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ROBOT ARM PLATFORM FOR ADDITIVE MANUFACTURING USING MULTI-PLANE TOOLPATHS

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ABSTRACT

This article discusses the concept of using an industrial robot arm platform 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 develop 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 control the robot and the extruder. To communicate with the robot, MotoCom SDK libraries is used to develop the interfacing software between the higher level controller and the robot arm controller. The integration of these systems enabled multi-plane toolpath motions to be utilized to produce 3D printed parts. A test block has been 3D printed using this integrated system.

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]. 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 from a digital model. The digital model is generated using Computer Aided Design (CAD) software and is preprocessed through a slicer algorithm in order to generate an additive layer from which the design can be built up 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 planar layers. Gantry-style 3D printers cannot perform multi-plane layering because the extruder head will collide with the part being printed if using different layering planes due to the workspace geometry.

Fused deposition modeling (FDM) is a technique used in

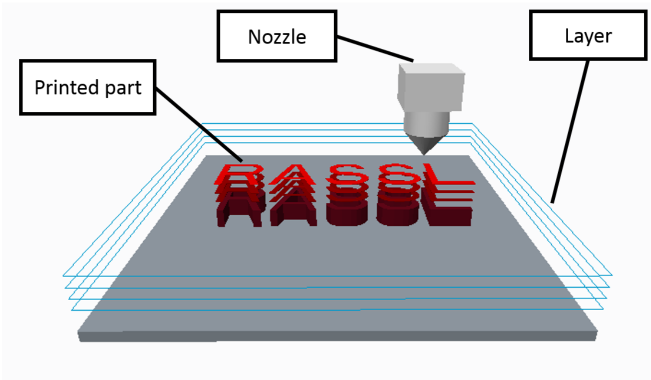

FIGURE 1: CONVENTIONAL 3D PRINTER SURFACE LAYERED UP STRATEGY.

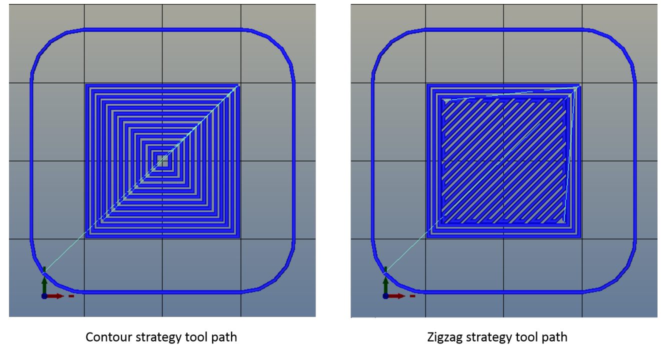

FIGURE 2: TOOL PATH STRATEGY CREATED USING SLIC3R [7].

3D printer extruder heads. The FDM process is performed by extruding a material through a nozzle 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. The layering of these planes vertically is what generates the 3D printed part (Fig. 1). The material being extruded needs to be heated 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]. In order to generate multi-plane motion to increase the layering capability, a serial link manipulator or robot arm can be used as a platform.

Industrial robot arms are a versatile platform used in most manufacturing industries. Flexibility in their motion capabilities is what allows them to be utilized in so many different applications including welding, painting, assembly, pick and place, product inspection, testing, and many more. 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 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 to perform planar layering.

The process performance and output product characteristics of a 3D printing process can be determined from certain parameters. Their parameters can be organized into two distinct groups: process parameters and process planning parameters [3–6].

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*. 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*. Deposition speed is the speed at which the extruder head moves. It is dependent upon the machines capability to translate in the horizontal (x-y) plane to build a layer of the part. Since the part is built in 2D layers, translation in the z direction is only used after each layer is completed. Because of this, the speed in the z direction is not a factor when looking at deposition speed. Having a high deposition speed can reduce the fabrication time of a part, however, it may lead to lower part quality. This is dependent on the repeatability of the 3D printing platform used.
3. *Flow rate*. Flow rate 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 are parameters that can affect the surface quality, material properties, dimensional accuracy, and building time of the 3D printed part [4–6]. These parameters are co-dependent with the process parameters. The four parameters considered are:

1. *Orientation*. Orientation in the 3D build volume of the printer can affect the quality of the parts outer surface, fabrication time, material property of a geometric feature and the amount of supporting structure needed.
2. *Support structure*. Support structure is used to support the fabrication part. Overhanging and hollow geometric 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*. Slicing is the process of converting a three dimen-

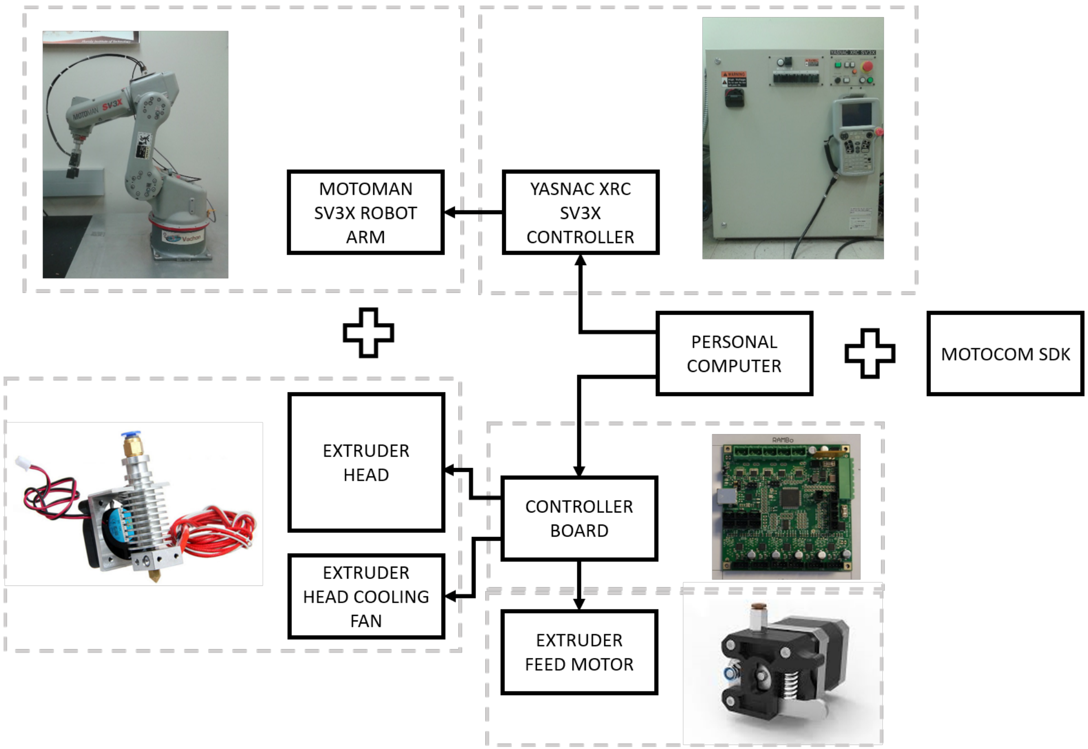

FIGURE 3: BLOCK DIAGRAM OF THE DEVELOPMENT SETUP.

sional part to a stack of two dimensional surface planes, each with a layer thickness. When these layers are placed one on top of one 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, but it will improve the part's surface quality. Low slice resolution can reduce the fabrication time but the poor approximation of the part's curvature may result in the surface appearing like a staircase, with each layer appearing as a step.

4. *Toolpath generation*. Toolpath generation is trajectory planning for the extruder nozzle. The toolpath can be divided into two sections; outer fill and inner fill. The outer fill toolpath produces the exterior surface of the printed part. The inner fill is a toolpath pattern for the interior of the printed part. 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. Examples of toolpath generation are shown in Fig. 2. Each toolpath strategy can affect the mechanical properties of the fabricated part, as well as the printing time.

Here, the concept of additive manufacturing using a robot arm as a platform is explored. The combination of 3D printing elements utilizing a fused deposition modeling method and a robot arm architecture that has a greater degree of freedom (DoF) in its interaction with the work environment, allows for the development of new toolpaths strategies that can offer better part performance. Compared to conventional gantry-style 3D printing parameters, new process planning parameters need to be developed to effectively utilize the increased number of DoF for multi-plane layering. New toolpath generation is develop by introducing a multi-plane toolpaths layering to utilize the capability of the robot arm platform. Finally, the future works on the robot arm platform in fabrication are discussed.

RELATED WORK

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 [8] and Lee et al. [9].

Keating and Oxman 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

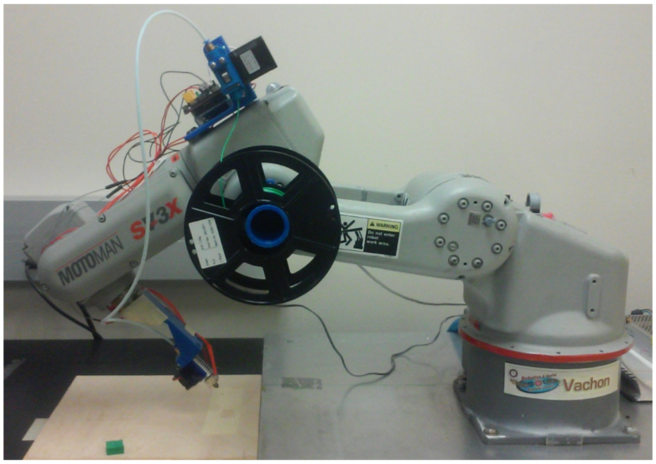

FIGURE 4: HARDWARE SETUP.

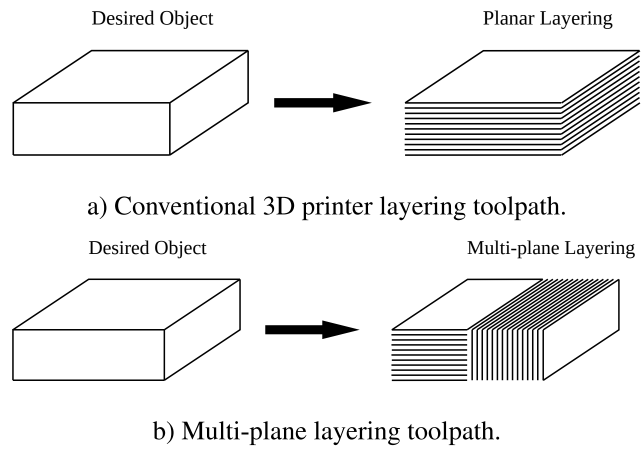

FIGURE 5: LAYERING TOOLPATH.

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. [9] 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.

Because the hardware architecture for higher DoF printers must change from the low DoF gantry CNC machine, to produce multi-plane motion, new toolpath strategies need to be developed. The higher DoF printers will allow users to leverage the capability of the multi-plane motions.

METHODOLOGY

To investigate the idea of performing multi-plane toolpaths in additive manufacturing, an industrial robot arm was utilized as the platform and integrated with an extruder head typically used in gantry-style 3D printing process.

Hardware

To enable multi-plane toolpath motions for 3D printing, a standard six revolute joint industrial robot arm from Motoman, model SV3X, is integrated with an extruder head from Reprap J-head type hotend for 1.75 mm filament with a 0.4 mm nozzle. The extruder head incorporates a remote Bowden style extruder motor setup as a filament feeder. The print head extrudes filament made of PLA plastic, which is a thermoplastic polymer. The Motoman SV3X has a maximum speed of 7.33 rad/s for the wrist angle, with maximum reach of 677 mm, repeatability of $\pm$ 0.03 mm, and the controller used is the Yasnac XRC SV3X. A block diagram of the system model is shown in Fig. 3.

Software

A program was created to interface the Motoman XRC controller with the extruder control board. Communication between these two systems is critical to developing a robust 3D printer as the robot and extruder need to be synchronized to deposit material appropriately. In order to be able to control the robot arm, the MotoCom SDK libraries are used to communicate between a personal computer (PC) and the robot controller through Ethernet communication. Besides controlling the robot arm, the program control the extruder parameters through the extruder controller board using an Arduino as an interfacing platform with USB UART protocol. The Arduino board is uploaded with Repetier-Firmware [10] to control the extruder parameters. The program uses a PC for preprocessing operations as well as control and synchronization of the robot arm and extruder system by acting as the common data connection between the respective controllers.

Interfacing hardware and software

The effective and efficient interfacing of the various hardware and the software components is crucial in order to successfully generate 3D printed parts. The process involved coordination between the extruder system and the robot arm motion parameters. The robot arm system has 7 parameters that need to be defined in order to generate motion of the extruder head in a printing workspace. 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 Fig. 7. For

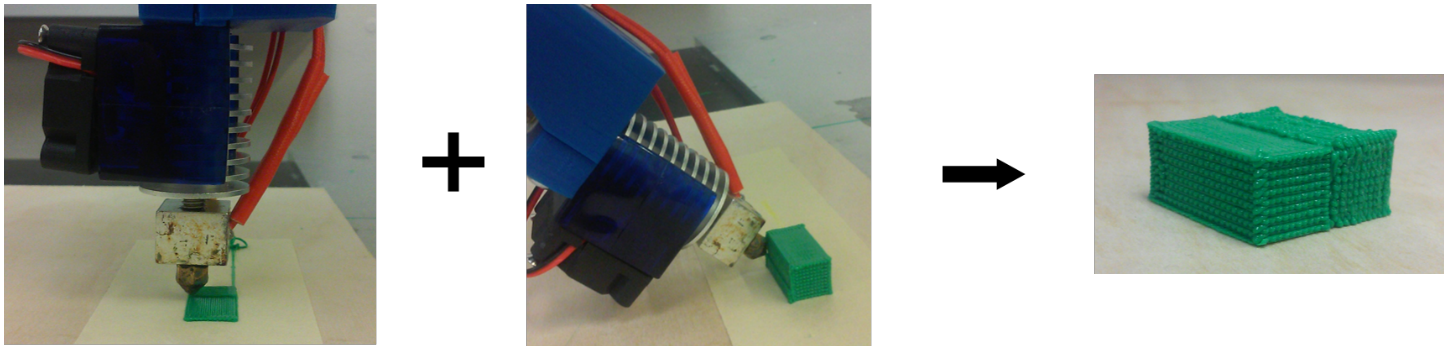

FIGURE 6: MULTI-PLANE PRINTING.

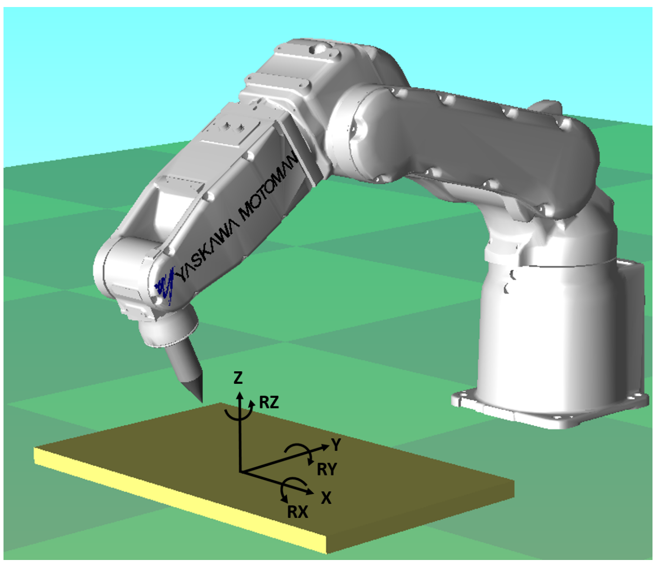

FIGURE 7: WORKSPACE COORDINATE FRAME.

the extruder system, certain parameters are needed to control the extruder head. The extruder parameters are flow rate, amount of extrusion, extruder fan speed, and extruder temperature. The deposition speed is depend on the motion of the robot arm. The robot arm motion and the flow rate of the extruder system were executed concurrently. A text file is used to store the instructions to control the robot arm and the extruder subsystems. The robot arm motion and the extruder system are written in GCode [11]. To control the printing process, the interfacing software sends the GCode command from the PC to the extruder controller board and the robot controller. The GCode command specifies the deposition speed, move location and orientation, flow rate and amount of extrusion of the extruder head along the desired toolpath (e.g. G1 X0 Y-10 Z0 RX0 RY0 RZ0 Q20 E0.3 F80).

MULTI-PLANE TOOLPATHS

In order to demonstrate the capability of the integrated system, a test block was printed using the platform. The test block is a rectangular prism with dimensions of 20 mm × 20 mm × 10 mm. The printing toolpath strategy used is a combination of x-y plane (horizontal) and y-z plane (vertical) compared to a conventional 3D printer toolpath that can print in only x-y planar motion. Graphical representations of the planar and multi-plane toolpaths are shown in Fig. 5. The horizontal and vertical planes are chosen for the toolpath layering because they demonstrate the motion capability of the robot arm platform to perform multi-plane motions.

Implementation

The printing process is started by uploading a text file to the interfacing software. After that, the process continues by initializing the robot arm and the extruder system connection using Ethernet and the USB UART protocol. Initial configurations for the extruder (i.e. fan speed and extruder temperature) are sent through the interfacing software. The interfacing software waits for the extruder to achieve the desired temperature before transmitting the GCode command containing the toolpaths. Interactions between deposition speed and flow rate of the extruder head effect the surface quality, material properties, dimensional accuracy, and building time of the printed part. To ensure a successful printing process, the deposition speed and the flow rate of the extruder head are tested by printing a single toolpath layer in each plane. The test print is done to verify the capabilities of the robot arm platform to perform different planes layering motion. Here, the deposition speed is set at 0.02 m/s and the extruder temperature is set to 190°C during the printing process of the test block.

The test block printing process is shown in Fig. 5(b) and Fig. 6. The printing started by extruding filament in the horizontal x-y plane. A zig-zag toolpath was used as the printing contour. The layers alternate between x-y and y-x contour toolpaths. The printing continued on the side of the block in the vertical z-y plane. The layering process also alternated in this operation. Alternating between the z-y and y-z planes with zig-zag contour toolpaths. The completed printed part is shown in Fig. 6.

FUTURE WORK

To show the viability of robot arms as rapid prototyping platforms, the system described here utilizes a robot arm platform for rapid prototyping to enhance the current capability of additive manufacturing. With these new possibilities offered by the multi-plane motion, new inner and outer fill toolpath strategies can be explored. Inner fill toolpaths can be developed into multi-plane toolpaths or lattice structure toolpaths. The outer fill toolpaths can also be developed by implementing a contour planar toolpaths or a contour multi-plane toolpaths strategy to provide smooth 3D surfaces.

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. With multi-plane motion, an overhang structure can be 3D printed without the use of support material [9].

The printed test block from the multi-plane toolpaths layering process had stepped edges on the side surfaces (see Fig. 6). This is cause by the filament overflow through the extruder as its direction of motion was changed. The additional deposited material, caused by the transition delay between each toolpath motion also affected the final dimensions of the test block. The measured dimensions of the actual test block were 21.95 mm $\times$ 22.05 mm $\times$ 10.31 mm. The test block was measured using a vernier caliper with a resolution of 0.01 mm. The variances were 9.75%, 10.25% and 3.1% for each dimension, respectively. The discrepancy between the design and the actual printed test block dimensions are caused primarily by the transition delays. Further calibration needs to be implemented to reduce the effect. One possible method being explored is to retract a small amount of the filament on each toolpath transition, reducing the flow rate through the nozzle, to overcome the overflow. The toolpath chosen also did not include an outer fill toolpath. An outer fill toolpath may have reduced or eliminated the formation of stepped edges. The shell contour on each layer could be done with the same or different planes as the inner fill pattern layer or it could utilize a multi-plane layering scheme. To reduce the printing time and usage of filament, inner fill patterns could be implemented into the toolpath strategies, rather than the solid zig-zag fill used. One of the new infill patterns that could be introduced is using lattice based structure toolpaths. By changing the infill pattern density, the printing time and usage of filament may be reduced but this may compromise the mechanical properties of the final part. The correlation between infill pattern strategies and material properties of multi-plane toolpaths layering need to be further studied.

CONCLUSION

In this paper we presented the integration of a 6 DoF robot arm and an extruder head used in conventional 3D printing systems. The advantage of the integration is the capability to perform multi-plane toolpath motions to produce 3D printed parts. This system architecture has the potential to increase the current additive manufacturing process capabilities with the new integrated system leveraging the advantage of the robot arm's kinematics. New material layout strategies can be explored that may lead to the improvements in the mechanical properties of the fabricated part, fabrication time to produce the part, and filament usage.

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