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Towards Continuously Reconfigurable Self-Designing Robotics

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Abstract

We propose a new process for continuously reconfigurable robotics. Given a task, a robot evolves a suitable morphology and control, then prints the assembled 3D structure, downloads into it and performs the task, and then recycles into a different form for the next task. This approach relinquishes the need to adhere to discrete or fixed components as well as manually designed configurations. Although the technology for fully realizing the proposed concept to is not entirely available, we have demonstrated a first case: Given the task of locomotion, various robots with different mechanics and control are evolved automatically. The design space is comprised of only linear actuators and sigmoidal control neurons embodied in an arbitrary thermoplastic body. The robots then print pre-assembled using rapid prototyping technology, and perform the task in reality. The robots are then recycled. This paper described one implementation and provides examples of successful physical robots generated by the proposed process.

1 Introduction

At the basis of reconfigurable robotics is the idea that robots need not have a fixed morphology. Instead, robots might consist of several components that can be rearranged to suit needs of various tasks. This idea has been extended to self-reconfigurable robots, where components can self-assemble and self-repair to attain and maintain configurations. In this paper we wish to extend these ideas further in two main directions. First, instead of using discrete and fixed components we propose the use of a continuously variable body or a set of components with continuously variable parameters. The notion of self-assembly of components climbing and sliding on top of each other would consequently be replaced by melting and reshaping of components using principles associated today with rapid prototyping. Second, instead of using manually designed configuration and choreographed behavior for preconceived tasks, we seek ways to allow for the actual configuration and control of the robot to be generated automatically for a given task, by the robot itself, without human intervention. In this case the robot would consist of the entire designing software, formable material/components and the forming/recycling apparatus. These two proposed extensions would allow a robot to self-configure into a larger variety of configurations as well as operate with less – and eventually *no* – human involvement beyond task specification.

In this paper we make one step towards this vision: Given the task of locomotion, we evolve various robots with different mechanics and control. The design space is comprised of only linear actuators and sigmoidal control neurons embodied in an arbitrary thermoplastic body. The robots are then printed pre-assembled using rapid prototyping technology. We manually snap in standard stepper motors and download the evolved control into an embedded microprocessor. The robots then perform the task in reality, and are next melted for recycling. We thus establish for the first time a self-designing infinitely reconfigurable robot

2 Background

At the intersection of mechanical engineering and artificial intelligence there has been much effort in the area of smart polymorphic robotics. This difficult problem has been addressed from several different aspects, such as the mechanical design, the controller design and optimal component configuration, as well as design automation and fabrication.

2.1 Reconfigurable robotics

The field of *reconfigurable robotics* has addressed issues in the mechanical design and control of real (physical) robots composed of multiple interchangeable segments. In some cases these units are capable of self-assembly. Some examples include Khosla's (1988) first reconfigurable manipulators, Chirikjian's (1994) metamorphic collection of self-assembling 2D hexagonal and square units, Chen's (1994) task optimal modular robot configurations, Fukuda's (1994) cellular robotic system (CEBOT) for cooperating autonomous self-organizing cells, Yim's

(1994) multi-component robot, Hamlin and Sanderson's (1996) highly redundant parallel robotic mechanisms and Hara's (1998) 2D polymorphic linear cluster chain robots. Rus (1998) describes task-reconfigurable robotics consisting of single or multiple identical modules that adapt their shape and function for a task like climbing, manipulating and walking. Murata et al (1998) has recently described a 3D reconfigurable structure with multiple connecting units capable of self-assembly, information processing and self-maintenance. So far these works have involved mainly discrete, manually designed and low-count components. Furthermore, their overall configuration and control are typically designed manually.

2.2 Evolutionary robotics

On the other hand, the field of *evolutionary design* has looked into design automation of products with an open-ended biologically inspired approach. Because of the impossibility of foreseeing the problems the robot will have to solve, because of the lack of basic design principles and because the scope of solution cannot (should not) be specified by a designer, a robot's design is progressively adapted to a specific environment and task through an artificial selection process that eliminates ill-behaving individuals in a population while favoring the reproduction of better adapted individuals. Bently (1996) describes automated evolutionary design of optical systems and of tables, and Funes *et al* (1999) describe the automated design of high-count Lego™ structures. In particular, the field of *evolutionary robotics* has focused mainly on evolutionary design of controllers, both in real and in virtual – yet always fixed – robot bodies. A major candidate robot platform for evaluation of evolved controllers is the Khepera robot (Mondada et al, 1993), which is a circular mobile robot with 2 to 4 wheels and two-dimensional motion. Various obstacle avoiding and light seeking behaviors were evolved, some in simulation only, some in simulation later embodied in the robot (Jakobi et al, 1997; Miglino et al, 1995, Nolfi et al, 1997; Salomon, 1996; Naito et al, 1997), and some directly in the robot (Floreano and Mondada, 1994). Other interesting attempts were carried out with different robot types, such as a visual-tracking gantry robot (Harvey et al, 1994), a NOMAD 200 mobile robot with 50 sensors (Grefensette and Schultz, 1994), six-legged robots (Gallagher et al, 1996) and eight-legged robot (Galt et al, 1997; Gomi et al 1997, and Gruau and Quatramaran, 1997). Another attempt to evolve controllers is Thompson's work (1997) to evolve hardware circuits as on-board controllers. In contrast with other work, Thompson tried to evolve the controller directly as an electronic circuit using Field Programmable Gate Arrays (FPGA's). Thompson's work, while basically a software controller, illustrates how evolutionary computation can take advantage of emergent physical effects.

2.3 Body-brain co-evolution

Recently there have been some notable efforts in design automation of both morphology and control – body and brain. Sims (1994) demonstrated a methodology for jointly evolving morphologies and controllers for three-dimensional creatures composed of blocks and joints. Both the architecture of the body and the motion controller were evolved to create various types of locomotion such as walking, swimming, and jumping, as well as competing over a target or seeking light. More recently, Komosinski and Ulatowski (1999) demonstrated their system *Framstics* in which tree-like creatures co-evolved and competed in a simulated world. Both Sims's and Komosinski's work yielded spectacular behaviors, in many respects reminiscent of natural insect life. Yet products of both these works remain virtual, and no attempt has been made to address their feasibility in reality, let alone being buildable without human intervention. There have been, however several attempts to evolve feasible hardware configurations; Lund *et al* (1997) have evolved in simulation both a robot control program and some parameters of its physical body such as number of sensors and their positions, body size and turret radius, etc. However, this evolution is parametric in the sense that it is limited only to parameters foreseen by the designer, and hence is not open-ended, and will not be able to adapt to unforeseen situations or provide new "creative" designs. A recent work by Dittrich *et al* (1998) describes a Random Morphology Robot, which is an arbitrary two-dimensional structure composed of links and motors; the controller of this robot is evolved, and then manual changes are applied to the robot to test its behavior with an impaired or mutated body. However, an evolutionary design of the robot's configuration was not attempted. Recent work by Chocron and Bidaud (1997) describes an attempt to evolve both the morphology and the inverse kinematics of a modular manipulator composed of prismatic and revolute joints. A genetic algorithm searches for suitable configuration for a task given as a set of required effector configurations. However, the simple serial construction precludes spontaneous emergence of any innovative "interesting" or unforeseen solutions.

3 Proposed approach

Our approach is based on *evolutionary computation* for the design stage, and on *additive manufacturing* for the fabrication stage. We consider the design unit, the

fabrication unit, and the active unit as a single complex robot. Indeed, at the current state of technology, rapid-prototyping (RP) equipment is rather cumbersome, and would be impractical as part of a robot. Similarly, fabrication ability of RP is limited to structural material. RP technology is also not yet adapted to handling recycled material. However, all of these difficulties seem temporary: It is foreseeable that future additive fabrication might consist of small devices that crawl on a structure removing material at one location and adding it to another, or smaller portable devices that can print bigger machines in segments. It is also conceivable that future technology will allow printing of multiple materials including conductive, non-conductive and semi-conductive materials, so that wires, motors and logic as well as structure can be printed in one pass without the need for assembly.

3.1 Design

The evolutionary design approach assumes two main principles: (a) to minimize inductive bias, we must strive to use the lowest level building blocks possible, and (b) the entire robot – both the morphology and the control – must be evolved together so that that components stimulate and constrain each other. As building blocks are more elementary, external knowledge associated with them is minimized, and at the same time architectural flexibility is maximized. Similarly, use of elementary building blocks in the fabrication process allows it to be more simple and systematic. As a theoretic example, if we could use only atoms as building blocks, laws of physics as constraints and nano-manipulation for fabrication, the potential would be maximized. Earlier reported work used higher level components and limited architectures and resulted in expedited convergence to working solutions, but at the expense of exploration power and reduced claims of innovation that might be attributed to the algorithm.

In this work we use a higher level of "atoms": linear actuators and bars for the morphology, and sigmoidal neurons for the control (Figure 1). Bars connected with free joints can potentially form trusses that represent arbitrary rigid, flexible and articulated structures as well as multiple detached structures, and emulate revolute, linear and planar joints at various levels of hierarchy. Similarly, sigmoidal neurons can connect to create arbitrary control architectures such as feed-forward and recurrent nets, state machines and multiple independent brains. Additive fabrication allows automatic generation of arbitrarily complex physical structures and series of physically different bodies. Moreover, the arbitrary constraint-free arrangement of these components can provide for various hierarchies of subcomponents, as well as groups of detached machines controlled by a single centralized brain or by multiple individual detached brains, etc. This is in contrast to other works in body-brain evolution (Sims, 1994; Komosinski and Ulatowski, 1999) whose morphological operators permit only tree-like architectures (and so, for example, could never evolve a simple four-bar mechanism). Sim's creatures also use various high-level control units that are capable of producing relatively complex operations such as oscillations – operations that require a recurrent net assembly in our case. Indeed, in some cases over 50,000 evaluations take place before even the first simplest "oscillating net and actuator" emerge – a single building block in Sims work.

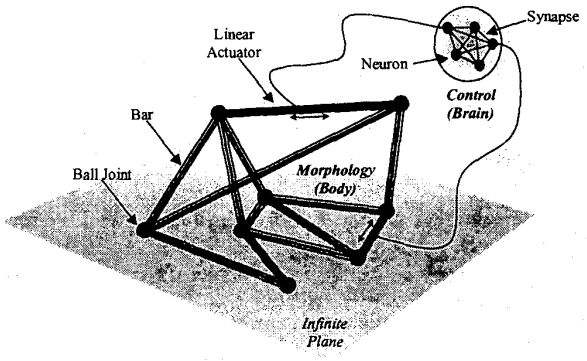


Figure 1. Schematic illustration of an evolvable robot, containing only linear actuators and control neurons. Some bars may form effectively rigid subcomponents.

3.2 Fabrication

The additive manufacturing process copies the design – part by part – volume by volume – from the virtual space into reality, using off-the-shelf rapid prototyping technology: Temperature-controlled head extrudes thermoplastic material layer by layer, so that the arbitrarily evolved morphology emerges as a pre-assembled solid three-dimensional structure without tooling or human intervention. Once the structure is printed, we snap in standard stepper motors and execute the evolved controller.

4 Implementation

We report an experiment in which robots for the task of locomotion evolved, replicated into reality, carried out their task, and finally recycled, with as little human intervention as possible.

4.1 The Evolution Process

We carried out a simulated evolutionary process[1]: The fitness function was defined as the net Euclidean distance that the center-of-mass of an individual has moved over a fixed number (12-24) of cycles of its neural control. We started with a population of 200-1000 null (empty) individuals. Random seed was randomized. Individuals were then selected, mutated, and replaced into the population in steady-state as follows: The selection function can be either random, fitness proportionate or rank proportionate. The mutation operators used to generate an offspring can be any of the following (with probability): Small mutation in length of bar or neuron synaptic weight (0.1), removal/addition of a small dangling bar or unconnected neuron (0.01), split vertex into two and add a small bar or split bar into two and add vertex (0.03), attach/detach neuron to bar (0.03). The dice is rolled until at least one mutation is applied. The mutations were applied directly to the phenotype (no genotype was used). After mutation, a new fitness is assigned to the individual by means of a simulation of the mechanics and the control (see details below). The offspring is inserted into the population by replacing an existing individual either chosen at random, chosen in inverse-proportion to its fitness, or using similarity proportionate elitism (deterministic crowding). Various permutation of selection-replacement methods are possible; we typically used fitness-proportionate or rank selection with random replacement, or random selection with similarity proportionate replacement where similarity was approximated by the distance in the ancestral tree. The process continued for 500-5000 generations (approx 10^5 to 10^6 evaluations overall). The process was carried both serially and in parallel (on a 16-processor computer).

The simulator

The simulator used in this research is based on quasi-static motion. The basic principle is that motion is broken down into a series of statically stable frames solved independently. While quasi-static motion cannot describe high-momentum behavior such as jumping, it can accurately and rapidly simulate low-momentum motion. This kind of motion is sufficiently rich for the purpose of the experiment and moreover, it is simple to induce in reality since all real-time control issues are eliminated. In this respect we permit only those effects that we are confident will transfer into reality, but at the same time introduce a severe constraint on the design universe.

Static solution of each frame is achieved by defining a global system energy term H and then slightly modifying each of the systems degrees of freedom so as to lower H according to its partial derivatives. This process continues until relaxation is reached or instability is determined. The terms included in H define the richness of the simulation. For example, a basic model including only bar flexion and weight would be:

$$H = \sum_{1}^{n} k\delta^2 + \sum mgh$$

where n is the number of bars, and for each bar i, m is the mass, h is the average actuator height, and the term k represents the stiffness,

$$k_i = \frac{E_i A_i}{l_i}$$

where E is the material's module of elasticity, A is the cross section, and l is the length of the bar, and δ represents the difference between the bar's current length and its original length, given by

$$\delta_i = \sqrt{(v_x - w_x)^2 + (v_y - w_y)^2 + (v_z - w_z)^2} - l_i$$

and v,w represents the two current endpoints of the bar. Differentiating the total energy H with respect to each of the degrees of freedom (coordinates of the endpoints, in this case), produces direction of adjustment (second derivatives would produce a more accurate adjustment, etc.).

$$\Delta w_x = \frac{\partial H}{\partial w_x} \cdot \Delta s$$

where Δs (the relaxation factor) represents the adjustment magnitude for each iteration. Each degree of freedom is then updated by its adjustment value, and H is recalculated. Small Δs produce a stable but slower convergence, whereas large Δs can solve static frames faster but may run into stability problems. This process is repeated until adjustments go below a certain threshold.

Although this solution method is slower that conventional finite elements, it is capable of solving correct highly-nonlinear cases (e.g. contact collision and snap-through buckling) and, more importantly, indeterminate states: for example, a truss in mid fall which is not yet fully supported (by six rigid-body equations), as it falls into

[1] Experiments were performed using version 1.2 of GOLEM (Genetically Organized Lifelike Electro Mechanics), which can be obtained from http://www.demo.cs.brandeis.edu/golem.

position. Indeed as machines move and function within the simulator they often pass through such stages.

As additional real-world energy terms are added to H, it becomes more accurate. We have included terms for friction, collision, gravity, external forces and noise.

Results

Several evolution runs were carried out for the task of locomotion. Fitness was awarded to machines according to the absolute average distance traveled over a specified period of neural activation. The evolved robots exhibited various methods of locomotion, including crawling, ratcheting and some forms of pedalism. Some are shown in Figure 2.

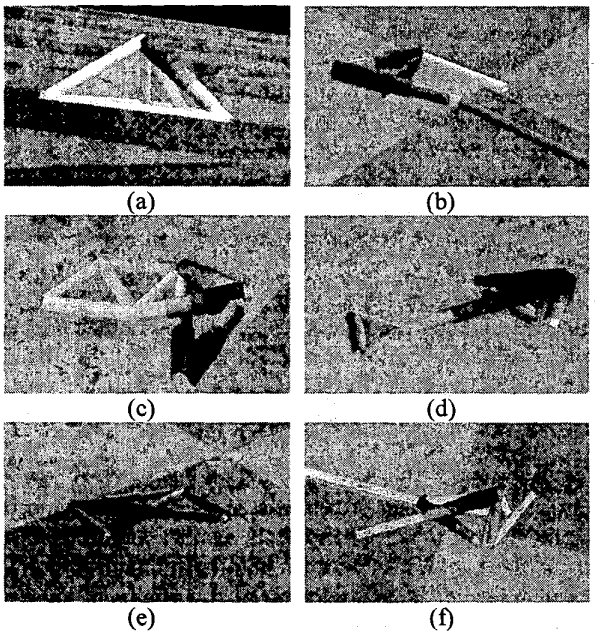


Figure 2. Several different solutions: (a) produces hinge-like motion and advances by pushing the central dangling bar against the floor; (b) advances using a sort of bi-pedalism: the left and right limbs are advanced in alternating thrusts; (c) a four-actuator mechanism moves its two articulated components to produce crab-like sideways motion; (d) a surprisingly symmetrical machine uses three highly coordinated actuators to advance: while the upper two limbs push, the central body is retracted, and vice versa. (e) uses the top bar to shifting the friction point to either side as it creates oscillatory motion and advances; (f) pushes an actuator directly onto the floor to create ratcheting motion[2].

The fabrication process

Selected robots are then *automatically* replicated into reality: their bodies are first fleshed to accommodate motors and joints (Fig 5a), and then copied into material using rapid prototyping technology (Figs 5b, 5c). Discrete moving components are connected at joints (Fig 5d) with fine supports that break away at first motion.

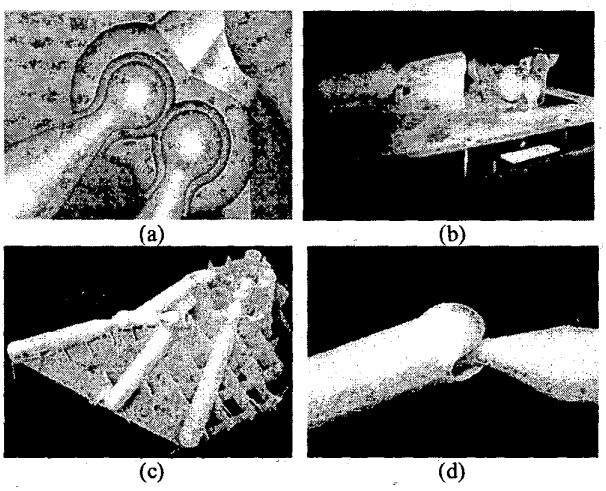


Figure 3. (a) Automatically fleshed joints, (b) replication progress, (c) robot in mid-print, (d) a close-up of a joint.

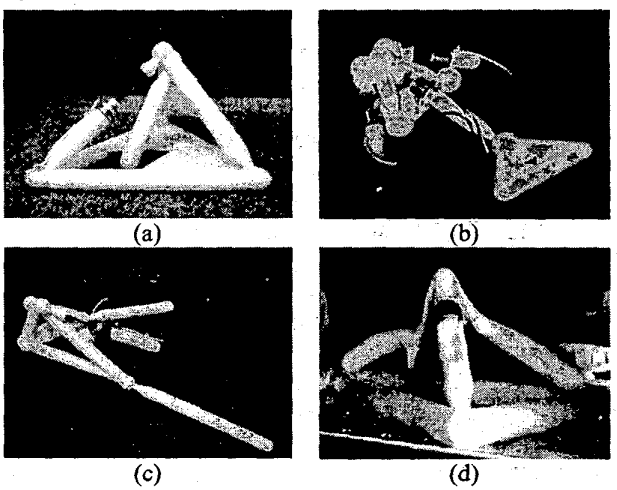


Figure 4. Three functional self-designed and self-assembled robots[2]: (a) Tetrahedron (Fig 2a), (b) Arrow (Fig 2d), and (c) Ratchet (Fig 2f). (d) Robot melted for recycling[3].

After the structure is printed, standard stepper motors driving a nut over a threaded shaft are snapped in as linear

[2] See http://www.demo.cs.brandeis.edu/golem for motion videos and downloadable code.

[3] Due to warranty restrictions, actual recycled material could not be re-fed into the rapid prototyping equipment.

actuators. The evolved controller is downloaded onto an embedded controller and the robot is ready to perform in reality (Fig 6). Table I compares the performance of the physical creatures versus their virtual origin.

Table I: Comparison of performance

Distance traveled [cm]	Virtual	Physical
Tetrahedron (Figure 1a)	38.5	38.4 (35)
Arrow (Figure 2b)	59.6	22.5 (18)
Pusher (Figure 3c)	85.1	23.4 (15)

Comparison of performance of physical creatures versus their virtual origin. Values are net distance [cm] center of mass traveled over 12 cycles of neural network. Distances in physical column are compensated for scale reduction (actual distance in parentheses).

Conclusions

In the *sci-fi* film *Terminator II*, a new kind of robot was introduced. The *T-1000 liquid metal poly-alloy* robot could change itself continuously to suit a particular task, and then melt and reshape for the next. Could this fiction ever become a reality? In this paper we attempted to show a glimpse of one possible path towards this vision. We demonstrated for the first time a complete cycle of fully automated design and manufacture. While the machines evolved are still far from being truly useful for a practical task, they do demonstrate the plausibility of this approach. In future work we intend to examine these ideas to more elaborate tasks and environments.

Many hard questions still remain: Can we further reduce our building blocks and perfect the simulation? Can we find better ways to co-evolve complexity? Will fabrication and recycling become still more versatile and self-contained? As our understanding of evolutionary process improves on one hand, and as manufacturing, material and computation technology advances on the other, there is reason to believe so.

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