Getting rid of the wires: Curved Layer Fused Deposition Modeling in Conductive Polymer Additive Manufacturing

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Abstract. This paper describes an additive manufacturing technology that has the potential to print plastic components with integral conductive polymer electronic circuits. This could have a major impact in the fields of robotics and mechatronics as it has the potential to allow large wiring looms, often an issue with complex robotic systems, to be printed as an integral part of the products plastic shell. This paper describes the development of a novel Fused Deposition Modeling (FDM) process in which the layers of material that make up the part are deposited as curved layers instead of the conventional flat layers. This opens up possibilities of building curved plastic parts that have conductive electronic tracks and components printed as an integral part of the plastic component, thereby eliminating printed circuit boards and wiring. It is not possible to do this with existing flat-layer additive manufacturing technologies as the continuity of a circuit could be interrupted between the layers. With curved-layer fused deposition modeling (CLFDM) this problem is removed as continuous filaments in 3 dimensions can be produced, allowing for continuous conductive circuits.

Introduction

Rapid Prototyping (RP) is an additive fabrication technology which creates complex 3dimensional prototypes in short times. The rapid prototyping process begins by taking a 3D computer generated file and slicing it into thin slices. 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 used, and the process used for creating each slice of the model [1].

RP technologies now exist that can make plastic parts and parts in metals such as titanium, and even stainless steel [2]. 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.

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. This is then repeated for each subsequent slice of the model. It, in fact, uses 2 deposition nozzles: One for the part material and another for the support material which is used to support overhanging parts [2].

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 relatively poor surface finishes caused by the ‘staircase’ effect on curved surfaces and a lamination weaknesses in a direction perpendicular to the layer direction (Fig. 1). If smooth surfaces are required for the component, the staircase effect can require sometimes substantial post-processing of the part (sanding and polishing) in order to produce smooth surfaces.

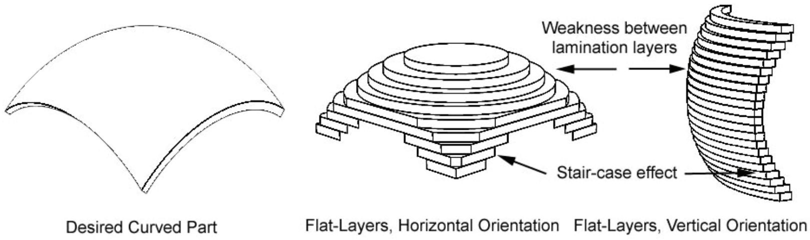

Figure 1. The staircase effect and lamination weakness problems of flat-layer rapid prototyping.

This paper looks at the application of curved-layer FDM [3] for producing plastic components with integral conductive tracks that eliminates wiring and printed circuit boards from products.

Curved Layer Fused Deposition Modeling

This project included the development of 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). 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. 2). The effect of these curved layers is to eliminate the staircase effect altogether, and removing the inherent lamination weakness in the layer direction.

The bulk of the research being carried out at different universities has been related to investigating alternative materials for FDM and working with a variety of materials including ceramics and metals [4], high performance thermoplastic composites [5] and metal/polymer composites [6]. 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 [7, 8], very little research has been done on depositing material as curved layer. The literature on RP reveals a research project in which the Laminated Object Manufacturing process was used to create curved layers [9] 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 small range materials that could be used.

This CLFDM technology opens up an entirely new possibility of building complex curved plastic parts that have conductive electronic tracks and components printed directly as part of the plastic component. It is not possible to do this with existing flat-layer additive manufacturing technologies, particularly on parts that are curved, as the continuity of a circuit would be interrupted between the layers (Fig. 2). With curved-layer fused deposition modeling (CLFDM) this problem is removed as continuous filaments in 3 dimensions can be produced, allowing for continuous conductive circuits.

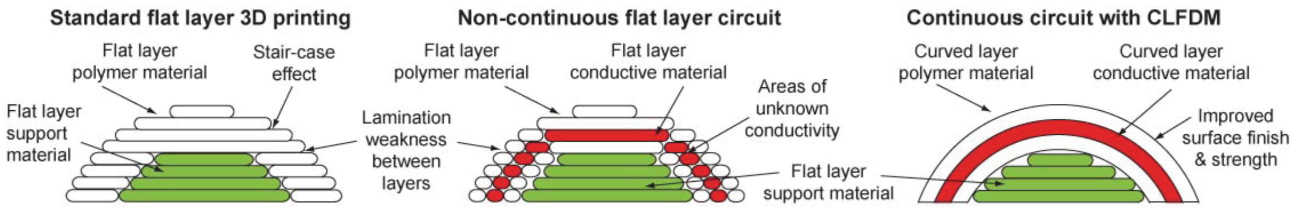

Figure 2. Curved layer vs flat layer for conductive polymers.

The elimination of the flat printed circuit boards (PCBs) and possibly even some of the electronic components, such as transistors, that are used in most electronic products creates a whole new type of product in which the housing of the product becomes its electronic circuit. This, in turn, could revolutionize the field of product design which would no longer be constrained by having to design around flat PCBs. It opens up new possibilities for miniaturization and could lead to a new paradigm in direct digital manufacturing in which the cost and size of many electronic components no longer affects the product as they are simply printed as part of the products plastic housing. It would also have a great impact on robotic applications, in which dealing with the often large wiring looms can be an issue, as these could now be an integral part of the products plastic shell and thus require no extra space, and not affect the flexibility of the system.

CLFDM System Overview

Two CLFDM systems were developed in tandem at the National University of Singapore and at Auckland University of Technology in New Zealand. On the system developed at NUS in Singapore composite material was extruded using an in-house, screw feed system mounted on a Sony Robokids Cartesian robot [Fig. 3]. The Auckland University of Technology machine used a modified Fab@Home machine (Fig. 3) to extrude light curing polymer to create curved layer parts.

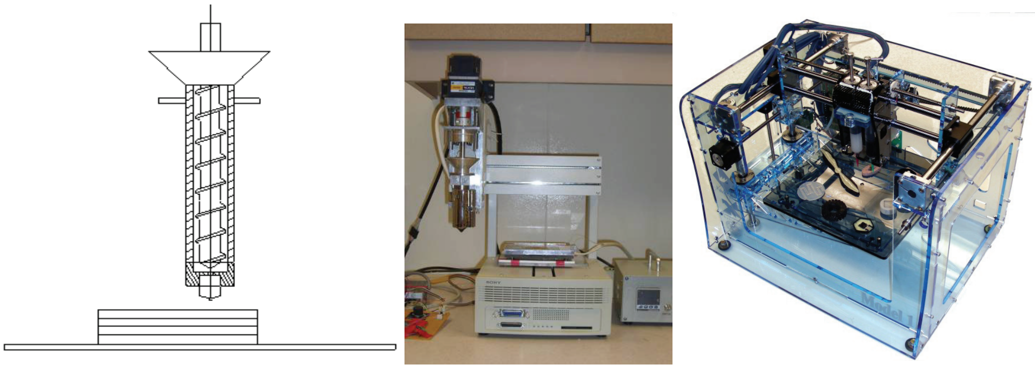

Figure 3. The NUS Screw Extrusion System, and Fab@Home system developed at AUT.

Since the curved surfaces are normal to the load direction, this also 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 (Yuan & Gibson, 2007).

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 fibres 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.

The curved layer rapid prototyping machine used at Auckland University of Technology was built by modifying an existing Fab@Home desktop RP machine (Fig. 3). The Fab@Home machine consists of an XY axis gantry type system that moves a dispensing head along a preprogrammed 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 XY 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 XS3525/8S4 Stepper Motor Driver Board, and an Olimex LPCH2148 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. This head is now being improved to have 3 depositions heads. One for support material, one for build material, and one for conductive polymer material.

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 xy 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 of the 3D part to be produced and slices it into flat slices. From these slices the software derives the xy coordinates for the tool path. A text file containing comma separated values (CSV) of the xy coordinates are then sent to the Olimex LPCH2148 microcontroller over USB.

This allowed for an easy method of creating curved tool-paths simply by including the z coordinate with every set of xy 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 de facto 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 an 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 from the first plane by whatever thickness variable had been set. 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 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 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.

$$\text{Original Matrix: } \begin{bmatrix} P_{1,1} & & P_{1,end} \\ \vdots & \cdots & \vdots \\ P_{end,1} & & P_{end,end} \end{bmatrix}$$

$$\text{Extended Matrix: } \begin{bmatrix} P_{1,exl} & P_{1,1} & & P_{1,end} & P_{1,exr} \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ P_{end,exl} & P_{end,1} & & P_{end,end} & P_{end,exr} \end{bmatrix} \quad (1)$$

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 the diagram 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.

$$\overrightarrow{PiP0} = \overrightarrow{Pi} - \overrightarrow{P0} \tag{2}$$

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.

$$\overline{P5P0_k} = d_k \times Thickness_k \times Weigh_k \tag{3}$$

Where $Thickness_k \times Weigh_k - Thickness$ and d_k represented the offset direction.

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

$$\overrightarrow{P5} = \overrightarrow{P1} + \overrightarrow{P5P1} \tag{4}$$

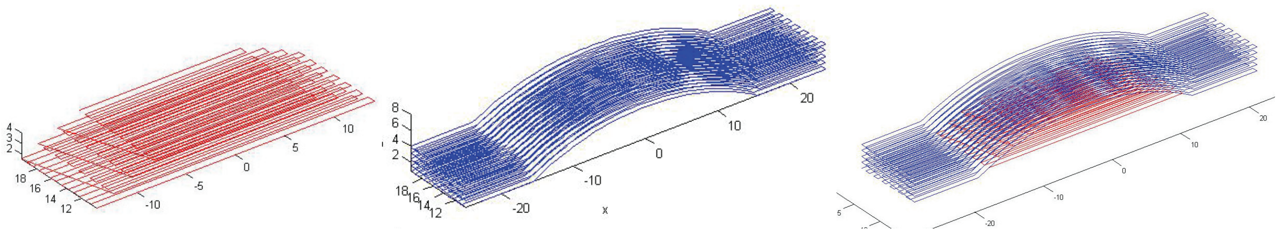

Figure 4. Matlab Program for flat support structure, curved layer structure, and combined structure.

An algorithm was then used to combine the results of the other algorithms into a single text file containing first the tool-path for the support material, and then that for the build material (Fig. 4). 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. With the system, parts were successfully produced that demonstrated the principle of curved-layer fused deposition modeling.

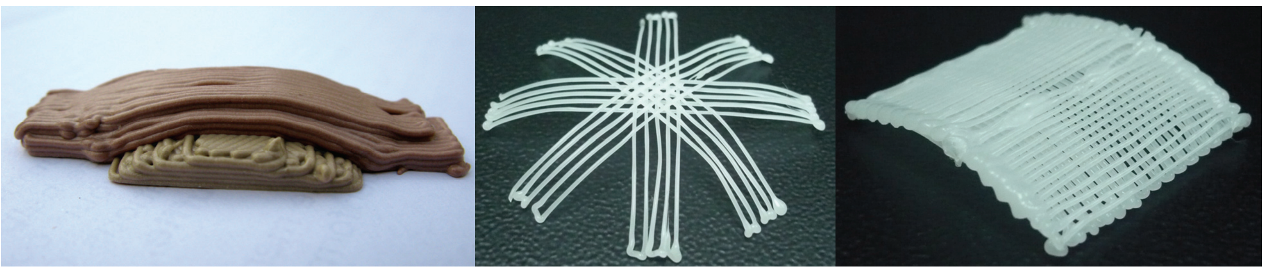

Figure 5. curved layer part produced by modified Fab@home rapid prototyping machine, And curved layer part produced by the National University of Singapore machine.

Figure 5 shows curved models using light curing polymer on the AUT machine, and parts made on the NUS machine using polymer made from short fibre reinforced composite material.

Work is now underway to allow the CLFDM system to print parts that contain tracks of conductive material within the plastic part itself. The conductive material project will extrude a polymer mixed with carbon nanotubes, and/or other conductive elements. The conductive polymer system will use three different deposition heads, one for each material. Work is also underway to develop effective methods of connecting components to such integral conductive tracks.

Conclusion

This paper describes a novel process known as Curved-Layer Fused Deposition Modeling. This new technology has the potential of being able to print conductive tracks integral to a product which is not possible with conventional flat-layer technologies. This opens up a new field of design in which products might be designed without the restriction of designing around PCBs and wiring looms.

Proof-of-concept machines were built 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. 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, the first of which is the printing of conductive polymer tracks as part of the other normal polymer tracks that make up the part.

References

[1] Chua, C.K., Leong, K.F., Rapid Prototyping: Principles and Applications. (2nd ed). World Scientific Publishing Co, Singapore, 2003

[2] Wohlers, T. Wohlers Report 2005, Worldwide progress report on the rapid prototyping, tooling, and manufacturing state of the industry, Wohlers Associates, 2005

[3] S. Singamneni, O. Diegel, B. Huang, I. Gibson, R. Chowdhury, Curved Layer Fused Deposition Modeling, Rapid Product Development Association of South Africa (RAPDASA) 2008, 9th Annual International Conference on Rapid Product Development, South Africa, 2008

[4] Agarwal M.K, Van Weeren R, Bandyopadhyay A, Whalen P.J, Safari A, Danforth S.C, 1996, "Fused deposition of ceramics and metals: An overview," Proceedings of Solid Freeform Fabrication Symposium, The University of Texas, Austin, p 38592.

[5] Gray R.W, Baird D.G, Jan Helge Bohn, 1998, "Effects of processing conditions on short TLCP fiber reinforced FDM parts," Rapid Prototyping Journal, 4(1), p 1425.

[6] Masood S.H, Song W.Q, 2004, "Development of new metal/polymer materials for rapid tooling using fused deposition modelling," Materials and Design, 25, p 587594.

[7] Tseng A.A, Tanaka M, 2001, "Advanced deposition techniques for free form fabrication of metal and ceramic parts," Rapid Prototyping Journal, 7/1, p 617.

[8] Anna B, Lauren S and Seluck I.G, 2005, "New developments in fused deposition modelling of ceramics," Rapid Prototyping Journal 11/4, p 214220.

[9] Klosterman D.A, Chartoff R.P, Osborne N.R, Graves G.A, Lightman A, Han G, Bezeredi A, Rodrigues S, 1999, "Development of a curved layer LOM process for monolithic ceramics and ceramic matrix composites," Rapid Prototyping Journal, 5/2, p 6167.