HETEROGENEOUS ROBOTIC SYSTEMS FOR ASSEMBLY AND SERVICING

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ABSTRACT

NASA's *Vision for Space Exploration* calls for an extended human presence in space and development of large-scale orbital structures. To reduce risk, it is essential to minimize astronaut exposure by limiting EVA and providing habitat infrastructure prior to arrival. Efficient assembly of space structures requires autonomous robotic teams with only high-level human supervision. Tasks will include component transport, precision component mating, structure inspection and analysis, and site surveying and clearing for surface structures. JPL is developing many of the required technologies for assembly and servicing to determine the challenges and required capabilities and to produce flight-relevant prototypes for maturing and testing these technologies in space-relevant environments.

1. INTRODUCTION

Structures in space and on planetary surfaces play key roles in the current NASA *Vision for Space Exploration* [6], Fig. 1. Due to the extended periods over which assembly and maintenance must be performed, the extreme environments, and, in most cases, long communication delays or blackouts, efficiency and safety will require that much of the construction and maintenance tasks be accomplished autonomously with only occasional high-level supervision and direct human intervention only in rare anomalous conditions. These complex tasks must be accomplished autonomously by intelligent systems despite severe limitations placed on such systems by the space environments and launch systems and in the presence of high uncertainty. These constraints limit the mass, power, volume of all components and limit the processing speed of the on-board computer. JPL is currently developing and testing technologies that will provide these capabilities for surface and on-orbit structure assembly and maintenance despite constraints imposed by space operations.

Assembly and maintenance of space structures will require component transport over potentially long distances, precision manipulation and mating of components, inspection of components and

Fig. 1. Johnson Space Center concept of a planetary habitat.

identification of failures, and replacement or repair of damaged components. To simplify the construction process, structural components will likely be large relative to robot size, requiring cooperative transport and mating by multiple robots. For efficiency and accuracy during assembly, as well as improving the ability to identify structure health, the structures themselves will require on-board sensing and data handling. Surface structures will additionally require site selection and clearing, and the environment will provide the added difficulties of interaction with terrain and soils. For orbital structures, the environment will instead provide added difficulties of operating in zero gravity and locomoting on delicate structures.

Key skills that must be developed to reliably perform assembly and maintenance tasks include robust autonomous task sequencing, precise hand-eye coordination, accurate robot and team positioning, tightly maintaining cooperative team formations, autonomous error identification prior to catastrophic failure, and identifying when fault recovery may be autonomous or require human intervention.

Several ongoing projects are addressing these issues by designing, developing, implementing, and testing prototype systems in flight-relevant conditions. The Robotic Construction Crew (RCC) is a multi-robot system for autonomous assembly of structures from large components, such as beams and panels. To handle large components under gravity, a team of two robots cooperatively transport and install components in a structure. A prototype system has demonstrated reliable transport and mating of individual components.

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The Distributed and Reconfigurable Electronics (DARE) project is developing electronics and sensors that will enable structural elements to cooperate with the robots that transport and assemble them by providing feedback information. These cooperative components will also provide an inherent ability to transfer power and information within the structure as well as identify potential failures. A prototype is in development. In-Space Assembly (ISA) is a collection of tasks, built around a dexterous limbed robot design, that is investigating assembly and repair of orbital truss structures using heterogeneous teams of robots. A single small prototype has demonstrated several walking gaits and the ability to precisely manipulate various tools.

2. CORE TECHNOLOGIES

2.1 Behavior-Based Architecture for Robust Real-Time Control

The current flight processors (Rad 6000) operate at 20Mhz, which severely limits the complexity of real-time control. Despite this limitation, the control must be highly robust and accurate despite uncertainty. In order to provide the required performance within this limitation, the basic software architecture is designed to be highly efficient. Much of the computationally complex aspects of the task are designed into the system, such as task decomposition and task sequencing, through the use of finite state machines. The behavior-based approach, which is highly reactive, can quickly adapt and select actions for changing state without having to plan extensively. The hierarchical behavior-based approach is based on the FIDO software architecture for real-time control and the CAMPOUT architecture for multi-robot coordination. [3] (Fig. 3). While behaviour-based control is not new [1], this particular implementation is specifically designed for real-time operations. This type of beavhior-based software architecture was implemented for the Mars Exploration Rovers for these reasons [17].

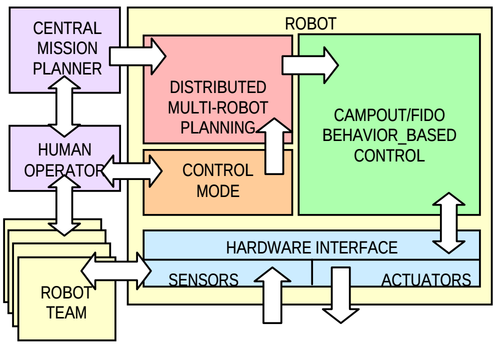

Fig. 2. CAMPOUT / FIDO architecture.

To achieve precise positioning, both of the robots and of their manipulators, the system must account for uncertainty and errors. The primary sensing modality is vision, due to the high content of information and low power required. Vision sensing also introduces error. Motions therefore typically employ an iterative approach in which a step is taken, progress is evaluated, and any necessary corrective step computed until the resulting position is within the required accuracy. This type of approach has been implemented (both autonomously and hand-programmed) for the Mars Exploration Rovers: autonomous go-to-waypoint iteratively adjusts position using visual feature tracking to verify progress and compute next actions [16, 17], and manipulator positioning is done in two steps with a visual verification by human on the ground so that any corrections can be made prior to activities . Sensing results average over multiple frames to reduce error.

Behavior-based control also allows adaptiveness in other ways, such as quickly identifying an unexpected state and directly mapping this state to an action that can achieve the desired result or to the need to call for human intervention for recovery.

2.2 Hybrid Image Plane Stereo (HIPS) for Hand-Eye Coordination

Precision hand-eye coordination is a difficult problem due to the many sources of error: rover pose, manipulator pose, manipulator kinematic model, visual target identification, and visual target pose. In order to reduce the magnitudes of these errors the cameras are calibrated relative to the manipulator's configuration space using a process called Hybrid Image Plane Stereo (HIPS). Unlike traditional stereo vision with forward kinematics [10], this allows the robot to determine the exact configuration to place the manipulator instruments at the visually identified target more precisely by eliminating errors due to manipulator model inaccuracies.

This calibration is accomplished by generating camera models directly in the manipulator's reference frame. Models are generated through comparing the visually observed position of a fiducial on the manipulator and the reported kinematics position of the manipulator. HIPS continually updates models to account for any changes to the kinematics, as well as account for other types of errors. Thus, unlike for traditional stereo and forward kinematics [10] computed target positions based on image coordinates match with arm configuration (rather than to ground truth) and improve manipulator placement accuracy relative to targets.

HIPS uses an 18-parameter CAHVOR model, a pin-hole camera with symmetrical radial distortion. The initial camera model estimation step fits the compared measured and observed manipulator position at known pre-determined positions to the CAHVOR model. This may be computationally expensive and is therefore done offline ahead of time. The initial model accounts for any systematic errors including frame transformation errors and kinematics model errors in link lengths or offsets. The second estimation step occurs online and readapts the models to time-varying errors and run-time uncertainties using newly collected measured/observed position pairs. Types of errors include the adaptive model estimation addresses include flexion and droop (which may be orientation-dependent), joint resolution limitations, effects due to wear, finite image-plane cue detection, and additional camera model errors. Quantitative results indicate placement accuracy improvements of 60-90% over traditional stereo with forward kinematics. More details are provided in [13].

2.3 Force-Sensing for Position Estimation

In the event that contact is required between a robot and an object, the sense of touch can be more accurate in determining contact than vision. This has been supported and utilized on the Mars Exploration Rovers in the form of contact switches on instruments [15, 17]. The instrument is commanded toward a position past the desired target and motion is stopped when the contact switch is triggered; thus, errors in positioning due to visual estimation are eliminated.

For JPL's assembly and maintenance tasks, this approach has been adopted and expanded in order to eliminate the effects of vision errors for many aspects of the task. In addition to contact switches on some instruments, manipulators have a 3-axis force-torque sensor positioned at the wrist. This allows the robot to sense not only contact, but the degree and direction of contact with many types of objects as well.

One of the most important applications of force sensing is in determining the relative formation of two robots carrying an object cooperatively. Typically, visual information on partner location is highly noisy (due to a robot's complex structure) and in many cases is completely unavailable. As in the case of two people carrying a large object, the primary cooperative cue for remaining cooperative with a partner is reaction force rather than vision. In the proper formation, reaction forces are minimal (the partner is neither pulling nor pushing on the object). As the formation moves away from nominal, forces and torques increase. By empirically calibrating magnitude and direction of force and torque with formation offsets, the team can quantify formation errors and correct them. Some work has applied force sensing for cooperative pushing (rather than with rigid contact) such as in [5].

A second application of force sensing is in determining proper alignment for component or instrument placement. In cooperative component acquisition or placement, for example, the robot (or team) visually determines the goal location for the component (and determines the manipulator joint configuration using HIPS) and computes a series of motions to achieve that goal position. If in the course of reaching that position the robot experiences resistive forces, the robot can infer that a position error has occurred and take steps to correct it. Ensuring tool contact is made and that contact is in the appropriate position and direction is also done using this approach. Simple force sensing, in the form of contact switches, is currently used for MER instrument placement.

A final application of force sensing is for walking delicately on fragile orbital structures. Force sensing is used in gait modification in order to minimize impact on the structures as well as during gait execution to ensure that slight errors in positioning do not result in structural damage. This application is in development.

3. SURFACE SYSTEMS

Robotic Construction Crew (RCC) is an ongoing program directed at developing prototype robotic systems for surface construction of habitats. Habitat construction by autonomous agents will eliminate the need for extended surface EVA for habitat assembly and provide a ready safe haven for astronauts prior to arrival in the event of difficulties. Efforts in this area have been in development for six years. The primary focus of RCC is cooperative manipulation of large components, including long distance traverse, precision placement and mating, and handling of heterogeneous component types with an adaptable system. This work has been primarily carried out in an indoor environment that simulates natural terrain (Fig. 3), with some work done in an outdoor environment.

To date, work in robotic assembly includes component mating using three specialized robots (vision, coarse manipulation, fine manipulation) [2,9]. Cooperative transport has focused on cooperative pushing [7,8].

The RCC team has two four-wheeled rovers, each with a stereo pair of cameras and a 4 degree-of-freedom arm (with gripper) (Fig. 6). RCC has demonstrated the ability to autonomously obtain and place a component into an in-progress structure. This includes acquiring the component, cooperatively transporting the component to the structure, precisely aligning with the structure for component installation, and placing the component into the structure and mating it with other structure components. Both beams and panels have been installed in the structure with high reliability.

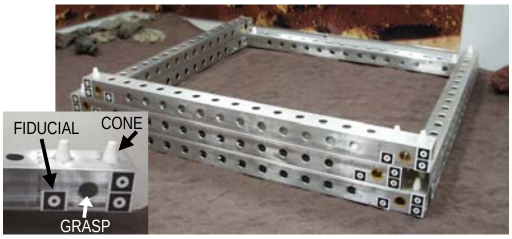

Fig. 3. Structure of interlocking beams. *Inset*: Component fiducials and two interlock cones.

Alignment and precision placement uses HIPS to guarantee the manipulator places the component correctly relative to the visually observed structure. Components are identified by sets of fiducials that provide position and orientation (Fig. 3). Force sensing is used to maintain the formation during transport; one team member adjusts velocity to oppose non-nominal forces. The mapping from force and torque to desired velocity was experimentally determined. The corrective process is shown in Fig. 4.

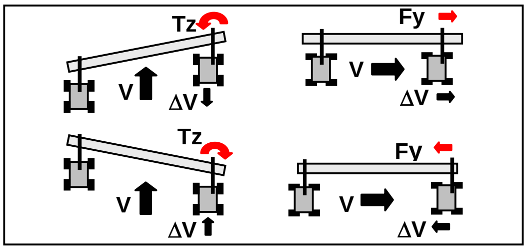

Fig. 4. Relationship of formation and force-torque. *Left*: Torque direction and magnitude indicates the follower should slow down (*top*) or speed up (*bottom*). *Right*: Force indicates the follower should speed up (*top*) or slow down (*bottom*).

Force sensing also verifies component acquisition; if resistive forces are experienced during acquisition, a misalignment is detected which is corrected using a local search. A comparison of forces for a correct and incorrect component grasp are shown in Fig. 5.

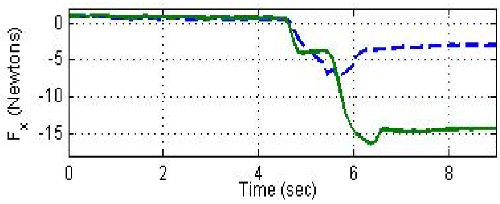

Fig. 5. In a nominal grasp (dotted) the robot sees small friction forces. In a missed grasp (solid), the gripper hits the component and the robot experiences large forces and detects failure.

Snapshots of the construction process (with beams and panels) are shown in Fig. 6 and Fig. 7. The ability of RCC to autonomously acquire, transport, and place a beam component has been quantitatively analysed. Individual experiments looked at specific aspects of the task as well as at the end-to-end task. The success rate is shown in Table I. More results are in [11,12,13].

Table I: Construction Results

Experiment	Runs	Failures
Acquire Beam	24	0*
Align at Structure	19	1
Place Beam	18	0
End to End	5	0

* Excludes a non-algorithmic failure due to a poorly calibrated wrist.

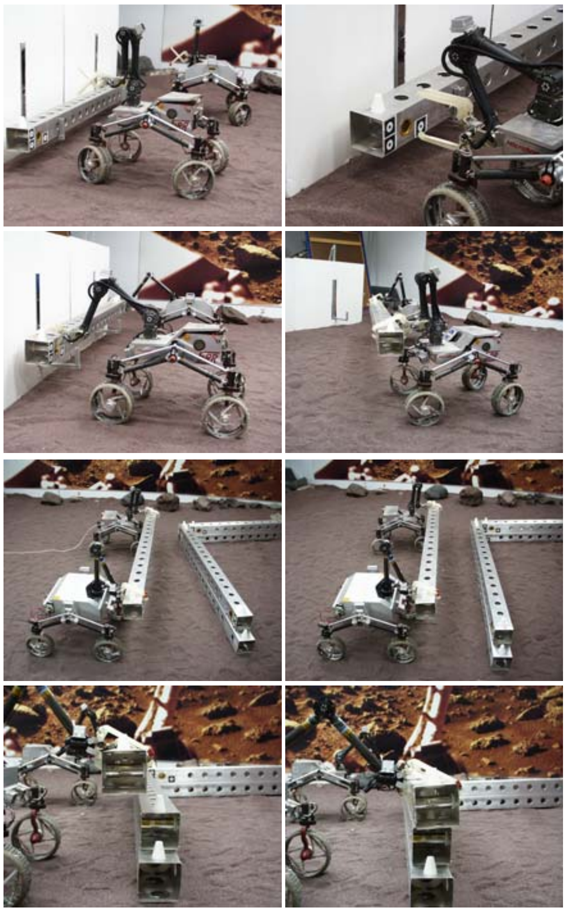

Fig. 6. *Top*: Rovers align in grasping position. *Second*: Team lifts the component and turns around. *Third*: Rovers align at the structure for placement. *Bottom*: Rovers place the component.

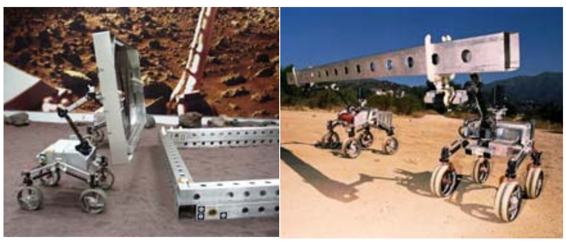

Fig. 7. *Left*: RCC carries a panel and aligns with the structure. *Right*: RCC carries a beam outdoors.

Preliminary results have demonstrated the ability to align with the structure and place a panel component with high reliability (8 of 10 preliminary runs). Additional results have illustrated the improvements obtained by using force feedback for component acquisition: a robot was able to successfully identify and correct an improper grasp 5 of 5 times. This is illustrated in Fig. 7 (left), along with outdoor cooperative transport (right).

Near term goals for RCC include building a next generation of robots geared toward construction tasks (higher payloads) and demonstrating these same capabilities with higher reliability. Longer term goals include adding more sophisticated use of force sensing for component placement and sequential component placement for building a structure.

4. COOPERATIVE STRUCTURES

The DARE project is aimed at investigating how cooperative components can aid in the assembly process and how structures composed of smart components can assist in inspection and maintenance. For surface structures, particularly those that serve as habitats for astronauts, the ability to quickly identify failures and recover is essential to keep humans safe. While mobile assembly/repair robots can aid in inspection and repair, the structure itself can vastly improve the efficiency of identifying potential failures by performing self-monitoring. This can bring the focus of attention of repair crews to critical locations and can provide information on systems that may not be easily observable by outside agents. The processing and sensing built into structural components may also aid in the assembly process itself by providing feedback on proper component connectivity, long-range beacons to component landing and construction sites, and pose information during transport. Building components that provide this type of information, as well as efficient data flow throughout large-scale structures (highly distributed systems with a multitude of individual elements), is the goal of DARE.

The DARE line of research will create electronic elements that will facilitate the data collection and command delivery throughout the system allowing a spectrum of control from a strict and transparent hierarchy (such as might be found within a robot), to a semi-autonomous hierarchy in which raw data is filtered by, and some command is ceded to, lower levels of the hierarchy (such as a human commanding a team of robots assembling smart payloads in smart structures), to an absolutely “democratic” system of electronic elements (as might be found in a sensor net). Moreover, these electronic elements will be able to be reassigned to take on different roles within different systems with different organizational principles.

As a relevant example of this concept (and the basis of a future demonstration) we have taken the case of a construction of a “smart” structure. In this scenario an awkward structural element is cooperatively carried by two robots and assembled onto an existing structure. Both the structural element and the existing structure have DARE units embedded into them. While the element is being transported by the robots, it communicates with them conveying useful state information. Once assembled, it communicates and shares resources with the rest of the structure.

Near-term goals of the DARE project (2005) include building a cooperative component with a 3-axis tilt sensor and communication. This smart component will provide, via communication, pose information to the team of robots transporting and installing it into a structure (RCC) in order to improve performance in terms of efficiency and reliability. Specifically, the rover team can use the pose information from the component in order to traverse more difficult terrain while remaining in formation as well as to indicate that the component is level during installation. Lastly, establishing connectivity with the partial structure can provide feedback indicating a successful installation. Longer term goals include monitoring communication connectivity and other health state indicators to identify component failure.

Currently, design efforts are in progress to design a reusable computation/communication system that is small enough to not significantly alter the size and mass characteristics of structure components, powerful enough to provide the necessary processing, and simple enough to be connected to adjacent components reliably by autonomous robot teams. An illustration of this process is shown in Fig. 8.

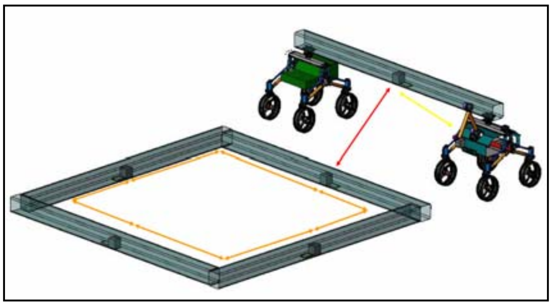

Fig. 8. Schematic of the data flow enabled by DARE in a construction scenario

A prototype computing and 3-axis sensor chip has been designed and built toward this effort.

5. ORBITAL SYSTEMS

In Space Assembly is a set of projects directed toward developing robotic systems for assembly and maintenance of orbital structures (Fig. 9).

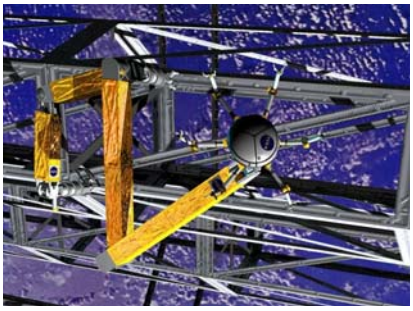

Fig. 9. JPL Concept of on-orbit construction by robot teams.

The assembly and maintenance requirements of permanent installations in space demand robots that provide a high level of operational flexibility relative to mass and volume. Such demands point to robots that are dexterous, have significant processing and sensing capabilities, and can be easily reconfigured (both physically and algorithmically). Evolving from Lemur I, Lemur IIa (Fig. 10, left) is an extremely capable system that both explores mechanical design elements and provides an infrastructure for the development of algorithms (such as force control for mobility and manipulation and adaptive visual feedback) [7]. The physical layout of the system consists of six, 4-degree-of-freedom limbs arranged axi-symmetrically about a hexagonal body platform. These limbs incorporate a "quick-connect" end-effector feature below the distal joint that allows the rapid change-out of any of its tools. The other major subsystem is a stereo camera set that travels along a ring track, allowing omnidirectional vision.

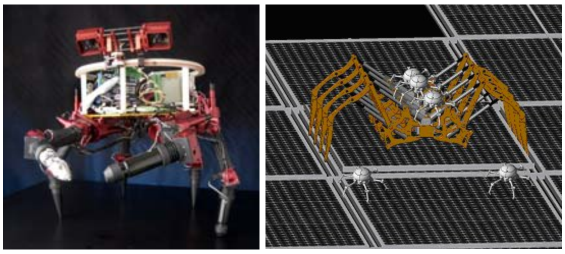

Fig. 10. *Left*: Lemur IIa robot using two tools. *Right*: ISA concept with large spiders and small lemurs.

To date, the basic Lemur IIa platform has been designed and built. The idea that Lemur was to have limbs, not arms or legs, dictated the arrangement of the degrees of freedom and the effective range of motion of each. This concept meant that the workspace and dexterity of the limb needed to be the union of those needed for walking and manipulation. Therefore, a 4 degree-of-feedom (DOF) limb was designed consisting of a kinematically spherical shoulder and a 1 DOF elbow. The simplifying assumption was made that any initial tool or gripper would be axisymmetric or have passive DOF designed in. Lemur has demonstrated multiple walking gaits, walking on a mesh using contact sensing, and tool placement with very high precision using HIPS. The current Lemur IIa platform represents the jumping-off point toward two more advanced robotic platforms as part of the ISA tasks.

The final design element of Lemur limbs is the inclusion of a tool quick-release and the tools that mate to it. The release itself is a socket with a spring-locked ball detent similar to others found throughout industry. To date, four tools have been designed to mate with the quick release (Fig. 11). Simplest is the default walking/poking tool. For inspection purposes, a ultra-bright LED task light tool can act alone or in conjunction with a "palm-cam" tool. Finally, a rotary tool with integral reaction torque sensing and its own bit chuck can be used for torqueing fasteners or other rotary operations depending on the bit used. In keeping with the limb concept, all of these tools can be used as feet as well as for manipulation operations.

Fig. 11. LEMUR tool set, left to right: rotary driver, camera, flash light, foot/pointer.

Current efforts are in progress with Johnson Space Center to develop and test prototype orbital assembly and maintenance systems based on the Lemur II concept (Fig. 10, right). In phase I (2005), Lemur II will cooperate with a new, larger limbed prototype (Spider) to simulate installation of an Orbital Replacement Unit (ORU); Spider will carry and place the ORU and Lemur II will connect it using HIPS and a driver tool and a threaded fastener. Phase II (2006-2008) goals include designing and building a flight-relevant Lemur (Lemur III) to perform a more complex cooperative transport/assembly task in simulated micro-gravity.

Additional efforts in conjunction with Northrop Grumman are currently aimed at designing and building another next-generation Lemur (AWIMIR) to perform inspection of a simulated orbital structure.

6. SUMMARY AND CONCLUSIONS

JPL is currently developing several core technologies for autonomous robotic construction and assembly capabilities, though many of these technologies are broadly applicable to other robotic tasks. These core technologies are aimed at improving the reliability and autonomy of such systems. Several projects have demonstrated robust performance in preliminary tests for tasks such as for hand-eye coordination and robotic assembly. Together, these core technologies will provide the foundation for performing reliable surface and orbital construction and maintenance.

7. ACKNOWLEDGEMENTS

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