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Exploration of multi-material surfaces as weighted shapes

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ABSTRACT

The introduction of multi-material additive manufacturing makes it possible to fabricate objects with varying material properties, leading to new types of designs that exhibit interesting and complicated behaviours. But, computational design methods typically focus on the structure and geometry of designed objects, and do not incorporate material properties or behaviour. This paper explores how material properties can be included in computational design, by formally modelling them as weights in shape computations. Shape computations, such as shape grammars, formalise the description and manipulations of pictorial representation in creative design processes. The paper explores different ways that material properties can be formally modelled as weights, and presents examples in which multi-material surfaces are modelled as weighted planes, giving rise to flexible behaviours that can be considered in design exploration.

1. Introduction

Additive manufacturing is rapidly becoming an essential and ubiquitous process in creative design, and has introduced new possibilities with respect to the types of shapes that can be realised. The technology continues to evolve, and over recent years has introduced variability in material properties alongside variability in form. This is achieved either by colouring material as it is extruded or by combining different materials within one fabricated object. The result is a greater range in the types of objects that can be fabricated, but these advances are not reflected in computational methods used in design. As discussed by Oxman and Rosenberg [9], computational methods are typically restricted to defining and exploring the structure and geometry of design models, and do not incorporate material properties or behaviour. This research explores how these can be incorporated into shape computations, which have been shown to formalise creative design processes [10, 12], and support generative design [15]. In this paper, the focus is on identifying how the material properties of a surface can be formally modelled. The paper explores mechanisms necessary to support computation with weighted shapes, building on theoretical developments presented by Stiny [14]. Ultimately, the aim of the research is to enable the generation and exploration of design models, with reference to material properties and expected behaviour.

2. Multi-material additive manufacturing

In additive manufacturing, multi-material fabrication is made possible via technologies such as the *Objet Connex*,[1] which combine different materials in a single fabricated object. Materials with various transparencies, colours and material properties, are combined as parts of the object, and can be defined as composites that simulate the properties of common materials such as plastic or rubber. For example, using the *Objet Connex* a hard white plastic material called *VeroWhitePlus*, can be mixed in different proportions with a soft rubber-like black material called *TangoBlackPlus* to produce a range of composite materials, as illustrated in Fig. 1. These composite materials vary in colour, from opaque white

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[1] http://www.sys-uk.com/Connex.

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1524-0703/

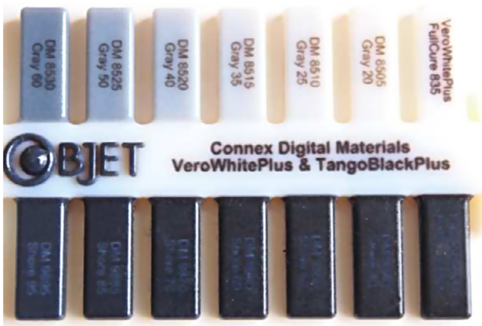

Fig. 1. Sample material for the Objet Connex.

through to opaque black. They also vary in material properties[2]: as the proportion of *TangoBlackPlus* increases the shore rating (a measure of resistance to permanent indentation) decreases, the tensile strength decreases, and the elongation at break increases. Consequently, composite materials become softer and more flexible as the proportion of *TangoBlackPlus* increases.

Fabrication processes that combine materials as parts of an object make it possible to produce objects that have variable material properties. The result is objects which exhibit different physical behaviours. For example, Fig. 2a illustrates a flat surface composed of composite materials that are a mix of *VeroWhitePlus* and *TangoBlackPlus*. In the surface the composite materials are arranged in stripes, where the darkness of a stripe reflects the amount of *TangoBlackPlus* included in the mix: the darker the stripe, the higher the proportion of *TangoBlackPlus* and the higher the flexibility of that segment of the surface. The result is a flat surface that has stripes of varying flexibility that are arranged to give a gradient of flexibility, starting from a very flexible stripe and ending with a very stiff stripe. The result is that the flat surface can be deformed into a curved surface, as illustrated in Fig. 2b and c.

The curved surface in Fig. 2b was generated using the Kangaroo Physics tools for Grasshopper[3] by modelling the stripes as springs, in a method similar to that described in Oxman and Rosenberg [9]. A bending resistance force is applied to each stripe, which corresponds to the weight applied to the stripe; as the proportion of *TangoBlackPlus* increases the resistance force decreases and the stripe allows a greater flexibility. Each corner point is modelled as an 'anchor' point, initially 'anchored' to the *xy* plane. Kangaroo allows anchor points to be moved in real time during the simulation, allowing the user to interact and explore the kinetic properties of a spring system, and so the potential flexibility of a weighted surface. This provides a simulation of the flexible behaviour of the multi-material plane, determined based on the weights applied to the plane in combination with the geometry of the plane. For comparison, the bending behaviour of the physical realisation of the model is illustrated in Fig. 2c.The simulation presents an interactive approach to designing material properties and behaviour: material properties are incorporated in representations used in shape computation, so that they, and the resulting behaviour, can be defined and explored during creative design processes.

3. Formalising creative design

Studies suggest that creative design involves creation, exploration and evaluation of design alternatives [1,12]. Sketching plays an important role in this, because sketches are more than just static representations of imagined concepts; they externalise designers' cognitive activity and are used as devices to support exploration of an emerging design [4]. Sketching supports creative design, because it enables designers to rapidly produce large numbers of concepts that are open to interpretation. Schön and Wiggins [13] describe this as a 'seeing-moving-seeing' process where seeing a sketch can result in its interpretation according to newly recognised forms or structures, and this in turn informs the development of future sketches. Such reinterpretation is a vital element in the exploration of designs and is believed to be a decisive component of innovative design [16]. But, sketching is not only a paper based activity; conceptually, a sketch is an informal representation, which is incomplete and is ambiguous [3]. In many creative industries, such as architecture and product design, physical models, e.g. of card or foam, play the role of the sketch in informing the development of a design. Provisional models are created, explored and evaluated, much in the same way that drawings are used [10]. And in recent years, additive manufacture has become a popular method for fabricating models for design exploration, to visualise and physically explore concepts.

Shape computation [15] provides a formal model of this exploration process, with a focus on representations, and the transformations applied to representations during the process [12]. In shape computation, design representations are formalised as shapes, and transformations of these shapes are formalised in shape rules. An example of a simple shape rule and its application is illustrated in Fig. 3. Shape rules enable the perceived structure of a shape to be freely recognised and manipulated without adherence to a predefined geometric structure, and application of a shape rule acknowledges the 'seeing-moving-seeing' process described by Schön and Wiggins [13]. In 'seeing', a rule formalises the perception of a shape by recognising an embedded part, and in 'moving', the rule manipulates the shape according to replacement of the recognised part. Shape computations formalise the interpretations and transformations of shapes that emerge during design exploration; they describe the process as a formal protocol of rule applications, and a set of rules formalises a potential design space according to a shape grammar [11]. When implemented in a computational system, such as Jowers and Earl [5] and Jowers et al. [6], shape grammars enable designers to actively explore a design space by generating designs via rule applications.

4. Shape computation and weighted shapes

In shape computation [15], design representations are formalised as shapes composed of finite numbers of geometric elements (points, lines, planes, etc.) of finite extent. Shapes are described according to their parts and these are ordered by a part relation, are combined by shape operations of sum,

[2] http://www.stratasys.com/materials/polyjet/rubber-like.

[3] http://www.grasshopper3d.com/group/kangaroo.