The Self-reconfiguring Robotic Molecule

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Abstract

We discuss a robotic module called a Molecule. *Molecules can be the basis for building self-reconfiguring robots. They support multiple modalities of locomotion and manipulation. We describe the design, functionality, and control of the Molecule. We show how a set of Molecules can aggregate as active three-dimensional structures that can move and change shape. Finally, we discuss our Molecule experiments.*

1 Introduction

A robot designed for a single purpose can perform some specific task very well, but it will typically perform poorly on a different task in a different environment. This is acceptable if the environment is structured; however if the task is to operate autonomously in unstructured environments, then a robot with the ability to change its shape to suit the environment and adapt to the required functionality will be more likely to succeed than a fixed-architecture robot.

A self-reconfiguring robot consists of a set of identical robotic modules that can autonomously and dynamically reconfigure in a variety of shapes to best fit the terrain, environment, and task. Self-reconfiguring robots can be viewed as a minimalist approach to designing versatile and extensible robots with multiple modalities of locomotion and manipulation. A single, architecturally-lean autonomous module can aggregate in a variety of structures with other identical modules. If the module is robust and the aggregation protocol is provably correct, the end result is a range of reliable robots. Applications include tasks that require different locomotion and manipulation gaits. For example, the modules could self-organize as a linear robotic structure for traversing a narrow tunnel, and reconfigure as a multi-fingered arm upon exit in order to manipulate objects.

In this paper we describe our work towards building self-reconfigurable robots. We describe the *robotic Molecule* (see Figure 1) we designed and built as the basic module for creating self-reconfigurable robots. The Molecule is a 4 degree-of-freedom, small-scale module capable of aggregating with other identical modules to form three-dimensional dynamic structures. The Molecule consists of two *atoms* connected by a right-angle rigid bond (see Figure 2.) Each atom has 5 inter-Molecule connectors and two degrees of freedom. One degree-of-freedom allows rotation about one connector. The second degree-of-freedom allows rotation of the atom about the bond.

A set of such Molecules can self-aggregate as arbitrary three-dimensional structures. We show this result by demonstrating several different tilings of the plane with the Molecule. The tilings can be stacked so that the resulting structures are three-dimensional. A structure made of a set of Molecules can self-reconfigure as a different structure by using basic Molecule motions. The Molecule is capable of (1) linear motion in a plane on top of a lattice of identical Molecules, irrespective of the absolute orientation of the plane; (2) convex 90-degree transitions between two planar surfaces composed of identical modules; and (3) concave 90-degree transitions between two planar surfaces composed of identical modules. These basic motions allow the creation of dynamic, self-reconfigurable structures that can have multiple locomotion modalities.

In our lab we have built a prototype Molecule and experimented with its basic motion capabilities. The Molecule performed linear motion and transitions.

This paper is organized as follows. We continue

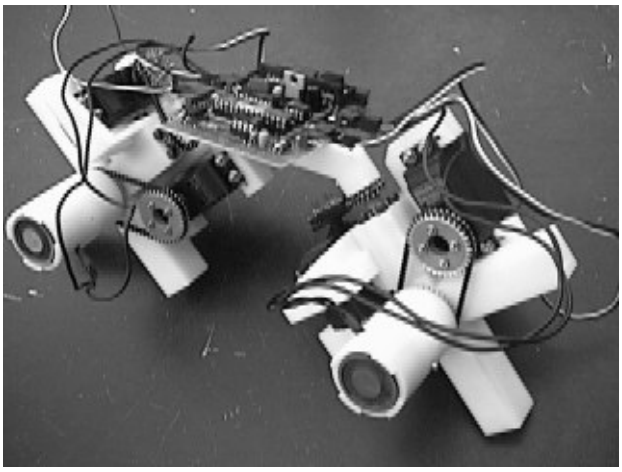

Figure 1: The robotic Molecule. The Molecule is composed of two atoms, connected by an right-angle rigid bond. The Molecule has 4 degrees of freedom: two rotational degrees of freedom about the bond and one rotational degree of freedom per atom about a single inter-Molecule connector. The connectors have been implemented with electromagnets.

with a summary of related work. We then describe the mechanical design of the Molecule and the fabrication process. We discuss briefly the control and communication architecture. We then address how this Molecule can form arbitrary three dimensional structures by showing different tilings. We continue with algorithms that implement the locomotion gaits. Finally, we discuss our experiments.

2 Related work

Our work draws on previous experiences with navigation algorithms [Lat91], designing self-organizing robots, and designing minimalist robot systems [DJR97]. We are inspired by [Mu94, Yim93, PCSC] who introduced the first systems capable of self-reconfiguration in the plane.

Related work in designing modular robots includes [PK95, PK93, NS96, HS96]. In [PK95] a method for designing various robotic arms with different reachability properties out of the same set of 7 modules is proposed. The mechanical design algorithm is implemented as simulated annealing that starts with a random mechanical design and converges to the design with desired reachability properties. The modules are assembled by hand as the computed shape. Our work is different in that our modules could self-aggregate (without human intervention) and the planning phase is of a task-directed, geometric nature. Our modular self-reconfiguring robots are aggregated according to task and we can view reachability as a specific kind of task.

Related work in self-organizing robots includes robots in which modules are reconfigurable using external intervention [CLBD92]. In [FK90] a cellular robotic system is proposed to coordinate a set of specialized modules. [CB97] describe a theoretical framework for counting the number of unique configurations realizable from a set of modules and joints, without considering implementation issues. [Yim93] studies multiple modes of locomotion that are achieved by composing a few basic elements in different ways. [Mu94, YM+97] consider a system of modules that can achieve planar motion by walking over each other due to changes in the polarity of magnetic fields. [PCSC] describes metamorphic robots that can aggregate as stationary two-dimensional structures with varying geometry and that implement planar locomotion. Our self-reconfigurable molecules are different from metamorphic robots in their design and functionality. The structures built from self-organizing Molecules are three-dimensional, can move along any axis in a three-dimensional space, and have motion autonomy relative to a three-dimensional world.

3 The Design of the Molecule

3.1 Concept

The initial goal for our Molecule design was to create a regular solid shape which could be closely packed in 3-D space, and which could move about by attaching itself to a substrate of similar units. Since a cube is the simplest regular solid which fully packs in 3-D space, we decided on a cube-shaped design similar to an atom in our current design (Figure 2). This design had inter-unit connectors on each face of the cube, with a rotational degree of freedom about each connector. This design was not capable of independent movement however, two cooperating connected units were necessary for movement. Furthermore, movement required that a unit be able to support the weight of its partner. Because each unit required 6 rotational degrees of freedom plus the weight of the connection mechanisms, we felt it would be very difficult to create a unit which was strong enough to lift another unit.

Consequently, we attempted to reduce the number of degrees of freedom in our unit without severely reducing its capabilities. The result is our robotic Molecule (see Figure 2). It consists of two atoms linked by a rigid 90 degree connection we call the *bond*. Each atom has five inter-Molecule connection points and two degrees of freedom. One degree of freedom

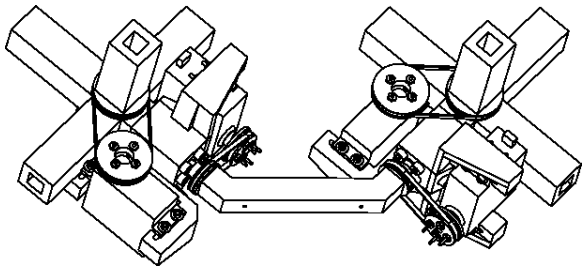

Figure 2: The CAD model of the molecule. The molecule consists of two atoms. A rigid bond that connects the two atoms so that their relative orientation is 90 degrees. The figure shows four actuators, one per degree of freedom. The stalks in the figure represent inter-Molecule connection points.

allows the atom to rotate 180 degrees relative to its bond connection, and the other degree of freedom allows the atom (and therefore the entire Molecule) to rotate 180 degrees relative to one of the inter-Molecule connectors (the rotational degree of freedom cannot be about the connector opposite the bond connection). This design is capable of independent movement on a substrate of identical Molecules, including straight-line traversal and 90 degree concave and convex transitions to adjacent surfaces. However, the L-shaped design cannot be as closely packed in 3-D space as a cube-shaped design (see section 6).

3.2 Implementation

Our current design uses R/C servomotors for the rotational degrees of freedom and electromagnets for the inter-Molecule connectors. The prototype Molecule uses only a single connector on each atom. This connector is attached to the non-bond rotational degree of freedom as described above. The rotating connection points on each atom are the only connection points required for Molecule motion. The other connection points are used for attachment to other Molecules to create stable 3-D structures. A Molecule to Molecule connection requires the connecting electromagnets to be oppositely polarized so that the electromagnetic fields will attract. The 1" electromagnets used on our prototype are sufficiently powerful to support an entire Molecule. To prevent the rotation of one electromagnet with respect to another, we developed interlocking sheaths which encircle the contacting faces of the electromagnets. The diameter of each atom is 5 inches (12.7 cm), making the atom-atom distance in the Molecule approximately 7.07 inches (18.0 cm). The weight of the Molecule is 1.8 pounds (0.8 kg). If all faces of each atom were equipped with connectors, the Molecule would weigh 2.8 pounds (1.3 kg). The Molecule actuators are capable of lifting the weight of a single Molecule. It is not possible for a Molecule to lift another Molecule attached to it.

Each Molecule also contains a microprocessor and the circuitry needed to control the servomotors and electromagnets. The microprocessor performs low-level control of the hardware but currently the high-level control of the Molecule takes place off-board in a workstation. The Molecule communicates with the workstation using an RS-485 serial connection. The cables needed for the serial connection and power are connected directly to our prototype Molecule. However, our goal is to supply power and communications to Molecules via the inter-Molecule connectors. This would make each Molecule autonomous with respect to wiring as long as the group of Molecules consist of a single connected component and at least one Molecule is powered through its connector. To this end we have constructed a special base environment which is designed to resemble the connectors of a 3-D lattice of Molecules. We plan to supply power and communications through these connectors so that any Molecule attached directly or indirectly to the base can receive power and communicate with the workstation. The base also allows us to perform mobility experiments using a single Molecule. Using this environment we have demonstrated that the prototype Molecule is mechanically capable of walking horizontally and vertically and of making concave and convex surface transitions.

3.3 Fabrication

We have built a prototype Molecule to demonstrate the feasibility of our approach. The parts cost of the prototype Molecule is about $1000, and it takes approximately three days to fabricate and assemble all parts. We have utilized several technologies to reduce the design iteration time, improve the mechanical precision, and reduce the cost of the prototype[1]. Our design begins with a fully detailed and dimensioned 3-D CAD model of the prototype developed with Pro/Engineer 18.0 from Parametric Technolgy Corp. We then fabricate most of the structure using an FDM1600 Fused Deposition Modeling (FDM) Rapid Prototyping machine manufactured by Stratasys, Inc. This machine and its associated software converts the data from our CAD model directly into high-strength, light weight ABS plastic parts. These ABS parts are assembled together with the electro-

[1]We thank Brian Locke and the Thayer School of Engineering for their help in this process.

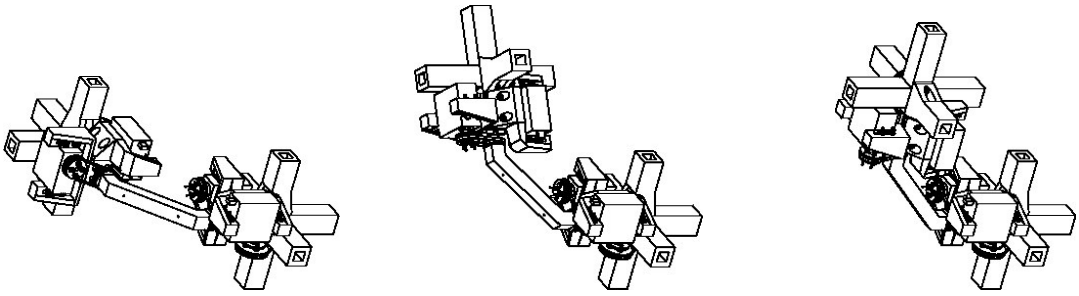

Figure 3: Illustration of the rotational degree of freedom of the Molecule actuated about the rigid bond connecting the two atoms. The right atom is stationary and the left atom rotates. The snapshots show the Molecule in configurations rotated 0 degrees, 45 degrees, and 90 degrees from the original configuration

magnets, the servos, and a few other parts to create a full Molecule.

4 Controlling Molecule Motion

An individual molecule moves by attaching an atom to some other Molecule and actuating one or more of its four degrees of freedom (see Figure 3). Our Molecule design is capable of linear walking on a planar lattice of Molecules, and concave and convex transitions to planar lattices of Molecules oriented at 90 degrees to the original surface. By composing these capabilities, what follows is that an individual Molecule is general : it can traverse any Manhattan-style[2] Molecular structure. We describe the algorithms for these basic motions in the following sections.

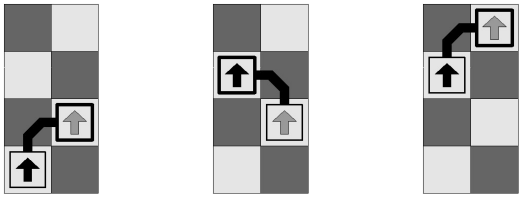

Figure 4: A linear walk sequence.

4.1 Linear walking

Figure 4 shows the three stages in a linear walk. The arrows represent the positions of the rotating connector actuators. The rotating connectors are facing the underlying Molecule lattice which is represented by the checkerboard pattern. The atom with the bold outline is connected to the underlying lattice. Figure 4(Left) represents the initial state of the Molecule. Figure 4(Center) shows the result after the Molecule has pivoted clockwise 90 degrees about the connected atom (the atom with the gray arrow) and has swapped atom connections. Note that the atom designated by the black arrow also performed a 90-degree rotation of its connector while it was being moved to its new position (if the connector had not rotated with respect to the atom it would be pointing right instead of up). This was done to compensate for the rotation required by the next move. Figure 4(Right) shows the result after the Molecule has rotated counterclockwise 90 degrees about the connected atom (the atom with the black arrow) and has swapped atom connections. Note again that the moving atom has also performed a 90 degree rotation of its connector. Since Figure 4(Right) shows the Molecule in the same pose as Figure 4(Left) and the Molecule has moved forward one white square, this algorithm can repeated as often as necessary to move the Molecule a given amount in a straight line, assuming that the underlying lattice exists to support the Molecule.

[2]A Manhattan object has all its surfaces either parallel or perpendicular to one another.

4.2 Concave transition

Figure 5 shows the sequence of Molecule moves necessary to perform a concave transition. Atoms are represented by the black cubes with the small cube on each face representing an inter-Molecule connector. The large gray and white cubes represent the underlying Molecular lattice. Figure 5(Left) shows the Molecule in the initial position. The atom nearest to the wall is attached to the floor surface. Figure 5(Second from Left) shows the pose after a 90-degree rotation about the bond DOF of the attached atom. This causes the unattached atom to be suspended in midair one atom position above and to the left of its original position. Figure 5(Second from Right) shows the pose after a 90-degree rotation about

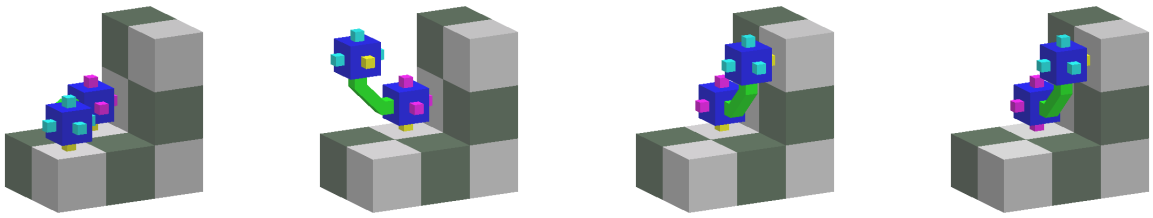

Figure 5: A concave transition sequence.

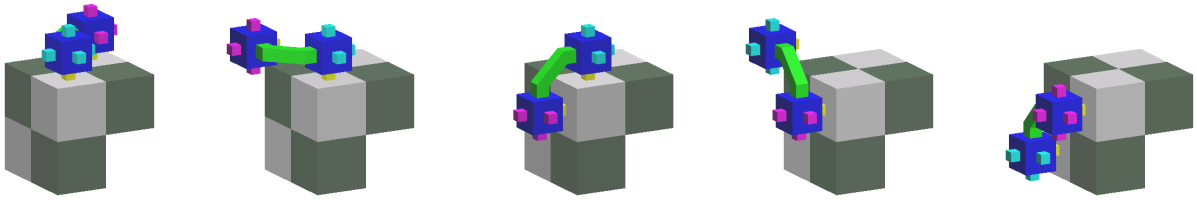

Figure 6: A convex transition sequence.

the inter-Molecule connector of the attached atom. The result of this motion is to bring the unattached atom into contact with the wall. At this point the atoms swap connections so that the previously unattached atom is now attached, and the previously attached atom is unattached. Figure 5(Right) shows the final stage of the transition in which the lower atom is rotated to place its rotating inter-Molecule connector on the wall. From this point the Molecule can execute a linear walk to climb the wall.

4.3 Convex transition

Figure 6 shows the sequence of moves necessary to perform a convex transition. Figure 6(Left) shows the initial position of the Molecule. The near atom is attached to the checkered surface by its rotating inter-Molecule connector. The first rotation is about this connector and it causes the unattached atom to swing out over the convex edge. Simultaneously, a rotation occurs about the bond DOF of the unattached atom positioning its rotating connector so that it faces the vertical surface. The result of these two rotations is shown in Figure 6(Second from Left). A rotation about the bond DOF of the attached atom then moves the unattached atom into contact with the vertical surface (Figure 6(Center)). Atom connections are then swapped allowing the previously attached atom to move freely. The next two rotations move the newly unattached atom into free space above the vertical surface and position the rotating connector of the unattached atom so that it faces the vertical surface (Figure 6(Second from Right)). Finally, the unattached atom is moved into contact with the vertical surface as shown in Figure 6(Right). At this point the Molecule can traverse the vertical surface using the linear walk algorithm.

5 Aggregating Three-dimensional Structures

In the previous section we demonstrated how the Molecule can move on a substrate of other Molecules. In this section we examine the class of structures that can be created with Molecules and hence can be considered a "substrate" for Molecular motion.

A Molecule can connect with other identical Molecules to create dynamic three dimensional geometric structures. Figure 7 shows examples of planar structures created by packing Molecules. It is possible to create arbitrary three-dimensional geometric shapes consistent with the Molecular structure. These three-dimensional shapes can only have surfaces that meet at angles of 90 degrees.

Molecules can be placed next to each other without explicit connections. To increase the robustness of the resulting structures, we insist that each Molecule in a structure be connected to at least one other Molecule.

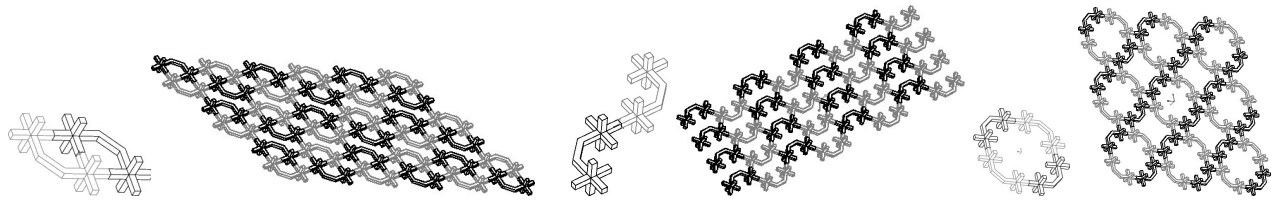

Figure 7: This figure shows three planar tilings using the Molecule. The "pair" generator on the left is used to create the leftmost tiling. The "string" generator in the middle is used to create the middle tiling. The "ring" generator on the right is used to create the rightmost tiling. The use of color (black or gray) assists in visualizing individual Molecule locations. In Section 6 we show that this particular color encoding of Molecular structures has interesting geometric properties with respect to planning.

One can imagine stringing Molecules together subject to this constraint in an arbitrary fashion. An interesting question is, what the class of three-dimensional structures that can be created using the Molecule? We propose examining this question by defining planar tilings using the Molecule.

Consider a possible tiling of the plane using the Molecule. It is interesting to observe that if we place an xy grid whose size equals the atom size on the plane, each Molecule will occupy three cells in this grid, arranged as an "L" shape. We would like to find ways of covering every cell in such a planar grid with the Molecule. Figure 7(Left) shows an example of a possible tiling that covers every cell in the grid. The generator for the tiling consists of a "pair" of two Molecules. Other tilings are also possible. Figures 7(Center) and 7(Right) show two other generators and the resulting tilings. Note that in all three figures the Molecules are simplified by omitting the actuators. In Section 6 we will show how such tilings can be used to generate dynamic structures made out of molecules that can travel along any direction. We now show how tilings help with constructing arbitrary three dimensional objects out of Molecules.

To show this result, we will use a cell-decomposition method. We define a cell decomposition of a three-dimensional object O to be the division of the object into a union of disjoint cells. An l-grid cell decomposition is a cell decomposition into equal cells where each cell is a square and the side of the square is l. An l-grid approximates a three-dimensional object with a Manhattan object that consists of a union of identical cubes.

Theorem 1 *Any connected three-dimensional Manhattan object that allows an l-grid cell decomposition where l, the size of the grid, is the size of a "pair" tile can be created using Molecule robots.*

Proof: It is possible to place an xyz grid of size equal to the tile size on the object. Since "pair" tiles pack tightly in the plane, we can construct each xy section of the object by selecting an appropriate planar shape. Since "pair" tiles are flat (i.e. all atoms are coplanar) we can stack these tiles on top of one another in a tightly packed fashion. So, we can construct each xy section of the object by selecting an appropriate planar shape. These layers can be stacked to obtain the desired object. □

Corollary 2 *Any three-dimensional structure that allows a cell decomposition where the size of the grid is the size of an individual atom, can be approximated using Molecule robots, with an approximation error of at most two cells for every cell on the xy exterior of the structure.*

Proof: Begin by outlining each xy slice of the desired Manhattan object. Stack "pair" tiles so that all cells in each slice of the object are completely covered. Now, remove any Molecules that do not cover at least one cell in the desired object. Among the remaining Molecules, there may be some that cover one or two cells that are not in the desired structure. These Molecules, must, however, cover at least one cell in the desired structure or they would have been removed already. Furthermore, since this cell is adjacent to a cell in the same plane that is not in the desired structure, it must be on the xy exterior. So, for each cell on the xy exterior of the desired structure, there can be at most two cells in the actual structure that are not in the desired structure. □

Note that Theorem 1 and Corollary 2 give a method for constructing objects out of Molecules and a measure for quantifying the approximation of the con-

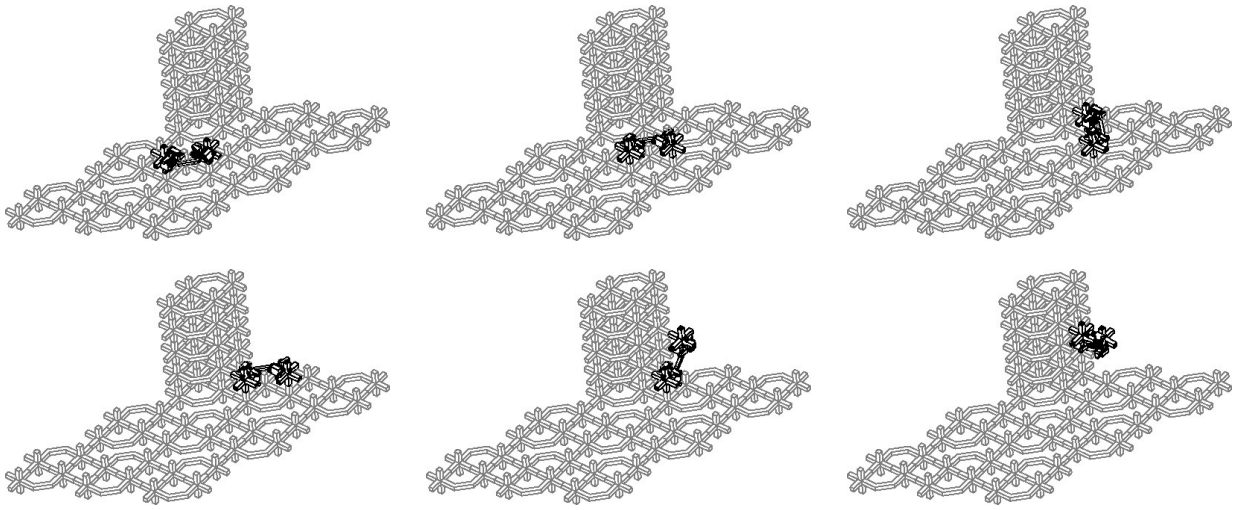

Figure 8: This figure shows a molecule walking on a structure composed of identical molecules. The structure, shown in grey, consists of a horizontal plane and a vertical tower. The molecule, shown in black, starts on the plane (Top, Left), rotates 180 degrees about the connector of its right atom to the plane (Top, Center), rotates 90 degrees about the connector of its right atom to the plane (Top, Right), rotates 90 degrees about the connector of its left atom to the plane (Bottom, Left), rotates vertically 90 degrees about the bond connector of the top atom to transition and make contact with the tower (Bottom, Center), and finally it rotates 180 degrees about the connector of its top atom to the wall to traverse the tower (Bottom, Right).

struction only when the size of the object is large relative to the size of an individual Molecule. One can imagine building Molecules at the MEMS scale. This would make possible the construction of objects with high-resolution surfaces.

A caveat of Theorem 1 and its corollary is that the weight of the object must be able to be supported by its Molecular layers. Since the body of our Molecule is currently made out of plastic, this places some restrictions over how many can be stacked on top of each other. We are currently investigating this question.

6 Mobility and Gaits

Molecules can walk on three dimensional structures by composing gaits for linear motion in the x and y directions, convex transitions, and concave transitions. Figure 8 shows an example in which the molecule travels to the base of a tower and climbs on the tower. The planar surface is composed with a "pair" tiling and the tower is created by stacking "pair" tilings. One can imagine several molecules moving with the same gait to aggregate as a larger tower.

Given a planar structure, the molecule will use the linear walk algorithm described in Section 4. While the basic idea of moving the molecule is what we have outlined in Section 4, the particular details depend on the geometric structure of the plane. The molecule will have to rotate by different amounts about one of its atoms to reach a position where the free atom can make contact. The pattern of individual rotations that achieves a given transition in the x (or y) direction is called a *gait*.

To decide which gait is most appropriate for a locomotion task, we introduce a gait complexity measure. The complexity of a gait with respect to a unit translation[3] is computed as the number and size of the distinct rotations required to do the motion. In our future work will examine how to use this complexity measure to choose appropriate gaits.

7 Experiments

We have built one Molecule and implemented the control algorithms for linear motion, convex transition, and concave transition. Because we only have one Molecule, we simulated a lattice of Molecules by building a plexiglass structure that supports linear translations as well as convex and concave transitions. We bolted inter-Molecule connectors at the locations

[3]Unit translations can be translations in the x direction by one molecular unit, translations in the y direction by one molecular unit, or any user-defined measure that is relevant to the required locomotion task.

where we expect to have Molecules. We performed experiments in which the Molecule successfully performed linear translations and convex and concave transitions.

8 Discussion and Future Work

Our vision is to create robots by using self-reconfiguration: hundreds of small modules can autonomously organize and reorganize as geometric structures to best fit the terrain on which the robot has to move or the shape the object the robot has to manipulate. In this paper we described our design for a module we call a Molecule that can be used to aggregate as arbitrary three-dimensional self-reconfigurable structures. We described the structure of the Molecule, the control algorithms for effecting linear translations, convex transitions, and concave transitions, and discussed the potential for this Molecule to be a universal module. Many questions remain to be explored to construct a science-base for self-reconfiguring robots. Key questions include: (1) Given n copies of the universal module, an initial configuration, and a goal configuration, is there a plan to reconfigure the structure?; (2) How long does it take to compute such a plan and what is its complexity?; (3) Given n copies of the universal module, can we characterize geometrically and/or algebraically the set of all structures that can be built?; (4) What locomotion gaits are supported by n-structures composed of the universal module?; (5) What manipulation gaits are supported by n-structures composed of the universal module? We will address these questions in our future work.

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