Skyworker: Robotics for Space Assembly, Inspection and Maintenance

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Abstract

Ambitions to explore and develop space call for the assembly and servicing of diverse in-space facilities. Robots will assemble future stations, spacecraft and facilities that are orders of magnitude larger, more complex and more remote than those of today.

Profiled here is Skyworker research developing robotic technologies for the assembly, inspection, and maintenance of large space facilities.

Introduction

Skyworker research is developing tools to enable visionary space endeavors. Exploring and developing space beyond earth's immediate vicinity requires the development of facilities characterized by immense size, distant venues, fragile components, and long-term missions. Such facilities will be assembled and maintained by robots that can build the facilities safely and cost effectively, in venues where transportation, radiation and safety concerns constrain astronauts' involvement (Figure 1).

Skyworker research is evolving robotic technologies to automate assembly, inspection and maintenance of future space facilities. These large and fragile facilities require robots that move softly when carrying components and perform precise assembly and servicing operations. To demonstrate carrying and assembly capabilities in micro gravity, a prototype robot is developed and operated in a relevant laboratory environment.

Skyworker research is developing the tools needed to determine the size and composition of robotic workforces for large scale space facility assembly. It is also addressing the auto-generation of robot configurations utilizing genetic design methods. This paper details these research areas and discusses results and lessons learned.

Figure 1. Artist's depiction of Skyworker class robots performing orbital assembly tasks.

Skyworker

Skyworker class robots belong to the attached mobile manipulator (AMM) archetype, which are distinguished by their ability to walk and work on the structure they are building, using it as a reaction platform. AMMs benefit from significant advantages over other robotic archetypes like free flyers and fixed base manipulators, which expend fuel or have limited reach [Whittaker, 2001].

Skyworker class robots are designed to softly and autonomously transport and manipulate payloads that range from kilograms to tons over kilometer scale distances. When transporting massive payloads, these robots employ a continuous gait. The gait allows robots to maintain the payload at a constant velocity, avoiding acceleration and deceleration with each step. As a result, reaction forces are minimized and the walking gait is more energy efficient. When manipulations are required, these robots modify their posture to perform assembly and maintenance tasks.

Demonstration Prototype

The demonstration prototype is an eleven-degree of freedom robot designed for operations in the laboratory environment (Figure 2). A gravity compensation system approximates micro gravity conditions in the horizontal plane by counterbalancing the prototype like a marionette [Staritz, 2001].

The prototype has a total of eleven joints, consisting of four different types. The joints share a common power train design to minimize unique components and allow for modularity. The robot is

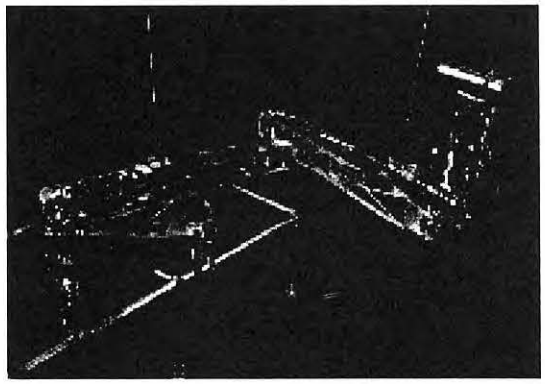

Figure 2. Skyworker Demonstration Prototype

equipped with three end-effectors for locomotion and manipulation. The grippers counteract both the dynamic torques generated by the gait and the disturbance forces from the gravity compensation system.

The robot's operational autonomy without tethers is about forty minutes. During this period, power is provided by NiMH batteries and the robot communicates via wireless Ethernet.

Computation is performed by an on-board Pentium class CPU and motor control is distributed to a network of PIC based motor controllers. The prototype utilizes a multi-layer control architecture. The layers are implemented as separate modules that can be distributed to separate computers as appropriate. Processes communicate with TCP/IP.

Experimental Results

The prototype demonstrates the continuous gait both with and without a payload (Figure 3). The experiments validate the gait's concept and assess its performance.

Three factors were found to limit the gait's performance:

- Tension from the gravity compensation system generates three-dimensional disturbance forces. Although partly compensated for by gripping friction in the feet, the forces produce limited tilting of the posture.

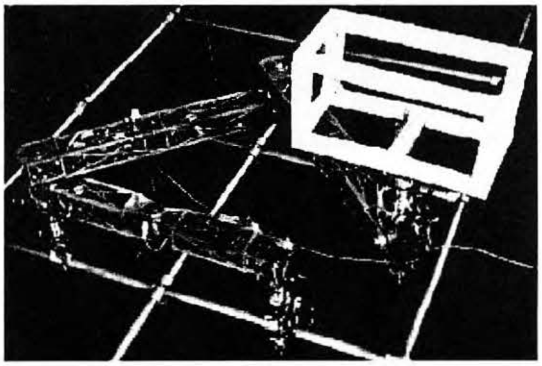

Figure 3. Skyworker prototype carrying mock payload

- To estimate the prototype's pose by dead reckoning limits the accuracy of the walk. Vision, inertial and contact sensors would significantly improve the walking performance.
- Experiments indicate some control instability when the robot passes through the gait's singularity.

Basic assembly operations are performed using robot cooperation, where the prototype mates a beam to a fixed structure using guidance from an independent vision robot. The beam's position relative to the structure is determined by visually analyzing fiducials attached to the components (Figure 4). This assembly technique demonstrated repeated success in mating the beam to the structure with a positioning precision better than 7mm.

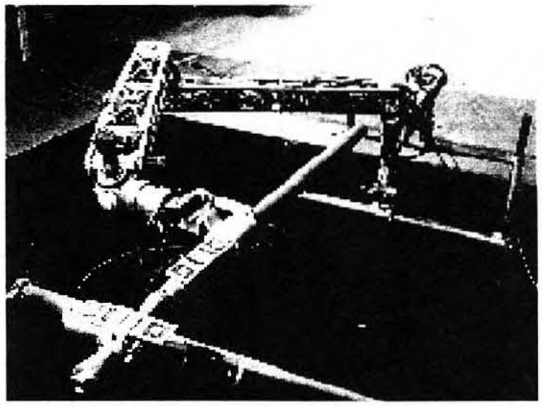

Figure 4. Skyworker prototype connecting beam to assembly structure

Genetic Configuration

Skyworker research is investigating new techniques for configuring Attached Mobile Manipulators. Genetic algorithms are employed to automatically generate robot configurations, optimizing designs for parameters like mass, control complexity or power consumption [Leger, 1999]. Preliminary results have yielded viable AMM configurations after the analysis of more than half of a million candidate configurations (Figure 5). Research is evolving the automatic designer to reliably produce fully functional configurations.

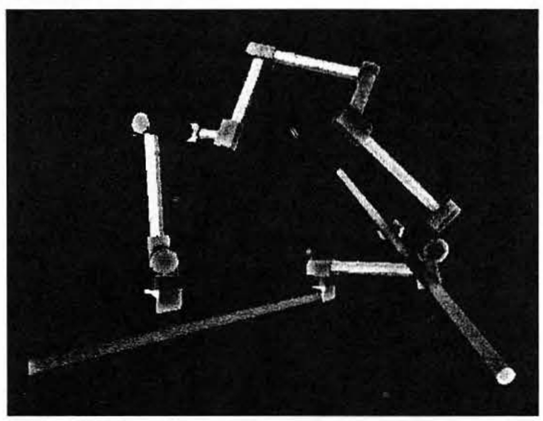

Figure 5. AMM configurations generated by genetic optimization

Robotic Workforce Analysis

The Robotic Workforce Analysis is a tool that determines the combination of robots best suited to perform the assembly of a space facility. The package optimizes the mass of a robotic team based on the time allowed to complete the task, the characteristics of the robots, and requirements of the subtasks.

This research is identifying the optimal team for the assembly of a space solar power microwave transmitting dish. Preliminary results indicate that heterogeneity of the robotic workforce can reduce team mass and increase assembly speed. Also, battery recharge time and technique have a significant effect on the workforce size (see Lessons Learned).

Lessons Learned

Skyworker research is providing key insight to the development of AMMs and the assembly of large structures. The following are some important lessons learned.

Separate long range transporter and manipulator
The prototype configuration, while specialized for long-range transportation, offers limited manipulation capabilities. Construction requirements call for robots optimized for assembly and capable of precise, two-handed manipulations. Developing different robots for transportation and manipulation becomes necessary for addressing such complex tasks. More generally, teams of task-specific robots can best accomplish challenging operations.

Evaluate alternate locomotion methods
Locomotion methods, like walking on a structure in Skyworker's case, produce best performance when adapted to the configuration of the facility. Alternate locomotion techniques, where robots roll, jump or float on the structure may significantly reduce reaction forces and improve energy efficiency.

Change gait in proportion to payload mass
When carrying heavy payloads, robots accommodate the added mass by adopting, for example, a continuous gait. With lighter payloads, robots can modify their gait, improving speed or efficiency. Adapting walking modes to payloads' dynamic characteristics is key for optimal performance.

Recharging strategy significant for overall performance
Exchanging drained power storage for fresh batteries in lieu of on-board charging minimizes robots' idle time and improves productivity.

Heterogeneous teams most efficient
Large assembly tasks often require a wide set of precise but diverse operations. Rather than employing a single type of versatile robots, an efficient workforce would be composed of different and specialized archetypes. Assembly operations would then call for the cooperation of complementary, task-specific robots.

Future Work

Skyworker research will evolve attached mobile manipulators to assemble and service large space structures and provide astronaut support. Development of advanced control techniques will enable robots to walk and work on a structure without causing damage. Methods for cooperating with astronauts to augment EVA effectiveness will be investigated. Research will also perform laboratory demonstrations of autonomous full-scale assembly in a space-relevant test facility (Figure 6). A flight program plan will be generated for an eventual flight demonstration.

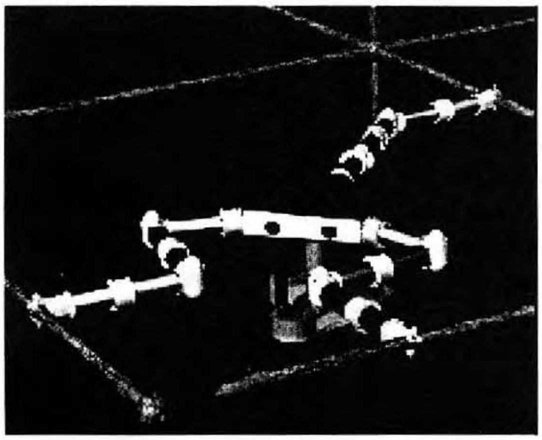

Figure 6. Artist's depiction of assembly in a relevant environment.

Conclusion

Skyworker research's preliminary steps leading to full-scale robotic space assembly will consist of developing a high performance laboratory attached mobile manipulator for comprehensive assembly and astronaut support. The prototype's configuration, hardware and controls will be evolved to achieve flight demonstrations. The research will establish AMMs as reliable and enabling tools for in-space construction and contribute to the development of robotic technologies for the exploration and development of space.

References

W. Whittaker, P. Staritz, R. Ambrose, B. Kennedy, S. Fredrickson, J. Parrish and C. Urmson. "Robotic Assembly of Space Solar Power Facilities." *J. Aerospace Engrg. ASCE*, April, 2001.

P. Staritz, S. Skaff, C. Urmson, W. Whittaker. "Skyworker: A Robot for Assembly, Inspection and Maintenance of Large Scale Orbital Facilities." *IEEE International Conference on Robotics and Automation*, June 2001

Leger, P. and Bares, J. "Automated Task-Based Synthesis and Optimization of Field Robots," *Proceedings of the 1999 International Conference on Field and Service Robotics (FSR99)*, 1999.