Prototyping large-sized objects using freeform thick layers of plastic foam.

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ABSTRACT.

Current Rapid Prototyping systems are primarily aimed at small-sized objects containing many shape details. In this paper a Rapid Prototyping technology is presented that is aimed at large-sized objects having a complex, freeform outer shape. This new technology builds the model out of thick layers, each having freeform outside faces. The paper will present: an overview of current methods to produce large prototypes, the basics of the new method, the technology used to produce the layers, the toolpath planning and finally the overall system design.

1. INTRODUCTION.

Most Rapid Prototyping systems build a model by stacking a large number of thin layers. Each of these layers has vertical front faces, which results in a so-called staircase effect on the surface of the object (zero order approximation). The thickness of each consecutive layer has to be very small in order to achieve a model of sufficient preciseness. This thin layer technology is well suited for prototypes of small-sized objects. For larger products however, the time and cost involved are far too high: a different approach is needed. A number of solutions to this problem that have been proposed are discussed in section 2. One of these being the combination of layers with ruled front faces (first order approximation) and a higher layer thickness, to enhance speed without loosing preciseness.

In section 3 of this paper we will present our new approach: a prototyping system based on higher order approximation (e.g. second order, i.e. circular, or better). Using this technology consecutive layers can be produced with outer surfaces that smoothly fit together. This way very high quality models can be produced at moderate cost. The actual technology to be used is based on cutting polystyrene slabs using a flexible (hot) blade as a cutting device. The shape of the cutter can be controlled during the cutting process, for which the theoretical base is given in section 4. Section 5 describes the method to calculate the toolpath and the shape of the cutter for every tool position. The overall system design is presented in section 6, and finally in section 7 the results will be discussed and conclusions will be given.

2. RELATED RESEARCH.

Rapid Prototyping is the process of automatically creating a physical prototype, based on a 3D CAD model, and within a short time. For this automatic creation of physical models three fundamentally different methods are possible [Kruth, 1995]:
- Incremental (adding material), commercially available in LMT systems.
- Decremental (removing material), commercially available in CNC systems
- Deforming (changing the shape of flexible material), no commercial RP systems available.
Next to these three base methods a number of hybrid methods have been developed too, for instance stacking layers (incremental) that have been cut out (decremental).

Incremental processes are mainly used for relatively small but complex (many shape details) models. A large advantage of these processes is that the price of the prototype is (almost) independent of its complexity. However, when the desired model has to be large, like one or more cubic meters, incremental techniques tend to be slow, complicated because of the small working envelope of these systems, and very expensive. So for the production of large models decremental methods are better suited, using large CNC milling machines. Currently easy-to-use CAM software is available, especially developed for Rapid Prototyping purposes [Lennings, 1997]. This approach is best suited for styling block models: detailed inside geometry is more suited for incremental processes. Thus, for the creation of models that both are large and contain many details no solution is available yet.

In recent years some steps forward were made in the field of large shape prototyping. Recently a system called Topographic Shell Fabrication (TSF) became commercially available, based on the incremental principle [Formus, 1997]. It uses sand as the building material, which is then bound using wax. This system is able to build models up to about 3.6 x 2 x 1.3 meters. The models produced by this technique are quite heavy and can melt by sunlight because of the wax used. The main application of the technique is to create molds for lay up techniques.

Furthermore, some new hybrid techniques have been developed or described. Research projects on the Universities of Utah [Thomas ea., 1996], Queensland [Hope ea., 1996, 1997a] and Delft [de Jager ea., 1996, 1997a, 1998] have delivered systems, algorithms and techniques that can be used to create large shapes out of thick layers. The main problems to be solved here were: how to build the shapes with as few layers as
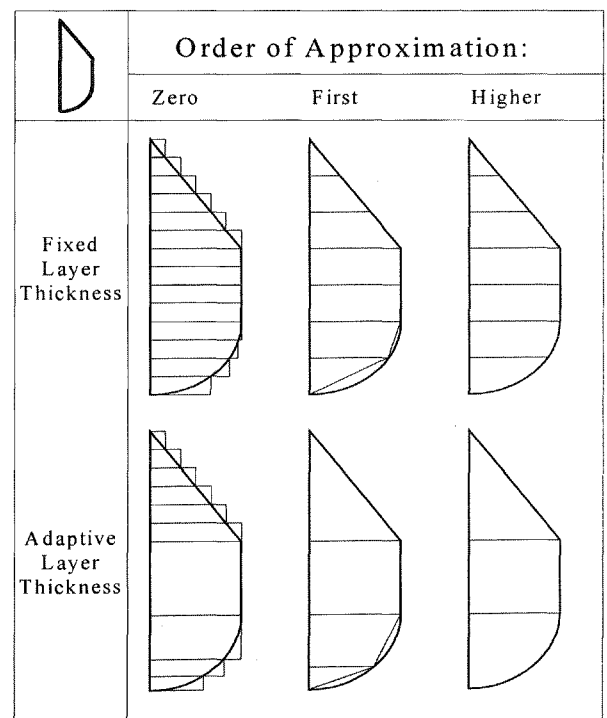
Figure 1: Available slicing techniques.

possible, and how to avoid the staircase effect which also exists in thin layer systems but is of much more importance in thick layer systems.

The solution for the first problem is adaptive slicing. Several algorithms have been developed [Hope ea., 1997b], [de Jager ea., 1997b] and [Marsan ea., 1996] that are able to generate layers with variable thickness from a CAD model. The thickness of each layer depends on the local shape that has to be approximated and the tolerance that is given. An extruded shape can be produced using one layer or a small number of the thickest possible layers, while a free formed shape of the same height has to be built using many more layers to approximate the shape accurately.

The second problem, on the staircase effect, can be reduced by using layers with sloped front faces (first order approximation) instead of the classical method which uses layers with vertical front faces (zero order approximation) [Hope ea.] and [de Jager ea.]. Production of layers with sloped front faces can be done using existing cutting equipment, like 4 axis hot wire cutters, laser cutters or waterjet cutters. Using these two solutions combined results in fewer layers needed to produce a model at a given accuracy: see the two leftmost columns of figure 1.
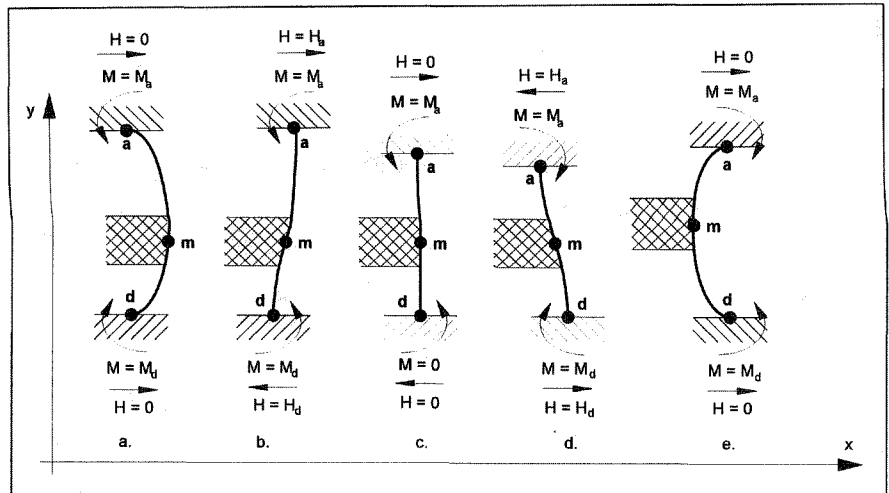

3. A NEW APPROACH.

Building a model by stacking a number of layers is in fact a perfect example of a discrete procedure: the layer either is or is not present, causing the staircase effect mentioned before. As said before: sufficient for small models, but very inefficient in case of large models. The use of sloped front faces does offer some improvement here, however is still insufficient for high quality prototypes. In our proposed method we use a higher order approximation for the front faces of each layer, to be created using an analog procedure.

In contrast to discrete methods, analog methods create shape by reproduction of a master, like a mold for injection molding (3D example). The craftsman modelmaker regularly uses 2D analog tools while creating a freeform model: all sorts of 2D templates that are being used as scraping tools [Trudeau, 1995]. A foam model of a sphere can for instance be created by scraping with a circle-formed tool, using one or more layers. In case of a more complex shaped geometry the front faces of the layers can also be created by scraping with circular tools, which is second order approximation. In many cases a better approximation is possible using freeform tools (higher order approximation). The use of analog tools is very efficient: complex shapes can be produced in a short time. Especially when combined with adaptive layer thickness: see figure 1.

However, the disadvantage of using an analog tool is that the tool first has to be created, because an infinite amount of possible toolshapes exists. In our proposal this problem is covered by using a computer controlled flexible tool, that can indeed be set to an infinite number of shapes. This tool is a heated flexible blade: a thin, flexible metal blade that is supported at both ends by active supports. By changing the length of the blade, the position and the orientation of the supports, the shape of the flexible blade can be influenced (figure 2). As the blade is heated it can be used to cut slabs of polystyrene foam, thus producing thick layers with freeform front faces.

These layers have to be stacked (either automatically or by hand) to produce the actual large prototype. At the connection between two layers now a continuous surface is created, with a high order continuity. Where standard LMT methods produce a discontinuous outer surface, and the ruled front face method a zero order continuity (positional), the new method creates a first

Figure 2: Possible shapes of the flexible blade.

order continuity (tangential), or even a second order continuity (same curvature). Using this method will result in a large prototype of high quality, produced within a short time and at moderate cost.

4. OVERALL DESIGN OF THE NEW SYSTEM.

Based on the idea of using a heated flexible blade to produce layers with freeform front faces, a complete Rapid Prototyping system has been designed, which is presented in figure 3. It consists of three phases. First the preparation phase, in which the geometry is imported, analyzed and if needed segmented. Segmentation is needed in case the total prototype cannot be manufactured in one piece because of size and/or geometry problems. We will not discuss the process of segmentation in this paper. Next the computing and simulation phase, in which the layers to be manufactured are calculated and the result is simulated. Especially important for a successful system is the layer thickness calculation (slicing), which has to produce layers of variable thickness in such a way that each layer can indeed be produced. For each layer the freeform front face (nominal shape) has to be approximated by curves that can be produced by the flexible blade. Finally the third phase: the physical fabrication phase, in which the prototype is actually built on a real (designed, built and tested) machine.

This overall system design consists of many processes, for all of which methods, algorithms and physical tools have to be developed. It is not possible to treat each of these processes in detail here. In this paper we will discuss the most crucial items of the systems design, which are the modeling of the flexible blade and the curve matching of the blade-curve with the nominal geometry.
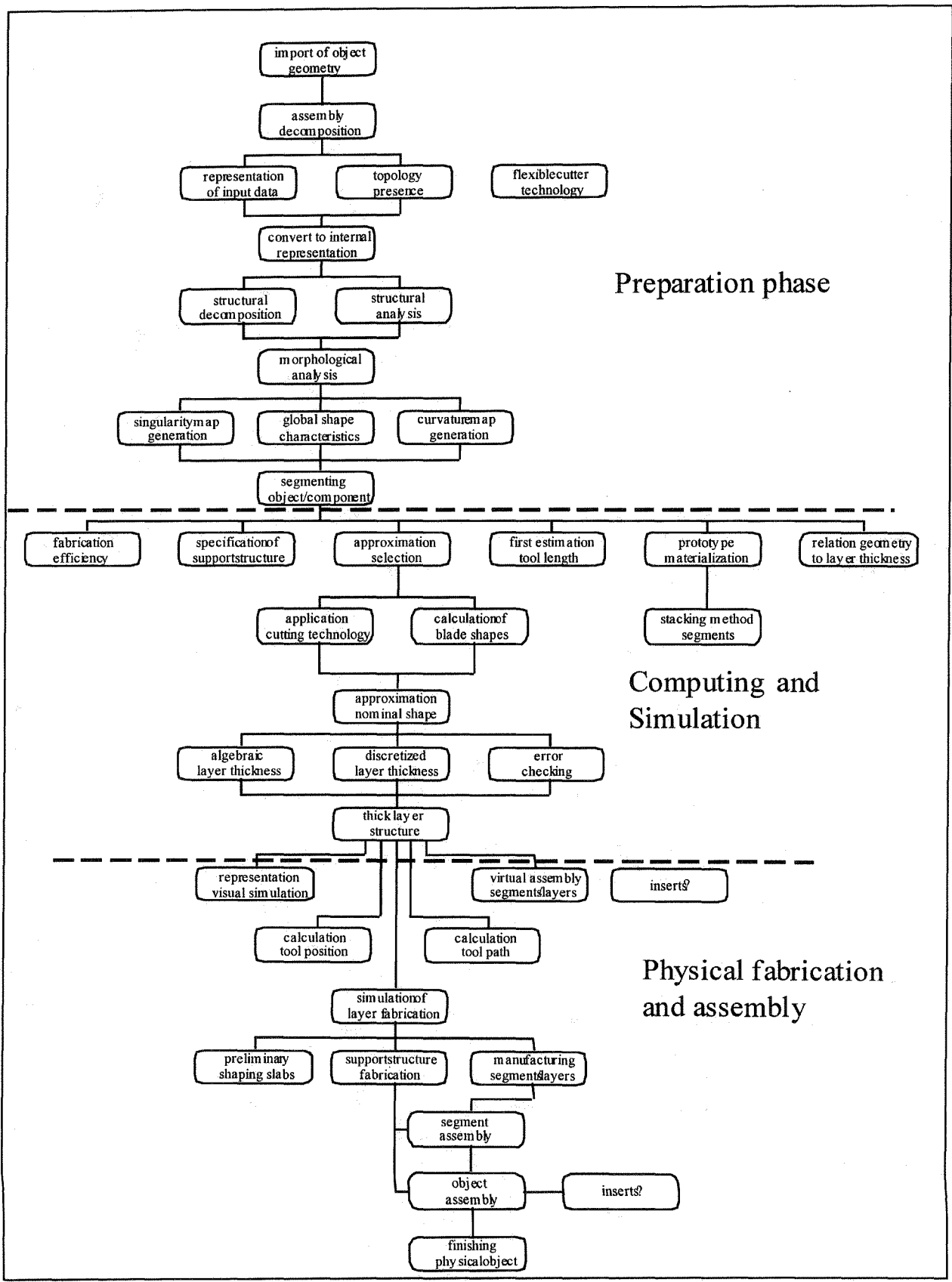
Preparation phase

- import of object geometry
- assembly decomposition
- representation of input data
- topology presence
- flexible cutter technology
- convert to internal representation
- structural decomposition
- structural analysis
- morphological analysis
- singularity map generation
- global shape characteristics
- curvature map generation
- segmenting object/component

Computing and Simulation

- fabrication efficiency
- specification of support structure
- approximation selection
- first estimation tool length
- prototype materialization
- relation geometry to layer thickness
- application cutting technology
- calculation of blade shapes
- stacking method segments
- approximation nominal shape
- algebraic layer thickness
- discretized layer thickness
- error checking
- thick layer structure

Physical fabrication and assembly

- representation visual simulation
- virtual assembly segments/layers
- inserts?
- calculation tool position
- calculation tool path
- simulation of layer fabrication
- preliminary shaping slabs
- support structure fabrication
- manufacturing segments/layers
- segment assembly
- object assembly
- inserts?
- finishing physical object

Figure 3: The overall design of the flexible cutting system.

5. THE FLEXIBLE CUTTING BLADE.

As mentioned in section 3, the flexible blade is attached to active supports, of which both orientation and position can be changed. A schematic view of cutting blade and supports is given in figure 3. Each support is capable of transferring a winding force (to set the length of the blade), a bending moment (to set the rotation) and a lateral force (to set the position). It must also isolate the heated blade in order not to loose too much energy.

From a mechanical point of view, the flexible blade behaves like a 'physical spline', which takes up its shape following the law of minimum strain energy. For the commonly used blades the ratio between the largest cross sectional dimension and the actual length is very small (< 0.01), which means that the blade is in fact a very tender bar. On this basis a physically based model of the flexible blade has been created, resulting in a non-linear differential equation which has no exact analytical solution. Details about these calculations can be found in [Horváth, 1998-a].

Figure 4: The cutting unit, consisting of a flexible blade attached to two active supports.

The problem could be solved using a geometrically based modeling. Again the issue was to find a curve of a given length that interpolates two points at a certain angle and takes up its minimal strain energy. For this calculation the assumptions are made that, irrespective of its cross section, the curved blade can be substituted by its profile curve, and that the curve is planar. The resulting B-Spline curve $r(u)$ is called the profile curve of the flexible blade [Horváth, 1998-b].

6. CURVE MATCHING.

As said in section 3, the flexible cutting blade will be used to create layers with freeform front faces, which are used to build the prototype. A geometric description of each layer is derived from the CAD model in a slicing process (see section 6). A cross-section of the freeform front face of the layer at a certain location is given by a curve $q(v)$, called the shape curve. As the geometry of the front face will vary following the layers circumference, an infinite number of shape curves exists for each layer. Obviously only a limited number of curves will be processed, interpolating the front faces geometry in-between.
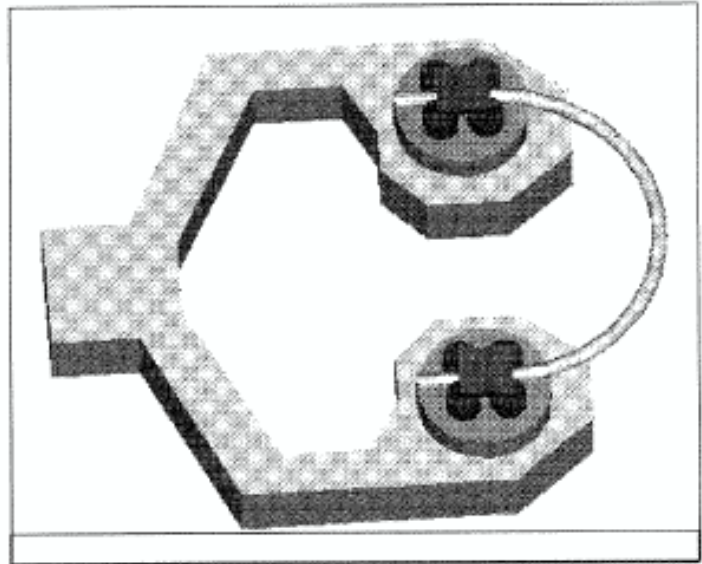
In order to calculate the toolpath for a certain layer, a number of shape curves **q** has to be selected for processing. Next for each shape curve an appropriate profile curve **r** has to be found that can be used to manufacture the layer. Curve **r** should approximate curve **q** within a certain tolerance δ. The evaluation of what can be achieved with shape curve **r** consists of shifting curve **q** along curve **r**, in such a way that the start- and endpoints **b** and **c** of **q** remain on **r** (see figure 4). For each shifted **r** the deviation δ between the two curves can be measured by comparing a number of points on each curve. This process is called curve matching. To find a suitable curve **r** a number of profile curves that potentially match will have to be evaluated. This can be done by just evaluating profile curves from a library one by one (current project status) or by developing a convergent process to find the desired profile curve in a few iterations. The curve matching process is described in more detail in [Horváth, 1998-b].
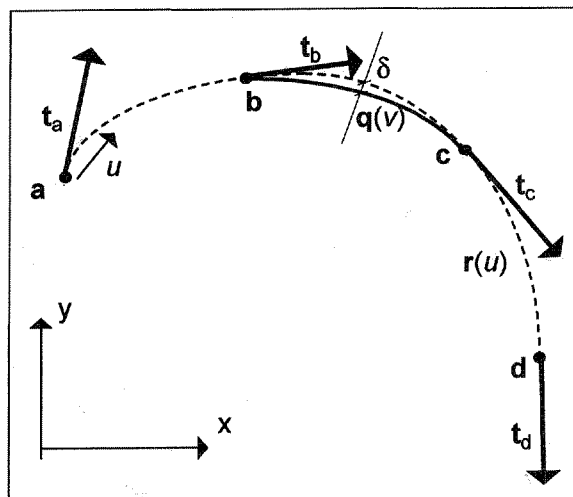
Figure 5: The given (solid) shape curve q(v) that describes the CAD geometry needs to be approximated by some portion of the (dashed) profile curve r(u) that describes the flexible blade.

7. DISCUSSION AND CONCLUSIONS.

The objective of our research and development has been to come up with an effective technology for the fabrication of large-sized, freeform physical models, based on higher order shape approximation. This technology proved to be feasible.

The geometry of the flexible blade can be properly generated/calculated with the assumption of minimum strain energy, specifying as boundary conditions the position and the tangency of each support.

Further work will focus on the slicing algorithms, the optimization of the process parameters and the calculations and the development of the machine to be actually used.

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