The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Simple Components for a Reconfigurable Modular Robotic System

Matthew S. Moses and Gregory S. Chirikjian

Abstract— **A set of modular components is presented for use in reconfigurable robots. The proposed architecture for large systems built with these components is a number of active mobile devices operating within a larger, passive structural grid. The mobile devices and grid are constructed from the same class of heterogeneous modular components. The components themselves are designed for low-cost simple fabrication methods. Results from some experimental demonstrations are presented.**

I. INTRODUCTION

The concept of machines that make machines has been around the science (and science fiction) literature now for more than half a century [1], [2], [3], [4], [5]. Our emphasis in this paper is the design and demonstration of robots constructed from a specific set of parts that is "complete" or "closed" in the sense that multiple different kinds of robots can be constructed from this set, and those robots will have the ability to construct copies of themselves. On the one hand, this goal is not as ambitious as von Neumann's "universal" constructor [5], but on the other hand, we are designing physical prototypes that function in the physical world, whereas no universal constructor has ever been demonstrated. Therefore, this work can be viewed either as a step toward realizing von Neumann's vision [6], or simply as a more modest engineering goal with potential applications in the physical world - particularly in the field of self-reconfigurable modular robotics (SRMR).

Some of the current "Grand Challenges" identified for SRMR [7] include demonstrating systems with large numbers ($\approx$ 1000) of modules, and reducing module size and cost. Additionally, accessing and manipulating objects at small length scales is a crucial challenge in the field of micro robotics [8]. The modular component system presented here may provide certain unique advantages for addressing these challenges. Namely, the components' simplicity and ease of construction facilitates the low-cost production of large numbers of modules, while the choice of materials and manufacturing techniques are quite similar to those already widely used in certain microfabrication processes [9].

Most state-of-the-art examples of SRMR [10], [11], [12], [13], [14], [15], [16] are based on homogeneous modules, each of which contain a full suite of sensors, actuators, power source, and computing hardware. This approach has seen remarkable progress and continues to be a very active area of research. However, systems based on heterogeneous modules have been proposed and built. There are several examples of SRMR in which active (complex) modules are combined with passive (simple) components to perform locomotion and reconfiguration. A bipartite SRMR composed of active links and passive cubical modules is presented in [17]. A similar system composed of active joints and passive truss elements is described in [18]. A collective robot system is proposed in [19] where locomotion and reconfiguration are accomplished by the interaction of a swarm of simple active robots contained within a passive membrane. Algorithms and simulations are presented in [20] for a system composed of passive blocks which are moved and connected by a smaller number of active mobile robots. A similar architecture of active robots and passive blocks was actually built and demonstrated in [21].

The authors are with the Department of Mechanical Engineering, Johns Hopkins University, Baltimore, Maryland {matt.moses, gregc}@jhu.edu

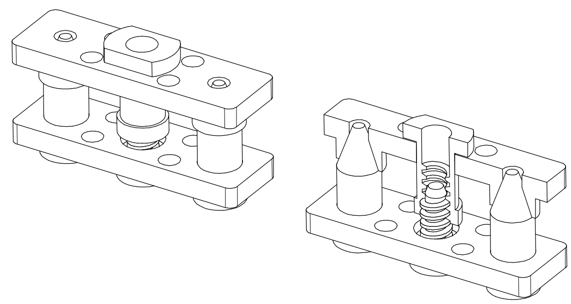

Fig. 1. The basic mechanical connection consists of a threaded fastener centered between two conical pin-bushing pairs.

A vision of SRMR based on our components most closely matches the systems in [20], [21]. We propose that a large grid be composed of simple, passive structural components. Mobile devices, composed of other structural blocks including some motorized components, operate within the grid. The mobile devices are able to reconfigure the structural grid, move components from place to place, and build other mobile devices using parts of the grid as assembly stations. In contrast to [20], [21] the mobile robots in our system are themselves composed of the same components as the larger structural lattice.

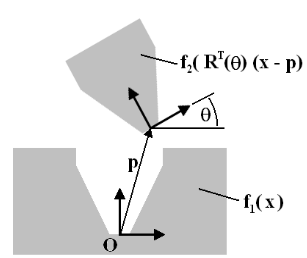

Fig. 2. Coordinate frame definition for 2D section of pin and bushing.

II. COMPONENT DESIGN

The mechanical inspiration for our system is not new: most engineers are already familiar with LEGO™, fischertechnik™and other off-the-shelf building sets. LEGO systems have been demonstrated that assemble simple devices also made from LEGOs [22], [23], but it is a much harder task to build a LEGO machine that can assemble arbitrary structures. The component set has been designed specifically to form general purpose constructing machines that can assemble arbitrary structures given additional components.

A. Assembly Error Tolerance

The building blocks (Figure 1) are designed so that when picked and dropped into place, they will reliably form low-error connections that can then be fastened using the rotary end-effector described in Section II-E. The art of designing automated assembly equipment is summarized in [24], and prior work of Boothroyd and coworkers that have been published over the past 40 years. Intuitively, we want the conical pegs and holes in our blocks to have geometric properties that will tolerate small errors in position and orientation, so that when blocks are dropped, they will be guaranteed to fall into place. In spirit, this is similar to the philosophy behind the pioneering work of Erdmann, Mason, Canny, Goldberg, and others on the use of minimal sensing and using the information contained in the mechanics of manipulation [25], [26], [27].

In a sense, the robot that we are presenting is one that is "isentropic" in that it picks up blocks that are initially stacked in an ordered lattice, and delivers and places the blocks in locations where they settle with the same amount of order that they started with. In this sense, the current work is similar to that in [28], in contrast to the situations studied in [29] where the environment (and initial arrangement of parts) had some uncertainty, and the robot assembled a replica.

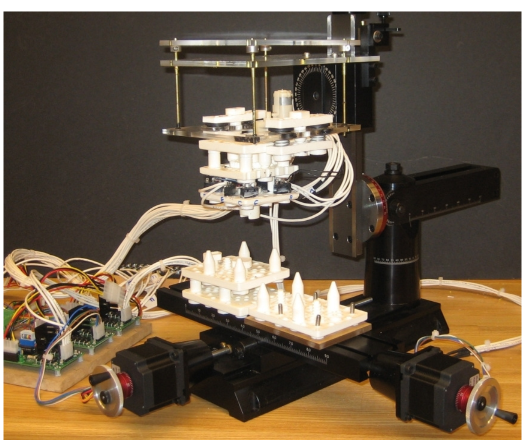

Fig. 3. Off-the-shelf 7-axis positioning stage instrumented for testing assembly error tolerance.

In practice, even the isentropic approach must tolerate small errors in the position of the manipulator end-effector due to imperfections in measurement and manufacturing. For a given commanded end-effector configuration g_0, the positioning error can be represented as a probability density function $\rho_{g_0}(g)$ on the group of rigid-body transformations $g, g_0 \in SE(3)$ [30]. Further, the allowable assembly tolerance between two mechanical parts can be represented as a function $\alpha(g)$. The function $\alpha(g)$ varies between 0 and 1 and represents the likelihood of a successful connection when the two components are placed with relative configuration g. The overall likelihood that an assembly process is successful for a commanded end-effector configuration is

$$\gamma_{g_0} = \int_G \alpha(g)\rho_{g_0}(g)dg.$$

This formalism provides a way to quantify the concept of "assembly error tolerance" in order to maximize likelihood of successful assembly operations. An ongoing topic of research in our lab is measuring the functions $\rho_{g_0}(g)$ and $\alpha(g)$. An instrumented 7-axis positioning stage fitted with a rotary end-effector (Section II-E) is under development for collecting supporting data (see Figure 3).

Determining γ requires extensive experiments or high fidelity simulations. The remainder of this section presents an entropy heuristic based on part geometry that can provide meaningful predictions about assembly error tolerance without the need for extensive tests or simulations. The method predicts error tolerance by quantifying the reduction in part entropy that takes place as two components are assembled.

We hypothesize that a gradual transition from a large to a small parts entropy corresponds to tolerance of large misalignments, while a sharp transition corresponds to less tolerant components. Certainly there are other factors that are important in determining suitable connector geometries, such as specificity (avoiding undesired connections), robustness, and prevention of jamming, which the entropy heuristic does not address. However, it provides useful information based only on part geometry, and can potentially be combined with other heuristics to help construct a systematic process for designing and evaluating mechanical connection systems for modular components.

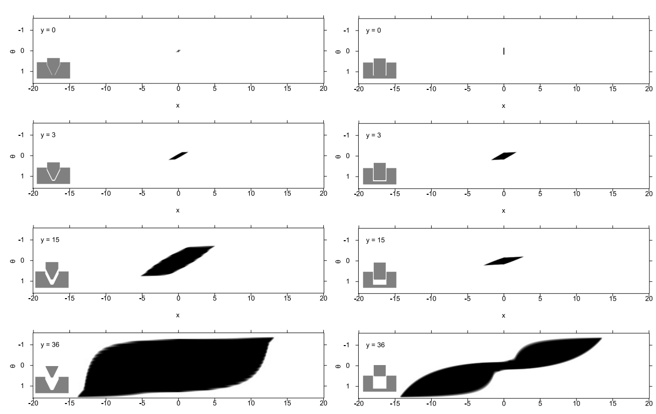

Fig. 4. Comparison of intensity plots of $V(x, y, \theta)$ for different values of y and tapered or straight pins. Dark areas indicate region of free motion. Insets indicate degree of assembly by illustrating a single configuration at $(0, y, 0)$.

A rigid component B, considered as a subset of points in $\mathbb{R}^n$, can be represented with a function

$$f_B(\mathbf{x}) = \begin{cases} 1 \text{ for } \mathbf{x} \in \mathbf{B} \\ 0 \text{ for } \mathbf{x} \notin \mathbf{B} \end{cases}$$

with $\mathbf{x} \in \mathbb{R}^\mathbf{n}$. Given two 2D rigid components represented by f_1 (the bushing) and f_2 (the pin), the amount of overlap between the components can be written as a potential function

$$V(x, y, \theta) = \int_{\mathbb{R}^2} f_1(\mathbf{x}) f_2(R^T(\theta)(\mathbf{x} - \mathbf{p}))d\mathbf{x}$$

where $\mathbf{p} = [x, y]^T$, and $R(\theta) \in SO(2)$ is a 2D rotation matrix. As shown in Figure 2, the coordinate frames for f_1 and f_2 are attached to the components such that they are in the assembled configuration when the two frames coincide. Assembly "progress" can be parameterized by the y coordinate. Arbitray unassembled configurations initially begin with a large value of y, which decreases to $y = 0$ for the final assembled state. This is an approximate representation of the actual assembly procedure, where the y coordinate is driven by a controlled mechanism, but there is some uncertainty in x and θ which must be accommodated by the passive alignment geometry of the pin and bushing.

Computationally efficient methods have recently been presented for finding parts entropy in systems of multiple 3D bodies [31]. However, for an initial treatment of the pin/bushing geometry, a naive brute force sampling of configuration space is used. The configuration of the moving pin is parameterized by three coordinates (x, y, θ). The coordinates x and θ are discretized with uniform spacing on bounded intervals, e.g. $x \in \mathcal{X} = \{x_1, x_2, ..., x_{N_x}\}$ with

$$x_i = x_{min} + (i - 1)\frac{x_{max} - x_{min}}{N_x - 1}, \quad i = 1, 2, ..., N_x.$$

A uniform spacing of the coordinates (x, y, θ) results in a uniform sampling of $SE(2)$. In general, e.g. for $SE(3)$, this is not the case and the coordinate spacing must be modified accordingly to guarantee uniform sampling of C-space [32].

The collision-free region of C-space available to the pin for a given value of y is represented by the set of discrete (x, θ) coordinates for which V is less than or equal to some threshold

$$\mathcal{C}(y) = \{(x, \theta) : x \in \mathcal{X}, \theta \in \Theta, V(x, y, \theta) \leq \kappa\}$$

where typically $\kappa = 0$. As a measure of how C-space is restricted during assembly, the joint entropy [33], [29], [31] of x and θ, conditional on a given value of y, is defined

$$H_\rho(y) = -\sum_{x \in \mathcal{X}} \sum_{\theta \in \Theta} \rho(x, \theta|y) \log_2 \rho(x, \theta|y). \qquad (1)$$

Note that $H_\rho(y)$ is a function of y, in contrast to *conditional entropy* which is equivalent to the expectation $E_y[H_\rho(y)]$ [34].

For a given value of y, all collision-free (x, θ) pairs are assumed equally likely, so the probability mass function ρ is

$$\rho(x, \theta|y) = \begin{cases} \frac{1}{|\mathcal{C}(y)|} & \text{for } (x, \theta) \in \mathcal{C}(y) \\ 0 & \text{for } (x, \theta) \notin \mathcal{C}(y) \end{cases} \qquad (2)$$

where $|\mathcal{C}(y)|$ maps a real-valued y to a non-negative integer on $[0 \,..\, N_x N_\theta]$, and simply indicates the number of (x, θ) pairs in the set $\mathcal{C}(y)$. Clearly, $\rho(x, \theta|y)$ is well-defined only for y such that $\mathcal{C}(y) \neq \emptyset$. For the probability mass function in (2), $H_\rho(y)$ evaluates to

$$H_\rho(y) = \log_2 |\mathcal{C}(y)|. \qquad (3)$$

$H_\rho(y)$ tells us something about the assemblabilty of parts. As an example, $H_\rho(y)$ is calculated for two different part geometries: a conical pin/bushing and a straight-edge pin/bushing. The components f_1, f_2 are represented with 99×79 pixel bitmap images. The collision threshold was set to $\kappa = 4$ to neglect the "rough edge" collisions due to image pixellation. Other parameters used were: $N_x = 161$, $x_{max} = 20$ and $x_{min} = -20$ (pixels), $N_\theta = 361$, $\theta_{max} = \pi/2$ and $\theta_{min} = -\pi/2$ (radians).

Intuitively, it is understood that the difficult part of assembling a straight pin in a straight hole is the initial alignment of the pin with the hole. Similarly, assembly of a tapered pin is easy because the conical surfaces gradually guide the pieces together. This is evident in Figure 5 where the "knee" (dashed line) at $y \approx 27$ corresponds to the sharp reduction in parts entropy that occurs as the straight pin is aligned with the hole, while the conical pin shows a gradual entropy reduction (solid line). This suggests a qualitative general heuristic for designing and evaluating component geometries: avoid sharp transitions in $H_\rho(y)$. One advantage of using this method is that high-dimensional information from C-space (such as that shown in Figure 4) is collapsed into a function of a single variable, allowing direct comparisons between different parts of complex geometry.

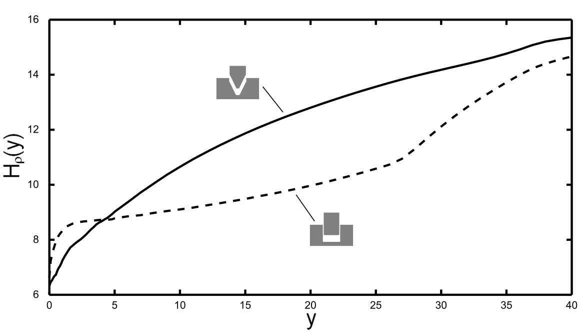

Fig. 5. Comparison of $H_\rho(y)$ for conical (solid line) and straight (dashed line) pin/bushings. Assembly proceeds with decreasing y.

B. Fabrication

The components are made of polyurethane. Each of the castings that make up a component are designed to be produced in a single-piece wax or silicone mold with minimal undercuts. This greatly simplifies the design and fabrication of the mold, simplifies the demolding process, and eliminates difficulties that arise with removing sprues and flash.

Master patterns are built manually by gluing together wax and plastic components produced via conventional machining, laser cutting, or 3D printing. A silicone mold is made

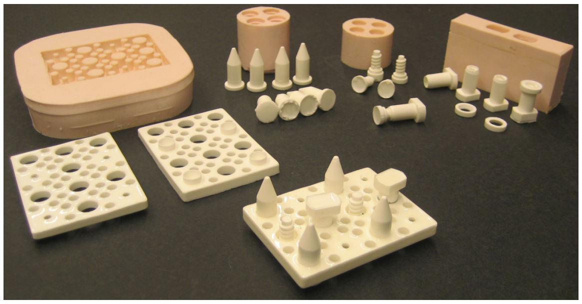

Fig. 6. Sub-components are cast in simple molds.

from the master patterns. Nearly all the molds are single-piece open molds with no undercuts. Except for components with screw-threads, none of the molds require undercuts. In the case of parts with screw-threads, the flexibility of the mold material allows a cast part to be removed from a mold despite the undercuts formed by the threads.

A flat surface cannot easily be created on the free surface of the mold (i.e. the face of the component exposed to the air) because of bubbles and the meniscus formed at the liquid-air interface. The components are designed so that multiple pieces produced from single-part molds may be assembled and bonded together to form components that maintain critical dimensions and good surface quality on all faces. This process is illustrated schematically in Figure 7.

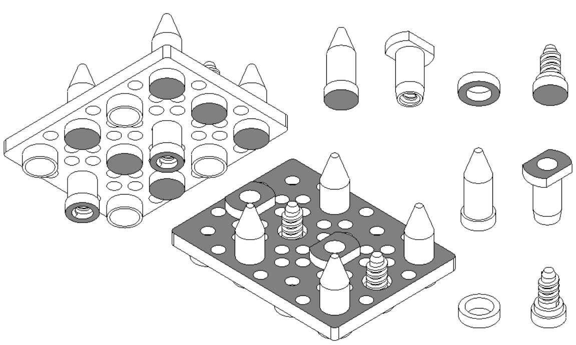

Fig. 7. Raw castings are bonded together to form finished components. Low-quality surfaces shown as shaded areas.

C. Mechanical Interconnection

Desirable characteristics in the interconnection mechanism include tolerance to misalignment, strong reversible connections, and ease of fabrication. Connectors utilizing self-aligning surfaces combined with a locking mechanism have been previously demonstrated, including devices based on snap-fits [35], actuated latches [36], [37], and magnets [38]. We chose a mechanism based on screw-threads, as shown in Figure 1. The conical pins allow for self-alignment during assembly. The threaded fastener between the compressed pins provides tension for a strong mechanical connection, and additionally helps to pull misaligned modules together during assembly. An important feature is that the connector is entirely passive and does not require every module to be equipped with an actuator.

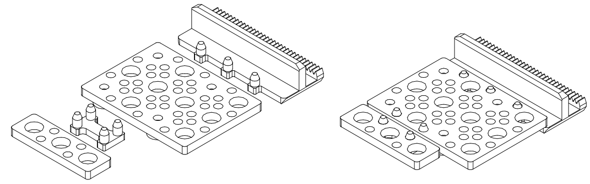

Fig. 8. Small holes in the basic plate provide locations for specialized sub-components.

D. Functional Features

Each module must have at least one connector of each type (i.e. one with pins and one with bushings). The connectors with pins are used as a standard handle so that components may be easily handled by a common end-effector. The presence of a bushing connector allows a module to be added to an assembly. The basic structural component consists of a plate with two pin connectors and two bushing connectors. Having two of each connector style allows the basic component to form trusses and columns.

The unit distance between centers for the large holes in the plates is chosen as an integral number of pitch lengths of the rack used for sliding motion. A standard size gear pitch was chosen so that off-the-shelf components could be used when building component masters. In this case, the gears are 24 pitch in English units (i.e. a gear with pitch diameter equal to one inch has twenty-four teeth). The center-to-center distance between plate holes is 1.047 inch, corresponding to 8 tooth-lengths of a linear 24-pitch rack. For convenience the vertical unit distance is also chosen to be 1.047 inch, although this is easily changed by substituting pins of a different length.

The small holes in the plates have multiple functions. Holes around the perimeter of the plate can be used to link plates together using a smaller pinned component (Figure 8). Vertical and horizontal sliding components are also added to plates in this way. The holes are also intended to incorporate smaller castings with embedded electrical contacts and wiring.

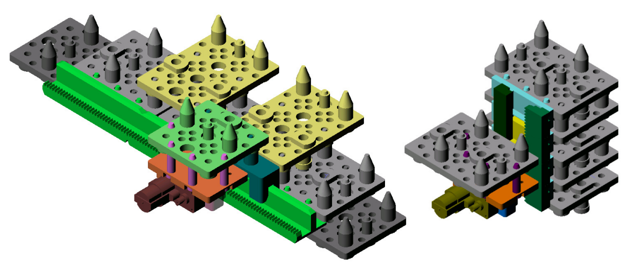

Fig. 9. Multiple components can be assembled into trusses and columns, which in turn can be augmented with additional parts to form horizontal and vertical tracks on which motorized components can move.

Multiple instances of the basic structural part can be assembled into trusses and columns as shown in Figure 9. Components in a truss can be augmented with horizontal rack pieces, allowing a truss to function as a track on which a motorized component can slide. Vertical tracks are made in a similar way using additional sub-components (Figure 10).

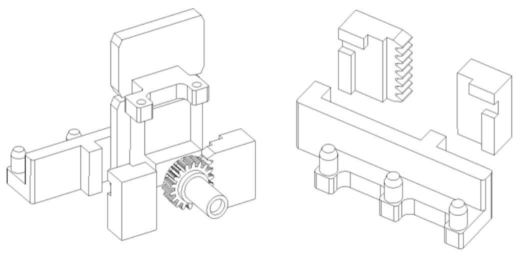

Fig. 10. Sub-components for building vertical sliding mechanisms.

E. Gripper Mechanism

A single end-effector is used for grasping components and to tighten and un-tighten the threaded fasteners (see Figure 11). The end-effector consists of a spring loaded tool-piece with a slot and internal thread. For grasping a part, the internal thread of the tool mates with the threaded tension pin on a component. After a component is placed, the tool is unscrewed from the tension pin and placed on the component's captured-nut fastener. The slot on the tool-piece self aligns with the fastener and tightens or loosens it in the manner of socket and nut. The grasper is composed of an off-the-shelf gear motor, a metal spring, and 21 plastic cast parts.

III. EXPERIMENTS

This section describes a system built to test the performance of the component set in assembly tasks. The machine is automatically controlled using a simple microcontroller (PIC16F690). Motorized components all utilize the same small, low-cost gearmotor (Solarbotics GM2). Low resolution optical encoders are used to provide a positioning accuracy of about 1 encoder count per mm. Power and signals are routed to each motor component using external cables (not through wiring embedded within the components). The controller follows a sequence of pre-determined position commands, driving each axis independently until a certain number of encoder counts is sensed.

A 3-axis Cartesian manipulator was constructed from about 80 modular components (Figure 12). The base of the manipulator consists of two parallel tracks, each with a gear rack along the length of the track. A mobile cross-slide sits across the tracks, itself containing another two tracks orthogonal to the base. A second smaller cross-slide sits atop this assembly, and carries a column of structural components fitted with a vertical sliding mechanism. Two vertical motorized assemblies move on either side of the column. The end effector rides on a platform connected to the vertical motor mechanisms. The manipulator is driven by seven motors. Two motors drive each of the axes in parallel, and the seventh is used to drive the end-effector. The task this machine performs is to assemble three components on an assembly station, then pick them up and move them off of the station (see supplemental file *moduleAssemblyDemo.wmv*).

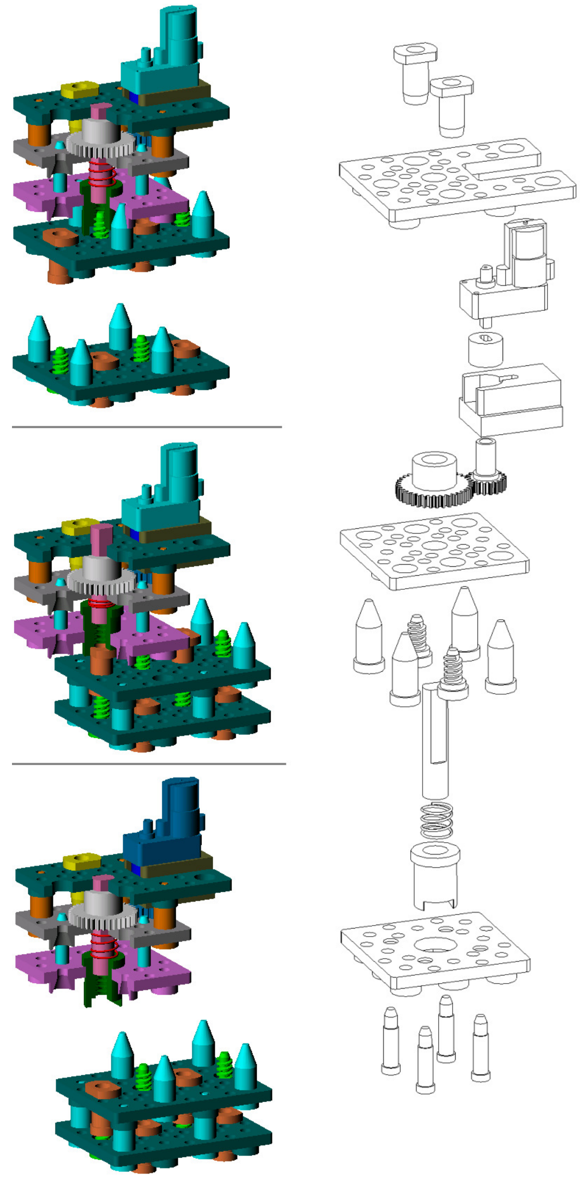

Fig. 11. A common grasper is used to manipulate, connect, and disconnect modules from each other.

Fig. 12. A 3-axis Cartesian manipulator performs a demonstration task of stacking three modules, then removing them from the assembly station.

IV. CONCLUSION

We have designed and built a new set of mechanical components specialized for building robots that assemble the same type of components they are made from. The initial motivation for this work is for self-replicating machines, but the components can also be applied to self-reconfigurable robotics. We have demonstrated that it is straightforward to produce large numbers of modules, and that machines built from them pass the rudimentary test of being able to handle and assemble other modules under automatic control. There is an obvious need to incorporate electrical contacts and feedthroughs within the modules, while preserving their low-cost and ease of fabrication. There is also a need to develop a systematic lattice architecture in addition to algorithmic methods for reconfiguring the lattice. While this approach of heterogeneous "active robot" - "passive lattice" lags behind the more developed systems composed of homogeneous full-featured modules, we think that the idea is worth investigating for future systems. Other ongoing topics for future work include a rigorous investigation of the assembly error tolerance functions $\rho_{g_0}(g)$, $\alpha(g)$, γ, and $H_\rho(y)$. In addition we are developing complementary design heuristics to address other important aspects of assembly such as specificity, robustness, friction, and dynamics.

REFERENCES

[1] H. Jacobson, "On models of reproduction," *American Scientist*, vol. 46, pp. 255–284, 1958.

[2] R. A. Freitas, Jr. and R. C. Merkle, *Kinematic Self-Replicating Machines*. Landes Bioscience, 2004. [Online]. Available: http://www.molecularassembler.com/KSRM.htm

[3] L. Penrose, "Self-reproducing machines," *Scientific American*, vol. 200, no. 6, pp. 105–114, 1959.

[4] M. Sipper, "Fifty years of research on self-replication: An overview," *Artificial Life*, vol. 4, no. 3, pp. 237–257, 1998.

[5] J. von Neumann and A. W. Burks, *Theory of Self-Reproducing Automata*. University of Illinois Press, 1966.

[6] M. Moses, H. Yamaguchi, and G. S. Chirikjian, "Towards cyclic fabrication systems for modular robotics and rapid manufacturing," in *Proceedings of Robotics: Science and Systems*, June 2009.

[7] M. Yim, W.-M. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, E. Klavins, and G. Chirikjian, "Modular self-reconfigurable robot systems [Grand Challenges of Robotics]," *IEEE Robotics & Automation Magazine*, vol. 14, no. 1, pp. 43–52, Mar. 2007.

[8] M. Sitti, "Microscale and nanoscale robotics systems [Grand Challenges of Robotics]," *IEEE Robotics & Automation Magazine*, vol. 14, no. 1, pp. 53–60, Mar. 2007.

[9] Y. Xia and G. M. Whitesides, "Soft Lithography," *Angew. Chem. Int. Ed.*, vol. 37, pp. 550–575, 1998.

[10] W.-M. Shen, "Self-reconfigurable robots for adaptive and multifunctional tasks," in *Proceedings of the 26th Army Science Conference*, Florida, USA, Dec. 2008.

[11] H. Kurokawa, S. Murata, E. Yoshida, K. Tomita, and S. Kokaji, "A 3-d self-reconfigurable structure and experiments," in *Proceedings of the 1998 IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, Oct. 1998, pp. 860–865.

[12] S. Murata and H. Kurokawa, "Self-reconfigurable robots: Shape-changing cellular robots can exceed conventional robot flexibility," *IEEE Robotics & Automation Magazine*, pp. 71–78, Mar. 2007.

[13] V. Zykov, A. Chan, and H. Lipson, "Molecubes: An open-source modular robotics kit," in *IROS-2007 Self-Reconfigurable Robotics Workshop*, 2007. [Online]. Available: http://www.molecubes.org/

[14] M. Jorgensen, E. Ostergaard, and H. Lund, "Modular ATRON: modules for a self-reconfigurable robot," in *Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 2, 2004, pp. 2068–2073.

[15] M. Yim, B. Shirmohammadi, J. Sastra, M. Park, M. Dugan, and C. Taylor, "Towards robotic self-reassembly after explosion," in *Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on*, 29 2007-Nov. 2 2007, pp. 2767–2772.

[16] J. D. Campbell and P. Pillai, "Collective actuation," *International Journal of Robotics Research*, vol. 27, no. 3-4, pp. 299–314, 2008.

[17] C. Ünsal, H. Kiliççöte, and P. K. Khosla, "A modular self-reconfigurable bipartite robotic system: Implementation and motion planning," *Auton. Robots*, vol. 10, no. 1, pp. 23–40, 2001.

[18] C. Detweiler, M. Vona, K. Kotay, and D. Rus, "Hierarchical control for self-assembling mobile trusses with passive and active links," in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, May 2006, pp. 1483–1490.

[19] D. M. Kriesel, E. Cheung, M. Sitti, and H. Lipson, "Beanbag robotics: Robotic swarms with 1-dof units," in *ANTS '08: Proceedings of the 6th international conference on Ant Colony Optimization and Swarm Intelligence*. Berlin, Heidelberg: Springer-Verlag, 2008, pp. 267–274.

[20] J. Werfel and R. Nagpal, "Three-dimensional construction with mobile robots and modular blocks," *International Journal of Robotics Research*, vol. 27, no. 3-4, pp. 463–479, March/April 2008.

[21] Y. Terada and S. Murata, "Automatic modular assembly system and its distributed control," *International Journal of Robotics Research*, vol. 27, no. 3-4, pp. 445–462, 2008.

[22] D. Esterman, M. Sullivan, J. Bergendahl, and C. G. Cassandras, "Computer-controlled lego factory," University of Massachusetts/Amhherst, Tech. Rep., June 1995. [Online]. Available: http://vita.bu.edu/cgc/newlego/index.html

[23] (2006, Dec.) Mindstorms autofabrik. [Online]. Available: http://www.youtube.com/watch?v=GQ3AcPEPbH0

[24] G. Boothroyd, *Assembly Automation and Product Design*. CRC Press, 2005.

[25] T. Lozano-Peréz, M. T. Mason, and R. H. Taylor, "Automatic synthesis of fine-motion strategies for robots," *International Journal of Robotics Research*, vol. 3, no. 1, pp. 3–24, 1984.

[26] M. Erdmann and M. Mason, "An exploraion of sensorless manipulation," *IEEE Transacations on Robotics and Automation*, vol. 4, no. 4, pp. 369–379, 1988.

[27] J. F. Canny and K. Y. Goldberg, "A RISC approach to sensing and manipulation," *Journal of Robotic Systems*, vol. 12, no. 6, pp. 351–363, 1995.

[28] W. Hastings, M. Labarre, and A. Viswanathan, "A minimalist parts manipulation system for a self-replicating electromechanical circuit," in *Proceedings of IMG04*, July 2004. [Online]. Available: http://custer.lcsr.jhu.edu/wiki/images/e/e6/Hastings04.pdf

[29] K. Lee, M. Moses, and G. S. Chirikjian, "Robotic self-replication in structured environments: Physical demonstrations and complexity measures," *International Journal of Robotics Research*, vol. 27, pp. 387–401, 2008.

[30] Y. Wang and G. Chirikjian, "Nonparametric second-order theory of error propagation on the euclidean group," *International Journal of Robotics Research*, vol. 27, no. 11-12, pp. 1258–1273, 2008.

[31] G. Chirikjian, "Parts entropy and the principal kinematic formula," in *Automation Science and Engineering, 2008. CASE 2008. IEEE International Conference on*, Aug. 2008, pp. 864–869.

[32] G. S. Chirikjian, *Stochastic Models, Information Theory, and Lie Groups*. Birkhäuser, 2009.

[33] A. Sanderson, "Part entropy method for robotic assembly design," in *Proceedings of International Conference on Robotics and Automation*, 1984, pp. 600–608.

[34] T. M. Cover and J. A. Thomas, *Elements of Information Theory*. Wiley Interscience, 1991.

[35] M. Badescu and C. Mavroidis, "Novel smart connector for modular robotics," in *IEEE/ASME International Conference on Advanced Intelligent Mechatronics Proceedings*, July 2001, pp. 880–887.

[36] M. Delrobaei and K. McIsaac, "Docking joint for autonomous self-assembly," in *Electrical and Computer Engineering, 2008. CCECE 2008. Canadian Conference on*, May 2008, pp. 001 025–001 030.

[37] A. Castano, A. Behar, and P. M. Will, "The Conro modules for reconfigurable robots," *IEEE/ASME Transactions on Mechatronics*, vol. 7, no. 4, pp. 403–409, Dec. 2002.

[38] E. Klavins, "Programmable self-assembly," *Control Systems Magazine*, vol. 24, no. 4, pp. 43–56, Aug. 2007.