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DESIGN AND IMPLEMENTATION OF METAMORPHIC ROBOTS

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ABSTRACT

This paper discusses issues in the design and implementation of *metamorphic* robotic systems. A metamorphic robotic system is a collection of independently controlled mechatronic modules, each of which has the ability to connect, disconnect, and climb over adjacent modules. A metamorphic system can dynamically reconfigure by the locomotion of modules over their neighbors. Thus they can be viewed as a collection of connected modular robots which act together to perform the given task. The planar metamorphic robots described in this paper consist of hexagonal or square modules. Because of their shape, the modules completely fill the plane without any gaps, their centers forming a regular lattice. Both the hexagonal and square modules are provided with electromechanical coupling mechanisms actuated by D.C. motors. These connectors help to couple and uncouple modules as they move around each other to form different configurations. The modules are currently controlled by an external processor.

1 INTRODUCTION

A *metamorphic* robotic system [Ch94] is a collection of independently controlled mechatronic modules, each of which has the ability to connect, disconnect, and climb over adjacent modules. Each module allows power and information to flow through itself and to its neighbors. A change in the metamorphic robot morphology (i.e., a change in the relative location of modules within the collection) results from the locomotion of each module over its neighbors. Thus a metamorphic system has the ability to dynamically self-reconfigure.

Metamorphic systems can be viewed as a large swarm (or colony) of connected robots which collectively act as a single entity. What distinguishes metamorphic systems from other reconfigurable robots is that they possess all of the following properties:

1. All modules have the same physical structure, and each must have complete computational and communication functionality. This allows uniform treatment of modules in the planning problem.

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2. Symmetries in the mechanical structure of the modules must be such that they fill planar and spatial regions with minimal gaps. In this way, a lattice of modules is formed for any task.
3. The modules must have enough degrees of freedom to be able to 'walk' over adjacent modules so that they can reconfigure without outside help.
4. Modules must adhere to adjacent modules, e.g., there must be electromechanical or electromagnetic connectors between modules which can carry load. This causes the collection of modules to act as a single physical object.

Potential applications of metamorphic systems composed of a large number of modules include : (1) obstacle avoidance in highly constrained and unstructured environments; (2) 'growing' structures composed of modules to form bridges, buttresses, and other civil structures in times of emergency; (3) envelopment of objects, such as recovering satellites from space; (4) Performing inspections in constrained environments such as nuclear reactors. Some of these applications are shown in Figure 1.

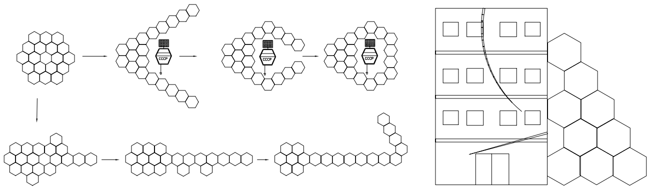

Figure 1. Examples of Metamorphic Robot Applications

This paper discusses issues in the design of two different planar modules. Section 2 contains a brief literature review. In Section 3 the basic design of planar hexagonal modules and their locomotion process is discussed. One of the most important aspects of the above design is the connector mechanism. The connector not only has to adhere to the adjacent module but also has to allow sliding motion of the links. In addition it should be a passive or a quasi-passive mechanism so as to use minimum power i.e, once it has coupled or uncoupled the modules, it should require no power to maintain the connection. This paper describes one such *error-tolerant* coupling mechanism design for hexagonal modules, i.e the coupling mechanism can take into account wide variations in connector position on the mating link. Section 4 describes some alternatives in the design of couplings for hexagonal modules and discusses the design and implementation of an error-tolerant connector mechanism satisfying the above conditions. In Section 5 the basic design of planar square modules and their locomotion process is discussed. One important aspect of such design is that the centers of the square modules form a Cartesian lattice, thus can be easily extended to spatial case with a cubic module design. Section 6 presents the conclusions.

2 LITERATURE REVIEW

The idea of a metamorphic robotic system differs from related concepts presented in the literature. Three types of modular reconfigurable robotic systems have been proposed in the literature: (1) robots in which modules are reconfigured using external intervention, e.g., [BeZL89, CoLDB92, Sci85, Wu86]; (2) cellular robotic systems in which a heterogeneous collection of independent specialized modules are coordinated, e.g., [Be88, BeW91, FuN88, FuK90]; (3) swarm intelligence in which there are generally no physical connections between modules, e.g., [HaB91]. Most recently, two other types of modular reconfigurable robotic systems have been considered. [Yim93,Yim94] considered modular robots composed of a few basic elements which can be composed into complex systems, and used for various modes of locomotion. [MuKK94, MuKK95] considered a 'fractal' system composed of modules with zero kinematic mobility, but which can 'walk' over each other in discrete quanta due to changes in the polarity of magnetic fields.

In the present work, where the design of a mechanically error tolerant coupling mechanism is also important, another body of literature is relevant. Namely, work that deals with the mechanics of pushing and friction and work that uses geometric and physical constraints to guarantee desired performance with minimal numbers of crude sensors, e.g., [AkM92, CaG94, ErM88, Ma93, PeS89, PeBG93]. By using this 'minimalist' philosophy, we have developed a coupling device for metamorphic robots that requires no sensors and has a geometry that allows for significant errors. This is important because a metamorphic robotic system may frequently need to reconfigure, and so the connection between modules must be reliable.

The motion planning problem of a metamorphic robot has been previouly discussed by [Ch94, PECh95]. [SMCh93] consider the motion of planar hexagonal metamorphic modules using 'local' constraints and describe the performance of various algorithms under these constraints.

3 BASIC DESIGN AND LOCOMOTION OF HEXAGONAL MODULES

This section describes the design of planar hexagonal modules and the locomotion process of the modules.

3.1 Module Design

Section 1 described the four important properties of metamorphic robots. One of the designs which satisfies all those properties in the planar case involves the use of hexagonal modules. Each module, as shown in Figure 2, consists of six links of equal length forming a six bar linkage.

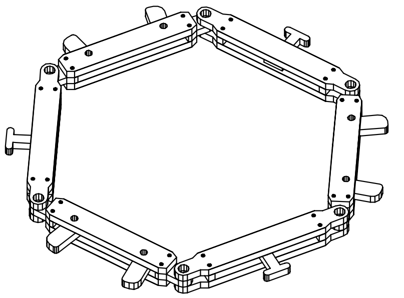

Figure 2. Design of a planar hexagonal module.

Because of the hexagonal shape, the modules completely fill the plane without any gaps. The centers of the hexagonal modules form a regular lattice and thus each module can be treated as part of a lattice structure. Each hexagonal module can be viewed as a closed six bar linkage with three degrees of freedom which are controlled by placing actuators at alternate joints of the module. This enables each module to move around another while remaining connected at all times during this motion. The modules are provided with electromechanical connectors or coupling mechanism actuated by D.C. motors. The connectors serve the important purposes of coupling adjacent modules, facilitating power and information flow and allowing sliding motion of links to enable the module to reconfigure. In addition, they have to be passive or quasi-passive mechanisms and error tolerant to take into account variation in module position. Each module carries male and female connectors or different polarities on alternate links. Because of the symmetry of the module, male connectors always meet female connectors and vice-versa as illustrated in Figure 3. In addition this symmetry is maintained over the entire structure, i.e. the adjacent links on the boundary of the collection of all modules are of different types or of different polarities. The connector mechanism is one of the most important aspect of module design and is explained in greater detail in Section 4.

Each module must also contain a microprocessor which controls the link actuators and the connector motors making the module computationally self-contained. However, presently the modules are controlled by an external motorola 68HC11 controller which determines the direction of motion and issues signals to the actuators. It is also assumed that eventually power and information between modules will be transmitted through the coupling mechanism.

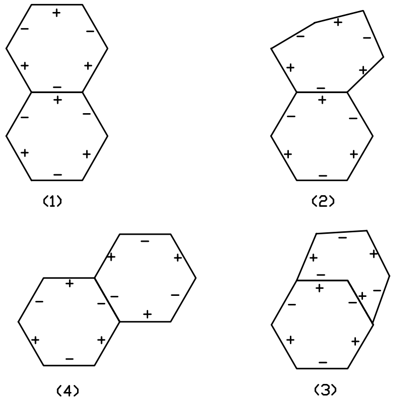

Figure 3. Polarity matching in the reconfiguration of metamorphic robot.

3.2 The Locomotion Process

There are three ways to view the macroscopic motion of the modules of a metamorphic robot: (a) Single module motion, which involves the motion of one, and only one, module per time step from one lattice point to another; (b) Motion involving two or more modules, moving together or separately at each time step; (c) *Fixed morphology* motion in which the connection between the modules remains the same, and a change in configuration occurs by changing the joint angles of the modules. The present work discusses issues involving the first type of motion (single module motion).

The reconfiguration of metamorphic robots with single module motion takes place by the locomotion of modules around each other while remaining connected to each other at all times. This can also be described as the 'rolling' of one module over others. Figure 4 illustrates the locomotion procedure. Observe that the module which is moving remains connected to the other module during the entire process. For clarity, let's define the module which is moving at a given time to be *mobile* and the module over which it moves to be *fixed*. The motion of the *mobile* module is achieved by controlling the three degrees of freedom of the module by three actuators on alternate joints. For a detailed description of the kinematics of the mechanism and how joint angles are altered see [Ch94].

Any implementation of the locomotion process described above in practice has problems because of the finite thickness of the links. Due to the finite thickness, the axes of rotation of the joints of two mating links are not

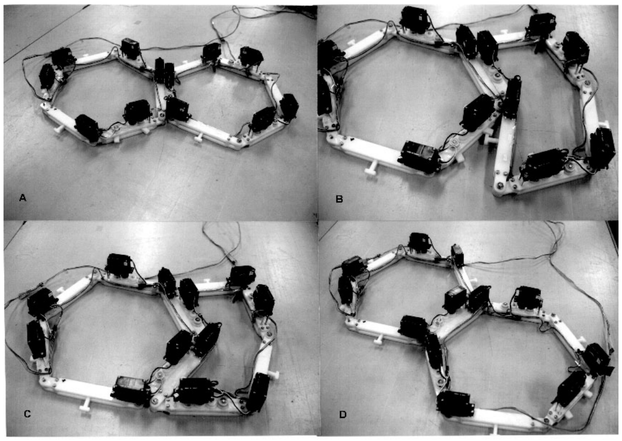

Figure 4. The locomotion of one module around another. One of the links of the *mobile* module always remains connected to the *fixed* module.

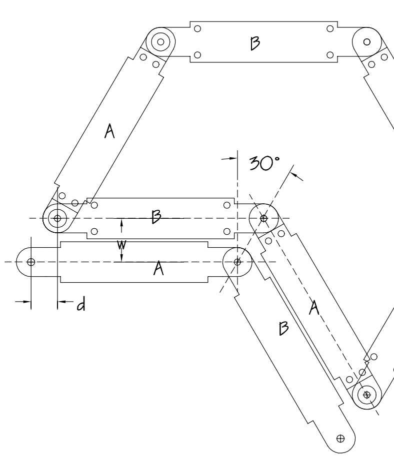

Figure 5. Displacement between the links due to finite link thickness

coincident. As a result, when a module moves around the other, the links in the new position are not aligned. For an illustration of this see Figure 5. The displacement (d) between the two links is a function of the width (w) of the links and is given as $d = w \tan\theta$ where θ is 30^o. This can be derived very simply by observing the module geometry in Figure 5. If this displacement or misalignment is not eliminated, the next motion of the module in the same direction cannot take place. Another problem due to this misalignment and due to the possibility of motion in both clockwise and counterclockwise directions is that the connectors on the two opposite links do not meet at an exact point on the links, i.e. the connectors themselves get displaced with respect to each other.

An alternative strategy for motion is one in which the *fixed* and the *mobile* modules move together so that the old connection and the new one are parallel to the mating links, i.e. each of the two mating links moves by 60^o towards each other instead of the link of the *mobile* module moving by 120^o. This ensures proper alignment but requires a coordinated simultaneous movement of other modules in the structure.

The above argument indicates that the locomotion procedure of modules warrants a mechanism that somehow removes the displacement between the links. Also, since the connectors do not meet at the same position relative to the links, an error tolerant connector mechanism is required. The next section discusses some of the alternatives which overcome the above problems.

4 DESIGN OF CONNECTOR MECHANISM

As described in the previous section, the locomotion of modules necessitates the use of an error tolerant connector design which also aligns the mating links of the modules. A number of possible designs can satisfy the above requirements. This section first describes some of the possible alternatives and then describes the design actually used for overcoming the limitations of the earlier designs.

4.1 Alternatives in Connector Design

One alternative for module locomotion is to make the links extensible, i.e. the links can contract or expand relative to their normal length. In this case the mating link on the *mobile* module extends (Figure 6, step 1) aligning itself to the link of the *fixed* module (Figure 6, step 2), locks in, releases the old connection and contracts to regain the normal shape (Figure 6, step 3). The obvious problem with this method is that it needs an actuator for each link to extend or contract in addition to the actuators required for the motion of the joints and for locking unlocking of connectors.

Another approach which tries to solve the two problems is one in which the connector is a spring loaded mechanism which aligns the two links together. For an illustration of this see Figure 7. The connector on the link of the *mobile* module slides into a wedge shaped connector on the opposing link by compressing the spring. The relative compression and extension of the springs on the links is given by the minimization of the strain energy function associated with the springs. When the old connection gets released the spring aligns the entire module to normal position. The problem with this method is that for moving the entire module once the old connection gets released, a stiff spring is required which in turn requires a high torque actuator to act on it in the first place. As a result this design is difficult

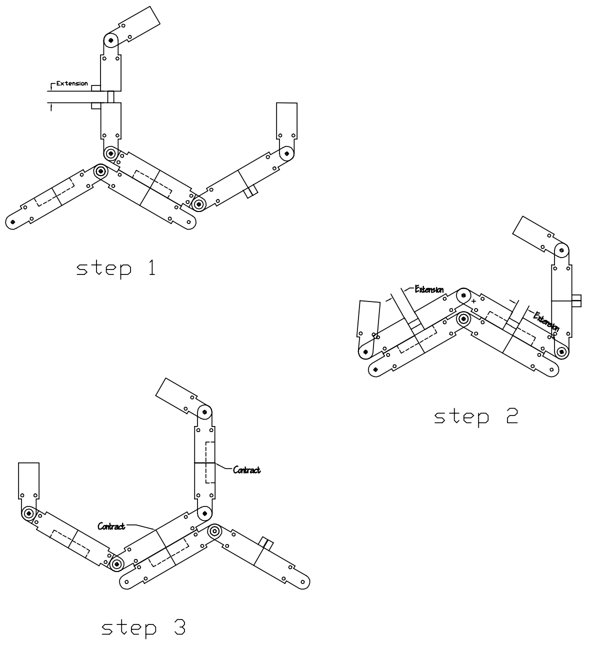

Figure 6. Motion involving link extension and contraction.

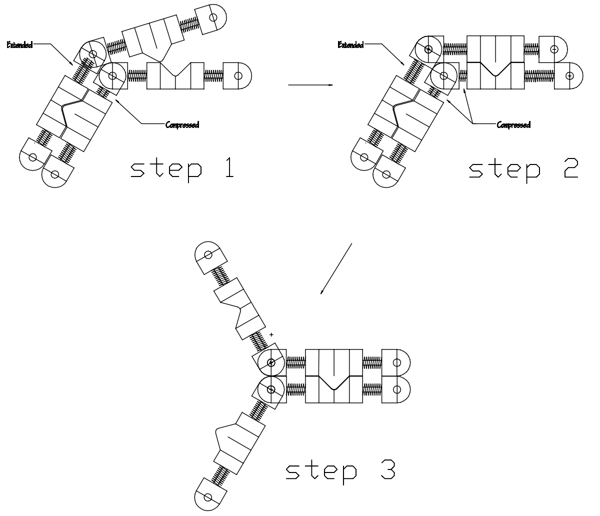

Figure 7. The spring loaded connector shown for two links from each module.

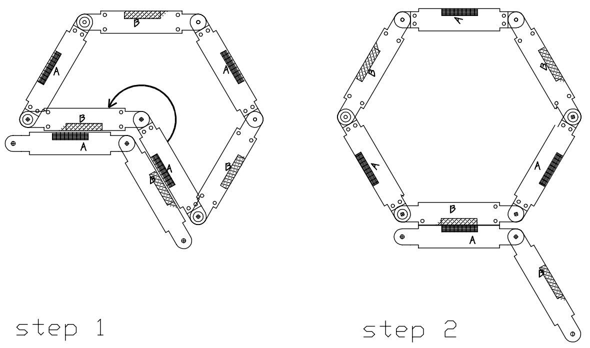

Figure 8. Module motion using electromagnetic coupling.

to implement and increases the power requirement.

Yet another option is to use electromagenetic connectors which serve the dual purpose of aligning the two mating links and connecting the two modules. One design employing such a method is shown in Figure 8. Each link has an electromagnet as a connector. When the old connection is released (by repulsing the electromagnets forming the connection), the electromagnets align the links completely due to magnetic force. The rigid connection between the modules is provided by the magnetic force between the two connectors . A similar scheme has been used by [MuKK94, MuKK95] in the development of self-assembling machines or 'fracta'. The problem with this approach is that connection between different modules are active instead of passive. This means that a large amount of power for the electromagnets is required at all times to keep the modules connected.

4.2 Error Tolerant Coupling Mechanism

The design used for the current modules consist of an error tolerant connector which tries to overcome the limitations of the above designs while providing proper alignment and a passive connection between the modules. The mechanism takes into account the finite link thickness and helps in carrying out the motion as described in Section 3.

The coupling mechanism consists of two different types of connectors, referred to as *male* and *female*. Let's define the link carrying the *male* connector as link A and the one carrying the *female* connector as link B. See Figures 9 and 10.

Link A consists of two parallel plates with space in between. The space carries a T-shaped protrusion mounted on a sliding mechanism. The protrusion is held in place by two springs, one on each side (see Figure 9). As a result, when force is applied to the protrusion, it can slide sideways by compressing the springs.

Link B also consists of two parallel plates with space in between. The space carries two cams, able to rotate 120^o about their axes. The cam dimensions are such that when they move in, they completely lock the protrusion on the corresponding link of the other module. The locking of the protrusion by the cams prevents any lateral movement while the T-shaped structure of the protrusion stops any longitudinal movement. The cams are operated in unison by a single actuator (a small DC motor in our case) which is connected to the cams by a set of 4 gears as shown in Figure

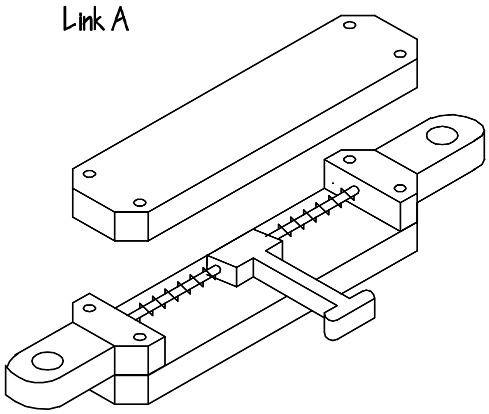

Figure 9. Semi-exploded view of link A showing the spring loaded protrusion.

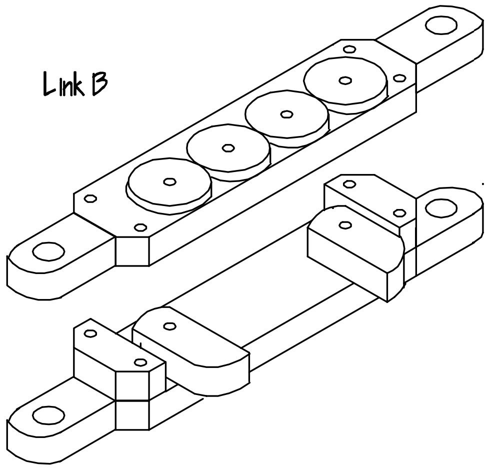

Figure 10. Semi-exploded view of link B showing the double cam mechanism. Shown here without the actuator

10. As a result the cams open and close simultaneously.

The motion sequence utilizing this mechanism is shown in Figure 11, steps 1 to 4. Step 1 shows the original position of the two adjacent modules, one of which is about to move around the other. In step 2 link A1 of the *mobile* module moves towards link B2 without displacing link B1. In step 3 this motion is continued, but as link A1 moves into B2, it slides the connector on link A2 by compressing one of the springs. As a result, link B1 gets displaced from its original position and shifts sideways. The cams on B2 now close in, aligning link A1 parallel to B2. This results in the connector on A1 getting displaced from it's mean position and one of the springs getting compressed. In step 4 the cams on link B1 open up, releasing the connector on A2. B1 then rotates by 120^o and the structure attains the configuration shown in the figure corresponding to step 4. The compressed spring on A1 now aligns link A1 and B2 completely. This completes one move of the module.

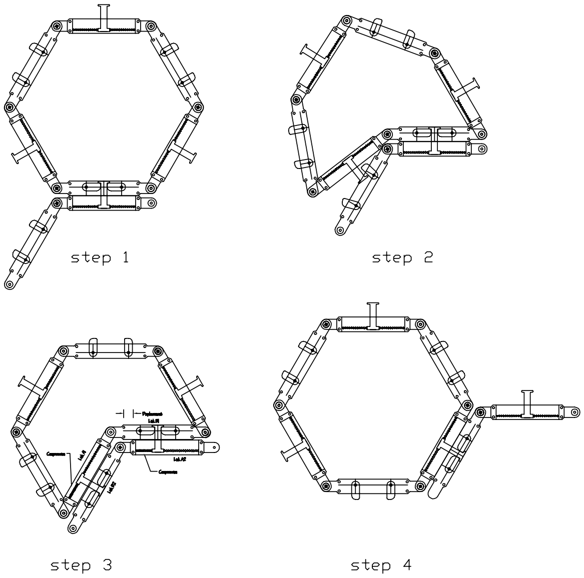

Figure 11. Motion sequence demonstrating action of the error tolerant coupling mechanism.

As can be seen, only one actuator is needed for each coupling mechanism i.e. one actuator for every two links of the module. The links are aligned exactly by the use of springs on alternate links. A large space is available between the cams(in their open position), as a result the protrusion or the connector on the opposing link can mate from both directions and need not mate at an exact position, i.e. the coupling mechanism is *error tolerant*. Another advantage of the above design is that the locking mechanism is passive in the stationary state and so uses very little power.

A working prototype using the above design is shown in Figure 4. For a video of the locomotion process involving error tolerant connectors, see [PCh95].

5 BASIC DESIGN AND LOCOMOTION OF SQUARE MODULES

This section describes the design of square modules and the locomotion process of the modules.

5.1 Module Design

Another design which satisfies all the properties mentioned in Section 1 involves the use of square modules. The square modules can completely fill the plane without any gaps as do the hexagonal modules. The centers of the square modules form a Cartesian lattice and each module can be viewed as part of a lattice structure. The fact that the centers of the square modules form a Cartesian lattice is important since we can easily adapt this concept and expand it into spatial case with a cubic module design. Unlike a hexagonal module, which has the required kinematic degrees of freedom to 'roll' over neighboring modules by changing its joint angles, a square module needs connecting mechanisms to couple adjacent modules and enable the module to 'walk' over neighboring modules by sliding.

Each module, as shown in Figure 12, carries male or female connectors, or different polarities, on each of its edges. Because of the symmetry of the modules, the locomotion always results in edges with opposite polarity or male/female connectors meeting with each other. This symmetry is maintained over the entire structure as illustrated in Figure 13.

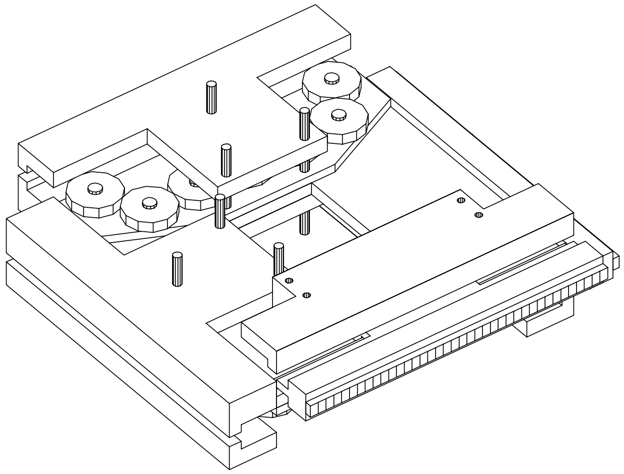

Figure 12. The mechanical structure of a square module

Figures 14 and 15 are semi-exploded views of the male and female connectors respectively.

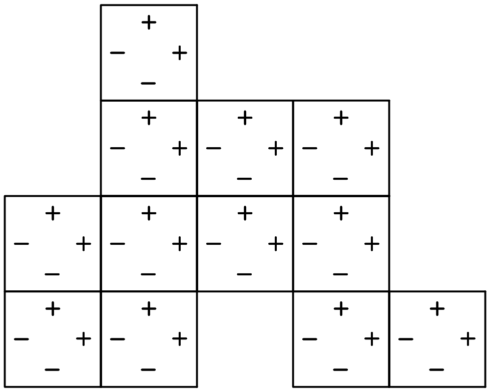

Figure 13. Polarity matching in the robot

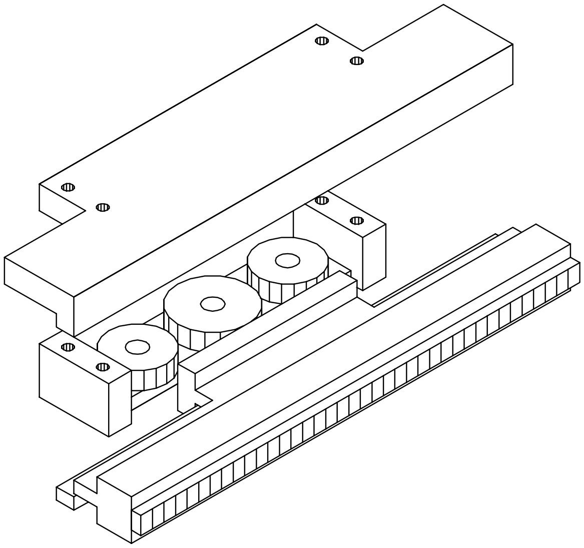

Figure 14. Male connector and the shuttle

The male connector consists of two parallel plates with space in between. There are one driving gear and two rollers mounted on the bottom plate. An H-shaped mating link called the *shuttle* with racks attached to both sides are to be driven by the driving gear. The shuttle will remain connected to the male connector while sliding back and forth in the rails formed by the tracks of both male and female connectors.

The female connector consists of three parallel plates with seven gears mounted on the middle plate. The two outermost gears mesh with the rack of the shuttle of its neighboring male connector. One of these two gears will be actuated by a D.C. motor and serves as a driving gear for the female connector. The top and bottom plates, called the *jaws*, can slide open or close along three guiding rods perpendicular to the plates. This opening and closing jaw movement is actuated by a D.C. motor. The jaws are to remain closed (see Figure 16) unless there is another module coming from the direction perpendicular to the edge of the female connector. In that case, we have to open the jaws (see Figure 17) so that the shuttle of the incoming module can come in. The shuttle will be locked in position when the jaws close, thus completing the mating process.

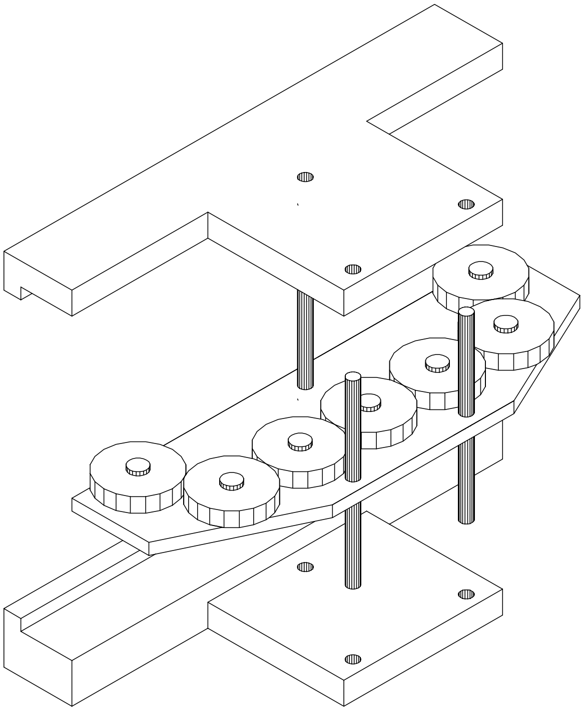

Figure 15. Female connector

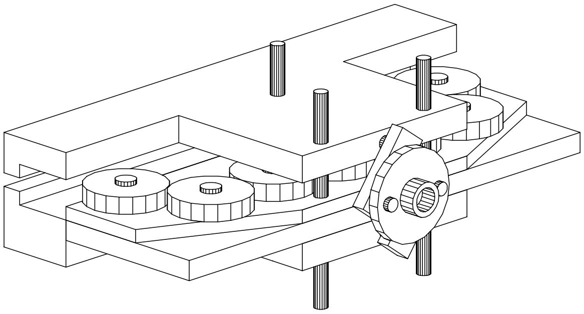

Figure 16. Closed position for the jaws

In the case of releasing the connection, we have to follow the above sequence in reverse order. A total of six D.C. motors are needed in a single module, two each for operating the driving gears in the male connectors, the driving gears in the female connectors, and the jaws opening/closing mechanisms. There should be some offset distance between the connectors along the vertical and horizontal directions to avoid the shuttle interference. This will be discussed in more detail in the next subsection.

5.2 The Locomotion Process

The reconfiguration of metamorphic robots with square modules takes place by the locomotion of modules around each other while remaining connected to each other at all times. There are two types of such 'sliding' motion: (a) Vertical or horizontal motion, which involves the motion of a mobile module in the vertical or horizontal direction; (b) Diagonal motion, which involves the motion of a moving module in the diagonal direction.

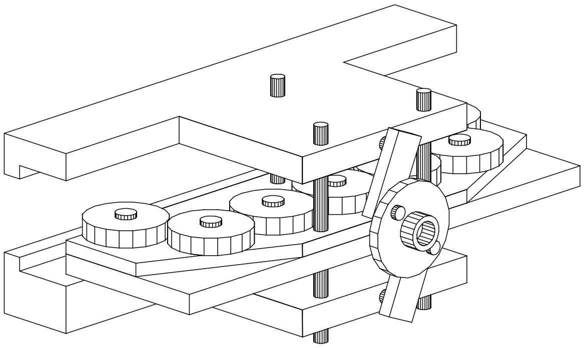

Figure 17. Open position for the jaws

The locomotion procedure for vertical or horizontal motion is first to identify the mating pair of connectors and actuate the driving gear of the female connector to move the module in the desired direction. Once the mobile module is making the initial connection with the new neighboring module, the driving gear of the female connector in the new mating pair of connectors is actuated until the mobile module reached the designated position.

The motion sequence demonstrating the locomotion procedure for diagonal motion is shown in Figure 18, steps 1 to 5. Step 1 shows the original position of the two adjacent modules, the left one, the mobile module, is about to move to its diagonal direction to the top of the fixed module. In step 2 the driving gear of the female connector drives the mobile module halfway up then the driving gear of the male connector takes over and moves the mobile module one full module distance up. In step 3 the driving gear of the male connector in the mobile module slides the shuttle one half of a module distance to the right to make connection with the female connector for the fixed module. In step 4 the connection between the first pair of connectors releases and the shuttle moves back up to its normal position. In step 5 the driving gear for the male connector brings the shuttle back to its normal position while the driving gear for the female connector moves the mobile module further right to the final position. This completes one diagonal move of the module.

A prototype using the above design is shown in Figure 19. A stamp-sized Basic microprocessor is used for each module to control the motion sequence.

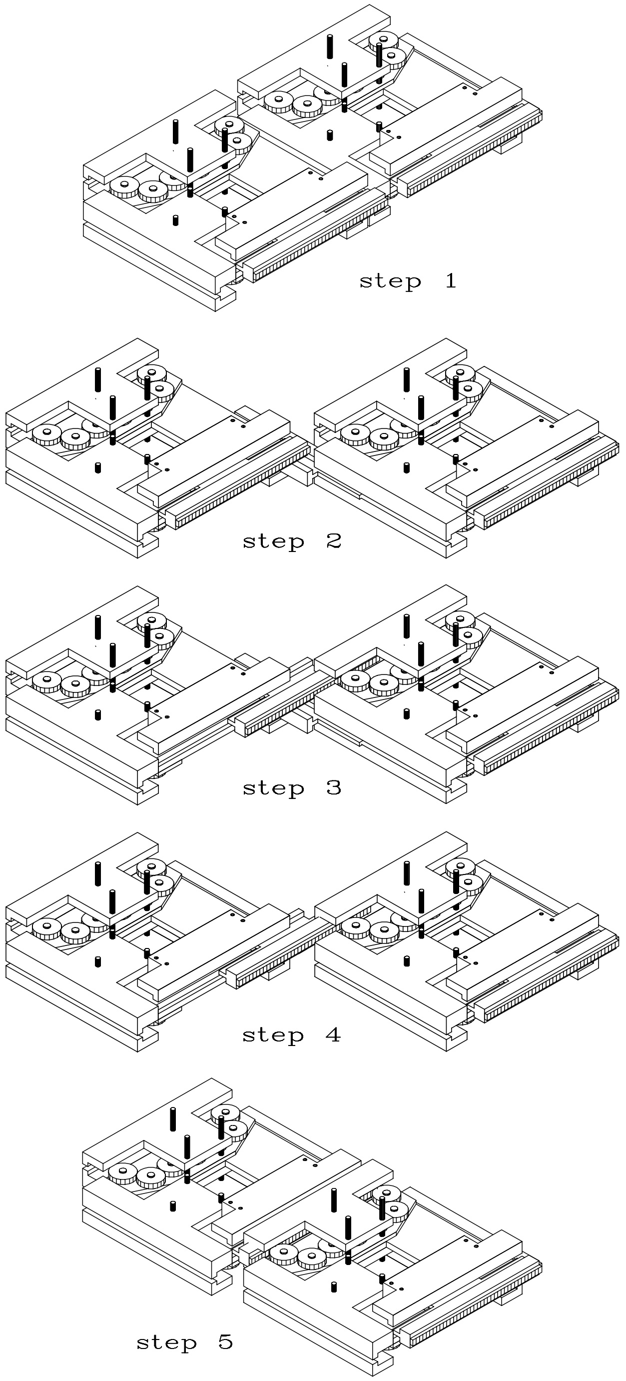

Figure 18. Motion sequence demonstrating the diagonal transformation

6 CONCLUSION

In this paper we described the design and implementation of metamorphic robots consisting of planar hexagonal or square modules. One of the most important issues in the design of such modules is the coupling mechanism. In the hexagonal module design, an error tolerant coupling mechanism was discussed and the resulting locomotion process demonstrated. In the square module design, a coupling mechanism consisting of a shuttle and male/female connectors was discussed and the resulting locomotion process demonstrated.

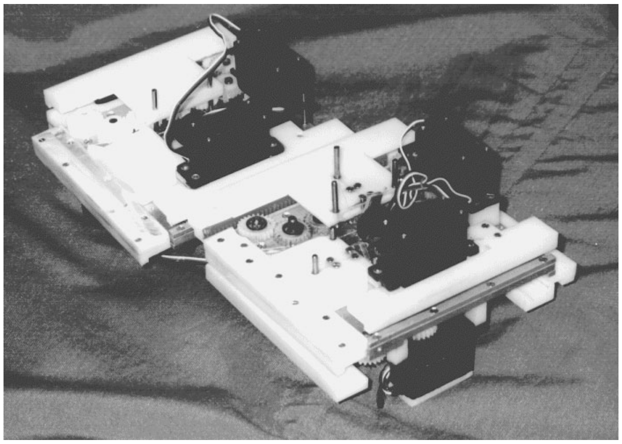

Figure 19. Hardware illustration of two mating square modules

7 ACKNOWLEDGEMENTS

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