A Review of State-of-the-Art Large Sized Foam Cutting Rapid Prototyping and Manufacturing Technologies

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Abstract: Current additive rapid prototyping technologies fail to efficiently produce objects greater than $0.5m^3$ due to restrictions in build size and build time. Conversely large hot-wire cutting machines, able to cut large objects, often lack the ability to create surfaces with complex geometrical features. Therefore there is a need to develop rapid prototyping and manufacturing technologies capable of producing large objects in a rapid manner directly from CAD data. Large sized freeform objects made of soft materials, such as polystyrene foam, have numerous uses including; conceptual design of commercial products, automotive design, aerodynamic and hydrodynamic testing, advertising, film making, medical supports, sporting equipment and props for the entertainment industry. Plastic foam cutting rapid prototyping is a relatively new technology capable of producing large plastic foam objects directly from CAD data. This paper will describe nine such technologies that have been developed or are currently being developed at institutions around the world.

Introduction

Large sized freeform objects made from soft materials have numerous uses including; conceptual design of commercial products, automotive design, aerodynamic and hydrodynamic testing, advertising, film making, medical supports, sporting equipment and the entertainment industry. One such soft material is polystyrene foam which exists in two basic forms; Expanded Polystyrene (EPS) and Extruded Polystyrene (XPS).

There are a number of well recognised manufacturing technologies capable of rapidly producing complex objects or large objects but there are few that can do both with low cost. Conventional additive rapid prototyping (RP) technologies are continuing to improve in speed and accuracy, however the ability to produce large ($> 0.5m^3$) prototypes, moulds or parts is still expensive, time consuming and often impossible [1]. CNC machining facilities are also used to machine objects with complex geometries, however for most applications the cost of a large CNC machine may be prohibitive. Also depending on the machine certain features (such as undercuts) may require multiple setups or specialist tooling. Computer controlled foam cutting machines have many attributes suited to large scale rapid prototyping and manufacturing (RP & M) such as fast build times and low material costs [2]. However, the geometrical features able to be created on conventional foam cutting machines are severely limited by the use of straight hot-wire cutting tools.

Foam cutting RP machines have been developed which enable the manufacture of large and complex objects with low cost, they bridge the gap between conventional RP machines and conventional foam cutting machines as is shown in figure 1. Development of foam cutting machines for rapid prototyping and manufacturing (RP & M) purposes began shortly after the first rapid prototyping machines became commercialised in the late 1980s. However few RP foam cutting machines have been commercialised to-date leaving significant opportunities for research and development in this area. The following paper will describe novel foam cutting RP machines that have been developed or are currently being developed at institutions around the world.

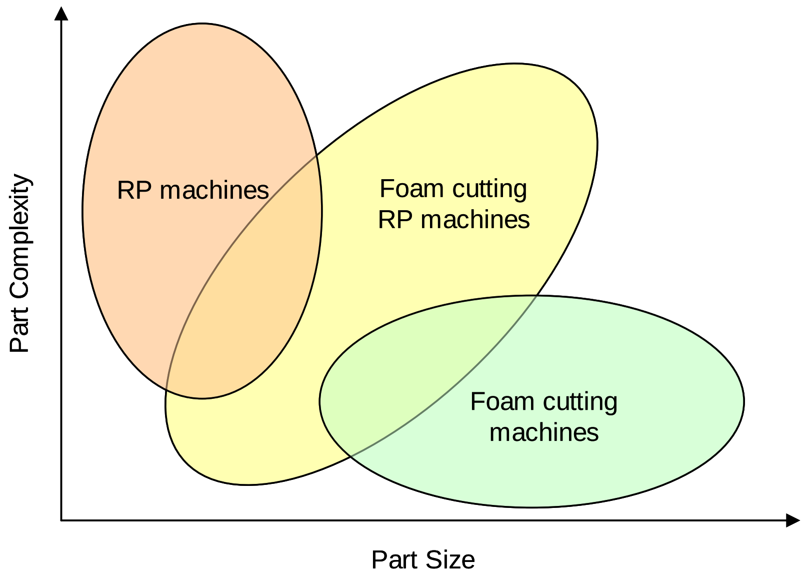

Figure 1. Comparison between conventional RP machines, foam cutting machines and foam cutting RP machines in terms of part complexity and part size.

Foam Cutting RP Machines

Foam cutting RP machines use a range of methods to produce plastic foam objects from CAD data. The criteria used to categorize foam cutting RP systems in this paper are as follows:

- The build material must be a plastic foam such as expanded or extruded polystyrene.
- The tool path and machining strategy should be determined directly from a 3D digital representation of the prototype.
- The system should be able to create complex freeform shapes.
- The system should have a software based user interface for efficient transfer of information between the operator and the RP system.

The following sections describe different foam cutting RP machines developed or currently under development around the world. The most common method of fabrication is layered manufacturing, in which the part is built up by assembling individual layers, however direct sculpting and heat ablation methods also exist.

Freeform Automated Sculpting Technology (FAST)

FAST is a system currently under development within the Department of Mechanical Engineering, University of Canterbury, New Zealand and is the motivation for this paper. The system currently consists of:

- A laser scanner for obtaining digital surface information.

- CAD/CAM software to prepare 3D models and produce cutting paths for the robot.
- A six axis Kuka KR6 industrial robot used to manipulate the cutting tool along the cutting paths.
- An electrically heated cutting tool used to cut the plastic foam.

This system is a form of robotic machining similar to that developed by Tangelder [1]. The main difference is the use of a hot-ribbon as the cutting tool and the method of producing the cutting paths.

The cutting elements used to date are 1/8” × 0.018” Nichrome ribbons which can be pre-bent into any desired profile. In practice a jig is used to form blades with known dimensions. Blades with large profiles are used for roughing while blades with smaller profiles are used for detailed features and surfaces with high curvature. This combination of tools greatly reduces cutting times when compared to standard milling operations. A pneumatic gripper is used for automated tool changes, allowing many different blade profiles to be used in a short time. Hot-wires can also be used for profile cuts and objects with ruled surfaces.

A method for producing the robot control program was developed by Posthuma et al [3, 4] in fulfilment of a Masters degree at the University of Canterbury. The process starts with an IGES model which is loaded into CAM software MasterCAM™. MasterCAM™ is then used to create roughing and finishing tool paths which are processed using a modified generic 5-axis post processor. The tool path data is then exported into an Excel spreadsheet where it is transformed into x y z A B C coordinates which can be read by another proprietary software package called RobotWorks™. RobotWorks™ is used to simulate the robot motion and carry out collision and joint limit checks. RobotWorks™ then converts the tool path data into Kuka language. The control program is then loaded into the robot PC and the program is executed. Figure 2 summarises the FAST Process.

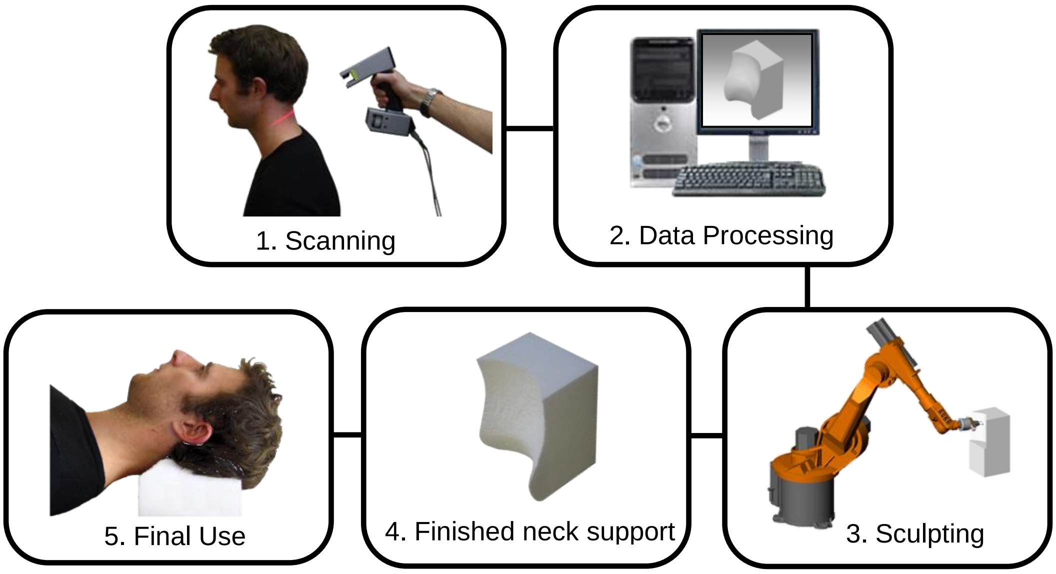

Figure 2. Rapid manufacture of a neck support for radiation therapy using the FAST system.

The FAST system has successfully sculpted a number of arbitrarily chosen freeform surfaces out of EPS and XPS as well as custom fit supports trialled for medical purposes. Figures 3 & 4 show some examples of parts sculpted with the FAST system and relevant CAD models.

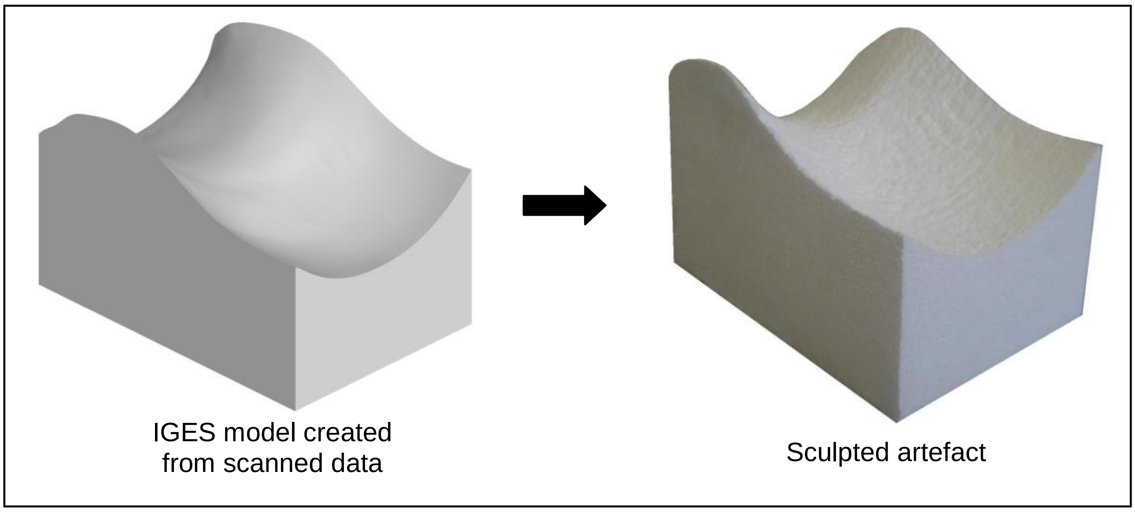

Figure 3. IGES model of neck support created from scanned data and the sculpted part ready for use.

The IGES model shown below was generated by lofting between 5 arbitrary profiles. These profiles were spaced 50mm apart to generate a surface with both concave and convex features. Generating and processing the roughing and finishing tool paths took approximately 40 minutes. The size of the foam blank was 160mm x 190mm x 50mm. The roughing pass was carried out using a 25mm wide square profile Nichrome cutting blade in 1.7 minutes. The finishing pass was carried out using an 8mm wide flat ended Nichrome blade in 2.2 minutes. The total process time required to make the part was 49 minutes.

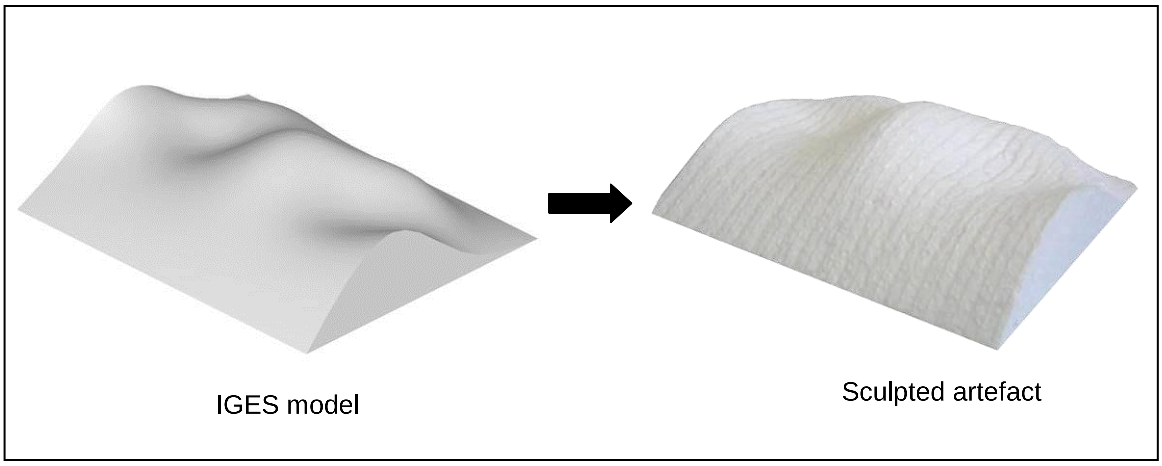

Figure 4. IGES model and part sculpted from EPS showing complex 3D surfaces produced with the FAST system.

Like many of the other systems included in this review research on the FAST project is still ongoing and a number of improvements are envisaged for the future which will dramatically increase the size, speed and accuracy of the system. These are expected to include; streamlined data processing and robot code generation, optimised cutting tool accuracy and tool path strategies and multi-axis workpiece manipulation. A number of papers have been published by Aitchison et al investigation plastic foam cutting mechanics with the purpose of increasing the speed, accuracy and surface texture of cutting plastic foams with hot wires/ribbons [5-8].

True Surface System (Trusurf)

Trusurf is a layered manufacturing method developed by Hope et al at the Department of Mechanical Engineering, University of Queensland, Australia [9]. The system was developed primarily to produce large (> 1 m^3) free-form models out of polystyrene foam. It uses a high-pressure, 5–axis water-jet cutter to cut the model's cross-sections from layers of polystyrene (10, 20 and 30 mm stock sizes). The 5–axis cutter cuts the cross-sections with sloping edges (as opposed to vertical cuts) to eliminate the stepped surface finish common to many LOM systems (see figure 5).

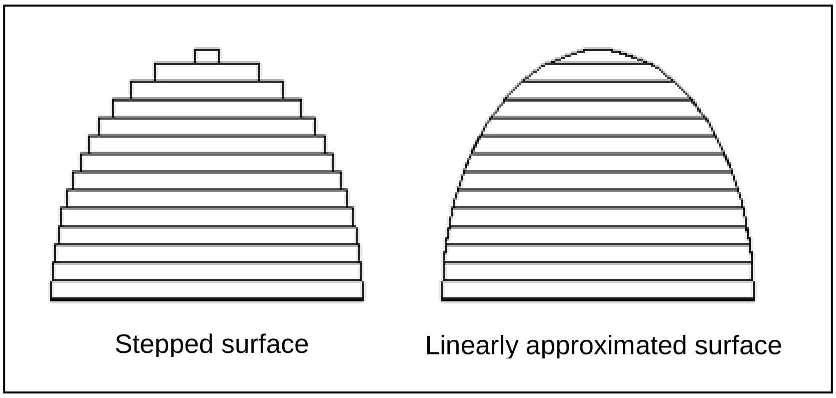

Figure 5. Stepped versus ruled cuts.

Once the thick cross-sections have been cut, they are assembled and bonded by hand to produce the finished model. The advantage of the Trusurf system lies in the fact that it can produce models with relatively thick layers as the linearly approximated sides reduce the number of layers required for a given model.

The Trusurf system generates B-splines directly from CAD models (as opposed to .STL files which are approximations of the CAD model surface) so the splines are exact, hence the name Trusurf.

Figure 6 below shows two objects made with the Trusurf system. Because the water cutter only produces linear approximations the surface finish is not ideal and discontinuities are visible between the layers. The errors can be minimised by decreasing the layer thicknesses although this also increases the build time.

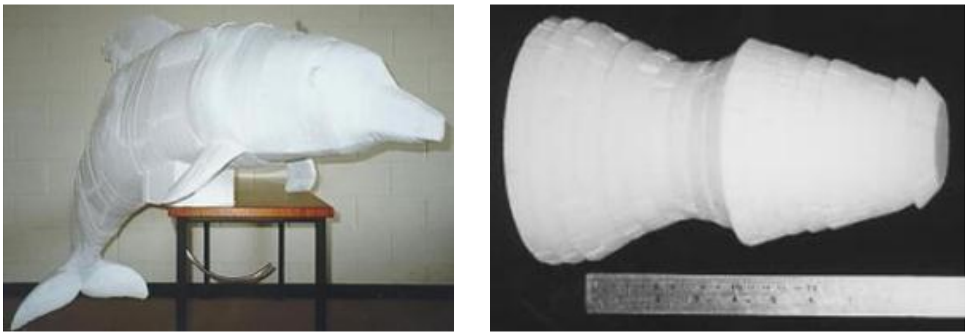

Figure 6. Life size dolphin and revolved shape created with the Trusurf system.

Shapemaker I & II

Shapemaker I and II are layer based manufacturing systems developed by the Manufacturing Processes Laboratory at the University of Utah [10, 11]. Shapemaker I is a simple LOM based system in which section profiles are cut using a plotter and manually stacked using a construction table and registration pins. After each individual layer is stacked, the backing layer is peeled off, thus exposing the adhesive and providing a bonding surface for the next layer. Materials used are paper, plastic foam and vinyl sheet attached to a backing layer. Shapemaker I is now commercialised as JP System 5 Desktop Rapid Prototyping by Schroff Development Corporation, and is used primarily as an education tool introducing university students to RP technologies. Figure 7 shows the JP System 5 and some paper models made from it.

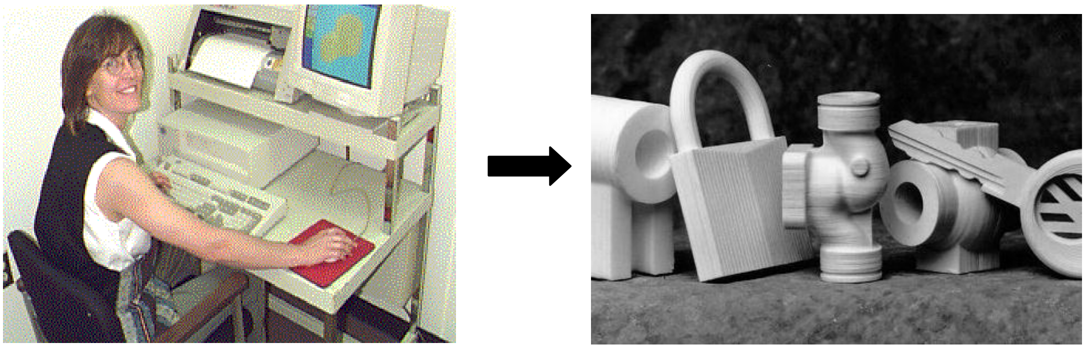

Figure 7. The JP-5 system and parts.

Shapemaker II (SMII) differs from its predecessor in that it is aimed at producing large (>1m³) full scale prototypes from polystyrene foam. The foam is cut using hot-wires which are attached to two plotting heads. The plotting heads move independently to create linear approximations of each section surface similar to the Trusurf system (in fact both were developed around the same time in 1996-1997).
Suggested applications of this technology include cores for large aerospace structures which would then be finished and covered in a composite material. SMII was successfully used to create a number of example objects including a wind turbine blade and a tail rudder. The turbine blade measured 1.2m x 0.18m x 2.1m and the fabrication time was approximately 11 hours excluding CAD modelling.

There are a number of limitations associated with SMII including:

- The cutting wire can not be tilted more than 45° limiting the accuracy for layers that require a larger slope.
- Models that have features less than 1" can not be reproducing using the required 1" thick foam.
- The individual layers have to be assembled by hand using registration holes and pins which could be cumbersome and time consuming.

ModelAngelo

This system was developed by the Department of Mechanical Engineering at the American University of Beirut in Lebanon [12]. It consists of unique foam cutting RP equipment and software collectively called "ModelAngelo". ModelAngelo utilises a combination of linear and rotational axis to cut foam with a heated cutting tool.

The foam blank is held in a lathe like fixture the motion of which is synchronised with the cutting tool. Figure 8 shows the cutting tool, a part being sculpted and the available degrees of freedom (for clarity the foam holding fixtures have been emitted). The 'γ' axis is used to rotate the foam part through a possible 90° to allow the ends to be sculpted, however one end of the part must remain flat so it can be held with clamping pins.

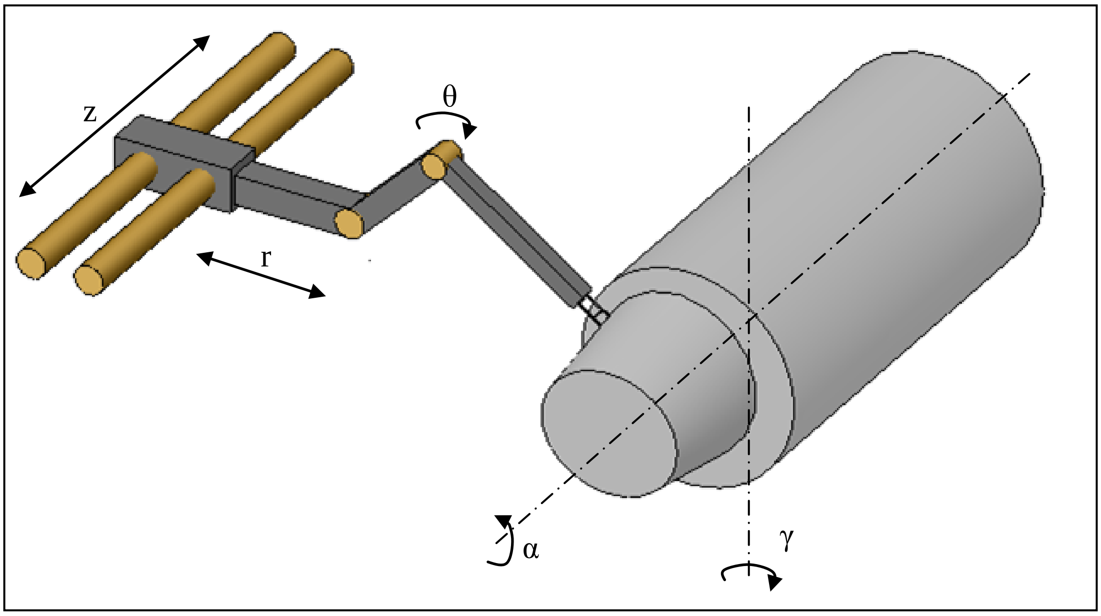

Figure 8. ModelAngelo apparatus.

The tool consists of two short stainless steel wires, which are electrically heated above the melting point of the plastic foam used. The cutting tool is schematically illustrated in figure 9. The outer loop is used to cut the foam while the inner loop is used to manage the swarf. The inner loop is hotter than the outer loop because it does not contact the foam. This causes the foam nearest the inner loop to melt and contract curling the swarf upward. If the swarf is not removed from the cut surface it risks sticking back to the model and would then need to be removed by hand.

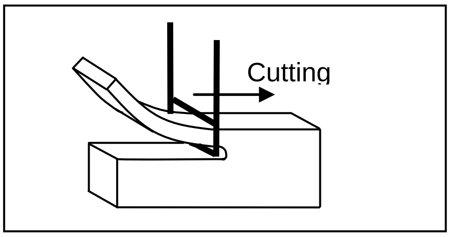

Figure 9. Electrically heated cutting tool.

The authors suggest a number of applications such as art sculpting, prototypes for fit and form evaluation, and casting processes for biomedical and engineering applications. Several finished products sculpted by ModelAngelo are shown in figure 10.

Figure 10. Parts sculpted using ModelAngelo.

Freeform Thick Layered Object Manufacturing (FF-TLOM)

This process is currently under development within the Faculty of Design, Deft University of Technology in the Netherlands [2, 13-19]. The proposed system builds models from XPS foam using a layered manufacturing method similar to the Trusurf system. FF-TLOM utilises an electrically heated Nichrome blade to cut section profiles which are then assembled manually.

The unique feature of this process is the flexible cutting tool which changes shape to provide high order approximations of the desired surface as shown in figure 11. By using higher order approximations it is possible to achieve far more accurate models while using thicker layers. The cutting tool is a flexible Nichrome ribbon which is held between two supports. The supports are accurately rotated with stepper motors to change the shape of the ribbon to match the surface geometry. The ribbon shape for any given support orientation is calculated using minimum strain energy theory.

A prototype of the flexible cutting tool is shown in figure 12, reproduced from [20]. The device has three degrees of freedom, the linear distance between the connection points and the rotational orientation of the supports. The length of the ribbon between the connection points is constant. A six axis Manutec R15 industrial robot was used to manipulate the foam slab while the tool remained in a fixed position this is because the prototype tool is rather large and heavy.

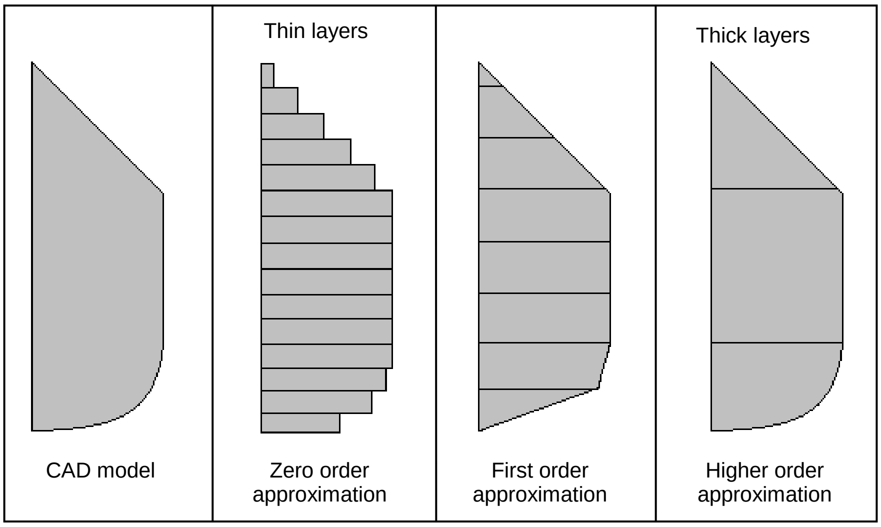

Figure 11. Effects of different order surface approximations.

The finite width of the blade provides limitations to the maximum rate at which curvature can change. While the ribbon is most suited to tangential cutting, rapidly changing surface curvature will require the ribbon to move with a transverse component. Any transverse movement of the ribbon will greatly reduce the maximum cutting speed of the ribbon and may negatively impact surface finish. For this reason FF-TLOM is most suited for revolved shapes or objects with slow changes in curvature.

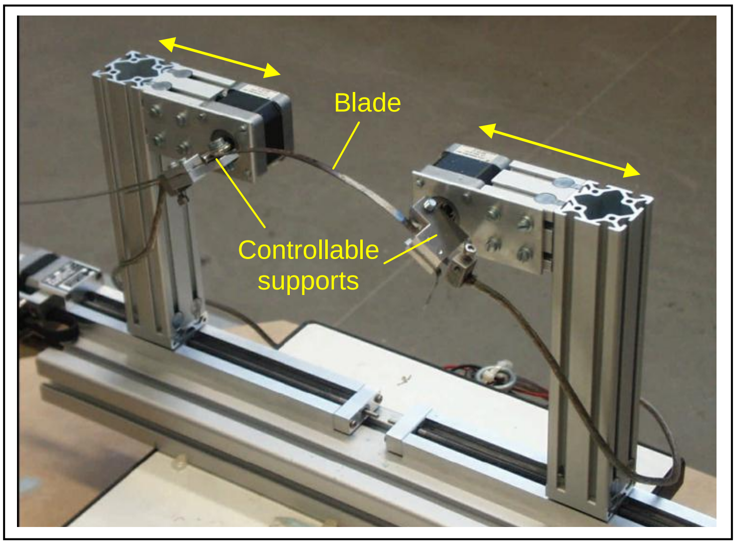

Figure 12. Prototype FF-TLOM cutting tool.

The prototype FF-TLOM system has been used to produce a number of multilayered examples with constant layer thicknesses. Figure 13 shows a Styrofoam sphere and a surface with convex and concave curves cut using FF-TLOM.

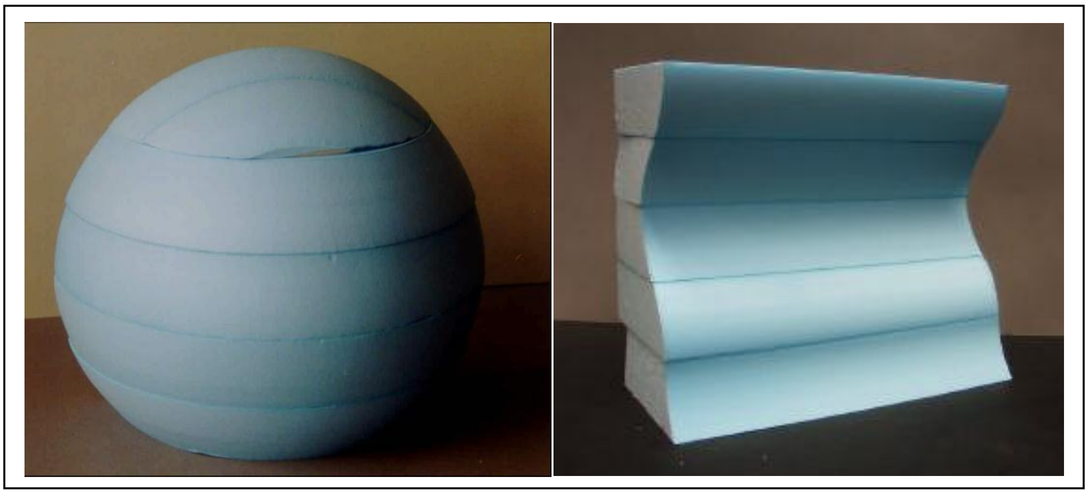

Figure 13. Examples of FF-TLOM multilayered stacked assemblies.

Variable Lamination Manufacturing (VLM)

This system is currently being developed by Ahn et al at the Department of Mechanical Engineering, Korean Advanced Institute of Science and Technology (KAIST) in Taejon, Korea for which a number of papers have been published [21-25]. The published work details a number of investigations into hot-wire plastic foam cutting mechanics based on both experimental and theoretical work.

The VLM system uses a hot-wire to cut out 'thick' EPS cross-sections, which are consequently bonded together to form the finished object. The hotwire cutter is controlled within a four axis machine to cut sections with sloped edges similar to Shapemaker II.

The main advantages of VLM over the Shapemaker II system is the material handling process and the VLM can use foam layers of varying thicknesses. The process consists of the following three main steps:

1. *Material feeding and storing:* EPS sheets (3.7-10 mm) are stored in a large roll and fed into the cutting area via several sets of rollers. Rollers act to both apply the bonding agent to the underside of the layer and to control the thickness of the layer by exerting pressure. Controlled suction part holders then hold the dimensionally accurate stock layer in place from above.
2. *Shape generation:* The next step involves cutting out the required shapes.

   As can be seen from figure 14, the layers consist of several individual pieces or unit shape parts (USP), which are assembled together like a jigsaw. The joining edges in the feeding direction are cut with opposite 5º angles and are staggered like brickwork in the transverse direction to improve the strength of the finished object.

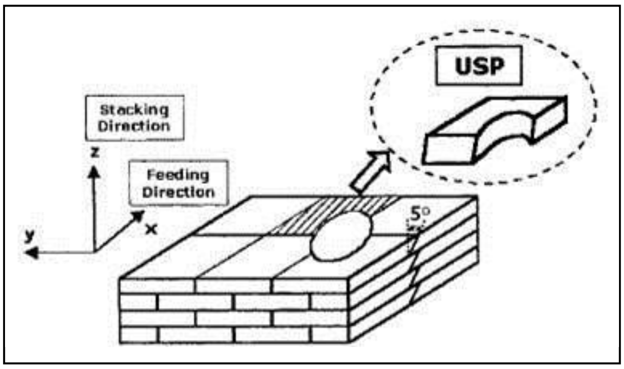

Figure 14 - Multi-piece layer concept

3. *Stacking and bonding:* Once the individual pieces have been cut out, they are stacked on a controllable x-y table. Once a layer has been assembled the table is moved below a pressing mechanism which is used to press the bonded layers in order to enhance the bonded strength of the finished model.

The un-cut material is then cut off and removed by gravity and the steps are repeated until the object is fully built. Figure 15 shows an example of a VLM produced part and a reference part, built with laminated object manufacturing (LOM) technology, used to evaluate the process.

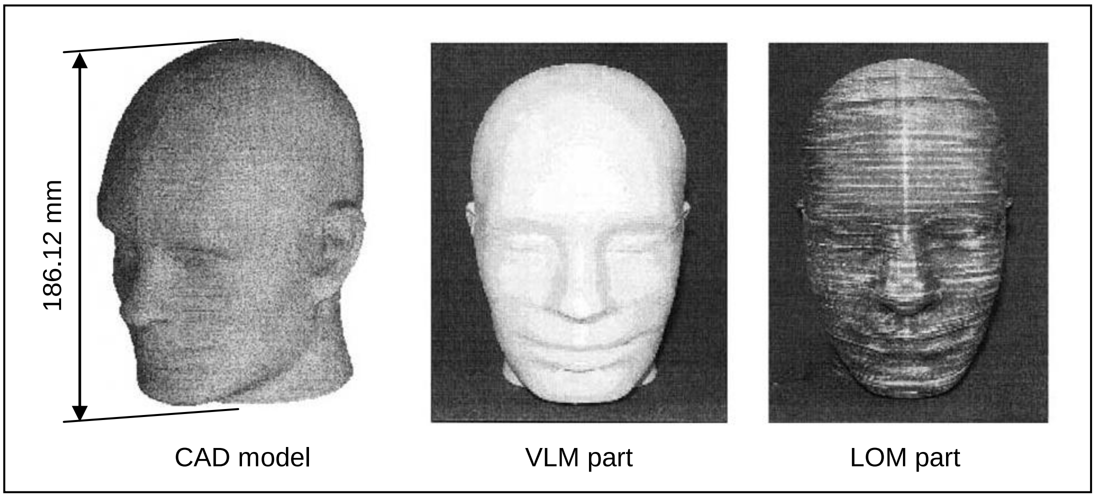

Figure 15. CAD representation of a human head and comparison of the fabricated parts.

The authors conducted a comparison between their system and a conventional LOM RP system using the human head shape. The following results, reproduced from [22], are shown in table 1 below.

Table 1. Comparison between VLM and LOM.

Process	Building Time (min)				Building Cost (USD)	Dimensional Accuracy %	
	Set-up	Building	Decubing	Total		In Plane (averaged)	Z-dir
LOM	80	2125	120	2325	720	0.7	1.8
VLM	-	35	5	40	8	0.8	1.1

The VLM process has been commercialised by Menix Engineering Co., Ltd under the Rapid Shaper product line. The VLM 300 produces parts using 3.7 mm thick A4 sheets of EPS while the VLM 400 uses 3.7, 5 and 10 mm thick A3 EPS sheets.

Figure 16. The Rapid Shaper range from Menix Engineering Co. Ltd based on technology developed by the Korea Advanced Institute of Science and Technology.

Rapid Heat Ablation (RHA)

The researchers at KAIST (Kim et al) have also published a number of papers describing a novel hot tool which is used to ablate plastic foams [26-28]. The process which the authors call rapid heat ablation (RHA), involves the use of a specially designed hot tool shaped similarly to a ball-end mill to create new surfaces by ablating foam. The process has been used for creating fine detail on VLM parts which can not be created with straight hot-wires. It can also be usedas a stand alone manufacturing method. Figure 17 provides a schematic of the tool.

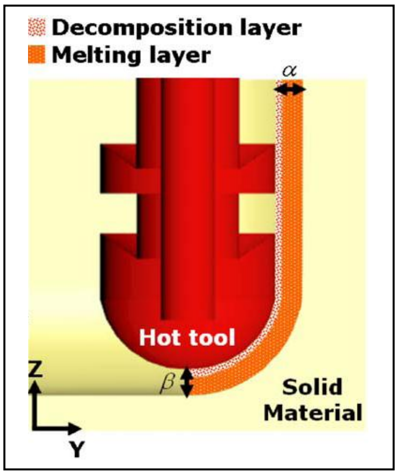

Figure 17. Schematic of RHA process.

The geometry of the RHA tool allows the tool path to be generated using conventional CAM software for a ball-end mill. Also because the entire length of the tool can be used to ‘machine’ the material it is possible to carry out the finishing cuts without the need for prior material removal. In a test carried out by the authors a large part was shaped in 55 minutes compared to 430 minutes by a commercial milling machine. This demonstrates a significant advantage can be gained by using RHA over conventional machining when shaping plastic foams. Other advantages include:

- Little to no swarf.
- Better surface finish and accuracy (R_a values 1/10th that of equivalent machined parts).
- Reduced machine time.

Figure 18 shows the RHA tool in action and a part produced by it.

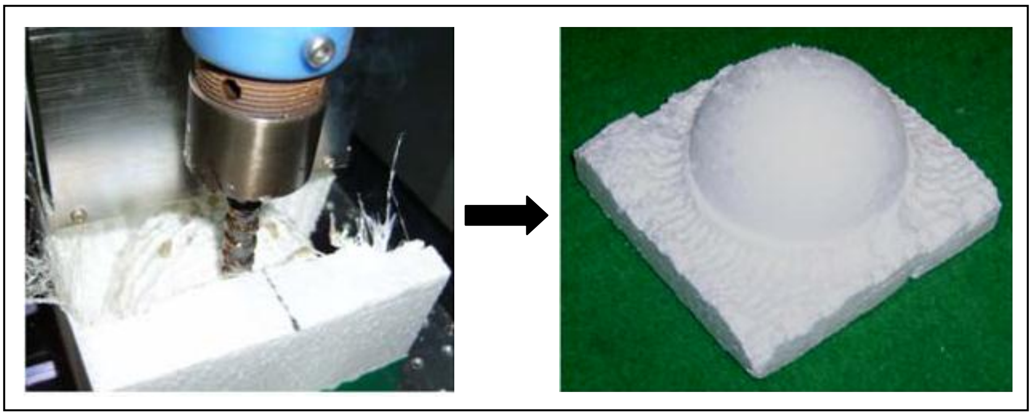

Figure 18. RHA tool and part.

Michelangelo

Michelangelo is an eight axis foam sculpting system developed by Zhu et al from the Tokyo Institute of Technology [29, 30]. It is composed of a six axis Motoman industrial robot and a two axis worktable. It carves simplified EPS models that consist of large flat faces with a hot-wire cutting tool.

A unique mesh simplification algorithm was created to reduce the complexity of the model by reducing the number of facets used to define the surface. Figure 19 shows an example of a model simplified using the mesh simplification algorithm. Once the mesh is simplified to the desired resolution a tool path generation algorithm is used to generate the tool path and a virtual reality simulation of the sculpting is run to ensure all faces can be cut without robot/work piece interference.

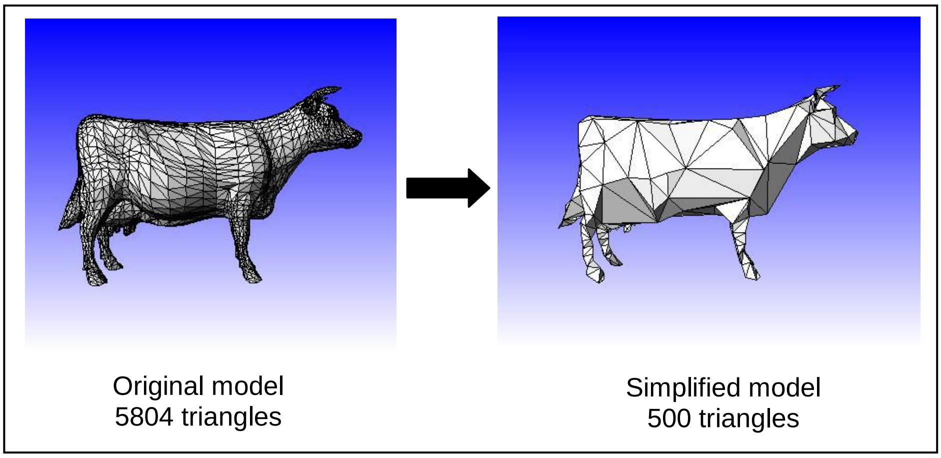

Figure 19. Example of mesh simplification.

By utilising a work table with an extra two degrees of freedom Michelangelo can sculpt relatively large models with a small machine as reaching behind the part is not an issue. Also because a hot-wire is used as the cutting tool the cutting process is much faster than conventional machining practices. Figure 20 shows the robot and worktable setup and a test part (shoe) produced by it.

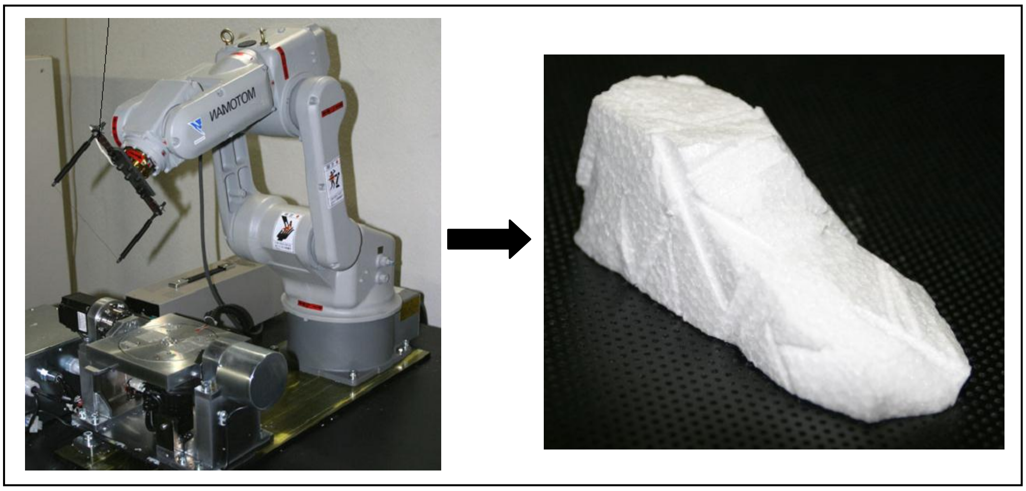

Figure 20. 8 axis setup and a test part (shoe) produced by it.

In summary Michelangelo is an effective sculpting system for the generation of rough objects. The unique mesh simplification algorithm and 8 axis robot system means large objects can be sculpted quickly and to a user specified accuracy. However, a number of disadvantages exist when applying this technology for more accurate models. The system cannot sculpt features with fine detail, double concave surfaces or pockets because of the straight hot-wire cutting tool.

Stratoconcept HW Series

The Stratoconcept HW series was developed through a collaborative effort between Croma, a French based manufacturer of hot-wire foam cutting systems, and Cirtes, the European centre of Rapid Prototyping and Tooling. This system uses a layer based manufacturing method to manufacture high volume parts at high speed. The foam parts include both interior and exterior details which allows for lightweight full scale prototypes [31].

Croma adapted a cutting machine for the rapid manufacturing of foam products so that it could implement Cirtes' software for layer based design and construction. Cirtes' adapted its patented software based Stratoconception® rapid prototyping and tooling process to be compatible with Croma's machine technology. The combined process operates as follows:

1. A CAD model is imported in .STL or DXF 3DFace format and is decomposes into 3D layers.
2. The system then automatically calculates the tool path for the 4 axis hot-wire cutter and the 'strata' are cut out. The surface of the layers are linear approximations similar to that of the VLM process.
3. The final prototype is then manually assembled by stacking the layers and aligning the inserts.

Figure 21 demonstrates the Stratoconception® process associated with the Stratoconcept HWC and shows an example of an assembled full scale boat hull.

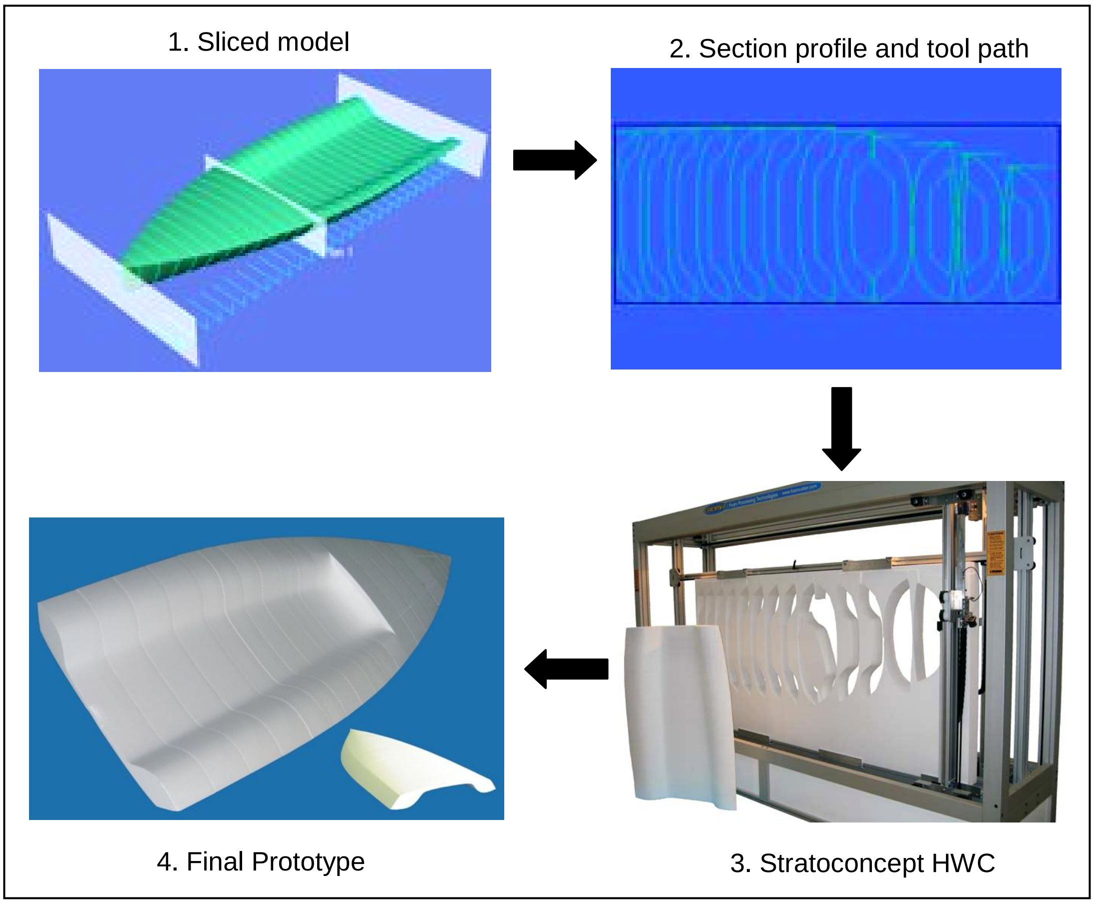

Figure 21. Example of the Stratoconception® process for the Stratoconcept HWC.

The Stratoconcept HWC series RP systems are ideally suited for manufacturing full scale large prototypes from polystyrene foams. The largest machine in the series is capable of producing parts with cross sections up to 5 m wide and 2.5 m tall with an infinite length. The prototypes can be made hollow for lightweight manufacturing. Inserts are used to align and strengthen the prototypes to withstand handling. Disadvantages of the system include:

- The final prototype must be assembled manually and glued.
- Detail in the z direction must be larger than the standard thickness of the foam stock.
- The surface is a linear approximation of the input model meaning some post processing may be required.
- Some ‘expert’ knowledge is required in placing the inserts and choosing the ‘strata’ orientation to maximise the strength of the prototype.

Summary of Foam cutting RP Machines

Nine different foam cutting RP machines were reviewed in order to provide a state-of-the-art overview of recent technological advances in large scale foam cutting rapid prototyping technologies. The majority of modern foam cutting RP systems use layered manufacturing to progressively build models from layers cut with hot-wires. Other manufacturing methods include water jet cutting, hot-ribbon cutting and rapid heat ablation. A small number of systems have been commercialised including the VLM Rapid Shaper series by Menix Engineering Co. Ltd, and the Stratoconcept HW series by Croma.

Figure 22 summarizes the difference in potential model size and model complexity between the nine reviewed systems. The Stratoconcept HWC system has the largest build volume with its largest machine capable of producing parts with a cross-section of up to $6m^2$ [32]. The VLM series machines are capable of producing the most complex and accurate parts with dimensional errors up to 1.1% in the build direction [22].

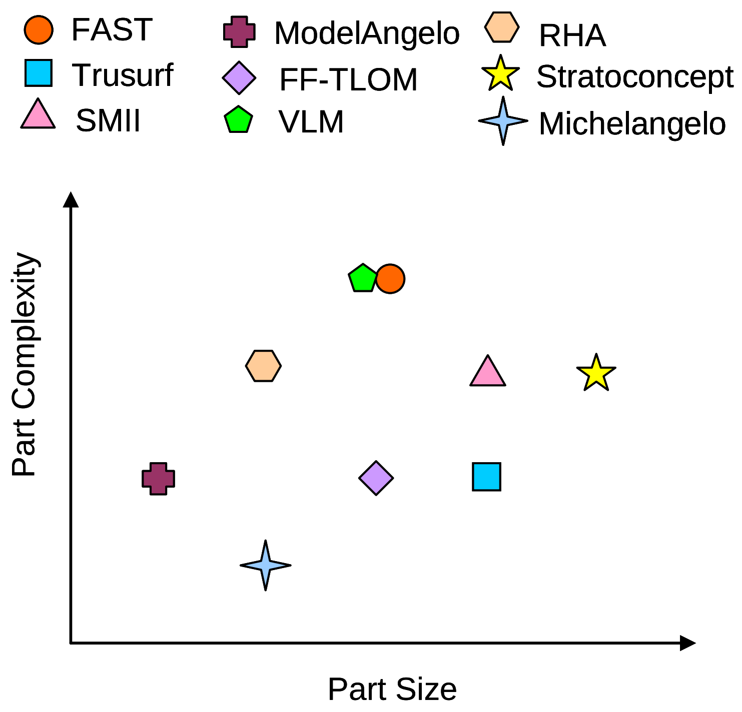

Figure 22. Qualitative comparison of complexity and size of parts made with nine foam cutting RP machines.

Table 2 summarizes the different build strategies, cutting tools and relative build times of the nine reviewed systems. It should be noted that the qualitative descriptions given are relative to the foam cutting RP machines reviewed and not to RP processes in general and only take into account the information presented in the referenced papers. Also the build speed does not include assembly time for layer based methods.

Table 2. Comparison of foam cutting RP machines.

System	Property		
	Cutting Tool	Build Strategy	Build Speed
FAST	Hot-ribbon	Direct sculpting	0
Trusurf	Water jet	Layer based	0
SM II	Hot-wire	Layer based	0
ModelAngelo	Hot-wire	Direct sculpting	- -
FF-TLOM	Hot-ribbon	Layer based	DATUM
VLM	Hot-wire	Layer based	+
RHA	Hot tool	Direct sculpting	-
Stratoconcept	Hot-wire	Layer based	0
Michelangelo	Hot-wire	Direct sculpting	+ +

Key: 0 = Same as Datum
- = Less than Datum
+ = Greater than Datum

Recommendations and Conclusions

All of the reviewed systems have proven themselves to be technically feasible; however few have been developed to the commercial stage. This is partly due to economic considerations and partly because many of the systems are still in the developmental phase. To-date the most successful build strategy is to cut and assemble individual layers, however with current advances in robotic machining this may change. Direct sculpting with robots offers increased complexity and reduced post-assembly of layers.

A number of unique ideas found in this review were deemed by the authors to be of special importance to the development of future foam cutting RP systems and are therefore listed here. These include:

- For systems that use direct sculpting, the use of a two axis turntable to tilt and rotate the work piece allows much greater reach-ability of the robot. This would greatly increase the potential build volume of the system.
- The innovative swarf management technique developed by Hamade et al with ModelAngelo. This would prevent swarf produced by cutting with hot-wires/hot-ribbons from rejoining the work piece.
- The layer based manufacturing method adopted by most of the systems could also be used to increase the size of parts built using the direct sculpting build strategy.
- The direct sculpting method could be applied to individual layers in the layer based systems to avoid the need for surface approximations.
- Many of the systems exhibited a high level of automation. In particular the automatic generation of tool paths directly from the CAD model was common among the systems. The automation of data creation (tool paths, control programs etc.) is very important if the fast, reliable and automated production of sculpted objects is to be realised.

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