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Skyworker: A Robot for Assembly, Inspection and Maintenance of Large Scale Orbital Facilities

Peter J. Staritz, Carnegie Mellon University
Sarjoun Skaff, Carnegie Mellon University
Chris Urmson, Carnegie Mellon University
William Whittaker, Carnegie Mellon University

Abstract

Future space facilities that could power our planet and expand our horizons will differ vastly from the satellites and space stations familiar today. Characterized by their immense size and the difficulties of human construction in orbit, future space facilities will be assembled in part by robots.

This paper profiles Skyworker, a prototype Assembly, Inspection, and Maintenance (AIM) robot designed for large mass payload transport and assembly tasks. Skyworker is an Attached Mobile Manipulator (AMM) capable of walking and working on the structure it is building.

Introduction

The dream of large scale space facilities like solar power stations, orbital hotels and interstellar probes, is enabled by fundamental advances in robotics technology. These space facilities are characterized by immense size, distant venues, fragile components, and long term missions. Some will be immense, weighing thousands of tons and measuring kilometers in length. Robots will not be daunted by assembly tasks of thousands of steps, they will not be hindered by the environmental concerns associated with distant locales, they can perform delicate work with fragile components, and they do not suffer ill effects from prolonged microgravity.

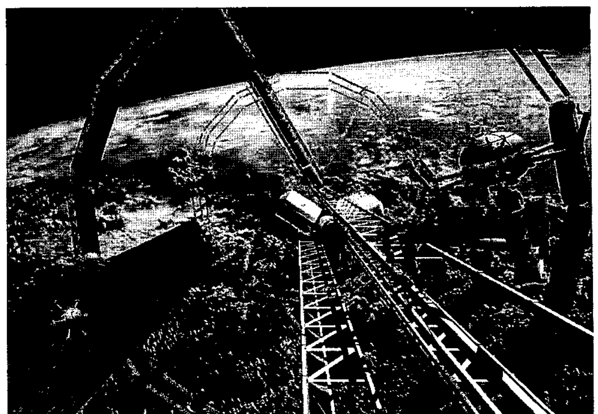

Figure 1 - Artist's depiction of Skyworker performing orbital assembly tasks.

The vision of these facilities calls for robots capable of orbital AIM that will require little or no oversight, and will be capable of attaching to, maneuvering on, and working with fragile space facilities.

Skyworker is an Attached Mobile Manipulator (AMM), a robot that locomotes by imparting reaction forces to the facility it is working on without requiring grapple points or handholds. The robot is a first generation prototype designed to demonstrate basic AIM tasks and investigate key technologies for orbital AIM.

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Task

Robots are needed to transport and manipulate massive payloads aboard space facilities. Standard payloads for such facilities will range in mass from kilograms to tons. Components will be optimized for mass, and will often be fragile. Robots will assemble such facilities over the course of years and will provide maintenance for decades. During this time, the facility may have little or no support from humans in orbit.

Robots designed for these tasks must be capable of transporting massive, and yet fragile, payloads quickly and efficiently. They must perform their duties with little human oversight. The robots will operate in a harsh environment, not only from those factors associated with distant locales like radiation, but also from facility dangers like high voltage and microwaves.

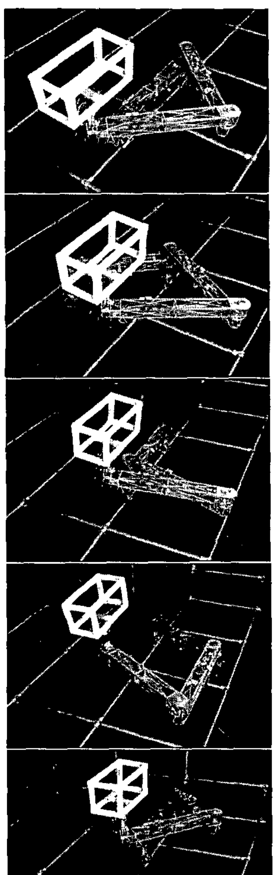

Figure 2 – Demonstration of continuous gait locomotion.

Configuration

Skyworker is configured to transport and manipulate payloads ranging in mass from kilograms to tons. Payloads will be transported characteristic distances of half a kilometer before being positioned and fastened. In order to maximize the speed and efficiency of transport, while minimizing the forces exerted on the structure, Skyworker utilizes a continuous gait (Figure 2). The continuous gait allows the robot to maintain massive payloads at a constant velocity while walking. To accomplish this, the payload is carried in the same way a waiter carries a heavy tray. By isolating the payload from the motions of the feet Skyworker does not need to accelerate and decelerate the payload with each step.

When a manipulation is required the robot attaches to the structure with one of its end grippers and manipulates with the other. When operating in this manner, Skyworker is a nine degree of freedom manipulator arm.

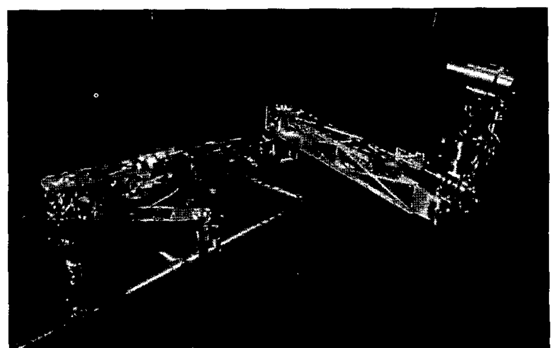

Figure 3 - Skyworker

Mechanical Subsystems

Joints

Skyworker (Figure 3) is configured to perform two major classes of operations, manipulation and transportation of payloads. Unlike terrestrial applications, where a minimum torque is needed to overcome gravity, in orbital operations less torque primarily means slower acceleration. Analysis has shown that a large portion of a robot's time will be spent performing transport tasks. Based on this, Skyworker's joints are sized according to the nominal walking speed of 10 cm/s. The robot has a total of eleven joints, consisting of four different types. All of the joints share a common power train design to minimize unique components and allow for modularity. The power train consists of a Maxon RE 35 mm motor driving a two stage transmission. The first stage is 4.8:1 planetary reduction which drives the second stage, a 100:1 harmonic drive. With this combination each joint is capable of producing 32 Nm of torque at 57 degrees per second.

Grippers

Skyworker's grippers are designed to counteract both the dynamic torques generated by the gait and the disturbance forces from the gravity compensation system.

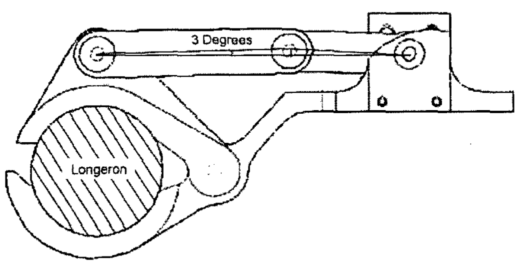

Figure 4 – Side view of Skyworker's gripping mechanism.

The gripper's design is inspired from the locking pliers mechanism (Figure 4). It is in essence a four bar linkage that employs it's geometrical singularity to generate the required grip. Closure is obtained when the actuator forces the linkage through the singularity and compresses it, generating the clamping force.

This mechanism combines speed and mechanical advantage, important characteristics for the implementation of a continuous gait. When the gripper is fully open, the rotation of the motor produces a fast response in the jaw. At the end of the motion, just before closure, the jaw's speed drops dramatically, and all the speed advantage is lost for a mechanical advantage. This allows a relatively small actuator to provide the required gripping force. From start to complete closure, the gripping process lasts less than a second.

By stopping the linkage's motion just beyond its singularity position and letting it rest against a stop, the gripper maintains closure without consuming energy.

Links

The Skyworker robot does not have a body or centralized cavity where components are mounted. Instead, the links that compose the arms serve as both physical structure and bus volume. Each of the four links contain electronics vital to the local joints in addition to components that are relevant to the entire robot. Mass is concentrated in the two shorter links, located at the bottom of the robot. This minimizes the forces that are exerted to perform the continuous gait.

The links have a square cross section with removable access plates, allowing for easy access to the contents. The longer links measure 1 meter in length and ten centimeters square. The shorter links share the same cross section but are half as long.

Power

Skyworker is capable of operating for approximately half an hour utilizing on board power and computation. In this way the robot can perform operations without any tethers. Power is provided by two onboard battery packs which utilize NiMH cells. These batteries have mass and volume characteristics which are significantly better than NiCd batteries, can be charged and discharged quickly and are relatively inexpensive.

The smaller of the two packs, composed of 20 cells, is designed to power the robot's onboard electronics. Three DC to DC converters power the 5 volt, and ± 10 volt busses. The larger of the two packs is composed of 30 cells and powers the 36 volt motor bus.

Skyworker is equipped with an emergency stop switch that disables the 36 volt bus, thus halting motion but maintaining power to the electronics. The robot can operate and recharge simultaneously using off board power via tether. When powered in this way, the robot can operate indefinitely.

Computation

Skyworker utilizes a PC104 stack combined with a distributed network of PIC based motor controllers for control. The main Pentium based stack communicates to the motor controllers utilizing an RS-485 network. This system allows the motor controlling servo loops to be performed at high rates without unduly burdening the onboard processor.

Control Software

Skyworker utilizes a four level control architecture (Figure 5). The layers are implemented as separate modules that can be distributed to separate computers as appropriate. Processes communicate with TCP/IP.

The top level of the architecture is responsible for coordinating the actions of multiple Skyworker robots (either simulated or real). It reads construction scripts and then commands individual robots to perform tasks such as "walk to this location" or "carry the object at this location to that location" in the appropriate sequence.

The second layer performs task execution. A task execution module is instantiated for each robot and tracks the sequence. Any failures are reported to the coordinator so that appropriate action can be taken. The controller determines how to decompose a task into a sequence of actions. The system has 5 basic actions: walk, carry, turn, perform a manipulation, and transition to a different plane. This sequence of actions is handed to the onboard control layer.

The third layer consists of motion synchronization and a sensor interface. Each action has an associated lower level script which describes the synchronized movement of the robot's joints. These scripts are transferred to the low level controllers, the lowest control layer, as velocity profiles. The velocity profiles are executed on embedded PIC based motor controllers. The controllers run a PID control algorithm at 20kHz to perform highly accurate motor position and velocity control.

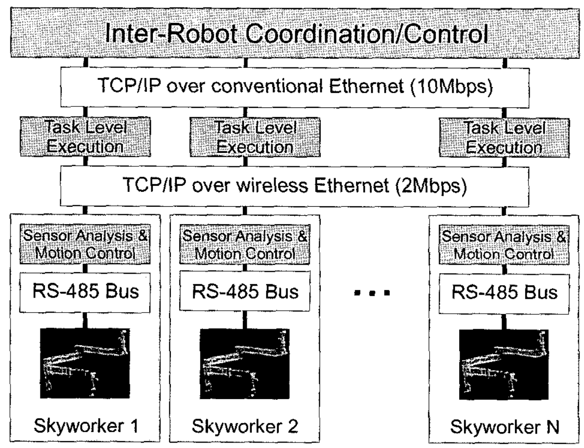

Figure 5 – Control Architecture Diagram

Simulation and Visualization

The simulator kinematically emulates Skyworker, provides the same software interface and generates the same telemetry information as the real robot. The top two control layers interact with the simulator or the real robot in an identical manner. At the task execution level, the only difference is that in simulation, the module instantiates a simulated motor controller instead of a real motor controller. The simulation environment allows the end-to-end testing of information flow through the Skyworker control system.

Telemetry generated through simulated and real operations can be monitored using an OpenGL based visualization engine (Figure 6). The combination of simulation and visualization engine allows scripts to be checked for errors prior to performing the operations with the real robot.

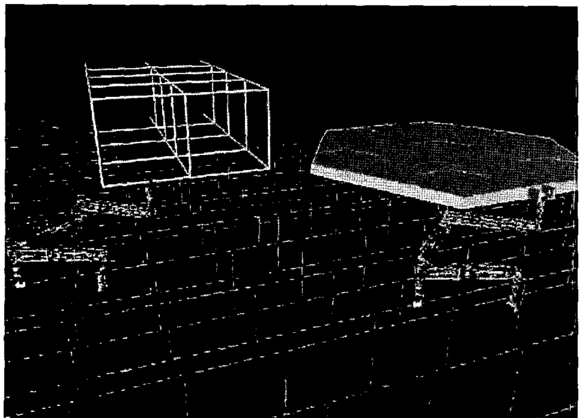

Figure 6 – Simulation Environment

Performance

Skyworker has demonstrated the continuous gait with and without a payload. Tests show that the robot has difficulty maintaining continuity through a singularity in the gait. It is anticipated that implementing a new gait, developed to reduce the forces the robot exerts on the structure, will reduce or eliminate this problem. Skyworker has also demonstrated the ability to turn and has operated in the manipulation posture.

A dynamic simulator and gait optimization tool have been developed that have helped reduce the effects of the singularity and contributed to the development of a new gait. This gait promises to reduce the forces and torques exerted on the structure by about 50% over the original.

Utilizing the simulator tools developed for the project, structure and transmitter assembly tasks have been visualized. Through this work insight has been gained into the nature of large scale orbital operations.

Future Work

Future research will examine the development of attached mobile manipulator configurations using novel genetic auto-configuration software [Leger]. This software generates potential configurations using genetic recombination techniques. These potential configurations are then evaluated based on task requirements and any number of evaluation criteria.

Skyworker will be outfitted with force/torque sensors that will enable the quantitative evaluation of the effects of new gaits on the forces exerted on the testbed. With this data the dynamic simulator can be evaluated and further reductions in forces and torques can be realized.

The Robot Workforce Analysis will examine the composition and characteristics of a full scale robotic assembly team. The work will determine the types and quantities of robots needed to perform various assembly tasks. The analysis will result in a computer program that will estimate workforce mass, volume and cost.

Conclusion

Skyworker is the first generation of attached mobile manipulators for orbital assembly, inspection and maintenance. The robot is demonstrating the fundamentals of continuous gait locomotion and is helping to identify key technologies for future development. The software tools developed provide a better understanding of large scale orbital operations. Future work will continue to demonstrate that attached mobile manipulators are an essential part of orbital AIM.

Acknowledgments

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