A Chronological Survey of Modular Self-Reconfigurable Robots

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Abstract

Since the late 1980's, many systems of self-reconfigurable robots have been developed. This report gives a chronological survey of many of these projects, and discusses several interesting features and capabilities of the robotic modules and structures. An overview of each robot system is presented, highlighting the most interesting aspects of the system. Following the survey of the various robot projects, a general discussion of self-reconfigurable robots is given, summarizing the main features and concerns of physical characteristics of self-reconfigurable robots and their modules, mechanisms of locomotion and reconfiguration, capabilities and applications of self-reconfigurable robots, and challenges for self-reconfigurable robot research.

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1 Introduction

A robot that is self-reconfigurable is able to dynamically and autonomously transform its structure in order to perform the task at hand and function in the current environment. A modular robot is comprised of many individual modules, which are roughly analogous to cells in organisms. The modules may be homogenous (identical) or heterogeneous (differentiated). Heterogeneous modules can be specialized to perform a certain function and thus increase the level of adaptability of the robot. On the other hand, homogeneous modules are easier to mass-produce, and they facilitate the process of self-repair, where a damaged module is discarded and replaced by another module. Modular self-reconfigurable robots can be lattice-based, chain-based, or a hybrid of the two. Lattice-based structures provide more connection points and thus ease the process of reconfiguration, however, the rigidity of these structures makes locomotion more restricted. Chain-based structures allow for more freedom of movement, however, fewer contact points make reconfiguration more challenging. Self-reconfigurable robots can move and operate in two or three dimensions. Many basic aspects of self-reconfigurable robots are discussed in the review article [25]. Since the late 1980’s, many self-reconfigurable robotic systems have been developed. A number of these robot structures are presented and discussed in this report.

2 Examples of Self-Reconfigurable Robots

The first modular self-reconfigurable robot appearing in the literature was the CEBOT [8] system in 1988, where the modules were considered cellular in structure. Since then, numerous other projects using modular self-reconfigurable robots have been undertaken and reported in the literature. A brief overview of many of these projects follows.

2.1 Fracta (1994)

A self-assembling machine using 2D fracta [21] is capable of reconfiguration, transportation in two dimensions, and self-repair. Three physical fracta have been built that are 125 mm in diameter and 160 mm in height, with a possibility for micro-scale fracta if the magnetic connections are replaced with electrostatic connections. Several fracta prototype modules are shown in Figure 1. Each fractum contains a microprocessor and an infrared optical communication channel. The individual fracta are homogeneous, autonomous, and use local relations to attach, detach, and cooperate with neighbors. The fracta are able to assemble into arbitrary three dimensional structures and the structures can move as a whole, as well as discard a damaged part, thus performing self-repair. Physical experiments have demonstrated basic fracta movements. Simulations of self-assembling fracta have been performed, where fitness evaluation, diffusion, and activation determine the sequence of movements towards the desired configuration. Future work includes further developing self-repair and adapting to changes in the environment by changing shape.

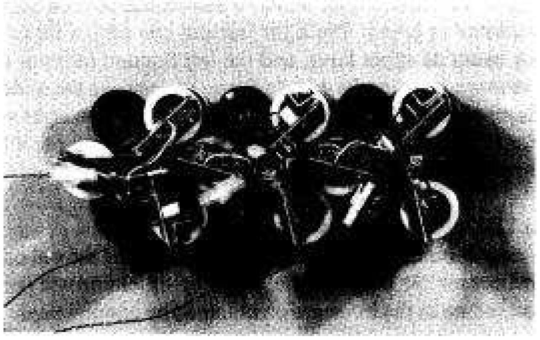

Figure 1. Fracta modules [21].

2.2 Metamorphic (1996)

Metamorphic robots [28] are two-dimensional, homogenous, lattice-based reconfigurable robots with hexagon or square-shaped modules, as illustrated in Figure 2. A module performs locomotion by rolling or sliding over neighboring modules. Hexagon modules roll over their neighbors where as square modules slide over their neighbors in a vertical, horizontal, or diagonal direction. Besides climbing over adjacent modules, each module can perform basic computation and connect or disconnect from neighboring modules with mechanical hooks or electromagnets. Modules are controlled by an external processor. Experiments using a physical prototype tested basic linking and locomotion abilities. The metamorphic structures could function as a swarm of connected robots that act collectively. Possible applications are obstacle avoidance in highly unstructured and constrained environments, forming bridges and other structures, encircling objects (such as recovering space satellites), and performing inspections (e.g. of nuclear reactors).

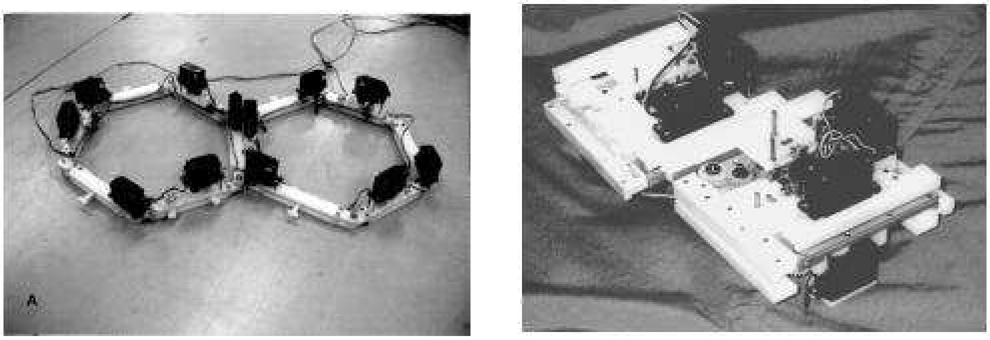

Figure 2. Metamorphic modules: hexagon (left) and square-shaped (right) [28].

2.3 3D-Unit (1998)

The 3D-Unit robot [22] was the first three-dimensional robot that was prototyped. Two units were built, each spanning 26.5 centimeters. Their shape is based on a regular hexagon. As depicted in Figure 3, a cube is in the center and an arm extends in each of the six directions. The modules are homogenous and are capable of changing their local connection, communicating with neighbors, and processing information. The connectors include a grasping structure with a key and keyhole mechanism. Each module contains sensors for position, angle, and contact. Two units must be moved together, where one is used as a pivot for the other. The modules can move on the plane or flip to the orthogonal plane. Physical tests involved rotational movement and lifting of modules. Simulations were performed on reconfiguring from a ladder shape to a tower shape. The simulations were successful for as many as 20 modules. The units of moveable type compare each reachable state to the goal and choose with a greater probability the move resulting in the smallest difference between the goal. The structures are also capable of self-repair. Possible real-world applications include use in hazardous or remote environments, such as space, deep sea, and radioactive environments. A limitation of this design is that some configurations are difficult to reach. Future plans involve constructing more complex structures.

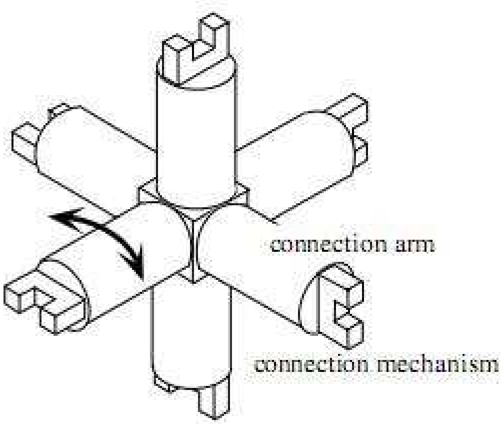

Figure 3. 3D-Unit module [22].

2.4 Molecule (1998)

The Molecule [18, 20] is a 3D lattice-based robot with modules comprised of two atoms connected by a bond, as shown in Figure 4. Connections between modules are established with electromagnets. Movement of these modules involves one atom rotating around the other atom. The basic types of motion are straight-line traversal and 90 degree convex (for climbing down) and concave (for climbing up) transitions to adjacent surfaces. Physical experiments have tested these modes of locomotion by using one prototype Molecule and a simulated lattice structure. Sixteen physical Molecules have been built, and the vision is to eventually create hundreds of these robots. The correctness of reconfiguration sequences has been verified with a Prolog simulator. The simulated structures are able to climb stairs, build a tower structure, and form a wall by tiling. Trajectory planning is implemented using graph search. A meta-module consisting of 16 Molecules with three levels of hierarchy has been constructed. This hierarchical structure allows the execution of polynomial-time planning algorithms. Physical experiments of locomotion modes have also been conducted on this meta-module. Future applications of Molecule-based structures may involve traversing different types of terrain, manipulating objects, and performing basic sensing functions. Work in the future includes various issues concerning general global motion planning algorithms. There are questions of the minimum number of Molecule robots that are required to satisfy the restrictions of known planning algorithms, as well as whether parallel transitions can speed up the planning and motion process.

Another question is how many Molecules are able to be stacked on each other to maintain a stable structure.

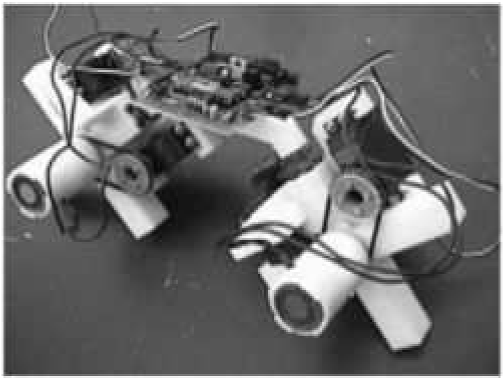

Figure 4. Molecule robot (two atoms connected by a link) [18].

2.5 Vertical (1998)

These robots [13] have the ability to reconfigure against gravity, as in the case of climbing stairs-like structures. Besides climbing stairs, another potential use for these robots would be to build a bridge structure for transporting cargo across a gap. Four prototype modules were built. Each has a cubic body with an edge length of 90 mm and a pair of arms. A schematic of the modules is given in Figure 5. Modules are connected with permanent magnets and a module can communicate with its neighbors. The arms of the modules perform rotating and sliding motions to change the bonding configuration of the modules. Movements are determined by local, minimum interactions between neighbors, very much like cellular automata. In a physical experiment, robots created a stairs-like structure and another robot was lifted to the top of the stairs. Simulations of creating and dismantling stairs were conducted using 15 modules. To build a stairs structure, a module can either move upper-left or left, and to dismantle the stairs, a module can either move lower-right or right. Future work involves building robots that contain processors and sensors.

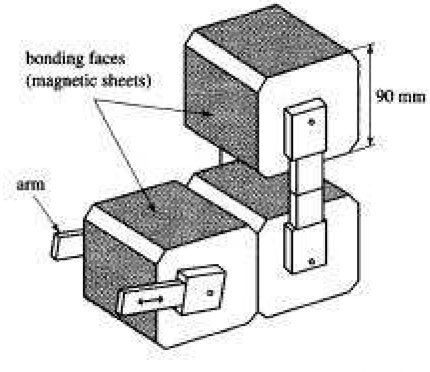

Figure 5. Vertical modules [13].

2.6 I-Cubes (1999)

I-Cubes [35] consist of active links and passive cubes, as illustrated in Figure 6. The links are moveable and the cubes can be rotated, translated simultaneously in two directions, and act as a pivot joint for a moving link. The structures assembled from I-Cubes are potentially able to move over obstacles, climb stairs, traverse through tunnels and pipes, manipulate objects, form bridges and towers, and be utilized for space applications. Experiments using a physical prototype demonstrated basic link function and cube movement. A sequence of actions for climbing a step and building a tower were created manually with the aid of a graphical interface. The cube component has an edge length of 8 cm, although the desired length is 6 cm. Future millibots are a possibility. The connections are established by a cross or cone-shaped piece that locks into place. The modules are able to sense joint position. The structures move by means of joint rotations of the cubes. The links are controlled externally by buttons or a graphical user interface. Future work involves constructing smaller and lighter cubes, constructing more links and cubes, enabling the modules to be autonomous, and devising motion planning schemes that combine learning and search techniques.

Figure 6. I-Cube cube structure (left) and link structure (right) [35].

2.7 Crystalline (2000)

Crystalline robots [30] are homogenous square (cubic) modules that perform locomotion using expansion and contraction movements similar to muscles and amoeba. A prototype module appears in Figure 7. The modules can also connect and disconnect to other modules by means of a key and lock (channel) mechanism, and they contain position sensors. Modules are autonomous in that they contain their own processor and power supply. Ten physical modules have been built, and each is 7 inches tall and 2-4 inches wide, depending on whether it is contracted or expanded. Modules are able to perform locomotion and automated shape metamorphosis. Physical experiments have involved a module expanding and connecting with a neighbor, inchworm locomotion with two atoms, and performing atom relocation by propagating across a row in the crystal structure. Simulations have involved inchworm locomotion and reconfiguring a dog-shaped structure into a couch-shaped structure, which was planned manually. Future work includes improving the hardware and developing distributed reconfiguration algorithms.

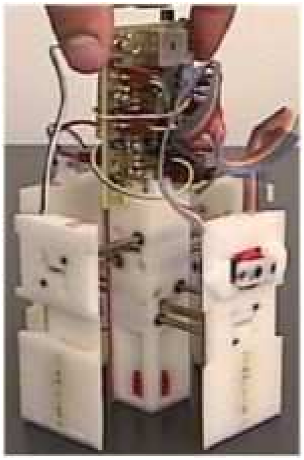

Figure 7. Crystalline module [30].

2.8 Polybot (2000)

A self-reconfigurable 3D robot named Polybot [38] is constructed from a chain structure consisting of segment and node modules. In Figure 8, a chain structure consisting of nine modules is displayed. These structures are capable of several types of locomotion, including rolling (for flat terrain), earthworm motion (for tunnels and steps), and spider-like motion (for hills). Physical experiments have involved several modes of locomotion: earthworm locomotion, snake-like locomotion, a rolling track, caterpillar-like locomotion, cilia-like locomotion, 6 legged locomotion, slinky-like locomotion, and spider-like locomotion. Arm manipulation and ball balancing have also been demonstrated. Simulations of additional forms of locomotion include cartwheel locomotion, carrying an object while rolling, a rolling loop, and slinky locomotion on an x-y grid. Potential real-world applications for Polybot include planetary exploration, undersea mining, and search and rescue operations. As many as 32 physical modules have been built, with a goal of 200, and simulations have included large numbers of modules. A goal in terms of module size is for a module to fit within a 5 cm cube. The modules connect by means of a pin/hole mechanism. Modules will possibly include proximity sensors, tactile sensors, force and torque sensing, and a camera. A hierarchy of modules can be formed in that modules can be grouped into larger virtual modules, which can then be grouped again. Work in the future will involve increasing robustness, implementing self-repair functionality, and addressing the issue of the motion planning space becoming exponential in the number of modules.

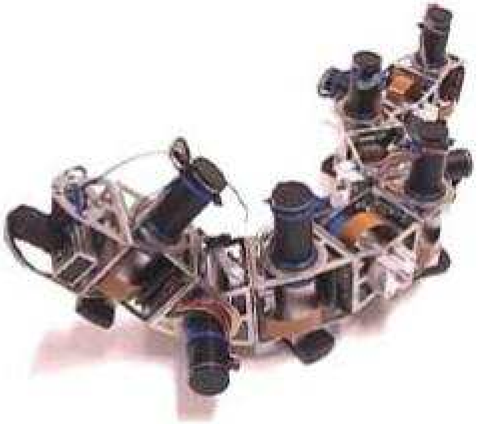

Figure 8. Polybot modules in a snake-like structure [38].

2.9 CONRO (2000)

CONRO (CONfigurable RObot) modules [3] are self-sufficient, autonomous, homogeneous, three-dimensional, and form into chain-like structures. Each module has a body and active and passive connectors, in addition to an infrared communication system and sensors and actuators. A pin/hole mechanism allows modules to connect. Modules can be assembled into snake and hexapod configurations. A photo of a physical module appears in Figure 9. Physical experiments have tested basic snake motion and a hexapod structure standing up. The structures can reconfigure based on the environment and current task. Small robots can merge and large robots can split. Many small robots can perform a task in parallel. Twenty physical modules with a length of 104 mm have been built. A work in progress is software to coordinate reconfiguration and locomotion of robots.

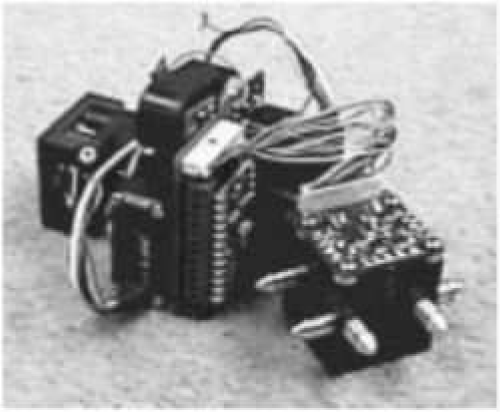

Figure 9. CONRO module [3].

2.10 Pneumatic (2002)

Pneumatic modules [14] are homogenous, three-dimensional, cubic-shaped structures, with pneumatic actuators consisting of flexible bellows, as illustrated in Figure 10. Motion and connection is achieved using compressed air from these bellow mechanisms. This scheme is inspired by animals such as worms and caterpillars with hydrostatic skeletons. The modules can perform rotational movements and stable contraction and elongation. Two prototype modules were built and basic rotational movement of these two modules was tested. Each module has an edge length of 20 centimeters. The goal is to scale up the size of these modules in order to utilize them for various space applications. Another possible application is to build a bridge structure and let a moving load pass through. Future plans are to improve the efficiency of the air supply and to install a power supply in each robot module.

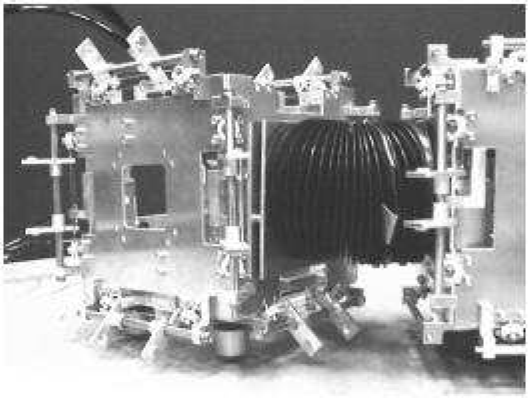

Figure 10. Pneumatic modules [14].

2.11 Telecubes (2002)

Telecube modules [34, 36] are 3D cubic-shaped units that perform motion by expanding and contracting the sides of the cube, similar to the way tiles move in an 8-puzzle. Both contracted and expanded versions are shown in Figure 11. The modules are homogeneous with simple communication and infrared sensors that are able to gauge the extension of each side of the cube, read the contact sensor on each face, and determine whether or not they are connected to a neighbor. The connection mechanisms are implemented using permanent switching magnets. Two physical modules have been built, with another 5-20 planned. Each side of the module cube is 6 cm in the contracted state. Simulations have tested basic reconfiguration algorithms. The researchers have constructed meta-modules composed of 8 modules with additional modules embedded within. This construction simplifies reconfiguration and allows more types of configurations that otherwise would not be possible. Possible capabilities of the structures formed by Telecube modules include locomotion, object manipulation, sorting, interacting with other systems, and adapting to the current environment.

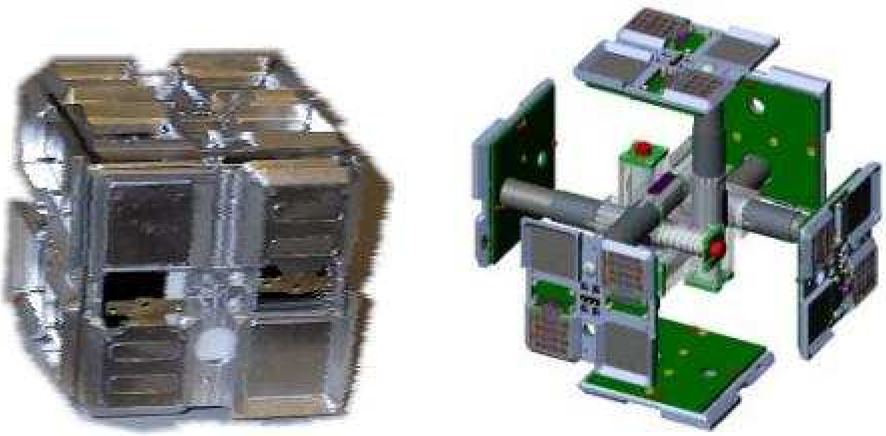

Figure 11. Telecubes contracted (left) and expanded (right) [34].

2.12 CHOBIE (2003)

The CHOBIE modules [17] reconfigure by means of slide motion and successive cooperative movements. The structure begins with a seed module, and a sprout is produced to extend the structure. Modules are capable of locomotion in three-dimensions, connecting to and separating from other modules, communicating with neighbors, and sensing stress in the environment. A CHOBIE module is shown in Figure 12. Potential applications of these robots are cooperative transportation, collection, and construction. Three physical modules have been built, each of whose dimensions are 8x8x7.5 centimeters. Mechanical grooves serve as the connection mechanism. The modules contain force sensors and photo sensors. Physical experiments involved structures transforming from an initial to a goal configuration. Mechanical constraints of the modules make transforming structures difficult.

Figure 12. CHOBIE module [17].

2.13 M-TRAN (2002, 2004, 2005)

A reconfigurable robot composed of a hybrid of lattice and chain structures is M-TRAN (Modular TRANsformer) [19, 23, 24]. The modules are homogenous and consist of active and passive boxes that can attach, detach, rotate, and lift other modules. The assembled structures are able to manipulate objects, perform autonomous 3D locomotion resembling a 4-legged walker, caterpillar, an H-shape, or multiple walkers, and assume a tower structure. A 4-legged walker and a caterpillar structure constructed from M-TRAN modules are shown in Figure 13. Locomotion sequences are determined using genetic algorithms, a central pattern generator, and an automatic motion planner. Ten physical modules have been built, each of size 60 cubic mm for each of the two boxes. The modules contain connection surfaces with permanent magnets. There are sensors for position and orientation. Hardware with mechanical connectors and infrared sensors is being developed. Modules may be connected and function as a larger module, called a “meta-module,” which simplifies the reconfiguration problem. An interactive motion design interface using the Open GL library has been developed. The software uses a locomotion planner that combines global and local planning using database rules. Reconfiguration and climbing over obstacles have been demonstrated. Physical experiments have demonstrated basic reconfiguration and forward motion. The plan devised by the software is transferred to the hardware. A possible real-world application is search and rescue operations. Future plans involve building simpler and smaller modules, more transformations between structures, implementing search and learning techniques for motion generation, devising distributed control schemes for facilitating self-repair, and finding optimal configurations for a given task or environment.

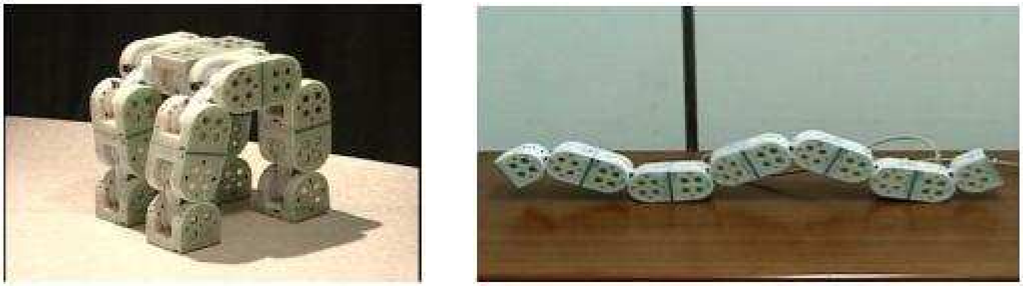

Figure 13. M-TRAN modules forming a 4-legged walker (left) and caterpillar (right) [19].

2.14 ATRON (2004, 2006)

ATRON [16, 27] robots are lattice-based structures consisting of homogeneous modules composed of two hemispheres, as shown in Figure 14. The modules are capable of sensing tilt, distance, and gravity; rotating around their equator; connecting and disconnecting with modules; sensing connected neighbors; recognizing dead modules, external objects, and nearby modules; communicating with neighbors; and detecting being lifted or tipped over. Infrared diodes are used for communication. Connectors use a point-to-point male/female hook scheme. A module is unable to move on its own, it must move with the aid of one of its neighboring modules. A group of modules can self-reconfigure in 3D. The researchers have considered control of meta-modules. Potential applications for these robots are: production lines (packaging), assembly lines (sorting), cleaning and maintaining hazardous machinery, search and rescue efforts, nano-robotics, space applications, assisting the disabled, entertainment, and automatic construction. Approximately 100 physical modules based on LEGOs or styrofoam have been constructed and each is 11 cm in diameter. The goal is to eventually build thousands to trillions of these modules on the millimeter or micrometer scale in the form of intelligent dust or nano-robots. Currently, scalability is unclear in terms of number of modules and it appears to be more difficult for lattice structures. Physical experiments have involved snake, cluster-walk, and car structures. One experiment tested a robot traversing an obstacle course with a step and tunnel. Simulations using hundreds of modules have performed reconfiguration. Recent work with ATRON involves the creation of scalable anatomical parts [4], which allow for the differentiation of modules based on their functional role. The modules can assemble into biological-like structures resembling bones, joints, muscles, arteries, and neurons. A bone structure based on ATRON modules is given in Figure 14. This construction enables a hierarchy of animal-like cells. Rather than manipulating a single module, the anatomical part is manipulated as a whole.

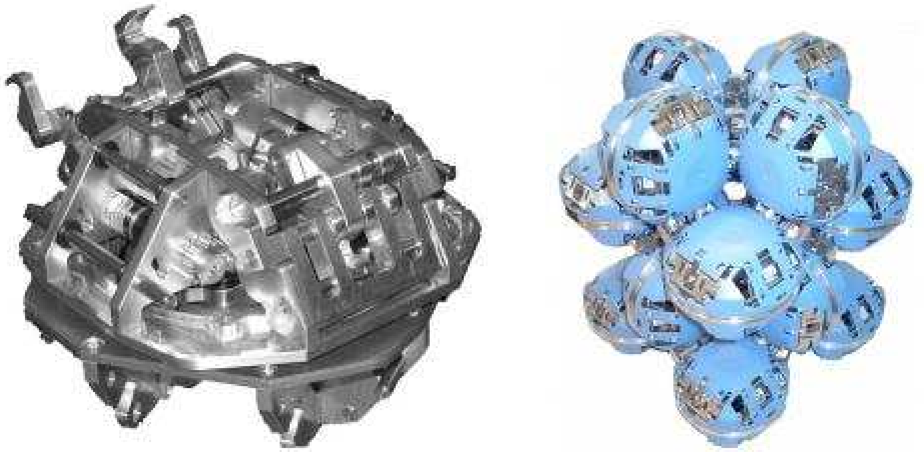

Figure 14. ATRON module (left) [16] and ATRON bone-like structure (right) [4].

2.15 Superbot (2004, 2006)

Superbot robots [31] combine features and advantages of M-TRAN [19, 23, 24], CONRO [3], and ATRON [16, 27], as illustrated in Figure 15. These robots are three-dimensional and consist of both lattice and chain structures. Both a physical prototype and Open Dynamics Engine based simulations have been studied. Simulation experiments have been conducted on several modes of locomotion, including snake, caterpillar, insect, spider, rolling track, and H-walker. Capabilities of a single real Superbot module are moving, turning, sidewinding, maneuvering, traveling, reconfiguring, recovering from failure, and flipping. Other potential functions include climbing, lifting objects, and using tools. Possible real-world applications include transportation, exploration, construction, inspection, maintenance, resource utilization, and support for astronauts. Modules contain a position sensor and a 3D accelerometer for gravity. Future work will involve reconfiguring from one mode into another, and testing different terrains and travel distances. An issue to be addressed is the tradeoff between efficiency and adaptability of the robot structures.

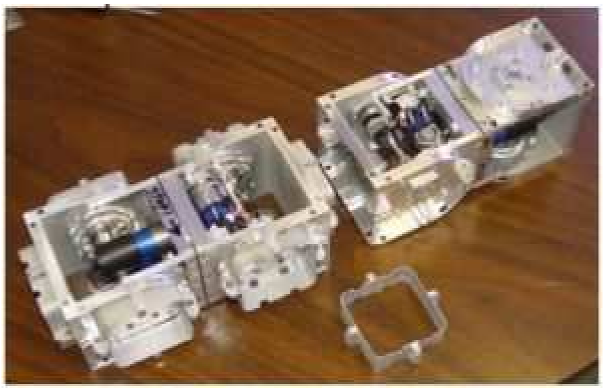

Figure 15. Superbot modules [31].

2.16 Claytronics (2004, 2005)

The Claytronics robots [9-11] are one form of programmable matter which behave according to the ensemble principle [12]. The goal is to develop millions of these units (called catoms) at the micron-scale, and possibly nano-scale. Macro-scale prototype catoms have been built. Figure 16 displays two of these modules along with their actual size. Each catom is cylindrical in shape and 44 mm in diameter. They are only two-dimensional, although a three-dimensional version is being developed. The catoms move according to local control determined by electromagnetic forces generated by two cooperating catoms. Another means of moving catoms and creating structures is by random motion of "holes" contained within the assembly [6], a technique based on semi-conductor device physics. The catoms are able to move in 3D relative to other catoms, adhere to neighboring catoms, and compute state information. The connections are magnetic and nanofiber adhesives are a future possibility. The catoms currently do not contain significant sensing abilities or autonomy. The catoms are able to form a hierarchical network for communication. Future applications of catoms include synthetic reality, where moving 3D objects in the real-world are reproduced and manipulated. These objects will be physical artifacts that mimic the shape, movement, appearance, sound, and tactile qualities of the original objects. The idea is to create high-fidelity 3D macro-scale objects by using micro-scale components.

Figure 16. Claytronics units [11].

2.17 Programmable Parts (2005)

The programmable parts project [2] is based on the use of graph grammars for determining the behavior of the modules. The rules of the graph grammar correspond to chemical reactions. It is possible to design a rulebook so that parts are able to assemble into any desired structure [2]. The modules passively float on an air table and bind upon random collisions. The local grammar rules determine whether or not modules will stay bound or detach. Besides binding and detaching, modules are able to communicate with their neighbors. Connections between modules are made with permanent magnets. The physical modules can form 2D hexagonal structures that will eventually be capable of locomotion, self-repair, and transport. Potential real world applications of these structures include planetary exploration and mass production of 3D objects. A physical prototype has been built and simulations using Open Dynamics Engine have been developed. A few physical modules are shown in Figure 17. Six physical modules have been constructed and the simulation is capable of simulating hundreds of modules. In both physical experiments and simulations, the modules formed two-dimensional hexagon structures, but in the simulations, 50 modules (instead of 6) were used, and three different grammars were tested and compared. The physical modules are triangular-shaped with an edge length of 12 centimeters and a height of 4 centimeters. Future plans involve building 100 physical modules, scaling down the size of the modules, and exploring different grammars that will assemble modules into other shapes and define processes such as locomotion, self-repair, and transportation.

Figure 17. Programmable parts partially forming a triangle structure [2].

2.18 Deformatron (2006)

Deformatron [32] is a homogeneous 3D modular robot with modules that resemble bone, muscle, and tendon structures. These modules can form either rigid lattice structures or flexible chain structures. Physical experiments have demonstrated that the muscle structures have actuation power, the joint structures can transfer translatory movement of muscles to rotational movement, and bone structures can transfer movement over long distances. Six LEGO-based prototype modules have been built that are cubic structures with a side length of 8 centimeters. A chain of several Deformatron modules appears in Figure 18. The connectors contain male and female part that fit into a ball and socket-type joint. Future connectors will use hooks instead.

Limitations of these robots are that there is no communication between modules and the modules do not contain a power source, and thus must be controlled externally. In the future, the researchers plan to build more modules, miniaturize the modules, and attempt to achieve point-based manipulation.

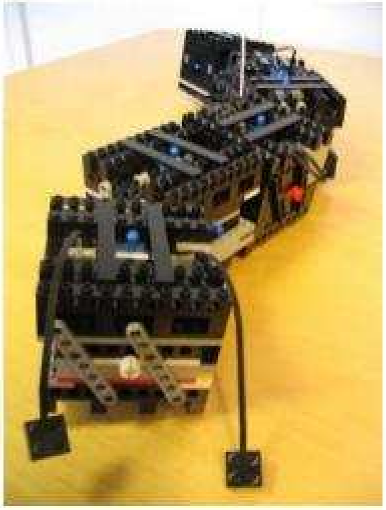

Figure 18. Deformatron prototype [32].

2.19 Amoeboid Robot (2006)

Self-reconfigurable robots with amoeboid locomotion use fully decentralized control mechanisms that are based on coupled biochemical oscillators [15]. Locomotion of modules is a result of interaction of forces on the robot. A symmetry breaking scheme generates a pumping motion between the anterior and posterior ends of the system. The robots are two-dimensional and are comprised of a protoplasm and outer skin layer. Each module has a light sensor and a ground friction control mechanism and is capable of local sensory feedback. The goal in experiments with these robots is to move towards a light source. The initial organization of these structures is 50 modules arranged in a circular shape. Figure 19 depicts basic movement of these amoeboid structures. In one experiment, the robots did not contain a protoplasm, and this led to the robot shrinking and thus unable to move. In another experiment, local sensory feedback was disabled, and this prevented the robot from generating any pumping action, resulting in immobility.

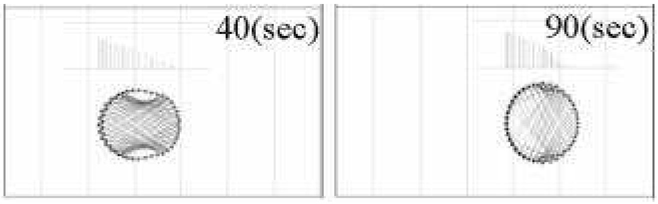

Figure 19. Basic amoeboid robot locomotion [15].

2.20 Odin (2007)

Odin [33] is a hierarchical lattice-based robot composed of two different types of modules- cylinder-shaped links and sphere-shaped joints. A prototype consisting of six links and four joints in a tetrahedron structure has been constructed, and this prototype is illustrated in Figure 20. The links are 35 mm in diameter and 110 mm in length, and the joints are 50 mm in diameter. Connections between modules involve a lock and key mechanism. The link modules are capable of communicating with neighbors, performing computation, and power sharing among modules. The modules use a hybrid global and local communication system. Locomotion is based on distributed role-based control. Physical tests were conducted to demonstrate forward movement, but so far Odin is only capable of locomotion in two dimensions. Future work includes performing more complex tasks, installing a power supply on each robot, and building four types of link modules -- structure, actuation, power, and sensing. Additional modules will also be built, which will allow multi-level hierarchies to be created. There is a question of which level of the hierarchy to implement specific functionalities. These robots are actually not self-reconfigurable, but it might be possible to achieve self-reconfiguration at a higher level.

Figure 20. Odin link and joint modules in a tetrahedron structure [33].

2.21 Morpho (2008)

The Morpho robot [40] is based on deformation and the tensegrity model of cellular structure, where cells exert expansion and contraction forces on the entire structure. Deformation is the critical biological process for transforming an embryo into a complex structure. Robots are assembled from four types of modules: active link, passive link, surface membrane, and interfacing cubes. The active links can change the shape of the structure, the passive links provide a supporting framework for the structure, the interfacing cubes provide attachment points for the links, and the surface membrane covers the skeleton and changes the structure into a volume or a surface. The modules can form 2D structures and 3D volumes, such as surfaces, cubes, and tetrahedrons, as well as compositions of those formations. Three types of physical prototype have been implemented: a self-deformable surface, an expandable cube, and a terrain-adaptive bridge. Open Dynamics Engine simulations have experimented with the dynamics of the three aforementioned prototypes, as well as biologically inspired structures that are volvox-like, amoeba-like, perform inchworm-like locomotion, and others that resemble programmable tissue material. Several examples of physical and simulated Morpho modules are depicted in Figure 21. Hardware experiments involve using a deformable surface for transporting a cubic object from one side to the other, maintaining a level bridge structure in a rough terrain, and expanding a cube structure. The movement and function of many of these structures have been compared to gut formation, heart contractions, travelling waves, and lamprey locomotion. These robots could eventually be capable of squeezing through small spaces, carrying loads, and used for prosthetic purposes. Future work includes creating adaptable programmable materials, as well as analyzing tradeoffs of different shape-formation techniques and distributed control algorithms for creating shapes that are complex, adaptive, and dynamic.

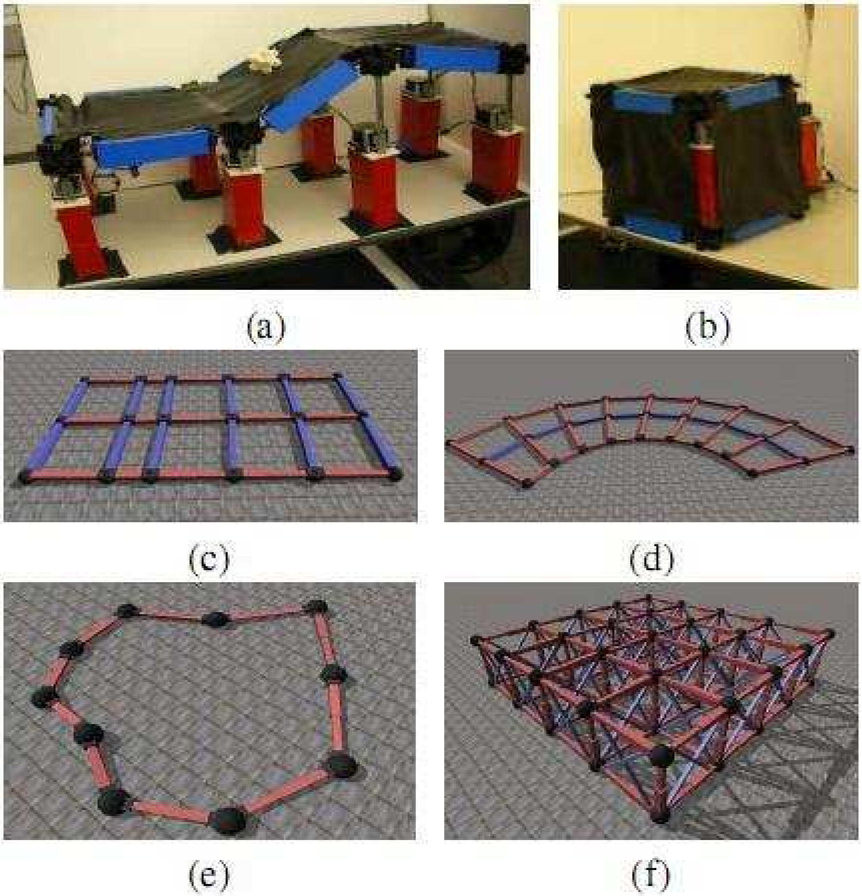

Figure 21. Several forms of Morpho. a. deformable track prototype, b. expandable cube, c. bio-inspired robot performing inchworm locomotion, d. robotic structure undergoing shape deformation, e. amoeba-like structure, f. tissue-like programmable material [40].

2.22 Anatomy-based Catoms (2008)

The anatomy-based catom robots [5] are inspired by the Claytronics project [9-11]. The robots have not yet been physically created, however, a number of promising simulations using Open Dynamics Engine have been implemented. They often involve thousands of sphere-shaped catom modules, and the researchers envision producing modules on the millimeter to micrometer scales (e.g. radius of 65 micrometers). The robots are hierarchical in both control and structure, in that modules form anatomical parts, which in turn form the robot structure. Modules can be combined to form biologically inspired lattice and/or chain structures that resemble muscle, cilia, bone, tendon, hinge-joint, and whisker. Two of these structures are shown in Figure 22. These structures are assumed to be capable of performing computation, communicating with neighbors, sensing points of contact with neighbors, sensing the direction of gravity, and local actuation. The simulated structures are able to achieve snake-like and crawler locomotion, form a cilia surface, assemble a muscle-actuated arm, and use whisker feedback for grasping objects. The behavior of the simulated anatomical parts is determined by local actuation of modules, artificial reflexes, synchronization using central pattern generators, sensor feedback, and gradients. The implementation of these anatomical parts is currently impractical on most platforms. However, miniaturization and the increase in number of modules may allow the creation of these structures to be feasible. The level of complex behavior attainable by the anatomical parts is also uncertain, although projects such as Odin [33] may allow an increase in the robot's behavioral complexity.

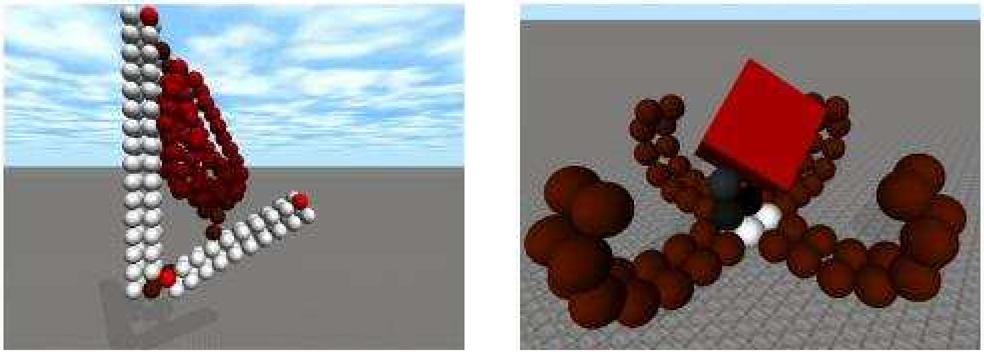

Figure 22. Anatomy-based catoms as a hinge-joint (left) and a feedback-based whisker structure catching a falling box (right) [5].

2.23 SWARMORPH (2009)

The SWARMORPH project [26] involves the development of a distributed scheme for generating morphologies using autonomous self-assembling mobile robots. Global structures emerge as a result of repeatedly applying local rules. This technique is applied to the swarm robot (s-bot) platform. A general limitation of self-assembling mobile robots has been the fact that there is little control over the structure of the formed robot assembly. This work proposes a mechanism for control of the growth of morphological structures based on self-assembly. One by one, individual robots connect to the forming assembly. Connecting robots are those currently connecting to the structure, and extending robots are robots that are already connected. Local rules consist of *Extend*, *Send*, *Wait*, *Decide*, *Balance*, and *GrowDense*. A limitation of this technique is that the growth pattern cannot be changed during its execution, thus, repeated structures are always generated. Experiments involving 7 physical s-bots generated shapes such as a line, arrow, star, and rectangle, as displayed in Figure 23. A real world application of this technique is robot navigation over rough terrain.

Figure 23. Structures generated from 7 real s-bots (line, rectangle, star, arrow) [26].

3 General Discussion

Following is a discussion of the above presentation in terms of features of self-reconfigurable robots that are of interest and relevance to ongoing research in the field.

3.1 Physical Characteristics of Self-Reconfigurable Robots

Most of these projects involve fewer than 10 physical modules thus far. Some have implemented as many as 20 modules and others have implemented as many as 100. Several of these projects may eventually involve hundreds to millions of physical modules. Simulations of robots have involved a much larger number of modules, hundreds to thousands in many cases. The size of the modules has generally been on the order of several centimeters. Researchers of many of these projects have goals for scaling these modules to be on the millimeter or micrometer scale. Projects such as Claytronics [9-11] envision modules on the nanoscale.

Several of these projects have experimented with a hierarchical structure of modules. Several modules are combined to construct a meta-module [1, 7], which in some cases, can group again to form another level of structure, as in the Molecule [18, 20] project. One major reason for the use of meta-modules is that it greatly simplifies reconfiguration planning algorithms, which would otherwise be impossible in some cases. Another reason is that several levels of structure allow for greater complexity and closer resemblance to biological structures, as in the ATRON anatomical parts [4] project. Most of the projects have involved homogeneous modules, although a few of them, including Odin [33], have prototyped heterogeneous modules.

The modules of many of the projects are capable of several functions, including connecting and disconnecting from neighbors, expanding and contracting, reacting to local interactions, basic computation, locomotion, rotation, climbing over neighbors, determining whether the module is connected to a neighbor, and communicating with neighboring modules. In some cases, modules represent biological structures such as bones, muscles, and tendons, as in the Deformatron [32], anatomy-based catoms [5], and ATRON anatomical parts [4] projects. For many of these projects, the modules are autonomous in that they contain their own processor and power supply. Sensing abilities for many of these modules include sensing position, orientation, contact, proximity, and gravity. Connection mechanisms among modules include electromagnets, permanent magnets, hooks, and a lock and key mechanism.

3.2 Mechanisms for Locomotion and Reconfiguration

Locomotion and reconfiguration of structures have been accomplished by numerous mechanisms. The Telecube [34, 36] modules expand and contract their sides to perform sliding motions similar to tiles of an 8-puzzle [37]. In the Molecule [18, 20] project, atoms of modules rotate around each other and execute convex and concave transitions. Crystalline [30] modules expand and contract to effect inchworm-like movement [29]. The Claytronics [9-11] modules are rearranged by means of random motion of “holes” within the structure [6]. The programmable parts [2] modules are controlled by graph grammars, which represent chemical reactions and involve random collisions of modules. Locomotion of the Morpho [40] robot is based on deformation and the tensegrity of cellular structure model. Anatomy-based catoms [5] employ several biologically inspired mechanisms such as artificial reflexes, central pattern generators, gradients, and sensor feedback. I-Cube [35] modules move according to rotations of the cube structures of the module. CHOBIE [17] modules perform sliding motions, where a seed module begins the process and a sprout is grown to extend the structure. The M-TRAN [19, 23, 24] project implements a motion planner that also uses genetic algorithms. Movement of Fracta [21] units is determined by fitness, diffusion, and activation. The Vertical [13] robots perform rotating and sliding motions similar to cellular automata. Metamorphic [28] modules roll and slide over their neighbors to achieve the desired structure. Bellows of compressed air is the motion mechanism for the Pneumatic [14] robot. Amoeboid [15] robots move as a result of a pumping motion between the anterior and posterior ends of the system. Structures of SWARMORPH [26] robots emerge from a repeated application of local rules. In movement for the 3D-Unit robot [22], one module acts as a pivot for the other, and modules can move on the plane or flip to the orthogonal plane. Superbot [31] combines mechanisms of M-TRAN, CONRO, and ATRON.

3.3 Capabilities and Applications of Self-Reconfigurable Robots

Numerous physical experiments have been conducted on prototype modules of the previously discussed projects. These experiments have involved basic connecting between units, basic reconfiguration, and basic forward motion. Many types of locomotion have been tested, including worm, inchworm, snake, rolling track, caterpillar, cilia surface, hexapod, slinky, spider, cluster walk, and car. Several other types of functions have also been tested, which include convex and concave transitions, flipping, rotating, recovering from failure, lifting another module, building a stairs structure, arm manipulation, ball balancing, an obstacle course with a step and tunnel, transporting an object across an adjustable ramp, maintaining a bridge structure in a rough environment, and an expandable cube [39, 40].

Simulations of numerous types of locomotion and reconfiguration have also been studied. Modes of locomotion include snake, caterpillar, insect, spider, rolling track, H-walker, inchworm, cartwheel, slinky, carrying an object while rolling, and climbing over obstacles (such as stairs). Reconfiguration sequences have been verified and executed and they involve transforming a dog-structure into a couch-structure [29, 30], converting a ladder into a tower [22], and creating and dismantling a stairs structure [13]. Several biologically inspired structures have also been created, including volvox, amoeba, programmable tissue [40], cilia surface, muscle actuated arm, and a whisker-like structure to provide sensing feedback to stimulate grasping of a falling object [5].

Besides locomotion and reconfiguration, the structures will eventually be capable of object manipulation, sorting, interacting with other systems, adapting to different environments, using tools, transportation, self-repair, climbing obstacles, traversing tunnels and pipes, and various sensing functions. There are numerous potential real-world applications of modular self-reconfigurable robots -- planetary exploration and various space applications, deep sea operations, radioactive environments, search and rescue, forming bridges and other structures, cooperative transportation, collection, construction, production lines and packaging, assembly lines and sorting, cleaning and maintaining hazardous machinery, nanorobotics, assisting the disabled, entertainment, synthetic reality, mass production of 3D objects, prosphetics, carrying loads, manipulating objects, avoiding obstacles in unstructured and constrained environments, encircling objects, and inspection.

3.4 Challenges for Self-Reconfigurable Robots

There are several limitations that challenge the researchers of many of these projects. These limitations include the fact that some of these robots are controlled externally, some types of configuration are difficult to reach, mechanical constraints of modules make transformations more difficult, and there is a tradeoff between efficiency and adaptability. Future work in modular self-reconfigurable robotics involves increasing the number of modules, constructing smaller, simpler, and lighter modules, building modules that are autonomous in that they contain their own processor, power supply, and sensors, improving the module hardware, strengthening self-repair capabilities, increasing robustness, constructing more complex structures and performing more complex tasks, improving adaptation to the current environment, improvements in motion planning, finding the optimal configuration for a given task, testing different types of terrain and travel distances, experimenting with parallel reconfiguration, and implementing distributed reconfiguration algorithms.

4 Conclusions

In this report, many different systems of self-reconfigurable robots were presented. Several interesting features and abilities of these robotic systems were discussed. Common goals among the researchers of a number of these projects include constructing thousands to millions of millimeter or micrometer robotic modules, and developing robotic structures that are self-repairing, able to perform more complex tasks, and have the ability to adapt to a variety of tasks and environments. If the researchers are successful in implementing these desired features, the use of robotic structures can be extended to domains and applications that are currently unrealizable.

References

[1] Bhat, P., Kuffner, J., Goldstein, S., Srinivasa, S. Hierarchical Motion Planning for Self-Reconfigurable Modular Robots, In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS*, 2006.

[2] Bishop, J., Burden, S., Klavins, E., Kreisberg, R., Malone, W., Napp, N., Nguyen, T. Programmable Parts: A Demonstration of the Grammatical Approach to Self-Organization, In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005.

[3] Castano, A., Chokkalingam R., Will, P. Autonomous and Self-Sufficient CONRO Modules for Reconfigurable Robots, In *Proceedings of the 5th International Symposium on Distributed Autonomous Robotic Systems*, pp. 155-164, 2000.

[4] Christensen, D. J., Brandt, D., Stoy, K. Towards Artificial ATRON Animals: Scalable Anatomy for Self-Reconfigurable Robots (extended abstract), In *Robotics Science and Systems: Workshop on Modular Self-Reconfigurable Systems*, Philadelphia, PA, USA, 2006.

[5] Christensen, D. J., Campbell, J. Anatomy-Based Organization of Modular Robots, In *Proceedings of the IEEE International Conference on Robotics & Automation*, Pasadena, CA, USA, pp. 3141-3148, 2008.

[6] De Rosa, M., Goldstein, S., Lee, P., Campbell, J., Pillai, P. Scalable Shape Sculpting via Hole Motion: Motion Planning in Lattice-Constrained Modular Robots, In *Proceedings of the IEEE International Conference on Robotics & Automation*, 2006.

[7] Dewey, D. J., Ashley-Rollman, M. P., De Rosa, M., Goldstein, S. C., Mowry, T. C., Srinivasa, S. S., Pillai, P., Campbell, J. Generalizing Metamodules to Simplify Planning in Modular Robotic Systems, In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS*, Nice, France, 2008.

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

[9] Goldstein, S. C., Mowry, T. Claytronics: A Scalable Basis for Future Robots (extended abstract), In *Robosphere*, 2004.

[10] Goldstein, S. C., Mowry, T. Claytronics: An Instance of Programmable Matter, In *Wild and Crazy Ideas Session of ASPLOS*, 2004.

[11] Goldstein, S. C., Campbell, J. D., Mowry, T. C., Programmable Matter, *Computer*, Vol. 38, No. 6, pp. 99-101, June 2005.

[12] Goldstein, S., Mowry, T., Campbell, J., Lee, P., Pillai, P., Hoburg, J., Gibbons, P., Guestrin, C., Kufner, J., Kirby, B., Rister, B., De Rosa, M., Funiak, S., Burak, A., Sukthankar, R. The Ensemble Principle (abstract), In *13th Foresight Conference on Advanced Nanotechnology*, San Francisco, CA, USA, October 2005.

[13] Hosokawa, K., Tsujimori, T., Fujii, T., Kaetsu, H., Asama, H., Kuroda, Y., Endo, I. Self-Organizing Collective Robots with Morphogenesis in a Vertical Plane, In *Proceedings of the IEEE International Conference on Robotics & Automation*, Leuven, Belgium, pp. 2858-2863,

1998.

[14] Inou, N., Kobayashi, H., Koseki, M. Development of Pneumatic Cellular Robots Forming a Mechanical Structure, In *Seventh International Conference on Control, Automation, Robotics, and Vision (ICARCV '02)*, Singapore, pp. 63-68, December 2002.

[15] Ishiguro, A., Umedachi, T., Kitamura, T., Nakagaki, T., Kobayashi, R. A Fully Decentralized Morphology Control of an Amoeboid Robot by Exploiting the Law of Conservation of Protoplasmic Mass, In *Proceedings of IROS: Self-Reconfigurable Robots, Systems, and Applications*, 2008.

[16] Jorgensen, M. W., Ostergaard, E. H., Lund, H. H. Modular ATRON: Modules for a Self-Reconfigurable Robot, In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Sendai, Japan, pp. 2068-2073, 2004.

[17] Koseki, M., Minami, K., Inou, N. Cellular Robots Forming a Mechanical Structure (Evaluation of Structural Formation and Hardware Design of "CHOBIE II"), In *Proceedings of the International Symposium on Distributed Autonomous Robotic Systems*, pp. 131-140, 2004.

[18] Kotay, K., Rus, D., Vona, M., McGray, C. The Self-Reconfiguring Robotic Molecule: Design and Control Algorithms, In *the 1998 Workshop on Algorithmic Foundations of Robotics*, 1998.

[19] Kurokawa, H., Yoshida, E., Tomita, K., Kamimura, A., Murata, S., Kokaji, S. Self-Reconfigurable M-TRAN Structures and Walker Generation, *Robotics and Autonomous Systems*, Vol. 54, No. 2, pp. 142-149, 2006.

[20] McGray, C., Rus, D. Self-Reconfigurable Molecule Robots as 3D Metamorphic Robots, In *Proceedings of the International Conference on Intelligent Robots and Systems*, 1998.

[21] Murata, S., Kurokawa, H., Kokaji, S. Self-Assembling Machine, In *Proceedings of the IEEE International Conference on Robotics & Automation*, pp. 441-448, 1994.

[22] Murata, S., Kurokawa, H., Yoshida, E., Tomita, K., Kokaji, S. A 3D Self-Reconfigurable Structure, In *Proceedings of the IEEE International Conference on Robotics & Automation*, Leuven, Belgium, pp. 432-439, 1998.

[23] Murata, S., Yoshida, E., Kamimura, A., Kurokawa, H., Tomita, K., Kokaji, S. M-TRAN: Self-Reconfigurable Modular Robotic System, *IEEE/ASME Transactions on Mechatronics*, Vol. 7, No. 4, pp. 431-441, December 2002.

[24] Murata, S., Kamimura, A., Kurokawa, H., Yoshida, E., Tomita, K., Kokaji, S. Self-Reconfigurable Robots: Platforms for Emerging Functionality, In *LNAI*, Vol. 3139, pp. 312-330, 2004.

[25] Murata, S., Kurokawa, H. Self-Reconfigurable Robots: Shape-Changing Cellular Robots Can Exceed Conventional Robot Flexibility, *IEEE Robotics & Automation Magazine*, pp. 71-78, March 2007.

[26] O'Grady, R., Christensen, A. L., Dorigo, M. SWARMORPH: Multirobot Morphogenesis Using Directional Self-Assembly, *IEEE Transactions on Robotics*, Vol. 25, No. 3, pp. 738-743, 2009.

[27] Ostergaard, E. H., Kassow, K., Beck, R., Lund, H. H. Design of the ATRON Lattice-Based Self-Reconfigurable Robot, *Autonomous Robots*, Vol. 21, pp. 165-183, 2006.

[28] Pamecha, A., Chiang, C., Stein, D., Chirikjian, G. Design and Implementation of Metamorphic Robots, In *Proceedings of the ASME Design Engineering Technical Conference and Computers in Engineering Conference*, Irvine, CA, USA, 1996.

[29] Rus, D., Vona, M. Self-Reconfiguration Planning with Compressible Unit Modules, In *Proceedings of the IEEE International Conference of Robotics & Automation*, Detroit, MI, USA, Vol. 4, pp. 2513-2520, 1999.

[30] Rus, D., Vona, M. A Physical Implementation of the Self-Reconfiguring Crystalline Robot, In *Proceedings of the IEEE International Conference on Robotics & Automation*, pp. 1726-1733, 2000.

[31] Shen, W., Krivokon, M., Chiu, H., Everist, J., Rubenstein, M., Venkatesh, J. Multimode Locomotion, via SuperBot Reconfigurable Robots, *Autonomous Robots*, Vol. 20, pp. 165-177, 2006.

[32] Stoy, K. The Deformatron Robot: a Biologically Inspired Homogeneous Modular Robot, In *Proceedings of the IEEE International Conference on Robotics & Automation*, Orlando, FL, pp. 2527-2531, 2006.

[33] Stoy, K., Lyder, A., Garcia, R. F. M., Christensen, D. Hierarchical Robots, In *IROS Workshop on Self-Reconfigurable Robots, Systems, and Applications*, 2007.

[34] Suh, J. W., Homans, S. B., Yim, M. Telecubes: Mechanical Design of a Module for Self-Reconfigurable Robotics, In *Proceedings of the IEEE International Conference on Robotics & Automation*, Washington DC, USA, pp. 4095-4101, 2002.

[35] Unsal, C., Kiliccote, H., Khosla, P. K. I(CES)-cubes: A Modular Self-Reconfigurable Bipartite Robotic System, In *Proceedings of SPIE*, Vol. 3839: Sensor Fusion and Decentralized Control in Robotic Systems II, Boston, MA, USA, pp. 258-269, 1999.

[36] Vassilvitskii, S., Kubica, J., Rieffel, E., Suh, J., Yim, M. On the General Reconfiguration Problem for Expanding Cube Style Modular Robots, In *Proceedings of the IEEE International Conference on Robotics & Automation*, Washington DC, USA, 2002.

[37] Weller, M. P., Karagozler, M. E., Kirby, B., Campbell, J., Goldstein, S. C. Movement-Primitives for an Orthogonal Prismatic Closed-Lattice-Constrained Self-Reconfiguring Module, In *Proceedings of the IEEE International Conference on Intelligent Robots and Systems IROS*, 2007.

[38] Yim, M., Duff, D. G., Roufas, K. D. PolyBot: A Modular Reconfigurable Robot, In *Proceedings of the IEEE International Conference on Robotics & Automation*, San Francisco, CA, USA, pp. 514-520, 2000.

[39] Yu, C., Willems, F., Ingber, D., Nagpal, R. Self-Organization of Environmentally-Adaptive Shapes on a Modular Robot, In *Proceedings of IROS*, 2007.

[40] Yu, C., Haller, K., Ingber, D., Nagpal, R. Morpho: A Self-Deformable Modular Robot Inspired by Cellular Structure, In *Proceedings of IROS*, 2008.