Morphological Evolution of Freeform Robots

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ABSTRACT
We demonstrate the evolution of locomoting amorphous robots composed of multiple materials. Research in evolutionary robotics has traditionally been limited to morphologies comprising rigid and discrete components, such as links connected with rotational or linear joints and actuators. In the continuous robots presented here, actuation is accomplished by periodic volumetric expansion and contraction of one or more materials composing the body of the robot. The challenges of representing evolvable multi-material freeform shapes and evaluation (simulation) of the resulting soft bodies are discussed. Several genotypic representations are explored which use a level-set threshold to generate the material distribution in the phenotype. Soft body simulation of the robot is accomplished using a relaxation algorithm to model the dynamics of the resulting amorphous machines under the actuation material expansion, gravity forces, and non-linear ground friction. These results open the door to a new design space that more closely mimics the freeform, amorphous and continuous nature of biological systems.

Categories and Subject Descriptors
D.3.3 [**Computing Methodologies**]: Artificial Intelligence – *Robotics*

General Terms
Algorithms, Design

Keywords
Amorphous, Freeform, Continuous, Flexible, Robot, Relaxation, Soft body, Locomotion

1. INTRODUCTION
Functional robot morphologies have been explored in the field of evolutionary robotics for some time [1]. Ever since the early work in evolving virtual [2] and physical [3] creatures, many examples have been published of evolved walking, running, and swimming robots. The requisite evaluations all use rigid-body simulations of discrete components connected by rotational or linear joints. In this paper we focus on evolving fully amorphous soft robots. Material distributions take the place of discrete links, and volume changing materials replace discrete actuators. These material distributions are not constrained to any given topology or shape. This freedom removes fundamental constraints, thereby opening a vast new design space to explore.

This new paradigm in robotics has recently emerged, inspired largely by the robustness and resilience of biological systems. These "soft" robots trade deterministic control for probabilistic models, but gain robustness. Here we consider pure volumetrically actuated materials in order to more accurately mimic distributed actuation and avoid imposing undue constraints. This new design space of soft robots is characterized by a nearly complete freedom over the spatial distribution of materials. Traditional computer aided design (CAD) tools are typically inappropriate for designing such structures. Therefore, new higher level design tools using genetic algorithms are necessary to meet functional goals without geometric constraints.

2. METHODS
There are many possible representations for three dimensional freeform shapes for an evolutionary algorithm. Most prior examples use geometric primitives [2] but these are not conducive to creating smooth freeform shapes. We use a level-set class of representations that create a four-dimensional landscape, which is then threshholded to create a three dimensional solid We explore three different representations that create 3D density fields: (a) The Discrete Cosine Transform (DCT) representation [4], (b) the Compositional Pattern Producing Network (CPPN) representation [5], and (c) the Gaussian Mixtures representation [6].

The discrete cosine transform (DCT) is a special case of the discrete Fourier transform, in which boundary conditions favorable to creating amorphous morphology shapes are enforced. In the DCT representation [4] the phenotype is a 3D matrix of frequency amplitudes to which the inverse 3D DCT is applied, converting from the frequency domain to the spatial domain.

Compositional Pattern Producing Networks (CPPNs) have been demonstrated to be useful for evolving two dimensional density fields (often interpreted as grey-scale images). Here, we introduce the third dimension to produce 3D density fields to threshold into amorphous morphologies. CPPNs are similar in concept to an artificial neural network (ANN), except that more geometrically-useful transfer functions are used instead of just sigmoids.

In the Gaussian mixtures (GMX) representation, points of density with Gaussian falloff are added within the spatial envelope. These points can have either positive or negative weights, which add or subtract from the density respectively. With a relatively small

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number of Gaussian Mixtures, interesting and complex shapes and topologies can result upon the level-set threshholding.

In order to efficiently evaluate amorphous soft robot morphologies with volumetric actuation, we developed a soft body simulator *ab initio* in C++. The interaction between individual voxels is modeled by a standard flexible beam model. This allows all 6 relative forces and moments to be calculated based on the relative 3D position and rotation of the two voxels. This simulation incorporates full 3D dynamics modeling for realistic, 2nd order momentum effects, large deformations, and any number of materials combined in any internal material distribution, each with varying stiffnesses and densities. Also, a nonlinear and collision detecting and handling is included, all with the goal of keeping computation time to a reasonable level. The solutions presented here were each evolved on a single quad-core desktop computer a rate of approximately 3-15 seconds per evaluation Deterministic crowding selection was used [7], with a population size of 20.

3. RESULTS

The evolved behaviors of the amorphous robots generally took advantage of a combination of dynamics and non-linear friction to make forward progress. Two modes of movement in the desired direction were generally observed: Several robots made significant progress by maximizing the distance traveled as they fell and flopped over. This movement was often aided by the actuation cycles gradually tipping the robot over, but this method of movement does not count as true locomotion because it cannot be sustained over an indefinite distance. The more successful mode of movement involved scooting, in which the robots expanded and contracted in specific ways, making and breaking contact friction selectively to make forward progress. Several observed solutions made use of a combination of flopping and scooting. An example solution is shown in Figure 1.

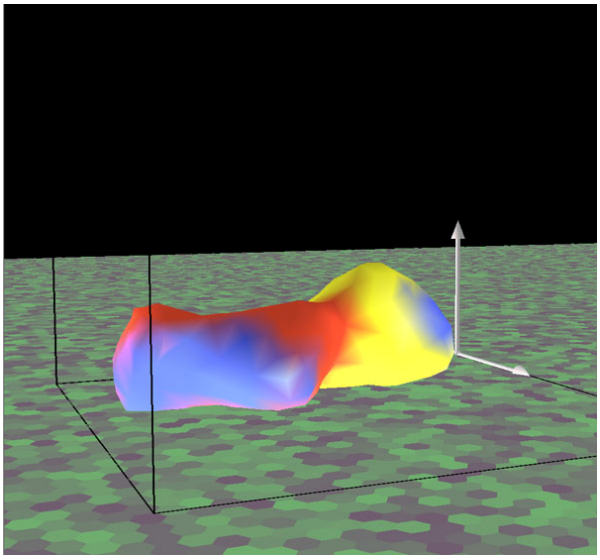


Figure 1: An example evolved blob using a passive (blue) and active (red and yellow) material locomotes to the left under sinusoidally varying actuation.

4. CONCLUSIONS

We have demonstrated that evolutionary algorithms are suitable for designing the freeform material distribution of locomoting amorphous robots, which would be a difficult task to perform in traditional CAD software. This opens the door to a new design space of soft robotics, where the functionality of the robot is determined by the material distribution, not by rigid links. Sensing, actuation, and computation can all be distributed, potentially making the design of these robots even more difficult without the aid of design automation methods. Thus, with the exponentially expanding design space of robotics enabled by additive manufacturing of multiple materials, genetic algorithms and other design automation methods will play an increasingly important role in designing robots to directly meet high level functional goals.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] S. Nolfi and D. Floreano, "Synthesis of autonomous robots through evolution," *Trends in Cognitive Sciences,* vol. 6, pp. 31-37, 2002.

[2] K. Sims, "Evolving virtual creatures," in *SIGGRAPH '94: Proceedings of the 21st annual conference on Computer graphics and interactive techniques* Orlando, Florida: ACM, 1994, pp. 15-22.

[3] H. Lipson and J. B. Pollack, "Automatic design and manufacture of robotic lifeforms," *Nature,* vol. 406, pp. 974-978, 2000.

[4] J. Hiller and H. Lipson, "Multi Material Topological Optimization of Structures and Mechanism," in *Genetic and Evolutionary Computation Conference* Montreal, QC, 2009.

[5] K. Stanley, "Compositional pattern producing networks: A novel abstraction of development," *Genetic Programming and Evolvable Machines,* vol. 8, pp. 131-162, 2007.

[6] F. Pernkopf and D. Bouchaffra, "Genetic-based EM algorithm for learning Gaussian mixture models," *Pattern Analysis and Machine Intelligence, IEEE Transactions on,* vol. 27, pp. 1344-1348, 2005.

[7] S. Mahfoud, "Niching methods for genetic algorithms," University of Illinois at Urbana-Champaign, 1995.