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ROBOTICS FOR ASSEMBLY, INSPECTION, AND MAINTENANCE OF SPACE MACROFACILITIES

William Whittaker, Carnegie Mellon University, Pittsburgh, PA
Chris Urmson, Carnegie Mellon University, Pittsburgh, PA
Peter Staritz, Carnegie Mellon University, Pittsburgh, PA
Brett Kennedy, NASA Jet Propulsion Laboratory, Pasadena, CA
Rob Ambrose, NASA Johnson Space Center, Houston, TX

Abstract

Space macrofacilities will be larger, more complex, sometimes fragile and often less accessible than the satellites and space stations of today. The need is for AIM robots to assemble, inspect, and maintain such facilities, but significant technical challenges exist. This paper profiles early results towards extensive, constrained, and humanoid approaches to AIM robots. Like the visionary facilities these robots will enable, visionary AIM robots call for their own significant development campaign.

Introduction

Future space facilities, like scientific outposts to expand our horizons, solar stations to power our planet, and space hotels to enrich our experience, will be a vast departure from the satellites, shuttles and space stations of today. Space macrofacilities are characterized by immense size, which precludes their launch from Earth as monolithic units, and compels in-space assembly. Facility venues like high orbits, LaGrange points and deep space are challenges to manned space flight due to risk, cost, and lack of appropriate spacecraft, hence robots are a workforce of choice. Macrofacilities, like solar power stations, will be optimized to such an extent that they will incorporate a wide variety of delicate elements. Hence robotic assembly, inspection, and maintenance (AIM) must succeed on fragile as well as robust facilities. Life expectancy of macrofacilities will be decades, so ongoing maintenance poses long-term requirements for resident robots and requires serviceable facilities. The vision of these facilities calls for robots that will be self-reliant, autonomous, and capable of attaching to, maneuvering on, and working with fragile space facilities.

A key feature of robotic AIM operations will be that they require little or no on-orbit human support. However, almost any conceivable scenario will require regular coordination of pre-planned activities with plan updates based on changing situations. This will entail the coordination of hundreds of robots with operations and/or construction managers on the ground. Because there could be hundreds of robots working simultaneously to build macrofacilities, each robot must have knowledge about its function, its location, and how it relates to other robotic activities. Additionally, robots will likely need to communicate with each other, with central coordination and even the facility. These needs will require a novel approach to construction management and operations oversight.

This paper profiles prototype robots developed for the AIM of macrofacilities. Recent results from three robots, representative of different classes within the umbrella of robotic AIM, are presented.

Background

The increasing need to develop larger, more complicated structures in space, requires a greater robotic capability. The Space Shuttle's Remote Manipulator System captures and releases payloads and assists orbital servicing tasks. Its successes have led space programs to adopt robots for a broader, more involved work agenda. For example, the International Space Station has developed the Space Station Remote Manipulator System (SSRMS) and the Special Purpose Dexterous Manipulator (SPDM). The former is a large symmetrical 7DOF robot that locomotes on the Station structure by successive attachment of two latching end effectors. With one end fixed to the Space Station, the SSRMS can manipulate large loads and capture free-flying objects. SPDM is a pair of 7 degree of freedom arms that can be attached to SSRMS or operate alone to perform more delicate operations, such as the change out of orbit replaceable units.

Progeny of shuttle and station manipulators could serve important roles in space macrofacility AIM. Fixed manipulators are useful, for example, receiving and warehousing material, but these require hard structure and fixed infrastructure and have

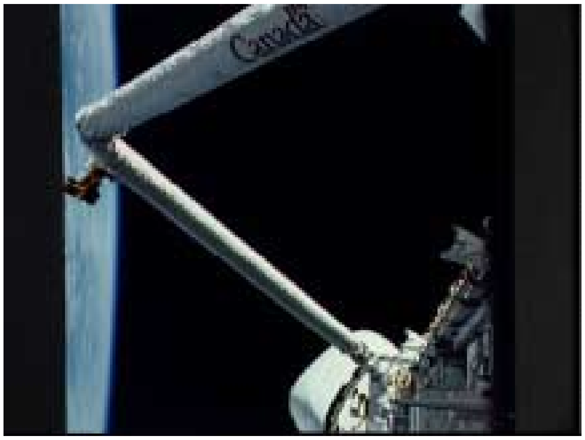

Figure 1. The Space Shuttle Remote Manipulator System

limited range relative to the scale of macrofacilities. Latching end effector locomotion overcomes the range limits of fixed attachment, but requires latch points on a facility and cannot transport payloads while walking. Dexterous manipulators like SPDM are relevant in macrofacility scenarios but must become self-contained, self reliant, and achieve a high degree of autonomy to be viable.

Free flyers have a role for limited operations in space macrofacility AIM, since they offer the ability to move without constraint. The major liability is that they expend significant amounts of non-renewable propellant to transport and manipulate payloads. A secondary liability is the possibility of collision during a failed docking operation. Ueno et. al. [1,2] deployed a free flying robot and a specially designed truss assembly kit to establish the basic technologies needed for on-orbit assembly and highlighted three key technological hurdles to be overcome: 3-D mobility in space (i.e., walking on or flying around structures), stable manipulator control during contact with objects, and teleoperation with time delay and narrow communications bandwidth.

There is a substantial tradeoff between the extent to which a facility is designed with robotic AIM in mind and the complexity of the robots. Successful AIM research must consider facilities and operations amenable to automation as much as the design of the robots. Will et. al. studied assembly and disassembly of a 102 member truss.[3]. The research facilitated automated assembly by: including passive guidance/positioning fixtures; designating a position in the finished assembly for each structural element; providing a specific assembly sequence; designing special end effectors and structural nodes in concert. Control procedures kept applied forces and torques below established thresholds.

Three novel classes, responsive to the needs and constraints of robotic AIM, are profiled in the following sections.

Figure 2. Skyworker

Skyworker

Materials on an orbital construction site must be transported great distances, positioned precisely, and interconnected. Skyworker, under development at Carnegie Mellon University, is an attached mobile manipulator. It is designed to softly and autonomously transport and manipulate payloads that range from kilograms to tons in mass over kilometer scale distances. This robot does not suffer from some of the drawbacks associated with the other robot archetypes. Attached mobile manipulators are distinct from free flyers and similar to fixed base manipulators in that that the robot uses the structure as a reaction platform. But the attached mobile manipulator is also distinct from the fixed base manipulator, having no permanent attachments to the structure, these robots are less massive and have a larger workspace.

Skyworker, shown in figure 3, moves by swinging its two "walking" grippers in a hand over hand gait. The robot's third gripper and arm behave much like a waiter carrying a heavy tray, isolating the payload from the motions of the feet. This ability to maintain the payload at a continuous velocity while always contacting the structure is both valuable and necessary. If a payload were to accelerate and decelerate with every step, Skyworker would consume more energy to move a given distance. In addition to the energy efficiency of smooth motion, the forces exerted on the structure to maintain the same average velocity are significantly smaller.

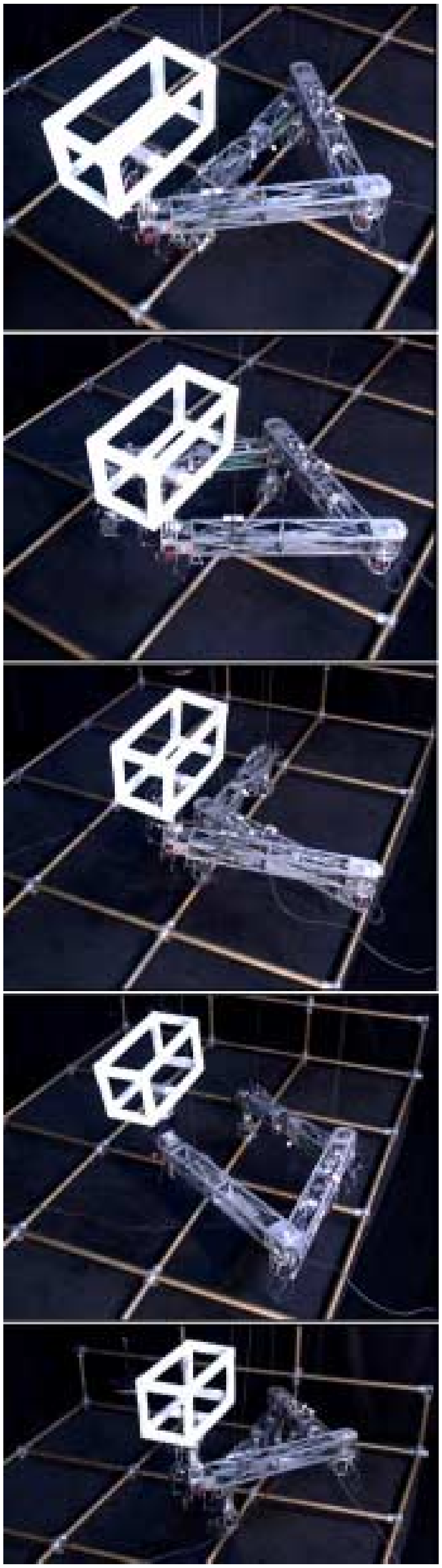

Figure 3. Skyworker's walking gait

If the payload mass is significantly larger than that of Skyworker, the payload can be used as a reaction mass and the forces exerted on the structure can be further reduced. In this case, Skyworker starts the payload in motion, and then walks under it, transmitting the walking forces to the payload. When performing this type of gait, the robot only contacts the structure to correct for defects in the payload trajectory.

In addition to payload transport, Skyworker is designed to perform attachment tasks. When a manipulation is required, Skyworker stands on a walking gripper and uses its free end to position tools and payloads. When attached to the facility in this way, Skyworker is a hyper-redundant 11-degree of freedom manipulator arm.

Skyworker is powered by NiMH batteries and uses wireless Ethernet as its command link. To offload computation from the onboard controller, Skyworker utilizes a network of PID controllers connected via an RS-485 bus. This allows the robot to use high frequency control loops internally while still being responsive to external user commands. High level commands, such as walk to a position, are sent to the robot and then parsed and implemented as motor control commands. This system allows Skyworker's control computers to be freed for higher-level activities.

Skyworker has demonstrated the fundamentals of continuous gait locomotion. The robot has demonstrated carrying a payload with a continuous gait, turning, and the manipulation posture. These demonstrations were conducted using wireless control and on board power, thus enabling the robot to operate free of tethers.

Current research is developing a new, smoother and gentler gait. Using a comprehensive dynamic model, Skyworker's gait will be re-optimized to reduce the forces exerted on the structure. This optimized gait will be implemented on the prototype and the effect of the gait on the structure will be analyzed and compared with projected results.

Skyworker's progeny are already being developed using novel genetic auto-configuration software [5]. This software generates tens of thousands of potential configurations using genetic recombination techniques. These potential configurations are then evaluated based on task requirements and any number of evaluation criteria. Using these techniques, the next generation of attached mobile manipulators will be created.

This first step for orbital assembly will enable future generations to efficiently and gently carry large payloads over long distances.

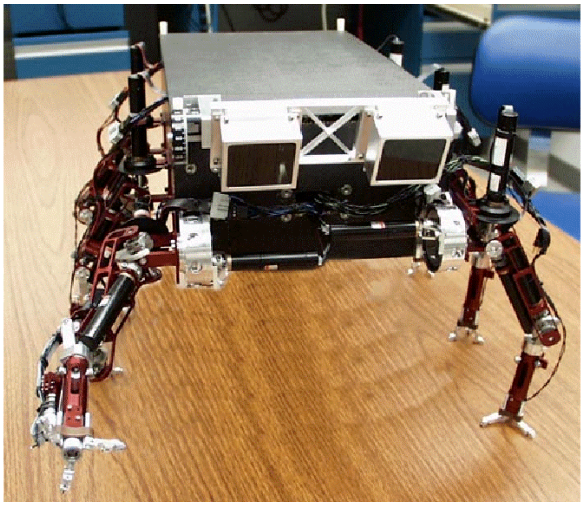

Figure 4. LEMUR

LEMUR (Legged Excursion Mechanical Utility Robot)

Although macro space facilities will be immense in scale, details will require intricate operations in restrictive, confined quarters. LEMUR is a small, agile and capable six-legged walking robot under development at the Jet Propulsion Laboratory to perform dexterous small-scale assembly, inspection and maintenance [6].

LEMUR's mechanism, shown in figure 4, consists of a lightweight graphite composite chassis with six independently operated legs. The rear four legs have three active degrees of freedom while the front two have four each. Each leg is reconfigurable to allow the integration of a variety of mechanical tools. In particular, the front legs, with their extra degree of freedom in the shoulder (a kinematically spherical joint), are especially useful as manipulators because they can place the end effectors into the workspace directly in front of the robot. Facilitating stability during such a maneuver, the body center of mass is located between the middle and rear pairs of legs, allowing for a four-footed stance.

To date, two different interchangeable tools, seen in figure 5, have been designed and demonstrated. The default tool is a three-fingered foot/hand with palm-mounted optics for a macroscopic imager [7]. With the incorporated passive grasp adjustment, LEMUR is capable of gripping spheres, cylinders or irregular objects. The optics feed a fiber optic cable that runs back to a CCD camera inside the body. Images from this point of view can be used for visual servoing of the gripper itself, as a second point of view for servoing the other front tool, or as an inspection tool. The other tool is a driver for tightening or loosening a standard fastener. This tool features a retractable foot that allows for greater dexterity and visualization of the tool at the work-piece. A current feedback motor controller governs the tool's output torque. In both tools, a single motor motivates all action, and a limit switch on each of the legs assures contact for each foot during movement, and contact with the work piece during manipulation.

Figure 5. LEMUR's three fingered foot and driver foot

Computing and navigation is based on PC104 stack architecture that is common to many development robots. Visual navigation information is provided by a stereo pair of color CCD cameras. The range maps created from these images are then used for path planning, hazard detection and obstacle avoidance maneuvers. In addition, fiducial marks will be added to objects within the robot's environment. These marks will be used both to calculate orientation and to convey information through a bar code incorporated into the fiducial pattern that can be used for part identification. For inertial navigation, an accelerometer triad is mounted in the chassis, providing feedback of pitch, roll, distance traveled, speed, and acceleration. To enable remote communication, a wireless modem is included as well.

Currently the work on LEMUR is focused on the integration of software. Modules for joint movement and coordination are in place, and the emphasis is on determining an effective walking algorithm. Moreover, vision/navigation modules also exist for range map creation, orientation determination from fiducial marks, and bar-code reading. Future work will include completing a semi-autonomous traverse-to-goal, visual inspection, driver task, and a gripper task demo is expected.

Figure 6. Robonaut

Robonaut

While the depth and breadth of human performance is beyond the current state of the art in robotics, experience with human servicing and existing tools for human space servicing inspires a humanoid approach to robotic AIM. The Johnson Space Center is developing an anthropomorphic robot called Robonaut. Design goals emulate the volume, ranges of motion, strength and endurance measures of space-walking humans. As a direct result of its unique anthropomorphic, EVA crew sized design, it can interface directly with EVA tools designed for the suited astronaut and can work within tight access corridors.

The manipulator and dexterous hand shown in figure 7 have embedded avionics elements within each link, reducing cabling and noise contamination. Robonaut uses a *Chordate* approach to data management, bringing all feedback to a central nervous system, where even low level servo control is performed. This centralization enables learning and optimization in mechanical, electrical and software forms [8].

Robonaut's broad mix of sensors includes thermal, position, tactile, force, and torque instrumentation, with over 150 sensors per arm. The control system for Robonaut includes an onboard, real time CPU with miniature data acquisition and power management in a small, environmentally hardened body. Off board guidance is delivered with human supervision using a telepresence control station with human tracking and trades control with instinctual and reflex levels of automation.

Robonaut has already demonstrated sufficient dexterity and control to handle a wide range of EVA tools including the Tether Hook, “T” Pin and Torque Tool. Additional task trials are now underway. Experiments manipulating medical instruments have already been conducted, demonstrating the ability to perform a manual exam, perform Arthroscopic exams with minimally invasive equipment, use forceps, remove an IV needle, and deliver an injection with a syringe.

Figure 7. Robonaut holding EVA tools

Path to the Future

Space macrofacilities will be larger, more complex, sometimes fragile and often less accessible than the satellites and space stations of today. The need is for AIM robots to assemble, inspect, and maintain such facilities, but significant technical challenges exist. This paper profiles early results towards extensive, constrained, and humanoid approaches to AIM robots. Like the visionary facilities these robots will enable, visionary AIM robots call for their own significant development campaign.

Future research will pursue new techniques for grasping and holding onto structures, powerful yet gentle forms of manipulation, and algorithms for intelligently controlling these abilities. Breakthrough capability would be the ability to ‘grasp anything’ on a structure while minimizing the loads exerted on that structure. Inter-robot coordination and robotic construction autonomy are essential. Beyond the underlying research agenda, AIM calls for new robotic forms, hardening of the robots for space, and ultimately exhibiting robotic AIM in space construction. On-orbit AIM requires robots to operate over very long periods of time, yet there is little real-world experience with operating autonomous robots in such environments, even over short periods of time.

The shovel, hammer, and handsaw built the skyscrapers of our civilization. Assembly, inspection, and maintenance robots will build the visionary facilities of our future in space, and will become a workforce of choice beyond the planet.

References

[1] W. Whittaker, T. Kanade, P. Allen, A. Bejczy, J. Lowrie, H. McCain, M. Montemerlo, and T. Sheridan, "Space Robotics in Japan," NASA/NSF Japanese Technology Evaluation Center Report, January 1991.

[2] H. Ueno, H. Satoh, S. Aoki, T. Yoshida, K. Matsumoto and S. Wakbayashi, "On-Orbit Construction Experiment by Tele-operated Robot Arm," in Proceedings of the 14th International Symposium on Automation and Robotics in Construction, Pittsburgh, June 1997.

[3] R. Will, M. Rhodes, W. Doggett, C. Herstrom, C. Granstham, C. Allen, P. Sydow, E. Cooper, C. Quach, and M. Wise, "An Automated Assembly System for Large Space Structures," in Intelligent Robotic Systems for Space Exploration, Alan A. Desrochers (ed.), Kluwer Academic Publishers, 1992.

[4] J. Heard, H. Bush, and J. Watson, "Space Truss Construction Studies" presented at ASCE Space 88 Engineering, Construction and Operations Conference, Albuquerque, August 1988.

[5] P. Leger and J. Bares, "Automated Task Based Synthesis and Optimization of Field Robots", Proceedings of the 1999 International Conference on Field and Service Robotics, 1999

[6] G. Hickey and B. Kennedy, "Six-Legged Experimental Robot", NASA Tech Brief NPO-20897

[7] B. Kennedy, "Three-Fingered Robot Hand with Self-Adjusting Grip", NASA Tech Brief NPO-20907

[8] A. Ambrose, C. Ambrose, "Robot models for Space Environments", IEEE International Conference on Robotics and Automation, 1995