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A Study on Co Evolutionary Robotics

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Abstract

In this paper we have provided the fundamental issue of fully mechanical design and building of economical robots and their controller. Rather than seek an bright general purpose robot — the humanoid robot, everywhere in today's research as the long term goal — we are increasing the information skill that can design and manufacture special-purpose mechanism and controllers to achieve specific short-term objectives. These robots will be constructed from reusable sensors, effectors, and computers held together with materials custom "written" by rapid prototyping tackle. By releasing the goal of designing software controllers for presented equipment in favor of the mechanical co-design of software and hardware mutually, we will be replicating the principles used by biology in the creation of complex groups of animals adapted to specific environments. Encoding control software has become as hard as more degrees of autonomy and task goals are added to robots, that the most advanced ones do not get past the stage of teleportation or choreographed behavior. In other words, they are puppets, not robots. Our most important suggestion is that the reason current approaches to robotics often fail is because of a dryness of the complexity of the software mean problem.
Keywords: Robotics, Genetic Algorithm, 2D, Software

I. INTRODUCTION

The field of Robotics today faces a practical problem: Flexible equipment with minds cost much more than manual equipment, human operators included. Few would spend $2k on a mechanical vacuum cleaner when a manual on a driverless car when a regular car is $20k. The high costs associated with designing, manufacturing and controlling robots has led to the current stasis, where robots are only applied to simple and highly repetitive industrial tasks.

The central issue we begin to address is how to get a higher level of complex physicality under control with less human design cost. We seek more controlled and moving mechanical parts, more sensors, more nonlinear interacting degrees of freedom — without entailing both the huge fixed costs of human design and programming and the variable costs in manufacture and operation. We suggest that this can be achieved only when robot design and construction are fully mechanical such that the results are inexpensive enough to be disposable. The focus of our research is how to automate the integrated design of bodies and brains using a co evolutionary learning approach. The key is to evolve both the brain and the body, simultaneously and continuously, from a simple controllable mechanism to one of sufficient complexity for a task. Within a decade we see three technologies which are maturing past threshold to make this possible. One is the increasing fidelity of "silicon foundries," advanced mechanical design simulation, stimulated by profits from successful software competition. The second is rapid, one-off prototyping and manufacture, which is proceeding from 3d plastic layering to stronger composite and metal (sintering) technology. The third is our understanding of co evolutionary machine learning in design and intelligent control of complex systems.

II. EVOLUTION ON ROBOTICS

Evolutionary Learning is about capturing the open world generative nature of biological evolution in software, to create systems of great complexity and flexibility without human design and engineering. It is different from ordinary genetic algorithms in that the "fitness function" is non-stationary, and these changing goals are created by the learning system itself, rather than being fully specified. There are many claims in the literature about the discovery of "arms races" and "coevolutionary feed forward loops," but in our opinion, there are only a few successful pieces of work to date on open-ended strategic discovery systems. There is a line of robotic coevolution work using predator/prey differential games e.g., at Sussex University. As a form of "genetic art," some of his work was to evolve walking or swimming animats for movies. But by matching pairs of robots in a competition to take possession of a single target, he was able to observe a sequence of co evolutionary attack/ defend stages in the evolved designs of his simulated robots. In TD-Gammon, Tesauro used temporal difference learning in a neural network architecture as the basis for an evaluation function for backgammon, which under further development became one of the best players in the world . Although TD Gammon may be seen as a success of Neural Networks or Reinforcement Learning, we suspected it was really the biggest success of a co-evolution strategy where a learner is embedded in an appropriately changing environment to enable continuous improvement.

We are working on co evolutionary algorithms to develop control programs operating realistic physical device simulators, both COTS and our own custom simulators, where we finish the evolution inside real embodied robots. We are ultimately interested in mechanical structures which have complex physicality of more degrees of freedom than anything that has ever been controlled by human designed algorithms, with lower engineering costs than currently possible because of minimal human design involvement in the product. It is not feasible that controllers for complete structures could be evolved (in simulation or otherwise) without first evolving controllers for simpler constructions. Compared to the traditional form of evolutionary robotics, which serially downloads controllers into a piece of hardware, it is relatively easy to explore the space of body constructions in simulation. Realistic simulation is also crucial for providing a rich and nonlinear universe.

III. RESEARCH SURVEY

We thus have three major thrusts in achieving fully automated design of high-parts-count autonomous robots.

The first is evolution inside simulation, but in simulations more and more realistic so the results are not simply visually believable, as in Sims work, but also tie into manufacturing processes. Indeed, interfacing evolutionary computation systems to COTS CAD/CAM systems through developer interfaces to commercial off the- shelf mechanical simulation programs seems as restrictive as developing programming languages for 8K memory microcomputers in the middle 1970's.

The second thrust is to evolve buildable equipment, using custom simulation programs. Here, we are willing to reduce the universe of mechanisms we are working with in order to increase the fidelity and efficiency of the simulators and reduce the cost of building resulting equipment. The third is to perform evolution directly inside real hardware, which escapes the known limitations of simulation and defines a technology supporting the final learning in embodied form. This is perhaps the hardest task because of the power, communication and reality constraints. We have preliminary and promising results in each of these three areas, which will be sketched out below.

A. *Evolution in Simulation*

We have been doing evolution of neural-network controllers inside realistic CAD simulations as a prelude to doing body deformation and co evolution we have used this system with evolved recurrent neural controllers for one and two segment inverted pendulums and for Luxo (an animated lamp creature, Fig.1). Many researchers have evolved such controllers in simulation, but no one has continuously deformed the simulation and brought the evolved controllers along, and no one else has achieved neural control inside COTS simulations. We believe this should lead to easy replication, extension, and transfer of our work.

Some of the ways to achieve continuous body deformation are:

- New links can be introduced with "no-op" control elements.
- The mass of new links can initially be very small and then incremented.
- The range of a joint can be small and then given greater freedom.
- A spring can be simulated at a joint and the spring constant relaxed.
- Gravity and other external load forces can be simulated lightly and then increased.

We have successful initial experiments consisting of evolving recurrent neural network controllers for the double-pole balancing problem, where we slowly "morphed" the body simulator by simulating a stiff spring at the joint connecting the two poles and relaxing its stiffness.

B. *Build Able Simulation*

These COTS CAD models are in fact not constrained enough to be build able, because they assume a human provides numerous reality constraints. In order to evolve both the morphology and behavior of autonomous mechanical devices that can be built, one must have a simulator that operates under many constraints, and a resultant controller that is adaptive enough to cover the gap between the simulated and real world. Features of a simulator for evolving morphology are:

- Universal — the simulator should cover an infinite general space of mechanisms.
- Conservative — because simulation is never perfect, it should preserve a margin of safety.
- Efficient — it should be quicker to test in simulation than through physical production and test.
- Buildable — results should be convertible from a simulation to a real object.

One approach is to custom-build a simulator for modular robotic components, and then evolve either centralized or distributed controllers for them. Our model considers the union between two bricks as a rigid joint between the centers of mass of each one, located at the center of the actual area of contact between them. This joint has a measurable torque capacity. That is, more than a certain amount of force applied at a certain distance from the joint will break the two bricks apart. The fundamental assumption of our model is this idealization of the union of two Lego bricks together.

The genetic algorithm reliably builds structures which meet simple fitness goals, exploiting physical properties implicit in the simulation. Building the results of the evolutionary simulation (by hand) demonstrated the power and possibility of fully automated design. The long bridge of Fig.1 shows that our simple system discovered the cantilever, while the weight-carrying crane shows it discovered the basic triangular support. The next step is to add dynamics to modular buildable physical components. Lego bricks are also not optimized for mechanical assembly, but for young human hands. We are currently developing simulation and modeling software for co evolution in a universe of 3-d "living truss" structures of 2-d shapes controlled by linear motors.

The simulated universe is based on quasi-static motion, where dynamics are this kind of motion as it is simple and fast to simulate, yet still approximated as a series of frames, each in full static equilibrium. We have focused on provides an environment sufficiently rich for enabling tasks such as locomotion and other dynamic behaviors. Moreover, it is easier to induce physically since real-time control issues are eliminated. The simulator handles arbitrary compositions of bars, connectors, actuators and controlling neurons, giving rise to arbitrary structures with natural hierarchy as bars aggregate into larger rigid components. The simulation involves internal forces, elasticity and displacements, as well as external effects such as collision, gravity, floor contact, friction, material failure, and energy consumption. Some examples are shown in Fig.1.

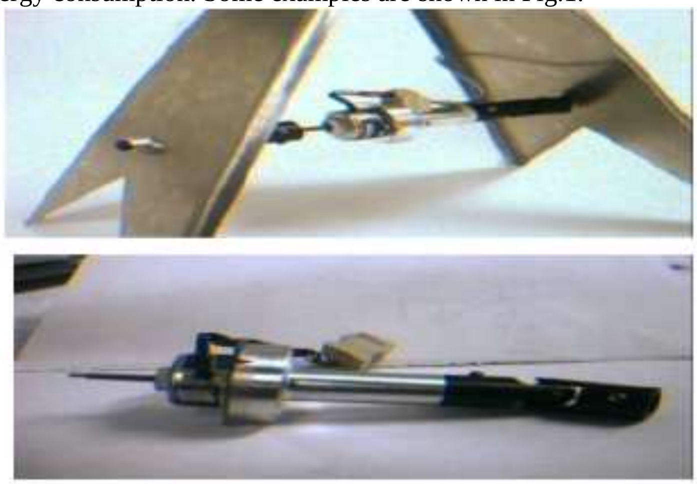
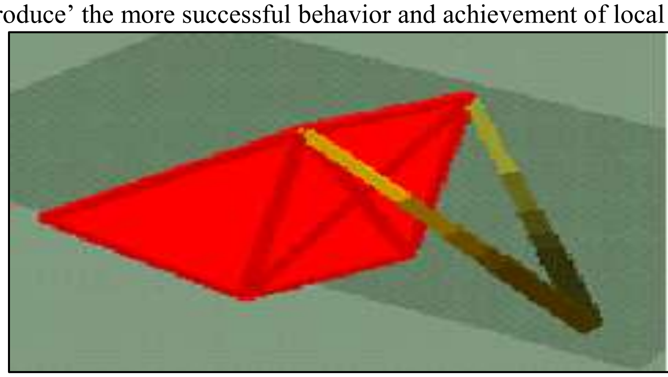


Fig. 1: Prototype "living truss" robot and detail of linear motor assembly

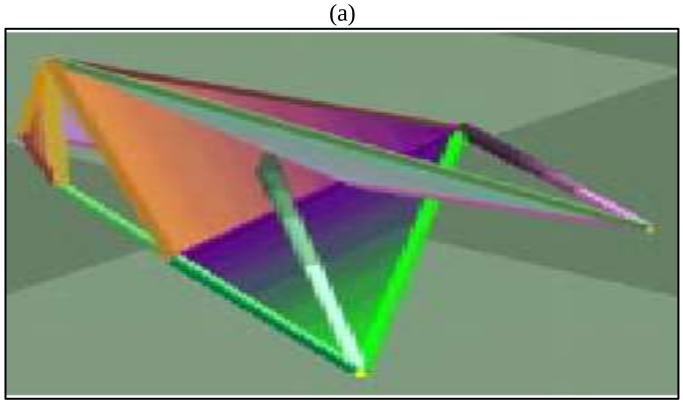
C. Embodied Evolution

Once a robot is built, learning must proceed in the real world. Anticipating robots composed of many smaller and simpler robots, our work on evolution in real robotic has focused technologically on two of the main problems — reprogramming and long-term power.

Many robots' batteries last only for a few hours, and in order to change programs, they have to be attached to a PC and the new program has to be downloaded. In order to do large group robot learning experiments, we have designed a continuous power floor system, and the ability to transfer programs between robots via IR communications. We are thus able to run a population of learning robots battery-free and wire-free for days at a time Fig.3. Evolution is not run by a central controller that installs new programs to try out, but is distributed into the behavior of all the robots. The robots exchange data and program specifications with each other and this "culture" is used to 'reproduce' the more successful behavior and achievement of local goals.



(a)



(b)

Fig. 2: Simulated "living truss" robots: (a) hand designed. (b) random structure

The control architecture is a simple neural network and the specifications for it are evolved on-line. That is, each robot tries parameters for the network and evaluates its own success. The more successful a robot is at the task, the more frequently it will broadcast its network specifications via the local IR communications channel. If another robot happens to be in range of the broadcast, it will adopt the broadcast value with a probability inversely related to its own success rate. Controllers compare favorably to human designs, and often surpass them when human designs fail to take all important environmental factors into account. The graph below Fig.3 shows averaged runs of the robots in a "light gathering" task, comparing a random controller to a human designed controller, to the robots learning themselves.

Fig. 3: Our 4" diameter robot picks up power from its environment and learns while on-line.

IV. IMPLEMENTATION & RESULTS

The mechanical design idea is perhaps the most challenging, as it entails imitation of one of humanity's most prominent acts of intelligence: creativity. Indeed, more recent approaches seek a more computational basis for engineering design, thereby relieving some of its dependency on experience, and relating it to foundations of information theory and set theory. At the core of these methods too, however, lies a human engineer or a human-generated knowledge base, and hence they can never be fully automated by definition.

While engineering design methodologies try to cover general-purpose practical design, a more limited arena of design research has emerged under the field of robotics. The set of solutions is required to meet a specification while residing within the scope of certain constraints. Both the specification and constraints can be thought of as assigning solutions a general attribute of merit, applied with a positive and negative stimulus, respectively. All three of these aspects — the specification, the constraints and the solution generating process — are crucial to the success of the design. Traditional robotic design has (wrongfully, in our opinion) addressed these by discipline in two separate efforts, that of designing the hardware components (the body), and that of designing the software controller (the brain). It developed at Stanford a reconfigurable robot composed of multiple components of two types. This robot has been shown to be able to attain eight different forms in three dimensions, corresponding to different locomotion gates. Fukuda at Nagoya University is developing the cellular robotic system (CEBOT) for cooperating autonomous self-organizing cells. The above works, however, are directly programmed and do not involve an evolutionary or other general optimization process to derive the actual physical configuration and its corresponding controller. We consider this attempt as being in the right direction. Again, however, the simple serial construction precludes spontaneous emergence of any innovative 'interesting' or unforeseen solutions.

V. CONCLUSIONS

Our work has both a theoretical and practical potential; we aim to understand and to innovate in software as well as in hardware. Our long-term vision is that both the morphology and control programs for self-assembling robots arise directly through hardware and software co evolution: Primitive active structures that crawl over each other, attach and detach, and accept temporary employment as supportive elements in "corporate" beings can accomplish a variety of tasks, if enough design intelligence is captured to allow true self-configuration rather than human redeployment and reprogramming.

When tasks cannot be solved with current parts, new elements are created through fully mechanical design and rapid prototype manufacturing. Once FAD and RP descend into the MEMS world, it is possible to contemplate a new "bootstrap," similar to the achievement of precision in machine tools, where artificial life gains control of its own means of production and assembly and is able to grow both in power, complexity, and precision. This vision is easy to imagine, as it indeed was by both NASA scientists and by SF novelists of the 1960's, but quite difficult to work out in practice. There are many problems that need interactive solutions where the primary problem is the relationship between software and physical devices: this vision cannot be achieved either fully in simulation or fully in hardware. It is not a problem for engineers to solve once, but a problem of having equipment learn how to mechanicalally engineer physical systems along with their controllers. It is not a situation where a gee-whiz new sensor or effect or (with "software-to-follow") can help.

We see several exciting research problems that are addressed by our recent work in this area: one problem is that global configurations of elements are dependent on local interaction, and simple processors inside each element will not suffice to calculate and control the overall configuration. That is why we first focus and develop the conventional algorithms for conservatively simulating structures, and then parallelize into agents, rather than hoping some simple pre-programmed behavior primitives will scale. A second problem is that computer aided design and manufacturing systems, where human designers work in teams to design mass manufactured products, is too expensive a system for a robot to call upon whenever it needs help. That is why we have to make state-of-the-art CAD/CAM subservient to our co evolutionary body-brain simulations rather than to their own human interface. A third problem is power distribution under changing configuration.

Plugging and unplugging wires will not suffice. That is why we focus on the problems of power distribution for reconfiguring embodied evolutionary systems. Our current research moves towards the overall goal down multiple interacting paths, where what we learn in one thrust aids the others. We envision the improvement of our hardware-based evolution structures, expanding focus from static buildable structures and unconnected groups to reconfigurable active systems governed by a central controller, and then the subsequent parallelization of the control concepts. We see a path from evolution inside CAD/CAM and buildable simulation, to rapid mechanical construction of novel controlled mechanisms, from control in simulation to control in real systems, and finally from embodied evolution of individuals to the evolution of heterogeneous groups that learn by working together symbiotically. We believe such a broad program is the best way to ultimately construct complex autonomous robots that are self-organizing and self-configuring corporate assemblages of simpler mechanicalally manufactured parts.

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