Hex-DMR: A Modular Robotic Test-bed for Demonstrating Team Repair

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Abstract— **This work presents a novel test-bed design for demonstrating techniques for team repair in modular robotic systems. The advantages of using modular and team repairable robots are discussed and theoretical constraints for creating a system capable of team repair are enumerated. These constraints are used to develop the Hex-DMR (Hexagonal Distributed Modular Robot) system which centers on a unique repair scheme based on modular components. The proposed system is demonstrated first with computer simulations, which outline the environment navigation scheme and team operation dynamics, and then with a physical prototype, with which a simple repair maneuver is shown.**

I. INTRODUCTION

Robot agents that are endowed with the ability to both repair themselves and other robotic teammates potentially may have greater field adaptability and extended operating lifetimes. The research presented in this paper provides a model system architecture for implementing general principles of robotic team repair. This test-bed is a cooperative multi-agent system, comprised of modular robots, in which functioning agents can repair passive teammates exhibiting a fault state. The advantages of using modular robots are discussed and fundamental principles for creating a system capable of team repair are enumerated. The design of the test-bed is discussed and its functionality is demonstrated through computer simulation and a physical prototype.

A. Cooperative Multi-agent Systems

A cooperative multi-agent system (CMS) is a team of physically independent robotic entities (agents) that can operate communally to accomplish some task. Such a system offers many advantages over single robot solutions. First, in a CMS, failure of one entity in the team may not equate to failure of the entire system. [1] Additionally, because of the cooperative nature of the system, each agent can be of reduced complexity and therefore easier, cheaper and simpler to manufacture [2] Finally, a CMS may be able to accomplish tasks of greater complexity as well as being more adaptive and flexible when carrying out its tasks. [3].

The research described in this paper is supported by NSF grant IIS-915542, RI: Small:Robotic Inspection, Diagnosis, and Repair and by a collaboration with the Research and Experimental Development Department of the Johns Hopkins University Applied Physics Laboratory.

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As the technology progresses, cooperative multi-agent robotic systems may be able to provide alternative solutions for duties and vocations in which human participation is undesirable. These systems could assist and oversee inspection, assembly, planned maintenance and disturbance handling in many diverse environments [4] [5].

B. CMS Team-repair

The many advantages of multi-agent, robotic systems can be further augmented by creating a method for addressing fault states within the team. A system capable of such repair processes would be more robust to operational fatigue as well as undesirable and unpredictable environmental factors, especially when functioning independently from humans. The benefits of team repair are evident in natural biological processes [6] and similar principles could be extended to robotic agents. In addition to nature's examples, the advantages of repair have been modeled and quantified using reliability theory, showing that a self-repairable CMS can have a superior lifetime and functionality to that of a non-repairable system. [7]

There is an abundance of literature regarding cooperative multiagent systems including the topics of organization [8], [9], reconfiguration [10], [11], [12] and even replication [13], [14]. However, when the topic of repair is addressed, it is usually done so in conjunction with systems having physically interconnected homogeneous agents. In these systems repair is accomplished by simply discarding a damaged agent and is therefore limited in application. [15], [16], [17], [18], [19].

There is a conspicuous absence of work concerning more complex and meaningful repair processes in which the heterogeneous components that comprise the agents are able to be repaired. Only two such projects were able to be found. The first, developed by Kutzer, et al., was a robotic agent comprised of multiple heterogeneous components that could be replaced [1]. However, most of this work focused on the diagnosis and not the actual repair process. The second, and furthest along the spectrum toward meaningful team repair, was work by Bereton and Kholsa. They created a system of two small-scale robotic agents that employed a forklift-like mechanism for module manipulation and a camera for navigation [20]. While this design exhibited a somewhat robust module replacement method, only three of the agent's components were replaceable. By examining the strengths and weakness of previous research in the area of team repair as well as adding new constraints to increase the robustness of the system, we have developed a design that we believe is the closest yet towards robot team repair.

II. DESIGN

The following is a discussion of the design of our proposed test-bed for demonstrating robust heterogeneous team repair. It begins with a discussion of the constraints and challenges involved in creating such a system, and then presents the components and characteristics of the design.

A. Necessary Constraints for Repair

As one of the only other research groups exploring heterogeneous component repair methods, Bererton and Khosla proposed a series of constraints that are necessary for a CMS to exhibit robust team repair [21]:

1. Homogeneity and robustness of repair - The replacement method of components in each agent should be homogeneous and robust. Not only should the repair process and the tools used be similar for every component, but components should be able to be replaced regardless of configuration and orientation of the system or arrangement of the environment.

2. Completeness of repair - As many of the components as possible in the system should be replaceable so as to increase the number of failure modes that can be addressed.

3. Resolution of repair - The resolution of the components that can be replaced should be as fine as possible to reduce the resource cost of the repair (the amount and complexity of components lost).

While these three characteristics are necessary, they are not sufficient for creating a CMS with robust team repair capabilities. It is proposed that the following additional constraints must be imposed on the system design to achieve this goal.

4. Independence of repair - It is essential that the repair process should not rely on any assistance by the agent being repaired. While this constraint does not exclude the opportunity that assistance could be offered (which could be used to facilitate the process), an agent must be repairable regardless of its component state. Repair should be possible even if the agent is completely passive as it is likely that its fault condition will render it incapable of actuation or communication.

5. Ubiquity of repair capabilities - As many agents as possible in the CMS (if not all) should be capable of preforming repair. Implementation of this constraint allows the CMS to quickly respond to faults as well as efficiently choose agents to perform the needed repair so that the other tasks being performed by the system are minimally affected.

6. Versatility of agents - An agent should not be limited to only being able to perform a repair task. Unless the number of agents is very large or constraint *5* is not imposed, repair tasks will constitute a small fraction of the CMS's operational time. Therefore, a more efficient design will allow the agents to complete other tasks when not executing a repair.

The test-bed proposed in this paper, named the Hex-DMR (Hexagonal Distributed Modular Robot) system, incorporates all six of these constraints in order to demonstrate the feasibility of robust repair in a CMS (Fig. 1). The modular nature of its agents gives a resolution and completeness of repair not yet achieved in any other system. Its modular design also allows each agent to be customized to specific tasks as well as to a repair operation. Additionally, homogeneity and robustness of repair are realized through the standardized nature of the modules as well as the design of the repair end-effector. Finally a unique mechanical latching system and electrical bus allow for any module to be removed easily by the repairing agent without assistance from the agent being repaired.

B. The Hex-DMR System Overview

The Hex-DMR system is comprised of modular hexagonal agents (hereby referred to as a "hex"), each of which includes a frame module and seven additional modules of five types that are placed into the frame or attached to other modules (Fig. 2, Table. I). Through the combined capabilities of each module, a hex can independently traverse and manipulate the environment, maintaining internal power and control, but also interact with other hexes through wireless communication and physical manipulation.

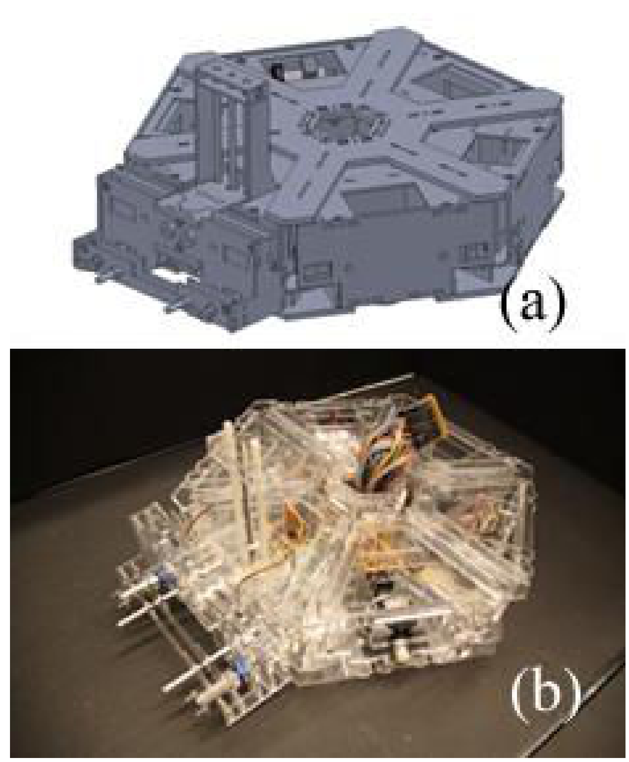

Figure 1. The Hex-DMR System: CAD model (a) and physical implementation (b).

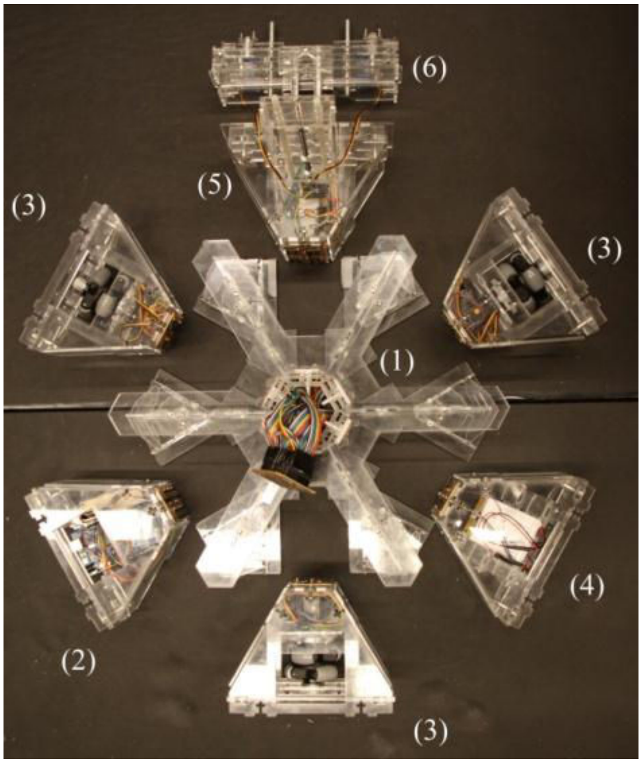

Figure 2. The modules of the Hex-DMR system represented in exploded view

TABLE I
Module list and descriptions for the Hex-DMR system

Module	Function	Important Components
(1) Frame	The passive structural module that houses and connects the others	Electrical Bus
(2) Control	Handles all computing and control of the other modules as well as external communication	Arduino Mega microcontroller, Xbee wireless radio
(3) Drive	Gives the hex its mobility. The three drive modules, together, create the "Kiwi-drive"	Continuous servo, Omni-directional wheel
(4) Power	Provides power to all the other modules	Polymer Li-Ion Battery
(5) Manipulator	Allows for out of plane manipulation for the end-effector	Geared DC motor, Leadscrew linear drive
(6) End-Effector	Incorporates the appropriate actuation elements for the module latching system; Other end-effector can be attached	2 mini-servos, passive lift prongs

C. Hex-DMR System Design Elements

The geometry and component makeup of each module allows the Hex-DMR system to overcome some of the challenges and shortcomings present in previous team repair research.

i) Modular configuration – increasing resolution and homogeneity of repair

The ultimate goal for repair resolution is on the micro-scale (eg. replacing circuit-board components). However, a more feasible system involves repair by replacement of modular "component families", each of which is represented in one of the separate module types of the Hex-DMR system. In this manner, every component is contained in an assembly which has similar geometry and connection points as every other module. While this increases the resource cost of the repair (eg. if a wheel breaks, the motor and axel must be removed as well), it allows every module to be replaced using a homogeneous repair method. A balance of complexity is essential because the modules used for repair (the manipulator and repair end-effector), must themselves be replaceable by identical modules.

ii) Hexagonal geometry – increasing completeness of repair

In order for the Hex-DMR system to demonstrate completeness of repair, all of the modules must be replaceable with relative ease. By positioning the modules around the outside perimeter of the frame, they are all directly externally accessible. The hexagonal geometry of the frame module strikes a balance between the amount of modules (resolution) in the hex and the ease at which a module can be accessed. If there are too many modules, either the overall scale is too large or the modules are too crowded to easily access. If there are too few, either the resolution of the repair or the complexity of the hex is too low.

iii) Omni directional drive - addressing the problem of docking

A large majority of the mobile robotics literature is devoted to robots with non-holonomic drive characteristics. When planning trajectories for a precise approach to a target (a docking procedure), using this type of drive can lead to difficulties [22]. An omnidirectional (holonomic) drive scheme was implemented in the Hex-DMR system which affords improved maneuvering capabilities and, therefore, effectiveness in docking procedures [23]. With this drive method, errors in orientation or position that are present can be easily corrected.

iv) Module latching mechanism - passive module repair

As has already been discussed, it is important, in a team repair operation, for the faulty module to be removed without any active participation from the module or its parent hex. Our unique module latching mechanism is actuated externally by the repairing hex and allows for the module to be locked either to its parent hex (if it is being placed) or the repairing hex (if it is being removed). Fig. 3 illustrates this process. To remove a module, the repairing hex aligns with the faulty module (a) and then inserts both the static lift prongs, in blue, and the latch actuators, in green, into the faulty module (b). The latch actuators rotate, simultaneous unlocking the faulty module from the parent and locking it to the repairing hex's end effector (c)-(d). The module is then removed (e). Placement of a module uses the same process, but in reverse.

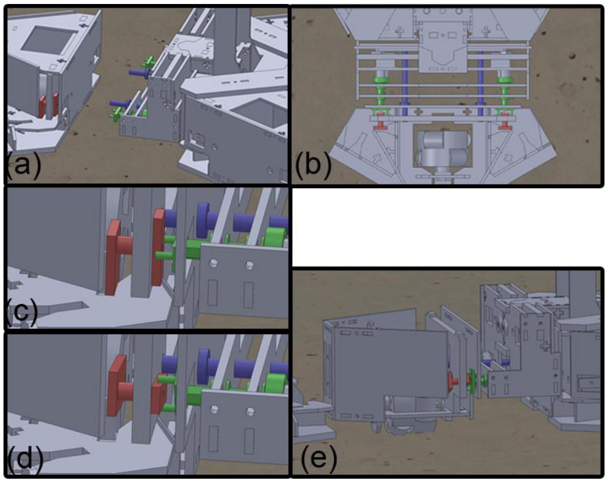

Figure 3. Module latching procedure

iv) Electrical Bus – increasing homogeneity of module placement

The electrical bus contained in the frame module enables power and signal transmission between the other active modules (Fig. 4). Upon being locked into place, each module is incorporated into the electrical system through compliant electrical contacts. Each module type utilizes a unique set of pins on the contacts so that they can be placed at any location in the frame, and yet, still have the appropriate electrical connections. Additionally each module transmits a specific analog identifier signal that is used to identify the specific modules present (this is especially important in determining the location of the drive modules). This signal can also be used as a simple one bit diagnostic feedback for module placement and removal.

III. SIMULATING TEAM REPAIR

Before the Hex-DMR system was physically implemented, we desired to test its capabilities through computer simulation. The simulation is based around a simple sorting task where the goal is for the team to move inactive modules between waypoints, from a source area to a staging area. Meanwhile each hex module has a probability of failing, causing that hex to become in need of repairs by another hex in the system. Fig. 5 displays a snapshot of the simulation.

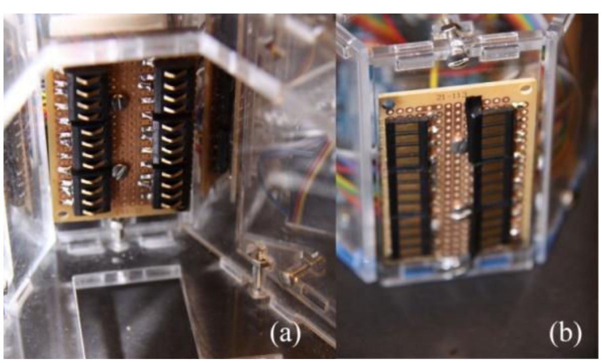

Figure 4. The male, frame mounted (a) and female, module mounted (b) connectors.

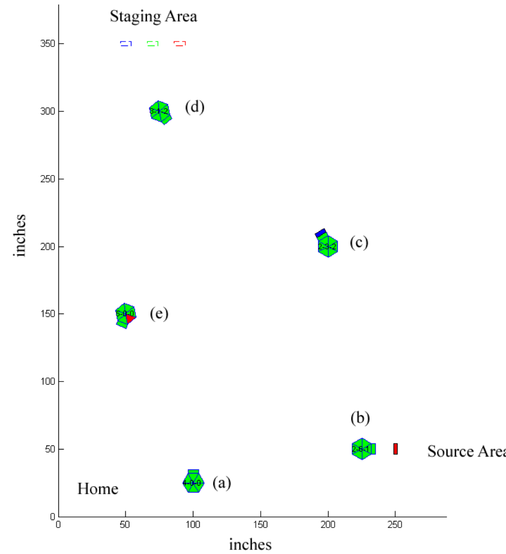

Figure 5. A snapshot of the Hex-DMR Simulation in which one hex directs the team (1), a hex docks with the source area (2) and another brings a module from the source area to the staging area (3). Additionally, a hex (4) is trying to locate another hex that is currently in need of repair (5).

The simulation was created in order to test the hex kinematics and drive maneuvers, and configure methods of hex interaction and communication.

A. Kinematics and Drive Maneuvers

Each hex has the capability for holonomic motion in the plane due to its omnidirectional drive configuration. By attaching reference frames to a hex as per Fig. 6, we can relate the velocities of the hex in the plane with the angular velocities of each of the three drive wheels. Using methods similar to [23] and [24], the kinematic equations of motion of a hex are given as follows, in Eq. 1:

$$\begin{bmatrix}\dot{x}_{world}\\ \dot{y}_{world}\\ \dot{\theta}_{world}\end{bmatrix} = \begin{bmatrix}\cos(\theta) & \sin(\theta) & 0\\ -\sin(\theta) & \cos(\theta) & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\dot{x}_{body}\\ \dot{y}_{body}\\ \dot{\theta}_{body}\end{bmatrix}$$
$$= R\begin{bmatrix}-\frac{1}{2} & 1 & -\frac{1}{2}\\ -\frac{\sqrt{3}}{3} & 0 & \frac{\sqrt{3}}{3}\\ \frac{1}{3b_1} & \frac{1}{3b_2} & \frac{1}{3b_3}\end{bmatrix}\begin{bmatrix}\dot{W}_1 r_1\\ \dot{W}_2 r_2\\ \dot{W}_3 r_3\end{bmatrix} = RT\begin{bmatrix}\dot{W}_1 r_1\\ \dot{W}_2 r_2\\ \dot{W}_3 r_3\end{bmatrix} \quad (1)$$

where r_i is the radius of wheel i and b_i is the radial distance from wheel i to the origin of the body frame.

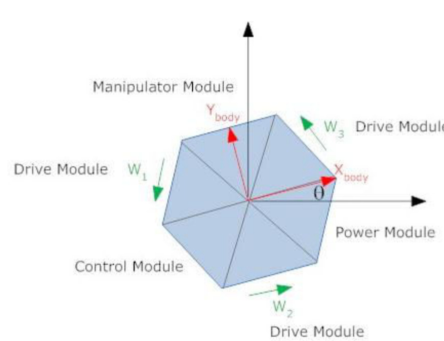

Figure 6. Hex coordinate frames in relation to module position.

These kinematic equations were used to develop various useful "driving maneuvers" in which a unique behavior of the hex in the plane can be achieved through applying specific wheel angular velocities. For example, to drive along the body fixed *y-axis* (ie. straight forward), with a constant linear velocity (v_y), the wheel velocities are as follows, in Eq. 2:

$$\begin{bmatrix}\dot{W}_1\\ \dot{W}_2\\ \dot{W}_3\end{bmatrix} = \left[\frac{\sqrt{3}v_y}{3}, \quad 0, \quad \frac{\sqrt{3}v_y}{3}\right]^T \tag{2}$$

In this maneuver, $\dot{W}_2$ can also be given a non-zero velocity which will rotate the hex body, acting as a rudder to steer the hex. A more complex maneuver, which is used heavily in the hex navigation, is "circling", during which the hex orbits a fixed point with a constant velocity (v), maintaining a constant radius of orbit (ρ) as well as keeping the *y-axis* aligned with the point of orbit (Eq. 3).

$$\begin{bmatrix}\dot{W}_1\\ \dot{W}_2\\ \dot{W}_3\end{bmatrix} = \left[\frac{bv}{\rho} - \frac{v}{3}, \quad \frac{bv}{\rho} + \frac{2v}{3}, \quad \frac{bv}{\rho} - \frac{v}{3}\right]^T \tag{3}$$

Here b is again the radial distance from a wheel to the origin of the body frame (now assumed to be the same for each wheel). Fig. 7 illustrates a simulated example of a hex using these driving maneuvers in order to navigate to a task waypoint. The hex first rotates till it observes the appropriate waypoint (a) and then aligns itself (b). Then the hex drives toward the beacon (3), stopping a predefined distance away (4), and preforms a circling maneuver to align itself with the correct location on the waypoint (5). Finally the hex drives forward and docks with the waypoint (6). At this point it would manipulate whatever element was necessary to its task (eg. a failed module).

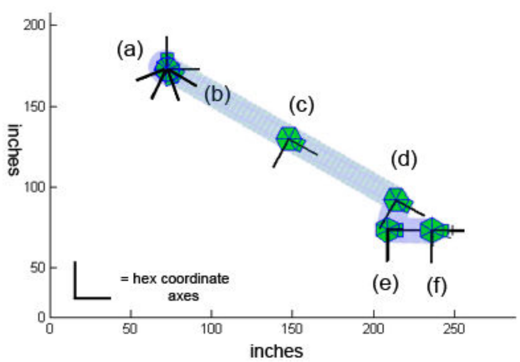

Figure 7. Navigating to a Beacon.

B. Hex interaction

To truly act as a team, the hexes in the Hex-DMR system are able to communicate using a network of wireless radio transmitters and receivers. In this manner, information can be passed between the hexes in order to direct and coordinate their efforts. More specifically, each hex is assigned two quantities that describe its current state to the team.

First, each hex has a "state vector" that indicates what it is (or should be) doing. The state vector of hex i is given as: $\Sigma^i = [\sigma_1, \sigma_2, \sigma_3, \sigma_4]^T$ where σ_1 is the current role assignment (Table II lists the possible hex roles), σ_2 the specific waypoint in the task being targeted, σ_3 indicates what stage of the task the hex is preforming and σ_4 is the time that has passed at the current stage of the task. The state vector is not only used internally by the hex to keep track of its current state, but is used externally, as well, to indicate its relative location and condition. For example, if a hex has taken longer than a set time to complete a task, it can be assigned as a patient and a physician can locate the failed hex by retracing the patient's previous navigation sequence.

TABLE II
Hex Roles

Role Title	Description
Idle	Is not currently assigned a role
Supervisor	Is responsible for making decisions regarding the operation of the team (including the assignment of roles)
Worker	Completes the team assigned task
Patient	Has been diagnosed as broken
Physician	Is in charge of repairing the patient

Additionally, each hex has a "status vector" that indicates the operational status of each module. The status vector of hex i is given as: $S^i = [s_1, s_2 \dots s_m]^T$ where m is the number modules in hex i and s_j is 0 if the module is functional and 1 otherwise. The status vector can be updated through internal diagnosis or by outside observation.

IV. REMOTELY ASSISTED REPAIR MANUEVER

After these concepts were developed and tested in simulation, the Hex-DMR system was physically implemented. We constructed the hex was constructed from laser cut acrylic sheeting, to allow for relatively simple fabrication and assembly, and then populated the modules with their necessary components (Table II). Having debugged the operation and interaction of the modules, we have begun testing with the prototype.

One of these test procedures is illustrated in Fig. 8, where the hex is wirelessly controlled through a mock repair maneuver. The hex is placed with an empty frame to its left and a template module to its right (a). The hex then preforms a zero axis turn (b) and drives forward to align itself with the module (c). By actuating the lift in the manipulator module, the hex adjusts the end-effector module to the appropriate height (d) and then docks with the template module (e). After latching to the module (f), the hex raises it from the ground so that it can be transported to the frame (g)-(h). Another zero axis turn is performed with the template module in tow (i) and the hex drives forward to align the template module with the frame (j). The module is then lowered, pushed into frame, and latched into (which also unlatches the end-effector from the template module) (k), at which point the hex drives in reverse to remove itself from the frame module (l).

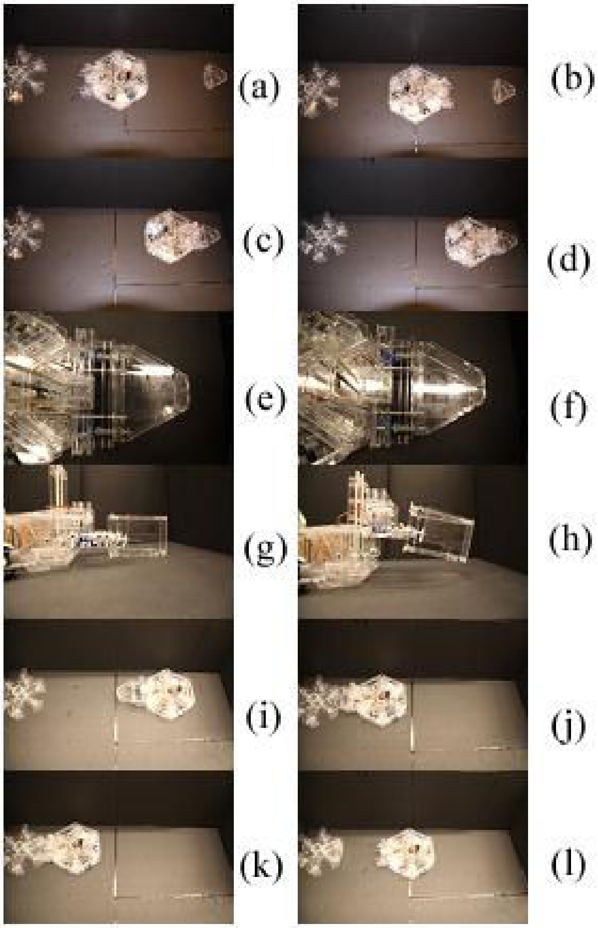

Figure 8. Physically demonstrating a repair maneuver (remotely controlled)

V. FUTURE WORK

Having demonstrated the basic capabilities of the Hex-DMR system through remote assistance, we will continue to perform more complex and robust testing procedures. One of our main goals to this end is to incorporate a sensor module with a vision system that will allow the hex to navigate the environment autonomously using a set of visual beacons located at each important task waypoint. In this way, each hex will be able to operate in its environment without the need for absolute position knowledge of either itself, the other hexes in the team or the task locations. Additional hex prototypes will also be constructed to test and demonstrate the proposed interaction methods and to demonstrate a fully autonomous repair procedure.

ACKNOWLEDGEMENTS

The authors thank Mr. Michael Kutzer for his suggestions and feedback regarding the design, fabrication, and control of Hex-DMR.

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