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Technical Section

Developmental modelling with SDS

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A R T I C L E I N F O

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A B S T R A C T

This paper describes modelling methods based on biological development for use in computer graphics applications, specifically the automated growth and development of complex organic shapes that are difficult to model directly. We examine previous approaches, including grammar-based methods, embedded systems and cellular models. Each system can be classified as endogenous (internally determined) or exogenous (externally determined), with some models exhibiting features of both. We then introduce a new model, the Simplicial Developmental System (SDS), which simulates individual cells embedded in a physical environment, with cell division, movement and growth controlled by morphogenetic chemical simulation. SDS uses a tetrahedral mesh as its base representation for geometric modelling and physical simulation. Cell growth, movement and division are determined by simulating chemical morphogens that are diffused between cells according to a set of user defined rules. We discuss the advantages and disadvantages of this model in terms of the competing goals of user control, developmental complexity and open-ended development (the ability to generate new component structures without explicit specification). Examples highlighting the strengths of the model are illustrated.

1. Introduction

One of the greatest challenges in biology is understanding the mechanisms that enable a single, fertilised cell to develop into a complex, multi-cellular organism. The developmental processes that lead to interacting functional components and self-organising, heterogeneous structures are complex and numerous, remaining the subject of on-going research. In this paper we focus on systems, inspired by biological processes of development, that begin with concise specifications for initial conditions and developmental rules, then proceed to grow and develop autonomously in simulation. Our application is in computer graphics, so we concentrate on the process of growing three-dimensional form rather than a complete simulation of biological function. Our goal is to define systems that allow the specification of complex organic shape and form, removing the tedium of trying to assemble such forms manually.

The process of simulating development in this more general context is referred to as *developmental modelling*. As a modelling methodology, developmental models[1] offer a vastly different modelling paradigm over commonly used methods in computer graphics. 'Traditional' modelling focuses on processes organised around the design of artefacts: the artist conceptualises a form, and then proceeds towards the goal of building the form explicitly. This is normally achieved through the direct instantiation and manipulation of geometry and texture to achieve the finished result. Procedural modelling uses the specification of procedures that automate the geometry and texture building process. *Generative models* exploit the generative properties of computation to achieve *database amplification* [2], where complex structures are built from relatively simpler specification (often by several degrees of magnitude). In this sense, developmental models are a subset of generative models.

There have been two complementary approaches to modelling development in computer graphics. In *endogenous* systems, development originates from, and is driven by, *internal*, rule-based mechanisms. Typically, the rules are specified by the user of the system. Endogenous models work well for the procedural specification of complex, static or time-varying geometry; however, there are limitations in how models generated by the system can be affected by, and interact with, their environment. For a system to develop in this way—an *exogenous* system—the form and space in which it develops must be coupled.

In this paper we will first review some of the literature for both endogenous and exogenous methods, with a brief discussion on the advantages and limitations of each approach (Section 2). In Section 3 we introduce the *Simplicial Developmental System* (SDS),

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[1] The term 'model' has a dual, context dependent meaning in this paper: in a developmental context it means a formal mathematical or procedural specification for a system; in a computer graphics context it means a spatiotemporal geometric structure generated for image synthesis and animation purposes (e.g. a time-dependent geometric mesh). We anticipate the reader will distinguish the meaning based on context.

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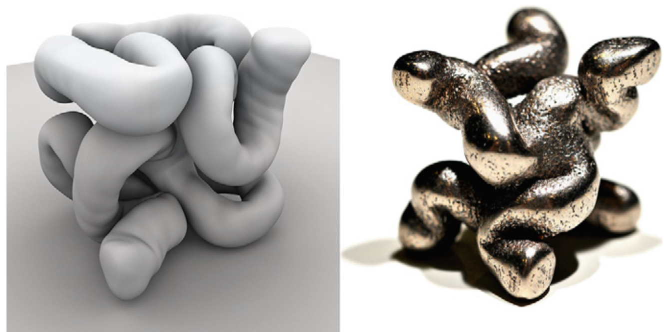

Fig. 1. (left) An abstract organic form generated using the system introduced in this paper. (right) A related form manufactured in stainless steel (by `Shapeways` [1]).

a tetrahedral mesh based system that supports exogenous growth through the physical simulation of a developing 3D form (e.g. Fig. 1). Finally, Section 4 discusses implications and further development of the SDS.

2. Modelling development

There are many established systems in computer graphics that incorporate aspects of biological development for modelling shape. The fields of theoretical biology and artificial embryology also contain models that are useful when considering shape formation from a developmental perspective. Surveys that cover these models in the literature are numerous [3–11] and hence only a brief overview is given here, with discussion pertinent to the model introduced later in the paper.

2.1. Grammar-based approaches

L-systems, introduced by Lindenmayer [12] to model the development of multicellular organisms, have been extensively used to simulate the development of trees, herbaceous plants, and many other biological structures. Early L-system models were endogenous, operating at a symbolic level, with component parts and their development specified using a set of distinct symbols, and the development simulated by parallel re-writing of those symbols. As development proceeds the set of active symbols changes in discrete time steps. Symbols representing component parts are converted to geometry as a unidirectional, post-development operation, i.e., no information from the environment or built geometry flows back to the symbols to affect their development.

Researchers recognised these limitations, over subsequent years devising enhancements and additional mechanisms to circumvent them. The primary goal in computer graphics applications has been the synthesis of visually realistic models, with an emphasis on the final, rather than developing, geometric form. L-system extensions include: continuous mechanisms [6,13], the modelling of physical and mechanical effects [14,15], specifying explicit hierarchy [16] and coupling the developmental process more closely to the environment [17]. These extensions address specific issues, a number incorporating exogenous development, but they diminish the simplicity and elegance of the original formalism.

In general, L-systems simulate growth and development at an abstracted macro-level (e.g. florets, meristems, leaves, branching segments), due to the complexity of defining interactions at the micro-level (cells, molecules). The appropriate choice of macro-level abstraction relies on a structural understanding of the entity being modelled, along with a means of inferring developmental relationships at the level chosen. In general, this is an ill-defined and ad hoc process, making it difficult for computer graphics users without significant experience to devise grammars that generate the desired form.

L-systems abstract the processes behind development to that of *replacement of parts by other parts*. In this respect they are related to other grammar-based approaches such as shape grammars [18], graph grammars and graph-based representations [19]. They have also been generalised to grammars that operate on polygonal surface representations [20–22]. These methods address the topologically focused bias of tree L-systems and provide generative methods for more complex geometric surfaces. Developments have enabled the application of grammar-based methods to a broader class of shape and form, such as architectural design [23] and legged animals [24].

2.2. Embedded models

Many systems directly *embed* development in a spatial environment, an idea that dates back many years in graphics [25,26]. A structure that is being generated within a space can be affected by its own parts, other static and dynamic objects, and environmental factors such as light and gravity. These interactions provide a mechanism for directing the growth of specific forms, and also result in an emergent complexity difficult to obtain using non-embedded systems. While embedded systems appear to be a natural and biologically realistic approach (after all, all real biological growth is embedded in a physical environment), taking full advantage of this embedded approach presents a number of challenges [27], particularly if the open-ended complexity of real biology is sought.

Cellular automata models demonstrate that exogenous growth factors, including environmental effects and spatial limitations, can contribute greatly to the complexity of a developing form [26,28–33]. Even if the mechanism behind the development is simple, environmental interaction can result in complex creations that far exceed the simple specification from which they emerge [34,35].

A developmental model of accretive growth that illustrates the combination of a geometric surface-based developmental model with a physical model of nutrients and hydrodynamics is presented by Kaandorp and Kübler [36,37]. These experiments reinforce the notion that a simple growth logic combined with a physical model can result in complex organic forms. This is further exemplified by Combaz and Neyret, who demonstrated a system that generates rich and abstract organic form through physical simulation and growth [38]. The user paints growth chemicals onto a surface, which causes that part of the surface to expand and grow, resulting in naturally wrinkled surfaces due to growth-induced deformation. Similar systems in computational biology can also be found [39,40].

2.3. Cellular models

Cellular models utilise the idea of building complex structure from a single underlying primitive—the cell—which typically divides, moves or changes based on an abstraction of chemical signalling or protein synthesis. Some of these models are embedded in restricted spatial arrangements (cartesian grids, isospatial sites), others operate at a more symbolic level. In computer graphics applications they have been used to model three-dimensional form and two-dimensional textures.

Fleischer and Barr [41] introduced a cellular programming model that could grow cellular texture elements over pre-defined