# Growing and Evolving Soft Robots with a Face-Encoding Tetrahedral Grammar

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## ABSTRACT

In this work we describe how the morphology of mobile soft robots can be evolved using a grammatical encoding operating on tetrahedral meshes. Actuation of the soft bodies is achieved by uniformly cycling tetrahedral stiffness. Evolved morphologies exhibit functional differentiation across body regions, and the grammatically derived phenotypes exhibit stable fitness across a range of their ontogenic trajectory, suggesting scalability.

## Categories and Subject Descriptors

I.2.9 [**Computing Methodologies**]: Artificial Intelligence—*Robotics*

## Keywords

Soft Robot, Generative and Developmental System, Simulation

## 1. INTRODUCTION

While robots played a part in the recovery efforts of recent natural disasters in China, New Zealand, and Japan, their relatively modest role highlights their limitations, and indicates a pressing need for more resilient and deformable search-and-rescue robots. The aim of *soft robotics* is to harness recent advances in engineering and material science in order to create soft, resilient, and deformable robots which would be able to change their shape in order to squeeze and flow through small cracks and apertures. Such robots would look less like tanks and more like caterpillars.

In this work we use a face encoding grammar [4] to grow multi-resolution tetrahedral-mesh robot morphologies, and evaluate their performance on a locomotion task within the PhysX physics engine. Movement is produced by uniformly cycling body stiffness. The multi-resolution nature of the encoding allows for functional differentiation of tetrahedral regions, in a manner not unlike ontogenic differentiation in biological systems. Moreover, morphologies grown by the grammars often exhibit stable fitness across a range of their ontogenic trajectory. This suggests that the encodings exhibit a degree of *scalability*, and that grammars are able to describe an entire *lineage* of soft robot morphologies.

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## 2. GROWING AND EVOLVING SOFTBOTS

Our approach is based upon the use of a grammar to grow tetrahedral meshes representing soft bodies within the PhysX engine, as illustrated by Figure 1. This variant of a Map L-System uses a sequence of rewrite rules which operate on the faces of tetrahedra. Grammatical encodings [5] have been used to grow objects ranging from 3-D surfaces[1] to robots [2].

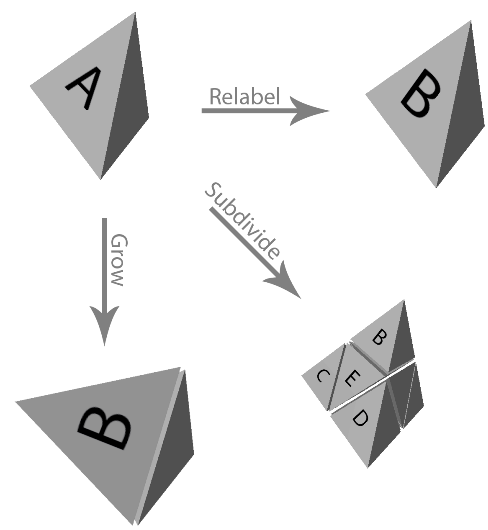


**Figure 1: An illustration of the three rules which can be applied to the face of a tetrahedron. Clockwise from top left: the original tetrahedron with face labeled "A", relabel replaces "A" with "B", subdivide replaces the face with four smaller faces (this requires subdividing the entire tetrahedron), and grow adds a new tetrahedron with face labels "B","C","D"**

A detailed description of this encoding is provided by Rieffel and Smith [4].

Rulesets describe a developmental *process*, or *ontogeny*. As such they are an *indirect encoding* of a physical phenotype. These grammars can be evolved by treating the rulesets as genotypes, and the tetrahedral mesh which results after a fixed number of iterations as the phenotype. An

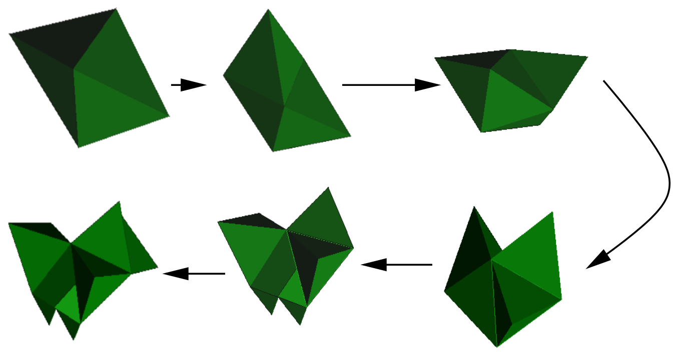

**Figure 2: The growth of a tetrahedral mesh by iteratively applying the rules from a face encoding ruleset.**

evolving population simply consists of collection of grammar genotypes. In our experiments, each individual was evaluated by applying its genotype grammar rewrite rules a fixed number of times and then placing the resulting robot in the PhysX environment. Tetrahedral mesh stiffness was then cycled and the displacement vector over each cycle recorded.

## 3. RESULTS AND DISCUSSION

Videos of several of the evolved soft robots can be seen on the Youtube channel "softrobotvideos". There are two interesting observations which arise from these evolved behaviors. The first observation is that the multi-resolution nature of the evolved tetrahedral meshes allows for a significant degree of regional functional differentiation [3] as illustrated by Figure 3. This functional differentiation exists as an emergent property of the grammatical encoding, rather than an explicitly planned feature. The second observation, more quantitative in nature, occurs when we measure the fitness of every intermediate stage of development. As the graphs in Figure 4 illustrate, there can be a high degree of fitness throughout the developmental trajectory. An insight suggested by these results is that this particular encoding possesses a high degree of *scalability*.

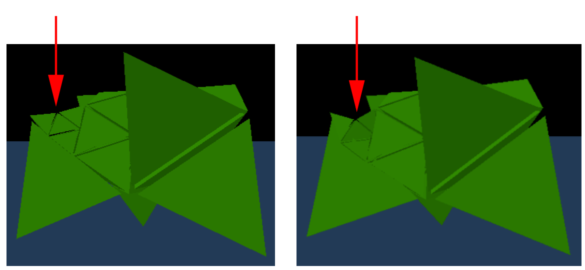

**Figure 3: An illustration of the regional functional differentiation exhibited by the evolved meshes. A region with smaller tetrahedra, indicated by the red arrow, is more flexible and tends to buckle as stiffness is decreased, while larger tetrahedra are less affected.**

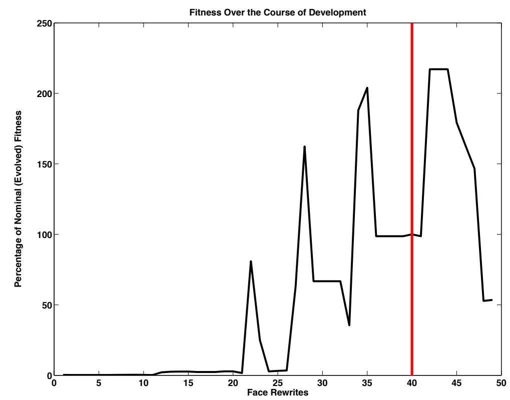


**Figure 4: Phenotype fitness measured over the course of development, and normalized around the fitness measured at the fixed iteration limit (vertical red line). Although during evolution fitness is only measured at that iteration limit, fitness often remains stable as development proceeds past the limit and is sometimes higher at earlier and later developmental stages.**

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