Improvement of Dimensional Accuracy of 3-D Printed Parts using an Additive/Subtractive Based Hybrid Prototyping Approach

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Abstract. At present, two important processes, namely CNC machining and rapid prototyping (RP) are being used to create prototypes and functional products. Combining both additive and subtractive processes into a single platform would be advantageous. However, there are two important aspects need to be taken into consideration for this process hybridization. First is the integration of two different control systems for two processes and secondly maximizing workpiece alignment accuracy during the changeover step. Recently we have developed a new hybrid system which incorporates Fused Deposition Modelling (FDM) as RP Process and CNC grinding operation as subtractive manufacturing process into a single setup. Several objects were produced with different layer thickness for example 0.1 mm, 0.15 mm and 0.2 mm. It was observed that pure FDM method is unable to attain desired dimensional accuracy and can be improved by a considerable margin about 66% to 80%, if finishing operation by grinding is carried out. It was also observed layer thickness plays a role on the dimensional accuracy and best accuracy is achieved with the minimum layer thickness (0.1 mm).

1. Introduction

Rapid Prototyping (RP) technology, also known as ‘Additive Manufacturing (AM)’ or ‘Layered Manufacturing (LM)’ is a key method to manufacture components without the involvement of the expert model-manufacturers’ services (1). RP technology is able to construct the complete object directly from CAD (Computer Aided Design) model without help of any types of heavy and complex tooling. While with traditional methods the prototype needed to be constructed and finished manually (2). This technology has gained significant attention due to its capability to overcome many drawbacks of old-fashioned manufacturing techniques. Its ability to form almost any geometric feature or shape is a great advantage of AM (3). On the other hand, CNC (Computer Numerical Control) machining process is a subtractive manufacturing process with high-precision, high-flexibility, high-accuracy and high-speed. However CNC machining is not cost effective to use it for producing prototypes. Among the vast area of RP, a number of methods are used: Fused Deposition Modelling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), Selective Laser Cladding (SLC) Laminated Object Manufacturing (LOM), Multi-jet Modelling or Solid Imaging (SI), Laser Engineering Net Shaping (LENS), Selective Binding (SB)(4, 5). Due to inexpensive machinery, ease of operation, and durability of built objects, FDM is considered as the most appropriate process for RP due to its ease of operation, inexpensive
machinery and durability of built parts (6, 7). Final parts from FDM have good mechanical properties compared to other RP technologies (8). In this process, a plastic material (ABS or PLA) is melted and extruded through a nozzle layer-by-layer by means of a feed motor to build the required object. Generally, this plastic material is supplied in the form of a filament. Resistive heaters are contained by the nozzle that help to keep the temperature of the plastic just above its melting point. So, the plastic can easily flow through the nozzle and create the layer. After that, it hardens instantly and bonds to the previous layer. This procedure is continued till the shape of the prototype is being created is shown in figure 1.

![FDM Process](image)

**Figure 1. FDM Process(9)**

High surface roughness is one of the most noteworthy disadvantages of FDM process, specially if compared to other processes. The FDM can yield parts with complex features: nevertheless, for the reason of having residual stresses and shrinkage which occurred during running the RP process, the precision and accuracy of the produced product is usually low. Staircase effect causes poor surface quality that is another limitation of FDM (10). The layer thickness was found out as the most important aspect for the finished surface in FDM process (11). If we want to reduce the layer thickness, then we have to increase build time that will create another issue. So, for the solution of the above problems we are integrating the CNC grinding operation for final finishing operation on the FDMed parts. The finishing of additively manufactured (AM) components may be categorized into three mechanisms, namely: (i) mechanical conversion and machining e.g. grinding, milling and shot-peening; (ii) thermal processes including electron beam and laser melting; (iii) electrochemical and chemical processes, such as electro polishing and etching. Several subtractive processes have been vastly used in near-net shaping processes, such as die-casting, casting and moulding. This has now been extended to additive manufacturing, allowing feature geometries to be realized with greater accuracy and surface quality via subtractive processing. CNC turning was used to finish AM parts (12). Taminger et al. (13) used high speed milling to finish aluminium AM parts. Grinding has also been used to finish MAM parts (14, 15)Complex and intricate geometries pose a challenge for conventional grinding. In an attempt to alleviate this, Beauchamp et al. (16) used shape-adaptive grinding to finish AM parts. Above mentioned finishing of the AM parts were performed in different workstations. Some other researches have been done to finish the AM parts in a single workstation combining additive and subtractive manufacturing processes to achieve short build time and high accuracy. A hybrid process was developed with the combination of three-axis milling and SLC in which the laser head and the CNC milling spindle were attached on two vertically isolated axes (17). Similar to this another process was developed where CO2 laser welding was used as the RP process (18). Some other researches have been done where the only change in the implementing of RP process for example gas metal arc welding (GMAW) (19) and arc welding (20). Another type of hybrid process was developed by using laser cladding (LC) technology and five-axis machining as RP process and machining process respectively. But the limitation of that machine was its complicated mechanism (21). A different approach was adopted for the combination of
conventional machining process and RP process (22). Any type of machinable material could be used for the fabrication of the product with that method but may not be simply valid to products with a complex shape. This drawback was solved by using multi-axis (5-axis) milling machine to construct the undercut feature, lastly screws and pins were used to make the assembly (23). A more robust assembly was reported in which ultrasonic welding was used to connect sheet material (24). A hybrid RP system has been developed with the combination of five-axis machining and FDM. The FDM extruder was installed in a relation to the cutter spindle so that two modes could be interchangeable by 180° rotation of the axis which prevented the interference between the cutter spindle and FDM extruder (25). But at the same time, this design was bulky and the system needs more motors and actuators. Recently we have developed a new hybrid machining system which incorporates Fused Deposition Modelling (FDM) as RP Process and CNC grinding operation as subtractive manufacturing process in a single platform (9). It is figured out that a little research has been performed on a hybrid system for thermoplastic materials.

2. Experimental Setup and Procedure:

2.1. Newly Developed Hybrid Machine:

Incorporating the CNC spindle and the FDM extruder together on a single workstation without unnecessary bulky mechanism was the major issue with respect to designing this hybrid machining system. Maintaining alignment of CNC Spindle and FDM heat extruder during changeover process was the main issue for this one. In our newly developed hybrid machine we have used a rotary stage along Z-axis to incorporate the spindle rectangular shaped aluminium attachment on which the heat extruder and spindle head is attached respectively just parallel to the rotary stage. The rotary stage can be operated both manually and automatically. Another rectangular shaped aluminium attachment was attached perpendicularly to the rotary stage on which IR sensors were placed in a significant distance. These sensors were used to omit the misalignment problem during exchanging the equipment of CNC machining and FDM process. The rotary stage is able to be moved accordingly the difference of analog signals coming from the IR sensors. When the equipment (spindle or heat extruder) is at the correct position, two reflected IR signals come from at the same distance that means there is no difference between the signals as well as no voltage difference. Similarly, if the reflected IR signals come from different distances then there will be voltage difference which indicates that the object is not at the aligned position.
Figure 2(a) and 2(b) shows the 3D design of the newly developed Hybrid machine with CNC spindle and FDM extruder respectively.

![Figure 2. 3D design of the Hybrid Machine with (a) CNC spindle and (b) FDM heat extruder](image)

2.2. Control System of the Hybrid Machine

The total control system for the newly developed hybrid machine is PC-based. The whole control unit for the machine was developed using separate controller, circuitry to handle the CNC machining and FDM process. LabVIEW programming was used to control the whole hybrid machining system from a user friendly GUI. We have used NI PCI-7344, UMI-7764 and NI DAQ USB 6211 for movement of the machine. We have used three servo motors, one stepper motor, one rotary stage and two IR sensors which are desired to be controlled: three motors for the X, Y and Z axis, and the other one is for the FDM heat extruder. NI PCI 7344 motion controller was used for controlling the four motors. This controller is able to achieve simultaneous three-axis motion trajectories through linear, spherical, circular or helical interpolation, which will placate all our requirements for concurrent three-axis machining and also for the FDM operation.

2.3. Procedure

To design and Slice the CAD model of the required parts we have used SolidWorks and Slice3R respectively. After getting the G codes of the CAD model, firstly we produced the FDM part on our hybrid machining system and after that without removing the part from the position we did the grinding on the outer surface of the part. This was done by implementing CNC Spindle along the Z axis. We have done the same procedures several times for the objects with different layer thickness.

3. Results and Discussion:

The aim of this research was to identify the differences in dimensions between the 3D design and the completed object made by newly developed hybrid machine. To get a better dimensional accuracy and to identify the effect of layer thickness we produced objects with 3 different layers such as 0.1 mm, 0.15 mm and 0.2 mm. At first FDM was used to build several cubes layer by layer. After that we did CNC grinding operation to finish the produced FDM objects. For making the FDM part we used PLA filament, and diameter of the filament was 1.75 mm. The design dimensions of the cube were 15mm×15mm×10mm. For different layers we got different dimensions of the completed object from the hybrid machining system. Figure 3(a) shows that when the layer thickness is 0.1mm the layers were uniformly overlapped whereas figure 3(b) shows the layers were not uniformly overlapped when the layer thickness is 0.15 mm. Objects with layers thickness 0.2 mm have several gaps between two layers and causes the worst dimensional accuracy which is shown in figure 3(c).
Table 1 shows the dimensions of the produced objects from newly developed hybrid machining system.

**Table 1. Measured Dimensions (mm) for different layer thickness**

| Layer Thickness (mm) | Measured Dimensions (mm) Without Machining | With Machining |
|----------------------|--------------------------------------------|----------------|
| 0.1                  | 15.25mm × 15.28mm × 10.07mm                | 15.05mm × 15.10mm × 10.07mm |
| 0.15                 | 15.57mm × 15.65mm × 10.13mm                | 15.25mm × 15.22mm × 10.13mm |
| 0.2                  | 16.05mm × 16.10mm × 10.35mm                | 15.55mm × 15.35mm × 10.35mm |

The differences were 1.67%, 1.87% and 0.7% for each dimension, respectively while the part is without machining and the layer thickness was 0.1mm. As the targeted dimension for both length and width were same 15mm, that’s why the differences were almost same. After completing the FDM operation we did the grinding operation along the outer surface (length and width) of the objects. Then we got an improvement upto 80% accurate dimension in both length and width compared to the targeted dimension. The results of the research suggest that Hybrid process lies in ± 0.05 mm, ± 0.25mm and ± 0.55mm limit in regard to dimensional accuracy for layer thickness 0.1mm, 0.15 mm and 0.2 mm respectively of 3D printed parts. The comparison of each dimensions for different layer thickness are shown in the following figure 4(a) and 4(b). Standard error for both cases without and with machining is also shown in the figures. We have figured out that there was a significant change in the dimension of height with the increment of layer thickness. The possible causes for the difference in dimensions between the C and the completed component are described in the following. Firstly, the diameters of the fused filament produced by the FDM process were inconsistent. The variation of the fused filament diameter caused the variation of the final FDM part that consisted of the filaments. Secondly, as the
FDM extruder changed the moving direction, it was not possible to maintain its speed at a constant value and the FDM extruded more and less PLA material at the locations where the speed slowed down and the speed was up respectively, thus causing the PLA filament to become thicker and create the dimensional variation

![Comparison of dimensions in (a) Length and (b) width between Targeted and final parts](image)

**Figure 4.** Comparison of dimensions in (a) Length and (b) width between Targeted and final parts

which is specially happened when the layer thickness was 0.15 mm and 0.2mm. Thirdly, when the layer thickness is kept (0.2mm) half of the nozzle diameter (0.4mm) the fused filaments did not stick with each layer properly; gaps existed between the melted filaments which caused difference in dimensions of the final parts. The reason of the gap was firmly correlated to the layer thickness and also to non-uniform diameter of the melted filament. Another cause for the gap was the environment. As our hybrid machining system is not covered that’s why environmental air affected the melted filament to stick properly.

4. Conclusion:

In this paper, it has been shown that better dimensional accuracy is achievable with small layer thickness. When it is kept ¼ th of the nozzle diameter then there are small difference in dimensions compared to the targeted dimensions having almost uniformly fused filament. On the other hand when the layer thickness is ½ of the nozzle diameter then there are gaps between the layers. With our newly developed hybrid system we were able to improve the dimensional accuracy by a significant margin (upto ~80%). Better control of the speed of the nozzle and the temperature of both heater and heat bed might solve the issue of gap between layers which would help to achieve more accurate dimensions.
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