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Metamorphic Hyper-Redundant Manipulators

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Abstract

A *metamorphic* manipulator is a collection of mechatronic modules, each of which has the ability to connect, disconnect, and climb over adjacent modules. A change in the macroscopic manipulator morphology results from the locomotion of each module over its neighbors. That is, a metamorphic manipulator can dynamically self-reconfigure. The word *hyper-redundant* describes manipulators which have a very large number of actuatable degrees of freedom. Metamorphic hyper-redundant manipulators can therefore be viewed as a large swarm of physically connected robotic modules which collectively act as a single entity. In this paper, issues in the design and motion planning of these manipulators are addressed.

1 Introduction

A *metamorphic manipulator* 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 manipulator 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 manipulator has the ability to dynamically self-reconfigure. Changes in configuration within a given morphology are achieved by changing joint angles, as is the case for standard (fixed-morphology) manipulators.

The word *hyper-redundant* describes manipulators which have a very large number of actuatable degrees of freedom [ChB91, Ch92, ChB93, Ch93ab]. Metamorphic hyper-redundant manipulators can therefore be viewed as a large swarm (or colony) of connected robots which collectively act as a single entity. What separates metamorphic hyper-redundant manipulators from other reconfigurable robots is that they possess all of the following properties: (1) self-reconfigurability without outside help; (2) a large number of modules (in the limiting case the configuration can be thought to approximate a continuous 'blob'); (3) physical constraints are required to ensure contact between modules; (4) uniformity and completeness of module function. The fourth condition is enforced in this work, though this condition need not be an integral part of the definition of metamorphic manipulators.

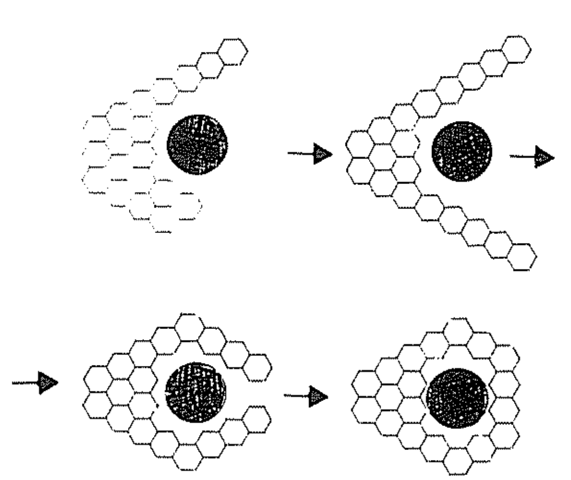

Figure 1: Recovering A Satellite from Space

This paper addresses issues in the mechatronic design and motion planning of metamorphic hyper-redundant manipulators. Mechatronics is at the core of these issues because mechanical, electrical, and computer technologies must be integrated during the development of a functional metamorphic hyper-redundant manipulator.

Applications of metamorphic hyper-redundant manipulators 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. Application (3) is shown in Figure 1. At the level of micro-machines, one could imagine such robots being used to provide structural reinforcement in the organs of the human body, or to surround and isolate tumors.

This paper is organized as follows. In Section 2, a brief review of the related literature is presented. In Section 3, the mechanical design of a planar three degree-of-freedom module is explained. These modules are each kinematically sufficient, which allows them the freedom to 'walk' over each other. Section 4 discusses the use of inductive power connectors between modules to provide an elegant and fault tolerant way of transmitting power and providing proximity detection. In Section 5, the motion planning problem is addressed. This is achieved by developing a hierarchy of rules which govern and coordinate the motion of modules. Sections 6 and 7 are respectively the conclusion and references.

2 Literature Review

The idea of a metamorphic hyper-redundant manipulator differs from related concepts presented in the literature. The word hyper-redundant has been used by the author to describe very high degree-of-freedom 'snakelike' manipulators in the past [Ch92, Ch93ab]. In this paper, the definition of hyper-redundancy is generalized to include any highly redundant morphology

Three types of modular reconfigurable robotics systems have been proposed in the literature: (1) robots in which modules are reconfigured using external intervention [BeZL89, CoLDB92, KeK88, Sci85, W86]; (2) cellular robotic systems in which a heterogeneous collection of independent specialized modules are coordinated [Be88, BeW91, FuN88, FuK90, FuKH91, HaW88]; (3) swarm intelligence in which there are generally no physical connections between modules [HaB92, HaB91, AsOJMIE91]. The concept of a metamorphic manipulator differs from all of the above because modules are homogeneous in form and function, contact between modules must always occur, and self-reconfiguration is possible.

As the number of modules in a metamorphic hyper-redundant manipulator becomes large, the manipulator could be viewed as a 'mechatronic amoeba' [Je73, Sch20, Bo67] (see Figure 2) because the manipulator takes on a continuous appearance. Figure 3 shows how a slime mold can reconfigure itself. Thus, the idea of metamorphic structures is not foreign to the natural world.

The next section discussed issues in the mechanical design of a particular metamorphic module.

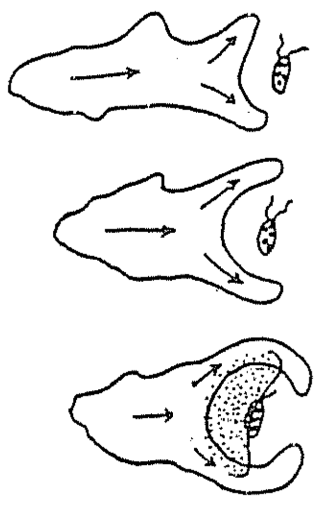

Figure 2: An Amoeba Grabbing Lunch (After [Sch20])

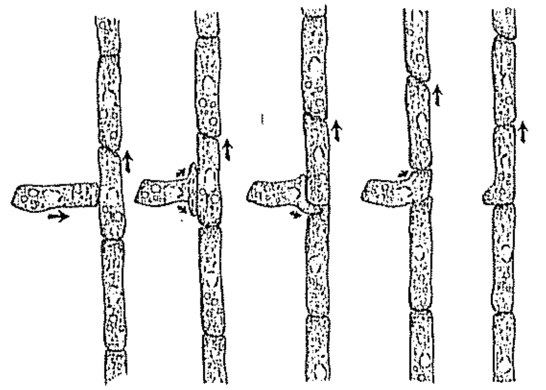

Figure 3: A Reconfiguring Slime Mold (After [Bo67])

3 Mechanical Design of Modules

This section addresses issues in the mechanical design of planar mechatronic modules used as components of a metamorphic manipulator.

The first step in the design of metamorphic manipulators is to ennumerate general properties which all such manipulators should have. Of course, many additional properties will depend on particular application domains in which the manipulator is expected to operate. However, only the most intrinsic, or core, properties to the idea of metamorphic manipulators are considered here. These are:

1. All modules should have the same physical structure, so that uniform treatment of modules in the planning problem is possible.

2. Symmetries in the mechanical structure of the modules must be such that they can be easily 'close-packed' ,i.e., fill planar and spatial regions without gaps. In this way, a lattice of modules is formed for any task.

3. The modules must each be kinematically sufficient with respect to the task of locomotion, i.e., they must have enough degrees of freedom to be able to 'walk' over adjacent modules.

4. A means by which modules are made to adhere to adjacent modules must be devised. In this way the collection of modules becomes a single physical object.

While an infinite variety of module designs satisfy the above conditions, one particular class is discussed here. These are closed-loop mechanisms.

In order to satisfy condition (1) above, regular polygonal module designs were chosen, i.e., closed loop mechanisms with uniform link lengths. In this way, the modules are not only uniform, but also possess a multiplicity of rotational symmetries. Condition (2) then reduced to finding what regular polygons close-pack the plane. This became a choice between the triangle, square, and hexagon, i.e., three, four, or six bar linkages. Since the triangle has zero mobility, condition (3) could only be satisfied with a square or hex. The hex was finally chosen, because its three degrees of mobility are superior for locomotion. Condition (4) is satisfied by specifying that alternating links in the hex have opposite 'polarity,' i.e., male/female connectors, magnetic fields of opposite signs, etc. It is assumed that locomotion of the module is implemented by a combined rigid body rotation and shape transformation produced by changing module joint angles. The resulting 'rolling' type of locomotion is shown in Figure

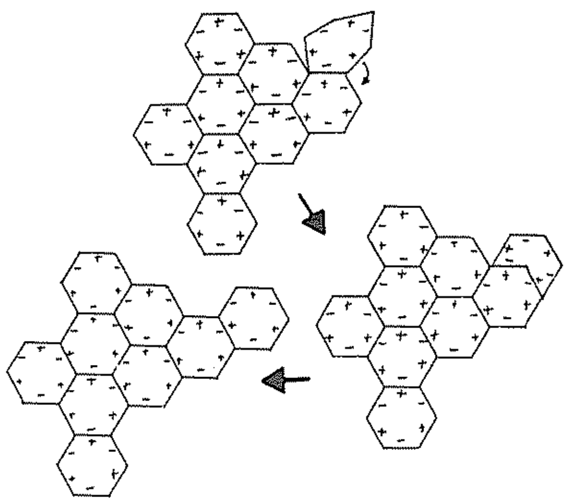

Figure 4: Locomotion of a Module

4 along with the alternating polarity links. In this way, as a given hexagonal module locomotes over a collection of other modules, opposite signs will always be in contact. Polarity matching is ensured since each module has an even number of links and the boundary of any collection of modules will also have alternating polarities.

Because the six bar linkage design has three degrees of mobility, three motors are required to specify the module geometry completely. This is accomplished by placing motors at alternating vertices. This also makes for a design with nice symmetries.

The fact that the links of each module have finite thickness must also be taken into account. Two ways to do this are: (1) as a module moves over a 'terrain' composed of other modules, the terrain can flex so as to ensure matching of module connectors; (2) the module links can be designed to be extensible, i.e., they can expand or contract relative to their nominal length, so that they can conform to rigid hexes composing the terrain.

It is important to note that the hexagonal design is by no means the only acceptable module design consistent with the specified conditions. However, it provides a simple and elegant vehicle by which the concept of metamorphic manipulators can be further investigated.

4 Power Transmission

In this section, it is shown how inductive power connectors between modules provide an elegant and fault tolerant way of transmitting power, enhancing connector self-alignment, and providing proximity detection.

Inductive power transmission is based on the phenomena that an alternating electric current produces an alternating magnetic field, which in turn can be used to produce a secondary alternating current.

Inductive power transmission is commonly accomplished by using a transformer (see Figure 5). A power transformer is an electromagnetic component consisting of an iron core and two sets of wire windings (called primary and secondary windings). An alternating current in the primary winding induces an alternating current in the secondary winding. Design and analysis of transformers can be found in any of a number of texts on electromagnetism and power transmission, e.g. [BrH84].

The method of inter-module power transmission advocated here for metamorphic manipulators uses connectors which are embedded in each link. These connectors are each equivalent to half of a transformer. The dashed line in Figure 5 represents the interface between the inductive power

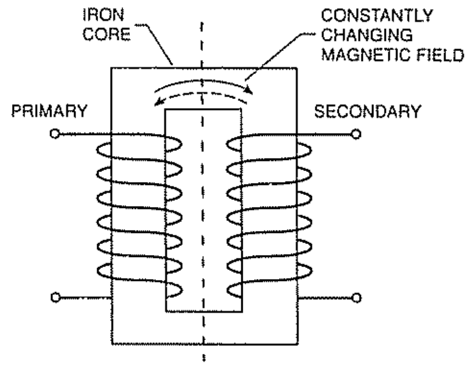

Figure 5: A Transformer (After [Li91])

connectors of two modules of this type. When links from one module contact with those of adjacent modules, a full transformer is formed. This transformer allows power to flow throughout the whole manipulator.

In designing a metamorphic manipulator, inductive power transmission has some very attractive features. Namely:

- Modules are electrically isolated from each other, and from the environment.
- The power connector provides a means by which modules automatically attach and stick to each other. Thus, a minimal number of moving mechanical components are needed for each module because physical connection of modules is made via electromagnetic coupling.
- The fact that electromagnetic forces tend to develop in such a way as to cause displacements (translation or rotation) which reduce the reluctance in a magnetic circuit can be exploited to enhance self alignment of modules.
- For modules with links facing the 'outside world' the inductive power connectors serve the dual use as close range proximity sensors.

Of course, connectors of this kind are not flawless. If there is air, or some kind of contaminant (dirt) which prevents two connectors from forming a good contact, then the effective magnetic permeability of the transformer core formed by proximal connectors will be reduced, and the efficiency of the power transmission would then be reduced. If such a reduction occurs in several locations throughout the metamorphic manipulator structure, severe limitations on the number of modules which can receive power will result. However, such adverse conditions would likely cause trouble for any kind of inter-module connector, especially one with many moving parts.

5 Motion Planning

In this section, the motion planning problem is addressed for the particular problem of using a metamorphic robotic system to form a bridge between two hubs. This is achieved by developing a hierarchy of rules which govern and coordinate the motion of modules. In this way, module motions are automatically linked with the task, and rules provide the 'glue' which links them together. Similar ideas have been developed by other authors, e.g., [WaB88], but those methods were not applied to metamorphic manipulators or to the current task.

In order to define laws by which metamorphic manipulator modules are to coordinate their motions, it is first necessary to define some new vocabulary:

(lattice) spaces - The plane can be decomposed into hexagonal units. These units are either filled by modules or hubs (see definition below) or remain empty. The whole plane is then viewed as a lattice of hexagonal spaces which are either empty or filled.

timestep - The unit of time required for a single module to leave its current space and fill one of the empty adjacent spaces.

hub - A solid object which completely fills one or more spaces, and has the ability to connect to modules.

An example of a set of consistent (and intuitive) rules for building a bridge between two hubs is given below:

- The number of modules is conserved.
- No more than one module may move from space to space per timestep.
- Modules can only move into spaces which are not already occupied by hubs or other modules.
- Every module must remain connected to at least one other module or hub, and at least one of the modules must stay connected to the hub from which the collection of modules originated.
- The morphology of the collection of modules will change in order to extremize a configuration based on given cost criteria.

Figure 6 shows the evolution of modules from an initial configuration to a final stable solution. The following cost calculation is used: Modules closest to the second hub (which is denoted by the number 72 in the figure) 'feel' the greatest impetus to move to an adjacent free space in the lattice of hexes with lower 'energy.' Energy is simply the distance between the second hub and a given space.

If two or more empty hexes have equally low energy, then the one with the lower lattice number is chosen. However, motions must be consistent with the rules. Therefore, if the closest module cannot move without violating the rules, the next closest module moves, etc. If two eligible modules are equidistant from the second hub, then the module occupying the space with lowest number moves. If no modules can move without violating the constraints while decreasing its energy, the configuration is stable. Using this cost, the configuration at timestep 35 is stable.

Figure 7 resulted from an alternate impetus for motion. In this case modules which are furthest away from the secondary hub feel the greatest need to move, i.e., those with greatest energy. Otherwise, the strategy is exactly the same. Again, these motions must be consistent with the constraints, and alternate choices in module motions are made until no modules are able to move in such a way as to decrease their distance from the second hub. The changes in morphology shown in Figure 7 converge in 40 timesteps with the same initial conditions as Figure 6. Qualitatively, these two different approaches achieve the same result, i.e., a bridge is formed.

6 Conclusions

The concept of a metamorphic hyper-redundant manipulator was presented and developed in this paper. Potential applications, design problems, and algorithms for task implementation were presented. It was shown how simple rules can be used to enforce rather complex (and useful) behavior. Two rules for 'bridge building' were demonstrated.

Currently, a prototype metamorphic robotic manipulator is under development. This manipulator consists of hexagonal modules, each of which are actuated with hobby servomotors under microprocessor control.

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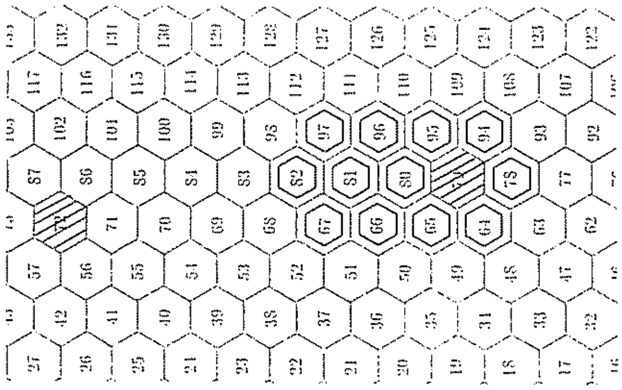

Figure 6(a) - Rules 1 or 2 at Time = 0

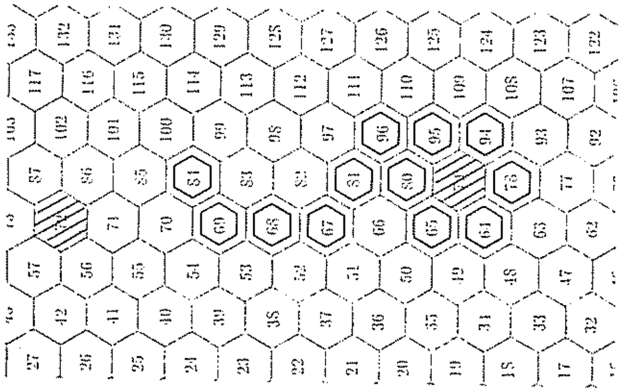

Figure 6(b) Rule 1 at Time = 7

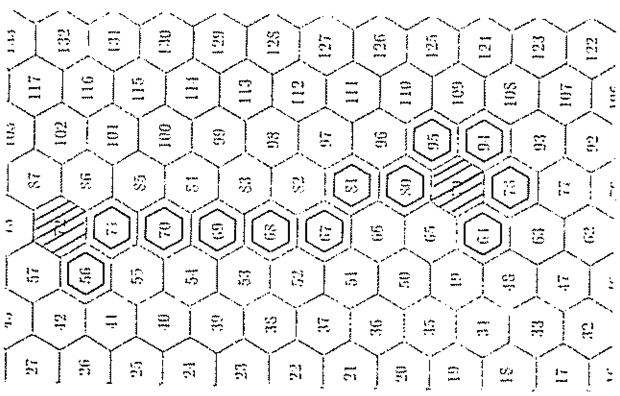

Figure 6(c) Rule 1 at Time = 21

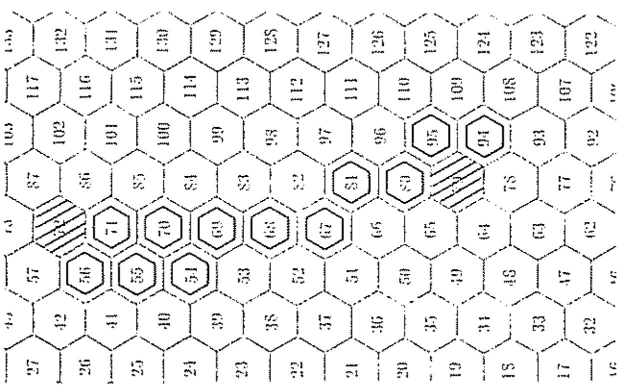

Figure 6(d) Rule 1 at Time = 35

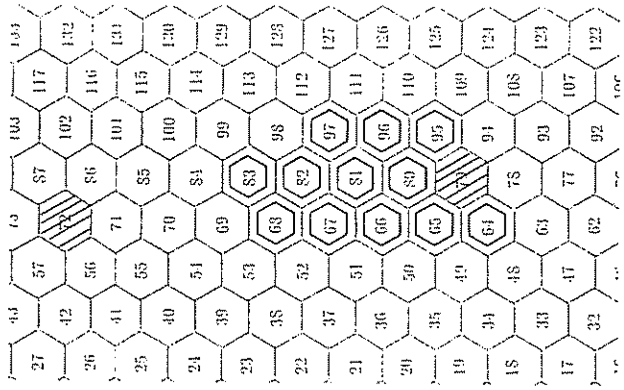

Figure 7(a) Rule 2 at Time = 10

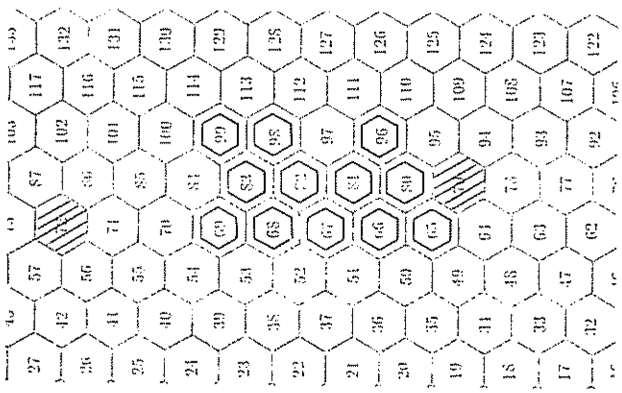

Figure 7(b) Rule 2 at Time = 20

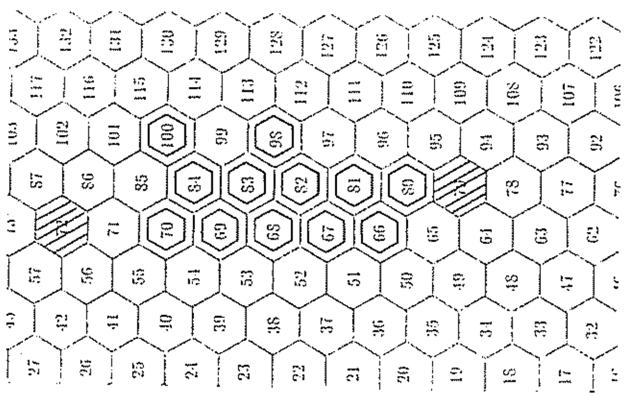

Figure 7(c) Rule 2 at Time = 30

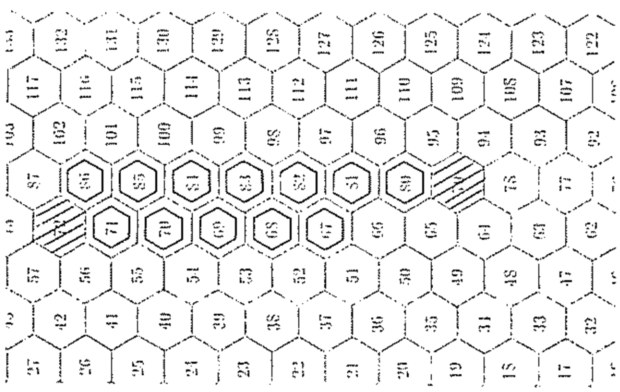

Figure 7(d) Rule 2 at Time = 40

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