

# Sustainable Cooperative Robotic Technologies for Human and Robotic Outpost Infrastructure Construction and Maintenance

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**Abstract** – Robotic Construction Crew (RCC) is a heterogeneous multi-robot system for autonomous acquisition, transport, and precision mating of components in construction tasks. RCC minimizes resources constrained in a space environment such as computation, power, communication, and sensing. A behavior-based architecture provides adaptability and robustness despite low computational requirements. RCC successfully performs several construction related tasks in an emulated outdoor environment despite high levels of uncertainty in motions and sensing. Quantitative results are provided for formation keeping in component transport, precision instrument placement, and construction tasks.

**Index Terms** – multi-robot systems, cooperative transport, space robotics, robotic construction

## I. INTRODUCTION

The current NASA vision for space exploration calls for sustained human and robotic presence in the solar system, beginning with a return to the Moon by 2020 [13]. A safe, sustainable human presence requires construction of infrastructure (habitat, power, atmosphere control, etc.) prior to human arrival, which can only be accomplished with robotic technologies. These same capabilities are required to build other types of self-sustaining robotic colonies for in-situ resource utilization, power production, mining, orbital facilities, and autonomous maintenance and repair facilities. Flight constraints limits these robotic technologies to be low power, mass and volume, and computing power; yet, space operations constraints due to communications delays and blackouts and uncertainty may require systems to be highly autonomous, reliable, and self-sustaining. Additionally, while habitat designs are not finalized, components are typically expected to be at least four times rover length, which will require cooperative transport and manipulation.

JPL's Planetary Robotics Lab (PRL) is currently developing robotic technologies with the capabilities necessary to support infrastructure construction under hard constraints on power, mass, communications, and computing. Research has focused on the issues of reliability in the presence of noisy sensing and multiple agents. Early work in cooperative transport was presented as part of Robotic Work Crew [24]. Current results for Robotic Construction Crew (RCC) include demonstrations of end-to-end component acquisition, transport, and precision deployment into a modular structure by a heterogeneous robotic team in irregular terrain. To minimize the need for computationally expensive processes such as high-level task allocation and planning, RCC uses a distributed multi-robot behavior-based

architecture with distributed sensing and explicit and implicit communication to coordinate agents in executing a series of high-level behaviors designed to accomplish the task.

## II. RELATED WORK

Current state of the art in autonomous construction provides for simple mating of marked components in a laboratory setting with a flat floor. Carnegie Mellon University has demonstrated multiple component mating using three specialized robots (vision, coarse manipulation, fine manipulation) [4][20]. The vision robot aligns where it can see the necessary work space and tells the manipulator robots how to adjust for alignment. Work in cooperative transport has primarily focused on cooperative pushing behaviors on flat floors [5][16][19][26], including some approaches that use the transported object to communicate implicitly. Most work in cooperative manipulation with force feedback focuses on fixed-based manipulators [12][18]. A robot has also stacked masonry blocks [17].

In order to transport rigid components cooperatively with tight grasp, the robots must simultaneously maintain a formation. Most formation work applies potential fields using vision and / or explicit communication [2][6][8]. These efforts have not required the explicit need to maintain a grasp on a cooperatively carried component or tight bounds on permitted formation errors. JPL has demonstrated cooperative pick up, transport, and put down of large components in an outdoor environment [10][24].

Instrument placement has relied on stereo vision with forward kinematics, visual servoing, and camera-space manipulation (CSM). Stereo with forward kinematics [22] can run near real-time on flight systems but is susceptible to camera model errors and, for manipulation, to manipulator kinematics errors. Visual servoing uses high-rate images to eliminate relative errors [1][9][11][14][15][25]. While robust to frame errors, delays between data or missing data can cause controller instability and large positioning errors [9][11][15], and it is not robust to noisy sensors [1]. CSM uses widely spaced cameras to determine the relationship between joint space and image space and provides high positioning accuracy (less than 1mm) [3][7][21]. However, CSM wide camera spacing requirements are impractical for rovers.

To date, no work has demonstrated end-to-end grasping, transport, and precision placement of a rigid component into a fixed structure by an autonomous team. In particular, work has not addressed such performance in

a natural environment with motion and kinematics errors, variable lighting, and high-precision requirements. RCC demonstrates these capabilities in an outdoor-like laboratory setting using iterative processes, force-torque feedback, and Hybrid Image Plane Stereo (HIPS) to provide robustness despite uncertainty [23].

### III. TASK DOMAIN

#### A. Environment

The task domain consists of two heterogeneous robot platforms, a structure to be constructed, and a large sand pit in Planetary Robotics Laboratory at JPL that simulates benign outdoor terrain. The robots must move to the storage area, acquire the component, cooperatively transport the component to the structure, and place the component into the structure on the next layer.

Structure components are of two types: rigid beams and flexible panels. Both types are four times the rover width in length. These components interlock when stacked. Each component has two grasping points (one left and one right) at which robots can hold the component. On the left and right of each component is a set of three fiducials that provide position and orientation of the component and, using a model of the component, the position and orientation of the grasping points. Figure 1 depicts the structure and beam components.

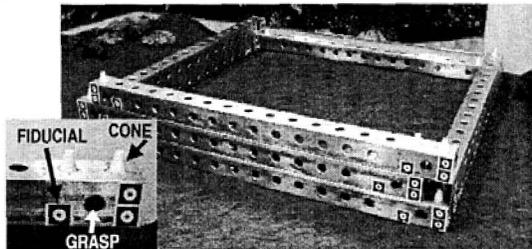


Figure 1. The structure of interlocking beams. *Inset:* Component end with three fiducials and two interlocking cones.

#### B. Platforms

The RCC team consists of the two heterogeneous platforms shown in Figure 2, SRR and SRR2K. The robots are flight relevant in terms of computation. Each is holonomic and has a four degree-of-freedom arm. Additionally, each rover is equipped with a forward-

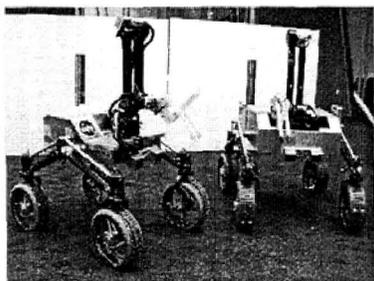


Figure 2. Rovers SRR (left) and SRR2K (right) in the laboratory sandpit in front of component storage.

facing stereo pair of cameras and a 3-axis force-torque sensor mounted at the base of the gripper. Power, computing, and wireless are all on-board.

#### C. Challenges

There are several primary challenges to performing robust construction tasks in a natural environment that this research specifically addresses. First is the need to perform these tasks in real-time using flight relevant processing and sensing. Another primary challenge is cooperative transport of components which require the team to remain in a rigid formation to avoid damaging themselves or the components. After transport, the robots must position themselves accurately enough so that they can cooperatively place the components into the structure with the required high level of precision. Additionally, sensing is very limited (due to power and mass constraints for spacecraft) and is noisy; thus the team must perform robustly despite limited and inaccurate information. In some cases, target positions may not be visible during all stages. Lastly, operating on natural terrain exacerbates any small errors in motion due to slippage.

To address these challenges, several techniques are applied. First, a behavior-based architecture is highly adaptive to changing environments, thus RCC applies a behavior-based architecture to make the system more robust to errors and uncertainty. To mitigate errors in sensing and motions, RCC uses an iterative process for positioning. Robots refine position based on additional relative visual information. Additionally, for cooperative actions the team fuses all available sensing information in order to select that most appropriate action (Section IV). All cooperative actions execute in small parallel steps and force-torque sensing provides indirect feedback on the relative formation through the component allowing the team to identify and correct errors. (Section V) Lastly, for precision placement, the camera models are calibrated relative to the arm frame to account for small errors in kinematics and models (Section VI). Catastrophic failures, those the team cannot handle autonomously, are identified and reported to the human operator.

### IV. BEHAVIOR-BASED CONTROL

The overall architecture is CAMPOUT, a behavior-based multi-robot control architecture. An overall view of the architecture can be found in [10]. CAMPOUT gives commands to a real-time control system performing low-level actuator and sensor control. Generally, complex CAMPOUT behaviors are composed of simple platform-specific control and sensing behaviors. Task-specific behaviors are built up using combinations of generic complex and simple behaviors.

For the construction task, several high-level task specific behaviors were developed, as illustrated in Figure 3. Figure 3 also illustrates the dependence of each task-specific behavior on the complex CAMPOUT behaviors

such as drive, turn, look for fiducials, and communicate. Each of these task-specific behaviors is implemented as an iterative process in order to accommodate the many sources of error.

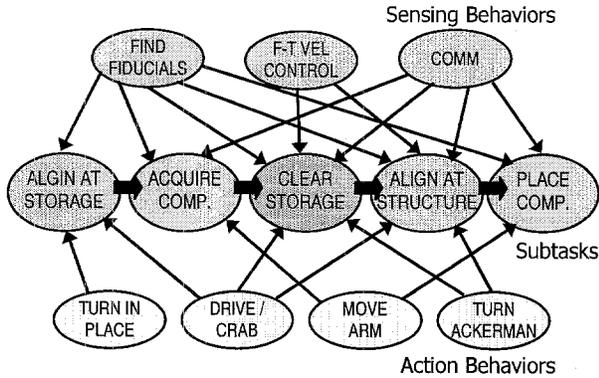


Figure 3. Execution begins with Align at Storage and completes after Place Component. Two-levels of the behavior hierarchy are shown. Large ovals are subtasks and small ovals are complex behaviors (sensing and action).

Figure 4 illustrates an example of how the iterative process for rover positioning cycles through crab, drive, and turn. Figure 5 illustrates how this process iteratively aligns the team for component placement. To maintain formation when operating cooperatively, the team moves jointly. At the start of each move the robots synchronize to ensure simultaneous actions. The leader determines the action and sends it to the follower for simultaneous execution.

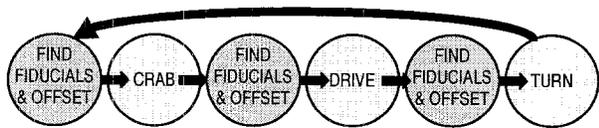


Figure 4. Alignments cycle through crab, drive, and turn. Before each action, robots compute magnitude and direction from visible fiducials. When no further correction is necessary or a timeout occurs, the iteration completes.

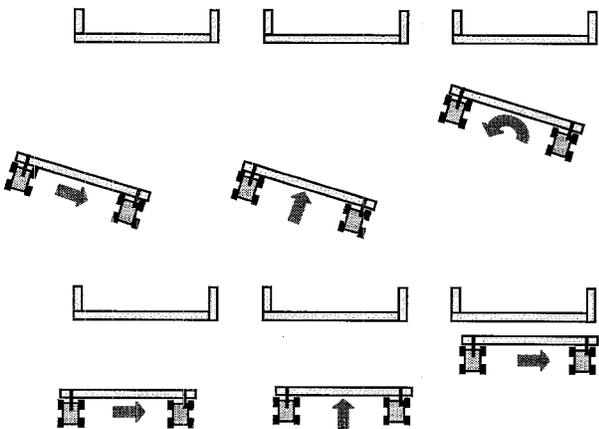


Figure 5. An example of team alignment cycles through crab, drive, and turn as needed to finally align.

Prior to action selection, robots exchange all available data so that the team selects the proper action. The team fuses data to ensure that both robots are selecting the same actions and that actions are based on all available information. The fusion method depends on the type of action. Typically, both robots will move the same magnitude and direction. For precision, however, small errors in formation must be corrected. Therefore, the robots incorporate small differences in desired motion by moving independently the desired distances.

For driving (forward or backward), the desired distance  $D_X$  for each robot is the distance to the structure  $G_X$  (as determined by the fiducials) minus the desired offset distance  $X_D$ . This distance is computed as in (1). If both robots see the structure fiducials, the team base drive distance is the individual distance with the smallest magnitude. If one robot sees the structure, the team base distance is that robot's individual distance.

$$D_X = G_X - X_D \quad (1)$$

For crabbing (left or right), the desired distance  $D_Y$  for each robot is the lateral distance to the grasp point  $G_Y$  (as determined by the fiducials) minus the desired offset  $Y_D$  to accommodate the robot's arm position relative to the robot's frame. This distance is computed as in (2). If both robots see the structure, the team base drive is the average distance. If one robot sees the structure, the team base distance is that robot's individual distance.

$$D_Y = G_Y - Y_D \quad (2)$$

For turning, the team must do complementary Ackermann turns around the center of the formation. The radius of the turn is half the distance between the grasp points of the component. If both robots see the structure, the angle is determined by the distance between the left and right grasp points  $\Delta Y_G$  and the difference in distance from the left and right structure grasp points to the left and right robot,  $\overline{F_{xR}} - \overline{F_{xL}}$ . This computes the angle of the team relative to the structure and reduces the effects of small vision errors. Figure 6 illustrates this angle that is computed as in (3). If one robot sees the structure, the positions of fiducials seen by the robot determine the angle: the difference in lateral distance between left and right fiducials  $F_{y_r} - F_{y_l}$  and difference in range between left and right fiducials  $F_{x_r} - F_{x_l}$ . This angle is illustrated in Figure 7 and computed as in (4).

$$A = \mp \tan^{-1}(\Delta Y_G, \overline{F_{xR}} - \overline{F_{xL}}) \quad (3)$$

$$A = -\tan^{-1}(F_{y_r} - F_{y_l}, F_{x_r} - F_{x_l}) \quad (4)$$

If at any time neither robot can see the structure (due to lighting conditions, for example), the team performs a small drive forward to attempt to reacquire the fiducials.

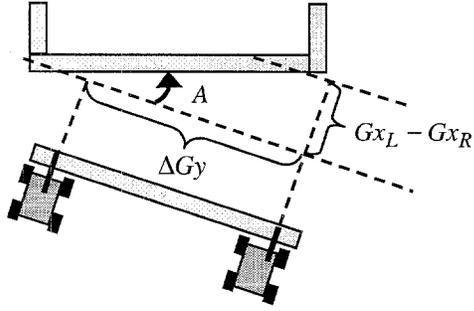


Figure 6. Computing turn angle from two sets of observed fiducial range and the known distance between grasp points ( $\Delta Y_G$ ).

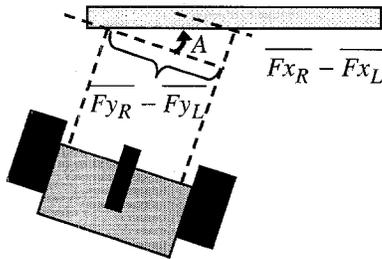


Figure 7. Computing turn angle from one set of observed fiducial positions (left  $L$  and right  $R$ ).

## V. FORCE-TORQUE FEEDBACK VELOCITY CONTROL

When cooperatively carrying a component, the component transmits forces and torques between the robots. The magnitude and direction of these forces and torques provide information regarding the relative position of the teammate. If the robots are in the correct relative formation, these forces and torques will be minimized. If one robot is front of the other, as shown in Figure 8, this will result in a torque in the direction of the lagging teammate about the vertical axis ( $T_z$ ). As shown in Figure 9, if the robots are at the improper separation, they will experience lateral forces ( $F_y$ ). Inward forces indicate they are too close together and outward forces indicate they are too far apart.

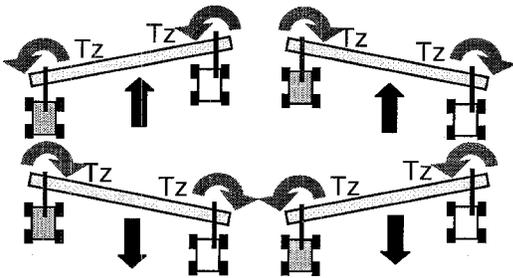


Figure 8. The relationship of formation errors and torque (leader gray, follower white). *Left*: Leader is lagging behind. *Right*: Leader is moving ahead.

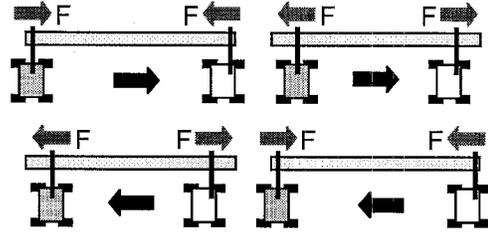


Figure 9. Examples of the relationship of formation errors and lateral force. *Left*: Leader is falling behind. *Right*: Leader is moving ahead.

Once the team detects an error in formation, they can correct it. In this implementation, only one robot (the follower, shown in white) takes corrective action to avoid overcompensation. If during a drive, the follower detects that the leader is ahead (Figure 8 right column), it will speed up. Conversely, if it detects the leader is behind (Figure 8 left column) it will slow down or stop. If during a crab, the follower determines that the leader is moving ahead (pushing as in Figure 9 top right, or pulling as in Figure 9 bottom right) it will speed up. If it determines the leader is moving behind (pushing as in Figure 9 top left, or pulling as in Figure 9 bottom left) it will slow down or stop.

Due to disturbances from soil, motors, and noisy force-torque sensing, simple controllers bound forces and torques rather than trying to fully damp them. The follower sets its velocity (slowing down or speeding up relative to the base speed) according to the simple PI controller shown in (5) to (7).

$$E = \begin{cases} T_z - T_{z0} - T_{F_y}, & \text{Drive} \\ F_y - F_{y0}, & \text{Crab} \end{cases} \quad (5)$$

$$V_{NEW} = V_B + K_P E + K_I \Sigma E \quad (6)$$

$$\text{if } |V_{NEW} - V| > \Delta V_{MAX}, V_{NEW} = V \pm \Delta V_{MAX} \quad (7)$$

The error  $E$  used to determine the desired velocity is relative to a reference point set when the robots are in the correct nominal formation ( $T_{z0}$  and  $F_{y0}$ ).  $T_{F_y}$  is the torque about  $z$  due to lateral force and is computed. The change in velocity for each step is maximized to  $\Delta V_{MAX}$  to prevent jerky motion or exceeding acceleration capabilities. The mapping from force and torque to formation error was hand calibrated through experimentation. The control parameters values were selected based on empirical performance.  $V_B$  is the base (nominal) velocity of 6 cm/s. For drive,  $K_P = 0.4$  and  $K_I = 0.0$ . For crab,  $K_P = 1.5$  and  $K_I = 0.05$ . If the force or torque exceeds a threshold for a sustained period of time, the formation has failed, and the team stops. These thresholds, experimentally determined, are 4.0 N-m in torque and 50 N in lateral force sustained over 0.5 seconds. Velocity control is active after the initial ramp-up (2 seconds) and until final deceleration.

## VI. HIPS

Hybrid Image Plane Stereo (HIPS) provides high precision manipulator placement despite errors and uncertainty in kinematics. The core of the approach is the generation of camera models in the frame of the manipulator's end effector. These models are generated through comparing observed position of a fiducial on the end effector and the reported kinematics position of the end effector. HIPS continually updates models to account for any changes to the kinematics, as well as account for other types of errors. Thus, computed goal positions based on image coordinates match with arm configuration (rather than to ground truth) and improve manipulator position accuracy. These models, while quite precise for manipulator positioning, may be highly inaccurate in terms of world coordinates.

HIPS uses an 18-parameter CAHVOR model, a pin-hole camera with symmetrical radial distortion. Full camera model estimation requires two steps. The initial calibration may be computationally expensive and is 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 model estimation step occurs online and readapts the models to time-varying errors and run-time uncertainties. Types of errors include flexion and droop (which may be orientation-dependent), joint resolution limitations, effects due to wear, finite image-plane cue detection, and additional camera modeling errors.

Initial estimation of this model begins by placing the manipulator at a sequence of predetermined poses that covers the portion of the manipulator work space that overlaps with the visual field of view. At each pose, the stereo pair of cameras takes images. The fiducial on the end effector is located in the images and the "actual" position of the fiducial on the end effector is computed using the measured joint angles and forward kinematics. Using the data from each of the preplanned poses, the CAHVOR model parameters are estimated using a least-squares error method, providing a mapping from image coordinates to rover coordinates.

Once initial models are generated, they can be refined online during nominal operations. At points along manipulator trajectories, current images and joint angles provide new data. HIPS makes an incremental change to the camera model using this new data. The weight of the new sample in the recalibration may vary, and in this implementation does increase as the manipulator approaches the goal position to improve precision.

Fiducials for model estimation and for identifying goal locations in images (shown in Figure 1) are identified in the image plane using gradient techniques to search for black-white-black transitions.

## VII. EXPERIMENTAL RESULTS

A number of experimental studies were conducted to determine the effectiveness of force-torque feedback to maintain formations by controlling velocity, of HIPS for precision manipulation operations, and of RCC to perform complex construction-related tasks. All studies were performed in the PRL large sand pit shown in Figure 1.

### A. Formations with Force-Torque Feedback

To test formation keeping using force-torque feedback to control velocity, the team carried a beam for the following scenarios:

- 300 cm drive with varying follower start time offsets (-2 to +5 seconds)
- 80 cm crab (left and right) with a -2 second follower start time offset.

Each experiment type was repeated without using velocity control. The 80 cm left and right crab tests were also repeated without velocity control without the start delay. In all cases, the follower is on the right of the formation.

Table I and Table II summarize quantitative results for these experiments, including mean and standard deviation for each run. Statistical analysis of data is performed only during the active control (2 seconds into the drive until stopping).

Table I: Mean Torque in Cooperative Transport: *Drive*

Start Delay	Fixed Velocity	Velocity Control
0 sec	-0.43 ± 0.25	-0.06 ± 0.22
	-0.26 ± 0.43	-0.01 ± 0.20
	-0.95 ± 0.43	-0.03 ± 0.14
	-0.06 ± 0.69	-0.02 ± 0.13
	-1.76 ± 0.79	-0.02 ± 0.13
2 sec	1.22 ± 0.50	-0.03 ± 0.18
	1.94 ± 0.53	-0.01 ± 0.21
	1.09 ± 0.63	-0.03 ± 0.21
	1.40 ± 0.91	0.00 ± 0.21
	1.46 ± 0.67	0.02 ± 0.16
-2 sec	-2.09 ± 1.02	-0.04 ± 0.16
	-2.22 ± 0.80	-0.05 ± 0.22
	Failure	-0.04 ± 0.21
	-2.03 ± 0.79	0.02 ± 0.20
	-2.30 ± 0.81	-0.03 ± 0.20
-5 sec	Failure	0.07 ± 0.21
	Failure	0.06 ± 0.15
	Failure	0.03 ± 0.17
	Failure	0.08 ± 0.16
	Failure	0.06 ± 0.18

Table 2: Force Profiles in Cooperative Transport: *Crab*

Drive	Fixed Velocity (0 sec)	Fixed Velocity (-2 sec)	Velocity Control (-2 sec)
80 cm	3.91 ± 8.67	Failure	-3.76 ± 7.16
	-1.48 ± 8.67	-14.04 ± 7.59	0.05 ± 5.38
	-5.54 ± 6.66	-7.30 ± 9.42	-0.44 ± 4.59
-80 cm	-6.73 ± 12.38	5.27 ± 9.90	1.61 ± 6.15
	6.98 ± 11.06	Failure	-0.02 ± 3.93
	15.56 ± 9.86	-3.56 ± 9.34	-0.78 ± 4.45

These results demonstrate the effectiveness of force-torque feedback velocity control for formation keeping. Using velocity control, the mean torque and force are consistently lower than they are without velocity control, reducing the stress on the manipulators. Mean torque during drive is (on average for 0 start time offset) 25 times greater without velocity control. Additionally, the standard deviation is much smaller, keeping the range of forces and torques much lower and nearer to zero. This reflects the robots remaining much nearer to the nominal formation and correcting errors that arise due to slippage and control differences. Without velocity control, the team reaches failure conditions much more frequently. Figure 10 shows an example of compared torque profiles for a drive and Figure 11 shows compared force profiles for a crab. Note that the velocity control line (solid) stays near zero while the fixed velocity line (dotted) produces large errors, even in cases with large initial errors.

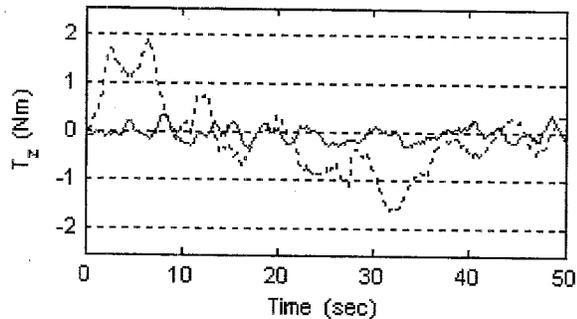


Figure 10. With velocity control during a drive (solid), torques remain near zero with little variance. Without velocity control (dotted), torques vary greatly and reach high values.

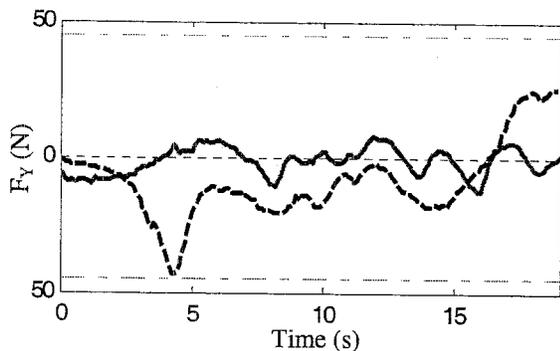


Figure 11. With velocity control during a crab (solid), forces remain near zero and have little variance. Without velocity control (dotted), the forces reach near failure (4.5 sec) and have large variance.

Velocity control can also correct errors arising from initial offsets in position or start time. If the follower starts ahead or behind it will adjust its speed until the forces return to nominal. If the follower (using velocity control) starts before the leader, it starts velocity control and becomes ready to respond to any formation errors. As a result, it slows down and waits for the leader to catch up

before returning to nominal speed. In this way, the formation can accommodate large head-starts by the follower. If the follower starts after the leader, it can speed up to catch up. This can accommodate offsets limited by the follower's ability to accelerate. Larger offsets will reach failure condition before velocity control can fully compensate, but the recognition of such a failure condition stops the team prior to damaging the manipulators and component.

Figures 12 and 13 show examples of correcting initial offsets. In Figure 12, the follower starts 2 seconds after the leader. This results in a build-up of force while the follower is stationary. Once the follower starts moving, it increases speed to catch up and reduces the forces to nominal. Figure 13 provides an example of a velocity profile in which the follower compensates for a late-starting leader. Initially, the follower starts to move and experiences a negative force. The velocity quickly reduces to zero while the leader is stationary (1 second). As the leader starts to move (2 seconds) and the negative force slowly reduces, the follower begins to increase velocity but remains below nominal speed. As the leader finally catches up at 5 seconds, putting forces near nominal, the follow reaches and maintains near-nominal velocity.

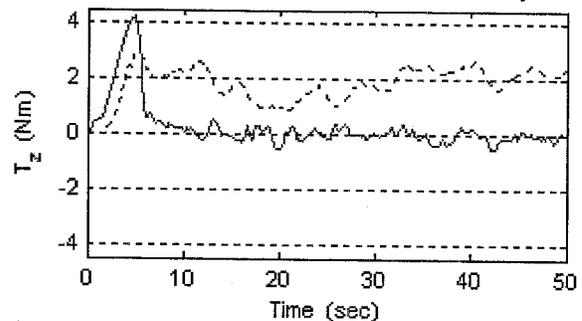


Figure 12. With velocity control (solid), a formation error causing high torques is corrected and torques return to near zero. With fixed velocity (dotted), initial error remains.

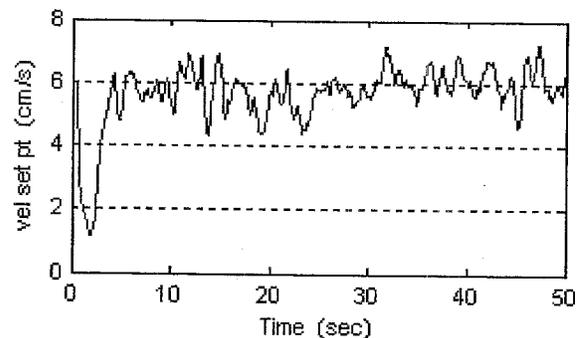


Figure 13. The follower starts moving while the leader is stationary (0 sec). The follower observes increasing torque indicating a lagging leader and stops (2 sec). As the leader starts to move and torque reduces, the follower gradually increases speed but remains below nominal speed. When the leader catches up (5 sec) the follower reaches nominal speed and remains near nominal with minor corrections.

In summary, force-torque feedback velocity control greatly increases the robustness of formation keeping. It corrects for small errors introduced due to slippage and control differences and compensates for many initial formation errors. Finally, it allows the team to stop motion if forces or torques exceed safe bounds to prevent catastrophic failure.

### B. Manipulator Positioning Accuracy with HIPS

Several types of experiments were conducted in simulation and using several research robotic platforms. These experiments include:

- **Simulation Verification:** This set of simulation experiments compares positioning accuracy of HIPS to that of traditional stereo and forward kinematics. Large kinematics errors were added after camera model estimation (combined total of 2.0 cm change in link lengths) to test robustness.
- **Manipulator Positioning Accuracy:** For these experiments, SRR places its manipulator on an observed target. Position error is measured.

Figure 14 illustrates the simulation results for 50 runs with each model. Using only initial HIPS camera models, performance improves relative to traditional stereo, with a mean error reduction of 60%. However, performance using initial models degrades as range increases as the errors in kinematics have greater impact at greater range. Using updates during operation reduces mean error by more than 90%. Additionally, updates correct the errors at larger range seen in the initial models.

Table III: HIPS Simulation Results

Experiment	Mean Error	$3\sigma$
Stereo	16.5 mm	1.7 mm
Initial HIPS	6.4 mm	9.3 mm
Updated HIPS	1.3 mm	0.8 mm

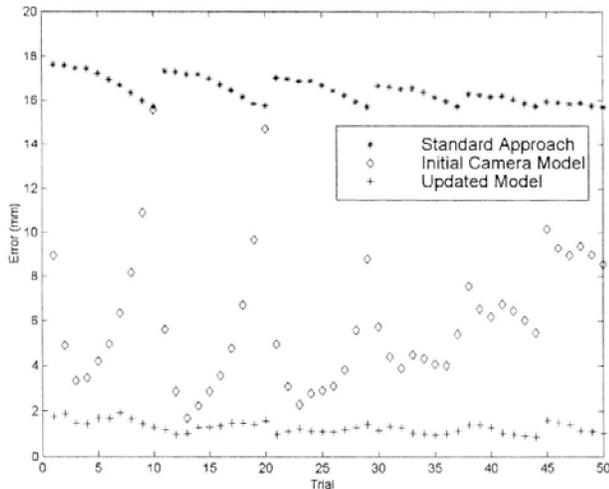


Figure 14. Average error was over 1.5 cm for standard stereo. Using only the initial model, HIPS shows an improvement to 6.4 mm. With model updates average error dropped to 1.3 mm.

For the experiments using SRR, initial camera models were generated using 35 manipulator poses. SRR attempted to position the manipulator to a goal on the target board shown in Figure 15 (in the middle of three fiducials). A total of 35 positioning tests were conducted.

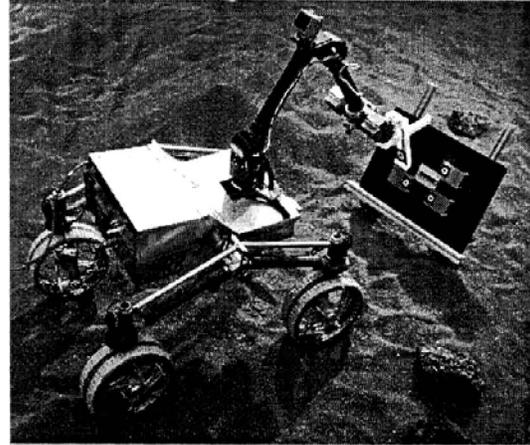


Figure 15. SRR demonstrates manipulator placement at a goal point on a target board.

Figure 16 shows the position test results. The average error in these tests was 1.96 mm with a  $3\sigma$  error bound of  $\pm 2.9$  mm. The terminal positioning error in nearly 85% of these tests was less than or equal to 2.5 mm. This is an improvement compared to the approximately 10 mm accuracy provided by traditional stereo on other flight-relevant platforms.

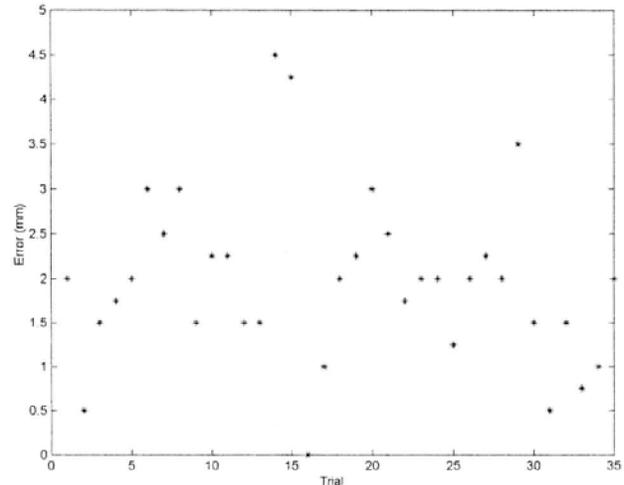


Figure 16. Results of 35 positioning tests show an average error of less than 2.0 mm.

The improvement in accuracy achieved by updating the model online during operation is apparent in Figure 17. Note that as the manipulator moves from the initial position (lower right) toward the goal point (center) the errors reduce.

In summary, HIPS improves the accuracy of manipulator placement by computing estimated camera models relative to manipulator kinematics rather than to

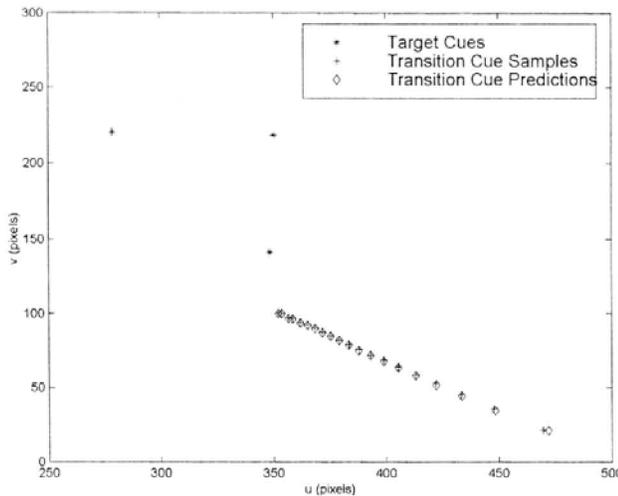


Figure 17. Updating the model as the arm approaches the goal at (350,100) improves accuracy during approach.

ground truth. This provides improved repeatability and a reduction of up to 90% in positioning error compared to traditional stereo and forward kinematics approaches.

### C. Construction Task Performance

The test environment for each of the construction task experiments is a large sand pit that provides benign outdoor-like terrain. In all cases, the structure foundation is in place at an unknown location and orientation but known direction. The team places the component into the structure on the first face of the structure they encounter. Three classes of experiment were conducted:

- **Acquire Beam:** The rovers begin at arbitrary locations where a component (is) storage is visible. The rovers independently align at a beam in storage. Then the rovers independently reach out to place their grippers into the grasp points. Finally, the rovers cooperatively lift the beam into a carrying position.
- **Align at Structure:** The rovers begin holding a beam, in formation, at an arbitrary orientation relative to the structure and such that at least one rover can see the fiducials on the structure. The rovers then align with the structure within 1-cm position accuracy for placement.
- **Place Beam:** The rovers begin immediately after completion of an Align at Structure experiment. The rovers cooperatively move the beam over the structure and then lower it into place. Finally, the rovers release the beam and stow their arms.
- **End to End:** The rovers begin as for an Acquire Beam experiment. They proceed to acquire the beam. After acquisition they back away from the structure, turn to face the direction of the structure, and drive until the structure becomes visible to at least one rover. The team then proceeds to complete Align at Structure and Place Beam.

Each experiment type was run several times. Any failure to achieve the desired result is noted, along with the cause of the failure.

Table III summarizes the construction task results. Figure 18 shows a series of photographs from several experiments, in operational sequence.

Table IV: Construction Results

Experiment	Runs	Failures
AB	24	0*
AS	19	1
PB	18	0
EE	5	0

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

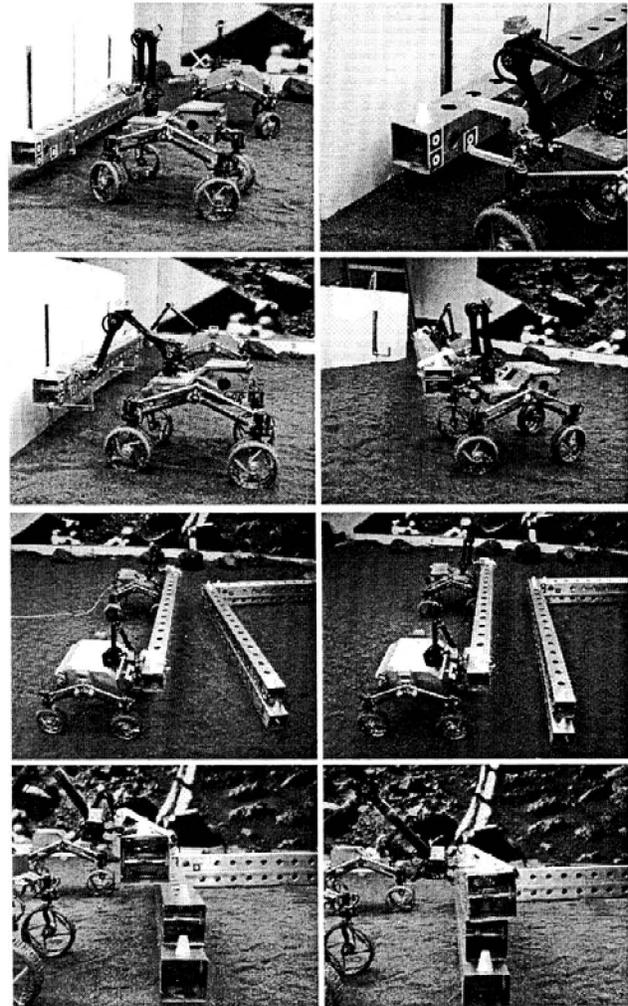


Figure 18. *Top left:* Align at Storage brings rovers into grasping position. *Top Right:* Align Grasp places hand in grasping position. *Second Left:* Team lifts the component out of storage in Grasp Component. *Second Right:* Team turns away from storage in Clear Storage. *Third Left:* Rovers begin Align at Structure. *Third Right:* Rovers complete Align at Structure at correct relative position. *Bottom Left:* Rovers begin Place Component. *Bottom Right:* Rovers complete Place Component.

The Align at Structure failure occurred when both robots reached a location from which they could not see the structure fiducials. This prompted the addition of the small bump forward described in Section IV, and no further failures of this kind occurred. The overall success rate of RCC for construction tasks (breaking end to end up into component parts) is 100% for acquiring beams, 95% for aligning at the structure (100% with bump mode for reacquiring the structure), and 100% for placing beams.

## VIII. ADDITIONAL PRELIMINARY RESULTS

### A. Flexible Panel Components

In addition to the beams shown in the construction experiments presented previously, some work has been done in handling flexible panel components, as shown in Figure 19. The RCC has successfully aligned with the structure while carrying a panel and deployed the panel into the structure in several preliminary trials.

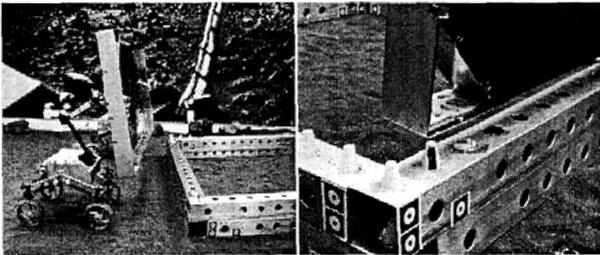


Figure 19. *Left:* The team carries a panel and aligns with the structure. *Right:* The team places the panel into the structure.

The adaptation of the behaviors from handling beams to carrying panels requires only providing several parameters representing the model of the panel (the side of the panel and the location of its grasp point relative to fiducials). Using force-torque feedback velocity control will require a calibration of parameters relating forces and torques to formation errors.

### B. Force Feedback for Position Error Detection

In order to make grasping and placement more robust, the force-torque sensing capabilities are being applied to detect errors. In approaching a desired position (for grasp or for placement), the robots monitor manipulator forces. Grasp misalignment results in the finger pushing the component rather than entering the grasp point, which increases axial forces on the manipulator. Similarly, lowering a misaligned component (such that it contacts cones) increases vertical forces. If forces increase above nominal an error condition is present. Figure 20 shows an example comparing forces during a successful and during an unsuccessful beam grasp.

In recent work, detecting these errors during grasping has been implemented. Upon detecting an error, the rover performs a local search, retracting and re-extending the arm at several points in an attempt to find the grasp. The rover has successfully compensated for small misalignments in several preliminary tests.

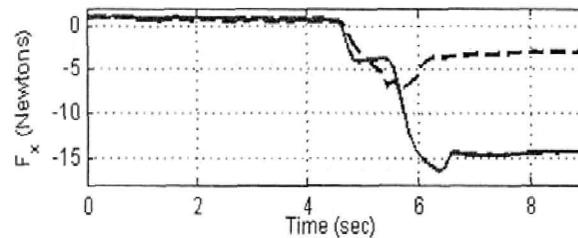


Figure 20. Examples of an arm approaching a component. In a nominal grasp (dotted) the gripper enters the grasp point but rubs along the grasp bottom. The robot sees small friction forces. In a missed grasp (solid), the gripper hits the component and pushes it. The robot experiences large forces and detects failure.

## IX. FUTURE WORK

Current efforts in RCC are focusing on increasing robustness and expanding the construction capabilities.

Currently, force-torque feedback velocity control can only correct forces or torques reflecting formation errors in the direction of motion. This may allow other forces to grow and lead to failure. To prevent this, in addition to compensating in velocity, the robot can adjust steering direction to minimize off-axis forces. This would also enable velocity control during Ackermann turns.

Force-torque feedback will be expanded to eliminate manipulator positioning failures, taking advantage of the failure detection capabilities described in Section VIII B. The force-torque sensor detects such increases, and the team could take corrective action.

Fiducial detection using current gradient methods is highly sensitive to lighting conditions. To improve robustness, this sensitivity needs to be reduced to handle the highly variable lighting outdoors.

The current acquire-transport-deploy scenario is only one step in the construction of a full structure. This work will expand to a larger-scale construction mission including more realistic types of habitats, multiple heterogeneous components and larger transport distances.

## X. CONCLUSION

The Robotic Construction Crew project has demonstrated autonomous multi-robot construction and assembly capabilities in simulated natural terrain. Construction tasks include acquisition, manipulation, transport, and precision placement of two types of construction components. A behavior-based system that tightly couples current state and sensor information with action within a hand-tuned task decomposition and sequencing structure provides performance reliability. The robustness of maintaining formations required for successful cooperative transport improves by using force-torque feedback for velocity control. Applying Hybrid Image Plane Stereo (HIPS) to directly calibrate cameras in the manipulator's frame also improves manipulator positioning robustness. Performance results demonstrate

a nearly 100% success rate in our single construction sequence task in an indoor natural environment. Future work will integrate more realistic habitat components, more complex construction scenarios, and greater fault detection and recovery.

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