trays. These two assembly agents unstow struts and nodes from their containers and cooperatively assemble them to form segments. EV1 then attaches these segments to the truss. The third assembly agent, RV2, rotates and stabilizes the assembly fixture as needed (Figure 5).

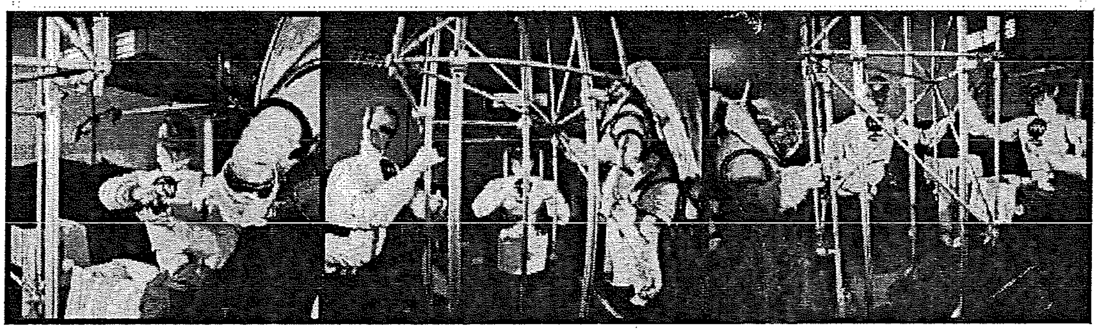

Figure 5. Selected elements of the multi-agent test (left-to-right): RV1 attaches a node to a strut supported by EV1, RV2 stabilizes the truss assembly as EV1 attaches a segment to the truss, RV1 passes a strut to RV2 as EV1 rotates the truss assembly.

The assembly procedure requires a high tier working position to mate connections along the top edges of a truss bay as well as a low tier position to access the bottom edges. This also allows the astronaut to interact directly with both robots, though not at the same time. Once all the high tier connections are locked, EV1 translates to the low tier position, beginning the second half of the task. To complete the truss bay, RV1 unstows struts and passes them to RV2, who, in turn, transfers them to EV1. EV1 then attaches them to the truss (Figure 5).

Once all the low tier connections are locked, the truss bay is structurally complete and the team begins installing an umbilical cable terminating in EVA electrical connectors around the exterior of the truss. An EVA cable tie caddy is first unstowed and passed from RV1 to RV2 to EV1, who attaches it temporarily to the truss. Next, the umbilical is unstowed and routed around the truss to EV1, who plugs the connector into a waiting socket on the assembly fixture. As EV1 rotates the fixture, RV1 and RV2 uncoil the cable and hold it in place against the truss, allowing EV1 to apply a cable tie at each corner. Once all the cable has been deployed and secured, EV1 plugs the remaining connector into a second socket on the assembly fixture. At this point, the assembly task is complete and task time stops.

A mix of manipulation and teaming skills are required to complete the truss assembly task. Truss assembly agents must not only be capable of mating nodes and struts, they must also be able to coordinate cooperative manipulation, hand-offs and other multi-agent interactions in the pre-planned assembly sequence.

The topics explored during this initial investigation include collaboration modalities between EVA and remote humans and skill mappings of dexterous robots and human workers. Timeline optimization is an important aspect of EVA planning examining both workload distribution between crewmembers and the sequence of tasks to be performed. The overarching objective in planning the activity is to employ the human EVA crewmember(s) as safely and efficiently as possible, thereby conserving consumables and limiting exposure to the hostile space environment.

3.3 Observations

In order to complete the assembly task within the EVA window (about 1 hour) allowed by EV1's breathing air supply, much of the workload fell on the astronaut. Although the robots were capable of performing nearly every subtask on their own, they would have taken more time. In order to be practical, the multi-agent team must be able to perform its task in less time (as measured in EVA astronaut-hours) than the conventional team consisting of two astronauts. An interesting exception is the multi-agent team consisting only of collocated robots and remote humans. Depending on the particular EVA task in question, there may be other considerations as well, such as risk mitigation and physical limitations.

Spacewalking astronauts have a very limited field-of-view restricted to the window in the EMU helmet, which does not swivel with neck motions. In general, two astronauts working side-by-side on an EVA cannot see each other. They are unable to communicate through body language or gestures and cannot anticipate each other's actions through observation. By necessity, EV1 and EV2 communicate almost exclusively by radio, employing very methodical handshaking to confirm mutual understanding. For similar reasons, participants in the Multi-agent Test developed a wireless headset communication protocol to help them function as a team.

The EMU encumbers the body motions of an EVA worker. Spacewalking astronauts have a restricted working envelope dictated by the EMU range of motion. The EMU glove also degrades the tactile sensing of the wearer. To a degree, the degraded tactile feedback and manual dexterity suffered by the human subject wearing the spacesuit and performing the task adjacently parallels the sensorimotor handicap suffered by the human controlling the robot and performing the task remotely.

4. CONCLUSIONS

The Multi-agent Test should be understood as part of a continuing effort to study how humans and robots can work together effectively in space. At the same time, these experiments test the limits of robotics and teleoperation, demonstrating new EVR capabilities and the feasibility of performing more tasks telerobotically. Higher-fidelity tests involving more sophisticated gravity compensation and more realistic mobility, communication time delay, lighting conditions, etc. will complicate some operational aspects of EVR but simplify others.

The multi-agent team featured in this test represents only one particular instance of humans and robots working together. It represents a novel integration of existing technology prototypes and test beds intended to meet test objectives but should only be interpreted as part of the solution to increasing EVA capability and productivity. More diversified multi-agent teams, improved EVA technology and new vehicles will all be required to meet future needs.

5. REFERENCES

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