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Development of a Hybrid Rapid Prototyping System Using Low-Cost Fused Deposition Modeling and Five-Axis Machining

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Abstract

Currently, two major processes are being used to produce prototypes, namely machining and rapid prototyping. Machining is generally more accurate and precise, but it is difficult to produce objects with certain complicated features. In contrast, rapid prototyping can produce objects with complicated features, which allows materials to be used more efficiently. However, due to the uneven shrinkage and residual stresses within rapid prototyping products, their accuracy is usually uncertain. This study attempts to integrate these two manufacturing processes and develop a hybrid rapid prototyping system in order to overcome the disadvantages associated with each process and to develop new applications. Fused deposition modeling (FDM) was used as the rapid prototyping process in this work. A spindle and a low-cost FDM extruder were designed to be placed on each end of a rotary axis in the five-axis machine tool. The proposed design allows the rotation of the axis on the five-axis machine to switch between machining and FDM, thus achieving the advantage of reducing costs for extra actuators without sacrificing working space. The case studies demonstrated that the proposed hybrid system can build FDM objects without using support materials and produce FDM parts with metal embedded to increase the stiffness. The system can also conduct five-axis machining on a completed FDM part or trim the freeform surface fabricated by FDM to achieve more accurate dimensions or better surface finish.

Keywords: Hybrid; five-axis machining; rapid prototyping; fused deposition modeling.

1 Introduction

Efficient and accurate production of prototypes or low-volume products can reduce the time to market and increase product versatility. The two most commonly used methods are machining and rapid prototyping (RP), which are briefly described in the following.

The machining process has gradually advanced from conventional three-axis machining to five-axis machining over the past several decades. A five-axis machine tool consists of three linear axes and two rotary axes. The machining process is based on the concept of a spherical coordinate system, which allows an object to be machined at any arbitrary position and angle within the working space by using the five axes. X, Y and Z represent the linear axes along three mutually perpendicular directions; the rotary axes around the X, Y and Z axes are represented by A, B and C, respectively. Since there are only two rotary axes for a regular five-axis machine tool, each tool has two out of the three A, B, and C axes. The location of the rotary axes determines the type of five-axis machine tool, of which there are three types: (1) Table/Table type, for which both rotary axes are installed on the working table; (2) Head/Head type, for which both rotary axes are installed on the spindle head; (3) Head/Table type, for which one rotary axis is installed on the spindle, and the other on the working table. Five-axis machining results in the product having a better surface finish and a longer tool life. In addition, a five-axis machine tool can machine a product from various angles without re-fixing. Although five-axis machining can make more features than traditional three-axis machining, the versatility of the products from five-axis machining is still quite limited as compared to the RP process.

In contrast, the RP process can be categorized as liquid base, powder base or solid base, according to the types of raw material used. The liquid-based RP process uses a light source to solidify the liquid polymer, layer by layer, in order to complete an RP product. The powder-based RP process is similar to the liquid-based RP, except that the raw material is replaced by powder and some of the light sources are replaced by a glue ejector. An advantage of the powder-based RP is that no support material is needed for fabricating the overhang feature as the powder itself can be the support. There are several different solid-based RP processes, one of which is fused deposition modeling (FDM). The FDM process first fuses a solid thermoplastic filament and then extrudes the fused material through a nozzle, as illustrated in Figure 1, to form an RP product layer by layer. The FDM process is relatively simple, as compared to the other RP processes, so there are many low-cost FDM systems on the market for hobbyists or those who cannot afford the expensive RP systems. The RP technique can produce parts with complicated features; however, the accuracy and precision of the RP product is usually uncertain due to the shrinkage and the internal stresses incurred during the RP process. The poor surface quality due to staircase effect is another concern associated with RP, as indicated by Pandey et al. (2003). Besides, RP techniques cannot be used to modify an existing part.

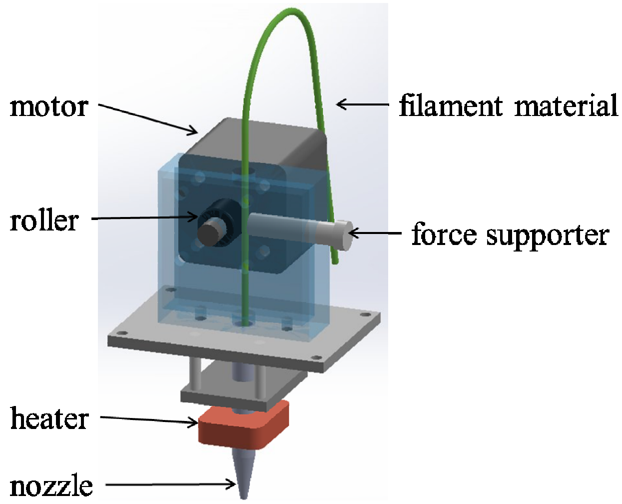


Figure 1: Schematic of an FDM extruder

As discussed above, the two processes have both advantages and disadvantages. The versatility of the RP products is definitely attractive; however, the accuracy and surface finish of the RP process, especially for low-cost FDM systems, is unacceptable for many applications. Anitha et al. (2001) found out that the layer thickness was the most significant factor for the surface finish in FDM. However, reducing the layer thickness will increase build time, which results in another issue: long build time. This motivated us to integrate the machining with the low-cost FDM process to achieve a hybrid RP system with high accuracy and short build time. The idea to integrate an RP process with machining can be found in several studies as described in the following.

Jeng and Lin (2001) developed a hybrid process by combining selective laser cladding (SLC) and three-axis milling. In their process, the workpiece was placed on an XY table; the laser head and the milling spindle were installed on two separate vertical axes, respectively. In that study, SLC was used to build a mold, which was then milled to the desired accuracy. Choi et al. (2001) proposed a similar hybrid machine by combining CO_2 laser welding and three-axis milling. However, the laser head and the milling spindle were installed on the same side of the vertical axis, and so could interfere with each other during the manufacturing process, thus limiting the traveling distances of the X and Y axes. Song and Park (2006) studied the integration of three-axis milling with gas metal arc welding (GMAW). Similar to the previous research, their hybrid machine used GMAW to form the contours of the product and the milling process was then used to obtain the final shape accurately and efficiently. According to that study, GMAW was more energy-saving than laser welding. In addition, the density of the finished product when using GMAW was higher. Karunakaran et al. (2010) performed a similar study by combining arc welding with three-axis milling to construct a low-cost hybrid system. They used arc welding because of its deposition rate, usually around 50-100 g/min, which was much higher than that of laser or electron beam-based processes.

The hybrid processes mentioned above were all based on three-axis milling with some RP techniques. Some studies extended the research scope to five-axis machining. Kerschbaumer and Ernst (2004) combined laser cladding (LC) technology using a YAG laser with a five-axis Table/Table milling machine. The LC nozzle was installed next to the milling spindle. To avoid interference between the LC nozzle and the workpiece during the milling process, the nozzle was designed to be retractable, thus complicating the machining mechanism. Instead of using LC or GMAW, Xiong et al. (2009) combined five-axis milling with plasma deposition, which was claimed to be the most economical way to deposit molten metal. Similar to some of the previous researchers, they installed the plasma torch and the milling spindle on the same side of the vertical axis.

Hur et al. (2002) adopted a different approach to combining the RP process and the traditional machining process. They divided the product into several portions, used machining to produce each portion on the sheet material and then glued them together. To fabricate the undercut feature, they implemented a mechanism to invert the material. The obvious advantage of this method was that any machinable material could be used to fabricate the product; however, the method may not be easily applicable to products with a complicated shape. Salloum et al. (2009) improved this approach by using 5-axis milling to fabricate the undercut feature, then used pins and screws to make the assembly. Karunakaran et al. (2012) reported a more robust assembly process, in which the sheet material was connected by ultrasonic welding, thus providing a better solution compared to the previous methods.

In summary, the above studies all combined certain metal deposition RP processes, including LC, GMAW and plasma, with multi-axis machine tools. The RP head was usually installed on the same side of the cutter, so the RP head and the cutting tool could interfere with each other, the working space might be reduced or an additional axis needed to allow the RP head to be retractable. Moreover, the advantage of using five-axis, instead of three-axis, in the hybrid process was not obvious. It can be noted that little research has been done on a hybrid system based on the RP process for thermoplastic materials.

The objective of the present research was to develop a hybrid desktop system by integrating an RP process with a five-axis machine tool in order to address the abovementioned problems. The RP process we adopted was the FDM method, which is easier to integrate with the cutting spindle, as compared to the other RP techniques.

2 Machine Design and Tool Path Generation

This section first presents the mechanical design of the hybrid system. Then, the concept of the integrated FDM extruder and the cutting spindle are introduced. Next, the control scheme for the hybrid system is briefly discussed. Finally, how to generate the tool path for FDM is explained and illustrated by using an example.

2.1 Mechanical design of the hybrid system

One of the critical issues with regard to designing this hybrid system was deciding how to integrate the cutter spindle and the FDM extruder together without excessive increases in the mechanism's complexity. The innovative design idea was to combine the cutter spindle and the FDM extruder on a rotary axis of a desktop five-axis machine tool. The FDM extruder was fixed on the opposite end of the cutter spindle; hence, no extra actuator or vertical axis was needed to combine the two modes on one machine. The FDM mode can be switched to the cutting mode by rotating the axis 180°, as illustrated in Figure 2. By placing the cutter spindle and the FDM extruder on the ends of the rotary axis, interference between the two can be prevented. Another benefit to having the FDM and machining capabilities in one machine is that it reduces the errors and time caused by re-fixing items. Without our hybrid system, people can still make an FDM object by using an FDM system and then moving it to a five-axis machine tool for subsequent machining. However, it is difficult or time-consuming to align the cutter with the reference of the FDM object, as indicated by Kulkarni et al. (2000) due to inaccurate dimensions or lack of references of the FDM parts. The proposed hybrid system eliminates this problem.

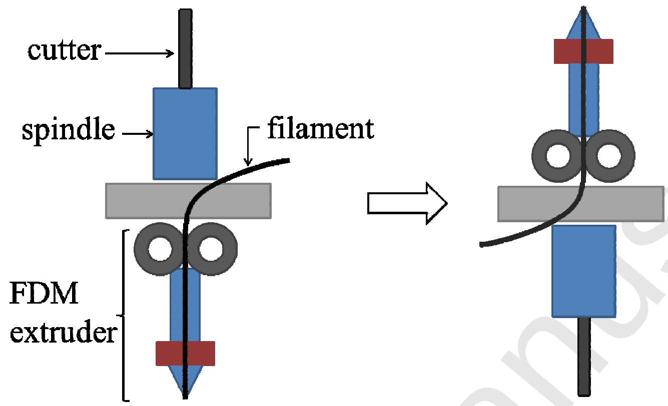


Figure 2: The FDM can be switched to the cutter by rotating the axis 180°

For the design of the desktop five-axis machine, an additional rotary axis can be installed either on the head to make it a Head/Head type, or on the table to make it Head/Table type. The Head/Head type can machine large workpieces, because the rotary axes do not need to carry heavy loads; however, the head mechanism that combines two rotary axes is heavy and complex. Therefore, we chose the Head/Table type for the five-axis machine tool. A gantry design was adopted to increase the rigidity of this machine.

Figure 3 illustrates the design of the hybrid machine, where the X axis is placed on the crossbeam of the gantry structure, the Y axis is placed in the base and the Z axis is attached to the X axis, respectively. Having the A axis placed on the Y axis and the B axis placed on the Z axis make the machine a Head/Table type. The working table is attached to the A axis and the integrated spindle and FDM extruder unit are attached to the B axis. The traveling distances of the X axis, Y axis and Z axis are 200 mm, 200 mm and 150 mm, respectively. The A axis can rotate ±90º and the B axis can rotate ±180º. The completed hybrid system is shown in Figure 4. The size of this machine shown is 700 mm (width) × 700 mm (depth) × 900 mm (height) approximately.

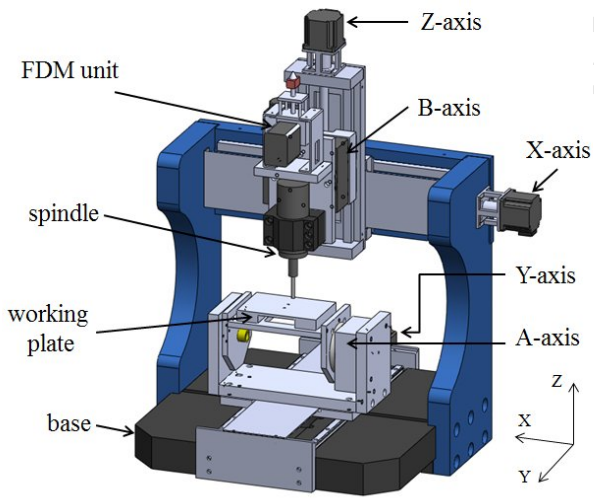


Figure 3: The design of the hybrid FDM and five-axis machine tool

Figure 4: The completed hybrid FDM and five-axis machine tool

2.2 Integrated spindle and FDM extruder

Since this hybrid system was not designed to perform heavy cutting, a simple tool spindle with a DC servo motor was adopted. The output power of the spindle was 200 W and the maximum speed was 9000 rpm. The spindle was attached to one end of the rotary B axis and the other end was the FDM extruder.

The FDM extruder used for this hybrid system was adapted from a low-cost commercial product for hobbyists and included a feeding stepper motor and a 40 W heater, as shown in Figure 5. The thermoplastic filament was made of acrylonitrile butadiene styrene (ABS). The filament entered the extruder, shown in Figure 5, from the top and the feeding motor brought it through the tube to the heater. The plastic was melted by the heater and then extruded through the nozzle. The size of the opening of the nozzle was 0.6 mm in diameter and the mean diameter of the melted ABS was 0.68 mm. We developed another nozzle to generate the melted filament with a mean diameter of 1 mm.

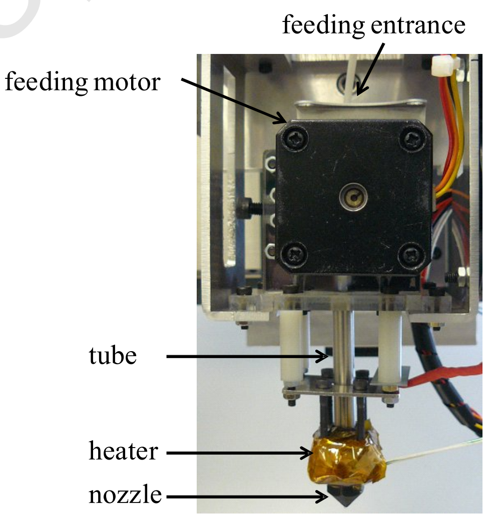


Figure 5: The FDM extruder including the feeding mechanism, the heater, and the nozzle

Two temperature control modules were used for the proposed hybrid system: one to control the temperature of the heater at 240ºC to melt the ABS filament; the other to control the temperature of the working table at 130ºC so that the ABS part adhered to the table during the manufacturing process.

Figure 6(a) shows the cross-section of the original FDM extruder. The original channel for the ABS filament was a tube made of polytetrafluoroethene (PTFE). The inside diameter of the PTFE tube was 3.3 mm, while the diameter of the ABS filament was 3.0 mm, allowing the ABS filament to easily pass through the PTFE tube. Although the maximum operating temperature of PTFE is 260ºC, the PTFE tube could not take the heat accumulated in the heating zone and started to deform after the unit was in operation for about five hours. To resolve this issue, we used a piece of stainless steel tube, 30 mm in length, to replace a portion of the PTFE tube, as shown in Figure 6(b). Compared to PTFE, stainless steel has a higher thermal conductivity and a higher melting point, thus allowing more heat to be transferred into the ABS filament without causing thermal deformation. In order to prevent the ABS filament from melting too early, which may affect the extrusion of the material, a section of the PTFE tube was kept near the feeding entrance. After this modification, the problem regarding the thermal deformation of the PTFE tube was resolved.

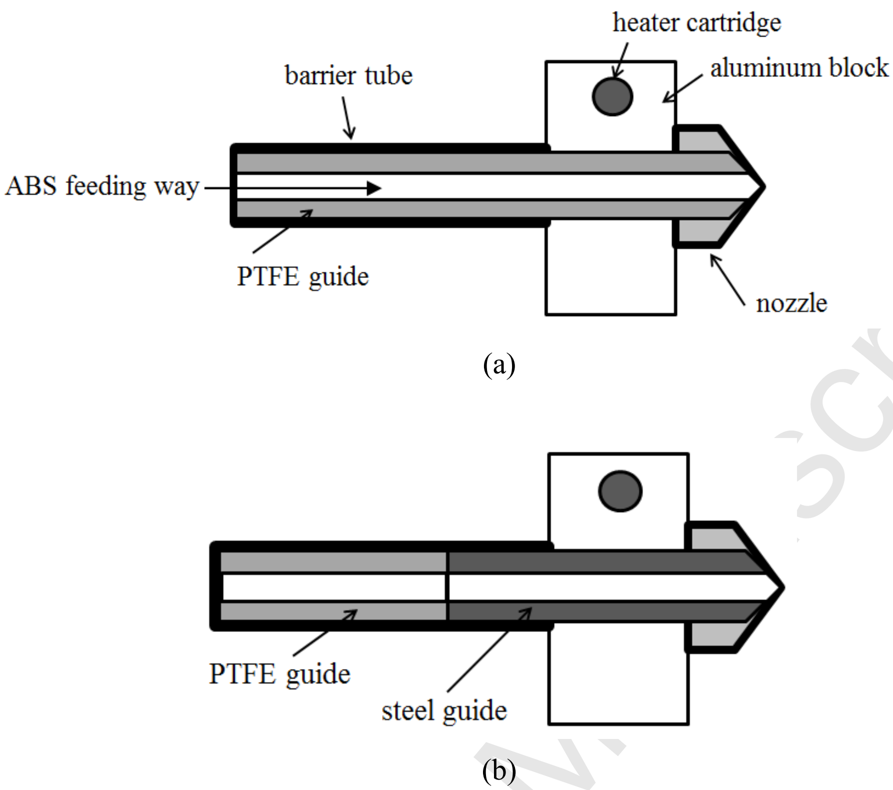


Figure 6: Schematic of the cross-section of (a) the original and (b) the modified FDM extruder

2.3 Control unit

The control of the hybrid system is PC-based. Users input the G codes of the tool paths into the control program so as to control the motion of the FDM extruder and the cutter through a PC and its motion controller. We adopted stepper motors with open-loop control on the hybrid system to simplify its control. Although stepper motors are generally less precise than servo motors, because of the lack of feedback, the proposed system was only for experimentation and demonstration of the design concept. Its accuracy was not the focus of the research. In the proposed hybrid machine, six stepper motors needed to be controlled: five for the linear and rotary axes and one for the feeder of the FDM extruder. Two four-axis motion controllers were used to control the six motors. The control scheme of the proposed hybrid system is shown in Figure 7. These controllers perform point-to-point and straight-line moves and can achieve simultaneous multi-axis motion trajectories through circular, spherical or helical interpolation, which satisfy all our needs for simultaneous five-axis machining.

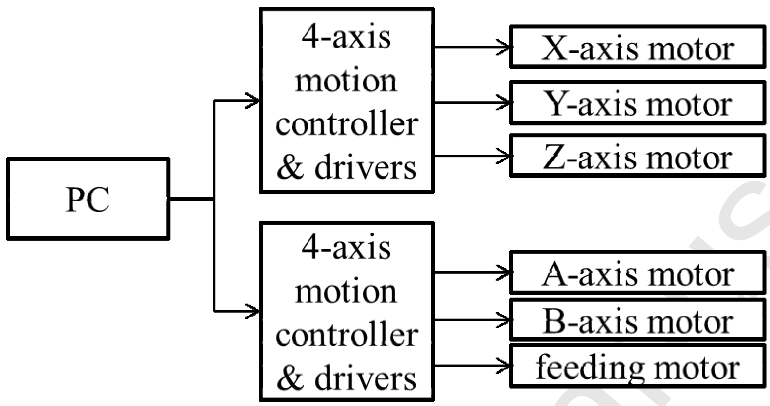


Figure 7: The control scheme of the hybrid system

2.4 Tool Path Generation for FDM and Machining

To use the hybrid system to build a prototype, we need to generate tool paths for the FDM and machining, respectively. A commercial CAM software package was used to generate the tool paths. Because the CAM software was not custom-made for FDM, we had to develop some procedures to allow the software to generate the paths. The CAD model, shown in Figure 8(a), was used to illustrate the procedures. First, we scaled up the model slightly so that we could have some materials to trim off after the FDM process. Then, we sliced the CAD model along the vertical direction to obtain the contours of the model, as shown in Figure 8(b). The distance between two adjacent slices was the layer thickness used in FDM. The generation of the tool path for the CAD model in FDM is explained as follows.

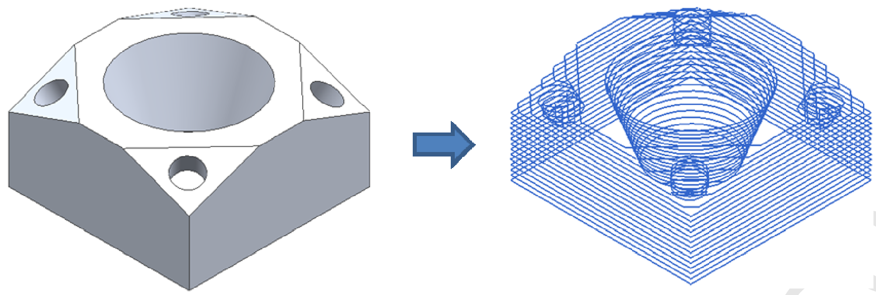


Figure 8: (a) CAD model of the object to be made; (b) contours of the sliced CAD model

We extruded a contour, as shown in Figure 9(a), with a distance equal to the layer thickness to convert it to a solid, as shown in Figure 9(b). Next, we generated the tool path inside the extrusion, as shown in Figure 9(c), and then the tool path along the contour, as shown in Figure 9(d), to complete the tool path generation for a single layer. We repeated the same procedure to generate the tool path for all the layers for FDM fabrication. A program was developed in our CAM system so that it could automatically generate all of the paths in G code. A corresponding program was also developed to convert the G code to the command that our motion controllers could recognize, so as to control the hybrid system's movements as planned in the CAM software. The tool path generation for subsequent trimming, drilling or machining are standard CAM procedures, so we will not elaborate on them here.

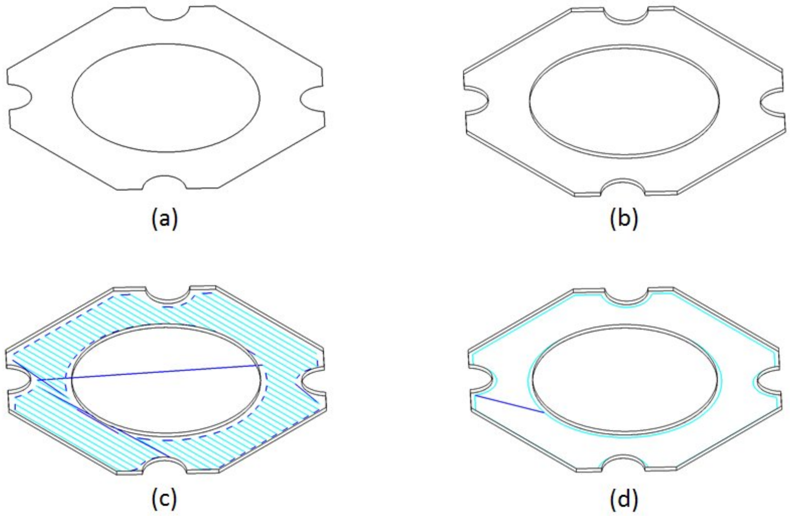


Figure 9: (a) Contour of a sliced layer; (b) the extrusion of the contour; (c) the tool path inside the extrusion; (d) the tool path along the contour of the extrusion

3 Case Studies

Five cases were studied to demonstrate the capability and the features of the proposed hybrid system. First, an FDM cube was produced to show the accuracy of the low-cost FDM used on the machine. Then, the hybrid system was used to produce a Γ-shaped object to show the benefit of the overhang feature being fabricated without using the supporting material. The next case was to use the hybrid machine to create an FDM cylinder with embedded material, which cannot be performed on regular FDM machines and can increase the stiffness of the FDM part. The last two cases involved FDM and multi-axis machining, which demonstrated that the hybrid technique greatly increased the efficiency of making prototypes, as compared to the regular FDM technique.

3.1 FDM without machining

The first case aimed to identify the differences in dimensions between the design and the completed object made by FDM. FDM was used to build a cube layer by layer. Prior to the making of the part, we measured the diameter of a single ABS filament, and the mean value was 0.68 mm; this value was used as the pitch for the tool path. The design dimensions of the cube were 20 mm×25 mm×20 mm, and the measured dimensions of the completed object were 20.94 mm×26.44 mm×20.45 mm. The differences were 4.7%, 5.8% and 2.3% for each dimension, respectively.

The possible causes for the discrepancy between the design and the completed component are discussed in the following. First, the diameters of the fused filament produced by the low-cost FDM were inconsistent. The diameter of the filament was measured 30 times, and the standard deviation of the results was 0.014 mm. The variation of the filament diameter caused the variation of the final FDM part that consisted of the filaments. Second, as the FDM extruder changed the moving direction, the speed was not maintained at a constant value and the FDM extruded more ABS material at the locations where the speed slowed down, thus causing the ABS filament to become thicker and create the dimensional variation. Third, as shown in Figure 10, the melted FDM filaments did not attach to the filaments underneath completely; vacancies existed between the filaments, thus increasing the dimensions. The cause of the vacancy was related to the non-uniform diameter of the fused filament. If we set the pitch of the two adjacent fused filaments as the mean diameter of the filament or a little larger, there was still a chance of interference between the fused filament and the adjacent filament, so that it could not completely attach to the filaments underneath. If we increased the pitch of the filaments so that two adjacent filaments did not touch each other, then there would be a gap between the two adjacent filaments, which would introduce a dimension accuracy problem for the subsequent layers. Better control of the temperature and the speed of the nozzle might improve the situation, but there was no guarantee that a fused filament with a uniform diameter could be created, especially when the nozzle speed changed. As such, there were several sources of inaccuracy in controlling the dimensions of an FDM item. In addition, the desired dimensions might not be exact multiples of the diameter of the fused filament, so the dimensions of the fused part are expected to be best controlled within a tolerance of ± (0.5×fused filament diameter).

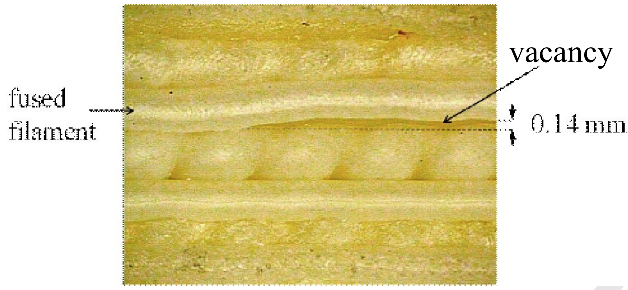


Figure 10: Side view of an FDM object showing the vacancy

3.2 FDM without supporting material

This case was to demonstrate one of the benefits of using five-axis FDM, which was one of the feaures of the proposed hybrid system. Using common three-axis FDM to fabricate an overhang feature requires using support material. However, with the use of five-axis FDM, the support material may not be needed. Figure 11 shows the steps for making a Γ-shaped object by traditional FDM. First, we had to make the vertical portion as well as the support by two different FDM extruders. Then, we could make the horizontal portion of the Γ-shaped object. Lastly, we removed the support material to obtain the final product. On the other hand, our hybrid system could be used to make this part without using the support, as per the following steps. The vertical portion of this object, as shown in Figure 12(a), was made first; then, the A axis of the hybrid machine was rotated by 90° to allow the FDM extruder to complete the overhang, as shown in Figure 12(b). The proposed hybrid system saved both time and the cost for making the support. It could be argued that the time and cost are not critical; however, removing the support may cause the FDM object to deform or warp due to the change of the internal stress distribution. Notably, using the hybrid system would be a solution to this issue.

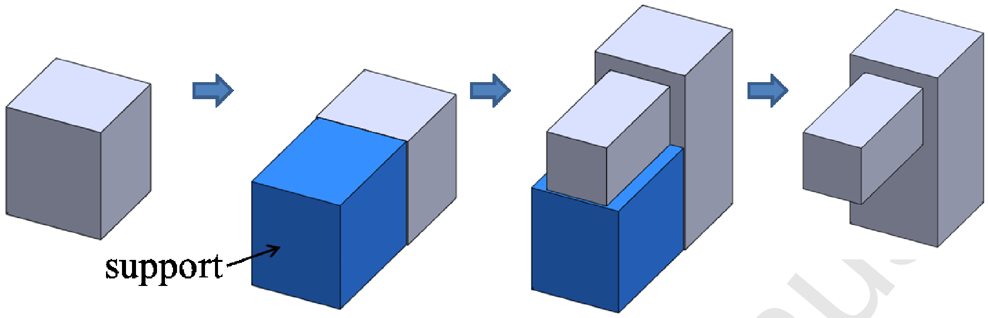
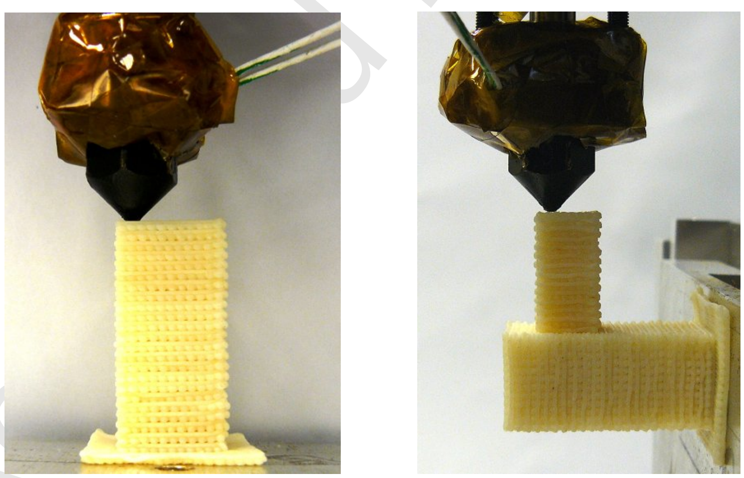


Figure 11: Steps for making an object with an overhang by traditional FDM



(a) (b)

Figure 12: Using five-axis FDM to fabricate (a) the vertical portion and (b) the horizontal portion of the Γ-shaped component

3.3 FDM on embedded material

In this case study, we used FDM and five-axis machining to produce an object with embedded material. The aluminum to be embedded, as shown in Figure 13, were pre-fabricated. The goal was to encapsulate the top of the aluminum with ABS using the proposed five-axis FDM. Common three-axis FDM is unable to achieve this goal because the embedded material may interfere with the FDM extruder, as illustrated in Figure 14(a). The proposed FDM machine avoided this problem because the orientation of the extruder could be adjusted, as shown in Figure 14(b). The completed ABS part with embedded aluminum is shown in Figure 15, in which the ABS item was trimmed to the same diameter as the bottom portion of the aluminum. At least two benefits can be obtained by performing FDM with embedded materials. First, the embedded material can increase the stiffness of the FDM part if using an embedded material with a higher stiffness than the FDM material. Thus, the embedded material can reduce the deformation or warpage caused by the shrinkage or internal stress incurred during the FDM process. Second, the embedded material can reduce the build time of FDM, as well as the cost, because the expensive FDM filament is not required to build the space occupied by the embedded material. Using embedded material can also adjust the center of gravity of the FDM parts when layering the polymer on top of a heavy material; this would prove beneficial when using FDM to produce objects, such as toy figures, that need to be stable and upright.

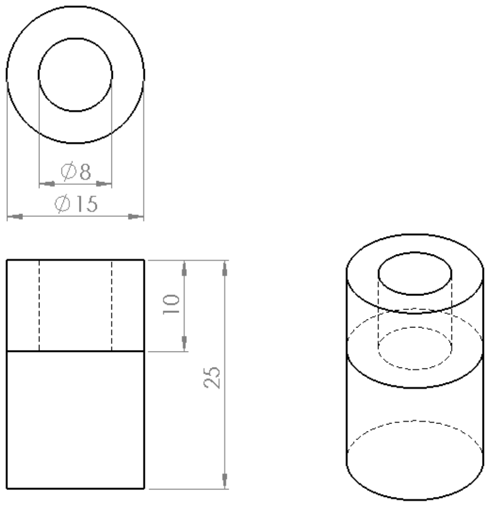
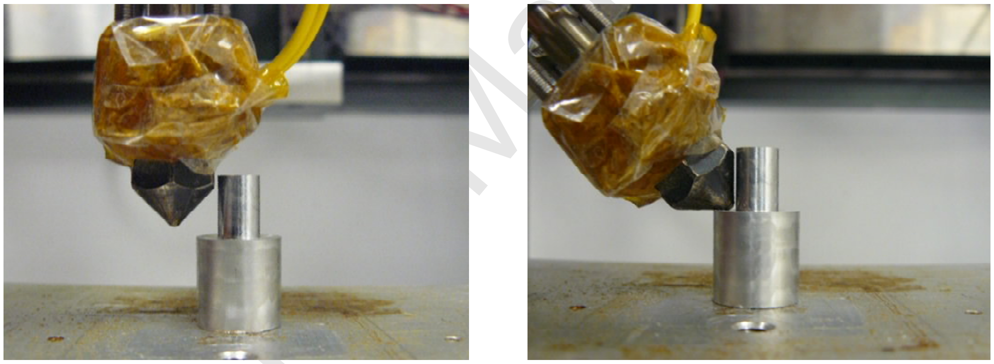


Figure 13: (a) Design of the aluminum to be embedded by FDM



(a) (b)

Figure 14: (a) Three-axis FDM cannot, but (b) five-axis FDM can, embed polymer around the aluminum

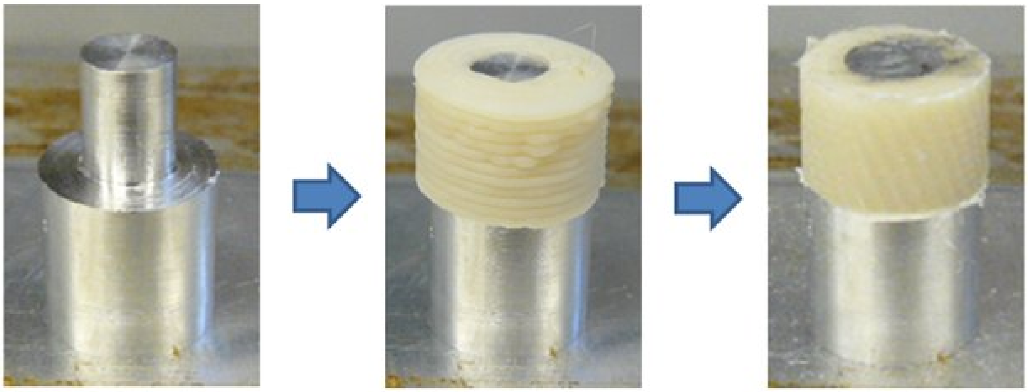


Figure 15: The stepped aluminum (left); the aluminum embedded in polymer before machining (middle) and after machining (right)

3.4 FDM with multi-axis machining

The purpose of this case study was to demonstrate the hybrid machine's three-axis, three-plus-two axis and five-axis machining capability. The model we created is shown in Figure 16. This part was fabricated by using FDM first. The layer thickness used for this case was 1 mm, which was relatively large compared to the general commercial FDM machine. As a result, the surfaces on the top had staircase shape and the holes' walls were rough. With the help of the hybrid machine, we could proceed to the next step by machining the part. Because both the FDM extruder and the cutting spindle were integrated on one machine, we did not need to re-fix the FDM part or align the cutter with a certain reference on the part, which resolved the re-fixing difficulty. We simply rotated the B axis of the machine; then, we could start trimming the staircase surfaces and the rough walls. We divided the machining into three parts: the top surface, as shown in Figure 17(a); the four corner surfaces and the associated holes, as shown in Figure 17(b); and the center tapered hole, as shown in Figure 17(c). These three portions could be trimmed by using three-axis, three-plus-two axis and five-axis machining, respectively. The completed model is shown in Figure 18. The roughness and the dimension accuracy were greatly improved after machining. Because this was a hybrid process, we could use a larger layer thickness to improve the efficiency of the FDM process without sacrificing the smoothness and the accuracy of the FDM part. The total build time, including FDM and machining, by using the hybrid system was about 30 minutes. We also had this part fabricated by a mid-priced commercial FDM machine.

The layer thickness for the machine was 0.254 mm; the total build time was 71 minutes. The build time for the hybrid system was about 58% less than that of the commercial FDM machine. In addition, the accuracy of our hybrid system could be predicted, but there is no guarantee for the accuracy of the part made by many general FDM machines.

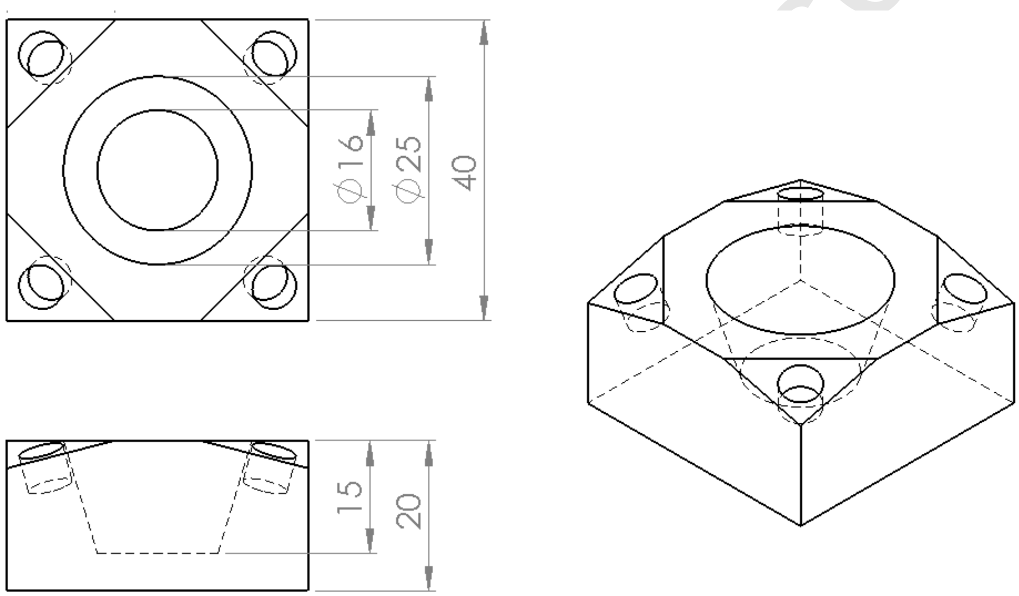
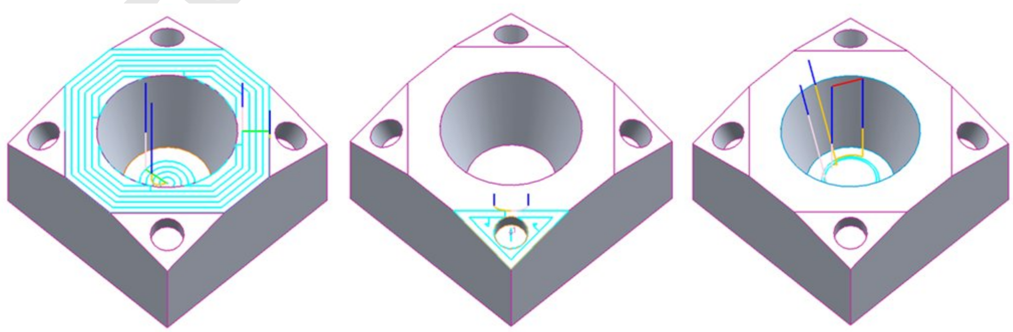


Figure 16: Design of the model used for hybrid FDM and multi-axis machining



(a) (b) (c)

Figure 17: The cyan lines represent tool paths of (a) three-axis; (b) three-plus-two axis; (c) five-axis machining

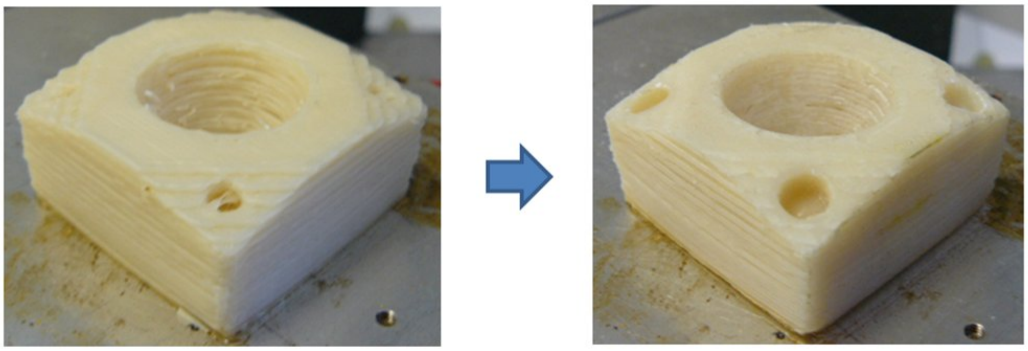


Figure 18: The FDM workpiece before machining (left) and after machining (right)

3.5 Creating freeform shape by FDM and multi-axis machining

The last case was to demonstrate the capability of the hybrid machine to fabricate the freeform shape. The model with the freeform shape is shown in Figure 19; the marks are the interpolation points used to generate the freeform surface. Figure 20(a) shows the model built by using our FDM. It was obvious that the freeform surface had staircase effect. With the use of the high-resolution FDM, it might be possible to create a smoother freeform surface; however, using high-resolution FDM may also increase build time and cost. Our hybrid machine would be beneficial in this regard. We could trim the freeform surface to achieve a continuous and smooth surface, as shown in Figure 20(b). To show the accuracy of the hybrid machine, we used a CMM to measure the surface profile, which was compared with the true profile created in the CAD software, as shown in Figure 21; the thick line represents the true profile and the thin line represents the measured profile. Based on the CMM measurement, the maximum error for the freeform surface generated by our hybrid machine was less than 0.3 mm. Again, we also made a comparison of the build time. The build time for a mid-priced commercial FDM machine as we used in the previous case was 18 minutes, but only 10 minutes for the hybrid system, a 44% reduction. The layer thickness for our hybrid system was still 1 mm, and that of the mid-priced commercial system was 0.254 mm. This result demonstrated that our hybrid system was more efficient than the FDM along process, and could achieve a predictable accuracy, which is approximately equivalent to the machine's accuracy. However, the accuracy of the FDM along process was usually uncertain.

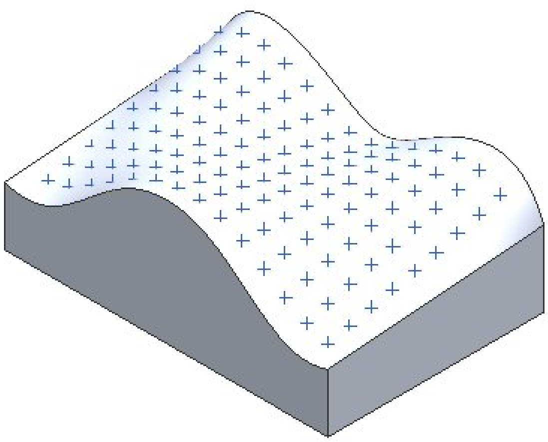
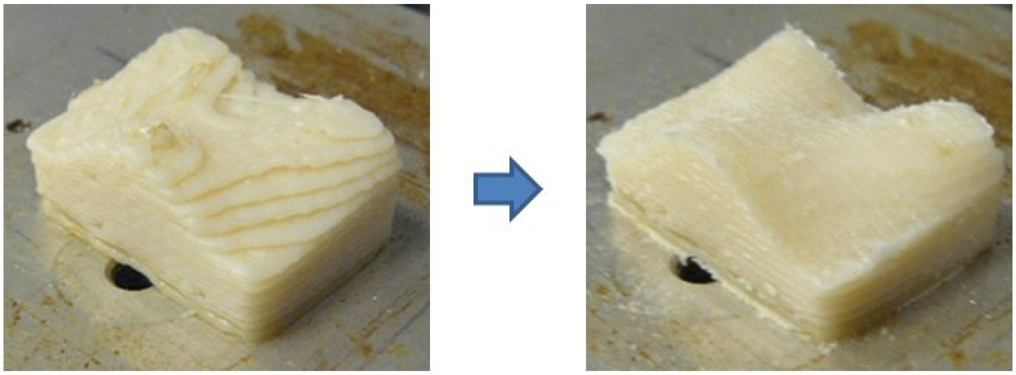


Figure 19: Freeform surface with interpolation points



(a) (b)

Figure 20: Freeform surface made by FDM before milling (left) and after milling (right)

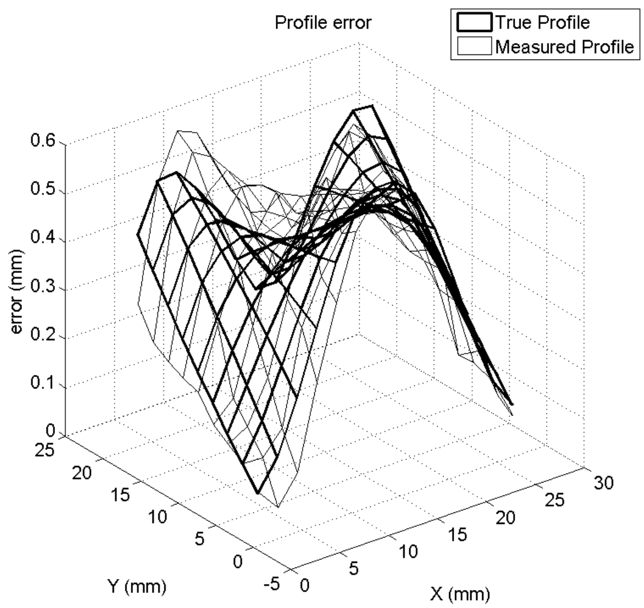


Figure 21: Comparison of the true profile and the measured profile of the freeform surface

Some literatures presented the integration of machining and FDM. For example, Kulkarni et al. (2000) performed a study on the integration of milling or sculpting with layer manufacturing, in which they focused on the tool path generation of the milling tool and the shape of the trowel used for sculpting. They did not resolve the problem on how to align the cutter with the FDM parts.

Pandey et al. (2003) used a hot blade-like cutter to smooth out the rough surfaces of the FDM parts. It was claimed that the method could generate much smoother surfaces compared to milling. However, the blade-like cutter cannot be used on the freeform surfaces. Both studies performed FDM and machining on two separate systems, respectively. Our proposed hybrid system is different from previous research. We integrated FDM and five-axis machining on one machine so as to eliminate the difficulty for the cutter to align with the FDM parts. In addition, the hybrid machine has the feature of five-axis FDM, which can perform many tasks that regular three-axis FDM cannot, such as fabricating overhang without the support structure, FDM with embedded material. The hybrid machine allows larger layer thickness to reduce the build time and enhance the surface finish by its machining capability. All these features are new and not seen in other literatures.

4 Conclusions

A hybrid rapid prototyping system, consisting of low-cost FDM and five-axis machining, was developed in this research. One of the innovative features of the system involved installing the cutter spindle on one end and the FDM extruder on the other end of the rotary B axis, thus allowing the machine to switch between the two activities without any extra actuation system, thereby simplifying the mechanism complexity and reducing the time to find the position of the cutter relative to the FDM part for subsequent machining.

This hybrid system can produce FDM prototypes, which can also be trimmed on the same machine for higher dimensional accuracy and better surface finish. Having five axes on this machine resulted in several benefits, and those benefits were demonstrated through the case studies in the paper. In one case, we showed that the five-axis machine could make the overhang feature without using the support material. This would not only reduce costs and the build time needed for the support, but also lower the possibility of deformation due to the removal of the support material. In addition, the five-axis hybrid system was used to make FDM parts with embedded material, a feat unachievable on a general three-axis FDM machine. The embedded material effectively increased the stiffness of the FDM item and reduced the time and the cost of making it. If used properly, the embedded material could also lower the center of gravity of the FDM part to create better stability. We also demonstrated that the hybrid system could trim the freeform surface and enlarge the tapered hole of parts made by FDM. None of the features mentioned above can be implemented using tradition three-axis RP machines. We also demonstrated that the hybrid technique reduced the build time by 44% and 58% in two of the cases, respectively. The benefits of using the proposed hybrid system, which combined FDM and five-axis machining, were readily apparent.

Acknowledgement

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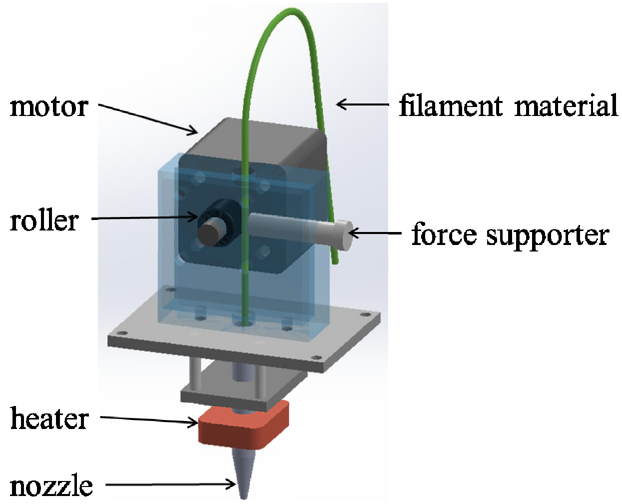


Figure 1:Schematic of an FDM extruder

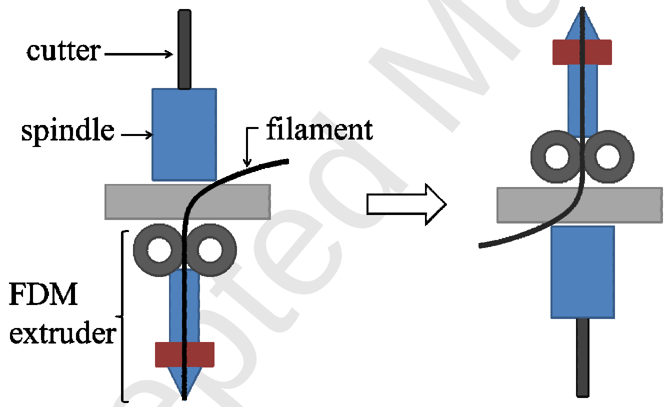


Figure 2: The FDM can be switched to the cutter by rotating the axis 180°

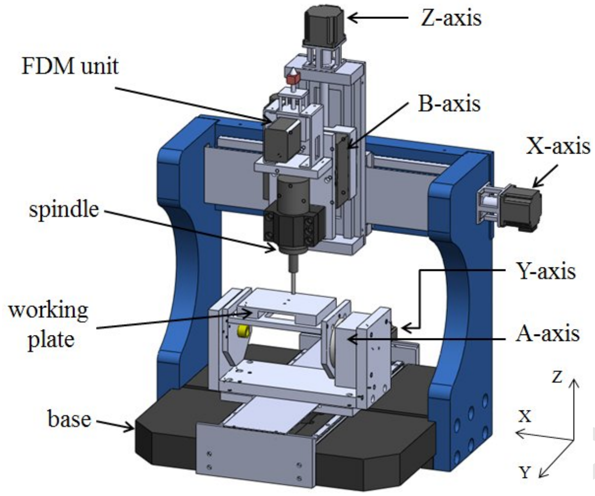


Figure 3: The design of the hybrid FDM and five-axis machine tool

Figure 4: The completed hybrid FDM and five-axis machine tool

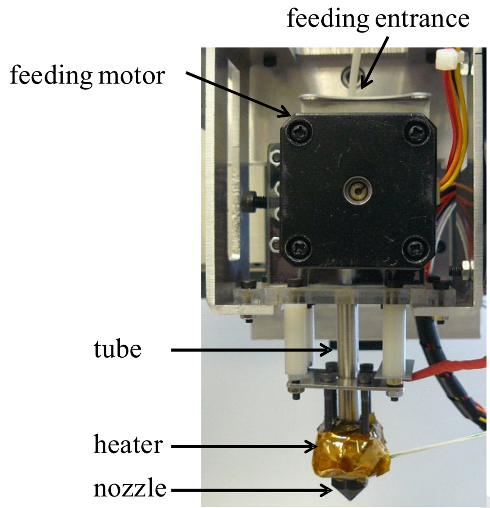
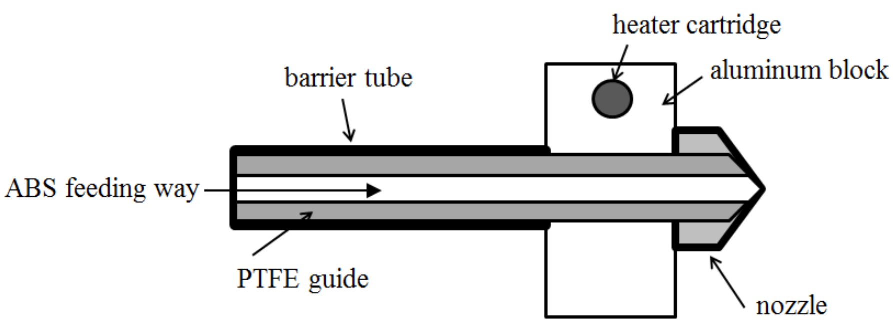
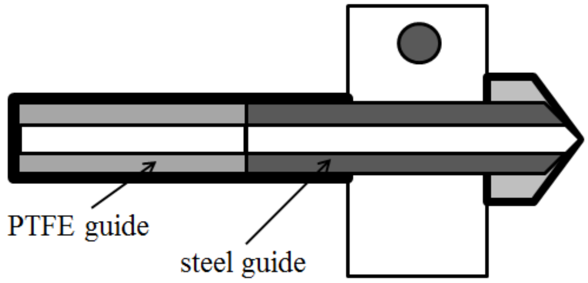


Figure 5: The FDM extruder including the feeding mechanism, the heater, and the nozzle



(a)



(b)

Figure 6: Schematic of the cross-section of (a) the original and (b) the modified FDM extruder

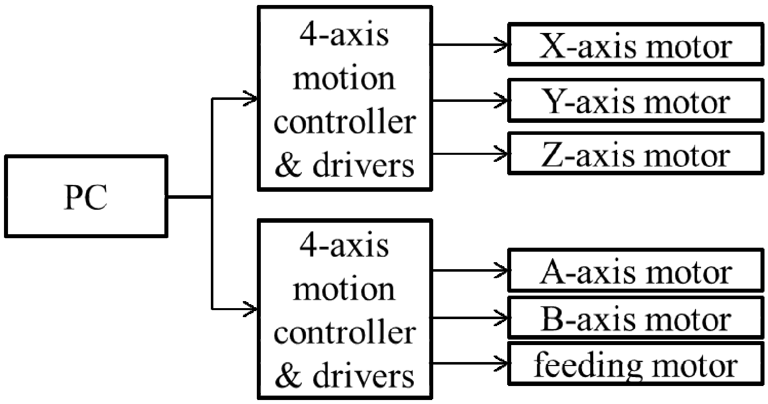


Figure 7: The control scheme of the hybrid system

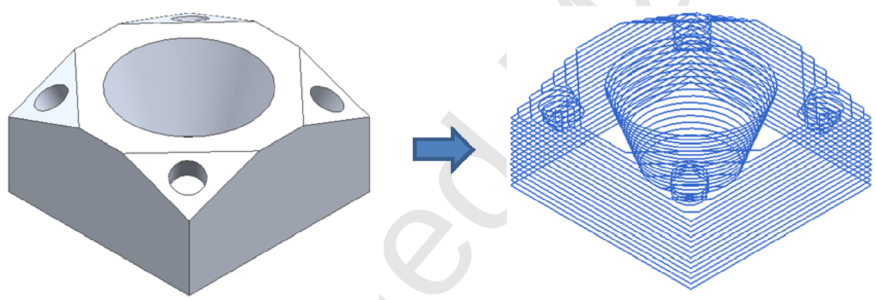


Figure 8: (a) CAD model of the object to be made; (b) contours of the sliced CAD model

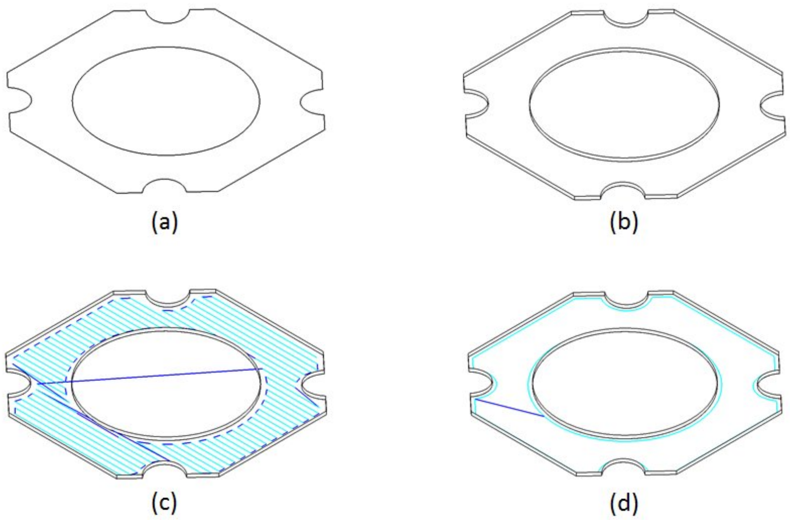


Figure 9: (a) Contour of a sliced layer; (b) the extrusion of the contour; (c) the tool path inside the extrusion; (d) the tool path along the contour of the extrusion

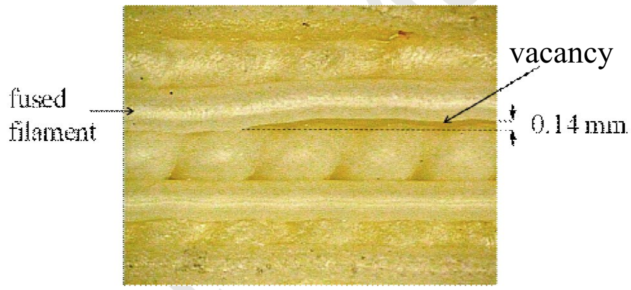


Figure 10: Side view of an FDM object showing the vacancy

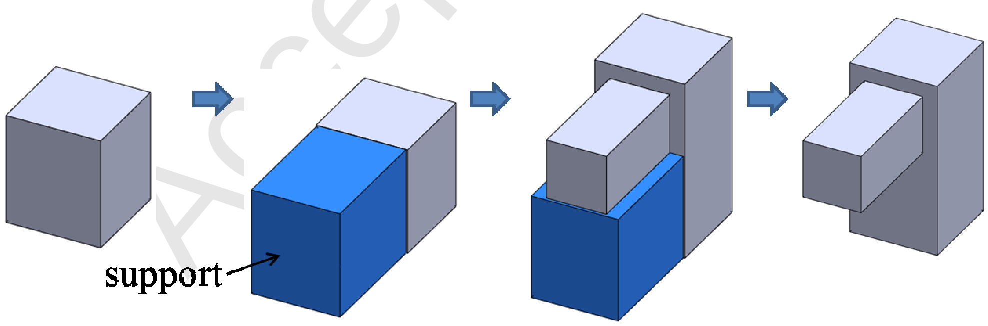
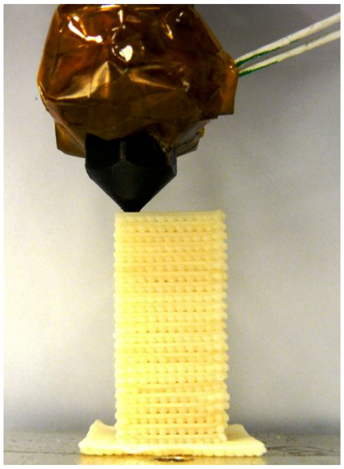
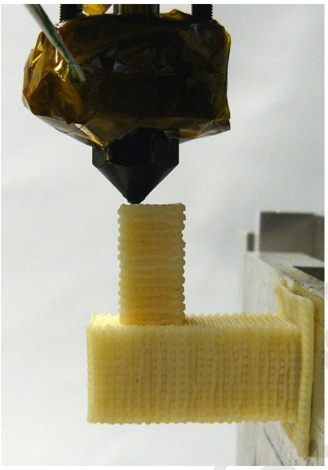


Figure 11: Steps for making an object with an overhang by traditional FDM



(b)



(b)

Figure 12: Using five-axis FDM to fabricate (a) the vertical portion and (b) the horizontal portion of the Γ-shaped component

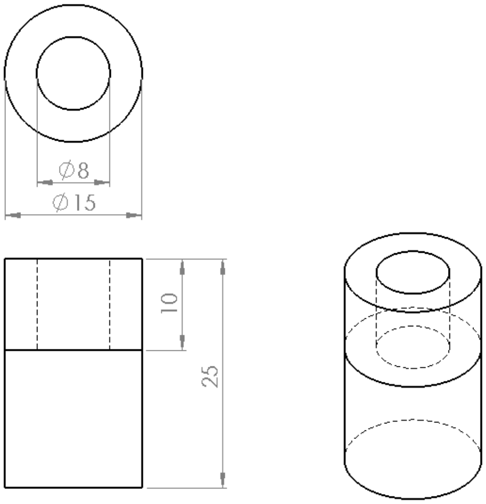
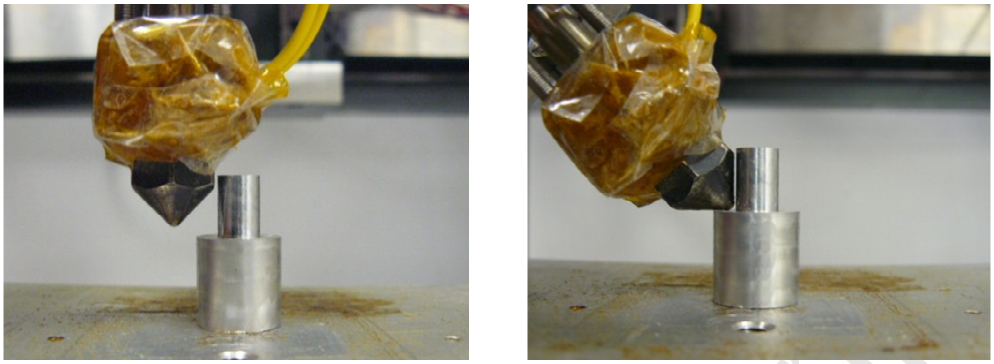


Figure 13: (a) Design of the aluminum to be embedded by FDM



(a) (b)

Figure 14: (a) Three-axis FDM cannot, but (b) five-axis FDM can, embed polymer around the aluminum

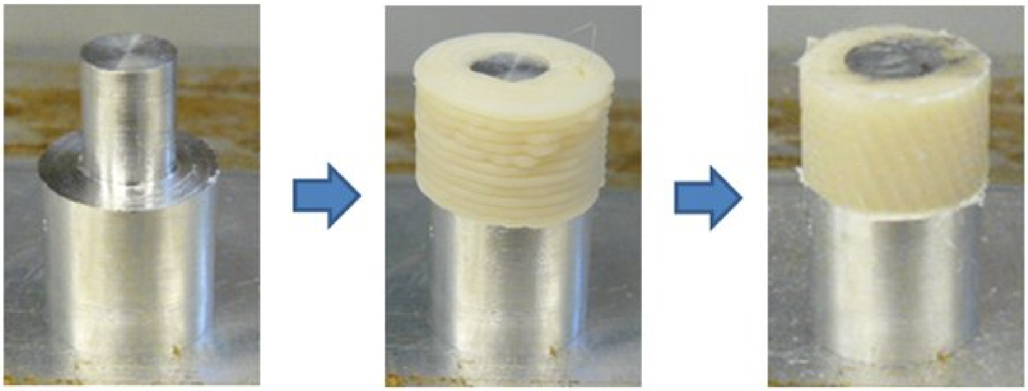


Figure 15: The stepped aluminum (left); the aluminum embedded in polymer before machining (middle) and after machining (right)

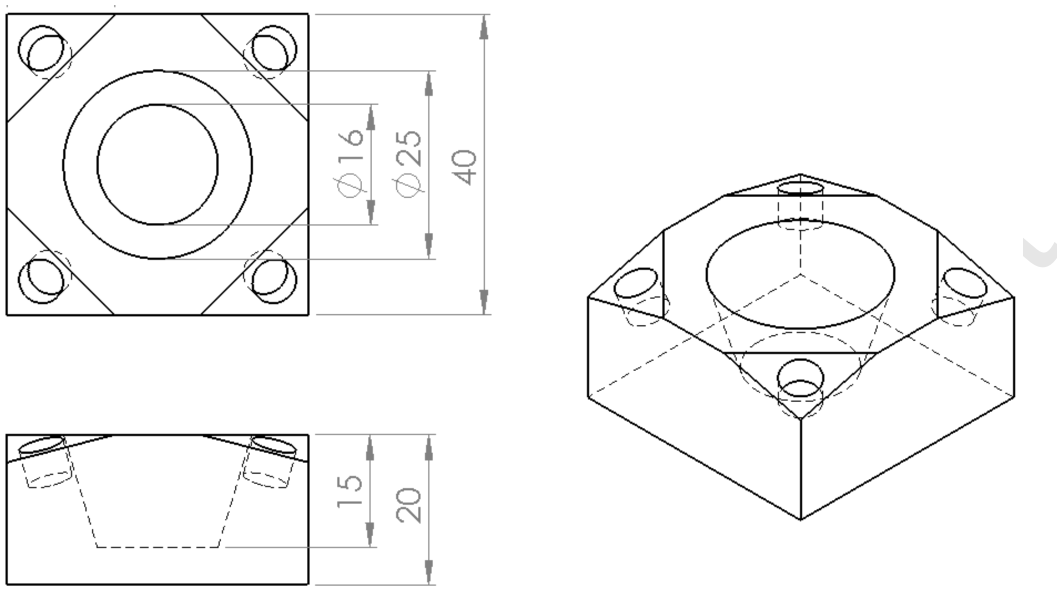
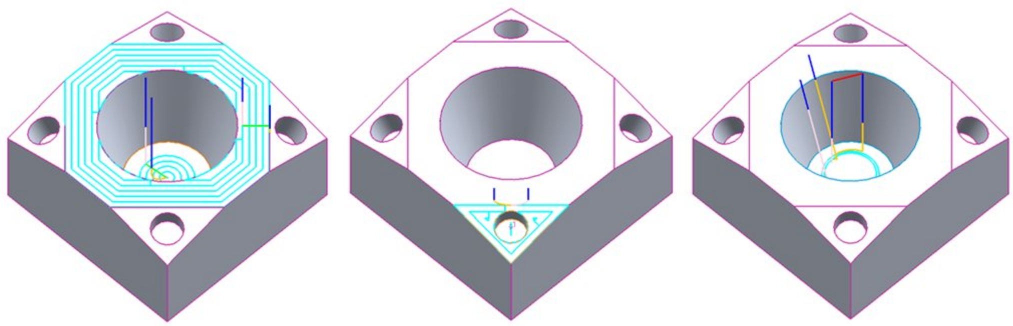


Figure 16: Design of the model used for hybrid FDM and multi-axis machining



(a) (b) (c)

Figure 17: The cyan lines represent tool paths of (a) three-axis; (b) three-plus-two axis; (c) five-axis machining

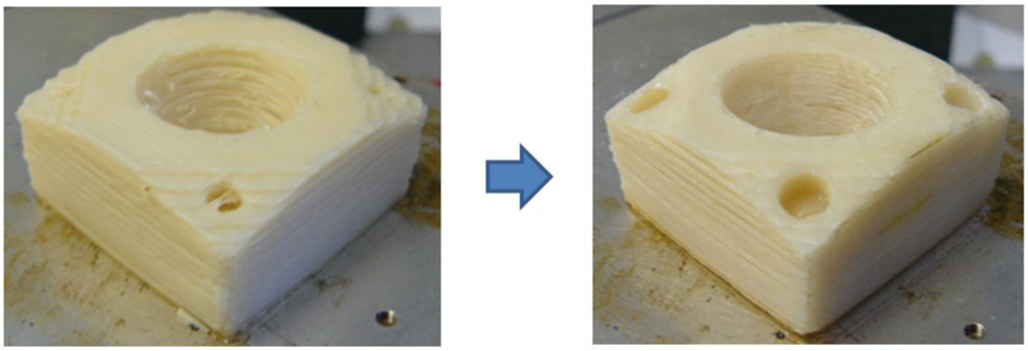


Figure 18: The FDM workpiece before machining (left) and after machining (right)

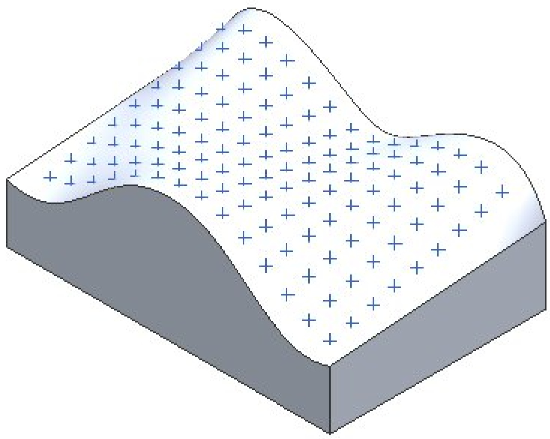
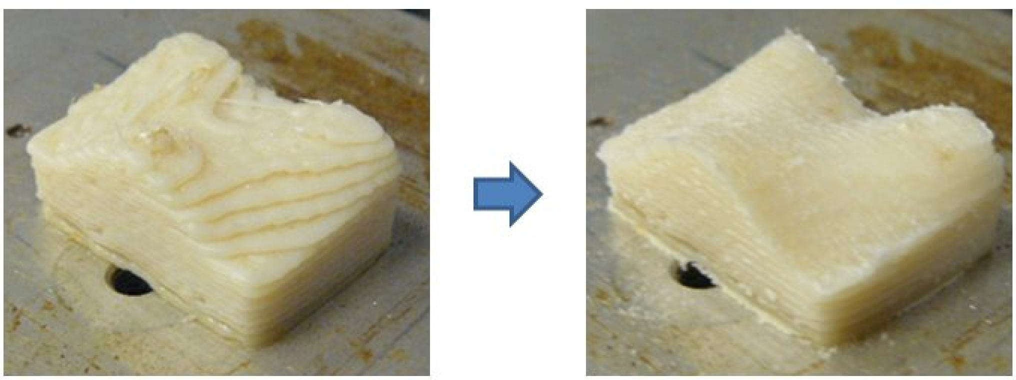


Figure 19: Freeform surface with interpolation points



(a) (b)

Figure 20: Freeform surface made by FDM before milling (left) and after milling (right)

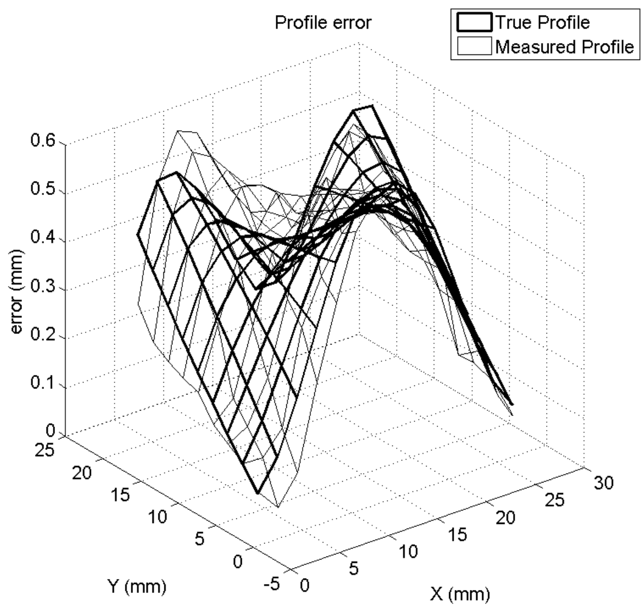


Figure 21: Comparison of the true profile and the measured profile of the freeform surface