Chapter 3
Modular Reconfigurable Robotic Systems: Lattice Automata

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Abstract Modular and reconfigurable robots hold the promises of versatility, low cost, and robustness. Many different implementations utilizing lattice structures exist, with varying advantages. We introduce, define terms for, and describe in full several key systems. Comparisons between connection mechanisms are made. We describe some of the software concerns for modular robots, and review the applications of self-assembly and self-repair.

3.1 Introduction

Modular and Reconfigurable Robotic Systems (or MRR systems, as they will be referred to in this chapter) are robotic systems that are made up of many repeated modules that can be rearranged. They can be classified by the underlying structure used to organize a group of modules; *chain* type systems are organized into a chain or tree structure whereas *lattice* type systems are organized on a lattice structure. *Hybrid* systems are those that can switch between these organizations. This chapter will serve to introduce the concepts of MRR systems specifically focusing on lattice and hybrid type MRR systems. More detail on the type descriptions is given in Sect. 3.1.2.

A **modular** robot is defined as one that is "built from several physically independent units that encapsulate some of the complexity of their functionality" [37]. A **reconfigurable** modular robot is defined as one where the module's connectivity can be changed. One example of a lattice type MRR system is shown in Fig. 3.1.

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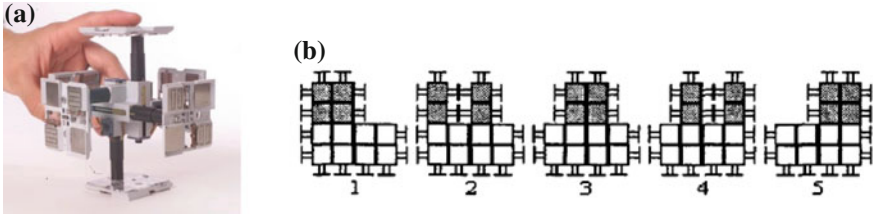e-mail: neck@seas.upenn.edu

(a)

(b)

Fig. 3.1 The Telecube [38] system is an archetypical 3D lattice-type modular reconfigurable robot system. The system can expand each side to accomplish motion along the lattice. Docking attachment is accomplished by means of switching permanent magnet faces. The figure on the *right* depicts Telecubes performing a reconfiguration operation [43]. **a** Telecube physical prototype, **b** Telecubes reconfiguring

3.1.1 Motivation

MRR systems hold three promises: versatility, robustness and low cost.

Versatility Typically, a robot is built to certain size and shape specifically for a given application with an associated set of tasks. MRR systems can be reconfigured into many different sizes and shapes and so can achieve many more tasks than fixed configuration systems.

Robustness MRR systems achieve robustness through redundancy and self-repair. If a module or set of modules malfunctions or is damaged, the robot can recognize this and utilize redundant module(s) from elsewhere in the configuration or replace good modules for bad ones.

Low cost MRR systems typically have many repeated modules. This repetition allows batch fabrication and mass production techniques to be utilized to lower the cost of the individual modules.

Note that of these three promises, only versatility has been proven so far. More redundancy means more opportunity for failure, so techniques must be developed that provide graceful degradation of performance with redundancy. Lower individual module cost can help reduce costs, but the overall system cost to achieve tasks is the ultimate goal.

3.1.2 Key Terminology

As mentioned earlier, MRR systems fit into several different types [37, 49]. Examples of these types are shown in Fig. 3.2.

Lattice type systems have modules that are nominally situated on a virtual lattice. Each module occupies one site in the lattice and is capable of moving to a neighboring site. This movement is characterized by a simple motion along a single degree of
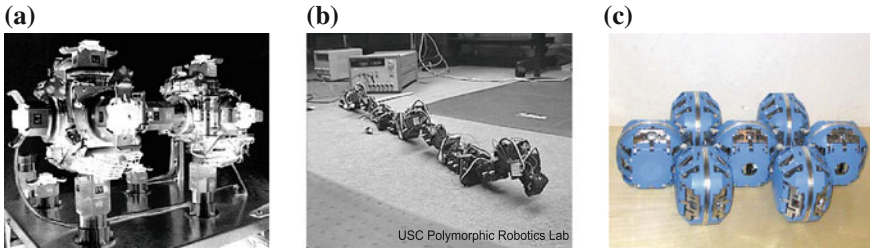
Fig. 3.2 Examples of MRR types. **a** 3D Unit, another lattice-type modular system, **b** CONRO, a chain-type modular robot in a snake configuration, **c** ATRON [27], a hybrid-type robot

freedom (DOF) path with a swept volume local to the neighborhood of the site. The local property of this motion means that the motion planning and collision detection is independent of the number of modules.

Chain type systems are organized in a chain or tree architecture. To reconfigure, chains of modules attach two ends together and break at a different point. Sequences of making and breaking loops serve to reconfigure a system from one shape into a goal shape. For these chains, the computational time complexity of motion planning scales with the number of modules. For this reason, reconfiguration planning, that is the determination of a sequence of motions, attachments and detachments of an MRR system has been much easier with lattice systems. However, chain systems can form articulated arms/legs and tend to be easier to use for robotic tasks such as locomotion or manipulation of objects.

Hybrid type systems can operate as either a lattice type or a chain type system. Their capabilities can be organized either way depending on the application.

Other types for MRR system categorizations [3] focus on reconfiguration mechanisms and include *mobile* type systems. Mobile systems have modules that can move independently in the environment. In this chapter however, the reconfiguration is not as central as the organization of modules, so the mobility of individual modules is listed simply as a property of the system.

Connectedness describes how many faces on one module can be connected to another module. For a given polyhedral base, the number of available connection faces describes the connectedness. For example, a cube has six faces and if all six faces are possible connection faces, the module is said to have full 6-connectedness. It is typically desirable to have full connectedness, but in many cases, it is difficult to implement.

A *configuration* refers to the arrangement of modules with the associated connectivity. Note this does not include the joint angles of the modules which result in a particular shape, or pose of the robot.

Terms for collections of modules include; *cluster*, meaning a small set of contiguous modules, and *meta-module*, which is a configuration of a small number of modules that acts as a repeated element within a larger configuration. Meta-module planning is often used to improve the speed of reconfiguration planning.

3.1.3 Environments

Lattice MRR systems exist in multiple environments, although the primary environment of choice is land or on a pre-existing lattice structure. Land systems will be shown in detail in the section focused on hardware, so here we will note only systems which perform in alternate environments.

Some lattice systems operate with at least one 'anchor site'. This anchor site is either a passive representation of the connector used between modules, or a stationary module others can attach to, serving as a base site and reference frame. Modules which make use of anchor sites include Xbot [46], 3D Fracta [23] and the Crystalline robot [2], all of which use the existing anchor sites for stability and are shown in Sect. 3.3.1.

Recently, the DARPA TEMP system accomplished reconfiguration of on the surface of water, as a testbed for a modular deployable seabase system [26]. Assembly consisted of arranging 33 modules autonomously into a bridge shape, which was then crossed by a remote controlled car. The TEMP system is a more modular version of an earlier project known as the Mobile Operating Base, composed of 3–5 large modules [13]. Other systems in fluid environments include stochastic-based assembly systems from Tolley et al. [39].

The only MRR system to perform in air of note is the Distributed Flight Array, a 2D planar array of rotors which perform decentralized flight control, driving, and docking. In this manner the system can self-assemble, take off, and perform controlled flight [28], though reconfiguration occurs on land.

3.2 Challenges and Practical Issues for MRR

3.2.1 General Limitations

Many limitations exist in the context of MRR systems, principally due to design requirements. Counterintuitively, the repetitive nature of MRR systems can be quite constraining. Required functionality of a system must be decomposed into identical modules, yet having the entire functionality in a single module would defeat the purpose of having and MRR system.

In any MRR system, requirements can be broken into two parts, task requirements and reconfigurability requirements. Since the task is unknown a priori, generic task requirements lead to system characteristics such as strength, size, weight, power capacity, efficiency and precision. Reconfigurability requirements lead to system characteristics involved with attaching and detaching mechanisms.

Development and improvements to an existing design are constrained by the form factor limitations. In a lattice MRR system, the given lattice structure has a characteristic size of a unit cell in the system. For example, the lattice size in the CKBot version 1.0 modules was 60mm × 60mm × 60mm. No part of the module may extend beyond this lattice size. The motor in particular often requires a large

footprint within the module, taking up space that could be used for battery, control board, sensors, etc. As with most designs, trade-offs must be taken with the most crucial features having the highest priority of space and position.

To help us further reduce the strain on the lattice space, some implementations of these types of systems move certain function requirements off-board or to separate specialized heterogeneous modules. These functions are then relayed through a tether, bus, or mechanical attachment to the full system. Functions which have been successfully moved outside of the module itself include power, sensing, communication/control, and even actuation [47], as we will note below.

3.2.2 Key Metrics

Comparing MRR designs is somewhat difficult due to the variations in intended application and design requirements. For example, measuring strength alone is not straight forward since modules with larger lattice sizes will typically contain larger motors. To that end, we must reformulate our metrics of comparison to better understand the advantages between different designs. A leading metric for modular systems is the number of modules in a system. The more modules the system supports, the more complex and interesting behaviors exist for the system to perform. Additionally, larger systems may be able to engage larger forces by parallel actuation.

The record for number of modules simulated is 130^3 (2.2 million), for a cube shaped conglomerate of lattice-type simulated modules 130 to a side [8]. The record for number of physical modules implemented at once in a single robot is held by M-TRAN (Mark III), which had produced 50 modules.

In order to accomplish sophisticated mass behaviors with many modules, we wish to have smaller modules—so small size is another desirable quantity. Externally controlled assembly systems have been built as small as $500 \times 500 \times 30\mu m$ employed by Lipson et. al. [39]. Self-actuated systems such as Smart Blocks [31] and Milli-Motein [19] are 10mm in size. With many modules on a significantly small scale, we increase the resolution of our systems and come closer to presenting a seemingly 'continuous' set of behaviors for locomotion, reconfiguration, etc.

Larger modules can be desirable as well—if for example we wish to construct a large structures with a minimum of materials. The Giant Helium Catoms (GHC) currently hold the record of largest module at a cube size approximately 1.9 m on a side.

A key metric to the reconfigurability requirements is the bonding strength of the attaching mechanism. For many systems which uses hooks or latches, the material strength of the hook or latch is the limiting factor and is typically large compared to the strength of actuators. For systems which use magnetic or electrostatic bonding, the strength of the bond is much weaker and can be a limiting factor in the size of a conglomerate system.

A related metric is the force required to un-bond or de-dock. Typically stronger bonds also require concomitantly large forces or energy to undo them. For example,

low temperature melting point alloys can be used to bond two modules, but require a large amount of energy to melt the bond.

3.2.3 Modular Robot Morphology—Shape and Connectedness

MRR Systems have had a variety of shapes and lattice types since the first system was created in 1989 [9]. Shapes that have the properties of being space-filling and easily calculated lattice positions are desirable. With the exception of the cube, most regular polyhedra do not tile space. Two other polyhedra that tile space include a rhombic dodecahedron and a right angle tetrahedron. This tiling implies the underlying lattice structure. For example, the rhombic dodecahedron is the resulting shell of one cell of the Voronoi diagram of the centers of a face centered cubic lattice structure.

Connectedness impacts the range of configurations possible with a given MRR system. Connectedness affects the available graph representations [18] and practical applications—i.e. a cubic system which connects four out of six faces cannot always represent all possible configurations. Most systems also construct the connector with symmetries in such a way that two connected modules can have more than one way to attach. In the M-TRAN system for example, any two eligible faces (that is, a male-female pair) can connect in up to four ways, each option representing a 90° change in orientation.

We will call the combination of the external shape occupied by the module (e.g. the angles of joints in the robot) and the configuration the *morphology* for the purposes of this chapter.

3.3 Example Lattice System Hardware

Here we profile several systems, and discuss relevant features compared across platforms. Each system presented represents a set of solutions to the unique design challenges faced in MRR systems design. We will first present each system in detail and then compare features as they were implemented. Systems are sorted roughly by lattice type.

3.3.1 Key Designs

3.3.1.1 Three-Dimensional Systems

The majority of implementations use cubic shaped modules. Early systems include the 3d-Unit, Molecule and Telecube systems.

The **3d-Unit** (or 3D Fracta, as it is sometimes called) exists on the cubic lattice with full 6-connectedness. The system uses a single motor and a clutch to individually actuate one of the 12 degrees of freedom as required (six for rotation of faces, six for connecting faces) [23]. The 3d-Unit system can be seen in Fig. 3.2a. The connectors are paired at 90° by a special handshake mechanism, meaning a successful connection may require rotation along a face. Power and communication are transmitted through this connection mechanism. Movement of a module in the lattice requires rotation by an adjacent module using a connection on that adjacent module on the axis of rotation. In this way modules can be moved laterally or vertically one position at a time. Actuation for both the face rotation and connection mechanism is accomplished by means of a single DC motor/harmonic drive combination for each module. A diagram of the motion pattern is shown in Fig. 3.3.

The Self-Reconfiguring Robotic Molecule [20], often referred to simply as the **Molecule** system also exists on the cubic lattice. Each molecule is composed of two 'atoms', connected by a right-angle bracket, so each contiguous module takes up three positions on the cubic lattice, in an 'L' shape. Each atom has five connectors to connect to other modules and two actuated degrees of freedom; one about the right-angle connection and one about a single connector. RC servomotors are used for the two rotational degrees of freedom. The connection is accomplished by means of oppositely polarized 1″ electromagnet faces, with an interlocking sheath pattern to prevent undesired rotations. Electronic hardware on the module is composed of a microprocessor and controllers for the electromagnets and servos, with high-level control of the system accomplished by a workstation connected to the module by RS-485 connection. Despite the somewhat strange shape of the module, it has no problems traversing the lattice in a straight line or over convex/concave edges, computing the straightest path in O(n) time. A Molecule prototype can be seen in Fig. 3.4.

The **Telecube** system (Fig. 3.1), like 3d-Unit, exists on the cubic lattice with full 6-connectedness. Each face has a prismatic DOF allowing any side to expand to more than twice its original length. Careful control of connections and use of the prismatic DOFs results in motion in the desired direction along the lattice. This method of module motion is a 3D extension of a 2D system called *Crystalline* [2]. Connection between faces is accomplished by means of permanent magnet faces. These perma-

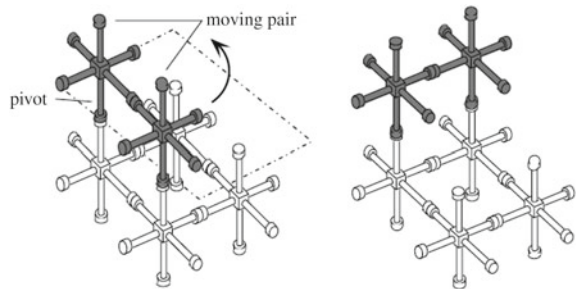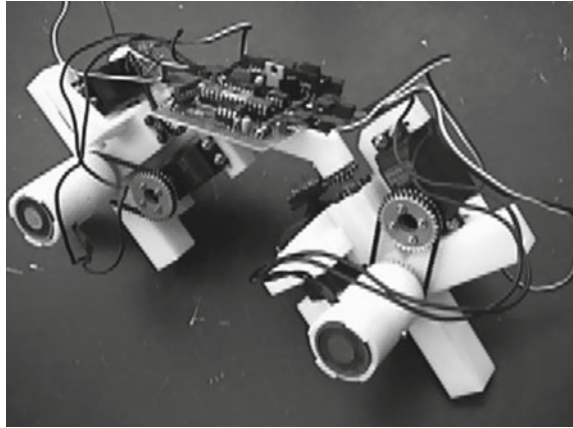**Fig. 3.3** 3d Unit Lattice motion pattern

nent magnet faces have two layers of neodymium magnets, and connection status
is changed by moving one set of magnets one pitch length thus changing the path
of magnetic flux. The magnets are moved by a shape memory alloy (SMA) mech-
anism which shifts the layer. The frame material is chosen both because it is light
and because it is internally lubricated to provide low friction. The linear actuation is
achieved via brushless DC motors attached to worm gears.

The largest MRR system in the literature is the **Giant Helium Catoms** (**GHC**),
developed at CMU. One possible application is extraplanetary structures where ultra-
light expandable modules would be useful for structural applications [17]. The GHC
exists on the cubic lattice with full 6-connectedness. Connection between modules is
accomplished by use of a novel electrostatic adhesion mechanism. Each face has four
flaps which contain two electrodes each, with a dielectric material (mylar) in between.
This allows charges to build up across the module interface, creating the electrostatic
attraction. Each flap corresponds to an edge on the face, as seen in Fig. 3.5. The flaps
themselves can be actuated to extend by means of Nitinol (SMA) wires, with reverse
actuation by a constant force spring to close the flap back down. Each module was
filled with helium, allowing for a total module weight of 50 g, despite the modules
being approx. 1.9 m on a side. Each module had a central processing board and six
outer slave boards, one for each face, as well as its own battery for power and Zig-
bee for wireless communication, although power transmission is proposed between
modules via the adhesion interface. Sensors and actuators are controlled using the
I^2C bus. Each flap angle was controlled and sensed by a combination of the flap
voltage and a potentiometer to measure angle.

The **M-TRAN** system (Mark III) [21] is a hybrid system that can be organized
on a simple cubic lattice (Figs. 3.6 and 3.7). Each module is composed of two cubes
with a revolute DOF about the center of each cube relative to a link that attaches to
both. The blocks each occupy a single simple cubic lattice site; thus each module
occupies two adjacent sites. As a hybrid system the modules can form chains to
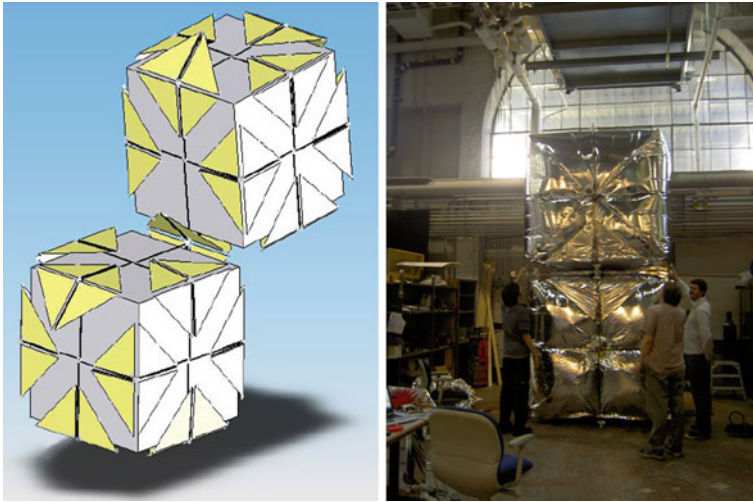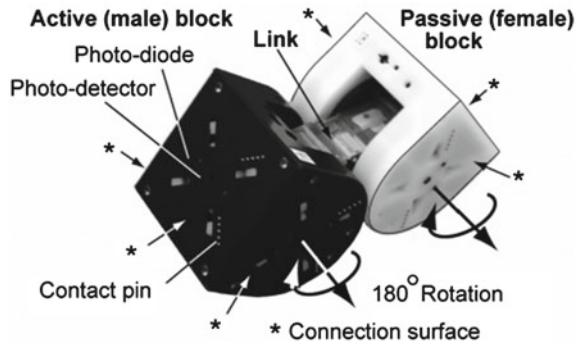perform articulated tasks but can also arrange themselves on the cubic lattice for

Fig. 3.5 GHC robot with 4 flaps on each face, 24 flaps total. Each flap can be rotated about the edge to accomplish module motion, as seen in the *left-hand* image. The image on the *right* shows two prototypes stacked on *top* of one another

Fig. 3.6 M-TRAN III
Module

reconfiguration. One block has three active latching male connection mechanisms; the other has three passive female connection plates. Each module has a total of five DC motors (two for the link section—one for each block, plus one for each of the three active male faces). Module motion is accomplished by the combined motion of the two link motors, as well as selective attachment/detachment to other modules in the lattice. The conjoined male/female combination of modules results in a tiling alternating block gender along each cartesian coordinate. It checkerboards the a three-dimensional space. Each connector pair can be oriented at an offset of 0, 90, 180, or 270°, giving four symmetric possible orientations. By clever arrangement of modules then it is possible to move modules from one axis-alignment to another during reconfiguration. M-TRAN III carries the distinction of having demonstrated

Fig. 3.7 M-TRAN Mark III
moving along a lattice
structure by reconfiguration
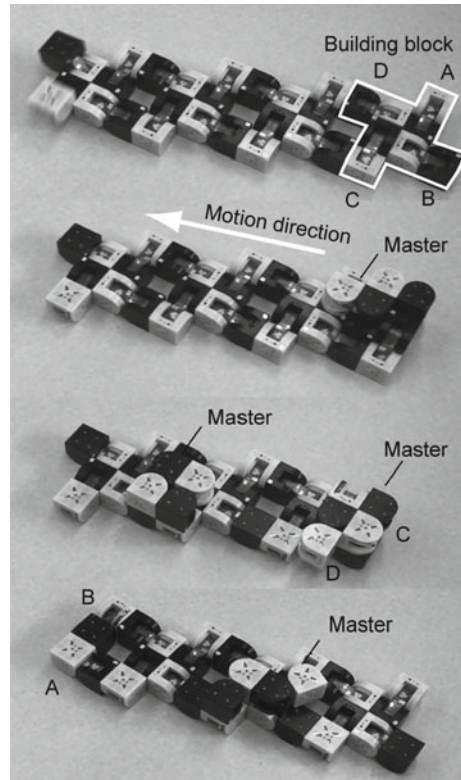
the most reliability of a system of its complexity, having changed surface connections by up to 24 modules over 100 times.

The **SMORES** modular system [5] are organized on the cubic lattice, forming a cube with four connection ports. It has four actuated DOF. Two of the DOF serve as wheels allowing each module to move independently, making SMORES a mobile system. The other two actuation degrees of freedom allow tilt and pan of the module faces. This design has the ability to emulate many other types of modular robots and progress towards a "universal" modular robot. In this way the SMORES system is capable of emulating many of the existing lattice and chain type modular robots successfully, in the hopes that the system will have the combined capabilities of many of the existing systems.

A recent system developed at MIT, **M-Blocks** (Fig. 3.8), exists on the cubic lattice with full 6-connectedness [33]. It uses internal inertial exchange to move modules in the lattice. A flywheel located within the module in combination with a belt brake allow the module to abruptly exchange angular momentum. The external frame contains of a set of 24 diametrically magnetized magnets (2 on each edge). These magnets ensure that edge-edge contact is maintained during the motion, with another set of 8 smaller magnets on the faces to ensure the module bonds in an aligned position.

Fig. 3.8 M-Blocks robots. *Top figure* shows the hardware, including the magnet patterns on the edges/faces, as well as the flywheel. *Bottom figures* show the path taken by a module during a typical convex transition pivot motion. *Photo* by John Romanishin (Daniela Rus's Distributed Robotics Laboratory at CSAIL, MIT)
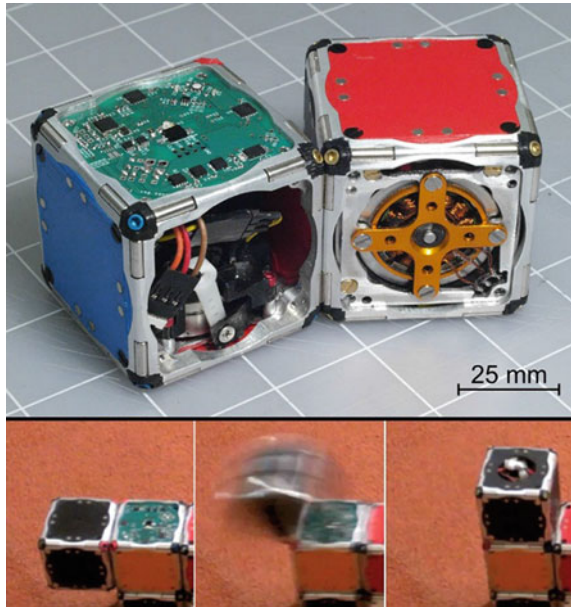
Presently the system can only move in the plane perpendicular to the axis of rotation of the flywheel, though developing a system with three perpendicular flywheels is feasible. Due to the unique mechanism for motion, modules are capable of moving independently of the lattice, making them a *mobile* system. Each module also contains its own power, wireless (Xbee) communication, and a 32-bit /ARM microprocessor. Sensors include a 6-axis IMU, an IR LED/photodiode pair for intermodule communication, and Hall Effect sensors to detect misalignments. Reconfiguration planning requires a bit of compensation for the way in which the modules pivot about an edge, precluding other modules from occupying corresponding positions which could block the motion. The authors address these issues with a Pivoting Cube Model (PCM) for reconfiguration.

ATRON, a system developed at the University of Southern Denmark, is the only modular system modeled on a "face-centered cubic" lattice, allowing connections to up to 8 other modules [27]. Its major components can be seen in Fig. 3.10. The module has two halves which can spin relative to one another somewhat like a wheel. This motion won't cause the module itself to move itself to another lattice position, but it will move two other modules relative to each other. Each half of each module has two actively-driven male connectors and two passive female connectors, as well as a microprocessor. Each module carries its own power, and the two halves of the module share power and communications through a large slip ring in the central plane of the module. This allows for continuous uninterrupted motion of one half relative to the other, for 'wheel' type functionality in a module.
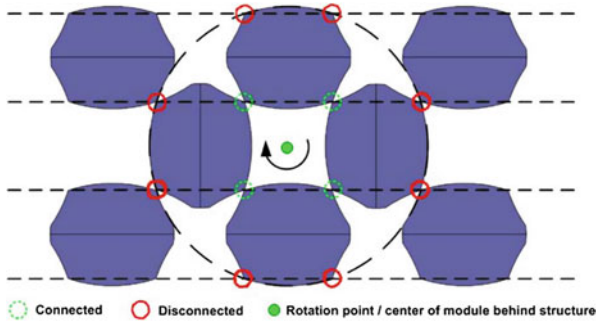
○ Connected   ○ Disconnected   ● Rotation point / center of module behind structure

Fig. 3.9 ATRON Robot, performing swap with a full lattice. The *center* point represents an out-of-plane module which rotates to perform the swap
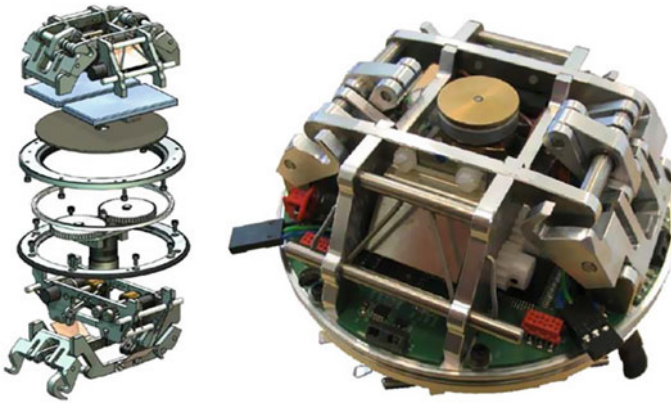

Fig. 3.10 ATRON Robot, Exploded view and full prototype without plastic cover

Inter-module connection is accomplished by mechanical arms which reach out and 'grab' the passive connector, simultaneously aligning it and making a solid mechanical connection. Inter-module communication is accomplished by an infrared emitter-detector pair which also serves as a proximity sensor. The lattice choice combined with appropriate shaping of the module exterior permits modules to be moved even in a fully-packed lattice, as shown in Fig. 3.9. ATRON can connect its modules only orthogonally (that is, at the 90° angles seen in Fig. 3.2c), and so has no orientation options between two modules like other systems. With the large hooks for latching, the connection system has one of the strongest bonds, but also consumes a majority of the space within each module.

3.3.1.2 Two-Dimensional Systems

Although full-scale reconfiguration would ideally be on a three-dimensional lattice, many two-dimensional systems have made interesting advances in the technology. In

particular, removing the necessity to compensate for gravity reduces the functional strength requirement, allowing experimentation with alternative actuation methods and reducing actuation overhead. The following systems are organized on a two-dimensional lattice.

The **X-Bots** system developed at the University of Pennsylvania [46] is organized on the 2D lattice with full 4-connectedness. Each X-bot is simplified by containing only local power, processing and connection systems. Communication is performed by conductor contact at the connection points. Actuation is located externally, by placing the system on an X–Y stage. In this way the system can use selective connection in combination with inertial motion to reconfigure the system, as shown in Fig. 3.11. In addition to rotations of a single module around an axis, by selective disconnection the system has demonstrated more complicated two-module 'motion primitives' to enable reconfiguration into arbitrary conglomerate shapes. As with many systems, a proof is shown that any arbitrary shape can be obtained. An algorithm is developed that determines a sequence of motions that transform any configuration into a canonical configuration (e.g. a single line of modules). This sequence is reversible so any configuration can transformed into any other by transforming into the canonical configuration and reversing the sequence into the goal configuration.

The **Micro Unit** system [53] exists on the 2D lattice with full 4-connectedness. Each module has two male and two female connectors at the corners, about which the modules rotate. All rotation and actuation of the latching for connection is accomplished by SMA wires heated electrically. These wires allow rotation at the corners between modules, as well as activation/deactivation of latches between modules. The Micro Unit system is one of the smallest systems prototyped at a system size of 2 cm. A prototype can be seen in Fig. 3.12.
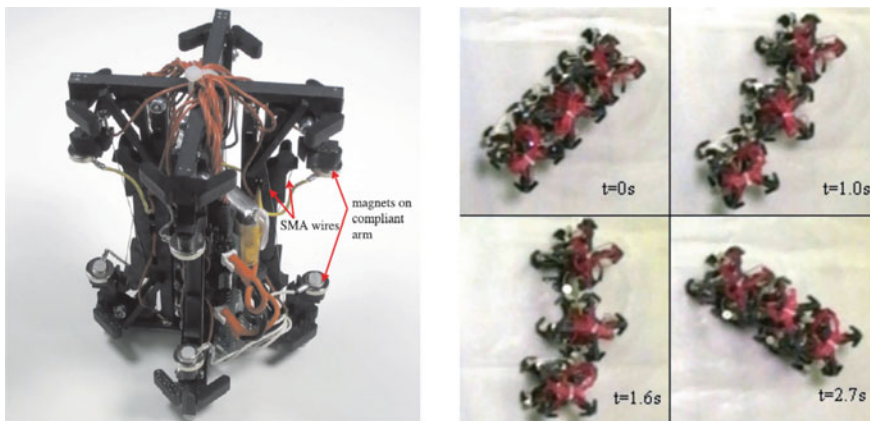

Fig. 3.11 *Left* X-Bots module. Connection magnets and SMA wires are visible, power and processing contained within frame. *Right* X-Bots module undergoing complex motion primitive. By disconnecting two modules at specific points, the inertial motion can reconfigure both at once
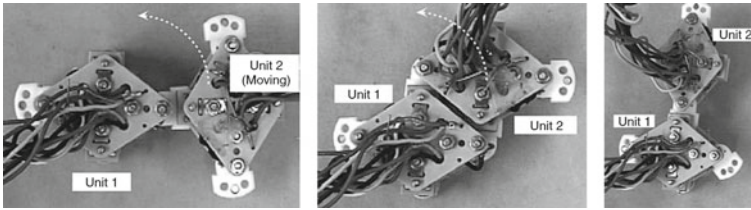
Fig. 3.12 The Micro unit system undergoing reconfiguration. Male and female connectors are visible

The 1-cm **Pebbles** system, developed at MIT, was the first to make use of electro-permanent magnets as a connection mechanism for modules. These devices consist of two rods of different types of magnet materials with nearly the same magnetic strength but widely differing coercivity, capped with iron and wrapped in an electromagnet coil. The two rods are made of Neodymium-Iron-Boron (NdFeB) and Alnico V, respectively. The Alnico magnet switches its polarity much more readily, so a pulse from the electromagnet coil switches this magnet, but not the NdFeB. If the two magnets have the same polarity, magnetic flux points outward and the module can attract other modules. If however, the Alnico is flipped by the coil and has the opposite polarity of the NdFeB magnet, the flux circulates within the EP magnet and does not leave through the poles. While this mechanism requires some power to change the polarity of the Alnico magnet and switch states, it does not require any power once a state has been set; it is bistable. Power is transmitted between modules by conductor contact and communication is transmitted by induction through the magnets. Module motion was not implemented for this system; the idea is for construction of a shape by *self-disassembly*, rather than self-assembly or self-reconfiguration. This means shapes are formed by deactivation of the EP magnets, allowing extraneous modules to drop out when external force is applied to the system. You can see several shapes formed by Pebbles in this way in Fig. 3.13, along with a prototype.

The **EM-Cube** [1], presented in 2008 by An, exists on a 2D square lattice, with full 4-connectedness. Each module contains a microprocessor and a Zigbee chip for wireless communication. Power is supplied externally. The motion method for the EM-Cube is novel; two faces (bottom and left) contain a pair of permanent magnets. The other two faces (top and right) contain three electromagnets. By changing the polarity of these electromagnets, the overall magnetic force changes, allowing the EM-Cube to move through a five-step process from one module to the next, as seen on the right in Fig. 3.14. So long as all modules are placed in the lattice with the same orientation, any module can be moved—either with its own electromagnets or by the neighboring modules. However, some creativity is required for a module to move around a convex corner, as you can see in Fig. 3.15. Since a surface of two modules is required to move a module, two modules must move together to accomplish the convex transition. An also presents other motion algorithms for four-module conglomerations, including one that accomplishes motion as long as it is allowed to run, automatically accounting for convex/concave transitions.
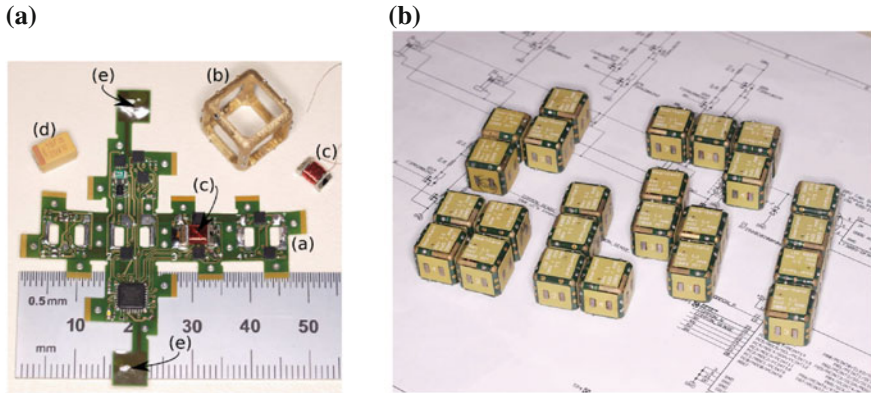
(a)

(b)

Fig. 3.13 Pebbles system. Photos by Kyle Gilpin (Daniela Rus's Distributed Robotics Laboratory at CSAIL, MIT). **a** Pebbles module, with flex circuit exposed. 4 sites for EP magnet placement are visible. A fully constructed module fits within the cube frame, **b** Pebbles arranged into a variety of 2D shapes [12]
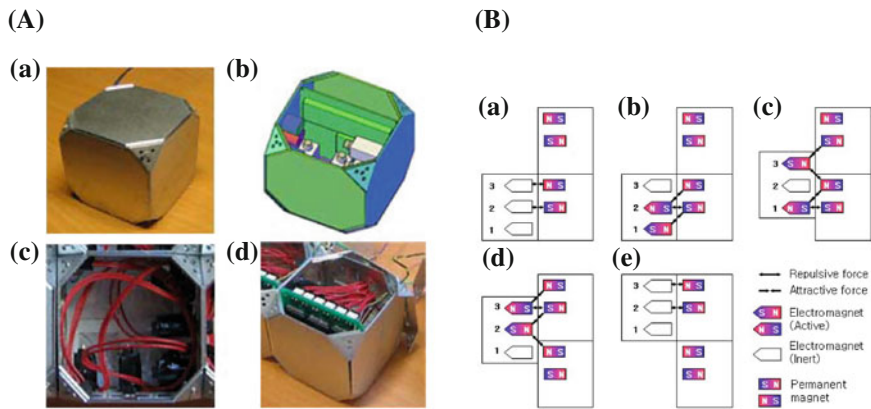
(A)

(B)

Fig. 3.14 EM-Cube System. [1]. **a** EM-Cube protype. Note in (**c**) that the electromagnets are only on two faces, **b** EM-Cube sequence of magnet switching for motion. The combination of repulsive and attractive forces at each step results in net motion

3.3.2 Lattice Locomotion

Many different types of lattice locomotion exist—each system seemingly has its own motion primitives capable of moving a module from one position in the lattice to another.

There are two types of module locomotion in MRR systems—pivoting (rotational) and sliding (translational). Rotational motion is easier to accomplish due to the ability to use standard motors without a linear drive mechanism, saving space. Typically the center of this rotation is at or near the center of a module connected adjacent to the
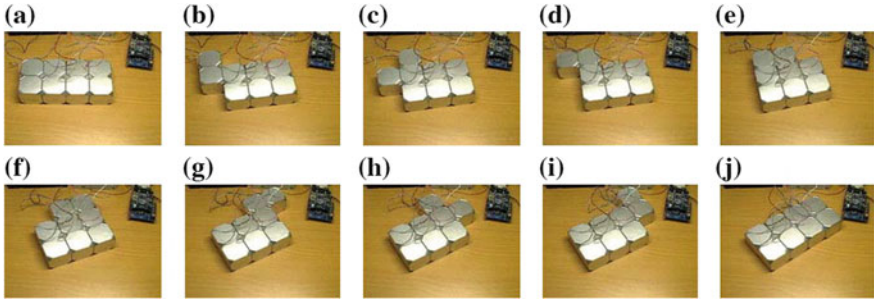
Fig. 3.15 EM-Cube undergoing a convex transition. More than one module is required to maintain a surface against which the module can move

moving module, but this is not always the case. Corners and edges are sometimes used as 'pivot points' to stabilize otherwise unstable motions, resulting in slightly different centers of rotation. Depending on the center of rotation, pivoting modules have some 'exclusion zone', where other modules cannot be located if the module locomotion action is to be successful. Pivoting systems with an exclusion zone thus have fewer locomotion options than sliding modules. Most systems are of the pivoting type. Sliding type systems are less common but include systems such as Crystalline [2], Telecube [43], EM-Cube [1], and Smart Blocks [31].

In pivoting type modules with only one motor (or multiple motors with the same axis) some limitation in locomotion results. For example, if all the modules in a configuration have the same axis of rotation they will be unable to leave the relevant plane, even if they otherwise exist on the three-dimensional lattice. So in systems such as M-TRAN [21] and CKBot [51], care must be taken to add sufficient modules of different axes to permit full reconfiguration capabilities.

3.3.2.1 Locomotion Actuators

Actuation in MRR is typically performed by traditional electric motors, or servomotors. These have the advantage of being relatively easy to use, having easy power transmission, and high strength. However, they have a tendency to take up a lot of space and do not scale well. In particular, scaling down electric motors quickly leads to a significant loss of strength. Functionality such as self-reconfiguration requires additional actuators for attaching/detaching, increasing the importance of actuation in platforms that self-reconfigure.

As a result, alternative actuation has been studied extensively for MRRs. Magnetic bonding methods are attractive due to their self-aligning properties. Standard electromagnets require very large currents to generate enough attraction or repulsion power and are not practical for battery powered MRR systems. Switchable permanent magnets and electropermanent magnets scale relatively well, and are utilized to perform attachment/detachment with a relatively low design burden. These

magnets make use of a permanent magnet-electromagnet pair to change the attraction behavior. Telecube and Pebbles both use this technology for face-to-face attachment [11, 43]. Telecube uses a physical SMA mechanism to move the magnets while Pebbles use electropermanent magnets. Electropermanent magnets can be electronically 'switched' off or on by application of the magnetic field from an electromagnet. Recently, an electropermanent magnet 'wobble' motor has been designed for the Milli-moteins system allowing for useful actuation at the 1-cm scale [19].

Another alternative actuation method proposed for modular robots uses active materials such as SMA [53] or DEA [48] (dielectric elastomer actuation) to perform the primary motion of the modules. These methods show promise for scalability, but can have other drawbacks; SMA is slow to respond and is not very consistent due to its dependence on ambient temperature, and DEA requires thousands of volts with reliability and robustness issues.

Incomplete actuation and external actuation is also presented in some types of systems, as we show in Sect. 3.5.1. These solutions are useful by giving up space inside a module for other components.

3.3.3 Connection Types

Essential to the act of reconfiguration (whether self-reconfigured or not) is the mechanism by which modules are physically mated together. There are many different ways to characterize these connection mechanisms. Table 3.1 shows many of the MRR systems and their connection mechanisms.

Several terms used here to categorize these connectors are explained below.

Self-Aligning Degree represents the degree to which the connector *passively* aligns the two faces, such as magnetic or mechanical forces. A 'High' Rating indicates self-alignment capability in one offset direction approximately greater than 20 % of the characteristic size of the module face. 'Low' rated systems have some self-alignment capability but less than 20 %. 'None' rated systems have no self-alignment capabilities and must be aligned carefully either by active robotic mechanism or by hand.

Gendering represents whether connectors are interchangeable or must be paired in a particular manner. Gendered connectors have a 'male' and 'female' face—male faces can only pair with female faces, and vice versa. Ungendered connectors do not have this restriction—any face can pair with any other face.

Connection Activity and **Disconnection Activity** indicate whether the act of connection/disconnection requires an action on the part of a module. **Connection Agency** and **Disconnection Agency** indicate which modules are required to be operational/active for the respective action. Double End Agency requires both faces to cooperate to accomplish the connection/disconnection, Single End Agency requires only one functioning face (either one), and Male/Female requires the indicated (single) face.

Table 3.1 Connector systems classification; various systems by year

Connector	Month/Year	Self-aligning degree	Gendering	Connection activity	Disconnection activity	Connection agency	Disconnection agency	Connection type	Connection maintenance	Compliance	Approach angle
CEBOT Mark II [9]	May/1989	High	Gendered	Active	Active	Male end	Male end	Latching	Zero-power	Rigid	Perpendicular
Fracta 2D [22]	May 1994	High	Gendered	Active	Passive	Male end	Male end	Magnet	Powered	Compliant	Non-perpendicular
Meta-morphic [29]	August 1996	High	Gendered	Active	Active	Female end	Female end	Latching	Zero-power	Rigid	Non-perpendicular
3-D Unit [23]	May 1998	Low	Ungendered	Active	Active	Double end	Double end	Latching	Zero-power	Rigid	Perpendicular
Molecules [20]	May 1998	Low	Gendered	Active	Passive	Double end	Single end	Magnetic	Powered	Compliant	Perpendicular
Telecubes [38]	May 1998	Low	Ungendered	Passive	Active	Double end	Single end	Magnetic	Zero-power	Compliant	Perpendicular
I-Cubes [41]	Apr 2000	None	Gendered	Active	Active	Double end	Double end	Latching	Zero-power	Rigid	Perpendicular
CONRO [4]	Nov 2001	Low	Gendered	Passive	Active	Female end	Female end	Latching	Zero-power	Rigid	Perpendicular
DRAGON [25]	Dec 2002	High	Ungendered	Passive	Active	Double end	Double end	Latching	Zero-power	Rigid	Perpendicular
Polybot G3 [50]	March 2003	Low	Ungendered	Passive	Active	Double end	Double end	Latching	Zero-power	Rigid	Perpendicular
Crystalline [2]	Sep 2003	Low	Gendered	Active	Active	Male end	Male end	Latching	Zero-power	Rigid	Non-perpendicular

(continued)

Table 3.1 (continued)

ATRON [27]	Oct 2004	None	Gendered	Active	Active	Male end	Male end	Latching	Zero-power	Rigid	Non-perpendicular
amour [42]	Apr 2005	High	Gendered	Active	Active	Female end	Female end	Latching	Zero-power	Rigid	Perpendicular
Slimebot [35]	Apr 2005	None	Gendered	Passive	Passive	Single end	Single end	Velcro	Zero-power	Compliant	Perpendicular
GHC (Catom) [17]	May 2005	None	Ungendered	Active	Passive	Double end	Double end	Electro-static	Low power	Compliant	Non-perpendicular
Molecubes [54]	August 2006	Low	Ungendered	Passive	Active	Single end	Single end	Magnetic	Zero-power	Compliant	Perpendicular
CKBot (SAE) [51]	Oct 2007	Active	Ungendered	Passive	Manual	Double end	Double end	Magnetic	Zero-power	Compliant	Perpendicular
M-TRAN III [21]	Mar 2008	None	Gendered	Active	Active	Male end	Male end	Latching	Zero-power	Rigid	Perpendicular
Roombots [36]	May 2008	None	Ungendered	Active	Active	Male end	Male end	Latching	Zero-Power	Rigid	Non-perpendicular
SINGO [34]	May 2009	High	Ungendered	Active	Active	Single end	Single end	Latching	Zero-power	Rigid	Perpendicular
RATChET [47]	Sep 2009	Low	Gendered	Active	Passive	Single end	–	Magnetic	Zero-power	Rigid	Non-perpendicular
Pebbles [11]	May 2010	None	Ungendered	N/A	Active	N/A	Single end	Magnetic	Zero-power	Compliant	N/A

(continued)

Table 3.1 (continued)

Vacuubes [10]	May 2010	High	Ungendered	Active	Passive	Single end	Single end	Air Pressure	Single pump per cluster	Rigid	Perpendicular
DFA [28]	Sep 2011	High	Ungendered	Passive	Passive	–	–	Magnetic	Zero-power	Rigid	Perpendicular
SMORES [5]	Oct 2012	Low	Gendered	Active	Active	Male end	Male end	Mag/Latching	Zero-power	Rigid	Perpendicular
M-Blocks [33]	Nov 2013	Low	Ungendered	Passive	Passive	–	–	Magnetic	Zero-power	Compliant	Non-perpendicular
DARPA TEMP [26]	June 2014	High	Gendered	Active	Active	Double end	Double end	Latching	Zero-power	Compliant	Perpendicular

Table 3.2 Table of ZRAA metrics, normalized relative to characteristic length of the face

System	Normalized ZRAA sum
GENFA connector	0.00353
Polybot	0.00503
M-TRAN III	0.00592
JHU	0.00592
I-Cubes*	0.0187
CONRO*	0.0425
Vacuubes	0.0555
ACOR(unpaired)	0.0711
SINGO Connector	0.306
DRAGON	0.353
amour	1.57
3D X-Face	2.00

These are exact where possible from the data available in the literature, otherwise estimated. Entries marked with a * indicate estimated ZRAA rather than exact. Table reproduced from [7]

Connection Type indicates the mechanism by which connections are accomplished. Most systems use either magnetic mechanisms or mechanical latching with a few systems using electrostatic forces or pressure to maintain the connection.

Connection Maintenance indicates the extent to which power is required to maintain a connection. Generally speaking, it is undesirable to have a system require power simply to maintain its shape. This is especially true in modular systems which often have a limited power budget.

Compliance indicates the flexibility of the connection. 'Rigid' connections have a mechanically rigid connection between module frames. 'Compliant' systems have some flexibility to external forces, either from springs/compliant parts or magnetic compliance.

Approach Angle indicates the direction of approach that the system most regularly encounters. Systems with a direction of approach perpendicular to the face are generally more responsive to self-alignment design features.

One metric by which connectors are measured is known as **Area of Acceptance**. Area of acceptance is defined as "the range of possible starting conditions for which mating will be successful" [6]. Practically speaking, what this means is that if the docking procedure is executed given some initial misalignment offset between connectors, the alignment features of the connector will correct the offset. The range over which this occurs is the area of acceptance. Area of acceptance can be difficult to determine; for three-dimensional systems it contains two positional offsets and three orientation offsets (we consider all points along the approach direction to be the same, removing one translational DOF). The concept of Zero Rotation Area of Acceptance (ZRAA) is one simplification which assumes that all orientation degrees of freedom are removed and the approach direction is perpendicular to the face. For purely mechanical self-alignment (e.g. no magnets) a set of active and passive connectors from the literature is characterized in Table 3.2 as a sum of the positions normalized with respect to the connector cross-sectional area.

The concept of area of acceptance is important because alignment and connection systems need to be error-tolerant in order to be successful. Long module chains in particular have a tendency to accumulate errors quickly resulting in failed connections if connectors are not sufficiently corrective. These errors could be in multiple dimensions at once, so it is best to measure the area of acceptance over as many dimensions as is feasible.

3.4 Software Systems for MRR

Software for modular robots poses some interesting problems. Since the robots themselves are typically not that complex, dynamic control issues are not generally discussed, although in some instances high accuracy in position and controllability is desirable. The relevant problem for lattice reconfiguration is at the system level, planning for the reconfiguration of the system in a failure-proof and distributed way. Since MRR systems do not always have a centralized controller, planning and issuing commands, decentralized planning algorithms become necessary.

3.4.1 Reconfiguration Planning

In addition to the typical collision-free motion planning problems that exist throughout robotics, MRR systems have a separate category of planning problem, called **reconfiguration planning**. These problems require the system to recognize its configuration and then find a sequence of reconfigurations to reach a goal configuration. The reconfiguration planning problem does not deal with the specific path or dynamics of the system; rather it is a sequence of viable configuration changes from the initial configuration to the goal configuration. These configurations can be represented in the literature as a diagram or graph of connected modules.

If the robot is not explicitly given its initial configuration, *configuration recognition* is a critical step. The robot or system must first identify the current configuration before reconfiguration can occur. This requires the ability to sense neighbors and can be done in a decentralized [30] or centralized [26] manner.

Once the initial configuration is determined, a *reconfiguration plan* must be calculated. Doing this in the smallest number of moves has been shown to be an NP-complete problem [14]. Reconfiguration planning is largely dependent on each particular system and its design. In particular the lattice type, connectedness, method of locomotion, torque limit, and exclusion rules due to method of locomotion all contribute to the set of rules that define the reconfiguration problem. Thus each system design typically has had specific algorithms to most effectively find a reconfiguration plan; for the Metamorphic system, a heuristic based on Simulated Annealing [29], for the M-TRAN system, a centralized two-layer planner (first with locomotion by meta-module, then locally cooperative behavior rules) [52]. The DARPA TEMP

system converts the goal configuration to a directed graph and grows the assembly outward from a chosen 'seed' module [26]. The methods are nearly as varied as the systems, and typically are developed to best fit the individual system with a quickly computed solution, or more optimally a quickly executed one.

3.5 Assembly Robotics

A common application for MRR systems is assembly. This assembly can be directed either externally to the formation of a superstructure such as a truss or other object, or internally to the assembly of robots from modules available. These tasks however have fundamental considerations in common such as the availability of materials, transport of materials, assembly order, etc. It is also often desirable to have some decentralized method of assembly so that a malfunction of one component does not hinder the system, and so that the system can be reconfigured at will. To this end algorithms have been developed which permit the centralized or decentralized assembly planning and execution.

3.5.1 Self-Assembly and Self-Repair

Thanks to the interchangability aspects of MRR systems, they are capable of performing operations such as self-assembly and self-repair. These operations contribute to the robustness and versatility of MRR systems by allowing for damage and failure scenarios.

Self-repair in modular robots has taken several forms. The intended mechanism is more like self-replacement or self-reassembly; non-functioning modules are abandoned and replaced with a functional module rather than repaired per se. Regardless, this mechanism is highly useful, and relatively less costly the more units exist in the system. The 'Unit' systems (2D, 3D, and Micro Unit) have demonstrated the capability for self-repair by moving defective modules out and replacing them with (previously) redundant modules [24]. This is due in part to the fact that each module is capable of moving a damaged module and disconnecting from it. These are essential qualities of the design for this kind of self-repair since the functions of the defective module cannot be relied upon. An alternate kind of self-repair in mobile clusters occurred with CKBot [51], where the clusters were attached manually and then kicked apart (Fig. 3.16). The clusters were then able to self-right, locate other clusters and cooperatively reassemble.

Self-assembling systems like Molecube [54] and White et. al's systems [45] are capable of creating large structures from very simple modules. Sambot has demonstrated self-assembly [44]. Self-assembly of structural components using an expanding spray foam has been accomplished to support standalone clusters of modules and create a conglomerate robot [32]. A more complete survey of self-assembly in robotic systems can be found in [15].
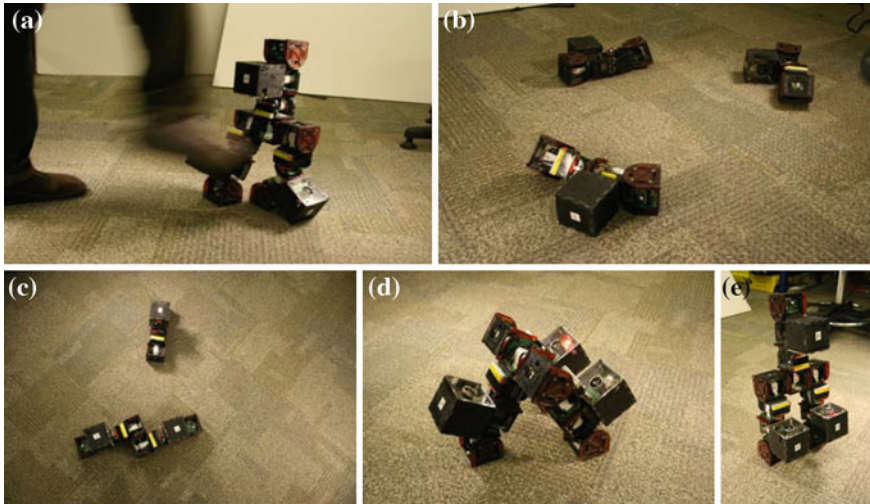
Fig. 3.16 CKBot Self-Reassembly procedure

A term that incorporates self-assembly is **Programmable Matter**. The goal of programmable matter is to have a massive conglomeration of very small mechatronic devices capable of reassembling themselves from one form to another. While the types of systems we have seen already may someday be capable of this kind of application, at present they are too large and make use of technology that is difficult scale down (i.e. electric motors, which lose strength relative to their size very quickly as they scale down). Therefore, alternative systems have been implemented to combat these kinds of problems.

The Pebbles [12] system, mentioned earlier, makes use only of EP magnets which is easier to reduce in size. The X-bots [46] system mentioned above uses inertia to move one or two modules about a lattice at a time. The RATChET system demonstrates how a system can be constructed using a long chain and two external actuators by a combination of inertia and smart design [47]. This implementation allows shapes to be formed from a chain of N modules, while keeping the number of actuators constant, and off-board of the modules. A typical formation sequence is shown in Fig. 3.17. Connection between modules is magnetic, with magnets being released into the 'active' (ready to connect) position by SMA wire. By activating the correct magnets and correctly utilizing external actuation nearly any shape can be formed from a chain of these modules.

Stochastic configuration of passive components on a lattice has been done at several different scales, mostly by Tolley, Lipson, et al. [16, 39, 40]. This is accomplished in a fluidic environment with an array of ports set up to perform as either source or sink. Totally passive mechanical modules with a passive latch are introduced, and then allowed to settle into the area around the desired sink(s), where they latch, reaching the desired assembly before being released. Larger structures require
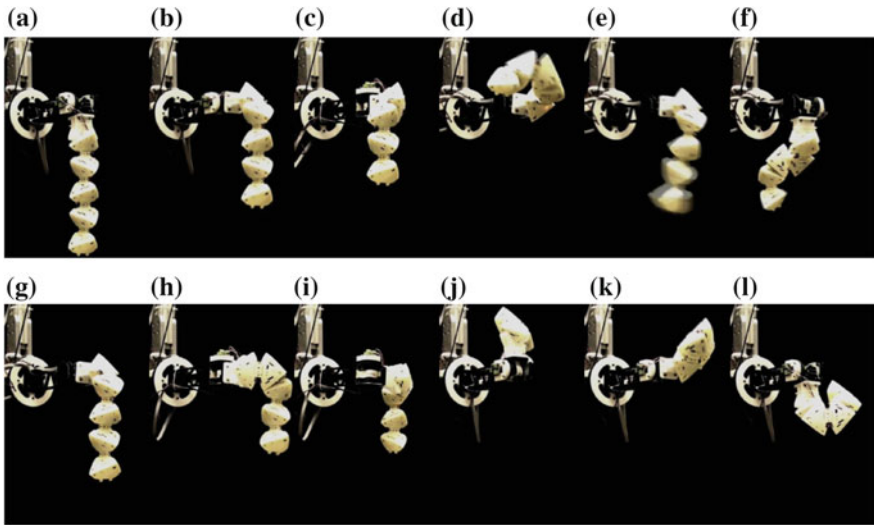
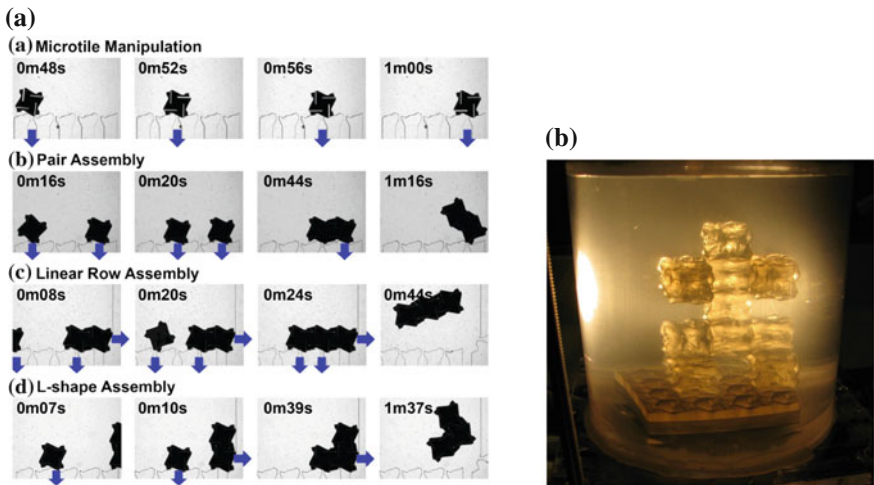**Fig. 3.17** RATChET Chain assembling under external actuation [47]

Fig. 3.18 Fluidic Systems **a** Microfluidic components in assembly procedure. Hydrodynamic forces accomplish the relative motion of the modules, with latching beginning a natural mechancial consequence of the shapes being forced together, **b** A three-dimentional fluidicstocgastic system. Each module is 1 cm in size, and is latched mechanically to its neighbors. Array of ports is visible at the *bottom* of the tank

re-trapping an assembly already made in a different orientation so that additional parts can be added. Since different control is required to attract, repel, and latch the modules, visual feedback is required. This means that presently the systems are not autonomous but rely on the input from a human operator. The system also relies

on stochastic motions present in the environment to attract modules, and have them approach in a way that results in alignment. Examples of these systems are shown in Figure 3.18.

3.6 Conclusions and the Future of MRR

MRR systems hold the promise of being versatile, robust and low cost. Several lattice and hybrid systems have been presented in the literature both in 2D and 3D. The lattice structures utilized have mostly been square or cubic but other lattice shapes have shown to be useful as well. These systems assemble, repair, and reconfigure themselves in various ways which enable versatile and robustly functional robotic systems.

In the future, we hope to see MRR systems which become smaller, stronger, and more numerous to enable greater utility. To date there are dozens of groups around the world working on these systems, from both hardware and software points of view. With the continued progress of the research literature the three promises of MRR systems will be seen.

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