**2010 IEEE International Conference on Robotics and Automation**
**Anchorage Convention District**
**May 3-8, 2010, Anchorage, Alaska, USA**

# Design of iMobot, an Intelligent Reconfigurable Mobile Robot with Novel Locomotion

Graham G. Ryland, *Member, IEEE* and Harry H. Cheng, *Senior Member, IEEE*

*Abstract*—**The design and novel features of a reconfigurable modular robot, called iMobot, with four controllable degrees of freedom is presented in this paper. iMobot, which is designed for search and rescue operations as well as other applications such as research and teaching, has versatile locomotion, including a unique feature of driving as though with wheels and lifting itself into a camera platform. Future work is envisioned for using these modules in clusters to achieve advanced mobility. The accompanying video demonstrates the various locomotion of the modular robot.**

## I. INTRODUCTION

MODULAR robots are made up of individual devices, which are typically simple in form and capability. Modules can be assembled by connecting together to form complex robots or clusters. They can be reconfigured in radically different ways to best suit an application, giving them versatility unmatched by application specific robots [1]. If a modular robot cluster is damaged in the field faulty parts can be replaced with new identical modules. This is made practical by reducing price through mass production of similar parts. Some modular robots can self-assemble and self-repair while deployed, making them a more rugged option than single-function machines [2, 3].

The individual module usually has one to six controllable degrees of freedom. They can be made using a wide array of manufacturing processes and materials depending on the application. Modules in the cluster do not necessarily have to be identical, but can be connected together [4, 5]. Modular robots can move using many types of locomotion, such as crawling like an inchworm, rolling end-over-end like a tank tread, undulating like a snake, walking with legs arrayed like a spider, or even balancing on two feet. If the modular robot is reconfigurable, these operation modes can overcome difficult terrain or accomplish complex tasks [6, 7].

Modular robots span a wide variety of physical forms and capabilities. There is a balance to be struck between simplicity and capability when designing individual modules. Most robots require multiple modules to traverse even simple terrain; others are so complex that they lose the inherent beauty of modularity. The simplest designs have a single degree of freedom, either a joint or two halves rotating in opposition, such as the ATRON [8]. In order to move forward or back, it requires at least two modules, plus a third one if the assembly is able to turn. Modular robots separated from the cluster are immobile. The next step up in complexity is a module having two axes of motion such as MTRAN [9], which can crawl forward and back, but requires a second module to turn. This is a more effective balance of simplicity and capability, but the fact remains that the mobility of the individual module suffers when it is independent from the cluster. Modules are unable to stand on their own or return to the cluster independently if separated.

In this paper the design of a novel reconfigurable modular robot having four controllable degrees of freedom and six mounting locations per module named *iMobot* is presented. This modular robot can be assembled into a cluster, which will be capable of different types of locomotion such as crawling rolling, undulating walking with legs arrayed or balanced self-lifting. However, when separated from the cluster, each module still has full mobility.

## II. CONFIGURATION OF THE MODULAR ROBOT

The basic geometry of each module has a significant effect on the assembly as a whole. When designing for a modular robot, it is critical that the shape is conducive with assembly into clusters. Each module should have as much freedom to move without colliding.

This modular robot design incorporates four controllable degrees of freedom, two joints in the center section and two

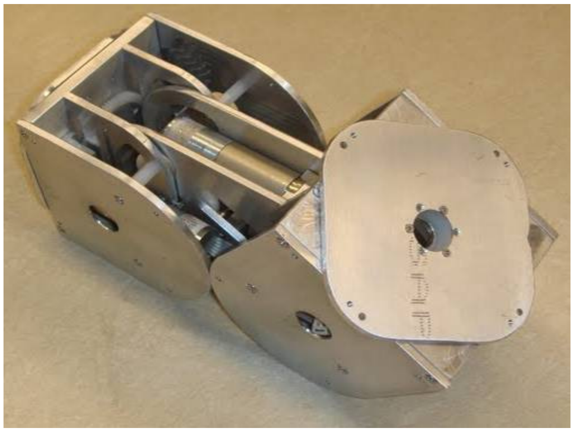


Fig. 1. A modular robot with the front section up and faceplate rotated.

---

Manuscript received September 14, 2009.

G. G. Ryland is a graduate research assistant in the Department of Mechanical and Aerospace Engineering, University of California, Davis, CA, 95616, USA (e-mail: gryland@gmail.com).

H. H. Cheng is a professor in the Department of Mechanical and Aerospace Engineering, University of California, Davis, CA, 95616, USA (530-752-5020; e-mail: hhcheng@ucdavis.edu).

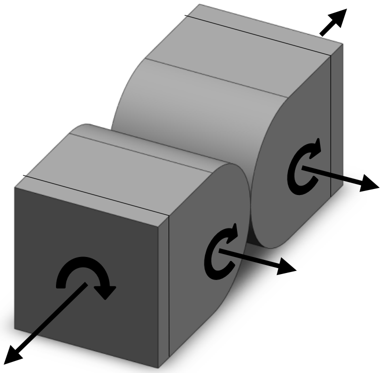


Fig. 2. An outline of the module showing controllable DOF.

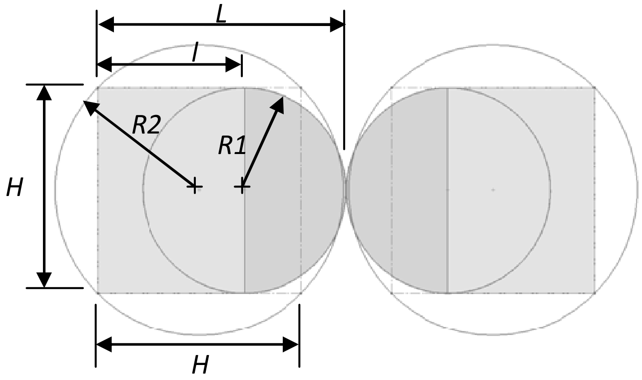


Fig. 4. An outline of modules when mounted to the side.

rotating faceplates at the ends, shown in Figure 1. The basic outline in Figure 2 shows each axis of the four controllable degrees of freedom. The two joints can rotate 180 degrees, while the faceplates at the ends can continuously rotate. This allows the module to turn while crawling and to drive as though with wheels. This significantly increases the mobility of each module, enabling it to traverse a wide variety of terrains.

## III. GEOMETRIC CONSIDERATIONS

Each module of the robot has six mounting positions along the front, back, and sidewalls. In Figure 3, the module shown in red is acting as the central body member, and additional modules are attached to the front and back to create a snake-like robot, or four along the sides to create a dog-like robot. All six faces can be attached to at once (not shown) to create a configuration with six legs.

In the case of the dog-like configuration, the outer modules need to rotate about the mounting faceplate. The design of the assembly must accommodate this rotation. The overall length of the robot can be determined by the need for clearance. The front outline of each module is square, so when rotated it scribes out a circle whose diameter is the diagonal of the face. Figure 4 shows a side-view of the modular robot where the circle R1 represents the axis of rotation for the body joint. The dashed box around each of the outer sections represents the face of modules attached to the side. If these boxes were rotated 360 degrees they would scribe out the circle R2. R1 and R2 are not concentric, which is necessary to allow the attached modules to rotate about their faceplates without contacting one another.

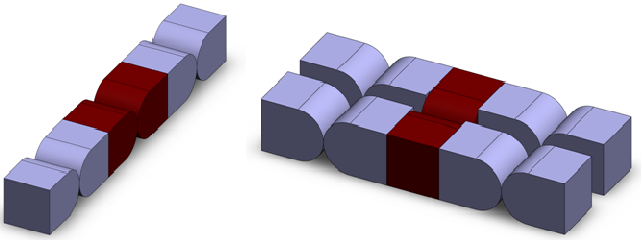


Fig. 3. An outline of modules assembled into clusters.

Therefore, with derivations shown in Equations (1) through (4), the length of each section of the module can be determined by Equation (5). These equations are dimensionless and defined in terms of *H,* which is the height of the module. This means the module can be easily sized, finding the overall length based off the height.

$$R1 = \frac{1}{2}H, \quad (1)$$

$$R2 = \frac{1}{2}\sqrt{H^2 + H^2} = \frac{\sqrt{2}}{2}H \quad (2)$$

$$l = \frac{1}{2}H + R2 - R1 = \frac{\sqrt{2}}{2}H \quad (3)$$

$$L = l + R1 = \frac{\sqrt{2}}{2}H + \frac{1}{2}H \quad (4)$$

$$\boxed{Overall\ Length = 2L = \left(\sqrt{2} + 1\right)H} \quad (5)$$

The face of the outer section is square, so the overall width is equal to the height *H*, but how that thickness is broken up between the center and outer sections depends on other factors. Two motors are required to rotate the outer sections, as well as two motors to drive each faceplate. It is possible to put all motors in the outer sections and leave the center section empty, but after trying out many possible configurations, it was decided to mount two motors in the center section and two in the outer sections on opposite sides to balance weight, shown in Figure 5. There is a gap between motors to allow for the frame material.

The overall size of the module can be roughly determined

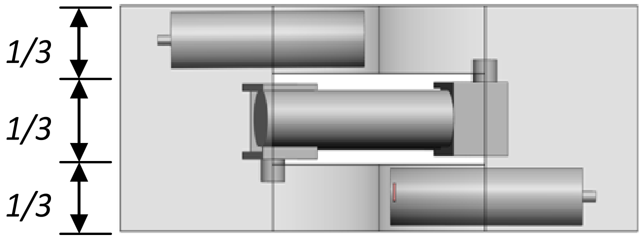


Fig. 5. A top view showing the motors.

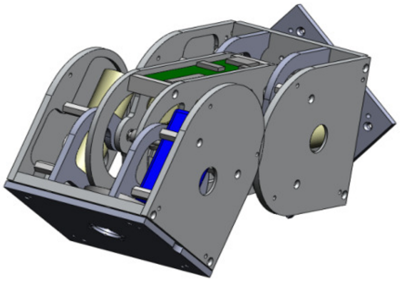


Fig. 6. The module showing mounting points.

by the diameter of the motor plus the required frame material between each motor. Preferably, the motor should be narrow and long, having enough torque to drive the resulting geometry of the module. In our design the motor has a diameter of 0.630" and a length of 2.175" with a low gear ratio well-suited to this robotic application which requires relatively slow rotation and high torque. The diameter of the motor can be used to estimate the overall size of the module. The material to be used to house the center and outer sections is assumed to be 0.125" thick aluminum. The overall length for our sample module can be calculated using Equations (6) and (7).

$$\frac{1}{3}H = .630 + .125'' + .125, \qquad H = 2.64'' \tag{6}$$

$$\boxed{Overall\ Length = \left(\sqrt{2}+1\right)(2.64'') = 6.37''} \tag{7}$$

The resulting geometry and estimated weight can be used to quickly calculate required torque, validating the motor selection.

## IV. CONNECTING MODULES

For modules to connect to each other, as shown in Figure 3, they must have some standardized method of mounting. In a search and rescue operation, it is assumed that the task is known. The modules must be designed to accommodate quick assembly without risk of falling apart in the field. This is why the faceplate of the module robot will be comprised of four #2-56 threaded holes, and four #2 countersunk through holes to create a secure connection. The through holes are used to mount the faceplate to the four mounting positions along the sides of the module. The four countersunk through holes and four threaded holes are offset symmetrically so faceplates can mount one to another, as can be seen on the rear faceplate in Figure 6.

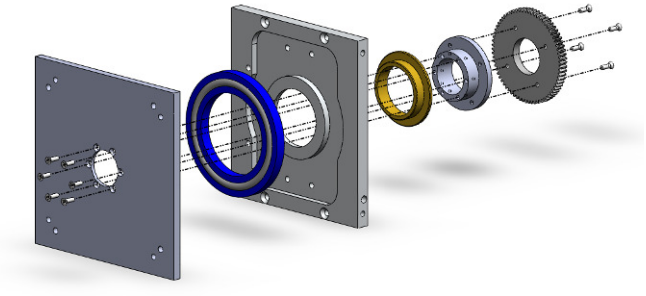


Fig. 7. An exploded view of the bearing design for the faceplate.

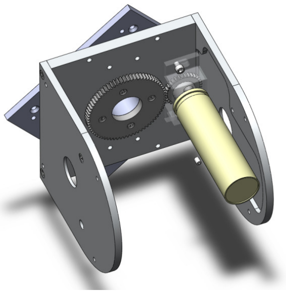


Fig. 8. The gear design for the faceplate.

## V. FACEPLATE DESIGN

The faceplate design must rotate while under differing loads without binding, while taking up as little thickness as possible. When the module is attached to the cluster, the faceplate will have rotational, sheer, and thrust loads applied. Also, the various modules must communicate to each other, so a hollow hub must allow for line-of-sight optical communication. The drive shaft of the motor is attached to a 32 tooth spur gear that drives a 70 tooth spur gear retrofit to bolt to a hollow shaft. This hollow shaft is connected to the faceplate, shown in Figure 8.

The faceplate bearing design is made up of two bearings, a thrust bearing shown in Figures 7 and 9 as blue, and a sintered bronze bushing, shown as gold. The bronze bushing inserts into the back of the frame piece and the hollow Delrin shaft rotates inside it, connecting the drive gear to the faceplate. The thrust bearing, similar to a Lazy Suzan bearing, rotates between the faceplate and frame. The bronze bushing acts axially when the faceplate rotates and as a thrust bushing when the faceplate is pulled away from the module while rotating, the bushing seats against the Delrin flange. The blue thrust bearing provides a smooth rotation when the faceplate is pressed against the module. The thrust bearing is located by the boss in the center of the frame piece.

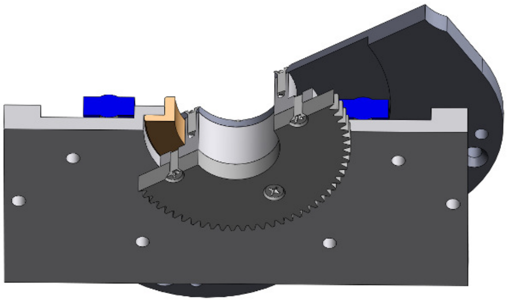


Fig. 9. A cutaway view of bearings with faceplate rotated 45°

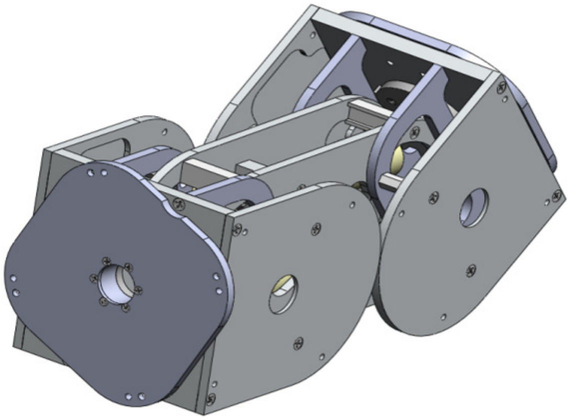


Fig. 10. An improved faceplate design.

## VI. DESIGN IMPROVEMENTS

When designing the modular robot several improvements showed themselves to be useful for operation and assembly. Until this point the faceplates were square, and, if they rotated, the module would lift up and slap down. This could lead to damage over time and, depending on the terrain, risk rolling backward. One solution would be to attach wheels to the faceplates using the mounting points, but this did not necessarily guarantee that the module could drive forward. If the wheels were larger in diameter than R2 in Figure 4, the module would spin while the wheels stayed in one place. This meant that some kind of third, unidirectional wheel needed to be added to the frame to allow the module to drive forward. For the mobility of an individual module, this kind of setup time was not acceptable just to get the module to roll forward.

A more elegant solution was to round the edges of the faceplate so driving forward was a smooth motion, shown in Figure 10. Because this makes the overall size of the faceplate smaller, it doesn't risk rolling backward because the edge of the body slides along the ground.

## VII. OPERATING MODES

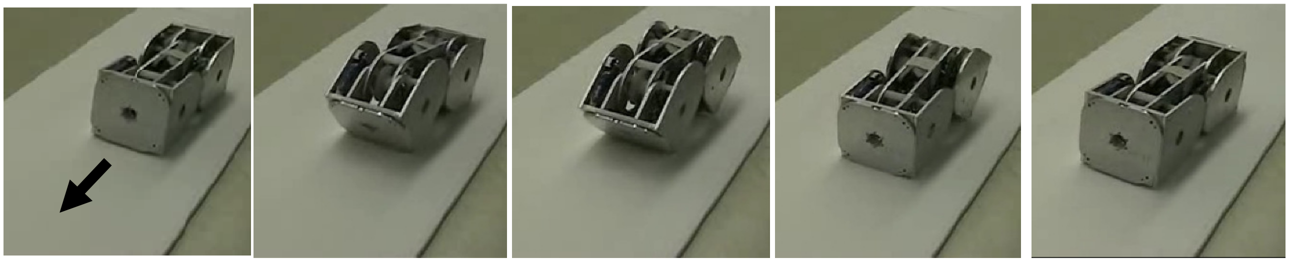
This modular robot design is capable of several types of novel locomotion without sacrificing basic mobility. Some of the operating modes are presented in this section.

### A. *Crawling*

The most basic motion for a modular robot is crawling. In Figure 11a, the robot is resting on the floor. To crawl forward, it rotates the front section downward to drag itself forward in Figure 11b, then the back section rotates downward in Figure 11c. Now that the back is planted, the robot can rotate the front section back up until parallel with the ground, sliding forward in Figure 11d. The rear section then straightens out to push the module forward in Figure 11e. This method of crawling along the ground can be slow, but extremely effective on difficult terrain. What separates this module from others is that if the robot needed to turn from its current trajectory, it can rotate the front or rear faceplate while crawling. Figure 12a through 12c shows the module on its side rotating one faceplate to turn counterclockwise. Another option is to rotate both faceplates in opposite directions.

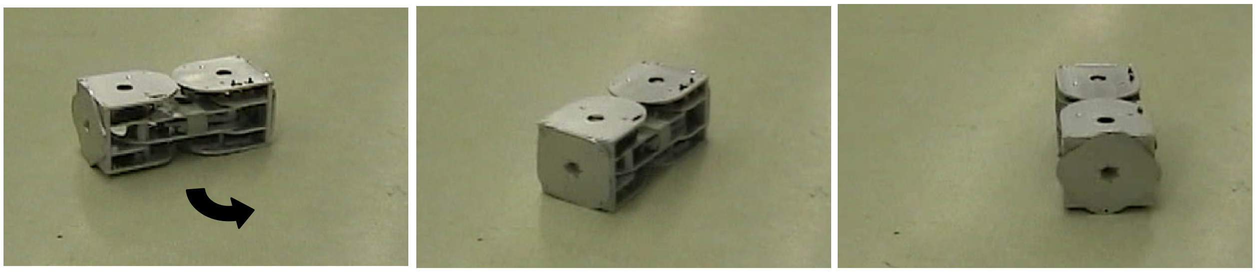
### B. *Driving*

The next operating mode is driving by continuously rotating the faceplates of the modular robot. The faceplates rotate forward at equal speed shown in Figure 13. It can be seen that because of the rounded edges of the faceplates, the modular robot does not violently rise up and slap down as would be the case if they were square. Also, the part of the



11a. 11b. 11c. 11d. 11e.

Fig. 11. Crawling like an inchworm by rotating front and back sections.



12a. 12b. 12c.

Fig. 12. Turning by rotating faceplates independently.

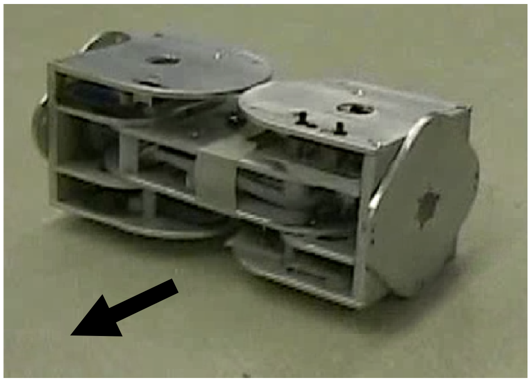


Fig. 13. The robot can drive forward by rotating both faceplates.

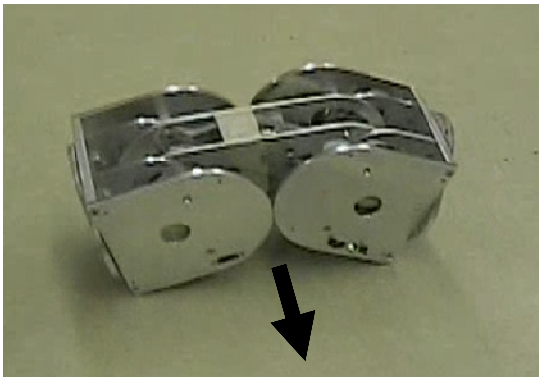


Fig. 14. The robot can gain clearance by arching in the middle.

body which makes up the outer sections, keeps the module from spinning in the air when the faceplates rotate. Again, if the modular robot needed to turn, it could rotate the faceplates individually, as previously described.

If the module requires more clearance while driving in rough terrain it can arch in the center, as shown in Figure 14. This motion also brings the faceplates at a more aggressive angle of engagement with the ground.

Another method of driving is rotating the front section 90 degrees and the back section -90 degrees and rotating the faceplates forward, shown in Figure 15a through 15c. This reduces the overall footprint of the modular robot, allowing it to maneuver in narrower areas. While the faceplates rotate at equal speeds the module can turn by articulating its body.

### *C. Camera Platform*

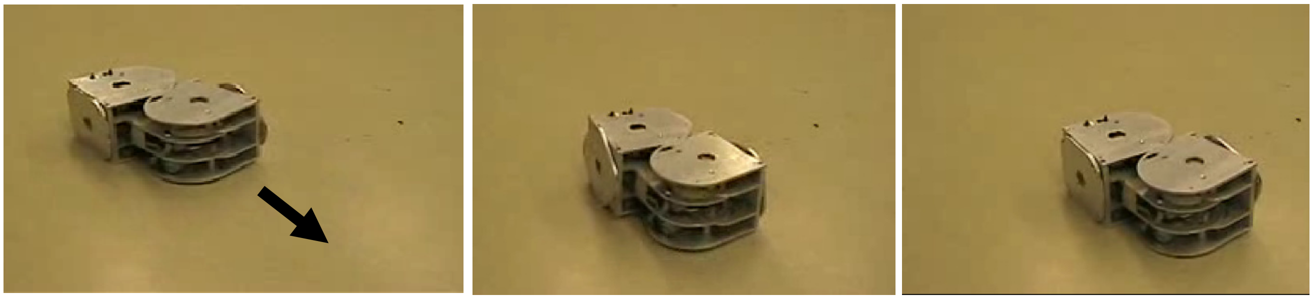
One of the more unique operating modes is where the module lifts itself into a camera platform. This is a capability unique to this modular robot design and is made possible by the rotating faceplate. The modular robot is flat on a table in Figure 16a. It rotates its rear section down until the faceplate is flat on the table in Figure 16b. The front section rotates down in Figure 16c, and the faceplate of the rear section rotates 45 degrees to provide a wider platform, which is critical to lifting into a vertical position. The rear section then rotates up to lift the module into the position shown in Figure 16d. Once in this position the module can tilt using the joints of the center section and pan using the faceplate of the rear section, rotating the module in Figure 16e. Future designs will have a camera inside the hollow faceplate, allowing the operator to view the environment from a slightly taller perspective than when crawling.

## VIII. FUTURE WORK

This modular robot design significantly improves the mobility of individual modules as well as the mobility of modules when attached in clusters. The axis of rotation for the faceplate is near to the axis of rotation for the body and, when combined, these two axes imitate a ball joint. This is an advantage because it only takes five modules to create a dog-like robot with articulated shoulders and haunches, as shown in Figure 17. The center section can arch up as though it were a back. Another method of locomotion with this configuration is to rotate all four feet out 90 degrees so the faceplates roll along the ground giving it four wheel drive, shown in Figure 18. If a more challenging terrain presented itself, the robot could go back to walking with four legs. A camera with wireless communication as well as various sensors will be integrated into the robot modules.

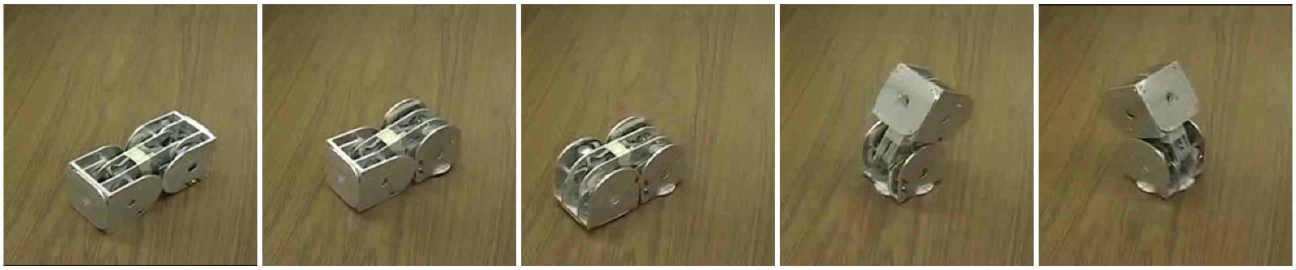
## IX. CONCLUSION

An intelligent reconfigurable mobile robot, called *iMobot*, with four controllable degrees of freedom has been developed to improve mobility of the individual module, shown in the accompanying video [10]. Modules have various locomotion capabilities, including a unique feature of lifting into a camera platform. One of our major design goals with *iMobot* was to improve the individual module's mobility without significantly increases its physical complexity. Our design blends the maneuverability of more complicated modules while keeping the compact shape,



15a. 15b. 15c

Fig. 15. Reducing footprint by rotating end sections and driving forward.



16a. 16b. 16c. 16d. 16e.

Fig. 16. Lifting into a camera platform.

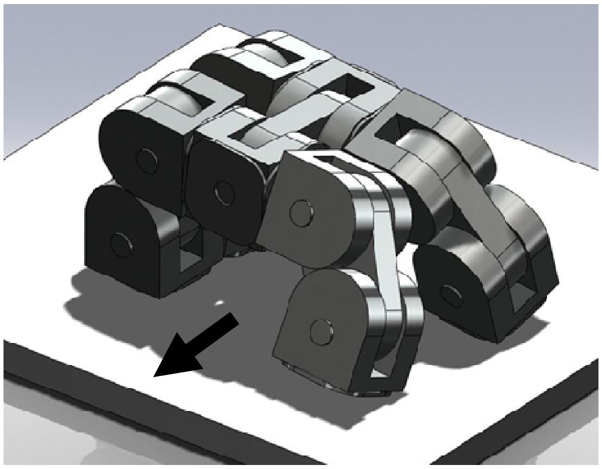


Fig. 17. A conceptual model of a dog-like modular robot cluster.

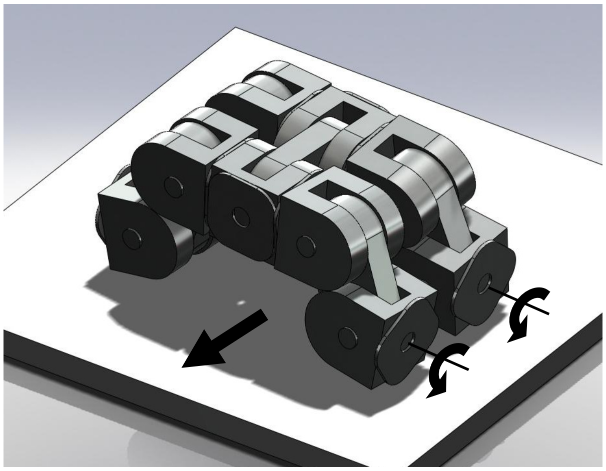


Fig. 18. The modular robot cluster using four wheel drive.

which lends itself to assembly in clusters. Modules can be assembled into various shapes capable of different types of locomotion, such as crawling, rolling, undulating or walking. The developed modular robot and the resulting cluster have many potential applications including teaching of robotics and related technologies and search and rescue operations. Detailed information about our work can be found in [11-13].

## ACKNOWLEDGMENT

The authors would like to thank Stephen Nestinger for his contributions to the implementation of the electronic design for the robot described in this paper.

## REFERENCES

[1] Craig Eldershaw, Mark Yim, Dave Duff, Kimon Roufas, and Ying Zhang. Robotics for Future Land Warfare: Modular Self Reconfigurable Robots. Seminar and workshop, Defence Science Technology Organisation, Adelaide, Australia, 2002.

[2] Mark Yim, Paul White, Michael Park, Jimmy Sastra, "Modular Self-Reconfigurable Robots," Proc. of *Encyclopedia of Complexity and Systems Science, 2009, pp. 19-32.*

[3] Kasper Stoy, Wei-Min Shen, and Peter M. Will, "Using Role-Based Control to Produce Locomotion in Chain-Type Self-Reconfigurable Robots," Proc of *IEEE/ASME TRANSACTIONS ON MECHATRONICS, VOL. 7, NO. 4, December 2002, pp. 410-417.*

[4] Hod Lipson, Josh Bongard, Victor Zykov, Evan Malone, "Evolutionary Robotics for Legged Machines: From Simulation to Physical Reality," Proceedings of the 9th Int. Conference on Intelligent Autonomous Systems (2006): 11-18.

[5] K. Matsushita, H. Yokoi, and T. Arai, "Robotics in Education: Plastic Bottle Based Robots for Understanding Morph-Functionality," Proc. of *IEEE International Symposium on Robot and Human Interactive Communication, 6-8 Sept. 2006 pp. 662-667*

[6] Wei-Min Shen, Maks Krivokon, Harris Chiu, Jacob Everist, Michael Rubenstein, and Jagadesh Venkatesh, "Multimode Locomotion via SuperBot Reconfigurable Robots," *Springer Science, April 2006.*

[7] Ying Zhang, Mark Yim, Craig Eldershaw, Dave Duff and Kimon Roufas, "Scalable and Reconfigurable Configurations and Locomotion Gaits for Chain-type Modular Reconfigurable Robots," Proc. of *IEEE International Simposium on Computational Intelligence in Robotics and Automation, July 2003, 893-899.*

[8] Morten Winkler Jorgensen, Esben Hallundbaek Ostergaard, and Henrik Hautop Lund, "Modular ATRON: Modules for a self-reconfigurable robot," Proc. of *IEEE/RSJ International Conference on Intelligent Robots and Systems, October, 2004, pp. 206-207.*

[9] Akiya Kamimura, Satoshi Murata, Eiichi Yoshida, Haruhisa Kurokawa, Kohji Tomita, Shigeru Kokaji, "Self-Reconfigurable Modular Robot," Proc. of *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2001, pp. 606-612.*

[10] Graham G. Ryland and Harry H. Cheng, "Novel Locomotion of iMobot, an Intelligent Reconfigurable Mobile Robot," *Video Proc of the 2010 IEEE International Conference on Robotics and Automation,* Anchorage, Alaska, May 3 - 8, 2010.

[11] iMobot --- an Intelligent Reconfigurable Mobile Robot, http://iel.ucdavis.edu/projects/imobot

[12] Graham G. Ryland and Harry H. Cheng, "Modular Robot Design Utilizing Rotating Faceplates and Dynamic Motion Control by Robot Pose Manipulation," UC Case No. UC09-598-1, US Patent (pending).

[13] Graham G. Ryland, "*Modular Robot Design and Pose Training,"* MS Thesis, Departemet of Mechanical and Aerospace Engineering, University of California, Davis, 2009.