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Towards building smart self-folding structures

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ABSTRACT

We report our initial progress on synthesizing complex structures from programmable self-folding active materials, which we call Smart Multi-Use Reconfigurable Forms. We have developed a method to unfold a given convex polygonal mesh into a one-piece planar surface. We analyze the behavior of this surface as if it were constructed from realistic active materials such as shape memory alloys (SMAs), in which sharp creases and folds are not feasible. These active materials can change their shapes when they are heated and have been applied to medical, aerospace, and automotive applications in the engineering realm. We demonstrate via material constitutive modeling and utilization of finite element analysis (FEA) that by appropriately heating the unfolded planar surface it is possible to recover the 3D shape of the original polygonal mesh. We have simulated the process and our finite element analysis simulations demonstrate that these active materials can be raised against gravity, formed, and reconfigured automatically in three dimensions with appropriate heating in a manner that extends previous work in the area of programmable matter. Based on our results, we believe that it is possible to use active materials to develop reprogrammable self-folding complex structures.

1. Motivation

This paper presents our initial progress for realization of complex and reconfigurable 3D surfaces and structures that are assembled from "programmable" 2D planar shapes made of self-folding active materials. Our goal is to develop structures that can be raised, formed, and reconfigured automatically in 3-space as depicted in the artistic interpretation in Fig. 1. In this paper we present a framework for modeling the geometry of the active material elements that can self-fold into a desired 3D shape and we demonstrate that these elements can be folded to create desired shapes. In our framework, we start with a polygonal mesh approximation of the desired 3D shape. Then, we unfold it into either multiple or single-piece planar panels, which are simply 2D polygons. By physically and virtually constructing the original shapes, we demonstrate the feasibility of this approach, which is well-suited for the consideration of deforming materials in which sharp folds or creases are not physically feasible. Our results can be summarized as follows:

Multi-panel unfolding and physical construction: (1) We have developed an approach to unfold any given polygonal mesh surface into a set of planar pieces. (2) We have developed and implemented a method to construct physical shapes that approximate original polygonal meshes by connecting and folding the planar pieces. (3) We have constructed a few examples of physical shapes using planar pieces to demonstrate the feasibility of the approach.

Single-panel unfolding and evaluation of construction: (1) We have extended the multi-panel unfolding method to reduce the number of planar pieces into one to be cut from a single sheet of continuous self-folding active materials. To unfold into a non-self-intersecting single-panel (i.e. a simple 2D polygon), the main restriction is that the original shape must be convex. If the shape is not convex, it can still be unfolded into a 2D polygon, but the resulting polygon can self-intersect. For single panel unfolding (2) we have created a few examples of unfolded single-panels and have physically constructed shapes using single-panels that are cut from paper and (3) we have evaluated self-folding behavior single panels that are cut from self-folding active materials using Abaqus, a physics-based Finite Element Analysis program. Favorable results indicate that we can obtain the same behavior once self-folding active materials are available. A useful property of this approach is that unfolding is not unique, i.e., there exists many 2D polygons that can be folded into a given desired shape. Because of this property, it is possible to allow engineers or artists to choose from a finite set the 2D shape of unfolded polygon.

2. Previous work

The efforts described in this work were inspired by the bodies of existing literature associated with two topical areas: paper

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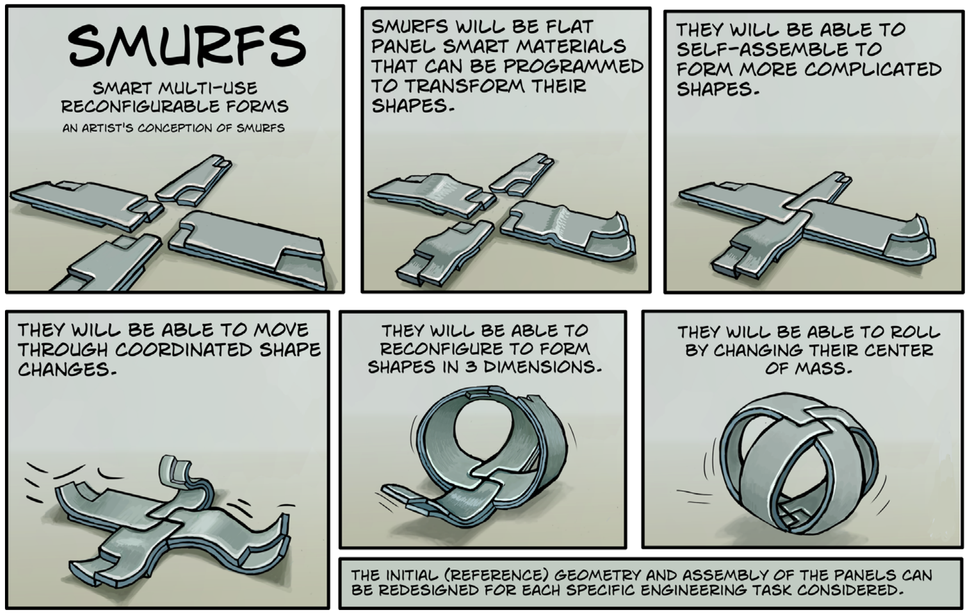

Fig. 1. An artistic representation of the ultimate goals of research on self-folding structures as smart multi-use reconfigurable forms.

sculpture/origami and morphing structures. The methods and advantages of paper-based design and analysis have been receiving an increasing amount of attention in the past few years [1,2], and the mathematical framework associated with these methods has continued to develop [3–5]. Moreover, methods to obtain paper sculptures and origami from any given polyhedral meshes are developed [6,7]. Though motivated in part by this progress, here we relax some of the restrictions of conventional origami theory (infinitely sharp folds, perfectly flat panels) and instead consider shape changes that could be obtained using active materials to drive the required deformations [8,9]. The combination of smart materials and origami research has previously given rise to the concept of *programmable matter* [10], though again, sharp folds and flat panels were an explicit goal. Other researches exist that also consider predefined folds in active materials [11,12].

In this work, a self-folding laminate including two shape memory alloy (SMA) thin film layers [13,14] that provide force and high deformation under the imposition of heat is considered. These active lamina are separated by a relatively compliant passive (e.g., elastomeric) layer. This approach is novel in that it eliminates the need for local predefined hinges as fold locations are simply determined by where heat is applied to the SMA. The location and intensity of heating can be changed over time, resulting in “massively reconfigurable” self-folding structures, where local fold angles may be relatively large (i.e., folds may not be sharp). This concept was only recently introduced [15], and it was shown via methods similar to those considered herein that such a laminate sheet could be configured to provide multiple shapes. Studies have continued [16], demonstrating that replacing the SMA thin film by a mesh of SMA wire might provide significant advantages.

After a description of the approaches used to “unfold” a desired three-dimensional form onto a 2D plane, we will return to the topic of SMA-based self-folding and demonstrate using physically based modeling methods how the planar “unfolded” shape can be thermally driven to return to the 3D form.

3. Multi-panel unfolding

Our initial goal was to identify a basic mathematical framework for converting any given polygonal mesh surface into a physical structure that is easy to construct. The concept of the “band decomposition” from Topological Graph Theory provides such a basic mathematical framework that helped us to develop a simple multi-panel unfolding method. Band decomposition is obtained by 2D-thickening the graph within the surface and is always contractible to the original graph. In a 2D-thickening, each vertex thickens to a polygon (or a disk) and each edge thickens to a band (see Fig. 3). Thus, each polygon corresponds to a vertex and each band corresponds to an edge that connects vertex regions. In the multi-panel method, we convert each vertex of the graph into a star-shaped panel. Edges of the graphs are converted to connectors (i.e., “flaps”). Using this method, we are able to unfold any given polygonal mesh into a set of planar panels, each coming from a vertex of polygonal mesh. We then assemble the panels by connecting corresponding flaps to build large structures. In other words, the multi-panel unfolding method simply converts each vertex of a graph that is embedded on a surface into a star shaped planar panel. By connecting and folding these panels one can construct a close approximation of the desired surface.

3.1. Motivation for multi-panel unfolding

The multi-panel unfolding is mainly useful for economical and easy construction of large structures. With the design and construction of more and more unusually shaped buildings, the computer graphics community has started to explore new methods to reduce the cost of the physical construction for large shapes. Most of the currently suggested methods focus on reduction in the number of unequally shaped components to reduce fabrication cost. In practice, for operative surfaces incorporating thin metals or thick papers, fabrication is economical even if each component is different. Such operative components can be manufactured fairly inexpensively by cutting large sheets of thin metals or thin paper using laser-cutters, which are now widely available.

One of the biggest expenses for construction of large shapes comes from handling and assembling the large number of components. This problem is analogous to the assembly of a large puzzle. However, while puzzles are intended to be difficult, we seek to simplify the construction process in such a way that the components can be assembled with minimum instruction to the sculptors or builders, who may not have extensive experience.