Evolving Quadruped Gaits with a Heterogeneous Modular Robotic System

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Abstract— **There has been much research into the development of robotic controllers in educational, industrial and government research labs, but limited hardware budgets constrain the types of morphologies in which researchers can experiment with. One option is to use LEGO components or other toy-grade kits, but these have well-known limitations. Here we present a heterogeneous modular robotic platform that can be reconfigured to a wide variety of robot morphologies, such as legged robots and manipulator arms. In addition, we have developed a simulation environment for our modules allowing for the artificial evolution, or learning, of behaviors to occur in simulation for transfer to reality. We demonstrate the effectiveness of our system by evolving a quadruped gait in simulation which successfully transfers to a hardware version of this robot.**

I. Introduction

There has been much research into the science of developing robotic controllers, with many educational, industrial and government research labs working with a variety of robot morphologies, including rovers, legged robots, manipulator arms and collaborative robot teams. However, since research budgets are often small, and hardware budgets are often smaller this can constrain the range of morphologies with which a given lab can experiment, and may limit the ability of the robotics community as a whole to explore new morphologies that are not already commercially available. Many institutions have attempted to work around this by using LEGO components or other toy-grade modular design kits, but these have well-known limitations. Here we present our heterogeneous modular robotic platform that is of greater versatility to toy-robot kits and of a quality comparable to typical robots built in robotics research labs. To assist in the development – whether using manual design, learning algorithms or evolutionary algorithms – of controllers for our hardware platform we have also developed a software simulation system for modeling these robots. We demonstrate the effectiveness of our system by evolving a quadruped gait in simulation which successfully transfers to a hardware version of this robot.

Heterogeneous modular robots, with their fundamentally open-ended morphological range, have the potential to alleviate this problem. A system of modules optimized for low cost could provide an extremely versatile research platform to researchers wishing to go beyond the standard rover and arm morphologies without investing in custom hardware. In this domain, manual reconfiguration of the sort used in our modules as discussed above would be entirely acceptable. Because all morphologies are derived from a relatively small number of module types, the manufacturing efficiencies associated with mass production promise to drive the price down even further.

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While most robot gaits are static and programmed by hand (for surveys see [27] and [21]), some work has used evolutionary or learning algorithms to produce gaits automatically. For initial work in evolving gaits for actual robots the experimenter evaluated and entered gait performance manually [12], [5]. A more automated approach has been the evolution of gaits in a simulator that were then transferred to an actual robot [4], [18], [8]. In addition, the evolution/learning of a gait has also occured using the actual robot itself [13], [6], [7]. A limitation of this previous work is that the robotic hardware for which the gaits have been evolved is fixed to a particular morphology.

To enable research into techniques for evolving/learning robot controllers which we can test on various robot morphologies, we have developed a reconfigurable modular robotic system along with corresponding physical dynamics modeling software. Reconfigurable modular robots first emerged in the eighties in the context of manipulator arms [29], and since that time the modular robotics community has focused primarily on *homogeneous* robots, those constructed from many copies of a single module type [30], [10], [23]. A homogeneous design can introduce unnecessary complexity into robot and module designs: for example, rolling locomotion in a traditional modular robot involves a long chain of modules connected in a tread-like topology[31], when in many situations it may be simpler to add wheel modules directly. Our modular robots differ from most existing robots in several respects. Most importantly, they are *heterogeneous*, consisting of modules of several different types each designed to perform a particular simple function.

In this paper we outline a modular robotic system intended as one step in the right direction. We first summarize related work in modular robotics, and we discuss a number of potential applications for modular robotics to future space exploration missions. We then describe the design and manufacture of our initial prototype hardware. Next, we outline a simulation and design environment capable of automated morphology and controller design and optimization, and we present initial results of a quadrupedal gait optimization. Finally, we discuss the immediate application of this form of modular robotics to the laboratory and classroom setting as a low-cost generic platform for robotics research.

II. MOTIVATION

Future NASA exploration missions [9], [11], [14], [19] will require advanced hardware systems architectures to achieve sustainability, affordability, and reliability. Critical to this goal is the need for generic autonomous robotic platforms than can be adapted to a variety of tasks, autonomously and in cooperation with humans. Some of the tasks and challenges for such systems are known in advance (pre-launch) and some are dynamic (post-launch), resulting from changing mission requirements and unexpected events.

In order to realize a sustainable campaign of space exploration, the underlying technologies must enable affordable, reliable, and effective exploration and infrastructure systems. For autonomous robotic explorers, these criteria can be met by using a modular robot (MR), which consists of a collection of standard modules, such as actuated links, sensors and end-effectors, that can be rearranged into different shapes [15], [17], [22], [26], [28], [33]. Because each robotic module is a simple device, and several of each type of module are constructed, design and manufacturing is cheaper than for a single complex robot with many unique modules. Spending can be spread over a period of time since only the minimal components need be purchased upfront with new modules purchased as funds allow. Modules can be shipped into space over multiple missions, allowing increasingly more complex robots to be assembled. The ability of a modular robot to reconfigure its shape for new functionality gives it versatility for changing tasks and environments [32]. Modules can be divided between multiple robotic systems as needed, allowing multiple tasks to be accomplished simultaneously, and a subset of modules may be shut down at any time, reducing power consumption. MR systems made up of repeated, regularly shaped modules can be more easily packed into a space, and the different modules can be distributed to fit into available spaces, which is useful for both launch and stowage [32]. Finally, a group of modules has greater fault tolerance than a single robot since failing modules can be removed from the system without impairing its ability to function and there is no single point of failure.

Space exploration can be divided into in-space operations and surface operations [19]. and in the following two subsections we discuss the advantages of MR in both domains along with example scenarios.

A. MR for In-Space Operations

In-space operations for robots include activities such as assembly, inspection, maintenance tasks and astronaut-assistance of orbital extra-vehicular activity (EVA) [16]. These EVA tasks involve moving about the structure and manipulating smaller-scale connectors and instrumentation attached to the structure as well as the handling of large-scale components, which is time-consuming and dangerous [3], [9], [20]. The diversity of tasks and different scales would typically require human involvement or several different robots.

Consider the limitations of existing, specialized robots for in-space operations. Robotic arms, such as the Remote Manipulator System (RMS) [20], are good for moving large objects around the ISS but are too large for manipulating smaller ORUs for repair tasks, they are hard to transport to position, and lack the ability to perform some construction tasks without aid. Humanoid robots, such as NASA's Robonaut [1] and the Canadian Space Agency's Dextre, are more capable for jobs involving smaller objects but are limited to those tasks that are well suited for a human, such as those tasks that require no more than two arms. Neither of these two types of robotic systems are adjustable to handle tasks outside the range for which they were designed.

Unlike specialized single-robot systems, reconfigurable modular robots are a robotic platform that provides the ability to handle a variety of assembly and maintenance tasks through their ability to form robotic structures of different size and with different manipulator capabilities. For example, a MR could distribute its active modules along the ISS in a type of bucket brigade so that an object could be passed along the entire length of the brigade while under full control the entire way.If there are not enough modules to be placed along the entire path, modules could move from the end of the brigade to the front of the brigade after they have passed the object along. Another advantage is that with enough modules a MR can reconfigure into a system large enough to manipulate a docking spacecraft, or can form a chain small enough to squeeze through a restricted space, such as a pipe, and then reconfigure to a different shape on the other side to perform the desired task. In addition, MR can form the necessary manipulation capability for the current job, such as by forming three or more arms to hold two truss elements together as well as the necessary tools to weld them together.

B. MR for Surface Operations

Even more expensive than putting a spacecraft in orbit is landing on another planetary surface since additional weight is required for the landing mechanisms and additional fuel for deceleration. Once on the surface, useful capabilities for surface operations are mobility, instrument and sample operations and science investigations [16], as well as the support of lunar and planetary bases [2]. If the same mass can be used for two or more of these tasks then extreme cost savings can be realized. In addition, by constructing robotic elements of explorers with modular robotic components greater versatility and fault tolerance of these mechanisms could be achieved.

Reconfigurable MR systems can result in a reduction of mass by allowing the same hardware components to be used for multiple tasks. For example, Phoenix, a lander planned for 2007,has the goal of landing at the north pole of Mars and using a robotic arm to dig through the upper few feet of the surface to look for ice. By using reconfigurable MR modules components could be used as both legs, for mobility, and an arm for sample collection.

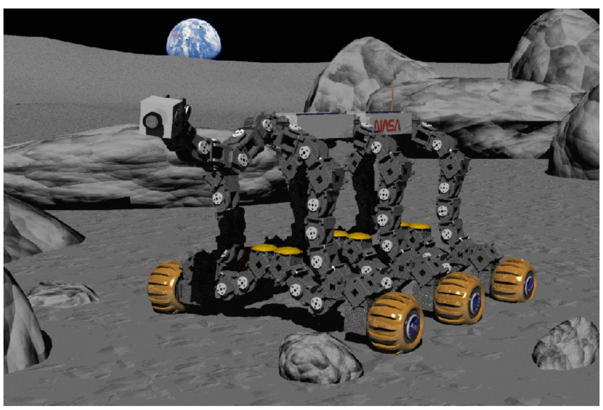
Versatility and fault tolerance are also enabled through modularity and reconfigurability. Spirt and Opportunity, the two mobile Mars Exploration Rovers, cannot roll up/down overly steep craters or hills or through rugged terrain and have experienced various mechanical difficulties throughout their mission. A MR version of the Martian rovers could perform the exploration of Mars with greater versatility by using a wheeled mode to drive over relatively smooth terrain and a legged configuration to walk over rough terrain (figure 1). Reconfigurability would allow legs to be used to form or extend one or more arms for feature examination.

In addition, one challenge that has been identified as not likely to be solved in the next decade is the ability for a mechanism to right itself from upset conditions [19]. Similarly, Opportunity had problems egressing from its landing craft which took ground based engineers several days to sort out. A mechanism with modular robotic components could right itself by re-assembling in an upright orientation or by using the MR components to form robotic arms and legs to re-orient itself.

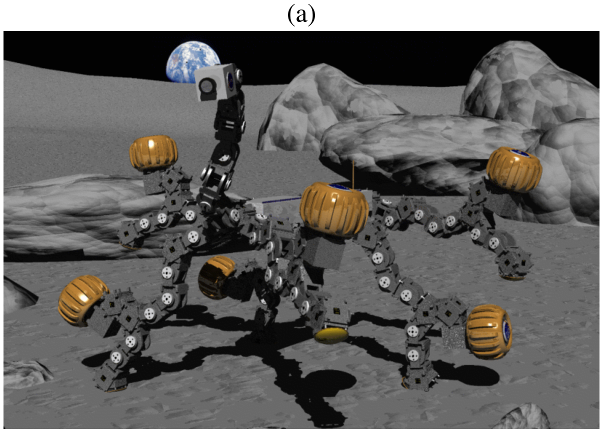
III. Modular Robot Hardware

Our modular robots differ from most existing such systems in several respects. Most importantly, they are *heterogeneous*, consisting of modules of several different types each designed to perform a particular simple function. A number of other labs have focused their attention on the problem of self-reconfiguration [34], [35], [10], [23], [25], however, as a type of "building bricks" for other making specific robots, self-reconfiguration is not necessary and the hardware to support it can add significantly to module weight, size, cost, and complexity. Thus the modules discussed in this paper were all designed for quick and easy manual reconfiguration, in this case using thumb-screws.

We present two generations of prototype hardware. The first generation was a quick and inexpensive design featuring a small number of module types intended to provide some insight into the issues that arise in the design, construction, and use of manually-reconfigurable modular robots. These are the hardware modules which used for our gait optimization experiments. The second generation, currently undergoing construction and testing, builds on the lessons of the first and expands the number of module types available.



(a)



(b)

Fig. 1. A modular robotic system for surface exploration: (a) wheeled mode for fast and efficient traversal of relatively smooth terrain; and (b) legged mode to navigate through rougher terrain.

A. First-generation hardware

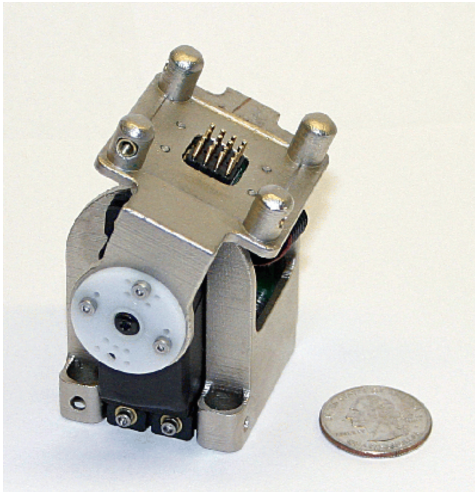
Our first-generation prototype modular robotic system included three module types: a rotational actuator module, a five-connector hub module, and a power and communications module. The design goals were low cost, low mass, and small size. Low mass and size are important so that the behavior of the robot is not limited by motor torque: a snake-like arm, for example, is less useful if it cannot support its own weight.

The joints are hinge-type actuated modules, shown in Figure 2(a), similar to those found in existing homogeneous robots such as PolyBot [34] and the NASA Snakebot. For this generation we used inexpensive servomotors of the sort designed for the hobby industry and manufactured in volume. We selected a medium-sized servo with a high torque/mass ratio, and the module scale was chosen to be as small as possible while accommodating that motor.

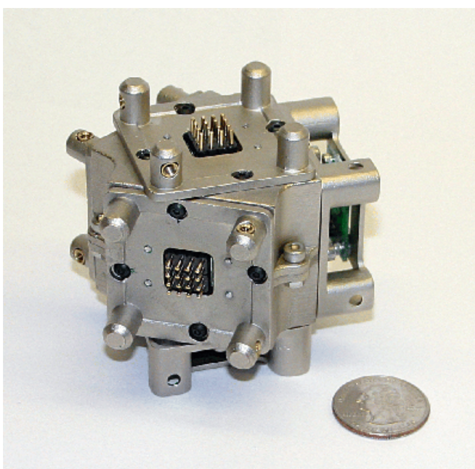
The hub, shown in Figure 2(b), has a novel structure with five connection points arranged to provide a variety of connection angles including 90° and 120°. With this design it is possible to construct both rectangular and hexagonal lattices for use in assembling larger structural configurations. The hub modules also provide power distribution and communications switching between neighboring modules.

The battery and communications module, shown in Figure 2(c), allows the robot to operate fully autonomously or in a tethered mode, and can be configured with either five or ten AA-size NiMH batteries. Finally, we have also constructed passive "foot modules" which can be installed using the module connector to protect the other modules and to provide a more uniform surface for locomotion.

The module connectors, shown in Figure 3(a), were designed for quick and easy manual reconfiguration. They are four-way symmetrical and slide together using alignment pins. Spring-loaded gold-plated contacts establish the electrical connections, and up to four thumbscrews may be used to lock each pair of modules together. There are gendered male and female connectors, but this is not restrictive since each face on each hub may be configured with either a male or female connector. (On the hub shown in Figure 2(b), the



(a)



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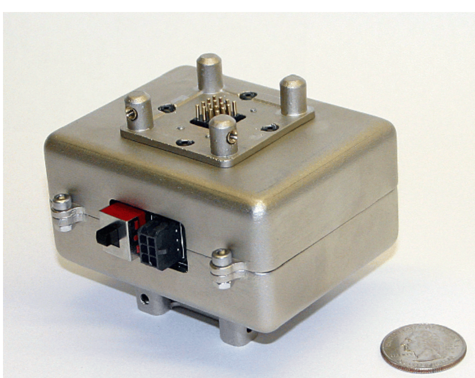
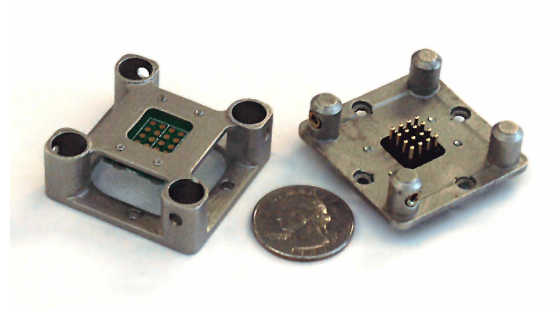
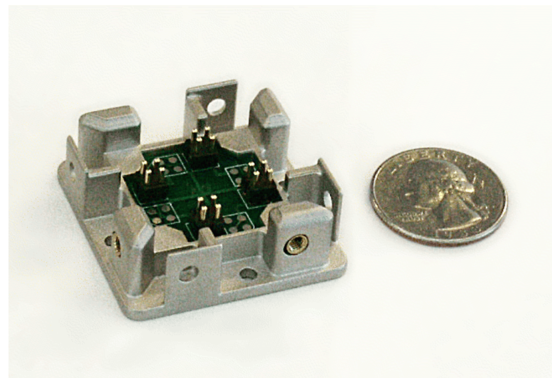


(c)

Fig. 2. The three primary module varieties in the first-generation prototype system: (a) a hinge-type actuator, (b) a five-connector hub, and (c) a battery and communications module.



(a)



(b)

Fig. 3. The first-generation gendered electromechanical connectors (a) and second-generation hermaphroditic connector (b) used in the prototype systems.

top, front, and left faces are configured with male connectors while the bottom and right faces have female connectors.)

Achieving low small-quantity module cost and low module mass also guided the selection of the primary module material and manufacturing process. The parts were first printed in an ABS-like plastic using stereo-lithography and were then plated with a layer of copper followed by a layer of nickel. The resulting parts have essentially the same density as common plastics but considerably greater stiffness, strength, and durability. This is a rapid-prototyping process with virtually zero set-up and tooling costs, making it much more attractive than traditional machining processes for production in research quantities. Moreover, experimentation with minor variations or new module types incurs no additional cost.

The finished 60mm-scale modules are smaller and lighter than those of other reconfigurable modular robots in the research community. The hinge modules weigh approximately 125gm, and each hub module, with no motor but considerably more structural material, weighs roughly 115gm. The heftier battery module weighs 390gm with ten batteries and 240gm with five. For tethered operation the batteries may be removed, in which case this module weighs only 90gm. The feet are virtually weightless at just over 10gm each.

Each powered module is controlled by an Atmel FP-SLIC microcontroller/FPGA. The FPGA provides as many communications ports as the module has connectors and interfaces to other on-board hardware such as motors. The microcontroller, a 25MHz AVR core, manages the higher-level communications and control functions. The modules communicate with each other, and optionally with one or more control computers, using a simple *ad hoc* peer-to-peer network scheme. Any module can send data packets to any other module, and the intermediate modules route the packets accordingly. This permits true distributed control of the modules in addition to the usual master/slave control strategy.

We have tested several different robot configurations using these modules, including the classic snake-like arm, robots with multiple arms, and legged robots with three and four legs.

B. Second-generation hardware

Our second-generation system has been designed to address several limitations of the first, and is now partially complete. The gendered connectors of the first system, while not strictly limiting, were nevertheless inconvenient, and the new system features the hermaphroditic connector shown in Figure 3(b). Two entirely new module types have been introduced. The first, shown in Figure 4(a), is an actuated wheel intended for rover-like locomotion at velocities up to approximately a meter per second. The control electronics and the motor are contained entirely within the hub of the wheel. The second new module type is a digital camera, shown in Figure 4(b). The camera transmits images wirelessly to a controlling computer, thus avoiding the need for a high-bandwidth inter-module communications system.

One of the chief limitations of the first-generation system was the low accuracy with which the hobby-grade motors could be controlled. The second-generation system is therefore being redesigned with high-precision brushless DC servomotors and backlash-free harmonic gearboxes. The feet modules are also being upgraded with tactile sensing capability based on QTC force sensors. Finally, the remaining electronics are being updated with a larger FPSLIC processor and support for a new higher-voltage power bus.

(a)

(b)

Fig. 4. Two new module types introduced in the second-generation prototype system: (a) an actuated wheel and (b) a wide-angle camera.

IV. Modular robot simulation

To make the most use of a modular robotic system it must be combined with software tools to assist in developing behaviors and controllers for a particular robot morphology. We have developed a physics-based software simulation environment for modular robots in C++, which allows users to construct simulated robots using a variety of module types and to extend the simulation by adding additional types with compatible connectors. The physical dynamics simulation engine, based on a modified version of the Open Dynamics Engine [24], was designed for high-speed medium-fidelity simulation. Thus it is suitable for use both by engineers wishing to rapidly explore design spaces by hand and also within the evaluation loop of a search or optimization tool. The simulator supports several levels of photo-realism, ranging from simple block representations useful for quick visualization (as shown in Figure 5(a)) to fully rendered images that can be used for simulated closed-loop visual servoing and other image-based control modes.

We have also developed an abstraction layer that allows robot control software to transparently operate both the simulated and real modular robots. This makes it trivial to transfer controller designs from simulation to hardware for testing or use, and also makes it possible to incorporate testing on real hardware into an automated design cycle.

V. Quadrupedal gait optimization

As an initial test of the simulation and automated optimization system, we optimized the walking gait of the quadrupedal robot shown in Figures 5. We held the morphology fixed and assumed a periodic gait. The trajectory of each joint parameterized by the first three Fourier basis coefficients,

$$\theta_i(t) = a_i + b_i \sin(\omega t) + c_i \cos(\omega t) \ .$$

Here $\theta_i(t)$ is the trajectory of the ith joint, ω is a constant chosen to set the period of the gate to 1 Hz, and a_i, b_i, and c_i are the three evolved paramters corresponding to each joint. We simulated each candidate controller operating for ten seconds, clamping all trajectories to conform to the mechanical constraints of the joints. In order to search for efficient gaits we chose our fitness function to be

$$F = \frac{D}{\sum_i b_i^2 + c_i^2} \ ,$$

where F is the computed fitness score and D is the total distance travelled by the robot. The denominator serves as an approximate measure of the energy required by the gait: this fitness function prefers controllers that produce minimal actuator motion.

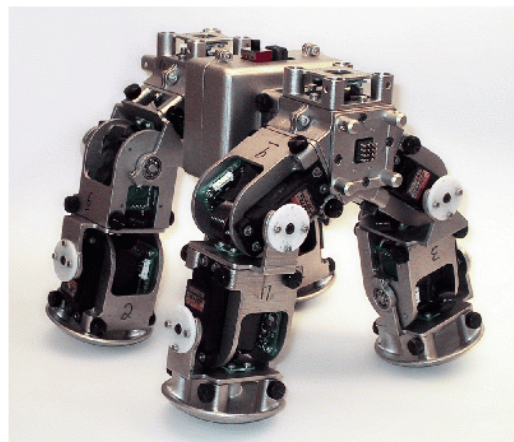
We used a steady-state evolutionary algorithm with a population size of four. At each generation, two individuals were chosen at random from the population and their fitnesses were compared. The weaker individual was then replaced by a mutated version of the stronger individual. Mutation consisted of adding to each parameter a random offset chosen uniformly from the range $[-\alpha, \alpha]$. The parameter α was reduced over the course of each evolutionary run according to

$$\alpha = \frac{1000}{1000 + n} \ ,$$

where n is the generation number. Five percent of the time a new individual was instead generated entirely at random. The results of ten runs are shown in Figure 6.

Seven of the ten runs converged to essentially the same high-performing result, while three experienced premature convergence to sub-optimal gaits. The seven all surpassed earlier efforts at manual optimization. They did so by discovering an unexpected gait which walks “sideways” relative to the originally-imagined direction of travel. Furthermore, this somewhat unintuitive gait eliminates the need for four of the eight actuators. In order to be sure that the gait was not taking advantage of some unrealistic property of the simulator, we transferred the gait to the real modular robot, where it performed as advertised.

(a)



(b)

Fig. 5. The quadrupedal walking robot used in the experiments shown in both (a) simulation and in (b) reality.

VI. Conclusion

Autonomous robotic systems are critical to achieving sustainability and reliability in NASA’s exploration mission. The current monolithic design approach to robotics offers little room for reuse, adaptation, or maintenance on long-duration or open-ended missions. Adopting a modular design could address these needs, by allowing a single system mass to be reconfigured to suit each task and by reducing the number of spare parts required to achieve redundancy. However, there are many challenges to the scalability, reliability, and usability of such a system that a must be addressed before it could be put to use outside the laboratory.

We have presented initial prototype hardware, intended as a platform for beginning to address those challenges. Though this hardware is still far from being immediately useful in a space mission context, its versatility and usability is steadily increasing and we believe it may have immediate applications in the robotics research setting. Each module implements a single core function, reducing individual module complexity and cost and allowing a robotic system to be tailored as needed by including special-purpose modules. By designing for a rapid-prototyping manufacturing technology, it is easy and inexpensive to add new module types when the existing types are insufficient or to make incremental changes between manufacturing runs.

Finally, we have described the first components of an automated design and optimization system for modular robots,

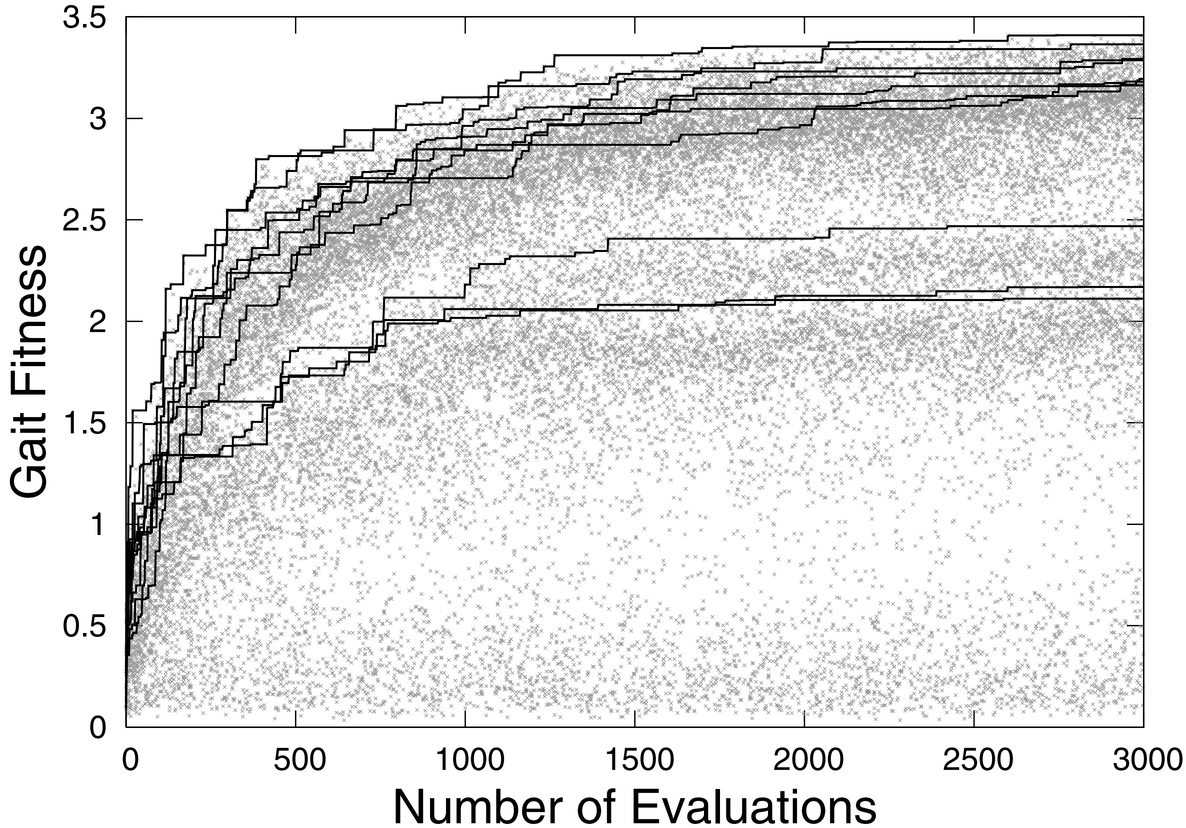
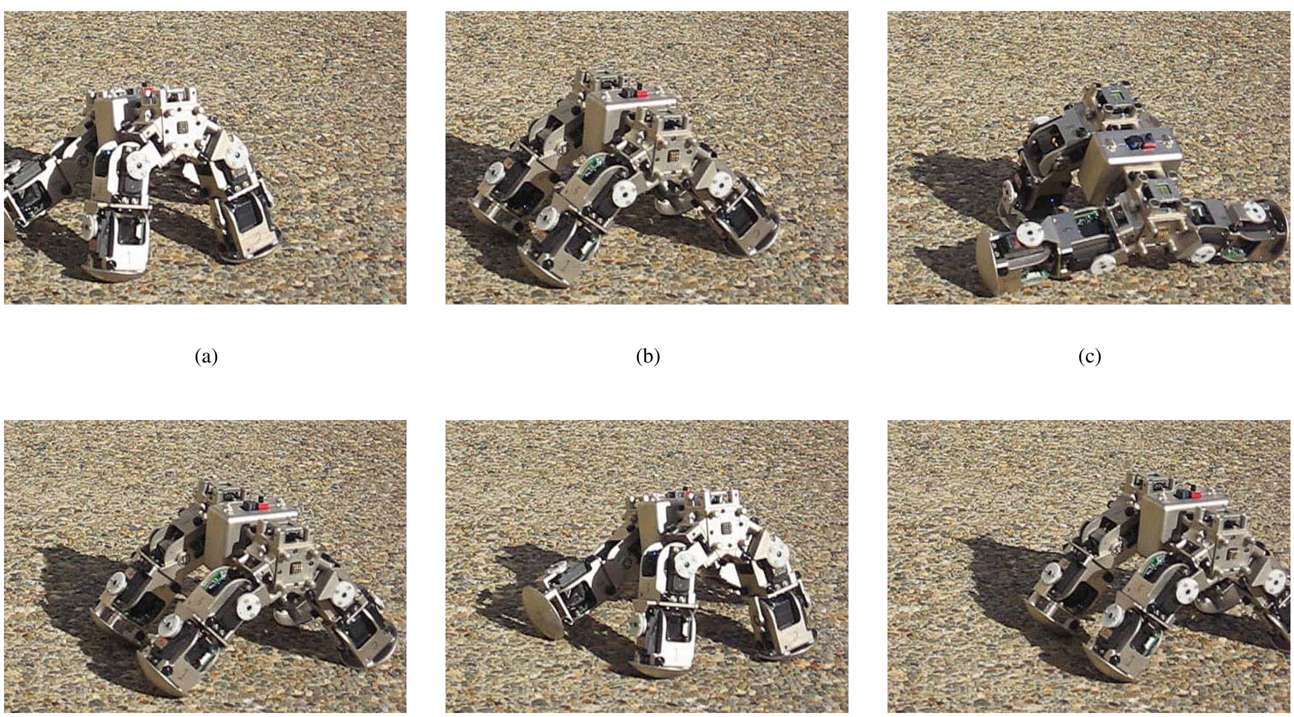


Fig. 6. Ten gait optimization runs. Grey crosses represent evaluated gaits, and black lines indicate the best found so far in each run.



(a) (b) (c)

(d) (e) (f)

Fig. 7. A sequence of images of the quadrupedal robot with an evolved walking gait.

including a modular robot simulator and an evolutionary controller optimization tool. We have presented the results of applying this system to the optimization of a walking gait, and discussed how the system was even able to outperform the human engineer. As the capabilities of both the robots themselves and automated design tools grow, we expect such tools to be of increasing importance in the use of modular robots.

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