New Themes in Robotic Exploration and Assembly for Space Applications

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1. Introduction

The questions that scientists seek to answer by looking into space include the search for life on other planets and the search for the origins of our universe. Exploration of space directed toward answering these questions is taking our spacecraft further and further from Earth and our guidance and protection. In order to send our robotic agents into the universe to become successful field researchers, robotics research must make them independent agents, able to think and fend for themselves, and to work together to achieve goals beyond the reach of individuals. Planetary surveys and large-scale facility assembly are campaigns beyond the capability of a single robot. Bold agendas such as these require teams of autonomous agents working in concert. Robot teams must organize themselves to perform successfully and efficiently despite team member heterogeneity, equipment malfunction and constantly evolving goals. Research must address the design of architectures that enable decentralized coordination of multiple agents to minimize the reliance of team performance on a single lead robot.

In this paper, we address two fundamental tasks that robots in space will be required to perform in the near future-- *exploration* and *assembly*. We discuss three recent space related projects at Carnegie Mellon University. The first seeks to demonstrate Sun Synchronous Navigation for planetary rovers. The second project is developing the architectural tools necessary for multiple robots to cooperate for performing tasks such as assembly. The third project is developing a class of attached manipulators that can operate on truss structures such as large antennae in earth orbit, performing assembly, inspection and maintenance.

2. Sun Synchronous Navigation

Robotic exploration of planetary surfaces is restricted by the availability of solar power and implications of thermal conditioning to survive extremes of hot and cold, of midday sun and overnight hibernation. Power and thermal cycling are fundamental reasons why exploration ambitions and accomplishments are compromised. With a constant energy source and moderate ambient temperatures, surface exploration missions could last for months or years. The number of daily accomplishments would be multiplied by remaining longer in sunlight and, in some cases, never experiencing nightfall. New mission concepts that dramatically expand operational goals and time frames will revolutionize planetary surface exploration.

We advocate sun-synchronous navigation as a mission concept for surface exploration. With the robotics technologies necessary to enable it, sun-synchronous navigation will provide the capability of persistent, in some cases perpetual, presence to explore, dwell in, and develop resource-rich regions near the poles.

Sun-synchronous navigation is accomplished by traveling opposite to planetary rotation, navigating with the sun, to remain continually in sunlight.[Shrounk 1995] At appropriate latitude and speed, rovers can maintain continual exposure to solar insolation sufficient for sustained operation.[Whittaker 2000] Furthermore by lagging the night-to-day terminator by the appropriate amount, these rovers can regulate their temperature, seeking the transient region between nighttime cold and daytime hot. Power and thermal limitations can thus be overcome on destinations like the Moon and Mercury. The same approach that extends planetary missions may also enable operations in the Earth s polar regions during periods of continual daylight. We believe that energy-efficient, solar-powered rovers can operate, even on Earth, during the polar summer. They must navigate around terrain features to avoid shadowing or seek locations of unobstructed sunlight. Someday polar field robots may operate seasonally, deriving most, if not all their power from sunlight.

Sun-synchronous navigation is made possible by a new class of rovers notable for their lower mass, reduced complexity and cost, and vertically-oriented solar panels. (Figure 1) These rovers will manage the collection of solar power, so that power storage requirements are minimized. This translates into further reductions in mass, complexity, and cost.

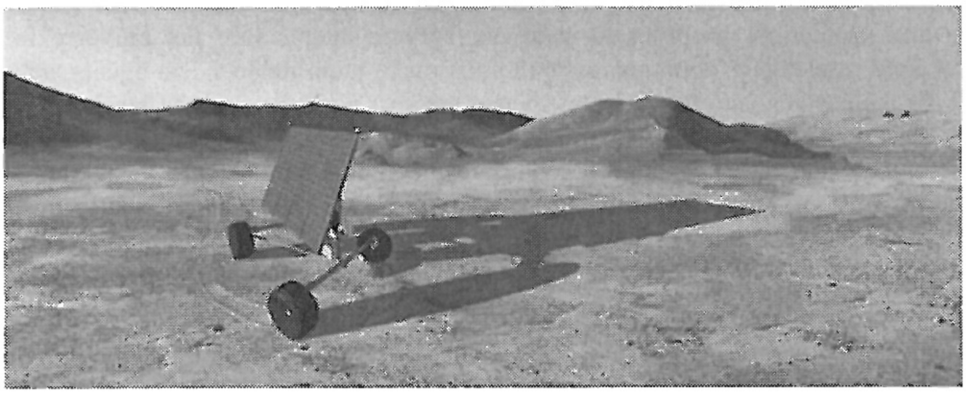

Figure 1: Sun-synchronous navigation in a terrestrial polar environment, concept illustration.

2.1 Scenario

The concept of sun-synchrony is simple: follow the motion of the sun to remain exposed to sunlight. At mid-lattitudes this means traveling opposite to the rotation of the planet. On Earth, equatorial sun-synchrony is not feasible because of the high speeds, and therefore power, required. On Mercury the solar irradience is 9 times greater than Earth and planetary rotation takes 176 Earth days, so a rover circumnavigating Mercury s equator need only travel 4 kilometers per hour. At higher latitudes the rate of traverse decreases. On the Moon at 80¡ lattitude a rover need travel at an averate rate of 3 kilometers per hour to track the sun. Depending upon the inclination of the planet s axis, a polar region of continual sunlight may exist seasonally. On Earth, at high latitudes, beyond the polar circles, 24-hour direct sunlight occurs for a period of the summer months (as a function of latitude.) In this region, a robot s solar panel must daily sweep 360¡ either trough rotation or by the spiraling path of the robot.

In addition to solar irradience for power generation, following the sun allows the robot to follow a moderate temperature band in the region of transition from nighttime cold to daytime hot. On the Moon as well as Mercury and Mars this temperature band may allow rovers with minimal thermal protection to operate in Earth-like temperatures.

2.2 A prototype for sun-synchronous navigation

Although the concept of sun-synchrony is simple and appealing, accomplishing it with a field robot may be difficult. The first challenge is to design a robot that is capable of traversing rough, natural terrain at sufficient speed while remaining energy efficient enough to be solar powered.

The lower the mass of the robot, the smaller the solar panel it must carry to drive itself, and vice versa. At Carnegie Mellon we are prototyping a rover to exploit the advantages and meet the challenges of sun-synchrony. We have conceived a vehicle physically capable of speeds of about 1/2 meter per second at a maximum locomotive power consumption of 150W. It has a wheel-base of approximately 2 meters by 2 meters to provide stable support for its 3 square meter, vertically mounted solar panel. The vehicle and power system have mass of approximately 70 kilograms with the sensors, electronics and computing payload adding 50 kilograms and a steady power consumption of 90W. Design refinements and component tests are currently underway.

To operate sun-synchronously, the rover must optimize the orientation of its solar panel with respect to the sun. This imposes significant new constrains on the navigation problem. Navigation must go beyond avoiding obstacles and reaching goal locations to maintaining a preferred orientation while accomplishing this. Further, there is an additional planning problem in determining the proper orientation at any given time. The orientation is computed from solar ephemeris but the effect of this preferred orientation on which goals can be reached and the direction of approach and departure must be reasoned about. And because the terrain encountered between goals is unknown, the onboard navigation system must be sun-cognizant so that it can recover from deviation from the mission plan.

We are developing sun-cognizant path and temporal planning software for rovers to dodge shadows, seek sun, and drive sun-synchronous routes. This requires planning capable of autonomous navigation in partially known, time-varying environments with additional considerations of power and thermal management. Rough mission routes (both temporal and spatial) can be planned a priori from orbital mapping. In order to optimize solar power gain each waypoint is only good for a specific duration of time due to the changing position of the Sun. On a perfectly spherical planet an arctic circle route might constitute a mission path for global circumnavigation. In planetary terms, mission paths will take the form of a sequence of points and regions such that movement from region to region accomplishes the circumnavigation. Path planners must select these regions to be large and widely spaced so that the rover has sufficient room to reach subgoals in the presence of unknown obstructions.

2.3 Field Experimentation

We intend to conduct initial field experiments with the rover in July of 2001 in the area of Haughton Crater, Devon Island in the Canadian high arctic. Our aim is to verify the algorithms for combining sun-seeking with autonomous navigation and to validate the parameters that will allow sun-synchronous explorers to be scaled for other planetary bodies. The viability of sun-synchronous navigation is dependant upon parameters such as planet diameter, axial tilt, rotation period, surface gravity, and solar irradiance. The rover will traverse a sun-synchronous circuit in 24 hours, using autonomous temporal path planning. Using a high-resolution digital elevation map, and a desired radius the rover will autonomously plan and then execute a temporal sun-synchronous path. The path must avoid shadows of local features while keeping up with the sun as it clocks around the center point of the traverse.

3. Large Scale Assembly using Multiple Robots

Large-scale facility assembly are campaigns beyond the capability of a single robot. Bold agendas such as these require teams of autonomous agents working in concert. Robot teams must organize themselves to perform successfully and efficiently despite team member heterogeneity, equipment malfunction and constantly evolving goals. Research must address the design of architectures that enable decentralized coordination of multiple agents to minimize the reliance of team performance on a single lead robot. Robot teams must decompose complex tasks, delegate subtasks to individuals and reallocate jobs as conditions and goals change.

While many multi-robot systems rely on fortuitous cooperation between agents, some tasks, such as the assembly of large structures, require tighter coordination. We are developing a general software architecture for coordinating heterogeneous robots that allows for both autonomy of the individual agents as well as explicit coordination. Recently we have experimented with three very differently configured robots. Working as a team, these robots are able to perform a high-precision docking task that none could achieve individually.

Here we discuss work to coordinate robots with very different capabilities for use in assembly of large-scale structures such as habitats on the surface of Mars. Our initial focus is on autonomous, multi-robot beam emplacement-- a large 5 m inverted Stewart Platform maneuvers a beam near the emplacement point, guided by a roving eye, and then a mobile manipulator grabs the beam and moves it into place. The coordination takes advantage of the heavy moving capability of the crane, the accurate perception of the roving eye, and the fine manipulation capability of the mobile manipulator to achieve a high-precision task that none of the robots could do on their own.

Our approach to coordinating multiple, heterogeneous robots is based on the layered architectures that are becoming increasingly popular for single-agent autonomous systems [Bonasso, 1997], [Muscettola, 1998], [Simmons 1997]. In our architecture, each robot is an autonomous agent, consisting of a planning layer that decides how to achieve high-level goals, an executive layer that synchronizes agents, sequences tasks and monitors task execution, and a behavioral layer that interfaces to the robot s sensors and effectors As is customary with single-agent tiered architectures, each layer interacts with those above and below it. In addition, in our multi-robot architecture, agents can interact with one another through direct connections at each of the three layers. This type of layer-specific interaction provides for increased flexibility and efficiency in the way the robots can coordinate.

3.1Experimental Testbed

Our experimental testbed is comprised of three robots a crane, a roving eye and a mobile manipulator (Figure 2). The crane, called Robocrane, is a 20-foot high, inverted Stewart platform [Albus, 1992]. Robocrane consists of a large triangular platform supported by six cables attached to winch motors. This enables Robocrane to move freely with six degrees of freedom in a roughly 10 foot cubed workspace. We have added a winch motor on the platform, which pays out a cable to which an 8-foot long beam is attached. The roving eye is the robot Xavier, a 4-foot tall, 2-foot diameter synchro-drive robot with stereo cameras mounted on a pan-tilt head [Simmons, 1997]. The mobile manipulator is built on top of a four wheeled robot testbed, called Bullwinkle, which can drive and avoid obstacles using stereo vision [Singh, 2000]. The manipulator itself, which mounts to the front of Bullwinkle, is a 5 DOF arm. The end effector is an electromagnet mounted on springs at the end of the wrist and is used to attach to the underside of the hanging beam. The three robots communicate with each other and an off-board workstation using radio Ethernet.

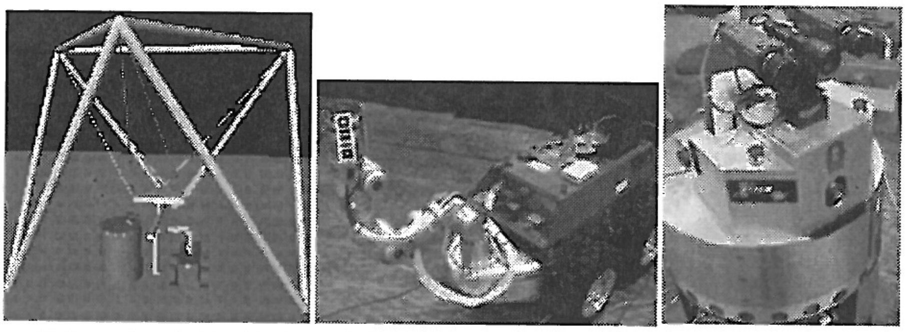

Figure 2: Experimental testbed consisting of 6 DOF crane, mobile manipulator, and roving eye robots.

We are developing an architectural infrastructure for coordination that allows expression of the necessary synchronization constraints but does not address what coordination needs to take place to do the task. This is the responsibility of "planning" modules. Consider, for instance, the following scenario for the task of connecting a beam at a given location: A call is put out for a foreman to manage this task, which could be filled by an agent that has sufficient knowledge and available computational resources. The chosen foreman would put out a request for an available crane, a roving eye or two and, possibly, a mobile manipulator, depending on the precision needed for the particular task at hand. Agents can participate in more than one task for instance, a roving eye with a pan-tilt head could conceivably assist in two different assembly subtasks, if they are within proximity. Once a team is chosen and roles assigned, the agents coordinate amongst themselves. For instance, the roving eye and the crane coordinate to exchange information, and the crane and mobile manipulator coordinate to decide which will move when and by how much.

3.2 Results

We have demonstrated preliminary results for the coordination of a team of heterogeneous robots performing a beam docking task. The key distinctions of this demonstration are that decentralized control is used to accomplish a task requiring high precision. To accomplish this task, three complimentary (but very differently configured) robots use their diversity to the best advantage. The roving eye provides higher servoing accuracy more consistently for a larger workspace than a fixed camera system. The roving eye has greater robustness to tracking failures because of its ability to stay aligned with the fiducials. Accurate camera calibration has not been necessary because visual servoing provides relative positions of the fiducials errors due to calibration affect all measurements roughly equally.

4. Skyworker

The ambition to explore and develop space calls for a vast scope of in-space facility construction. Autonomous robotic assembly, inspection, and maintenance of large facilities is an enabling technology for such space endeavors. Through the development of robots that can assemble spacecraft and space stations with minimal human intervention, structures that are orders of magnitude larger and more complex than those of today can be engendered. Facilities can then be assembled safely and cost effectively, in venues where transportation, radiation and safety concerns constrain a human workforce.

4.1 Scenario

We are investigating a class of robots designed to softly and autonomously transport and manipulate payloads that range from kilograms to tons in mass over kilometer scale distances. These robots will enable autonomous assembly, continuous inspection and maintenance of space structures. We have developed and tested a robot prototype called Skyworker to address these issues (Figure 3).

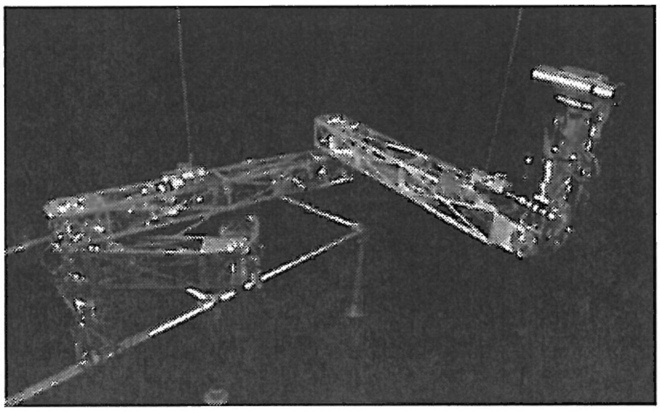

Figure 3: Prototype rover for Assembly, Inspection and Maintenance on Space Structures

Skyworker class robots belong to the attached mobile manipulator archetype (AMM) which are distinguished by their ability to walk and work on the structure they are building, using it as a reaction platform. Unlike fixed base manipulators, AMM s do not have permanent attachments to the structure. This reduces structure mass and provides relatively small, low mass, robots access to extensive facilities. AMM s differ from free flyers in that they do not need to expend propellant to move, eliminating mass loss and preventing plume affects. These differences make attached mobile manipulators uniquely capable for tasks like structural assembly, which require extensive transport and manipulation of components.

Skyworker robots locomote utilizing a continuous gait, swinging their two "walking" grippers in a hand over hand motion. Their 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.

To perform manipulation tasks, Skyworker class robots grapple to the structure with one end-effector and use a free end-effector to position tools and payloads. When attached to the facility in this way, Skyworker is a hyper-redundant 9-degree of freedom manipulator arm.

4.2 Results

A prototype robot has been developed and has demonstrated the continuous gait with and without a payload. Basic assembly has been accomplished using robot cooperation, where the Skyworker prototype successfully performed the task of assembling a beam onto a structure using guidance from an independent stereo vision system.

Skyworker research is also studying the composition of a robotic workforce necessary to assemble, inspect and maintain large unmanned space facilities. Preliminary results have shown that teams of robots that incorporate all three archetypes are more efficient than homogeneous teams. Also, recharging strategies, in which robots replace their drained batteries instead of stopping to recharge, significantly reduce the number of team members required.

Skyworker research is developing new and powerful tools to enable visionary space endeavors. Future research will evolve Skyworker s configuration, automate full-scale assembly, inspection and maintenance, and develop techniques to support astronauts in space operations.

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