Robot Arm Platform for Additive Manufacturing: Multi-Plane Printing

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ABSTRACT

A conventional 3D printer utilizes horizontal plane layerings to produce a 3D printed part. However, there are drawbacks associated with horizontal plane layerings motions, e.g., support material needed to printed an overhang structure. To enable multi-plane printing, an industrial robot arm platform is proposed for additive manufacturing. The concept being explored is the integration of existing additive manufacturing process technologies with an industrial robot arm to create a 3D printer with a multi-plane layering capability. The objective is to perform multi-plane toolpath motions that will leverage the increased capability of the robot arm platform compared to conventional gantry-style 3D printers. This approach enables print layering in multiple planes whereas existing conventional 3D printers are restricted to a single toolpath plane (e.g. x-y plane). This integration combines the fused deposition modeling techniques using an extruder head that is typically used in 3D printing and a 6 degree of freedom robot arm. Here, a Motoman SV3X is used as the platform for the robot arm. A higher level controller is used to coordinate the robot and extruder. For the higher level controller to communicate with the robot arm controller, interface software based on the MotoCom SDK libraries was implemented. The integration of the robotic arm and extruder enables multi-plane toolpath motions to be utilized in the production of 3D printed parts. Using this integrated system, a test block with an overhang structure has been 3D printed without the use of support material .

1. INTRODUCTION

The continuous development of the rapid prototyping process, starting in the mid-1980s and continuing to this day, has caused some to declare it a third industrial revolution [1]. With rapid prototyping, the whole design process can be managed easily by a single operator, starting from conceptual ideas to virtual design and on to part fabrication. Rapid innovation to rapid production is the key element of the rapid prototyping process advantages. Complex geometric structures usually have limitations in fabrication using a conventional manufacturing processes, many of these limitations can be overcome with rapid prototyping

technology. Conventional manufacturing processes use a material removal process in order to fabricate a part. However, the rapid prototyping process utilizes an additive material process (3D printing) instead. 3D printing allows for the creation of a three dimensional object direct from a digital model. The digital model is generated using Computer Aided Design (CAD) software and is preprocessed through a slicer algorithm that breaks down the digital model into finite layers. The 3D printer recreates the sliced object layer by layer. A conventional plastic 3D printer utilizes a gantry style computer numerical controlled (CNC) machine to move the printer head. One of the constraints with the current process is that the gantry machine limits the motion of the extruder head to only translate in the x, y, and z directions. Because the extruder head cannot rotate, conventional 3D printers are limited to only printing in flat layers.

Fused deposition modeling (FDM) is a technique used in 3D printer extruder heads. The FDM process is performed by extruding a material through a nozel to form an object. The FDM method utilizes the movement of the gantry system to control where the material is deposited in a two dimensional plane. Layering of these planes vertically is what generates the 3D printed part (Figure 1). The material being extruded needs to be heated to a certain temperature based on the material properties in order for it to be able to flow through the nozzle. FDM is a widely used method for conventional 3D printing due to an inexpensive platform and the open-source movement [2].

Industrial robotic arms are a versatile platform used in most manufacturing industries. Flexibility in their functions is what allows them to be utilized in so many different applications including welding, painting, assembly, pick and place, product inspection, testing, etc. The industrial robot arm has a freedom of movement based on the number and types of joints that have been connected. The main advantage of industrial robot arms is the relatively high degree of freedom, (DoF). Because of this, a serial arm with 6 DoF is capable of performing multi-plane motions in their work environment compared to the gantry machine style conventional 3D printers that have 3 DoF are only capable of performing planar layering.

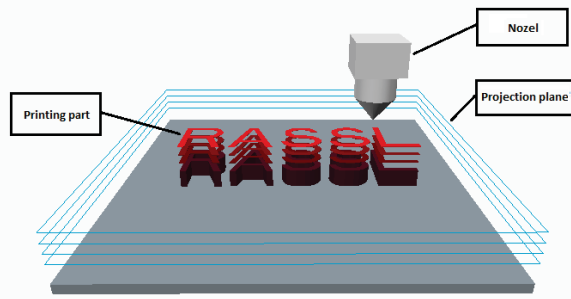In this paper, an additive manufacturing process using a robot arm as a platform is explored. The combination of a

Figure 1. Conventional 3D printer surface layered up strategy

3D printing element utilizing the fused deposition modeling method and a robot arm architecture that has 6 degree of freedom in its interaction with the work environment, allows for the development of multi-plane toolpath strategies that can offer better part performance and structural integrity. New toolpath generation is developed by introducing multi-plane toolpath layering to utilize the capability of the robot arm platform. The multi-plane toolpaths strategy allows for overhang features to be printed without support material. Finally, the future work on the robot arm platform in development is discussed.

2. LITERATURE REVIEW

There are many important factors which need to be considered to achieve the goal of developing a robot arm platform for rapid prototyping. The factors considered can be sorted into two groups, process parameters and process planning parameters, based on how they impact the performance of the system.

A process parameter can affect the dimensional accuracy and building time of the 3D printed part [3]. They are dependent on the 3D printing platform used. The three parameters we are considering are:

1. *Layer thickness* for traditional 3D printers, is how finely you can control the change in the vertical position of the extruder head between the printing of each slice or layer. A smaller layer thickness greatly increases the quality of the final part, however it increases the time needed to print.

2. *Deposition speed* is the speed of the extruder head movement. It depends on the machine's translation capability in the x and y directions to build up a surface layer. Since the part is built on a layer basis, z axis motion is only used after each surface layer is finished. High deposition speed can reduce the fabrication time to produce the part but may lead to lower part quality based on the machines repeatability.

3. *Flowrate* is the rate at which material leaves the nozzle of the extruder head. The flow rate must be synchronized with deposition speed and layer thickness to ensure that the correct amount of material is deposited to build the part.

Process planning parameters can effect the surface quality, mechanical strength (beside material properties), dimensional accuracy, and building time of the 3D printed part [4, 5, 6]. These parameters are co-dependent with the process parameters. The four parameters are:

1. *Orientation* can effect the part's outer surface quality, fabrication time, design of the support structure, and the slice thickness.

2. *Support structure* is used to support the fabricated part. Overhanging and hollow part features may need to have a support structure. The structure gives the printer a surface on which to build features that would otherwise be unsupported and consequently unprintable.

3. *Slicing* is the process of converting a three dimensional part to a stack of two dimensional surface planes. When these layers are printed one on top of another, they approximate the three dimensional part. High slice resolution will achieve a greater approximation of the part model. Fabrication time will increase as the resolution increases. Low slice thickness can reduce the fabrication time but may end up with staircasing outer surface quality.

4. *Toolpath generation* is trajectory planning for the extruder nozzle. There are several toolpath strategies that are being implemented on a fill pattern in current 3D printers such as zig-zag, contour, spiral and partition patterns. The choice of toolpath strategy can affect the mechanical properties of the fabricated part, as well as the printing time.

To achieve multi-plane motion of the extruder, many different hardware configurations may be used. The concept of multi-plane motion as it pertains to this project has been previously studied by Keating and Oxman [7], Lee et al. [8] and Ishak et al. [9].

Keating and Oxman [7] introduced a compound fabrication technique using a robot arm as a platform. It is a multi-functional robot platform for digital fabrication and manufacturing. The compound fabrication approach combines additive, formative and subtractive fabrication processes in one platform to produce a 3D part. One of additive fabrication process used from the setup is using a fixed extruder position with a moving building platform attached to a robot arm.

Multi-plane motion for additive manufacturing also can be achieved by the integration of a five-axis machine and a FDM printer head. Lee et al. [8] combined FDM extruder to the five-axis machine. The FDM extruder was installed to the tool post. The five-axis machine allowed the multi-plane printing process to be implemented. The 3D printing process is done by generating a toolpath in 2D planes and a rotating platform is used to orient building orientation. This setup allows for the elimination of support material.

Ishak et al. [9] introduced an integration of existing additive manufacturing process technologies with an industrial robot arm to create a 3D printer with a multi-plane layering capability. The integration enabled print layering in multiple planes whereas existing conventional 3D printers are restricted to a single toolpath plane (e.g. x-y plane). A
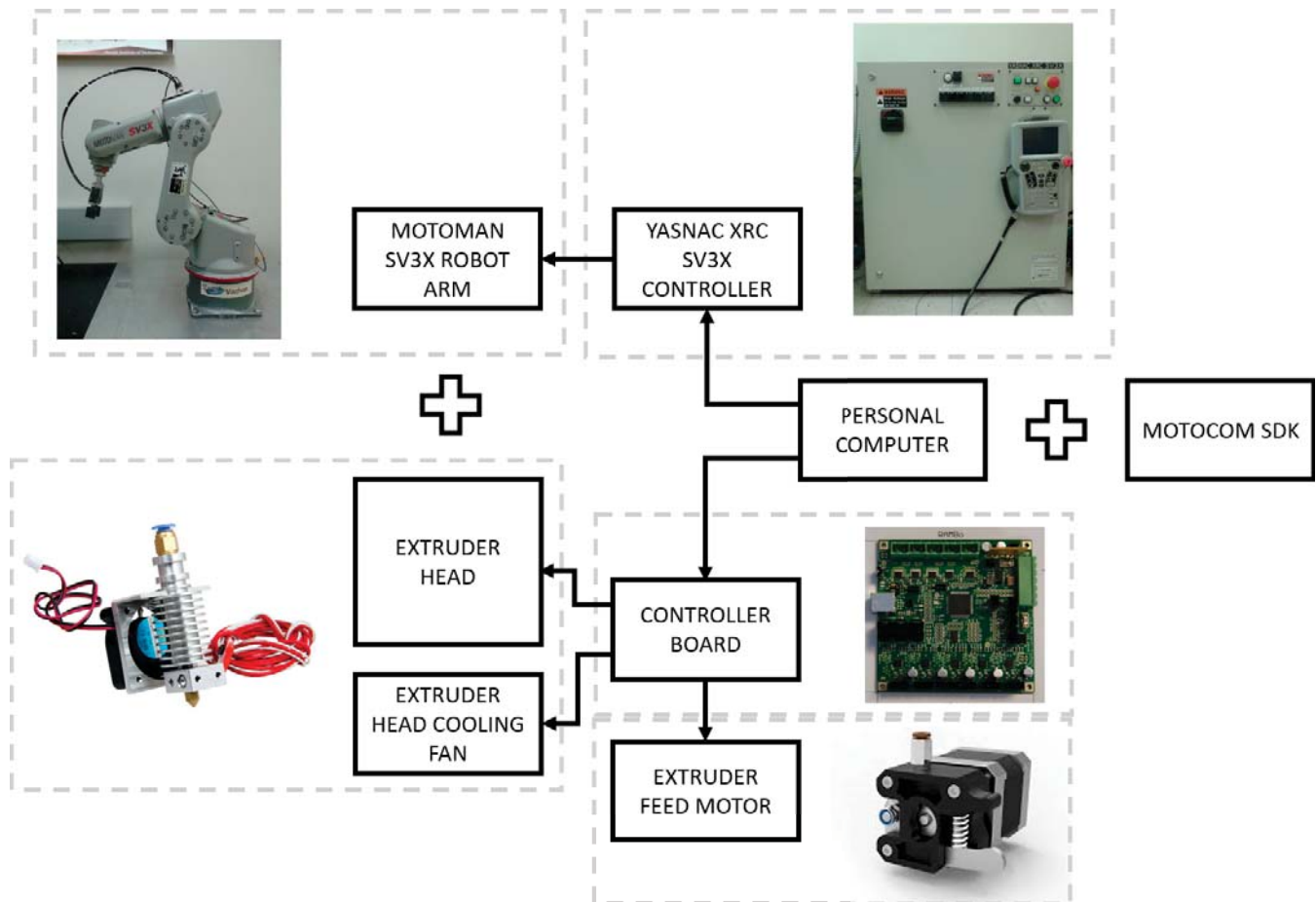
Figure 3. Block diagram for the development setup

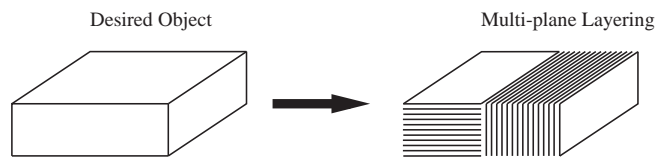Desired Object   Multi-plane Layering

Figure 2. Multi-plane toolpaths strategy [9]

test block was printed utilizing the the multi-plane toolpath strategy. The multi-plane toolpath strategy used by Ishak et al. [9] is shown in Figure 2.

Because the hardware architecture of higher DoF printers can perform multi-plane printing, a part with an overhang structure can be printed without the use of support material.

3. METHODOLOGY

In this section, we provide a general description of the robot arm as a platform for additive manufacturing. To investigate the idea of printing overhang structures without support material, an industrial robot arm was utilized as the platform to perform multi-plane toolpaths and integrated with an extruder head typically used in gantry-style 3D printing process.

3.1 Hardware

The robot system used includes a Motoman model SV3X arm driven by a Yasnac XRC SV3X controller. The SV3X has a maximum speed of 7.33 rad/s for the wrist angle, with maximum reach of 677 mm. The 3D printer components utilized are a Reprap J-head Hotend with a 0.4mm Nozzle and an extruder motor mounted in a remote Bowden configuration. The system is setup for filament made of PLA plastic. A block diagram of this system is shown in Figure 3

3.2 Software

A personal computer (PC) was implemented as the higher level controller. The PC runs custom software that interfaces with the XRC robot controller as well as the controller board for the extruder. Communication with the robot is accomplished by using the MotoCom SDK libraries. Communication between the PC and the extruder controller is facilitated by an Arduino board flashed with the Repetier Firmware [10]. Having a single program on the PC controlling the whole system allows for the movement and material deposition speeds to be controlled synchronously. The higher level control software was developed using Microsoft Foundation Class (MFC) Library created using Microsoft Visual Studio.
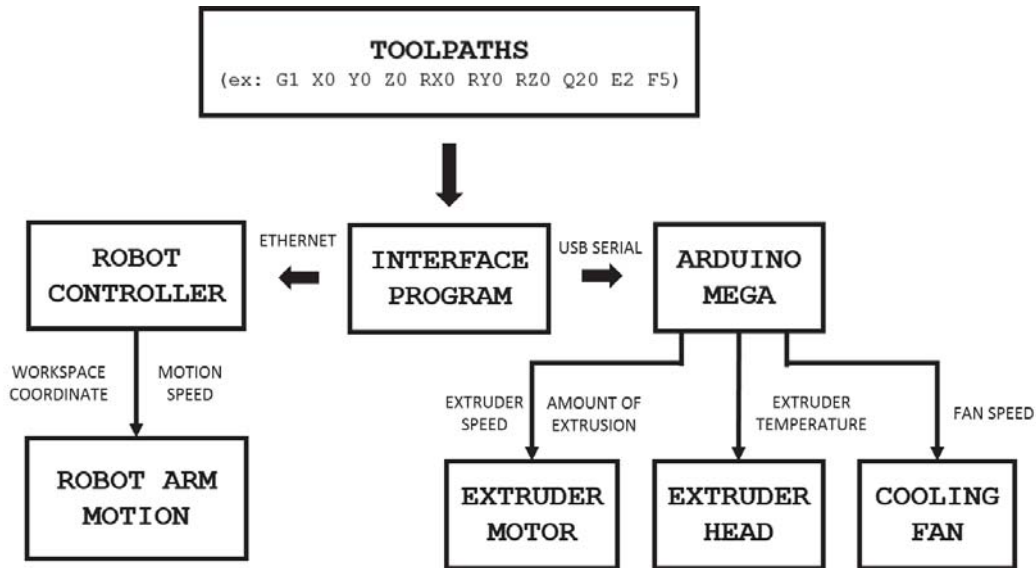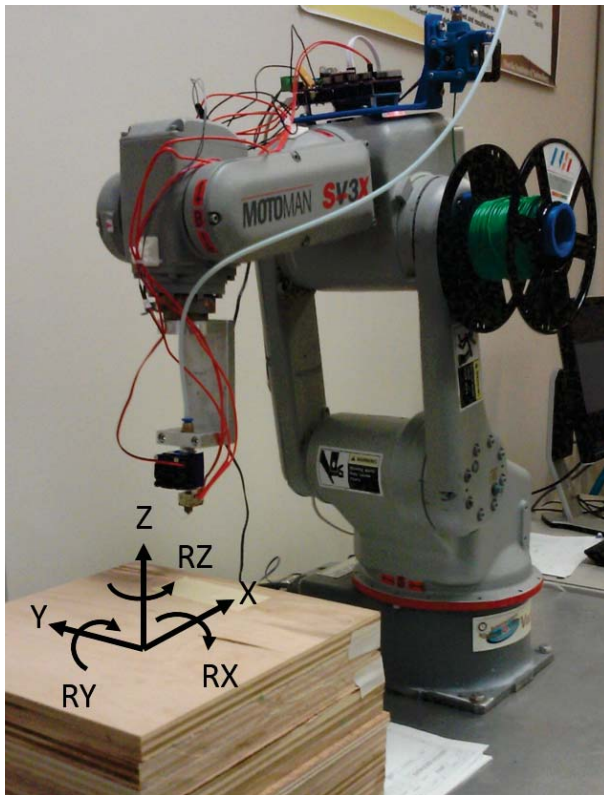
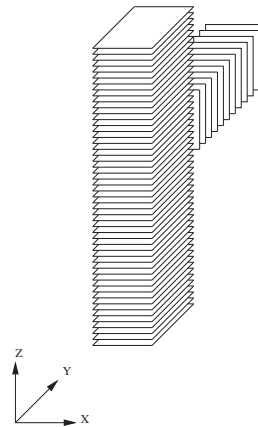**Figure 4.** Printing process architecture

Figure 6. Multi-plane toolpaths layering with overhang structure

3.3 Interfacing Hardware & Software

Communication between hardware and software is crucial in order to successfully 3D print parts. The process involved coordination between the extruder system and the robot arm. The printing process's architecture is shown in Figure 4. The printing process starts by reading toolpaths from a text file. The toolpaths contain information for the printing workspace and extruder parameters. The printing workspace parameters are X, Y, and Z axis coordinates, RX, RY, and RZ axis wrist angles and the motion speed. A graphical representation of the printing workspace for the robot arm system is shown in Figure 5. For the extruder system, it have four parameters, i.e., extruder flowrate, amount of extrusion, extruder temperature and cooling fan speed. The printing workspace and the extruder system parameters data are sent to the robot controller through the interface program. The communication with the robot arm is using Ethernet protocols and the extruder system is using USB UART protocols.
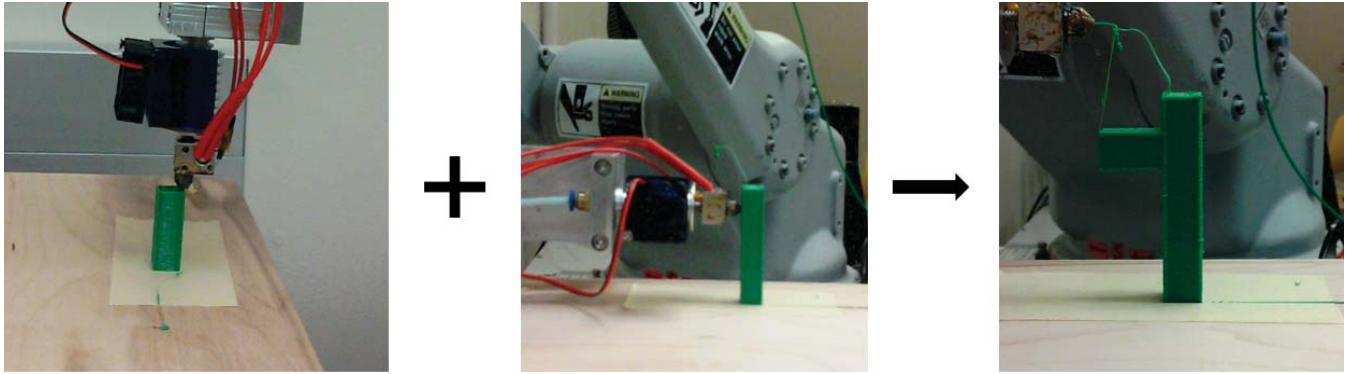

Figure 5. Workspace coordinate frame

Figure 7. Multi-plane printing

4. MULTI-PLANE PRINTING

In order to demonstrate the capability of multi-plane printing, a test block with an overhang structure was printed using the platform. The test block dimensions are 10 mm width × 10 mm length × 60 mm height and the overhang structure dimensions are 10 mm width × 20 mm length × 10 mm height. The printing toolpath strategy used is a combination of x-y plane (horizontal) and y-z plane (vertical) layering. A graphical representation of the multi-plane printing toolpaths is shown in Figure 6. The horizontal and vertical planes are chosen for the toolpath layering because they demonstrate the capability of the robot arm platform to perform multi-plane motions.

The test block printing process is shown in Figure 7. The printing process is started by extruding filament in the horizontal x-y plane. The x-y plane printing process is used to produce the 10 mm × 10 mm × 60 mm structure. To create the overhang structure, the extruder head was rotated -90° about the X axis. The printing process continued on the side of the block in vertical x-z plane. The x-z plane printing process was used to produce the 10 mm × 20 mm × 10 mm structure. To reduce the printing time, the test block only used two inner toolpaths for each layer.

5. FUTURE WORK

The use of the robotic arm platform for rapid prototyping enhanced the current capability of additive manufacturing. 3D printed parts with overhang structures are able to be printed with the use of multi-plane printing. With these new possibilities, new inner and outer toolpaths can be explored. The outer toolpaths act as the shell of the 3D printed part. Density of the inner toolpaths can be change to reduced the printing time and usage of filament. The inner toolpaths that could be introduced are based on 3D lattice structures which should provide substantial strength with minimal filament usage. We showed that current inner and outer toolpaths can be printed not only in the horizontal plane, but also in vertical planes. The continued development should focus on non-planar toolpath strategies that can be produced with the use of the robot arm platform.

6. CONCLUSIONS

In this article, we presented the integration of a 6 DoF robot arm with an extruder head used in conventional 3D printing systems. The integration of the system enables it to perform multi-plane printing to produce 3D printed parts. An overhang structure without support material can be printed with the use of the robot arm platform and the extruder head. New material toolpath strategies can be explored that may lead to improvement in the mechanical strength of the fabricated part, in the fabrication time to produce the part, and in the filament usage.

7. ACKNOWLEDGMENTS

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