Implementation of the Freeform Thick Layered Object Manufacturing technology (FF-TLOM)

A status review

Bram de Smit, Johan J. Broek, Imre Horváth, Lex Lennings
Faculty of Design, Engineering and Production
Sub-faculty of Industrial Design Engineering
Delft University of technology
Jaffalaan 9, NL-2628 BX DELFT, The Netherlands
phone: +31 (0)15 2783788, fax +31(0)15 2781839
E-mail: a.desmit@io.tudelft.nl, WWW: http://www.io.tudelft.nl/research/ica/

Abstract

For the production of large sized concept models, we propose the use of thick layers of extruded polystyrene foam. The layer cutter uses a shape controllable tool, thus creating freeform layer front faces. This novel technology is currently being implemented up to the level of a system, able to produce physical prototypes of large freeform shapes with a high visual quality in a relatively short period of time. The paper first discusses the geometrical topics involved and then focuses on the needed cutting and control technology, what experiments and tests have been performed to make implementation possible, what are the further steps and what are our expectations from this technology.

1. Introduction

Large foam models are being used in a wide range of applications varying from advertisement signs and scenery pieces in film industry to concept models of large size consumer products like boats, furniture and cars. The manufacturing technique for these large models is mainly by hand, using power tools to shape the material. CNC milling can be applied, but with restrictions. The LMT approach is not yet very common for the large size domain. Research projects on the Universities of Utah (Thomas et al., 1996) , Queensland (Hope et al., 1997) and Delft (de Jager, 1998) have generated systems, algorithms and techniques that can be used to create large shapes out of thick layers. The main problems they solved were: how to build the shapes with as little layers as possible and how to avoid the staircase effect which can be very disturbing in thick layer systems. The solution for the first problem is adaptive slicing: Several algorithms have been developed that are able to generate layers with variable thickness from a CAD model. The thickness of each layer depends on the nominal shape that must be approximated under constraint of a given tolerance.

Using layers with sloped sides instead of the classical type of layers with square sides can reduce the second problem, the staircase effect. Combining the two methods results in the need for fewer layers to produce a model with comparable accuracy and with higher visual quality than the classical methods. In Horváth et al., (1999b) the ICA research group introduced the Free Form Thick Layered Object Manufacturing technology. (FF-TLOM) This technology opens the possibility to manufacture layers with freeform front surfaces instead of the common straight or slanted surfaces. The technology enables the creation of large shapes from thick layers of foam with smooth non-facetted surfaces (figure 1). Since the introduction research has been done and experiments were performed in order to enable implementation of the technology. Although a complete, automated, FF-TLOM system is not yet available, important parts of the necessary technology have been researched and can be used.

2. The FF-TLOM technology

The FF-TLOM system can be divided in two parts. The first one is about the processing of the CAD data of sculptured objects, in order to decompose the object into layers that can be manufactured (Horváth et al., 1999b). The second part covers the manufacturing process that is needed to produce the layers. The processing of the CAD data consists of importing the shape into the system and converting it to a usable boundary representation. The user can than divide the object in so called components, which will be considered as separate objects. The components are geometrically analysed by the system and decomposed into segments based on curvature maps and singularity graphs. The segments are sliced into layers using an optimal orientation, calculated by the system (figure 2). The layer thickness is calculated by fitting calculated blade profiles to the nominal shape of the CAD model with a given tolerance. The layers are fabricated from standard slabs of raw material and must therefore have a standard thickness. Layers can be decomposed again into sectors because of size limitations of the manufacturing hardware. The manufacturing process starts by importing a standard slab of polystyrene foam into the manufacturing system. The slab must be fixed in a defined position and then the sector shape that was found during the decomposition process must be cut out of the raw material. It is necessary that the material is being fixed or gripped in such a way that the layer boundary can be reached by the cutting device. This cutting device needs to be manipulated with respect to the foam slab with five degrees of freedom, three linear degrees of freedom for positioning and two rotational movements for orientation. A roll movement of the cutting device is not allowed. The cutting device is a flexible blade that is heated by electrical power. Its shape is numerically controlled by four input parameters, which are again four degrees of freedom that have to be controlled by the system. Once the sector is produced, it is exported out of the system and assembled to the desired complete model. As it is our intention to make the produced models editable (Horváth et al., 1999c, Lennings et al., 2000) the assemblage technique must allow disassembly and replacement of specific parts in a later stage.

3. The foam cutting process

Several machines are on the market that are able to cut 2D shapes numerically controlled out of plastic foam using a hot wire as a cutting tool. To our best knowledge no machine is existent that is able to produce freeform cuts in a NC manner. In the packaging industry, hand held tools are available that use a hot blade, which can be manually bent in a shape, to cut out slots and holes in polystyrene foam. In order to make the hot blade cutting technology suitable for automated cutting the process must be well understood. To describe the process a list of parameters was generated that are influencing the process (de Smit et al., 1999a). Experiments have been carried out to determine what the influences are of these parameters, whether they are important and how they should be controlled (de Smit et al., 1999b). A comprehensive list of parameters that was generated is presented in table 1. Our first step has been to go into the process parameters to find whether it is possible to create an automated hot cutting system that can produce an acceptable surface quality with acceptable speed. Within the group of process parameters a ranking was made in order to reduce the number of experiments. The first five parameters in the list namely material, temperature, power, blade cross section and speed are considered basic parameters and were tested and elaborated extensively. The remaining process parameters as well as the tool parameters are considered secondary parameters. They will be elaborated further if this is necessary for the development of a working prototype of a cutting tool. The parameters ‘surface quality’ and production speed’ were used for evaluation of the results of the performed cutting tests. We found that the surface quality can be related to the amount of thermal energy per square unit of surface (figure 3). If the energy is within determined boundaries the resulting surface will have a high quality. The estimated production speed is high compared to conventional RP techniques.

4. The shaping of the blade

Hot blade cutting is used for cutting specific features out of foam with hand held tools. The shape of the blade in this type of application is fixed. The novelty that we have introduced is the direct control of the shape of the blade. It is controlled numerically by the same system that controls the cutting movement. Applying this technology offers the possibility to create a complex double curved surface in one cut. In order to enable implementation of the technology we must determine how a flexible blade takes its shape if certain end conditions are applied to it. A number of algorithms and calculation methods exist, able to calculate the shape of a thin flexible beam when constraining end conditions are applied (figure 4). Some of the methods are highly accurate but expensive in computation time. The applicable methods for the real time calculation of the tool shapes are approximating ones. They need to be validated by experimental verification. It is crucial to know the correctness of the used algorithm and how the modelled supporting conditions of the blade relate to the actual ones. This will strongly influence the accuracy of the flexible cutting technology. We performed a series of experiments, comparing the shape of a physical curved blade to a virtual shape that was calculated from the four input parameters angle a, angle b, length of the blade and distance between the connecting points of the blade (figure 4) (de Smit et al., 2000). The physical shapes were scanned, and the calculated shapes were matched with the scanned shapes (figure 5). The deviations between the two shapes were analysed and it was determined that they were smaller than 2% of the blade length in most cases. That means that using a 200 mm. blade an error of 4 mm. can be expected. Analysis of the test data revealed small inaccuracies in the measurement method. It is expected that using a more precise measuring configuration will further reduce the deviations.

5. Analysis of kinematics

Unlike other LMT technologies the FF-TLOM process is not a simple two degrees of freedom process. In conventional LOM the contour is cut out of a sheet by a laser that is controllable only in X and Y. In FF-TLOM the kinematics are much more complex and must be analysed in order to find an optimal configuration for the system. For a proper cutting process the tool holder must have five degrees of freedom with respect to the foam slab (figure 6). The way these five degrees are distributed over the foam slab and the tool will influence the performance of the resulting system. We performed a number of simulations and analytical calculations in order to determine which is the optimal configuration (Ferro Pozo, J.M., 1999). It was concluded that from the kinematics point of view the best option is to put as many degrees of freedom as possible into the tool support because this allows a relatively light construction, allowing high speed and acceleration. From an accuracy point of view it can be preferable to put some of the degrees of freedom to the foam slab. If this is necessary, these will be one or more linear positioning movements. It was concluded that the FF-TLOM motion system can be implemented using existing technology and standard components. Because we want to apply a constant cutting speed, high accelerations and speeds will be needed in the motion system. Therefore high performance drives and actuators will be used in the final system. The pilot implementation that is being developed now uses a six axes industrial robot for the motion system.

6. Gripping and fixing the material

The gripping and fixing of the foam material is a complex problem because it must be done in such a way that the cutting process is not obstructed. As all layers are different in shape and size, it means that the gripping points will differ for each layer. The material can not be gripped on the outside boundaries because the sector must be reachable from all sides. Therefore the slab must be gripped somewhere in the central area. Different gripping principles have been considered and it was concluded that the best option is the use of a number of hole grippers which are distributed over the layer in such a way that the layer is adequately fixed and the boundary of the layer is completely reachable. (Gil Docampo, 1999) For the use of this kind of gripper, a pattern of gripping holes is needed that will be different for each layer, depending on its shape. The use of holes has a secondary advantage related to the assembly of the complete model. We want to create prototypes that can be locally edited in a later stage by replacing small sections. This implies that the possibility to disassemble the model must exist. Our solution is to use pen and hole connections that can be assembled without gluing. The holes for that purpose can be created in the same way as the gripping holes. In many cases the holes are used combined for gripping and for assembly.

7. Development of a cutting device

The cutting device for the FF-TLOM system must be able to manipulate the shape of a flexible blade with a high temperature in such a way that the resulting curve represents the local curvature of the CAD model. It can only be managed if the blade is deformed within the elastic domain. If the blade is deformed plastically it becomes impossible to predict the shape after a number of deformations. The high temperature of the blade influences the elastic behaviour of most metals in a negative way. The Nickel Chromium alloys applied in manually operated cutting tools have rather poor elasticity performance. Literature search resulted in a number of alternative materials that are currently being tested. Among the candidate materials are various sorts of stainless steel, a number of nickel alloys, titanium alloys and metal matrix composite materials (Wibowo, 2000). The manipulation of the blade can partly be implemented using existing conventional actuators (Sudijono, 1999). Topics, like fixing the heated blade and controlling its length, need dedicated designs and are still under elaboration. First designs for a tool were made (figure 7) and evaluated. A tool with manual blade shape control was already built and used in cutting tests.

8. Conclusions

From experimental and analytical results we conclude that the FF-TLOM technology is feasible. For the implementation standard technology can be used but also new developments are needed. The novelties are mainly situated in the cutting device. Currently a pilot implementation is being realised using a six axes industrial robot for the tool manipulation and a cutting device with fixed blade shape. Using the experience gained from this pilot implementation a dedicated system will be developed. The technology enables the production of large size editable prototypes with high visual quality and low building time (figure 8).

References

de Jager, P.J., (1998), “Development of a New Slicing Methodology to Improve Layered Manufacturing”, Ph.D. thesis, Delft University of Technology, pp. 129.

de Smit, A., Horváth, I, Broek, J.J, Lennings, A.F. and Sudijono, S, (1999a), "Tool- and Process Control Issues relating to the use of a Flexible Cutting Tool", at the 1999 International CIRP Design Seminar, March 24-26, 1999, University of Twente, Enschede, the Netherlands p. 405-415.

de Smit, A., Broek, J.J., and Horváth, I., (1999b), Experimental Investigation of Factors Influential for the Flexible Blade Based Prototyping Process, Proceedings of the 1999 ASME Design Engineering Technical Conference, paper DETC99/DFM-8960.

de Smit, A., Broek, J.J., Medland A.J., and Horváth, I., (2000), Comparative analysis and experimental verification of the computed shape of a flexible blade tool for FF-TLOM, Submitted to ASME Design Engineering Technical Conference 2000.

Ferro Pozo, J.M., (1999), Design of a Foam Slab Manipulator for the FF-TLOM Equipment, tentative title, Technical report, Delft University of Technology, (1999), to be published.

Gil Docampo, I., (1999), Design of a Foam Slab Gripper for the FF-TLOM Equipment, tentative title, Technical report, Delft University of Technology, (1999), to be published.

Hope, R.L., Jacobs, P.A., and Roth, R.N., (1997), Rapid Prototyping with Sloping Surfaces, Rapid Prototyping Journal 3-1, pp. 12-19

Horváth, I., Vergeest, J.S.M., Broek, J.J. & de Smit, A., (1999a), “Tool Profile and Path Calculation for Freeform Thick-Layered Fabrication”, Computer Aided Design, 30-14 (1999) 1097-1110

Horváth, I., Broek, J.J., Rusák, Z., Kuczogi, G., and Vergeest, J.S.M., (1999b) Morphological Segmentation of Objects for Thick-Layered Manufacturing, Proceedings of the 1999 ASME Design Engineering Technical Conference, paper DETC99/DFM-8932

Horváth, I., Broek, J.J., Lennings, A.F., and Vergeest, J.S.M., (1999c) Reshapeable Concept Models by FF-TLOM: A True Alternative of Conventional Clay Modeling, ISATA'99, paper 99ME069

Lennings, A.F., Broek, J.J., Horvath, I, Sleijfers, W, de Smit, B, (2000), “Editable physical models for conceptual design”, proceedings of the TMCE 2000 symposium, April 2000, Delft University of Technology, Delft, the Netherlands, pp 10.

Sudijono, S., (1999), Design of an Adjuster for a Flexible Cutting Blade for the FF-TLOM Process, Delft University of Technology, Techn. report ICA-TR-03, 1999

Thomas, C.L., Gaffney, T.M., Kaza, S. & Lee, C.H., (1996), “Rapid Prototyping of Large Scale Aerospace Structures”, Proceedings of the 1996 IEEE Aerospace Applications Conference, IEEE catalog #96CH35904, ISBN 0-7803-1396-6.

Wibowo, M., (2000), The specification and selection of an appropriate blade material for the flexible hot blade cutter, Delft University of technology, Technical report, to appear.

Process parameters	**Tool Parameters**	**Evaluation Parameters**
Foam material	Blade length	Surface quality / roughness
Blade temperature	Blade flexibility	Surface preciseness
Dissipated blade power (electrical)	Thermal behaviour of blade material	Production time
Cross section of the blade	Bending force for the blade	Dynamics of the process
Cutting speed	Blade support	
Cutting force	Accuracy of support	
Blade material		
Blade temperature distribution		
Blade radiation pattern		
Manoeuvrability of the blade		

Table 1: Overview of influential parameters for the hot blade cutting technology

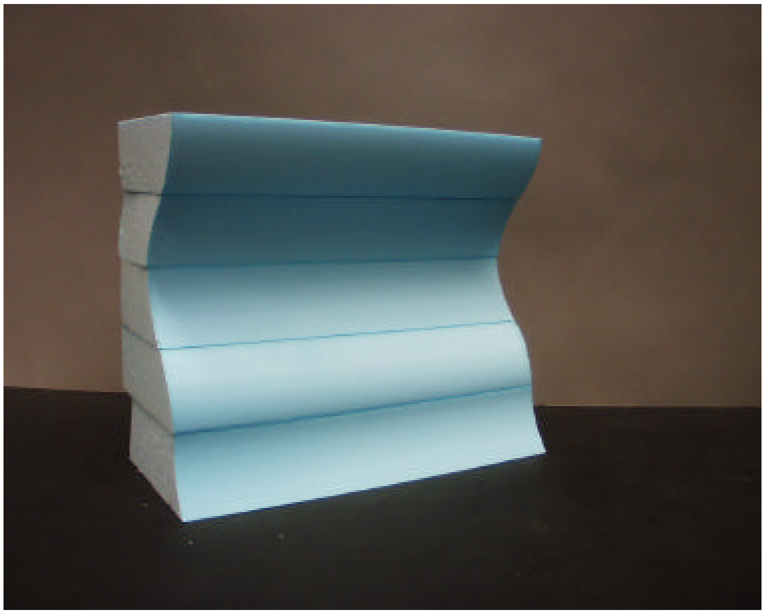


Figure 1. A segment consisting of 5 layers with freeform front surfaces. Size: 300 * 250 mm., cutting time 150 sec

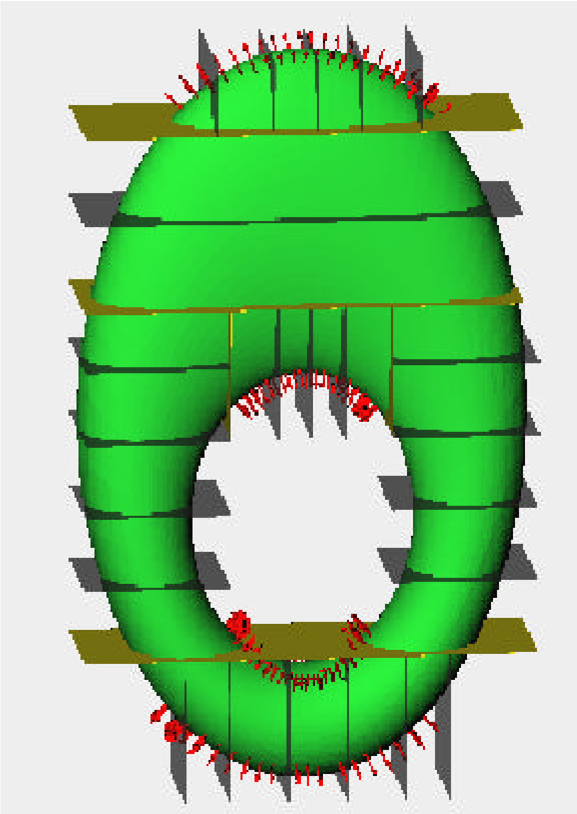


Figure 2 An example of decomposition of a CAD shape into segments and layers that can be manufactured

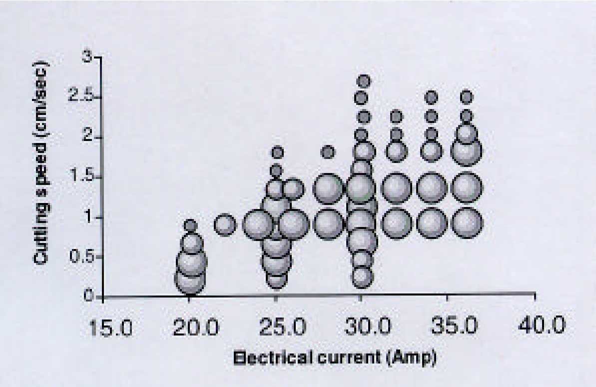


Figure 3. Surface quality as the result of different combinations of current and speed during cutting. The large bulbs represent results with good surface quality, The mid sized bulbs represent moderate surface quality and the small bulbs represent bad surface result

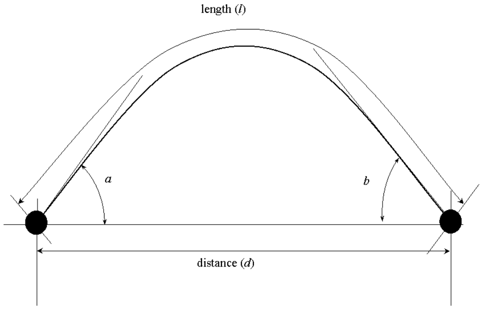
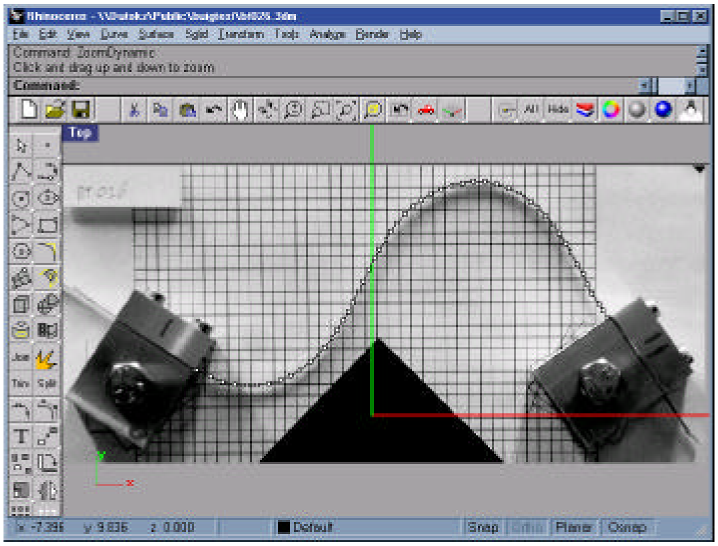


Figure 4. The input parameters that are being used to control the shape of the flexible cutting blade: Two angles a **and** b**, a length** l **and a distance** d**.**



Command: ZoomDynamic
Click and drag up and down to zoom
Command:

x -7.396 y 9.836 z 0.000

Figure 5. Tracing a scanned image of a physical curve. The scanned image is put on the background of the working environment in a CAD package and then manually traced with a polyline

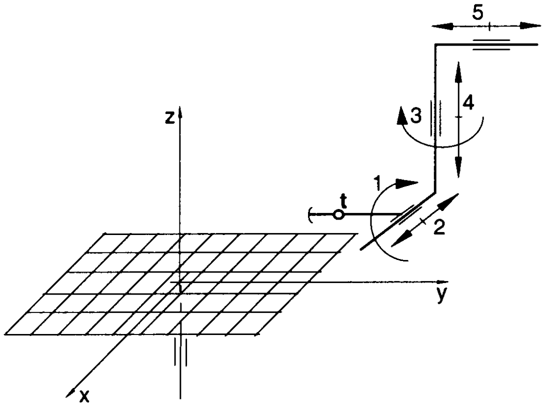


Figure 6. The needed degrees of freedom of the tool (t) with respect to the foam slab. The given degrees of freedom can be distributed over the tool and the foam slab in various ways.

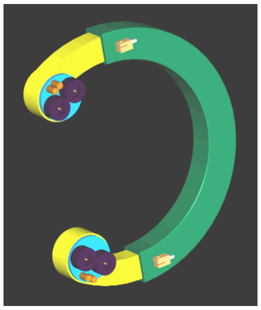


Figure 7. A concept design of a tool with the possibility to control the four input parameters for the blade shape.

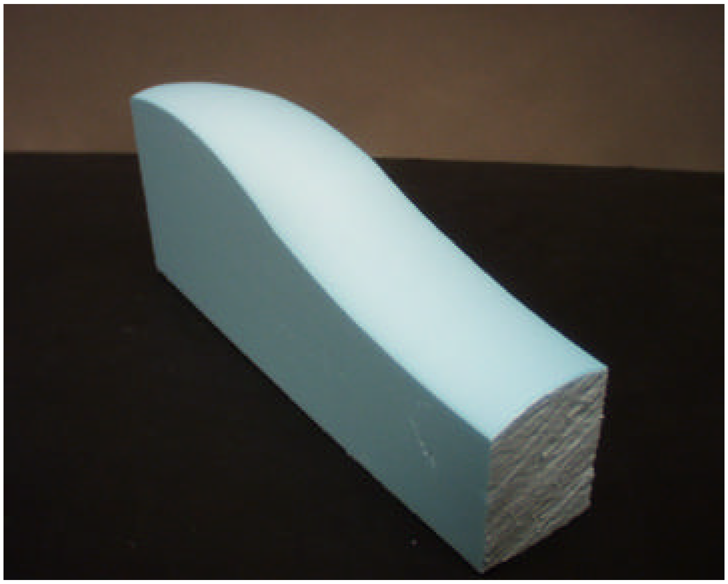


Figure 8. A sector with a freeform front surface of high quality, cut in approximately 25 sec. Size of the cut surface is 300 * 50 mm.