In Proceedings of SPIE, Volume 3839: Sensor Fusion and Decentralized Control in Robotic Systems II
19-20 September 1999, Boston, MA
pp. 258-269.

I(CES)-cubes: a modular self-reconfigurable bipartite robotic system

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ABSTRACT

In this manuscript, we introduce *I(CES)-Cubes*, a class of three-dimensional modular robotic system that is capable of reconfiguring itself in order to adapt to its environment. This is a bipartite system, i.e., a collection of (i) active elements capable of actuation, and (ii) passive elements acting as connectors between actuated elements. Active elements, called *links*, are 3-DOF manipulators that are capable of attaching/detaching themselves to/from the passive elements (*cubes*). The cubes can then be positioned and oriented using links, which are independent mechatronic elements. Self-reconfiguration property enables the system to perform locomotion tasks over difficult terrain. For example, the system would be capable of moving over obstacles and climbing stairs. These tasks are performed by positioning and orienting cubes and links to form a three-dimensional network with required shape and position. This paper describes the design of the passive and active elements, the attachment mechanisms, and several reconfiguration scenarios. Specifics of the hardware implementation and results of experiments with current prototypes are also given.

Keywords: Modular robots, self-reconfiguration, collective robotics.

1. INTRODUCTION

Recent progress in technology forced the research thrusts in autonomous mobile robots to consider locomotion in non-ideal environments, mainly on unstructured terrain. Statically stable gaits that are currently available for mobile robots include wheels, treads and similar methods that limit the locomotion capabilities of a particular robot. For example, a robot using a wheeled locomotion system is probably incapable of climbing a set of stairs, or move over relatively large obstacles. Although there are many examples of robots with climbing capabilities, a robot that can move with relative ease on flat terrain with an ability to climb over large obstacles is yet to be designed. On the other hand, new technologies such as micro electromechanical systems (MEMS) opened the pathway to small-scale mobile robots. MEMS technology enables multi-actuator, multi-sensor systems that can be implemented in millimeter scale, if not smaller. Applications to use small inexpensive robots to accomplish tasks in unstructured environments and narrow spaces are slowly emerging.

Drawing from the recent research on modular robots (e.g., Chen and Paredis' works[1,2]) and on small mobile robots with limited capabilities (e.g., *Millibots*[3]), we envision a modular self-reconfigurable group of robots that consists of two modules with different characteristics. A sufficient number of modules combined as a single entity will be capable of self-reconfiguring themselves into defined shapes, which in turn will provide a new type of locomotion gait that may be combined with other capabilities. A large group of modules that can change its shape according to the locomotion, manipulation or sensing task at hand will then be capable of transforming into a snake-like robot to travel inside a air duct or tunnel, a legged robot to move on unstructured terrain, a climbing robot that can climb walls or move over large obstacles, a flexible manipulator for space applications, or an extending structure to form a bridge.
Designing identical elements for a modular system has several advantages over large and complex robotic systems. The units can be mass-produced, and their homogeneity can provide faster production at a lower cost. A large system consisting of many elements is less prone to mechanical and electrical failures, since it would capable of replacing nonfunctioning elements by removing them from the group and reconfiguring its elements. Homogeneous groups of modules that are capable of self-reconfiguring into different shapes also provide a manufacturing solution at the design phase where identical elements are considered, while providing a modular system that can be re-arranged for different tasks.

To obtain the advantages listed above, a modular system must have several essential properties, such as geometric, physical and mechanical compatibility among individual modules. Furthermore, several design issues need to be considered for a

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modular self-reconfiguring system to become autonomous. Essential properties of our particular system as well as design issues relating to the implementation are given in Section 2.

Previous work on modular robotics include serial link manipulators that can be designed based on task specifications[4], design of kinematic structures that can be modularly synthesized[5], and cellular systems as self-organizing manipulators[6]. These and similar ideas on modularity has been applied to modular structures that are capable of self-reconfiguring into desired shapes. Previous 2-D examples include Inchworm[7] and self-organizing robots[8] moving in vertical plane, self-repairing modular machine[9] and metamorphing robots[10] moving in horizontal plane. Recent 3-D systems include Polypod that can combine different gaits[11], and the self-reconfiguring molecule[12] and another self-reconfigurable structure[13] that are both capable of moving in any direction using neighboring elements as pivot points.

The system described here is a self-reconfiguring bipartite system that separates the components that provide computation, sensing and power from the components that provide actuation in order to combine different gaits and task-oriented modules with self-reconfiguration capabilities. In the next section, we introduce our approach to modular self-reconfiguring robotics system, defining its characteristics and advantages. Section 3 illustrates simple examples of reconfiguration and motion in three-dimensional space. Section 4 describes the hardware implementation while Section 5 discusses the experiments on recent prototypes. Section 6 concludes the paper with a discussion on current implementation and future additions.

2. A MODULAR SELF-RECONFIGURING SYSTEM

I-Cubes (or ICES-Cubes) are a class of modular self-reconfigurable bipartite robotic system. This system is a collection of independently controlled mechatronic modules (*links*) and passive connection elements (*cubes*). Links are capable of connecting to and disconnecting from the faces of the cubes. Using this property, they can move themselves from one cube to another. In addition, while attached to a cube on one end, links can move a cube attached to the other end. We envision that all active (link) and passive (cube) modules are capable of permitting power and information flow to their neighboring modules. A group of links and cubes does in fact form a dynamic 3-D graph where the links are the edges, and the cubes are the nodes. When the links move, the structure and shape of the graph change.

This self-reconfiguring system has the following properties:

- Elements can be independently controlled; only the cube attached to the moving end of a link is affected by link motions.
- All elements have the same characteristics and are mechanically/computationally compatible, i.e., any link can connect to any cube.
- The 3-D graph formed by the elements fits a cubicle lattice to guarantee interlocking of neighboring elements, i.e., the distance from one cube to another is constant while in a position to accept links (Figure 1).
- Active elements have sufficient degrees of freedom to complete motions in three-dimensional space.

Since all the actuation for self-reconfiguration (with the exception of attachment mechanism) is provided by the links, cubes can be used to provide computation, sensing and power resources. If the modules are designed to exchange power and information, the cubes can be equipped with on-board batteries, microprocessors and sensing modules to become the “brains” of the system. Furthermore, it is possible to remove some of the attachment points on the cubes to provide these modules with different and faster gaits, such as wheeled or treaded locomotion. Specifically, we envision small robots that can reposition themselves to form a group that is capable of changing its gait in order to move over obstacles that single elements cannot overtake. Similar scenarios that require reconfiguration include climbing stairs and traversing pipes.

The required attachment points between the links and the cubes need to be mechanically feasible to hold multiple elements together and must be designed to transfer power and information between elements. In the following sections, we will introduce the specifications of these elements and the two different attachment mechanisms implemented as prototypes.

2.1. Geometric Design of the System and Link Actuation

Figure 1 below shows two links connecting three cubes. Assuming the length of a cube edge is L, the links should have four sections of length $L/2$, L, L, and $L/2$. The three rotational DOF for the links are provided by the joint (J2) between sections two and three and the joints located at both ends of the link (J1, J3). The details of these joints and gear mechanisms are given in Section 2.2. Joints J1 and J3 are both capable of providing continuous 360-degrees rotations, while J2 can only rotate 270 degrees. In order to keep the lattice structure formed by the cubes intact, the distance between cubes must be exactly L. Therefore, the links must be designed to provide this exact distance when the middle joint is at 0 degree (See the link on the right in Figure 1).

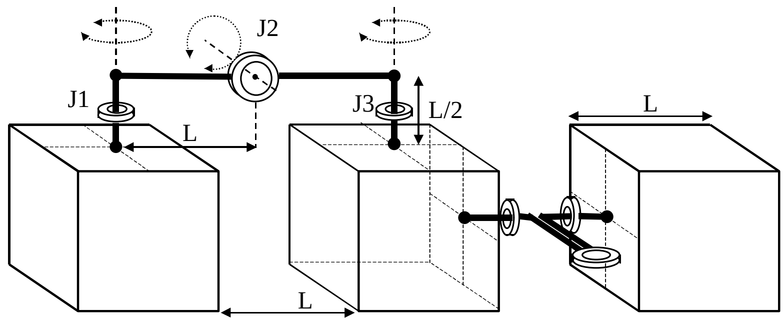


Figure 1. Links attached to cubes.

The design properties given above and the attachment/detachment capabilities of the links and cubes enable the links to:

- move from one face to another face on the same cube (Figure 2a).
- move one cube while attached to another cube (Figure 2b).
- move from one cube to another (Figure 2c).

All these motions require links to be capable of attaching to the cube faces, and performing middle or end joint rotations in a sequence. Note that it is also possible for a link to move a cube by rotating its middle joint, although not shown here. The separation of the system into two different modules doubles the group resolution, i.e., the minimal distance required for identical elements to move. In a system where the cubes could attach to and move over neighboring cubes (e.g., 3-D self-reconfigurable structure[13]) the resolution would be L, the size of a unit. In this system, however, the action displaces elements by $2L$. Due to the design, the 3-D space is separated into two disjoint regions that are occupied by the links and the cubes (The region for the cubes is discontinuous). The volumetric ratio of these regions is 1:6, i.e., the links have six times more space than the cubes to occupy.

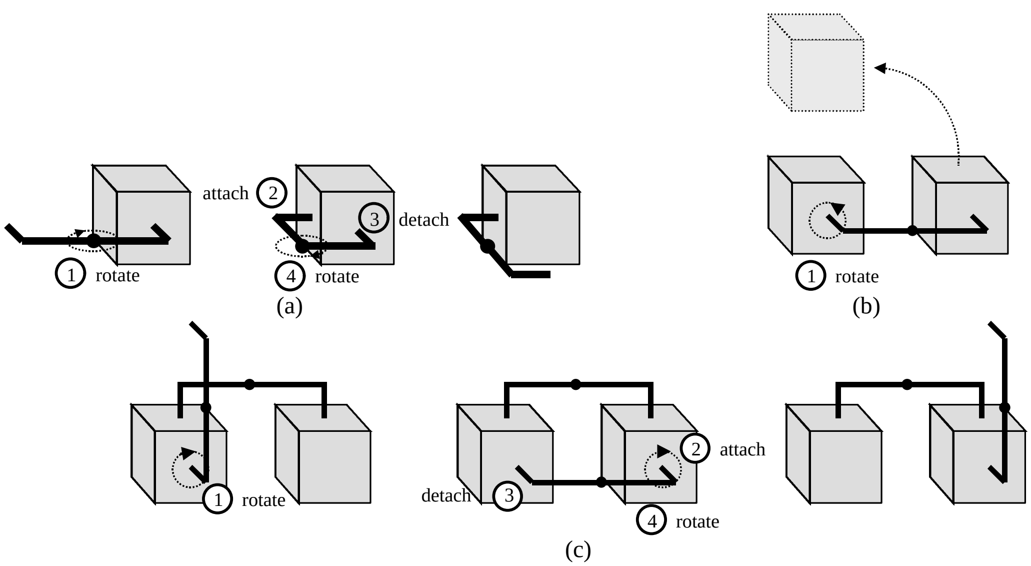
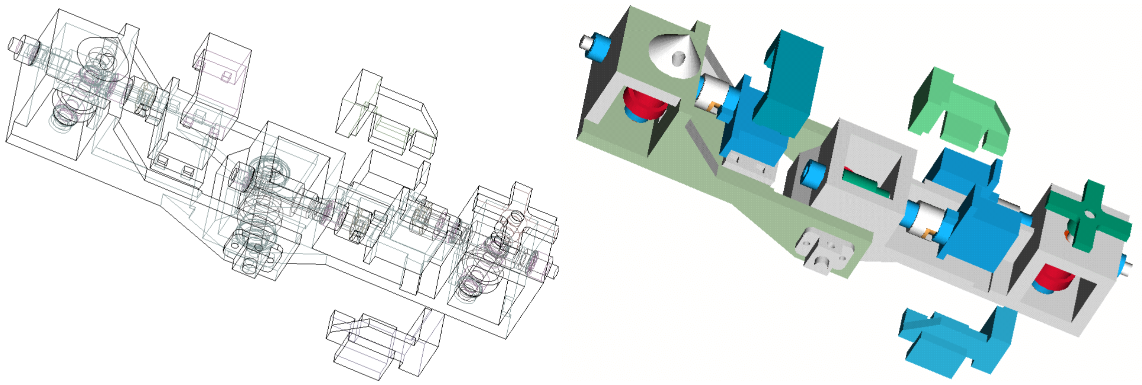


Figure 2. Link motions.

2.2. Links

The links have three worm-wheel gear mechanisms driven by small servos to provide continuous rotation at the end joints, and 270-degree rotation at the middle joint (Figure 3). All servos are coupled to worm gears driving the wheels. At the end joints, the wheels are aligned with the connectors that attach to cube faces. At the middle joint, the servo and the worm are located on one side of the link body, while the wheel and its shaft are attached to the other side of the link body. Thus, rotating the servos will rotate the connector shafts at the ends, and move one side of the link with respect to the other at the middle. Figure 3 shows the design of a link equipped with the servos and the gear structures. The middle wheel shaft is coupled to the piece holding the single servo, while the middle worm is coupled with one of the servos on the other side. The distance from one wheel shaft to another is again equal to L.

There are two main advantages of using a worm-wheel structure coupled with the servos. First, the rotational speed of the servo is reduced by the ratio of the gear mechanism (However, higher values cause the system to move slowly). Similarly, the torque provided by the servo is increased by the same ratio. A ratio of 1:40 is a good trade-off point for this particular application. Second, the worm-wheel system is an energy efficient solution for actuation. Since the wheel cannot drive the worm, the servos do not have to be powered all the time to hold the links in a specific position.



(a) (b)

Figure 3. Wireframe (a) and shaded (b) images of link assembly: servos holders shown *expanded*; two different connectors types shown.

2.3. Cubes

The cubes are passive elements that consist of at most six attachment points for the link connectors. They are not capable of moving by themselves (except for the case where an additional gait mechanism is incorporated in place of one or to attachment points; see Section 3 for typical examples). A cube attached to a link can either (i) be rotated, (ii) translated in two dimensions simultaneously, (iii) act as a pivot point for moving link. The role of the cube depends on the position and motion of the link as well as the connections on the 3-D graph formed by the elements.

We have designed individual faceplates with male and female matching edges. This enables us to use the faceplates on a platform to test the links and combine them to form cubes with different number and type of attachment mechanisms. For both types of attachment mechanisms, there are two different faceplate designs, one differing from the other by the 90-degree rotation the male/female edges. This is required to configure all the faceplates without interference inside the cube.

Figure 4 shows CAD images of a cube retrofitted with six attachment points for cross-shaped link connectors. The attachment mechanism is based on twist-and-lock mechanical behavior, and the details are given in the next section. When six faces with the latest version of the cross-shaped attachment mechanism are combined to form a cube, the maximum available volume inside the cube for computational elements and power source is approximately 151 cm^3, or 40% of the total volume of the cube excluding the walls. Note that one edge of the cube is equal to 8 cm. The available volume inside a cube with six cone-shaped attachment points is significantly larger than the version shown in Figure 4. For the configuration shown below, the available space is slightly less that 151 cm^3, since relatively smaller volumes around the servos and servo holders are not included.

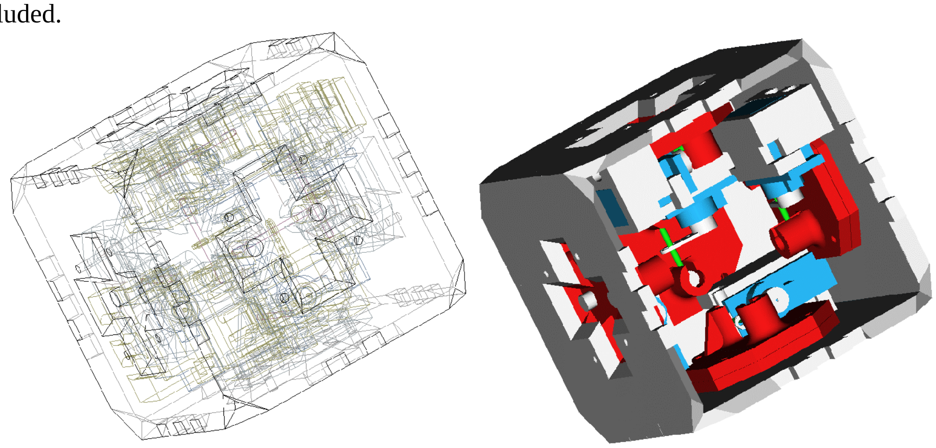


Figure 4. A cube with six cross-shaped attachment points (shaded image has one face removed).

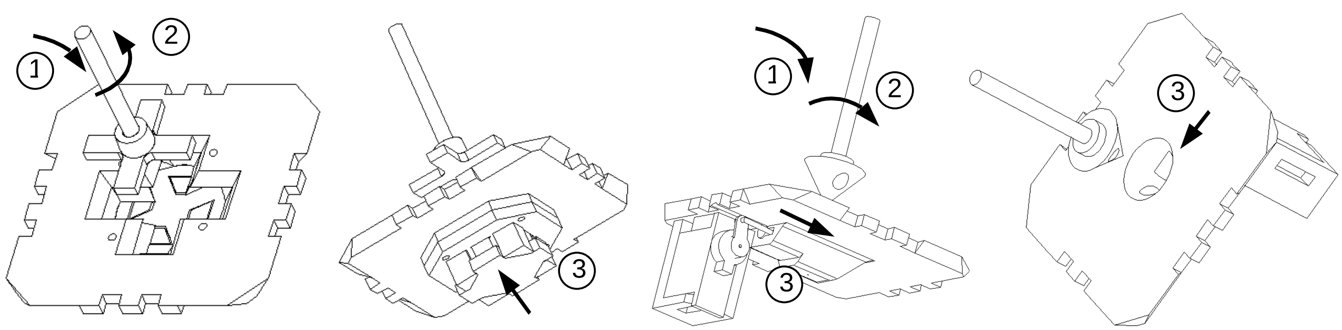
2.4. Attachment Mechanisms

A self-reconfiguring modular robotic system must consist of elements that are capable of attaching/detaching themselves to neighboring elements. This attachment system must also be energy efficient. Actuation for the latching mechanism should be limited, preferably for a few seconds during the locking/latching phase. Any actuation system enabling the modules to lock together must be designed to provide a statically and dynamically stable system that holds the elements together. An ideal candidate for such a system is an attachment mechanism that is in locked position while idle and that can easily switch to unlocked position for a short period of time during attachment/detachment. The mechanism should not open without actuation. To obtain such a mechanism, the latching motion on the cube side must be decoupled from the locking motion of the link connector. The aim is to create a lock that will only change state when actuated, and that needs to be actuated only when changing state. The following sections describe the two slightly different attachment mechanisms that have been tested.

2.4.1 Cross-shaped attachment mechanism

The first attachment mechanism we have designed uses a cross-shaped connector that enters and twists inside an opening on the cube face (Figure 5a). After entering the cross-shaped opening on the cube face, the link connector will twist to lock in place. This motion will limit the translation motion, while the upward motion of the locking piece with four pegs will stop free rotation of the link end with respect to the cube. This mechanism requires a single actuator to move the locking piece up and down for latching (See 3 in Figure 5a). The edges of the opening on the cube face are chamfered to guarantee that the connector clears the cube face while approaching the attachment point. Note that the connector does not approach the cube face from the normal, but following a curve that is normal to the face plate only at the surface of the supporting piece. The edges of the connector are also rounded to facilitate sliding into locked position.

The locking piece with four pegs holds the cross-shaped connector in place when pushed forward, and is actuated by a servo pulling and pushing it from under. Therefore, a rotation of the link end results in two different actions depending on the lock state: (un)locking the connector to the cube, and rotating the cube in place. The cross-shape connector must be correctly oriented with respect to the opening on the cube face before attempting to latch.



(a) (b)

Figure 5. (a) Cross-shaped connector with twist and lock mechanism, and (b) cone-shaped connector with the sliding latching mechanism.

2.4.2 Cone-shaped attachment mechanism

While working on the first prototype, we have designed a second attachment mechanism that provides a more packed servo assembly under the cube face, thus resulting in a larger volume for additional components to be added into the cube. This mechanism uses a conical connector that fits into a similarly shaped opening on the cube face (Figure 5b). The connector also has a circular opening that can be aligned to a sliding bar driven by a servo. Before of after the initial approach, the link connector must be rotated in order to align this opening with the sliding bar. Once the cone-shaped piece is in place and oriented correctly, the steel bar can be moved to lock the link connector in place (See 3 Figure 5b).

2.5 Design Issues and Other Characteristics of the System

We have designed our 3-D system to overcome common problems in modular self-reconfigurable systems. Capabilities such as efficient power consumption, on-board power resources, information and power transfer between elements, and autonomous motion, are required in order to have a feasible practical implementation. Our design of actuators for the links and the connection mechanisms significantly reduces the energy use. The worm-wheel structure and the latching elements need to be actuated when link or locking motion is required. The available space in the cubes can be used for small batteries that power all actuators, sensing and control modules in the system. We hope to design simple electromechanical connectors that will provide multiple lines for power and serial communications while keeping continuous link rotations. Furthermore, feasibility tests for encoders, and other custom circuitry to provide position feedback on the link joints are carried out.

While designing the system, we assumed that one link can only move a cube at a time. There might be a possible situation where a link holds a cube in place while another moves using the same cube a pivot point. This situation is often encountered in small groups translating in its elements upward (See Section 4). The main constraint in designing such a system is the weight of the individual elements.

The choice of using two different elements complicates the design and implementation of the system while doubling the group resolution, but presents an extension to a task-oriented, self-powered robotic system. Furthermore, this design approach enables us to reduce the minimum number of elements for stable motion. A group of four links and four cubes is capable of moving in three dimensions (e.g., moving over obstacles, translation without tipping over) for most situations. In situations that a statically stable state cannot be found, it may be possible to use a free link (with one attached end) to support the structure.

Assuming one link is capable of moving itself and an attached cube, simultaneous motions in three-dimensional space are possible for the cubes. Some examples are shown in Section 3. Combining several of these motions in sequence, it is possible for a group of links and cubes to change shape and travel in a certain direction. Few simple examples of motion for relatively smaller groups are given in the following section.

3. RECONFIGURATION AND 3-D MOTION

In this section, we give examples of action sequences and scenarios in which a group of cubes and links move and self-reconfigure from one position/shape to another. Figure 6 shows the top view of a group of three links and three cubes traveling from left to right. Gray color indicates active link and cube, i.e., link and/or cube that are moved to reach the next state. Numbers next to figures show the total number of 90-degrees actions to be completed by the active link. Although the given sequence of actions may not be feasible for an actual implementation due to static and dynamic equilibrium constraints, we present the case for its simplicity. Note that there are many alternative solutions combining individual link actions in a different sequence as well as simultaneous link motions, which probably result in faster group movement. However, these solutions are difficult to illustrate with still images. As it can be seen from Figure 6, the direction of motion can be changed during any of the phases described above. After the first five sets of actions, the group is already positioned to move upward if the same set of actions is used.

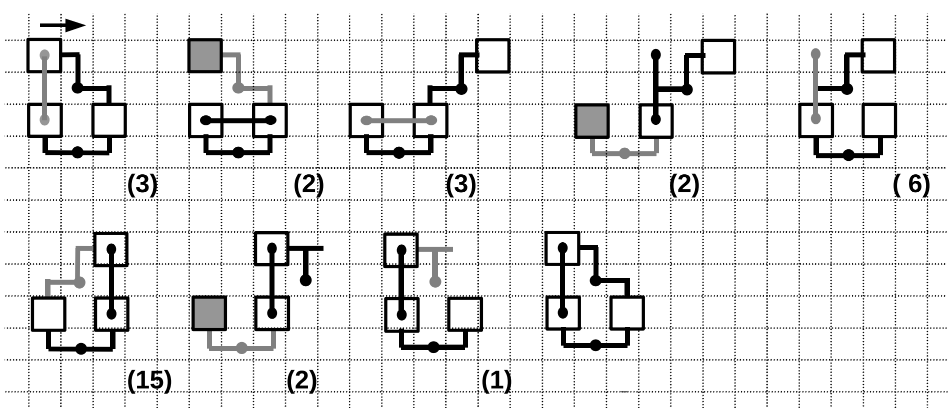


Figure 6. A group of three links and three cubes in linear motion (image sequence left-to-right).

To illustrate more complex motion sequences, we present few snapshots of a possible scenario for a group of four links and four cubes. As shown in Figure 7, this group is capable of moving to a higher surface (e.g., stair climbing) by reconfiguring itself. Connections between elements are kept such that the system forms a single connected graph at any time. This would enable all elements to exchange information and power during the rearrangement. There are several time intervals where multiple links move simultaneously. Furthermore, the links do not have to complete 90-degree motions to, for example, detach from a cube or move from one cube face to another. There are few positions, where a link moves on a pivot cube held in the air by another link, which may be statically non-feasible. Tests on the actual components will provide more insight into the problem. Also note that cube faces that are initially on the ground and several other faces (i.e., attachment points) are not used for reconfiguration. It may also be possible to find other solution sequences that minimize the number of faces used in the reconfiguration process.

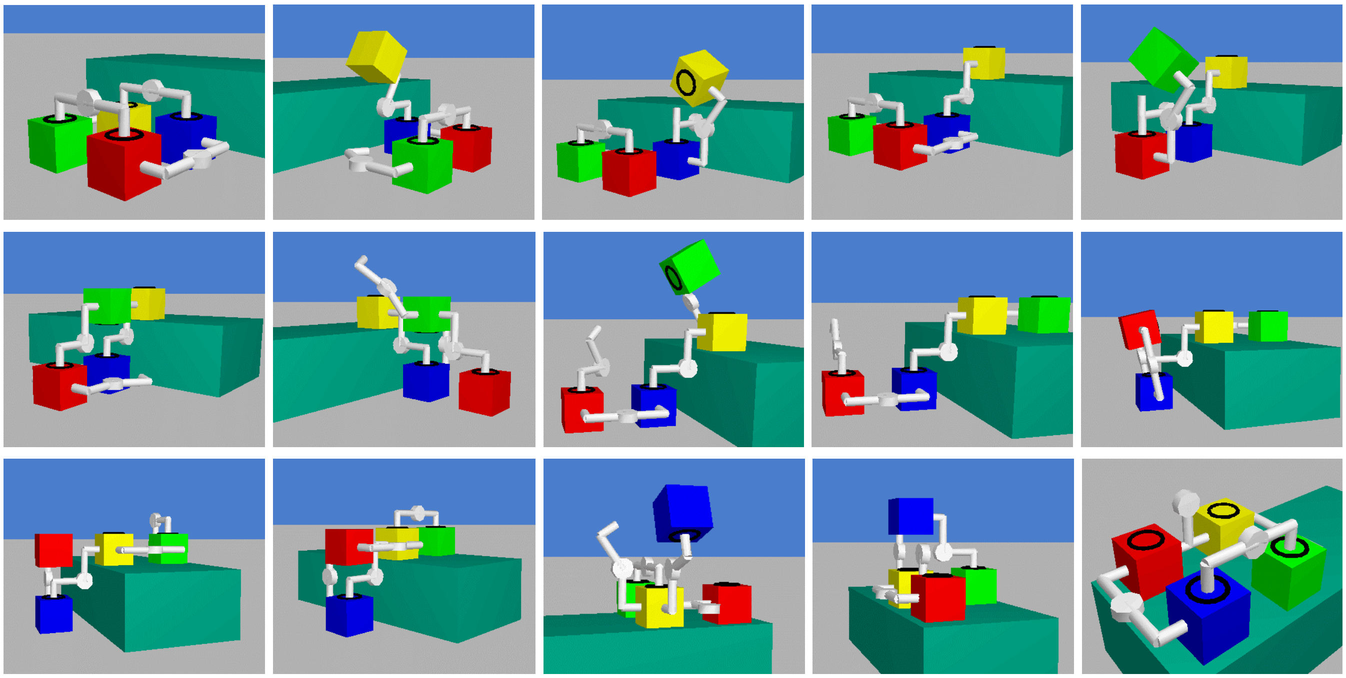


Figure 7. A group of four links and four cubes reconfiguring to move over an obstacle (image sequence left-to-right; top left image is the starting state, lower right is the final).

The black circles on the cubes indicate faces initially oriented upward. As seen in the final image, the cubes are still oriented correctly at the end of the action sequence. To guarantee this result, cubes need to be re-oriented in the earlier phases of the solution, as seen in third and fifth images (Figure 7). Note that this sequence of actions for the problem is generated manually. We believe that the combination of four cubes and four links is the minimal group that is feasible for 3-D motion and self-reconfiguration. Increasing the number of modules in the group will result in more stable and capable reconfigurations. However, doing so will increase the complexity in motion planning.

Another example that combines a self-reconfiguring system with one that is capable of faster locomotion is shown in Figure 8. Since the cubes are passive elements that do not contribute to the reconfiguration motions with the exception of locking mechanism, these modules can be equipped with capabilities that provide different gaits (such as wheels or treads) and task-oriented modules (such as cameras, microphones, etc). In Figure 8, the leftmost robot in the first image includes a camera directed at the wall. Obviously, this robot is not capable of seeing what is behind this obstacle. Assuming these wheeled robots are capable of carrying one or more links, they can move into a position to form a single entity and self-reconfigure into a tower. For an initial configuration and a sequence of actions dependent of this configuration, it is possible to move the robot with the camera on top of others, and use the link under this robot for camera tilt and pan. The required number of faces with attachment points for each robot are three or four for this specific scenario. These must include the one on the top and two opposite or adjoin faces on the sides.

This scenario illustrates an important characteristic of the system. A heterogeneous group of small robots combines individual robot capabilities with self-reconfiguration to complete a task that would not be possible with individual robots of small size. It is also possible for some robots to carry multiple links in order to enable other teammates to roam around without additional payload (link) while carrying out a task that requires only individual capabilities. Furthermore, note that the only requirement on the shape of the robots is that the distance and orientation of the attachment points be such that links can attach to these. Beyond this requirement, the robots could have any shape.

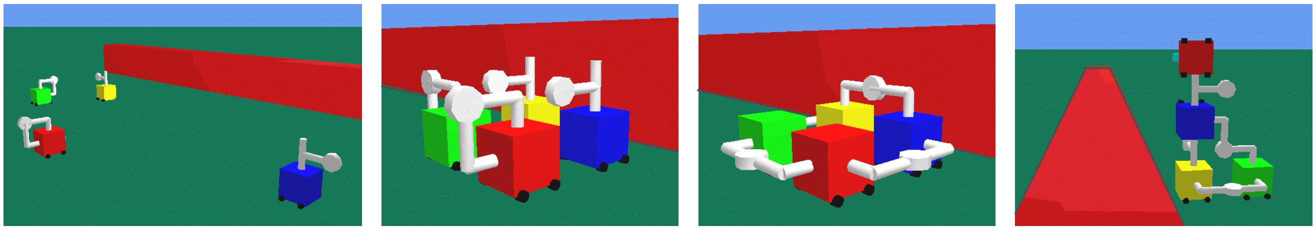


Figure 8. A group of four links and four cubes forming a tower (left-to-right).

4. HARDWARE IMPLEMENTATION

The designs described in the previous sections were implemented using plastic link and cube bodies assembled with off the shelf mechanical and electronics components. The body of the link, cube faces and additional pieces required for attaching off the shelf elements are created using P1500 prototyping plastic with Genisys© fused deposition modeling machine. Files generated on CAD programs can be sent to this “3-D printer” for creating complete pieces that require minimal assembly. The printer resolution is 0.3mm. The design of the links and the cubes is completed using *ProEngineer*© CAD program. Off the shelf elements are measured and created in ProEngineer in order to design and test plastic bodies of the robotic elements. All components are combined into multiple assemblies at different positions to guarantee compatibility and unrestricted motion of the elements.

Actuation of the worm-wheel gear mechanism is provided by a small-size high-torque servo. These servos are placed on the link body and coupled to the worm shafts with custom plastic pieces. The potentiometer feedback circuitry and mechanical stops on gearbox of the servo are removed to obtain continuous 360-degree turns on the worm shaft. Mechanical elements such as gears, worms, steel shafts, ball and oil-impregnated bearings, and collars are available from several companies selling precision mechanical components. The size limitations of these off the shelf components impose another constraint on the size of the prototype.

A link equipped with three servos and three worm-wheel pairs, complete with shafts, couplers, collars, and bearings measures approximately 326 gr. The length of an edge of the cube is taken as 8 cm, therefore the length from the axis of one end joint to another is 16 cm. One side of the link is shifted 0.16 cm down to enable the link to complete a 270-degree turn around its middle joint. All steel shafts are cut to fit the dimensions and keyed to couple with plastic servo heads. One faceplate for the cube including the actuator, metal bars and joints measures approximately 48 gr.

Figure 9 shows a link equipped with servos and other off the shelf components. The servos are held in place with plastic holders that slide between the link and servos. The servo heads are coupled to the worm shaft with a custom-designed plastic piece. Figure 10 shows cube faces with cone- and cross-shaped attachment mechanisms. The servos are used to move the locking bar or pegs into place. A four-faced cube is shown in Figure 11. In this picture, the faces are held together only by the matching edges, i.e., no additional attaching pieces are used. This implementation also includes a simplified version of the attachment mechanism that uses two metal bars instead of the four pegs shown in Figure 5.

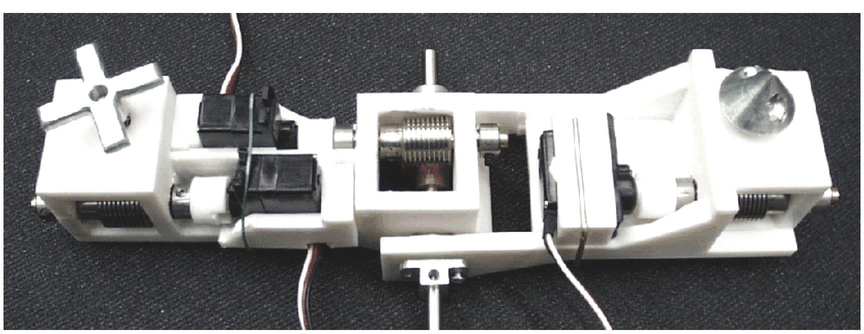


Figure 9. Link prototype.

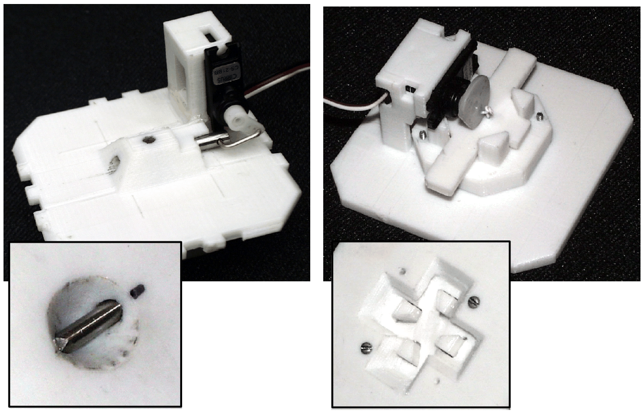


Figure 10. Prototype faceplates with cone- (left) and cross-shaped (right) attachment mechanisms.

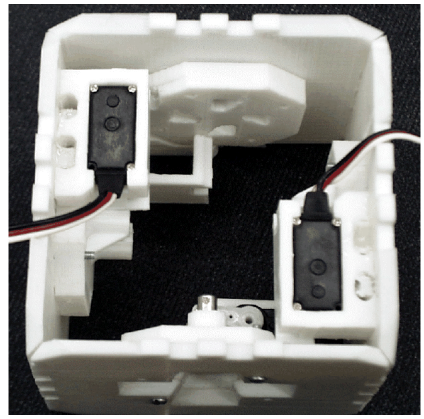


Figure 11. A four-faced cube.

As indicated in the previous section, the current prototypes have small servos for actuation of the worm-wheel structures. These servos are capable of providing a torque of 1.7 kg-cm at 6 volts. Current worm and gear pairs have a torque/speed ratio of 1:40. The worst-case scenario for maximum required torque calculations is encountered when a link tries to lift a cube while attached to a side face (Figure 12). We assume 500 gr. lumped masses at the center for the cube and the link. The current link and cube prototypes weight less, as given in previous section. Therefore, the approximate torque requirement at the other end is equal to $T_{REQ} = 8 \times 0.5 + 16 \times 0.5 = 12\ kgcm$. On the other hand, the worm-wheel gear structure can provide a maximum torque of $T_{MAX} = 1.7 \times 40\ kgcm$. Thus, the link should be able to lift the cube if the worm gear efficiency is approximately 18%. Note that this result is obtained assuming a weight of 0.5kg, lumped at the center, for the link and cube. Furthermore, the gear ratio can be increased to provide more torque at the expense of speed. Current implementation of the link is capable of lifting of a cube formed with four combined faces.

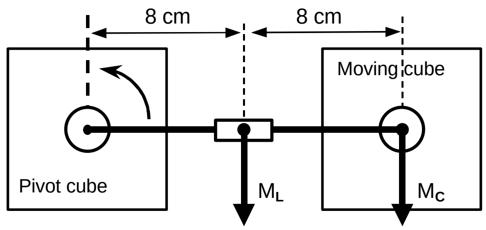


Figure 12. The worst-case scenario for a link lifting a cube.

The use of servos and other off the shelf mechanical components introduces a lower limit on the size of the links. Available precision components for mechanical structures on the link are relatively larger than custom-made components. Inside the cubes, the servos are still taking most of the space. New prototypes with different attachment mechanisms are tested to solve this problem. The size and consequently the weight of the elements directly affect the torque requirements on the actuators.

The resolution of the 3-D printer we are currently using (0.3mm) and the stiffness of the plastic material used to build the link and cube bodies are two other factors limiting the design. Due to printer resolution, the locations of the shaft openings are not exact and create problems with gear efficiency. Several problems for the worst-case scenario mentioned above are encountered. Also, plastic material P15000 is less strong than other plastic materials such as ABS or Delrin, and therefore limits the minimum thickness of the link body.

The links have only three DOF, limiting the approach angle to only one. Since the distance between the cubes is constant, the link always approaches the connection point of the cube face following the same curve. The lack of additional degree of freedom for moving the link connector with respect to the attachment point on cube created problems with the cone-shaped attachment mechanism. Our tests with the current hardware show that the cross-shaped attachment mechanism works better than the cone-shaped version. Error tolerance of the cross-shaped mechanism is significantly better.

5. EXPERIMENTS

The prototypes described in the previous section are used to test the feasibility of the system on a platform that incorporates horizontal and vertical attachment points. These tests are carried out to show that the links are capable of moving form one attachment point (i.e., cube face) to another. We also present the results of an experiment where two links interchange a cube with four attachment points. Our work toward populating the group with more links and cubes to create multi-cube multi-link demonstrations to our feasibility tests will continue.

Figure 13 shows a link that translates between three connection points. The command signals and power are currently external. A 6V 650mAh battery is used to power all three servos on the link, and the servos actuating attachment mechanisms on the platform as well as the microprocessors controlling these actuators. As seen in the series of pictures in Figure 13, the link attached to the horizontal faceplate rotates and moves to the faceplate on a vertical wall. After locking its free end to this vertical attachment point, the other end is detached and series of similar actions move the link to the second plate on the vertical wall. The link is then capable of transferring itself from one vertical connection point to another. This demonstration shows that the links are capable of transferring from one cube to another while the locking mechanism enables the links to attach to the cube faces.

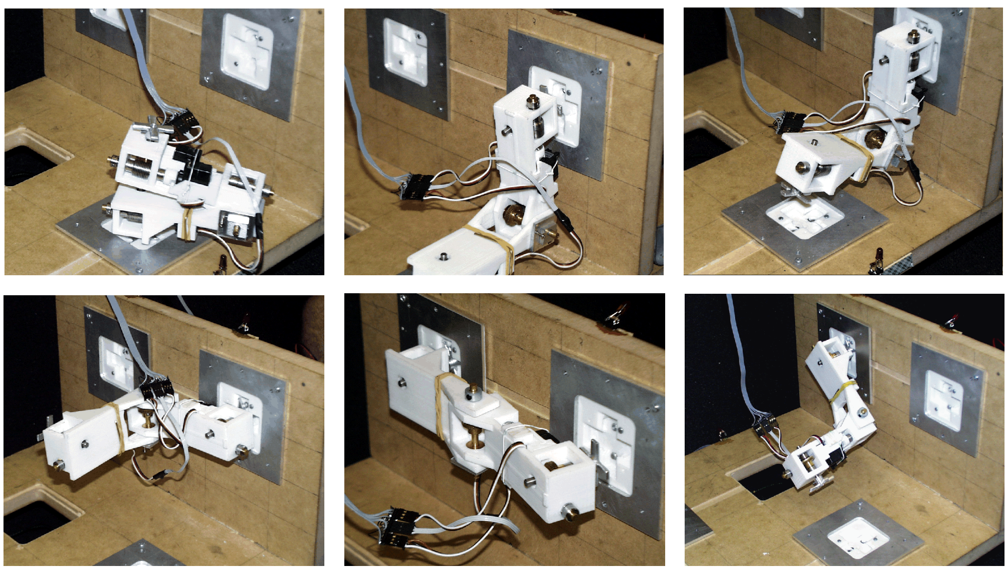


Figure 13. A link moving from horizontal attachment faces to vertical faces (image sequence left to right).

In Figure 14, two links and a cube with attachment points on four faces are shown. The control signals to the cube actuators are also external, i.e., all actuators are powered with a single 6V battery. As seen in Figure 14, the first link moves the cube to the correct position by a series of joint rotations. The cube is also rotated to reorient the attachment mechanism on the cube for the second link connector to attach. The second link then moves into position and attaches its free end to the cube face by rotating the cross-shaped connector in counterclockwise direction. The mechanism on the cube face is activated to lock the components. First link detaches from the cube with the reverse sequence of actions carried out by the second link, and the second link is now able to move the cube to the next position.

During our tests, cross-shaped attachment mechanism is found more suitable than cone-shaped mechanism for this specific application. Its shape and latching structure make this mechanism less prone to positioning errors due to the servo control input and buckling/bending of the link body. The link body and the cube faceplates are bending slightly because of the poor physical properties of the plastic material we used. However, these errors can be minimized by using materials with better physical properties and by supporting the cube faces and the link body with additional structures.

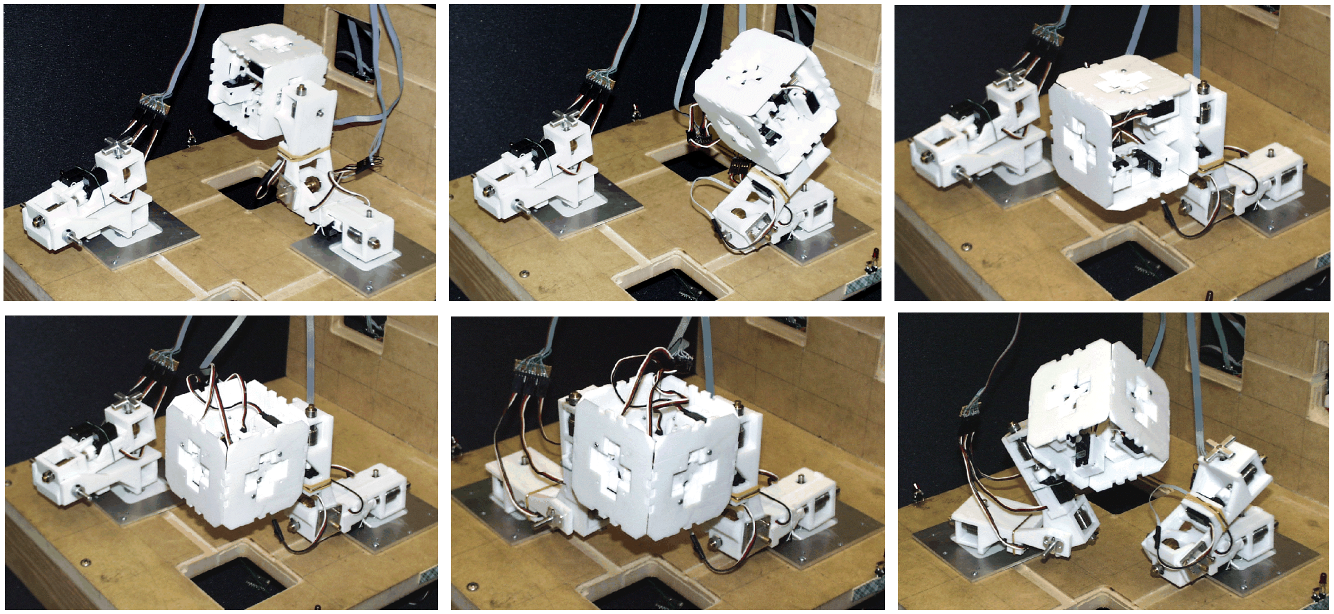


Figure 14. Two links transferring a 4-faced cube (image sequence left-to-right).

6. CONCLUSIONS AND DISCUSSION

In this manuscript, we have presented a new three-dimensional modular robotic system that is capable of reconfiguring itself in order to adapt to its environment. The system is designed with energy efficiency, feasibility and task-oriented robots in mind. We described the design of the passive and active elements, the attachment mechanisms, and several reconfiguration scenarios. Partitioning the system into two different modules provides an ability to change shape, combined with different and faster types of statically stable locomotion modes, as well as modules that can be geared toward a specific task.

There are several design issues that need to be addressed. The limitations on the approach angle of a link connector to a cube surface are found to be a common problem when combined with the physical characteristics of the current implementations of the cubes that are not robust under high weight/torque conditions. These cause additional problems in the attachment phase, which we hope to solve by using stronger plastic materials manufactured on CNC machines.

Currently, the links can be controlled by buttons or graphical interface on a PC connected to the microprocessor driving the servos. We plan to redesign the control circuitry and place it on the links and inside the cubes. Our plans also include incorporating encoders for the end joints and custom-made position feedback circuit for the middle joint of the links. Closing the loop at the microprocessor level would initially provide semi-autonomous motion control, opening the way to fully autonomous link/cube motion. We are currently trying to simplify the attachment mechanisms on the cubes for smaller and lighter cubes, and hope to remove the actuation servos from the cubes. Scaling the cubes and the links down will decrease the torque requirements on the actuators, and consequently the capacity requirements on on-board power resources. Besides the attachment mechanisms, custom designed mechanical components would be helpful in reducing the link size. We hope to use custom-made components to reduce the length L to 6 cm.

An interesting area of research that we are currently pursuing is path/motion planning for this 3-D reconfigurable system. Tests of a motion planning system are underway. We hope to combine the advantages of knowledge-based and learning/adaptive systems with straightforward search techniques to provide near-optimal solutions for given initial and final positions of a group of links and cubes. Although the motion examples given in Sections 4 and 5 include small groups of links and cubes, actual implementation of the system may render finding a suitable sequence of actions impossible. A relatively small numbers of modules would suffer from static or dynamical unstability during a sequence of actions. Specifically for a group of three links and three cubes, a solution may not exist. We hope to incorporate into our simulator a simple algorithm checking widely encountered positions and shapes for static feasibility using relative link and cube weights.

ACKNOWLEDGMENTS

This work is supported by DARPA/ETO under grant #DABT63-97-1-000, and by the Institute for Complex Engineered Systems. The authors would like to thank William F. Hein, Michael C. Lee, Michael Sergi, Ryan J. Thomas, Stephen M. Wolfe, and Zoe C. Woodworth for their valuable contributions on design, implementation and testing of the I-Cubes.

REFERECENCES

[1] Chen, I.-M., Theory and Application of Modular Reconfigurable Robotic Systems, Ph.D. Dissertation, Department of Mechanical Engineering, California Institute of Technology, 1994.

[2] Paredis, C.J.J., An Agent-Based Approach to the Design of Rapidly Deployable Fault Tolerant Manipulators, Ph.D. Dissertation, Carnegie Mellon University, Department of Electrical and Computer Engineering, Pittsburgh, PA, 1996.

[3]Navarro-Serment, L.E., R. Grabowski, C.J.J. Paredis, and P.K. Khosla, "Heterogeneous Teams of Modular Robots for Mapping and Exploration", Tech. Report, Institute for Complex Engineered Systems, Carnegie Mellon University, Pittsburgh, PA, 1999.

[4] Paredis, C.J.J., and P.K. Khosla, “Kinematic Design of Serial Link Manipulators from Task Specifi *International Journal of Robotic Research*, Vol. 12, no. 3, pp. 274-287,1993.

[5] Neville, B., and A. Sanderson, “Tetrabot Family Tree: Modular Synthesis of Kinematic Structures for Parallel Robotics,” *Proceedings of the IEEE/RSJ International Symposium of Robotics Research*, pp. 382-390, 1996.

[6] Fukuda, T., and Y. Kawauchi, “Cellular Robotic System (CEBOT) as One of the Realization of Self-Organizing Intelligent Universal Manipulator,” *Proceedings of the IEEE Conference on Robotics and Automation*, pp. 662-667, 1990.

[7] Kotay, K., and D. Rus, “Self-reconfigurable Robots for Navigation and Manipulation,” Proceedings of the International Symposium on Experimental Robots, 1997.

[8] Hokasawa, K., et. al., “Mechanisms for self-organizing robots which reconfigure in a vertical plane,” *Distributed Autonomous Robotic Systems 3*, T. Lueth, R. Dillmann, P.Dario, H. Wörn, editors, Springer-Verlag, 1998.

[9] Yoshida, E., et al, “Experiments of Self-Repairing Modular Machine,” *Distributed Autonomous Robotic Systems 3*, T. Lueth, R. Dillmann, P.Dario, H. Wörn, editors, Springer-Verlag, 1998.

[10] Pamecha, A., C.-J. Chiang, D.Stein, and G. Chiricjian, “Design and Implementation of Metamorphic Robots,” *Proc. of the 1996 ASME Design Engineering Technical Conf. and Computers in Engineering Conference.*, Irvine, CA, 1996.

[11] Yim, M., *Locomotion with Unit-Modular Reconfigurable Robot*, Ph.D. Dissertation, Department of Mechanical Engineering, Stanford University, 1994.

[12] Kotay, K. , D. Rus, M. Vona, and C. McGray, “The Self-reconfiguring Molecule: Design and Control Algorithms,” *Algorithmic Foundations of Robotics*, P. Agrawal, L. Kavraki, M. Mason, editors., A. K. Peters, 1998.

[13] Murata, S., H. Kurokawa, E. Yoshida, K. Tomita, and S, Kokaji, “A 3-D Self-Reconfigurable Structure,*” Proceedings of the 1998 IEEE Intl. Conference on Robotics and Automation*, pp. 432-439, 1998.