Curved Layer Fused Deposition Modeling

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Abstract

Current Fused Deposition Modeling (FDM) technologies deposit material as flat layers. The result is a "stair-case" effect on non-vertical or horizontal surfaces, and compromised part strength because of weakness between the laminations. This paper describes a FDM method through which layers of build material are deposited as curved layers following the shape of the part, thus removing the stair-case effect and creating parts that have an even strength distribution over their entire surface. Support material is first deposited as conventional flat layers, and build material is then deposited over the support structure following the curves of the part. The paper discusses a proof of concept of the system, the algorithms used to generate the curve paths for the deposition head, and examines the challenges and possibilities of this technology, including the capability of including composite materials.

Keywords: Curved Layer Fused Deposition Modeling, Rapid Prototyping

1.0 Introduction

Conventional Rapid Prototyping (RP) is an additive fabrication technology which creates complex 3-dimensional prototypes in short times: a 3D computer model is cut into thin 2D slices; these are transferred to a machine which stacks the thin flat layers sequentially to recreate a physical version of the Computer Aided Design (CAD) model [1].

The latest generation of rapid prototyping technologies, such as stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM) and 3D printing now allow physical prototypes to be produced within hours rather than days. Fused metal deposition systems and processes such as Laser Engineered Net Shaping (LENS) and Electron Beam Melting offer great potential not only for rapid manufacture of end-use products but Functionally Graded Materials (FGM) in high temperature metals including titanium alloys [2].

The rapid prototyping process begins by taking a 3D computer generated file and slicing it into thin slices (commonly ranging from 0.01mm to 0.25mm per slice depending on the technology used). The rapid prototyping machine then builds the model one slice at a time, with each subsequent slice being built directly on the previous one. The technologies differ mainly in terms of the materials they use to build the part, and the process used for creating each slice of the model.

Some of the earlier rapid prototyping processes, which were only able to make plastic-like parts, are now producing metal parts in aluminium, titanium, and even stainless steel [3]. Not only is the choice of materials and processes increasing, but the last few years have seen a significant reduction in the cost of these technologies.

The combination of Computer Aided Design (CAD) and rapid prototyping technologies mean that it is now possible to construct highly advanced virtual prototypes, and then quickly working physical prototypes almost as fast as they are designed, thus allowing more iterations of a design within a shorter timeframe. This, in turn, potentially allows for products that are even better suited to their intended users in even shorter times [4].

Fused Deposition Modeling (FDM), the core technology used in this particular project, works by extruding a thin ribbon of plastic as the nozzle of the machine traces each slice. It is, in effect, not dissimilar to an inkjet printer but prints in plastic instead of ink [3].

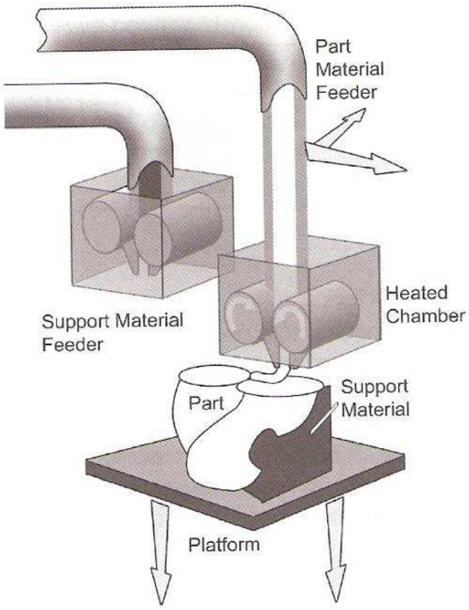

Figure 1: The FDM Process Used by the Dimension Printer

The parts currently produced by FDM systems are reasonably strong plastic components that are well suited to basic functional testing and can easily be sanded and painted to reproduce the aesthetics of the production product thus also making them useful for consumer testing.

Though each RP technology has advantages and disadvantages over the others, one of the weaknesses common to all current flat-layer RP technologies is a poor surface finishes caused by the 'stair-case' effect on curved surfaces and a lamination weaknesses in a direction perpendicular to the layer direction (Fig. 2). If smooth surfaces are required for the component, the stair-case effect can require sometimes substantial post-processing of the part (sanding and polishing) in order to produce smooth surfaces.

Application of flat layer RP technology in medical endeavors, for example, encompasses several areas including orthopaedics [5, 6], dentistry [7], and maxillofacial surgery [8]. However, to be truly useful, the technology needs further development to be able to work with metallic or biosorbable materials. An example of a good possible application in which curved-layer RP would have advantages would be in cranial reconstruction [9, 10, 11] where the current poor finish and weaknesses in flat-layer RP technologies render them unsuitable for direct manufacture of cranial implants. Curved layer technology, however, may allow the direct production of useable cranial implants. This would greatly reduce the waiting time in cranial surgery between the initial surgery to remove skull fragments and the following surgeries to implant a replacement part (Fig. 3).

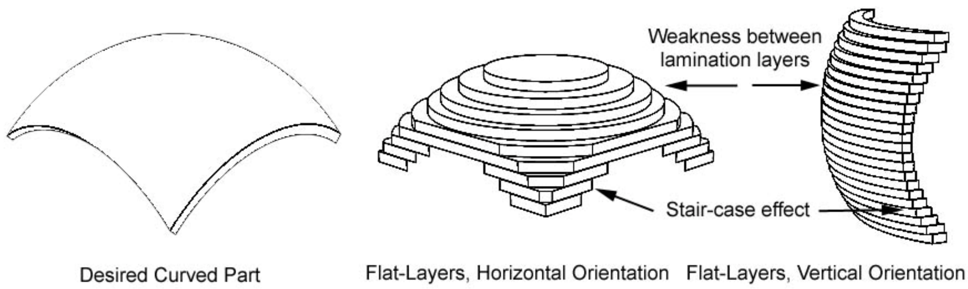

Figure 2. The stair-case effect and lamination weakness problems caused by conventional flat-layer rapid prototyping.

2.0 Curved Layer Fused Deposition Modeling

The objective of this project was to build a machine capable of constructing a part by depositing the layers of material as curved layers instead of the current flat layers. This new process could be named Curved-Layer Fused Deposition Modeling (CLFDM).

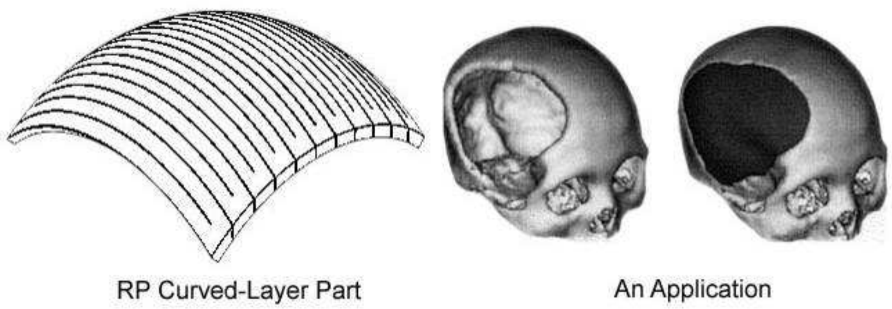

Figure 3. A curved-layer part and a potential application for the technology.

The concept behind the technology is as follows: A substructure of 'support material' to the curved part is first created through existing flat-layer methods using a soluble support material. This support structure forms the base onto which the curved layers of product material can then be deposited by having the deposition head precisely follow the contour of the part (Fig. 4).

The effect of these curved layers would be to both eliminate the staircase effect altogether, as well as removing the inherent lamination weakness in the direction of the layers.

The bulk of the research being carried out at different universities has been related to investigating alternative materials for FDM (and other RP methods) and working with a variety of materials including ceramics and metals [12], high performance thermoplastic composites [13] and metal/polymer composites [14]. While special FDM systems have been designed for experimental deposition of different types of materials with different techniques and much work has been done on the analysis of the mechanism of deposition [15, 16], very little research has been done on depositing material as curved layer. The literature on RP reveals one research project in which the LOM (Laminated Object Manufacturing) process was used to create curved layers [17] at the University of Dayton in the USA but the results were limited by the ability to evenly stretch a material over a curved mandrel and the very small range materials that could be used in this process.

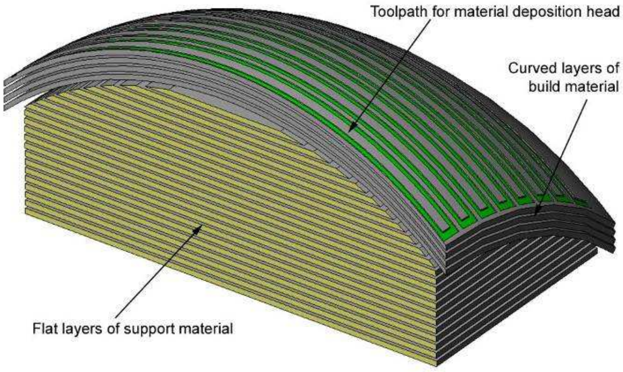

Figure 4. Support material deposited as flat layers to form structure onto which build material can then be deposited as curved layers.

The specific engineering challenge in this project was enabling the mechatronic integration of several contributory technologies including 4 axis CNC technology, FDM deposition, and CAD software to work in a novel way.

The paper first briefly examines the mechanical and systems design of the RP machine, and then looks at the algorithms developed for the model slicing, and for the control of the hardware. It then describes some challenges and future work that needs to be done on the system.

The rapid prototyping system is being built as part of a student Masters project and is also being used to research several other new methods for Fused Deposition Modeling.

3.0 System Overview

The curved layer rapid prototyping machine was built by modifying an existing Fab@Home desktop RP machine (Fig. 5). The Fab@Home machine consists of an X-Y axis gantry type system that moves a dispensing head along a pre-programmed path. This constitutes a relatively low-cost apparatus that is ideal for doing development work on rapid prototyping technologies, or for other research work.

The platform provides a Z axis which, on the standard machine, moves a build platform down by a unit of measure after each X-Y slice is completed.

The standard dispensing head that is included with the machine allows for the dispensing of material from a syringe. The motor control system consists of 4 stepper motors, a Xylotec XS-3525/8S-4 Stepper Motor Driver Board, and an Olimex LPC-H2148 Microcontroller Board.
On the mechanical side of the design, a new deposition head was designed and built with an extruding unit that allows a filament of molten plastic to be extruded. This was to allow for the eventual production of more durable parts than that allowed by the materials that could be deposited through the syringe system.

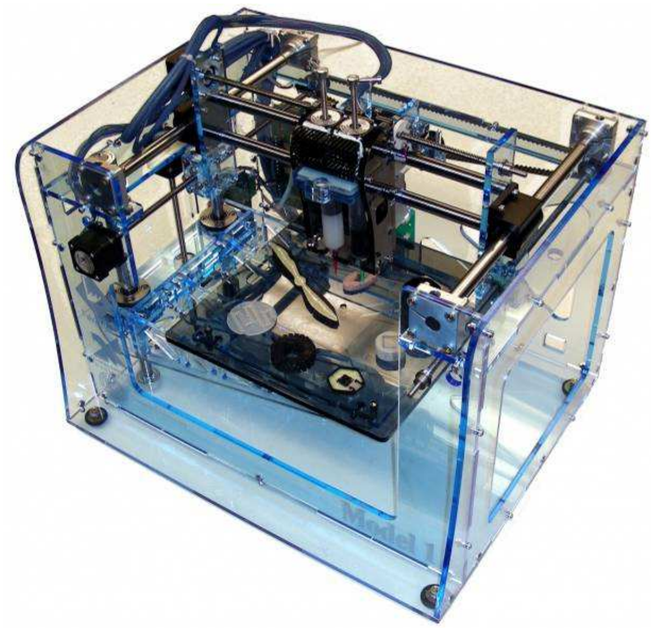

Figure 5. Fab@Home desktop RP machine.

The standard machine comes with a single syringe deposition head, thus only allowing the deposition of one type of material at a time. To further increase the number of deposition material options, the single syringe deposition head was replaced with a two-syringe head that allowed the system to deposit both the support material and the build material without needing to stop the build operation in order to change from the support material to the build material. The addition of an extra syringe meant the addition of an extra syringe drive motor which, in turn, meant the addition of an extra motor control board. The modular design of the system, however, meant that the addition of extra motors or an extra control board was not a great problem.

A number of materials were initially tested for the proof of concept stage of the project. These materials included silicone, icing sugar, RTV sealant, light curing epoxy and standard two pot epoxy all of which were able to produce parts, though of varying quality. The material finally selected was Fab-Epoxy, a special epoxy formulated for the machine to be thixotropic, so it does not flow after extrusion.

The standard Fab@home machine is designed to receive a set of tool-path commands contained in a standard text file. The tool-paths consist of a series of x-y coordinates that define how the deposition head moves for each flat slice. At the end of each slice program a z control command is sent which moves the build platform down by one slice height increment. The program then continues with the next slice of the model.

The PC software provided with the machine takes an stl file, the de-facto standard file format for RP applications, of the 3D part to be produced and slices it into flat slices. From these slices the software derives the x-y coordinates for the tool path. The text file containing the comma-separated-values (CSV) of the x-y coordinates are then sent to the Olimex LPC-H2148 microcontroller over USB.

This allowed for an easy method of creating curved tool-paths simply by including the z coordinate with every set of x-y coordinates in a set of CSV data, and allowed the deposition head to be dynamically controlled in any of the 3 axis much like a conventional 3 axis CNC machine.

New software was written, in Matlab, that accepted an stl file of a curved part. STL is the accepted defacto international standard for rapid prototyping machines, and it was therefore important that the software for this system be able to directly import files in this format.

The software used a simple algorithm to split the part up into the real component and its support material structure by examining the bottom most surface of the part. Any section of that surface that was not at the zero point of the part was considered to have support material below it.

The support material component of the part was then put through a separate algorithm that sliced it up into flat layers spaced, in the case of the Fab@Home machine, at 1mm spacings. This resolution was a variable that could be reduced or increased as needed. The algorithm started at the bottom surface and created a new flat plane above the first surfaces spaced away form the first plane by whatever thickness variable had been set.

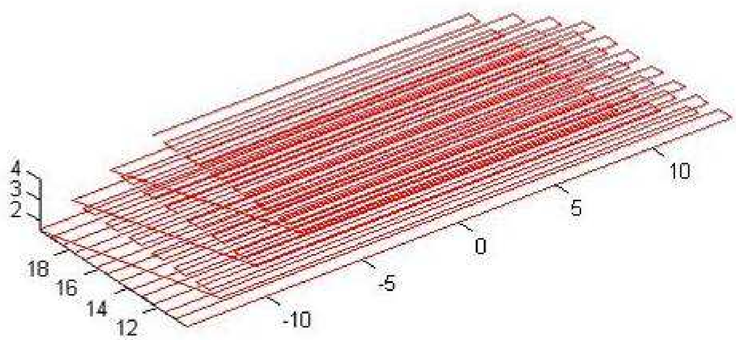

Figure 6. Matlab Program for flat support material structure.

Points were located wherever this plane intersected the bottom surface of the curved part, and these points were used as the extremities of the new flat layer that was to be created. The process was then repeated by adding a new plane above the previous one, until no new intersecting points could be added.

A separate algorithm was then written to take the real component part of the stl file and split it up into curved layers, also spaced 1mm apart. By treating the bottom surface of the model as an infinitely thin geometry, x, y and z, coordinates could simply measured from the model slice and used to approximate the 3D geometry for that slice. A variable was introduced into the algorithm that determined how close any x, y and z sets of coordinates were to each other. This, in effect, determined the resolution of the tool-path. In the initial trials, this resolution, like the z resolution, was set to 1mm.

From the stl input data, the Cartesian coordinate values of each point were individually recorded in the form of matrices. A matrix extension procedure was used, which made the boundary conditions of the surface lift offset available. The extension direction used was perpendicular to the filament deposition direction, and along with main deposition tool path direction. After the extension procedure, a new extended M by (N+2) matrix was obtained which compared to the original M by N matrix, as shown below.

Original Matrix:

$$\begin{bmatrix} P_{1,1} & & P_{1,end} \\ \vdots & \cdots & \vdots \\ P_{end,1} & & P_{end,end} \end{bmatrix}$$

Extended Matrix:

$$\begin{bmatrix} P_{1,exl} & P_{1,1} & & P_{1,end} & P_{1,exr} \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ P_{end,exl} & P_{end,1} & & P_{end,end} & P_{end,exr} \end{bmatrix}$$

Then, A Four Vector Cross Product (FVCP) algorithm was used to process the way in which each subsequent layer was offset form the previous surface. The FVCP algorithm used four different vectors to solve the new locations of every single point in the offset layers. The four vectors were formed by a point (P0) (which is the point being offset), two adjacent points (P1, P2) in the X axis direction and two presumption points (P3, P4) as shown in Fig. 8 below.

P1 and P2 were used to calculate the positions of the new lifting points, whereas P3 and P4 were used to define that the new offset point was on the plane which P0, P2 and P3 were on. This, in effect, determined the direction normal to the surface being worked on.

The four vectors formed by the equations are shown below.

$$\overrightarrow{P_1P0} = \overrightarrow{P_1} - \overrightarrow{P0}$$

Then, the direction of the new vector was required. As the new vector is a combination of four different vectors, a further calculating procedure was needed.

$$\overline{P5P0_k} = d_k \times Thickness_k \times Weigh_k$$

Where $Thickness_k \times Weigh_k = Thickness$, d_k represented the offset direction.

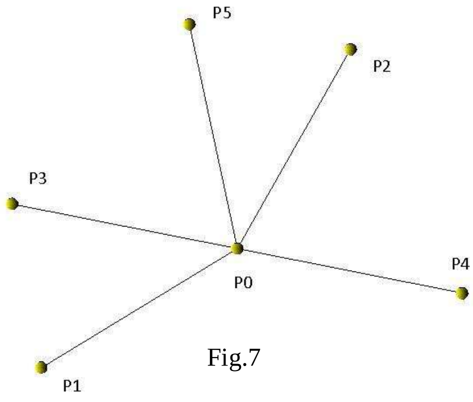

Fig.7

After combining these vectors, the final offset vector was obtained. The offset position of new point was given by the equation below:

$$\overrightarrow{P5} = \overrightarrow{P1} + \overrightarrow{P5P1}$$

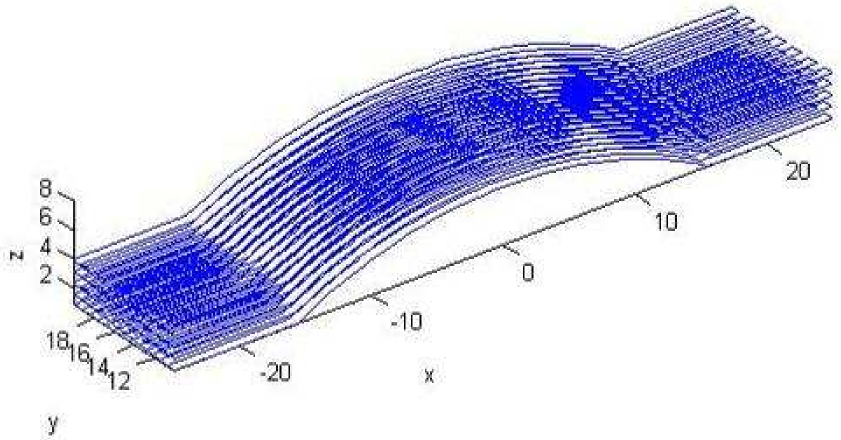

Figure 8. Matlab Program for curved build material structure.

Using the same procedure, every point on the surface was calculated and the offset surface was generated from these points.

A fourth algorithm was then used to combine the results of the second and third algorithm into a single text file containing first the tool-path for the support material, and then that for the build material. The order of the combined file was critical, as the support material needed to be printed in flat layers before the build material was to be deposited as curved layers.

The text file was then sent to the machine's microcontroller and used to control the appropriate x, y or z stepper motor to build first the support material structure, and then the real component on top of the support structure. The extrusion head, in the initial tests, was kept extruding at a constant rate.

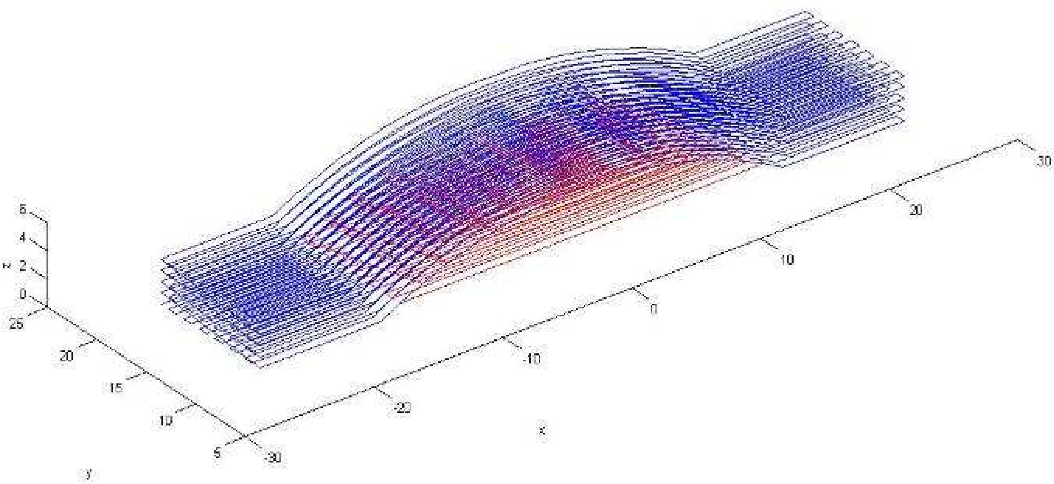

Figure 9. Matlab Program for combined support and build material structures.

Through this system, parts were successfully produced that demonstrated the principle of curved-layer fused deposition modeling.

Figure 10. First complete curved layer part produced by modified Fab@home rapid prototyping machine.

4.0 Future Work

Though the parts produced on the system were not particularly elegant, they proved the overall concept of curved layer fused deposition modeling. The modified Fab@home platform will now be used for further research into various aspects of the process including:

- The effects on part strength of alternating the angle of approach for each successive build layer
- The effect on part strength and surface finish of having the deposition nozzle always vertical as opposed to having it perpendicular to the build surface.
- The effect of dynamically varying the pressure between the deposition head and the surface to create parts of varying thickness.

Work will also soon be underway on a Stratasys Dimension 3D printer that will allow higher resolution curved-layer parts to be printed out of ABS plastic.

Since the curved surfaces are normal to the load direction, this makes it feasible to investigate the use of fibre reinforcement within the build material. In conventional FDM, the inclusion of fibres would not make sense since loads may be applied to have the effect of separating the layers. In curved FDM, the fibres would make it possible to spread the load over the surface. This would be particularly true if subsequent layers were built in a different direction to provide a simple weave pattern. Work carried out at the National University of Singapore has focused on the effect of inclusion of short wood fibres into a polypropylene matrix [18].

It was found necessary to include a coupling agent to facilitate a good bond between the two materials. The composite material was extruded using an in-house, screw feed system mounted on a Sony Robokids Cartesian robot (called the Screw Extrusion System (SES), shown in fig. 9, with example extrusions shown in fig. 10). Test samples were found to be approximately 30% stronger under tensile loading. Little difference was noted under compression load. It is hypothesized that further improvements can be made should a higher temperature filler material be used. The wood fibre showed signs of degradation caused by the elevated temperature inside the heated chamber of the extruder. Further research is currently being conducted using short glass fibres. Should these fibres indicate an improvement over regular particulate fillers, the research will continue using biodegradable polymers and calcium phosphate fibres that could be used for tissue engineering applications.

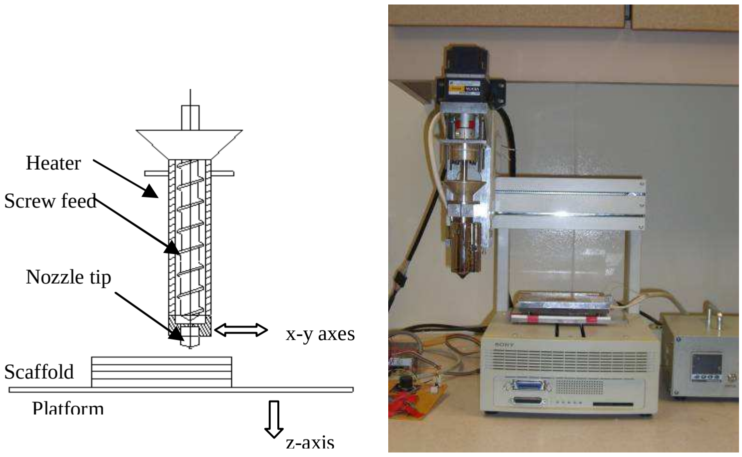

Figure 11. The Screw Extrusion System developed at NUS.

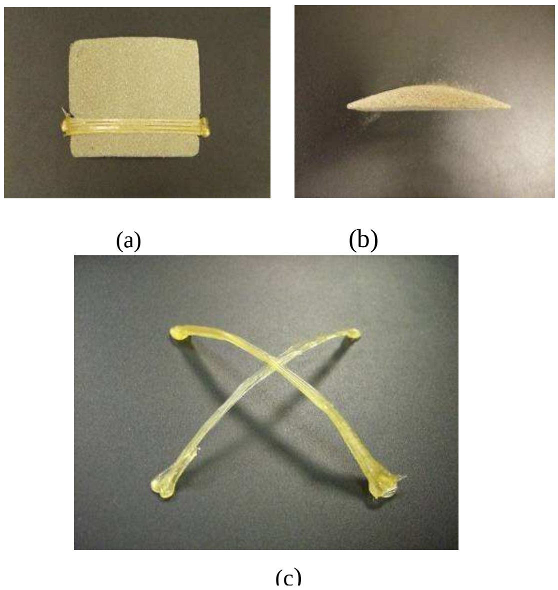

Figure 12. Curved models using the SES made from short fibre reinforced composite material. Figures a and b show samples using a simple foam support. Figure c shows crossover paths with the support removed.

5.0 Conclusion

This masters student project was an interesting application of mechatronics through which a combination of mechanical hardware, electronic motor control systems, and software were combined to produce a machine capable of producing rapid prototyped parts through a novel process known as Curved-Layer Fused Deposition Modeling.

A Fab@Home desktop rapid prototyping machine was modified and software algorithms were written that allowed the system to create parts in which support material was first deposited as conventional flat layer structures, and build material was then deposited over the support structure as curved layers. Though crude, the initial components built by the machine successfully demonstrated the proof-of-concept of Curved-Layer Fused Deposition Modeling.

The creation of the research platform now opens the field to further areas of investigation into curved-layer fused deposition modeling.

6.0 References

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