

A ROBOT ARM BASED ADDITIVE MANUFACTURING SYSTEM

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ABSTRACT

This article discusses lessons learned in the conceptualization and realization of using an industrial robot arm platform for additive manufacturing. Conventional 3D printers, especially those employing fused deposition modeling (FDM) processes, are restricted to depositing material in a single toolpath plane (e.g. x-y plane). To ameliorate this limitation, we have been exploring various kinematic architectures and motion planning methods. The focus of this study was to explore the feasibility of integrating commercial off the shelf (COTS) additive manufacturing technologies with a six degree of freedom industrial robot arm to yield a 3D additive manufacturing system with the capability to perform free-form six degree of freedom fused deposition modeling. Here, we utilized the general motion capabilities of an industrial robot arm to yield the ability to deposit material as desired in three dimensions. A Yaskawa Motoman SV3X six degree of freedom general purpose industrial robot arm was equipped with a fused deposition modeling extruder print head. This integration combined two mature technologies, industrial robot arms and FDM print heads, into a new system with new additive manufacturing capabilities that we call *MotoMaker*. In this paper we summarize the knowledge gained and lessons learned in developing the MotoMaker robot platform for additive manufacturing.

Keywords: 3D printing; additive manufacturing; fused deposition modeling.

UN SYSTÈME DE FABRICATION ADDITIVE À BASE DE BRAS DE ROBOT

RÉSUMÉ

Cet article traite des leçons tirées de la conceptualisation et de la réalisation de l'utilisation d'une plateforme de bras de robot industriel pour la fabrication additive. Les imprimantes 3D conventionnelles, en particulier celles qui utilisent des processus de modélisation par dépôt fondu (FDM), sont limitées au dépôt de matériau dans un seul plan de trajectoire d'outil (par exemple, le plan x-y). Pour améliorer cette limite, nous avons exploré diverses architectures cinématiques et méthodes de planification de mouvement. L'objectif de cette étude était d'explorer la possibilité d'intégrer des technologies de fabrication additive sur le marché (COTS) avec un bras de robot industriel à six degrés de liberté pour créer un système de fabrication additive 3D capable de réaliser des formes libres à six degrés modélisation par dépôt fondu. Ici, nous avons utilisé les capacités de mouvement générales d'un bras de robot industriel pour permettre de déposer le matériau souhaité en trois dimensions. Un bras de robot industriel polyvalent à six degrés de liberté Yaskawa Motoman SV3X était équipé d'une tête d'impression d'extrudeuse permettant de modeler le dépôt par fusion. Cette intégration combinait deux technologies matures, des bras de robots industriels et des têtes d'impression FDM, dans un nouveau système doté de nouvelles capacités de fabrication additive, baptisées MotoMaker. Dans cet article, nous résumons les connaissances acquises et les leçons tirées du développement de la plate-forme de robot MotoMaker pour la fabrication additive.

Mots-clés : impression en 3D ; fabrication additive ; modélisation par dépôt fondu.

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]. 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 utilizing 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. The extruded material needs to be heated 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]. 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. Their flexible 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 their relatively high degrees of freedom (DoF). Because of this, a serial arm with 6 DoFs is capable of performing multi-plane motions in their work environment compared to the gantry machine-style conventional 3D printers having 3 DoFs that are only capable of performing 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 machine's 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

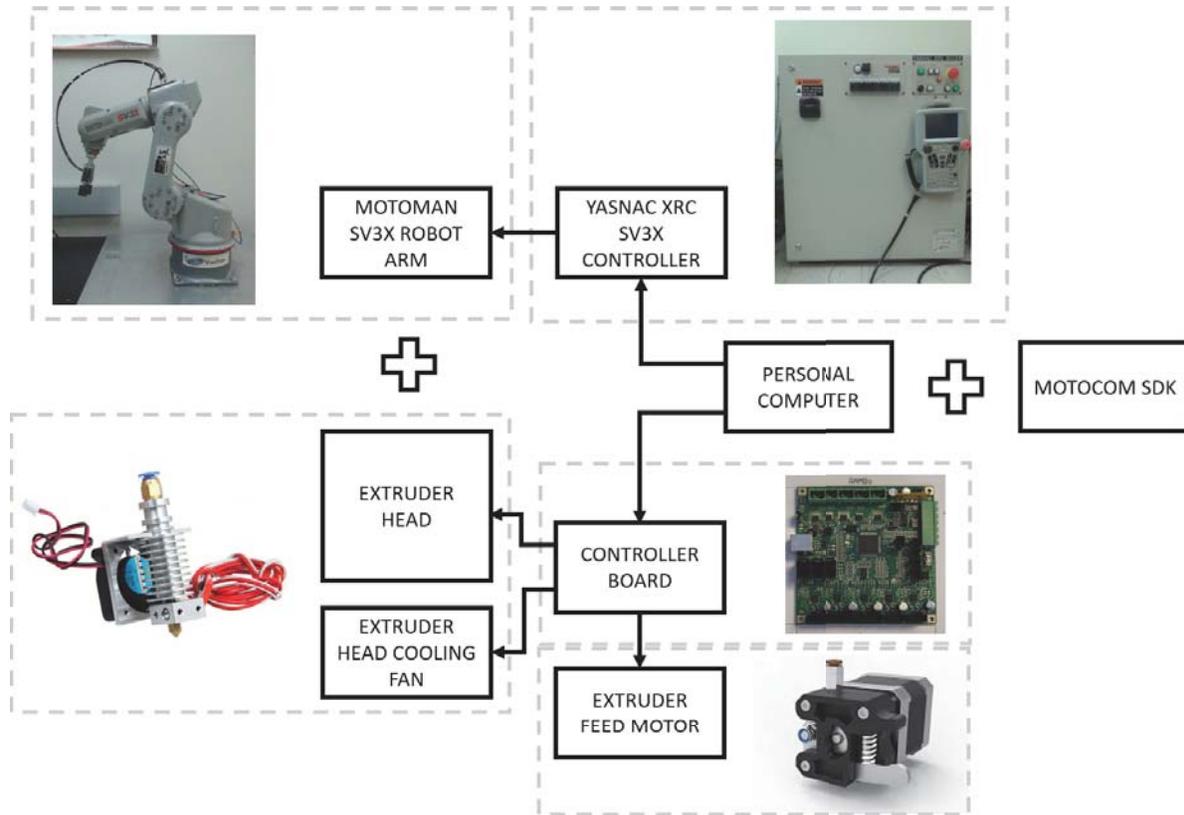


Fig. 1. Block Diagram of the MotoMaker System

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.* A support structure is used to support part fabrication. Overhanging and hollow geometric features may necessitate 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-dimensional 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 resembling 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. 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 developed by introducing a multi-plane toolpaths layering to utilize the capability of the robot arm platform. Finally, the future works with the robot arm platform in fabrication research are discussed.

In related works, the concept of multi-plane motion as it pertains to this project was studied by Keating and Oxman [7] and Lee et al. [8]. 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 the additive fabrication processes used from the setup employs a fixed extruder position with a movable building platform attached to a robot arm. Multi-plane motion for additive manufacturing may also be achieved by the integration of a five-axis machine and a FDM printer head. Lee et al. [8] combined an FDM extruder with a five-axis CNC machine tool. The FDM extruder was installed to the tool post. Here the 3D printing process is done by generating a toolpath in 2D planes and a rotating platform is used to adjust the building orientation. This setup allows for the elimination of support material.

2. MOTOMAKER PLATFORM

The MotoMaker platform is an industrial robot arm based system for additive manufacturing applications. The robot arm platform, integrated and programmed for this research, combined a six DoF robot arm and FDM printing technology. The MotoMaker platform was developed by the authors and reported in Ishak et al. [9–11]. The hardware architecture of the MotoMaker platform is illustrated in Figure 2, the hardware is shown in Figure 3, and the coordinate system is shown in Figure 4.

2.1. Robot Arm System

The robot arm used for the MotoMaker platform is a Yaskawa Motoman model SV3X. The robot arm is controlled by a Yasnac XRC 2001 controller. The Motoman SV3X is a compact (maximum speed of 920 (deg/sec)), ± 0.03 (mm) repeatability, 3 (kg) payload) industrial robot arm. It has a maximum reach of 677 (mm). The Motoman SV3X robot arm can be controlled and programmed using either a teach pendant or a personal computer via an ethernet connection.

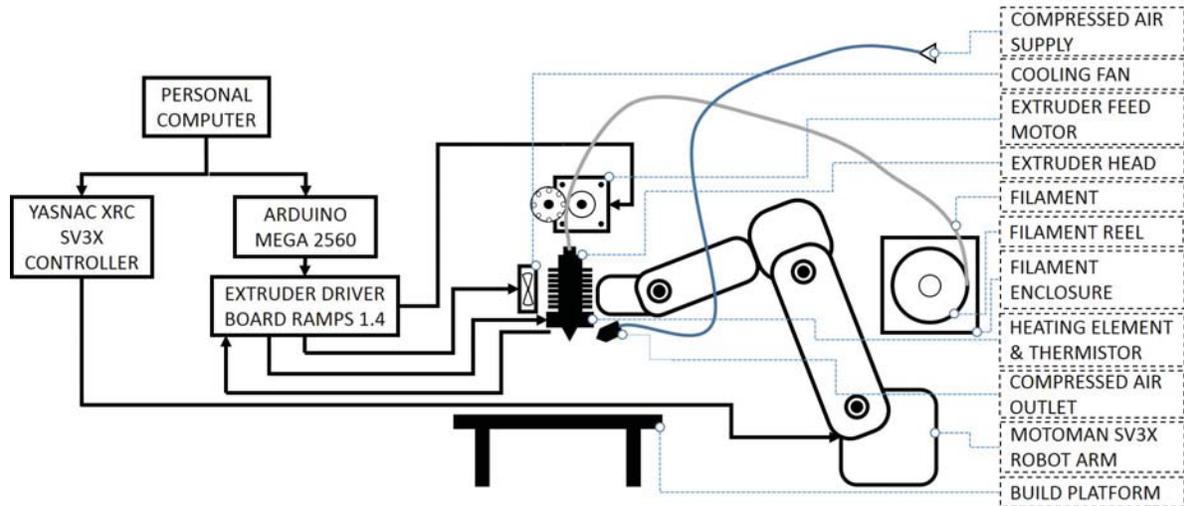


Fig. 2. MotoMaker Architecture

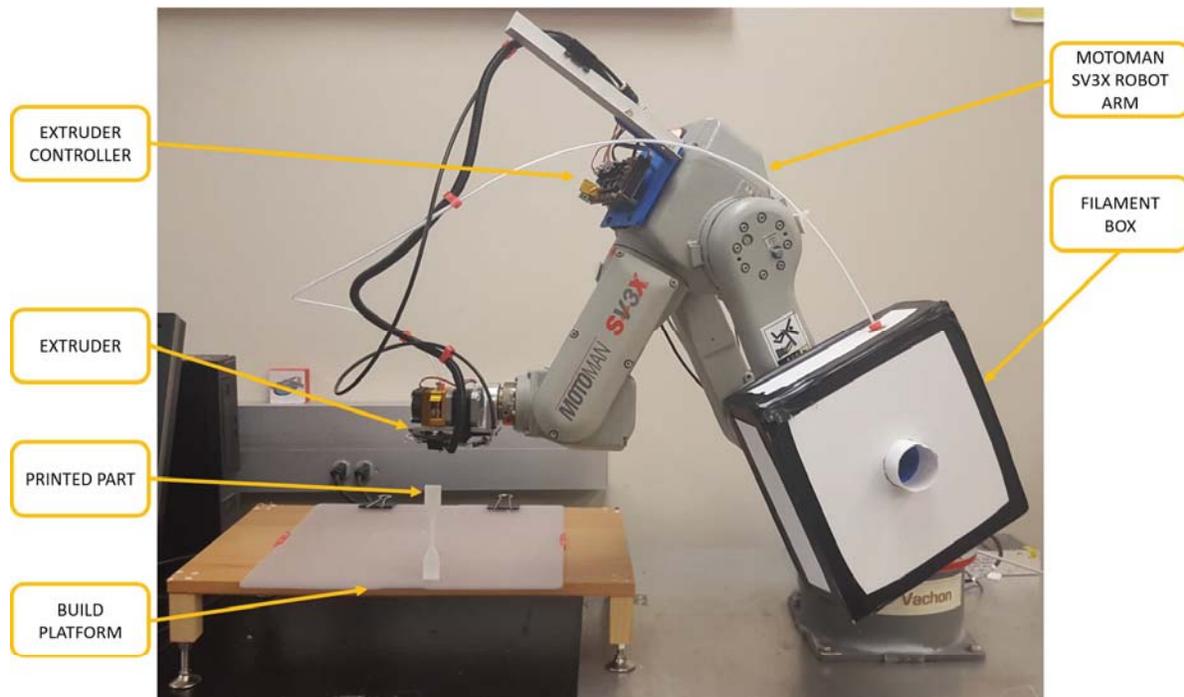


Fig. 3. The MotoMaker Hardware

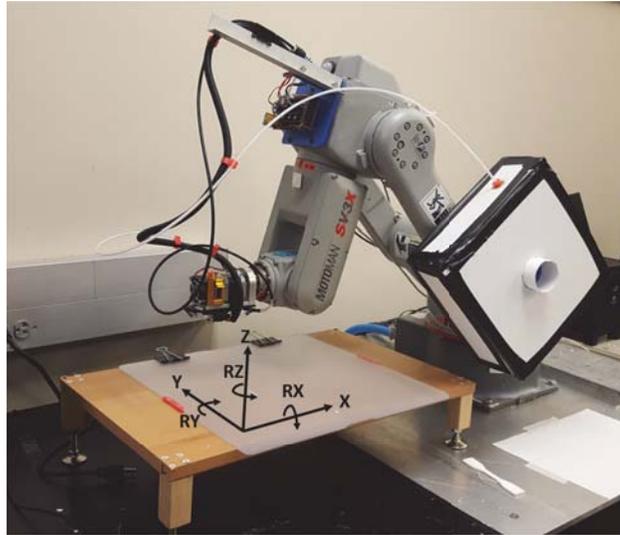


Fig. 4. The MotoMaker Coordinate System

2.2. Extruder System

The extrusion system, see Figure 5, consists of an extruder head, an extruder feed motor, a cooling fan, a heating element, a thermistor, and compressed air. The extruder controller consists of an Arduino Mega 2560 with a Ramps 1.4 extruder driver board. The extruder head system includes a thermal isolator, a heat block, and a nozzle. A 0.4 (mm) nozzle was used to feed a polylactic acid (PLA) filament through the extruder head. A NEMA 17 stepper motor was used as the extruder feed motor to feed the PLA filament. Specifications of the NEMA 17 stepper motor used for the extruder system were 3.3 (V) rated voltage, 1.5 (A) rated current, 1.8 (deg.) step angle, and 0.4 (N.m) holding torque. In order to keep the filament melting only at the extruder heat block, a cooling fan was used to lower the temperature of the thermal isolator. The cooling fan was used to prevent filament from clogging the extruder head. The compressed air was used to assist the extruded filament solidification process by providing convective cooling. The filament was stored in an enclosure box to prevent the filament from becoming brittle from the humidity based on the work environment conditions. Repetier [12] firmware was applied, i.e. flashed, to the Arduino Mega 2560 board to control the extrusion process. The tunable extrusion parameters include the heating temperature, the cooling fan speed, extrusion speed for the extruder feed motor, and volume of filament extruded. The extrusion process was controlled from a program executed on a personal computer through a USB connection.

2.3. Software

The MotoMaker was controlled using a custom interface program developed by the author, using the Microsoft Foundation Class (MFC) Library and Microsoft Visual Studio. Communication with the Motoman SV3X robot arm was successfully established using MotoCom SDK libraries. The MotoCom SDK libraries provided tools to access and control some of the functionality of the Yasnac XRC controller. For the application of the MotoMaker platform, the current position, alarm, error code, and move functions were used for the 3D printing application. The program printing process architecture is shown in Figure 6. The developed program loads in a text file containing GCode information for the toolpath of the printing process. The GCode information contains the type of motion for the robot arm, the workspace coordinates it will travel, the orientation of the extruder head, the speed of the robot arm motion, the extrusion volume during the

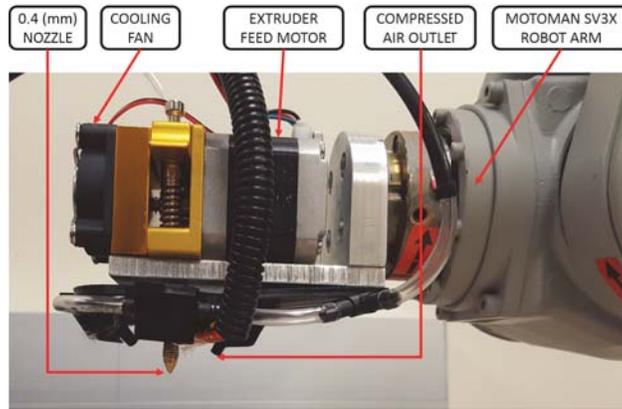


Fig. 5. The MotoMaker FDM Extruder

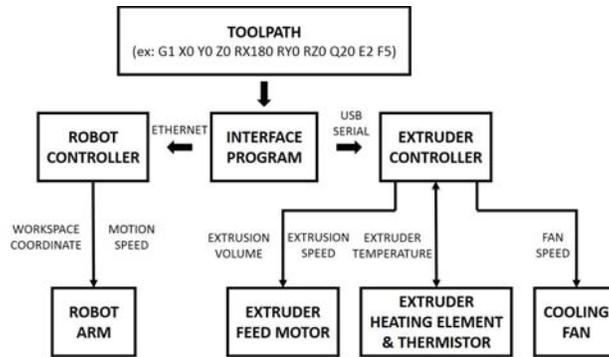


Fig. 6. The MotoMaker Control Software and Communication

printing motion, and the extruder speed. The program then transforms the GCode information into motion command parameters for the SV3X robot arm and extrusion system parameters. An example of a motion command from a toolpath is shown in Figure 6 where in the toolpath block, the G1 represents a linear motion, the $X0 Y0 Z0$ values represent the coordinates, the $RX180 RY0 RZ0$ values represent the wrist angles, the $Q20$ represent the robot arm motion speed, and the $E2 F5$ values represent the length of extrusion and extruder speed, respectively.

3. MOTOMAKER PRINTS

Here we include example prints that illustrate the capabilities of the MotoMaker system.

3.1. Multi-Plane Test Block

The test block printing process is shown in Figure 7. The printing process was started by extruding filament in the horizontal x-y plane. The x-y plane printing process was used to produce the $10 \text{ (mm)} \times 10 \text{ (mm)} \times 60 \text{ (mm)}$ 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 the vertical x-z plane. The x-z plane printing process was used to produce the $10 \text{ (mm)} \times 20 \text{ (mm)} \times 10 \text{ (mm)}$ structure.

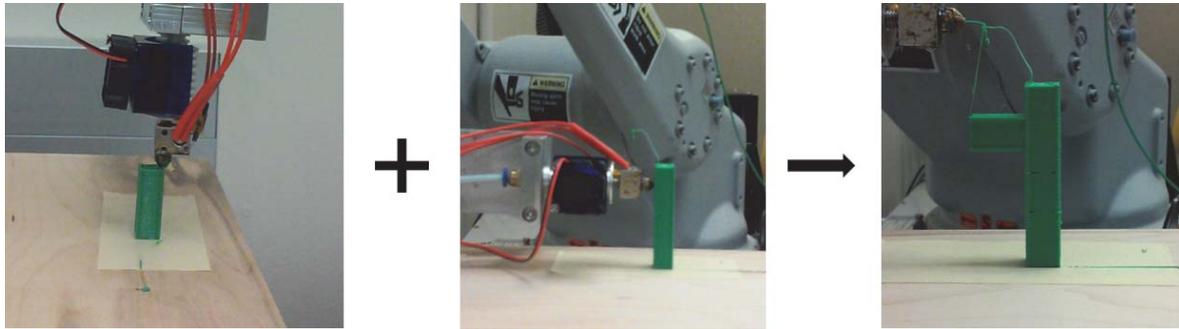


Fig. 7. Multi-Plane Printing

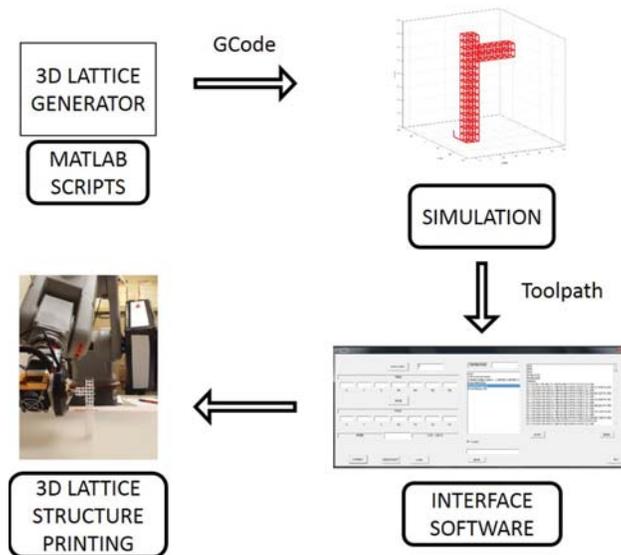


Fig. 8. 3D Lattice Structure Printing Process Overview

3.2. 3D Lattice Structure Test Block

In order to demonstrate the capabilities of multi-plane printing to create 3D lattice structures, a 3D lattice structure test block with an overhanging structure was printed using the platform. The test block's dimensions were 10 (mm) width \times 10 (mm) length \times 80 (mm) height and the overhang structure dimensions were 10 (mm) width \times 30 (mm) length \times 10 (mm) height. Overview of the 3D lattice structure printing process is shown in Figure 8. The printing toolpath strategy used was based on the geometric features of the 3D lattice structure. The horizontal and vertical planes were chosen for the toolpath's layering because they demonstrate the capabilities of the robot arm platform to perform multi-plane motions. The 3D lattice structure test block printing process is shown in Figure 9. The printing process was started by extruding filament in the horizontal x-y plane. The x-y plane printing process was used to produce the 10 (mm) \times 10 (mm) \times 80 (mm) structure. The toolpath of the printing process was based on the strut profile. 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 the vertical x-z plane. The x-z plane printing process was used to produce the 10 (mm) \times 30 (mm) \times 10 (mm) structure. The printing speed was set to 1 (mm/s) in order for the extruded

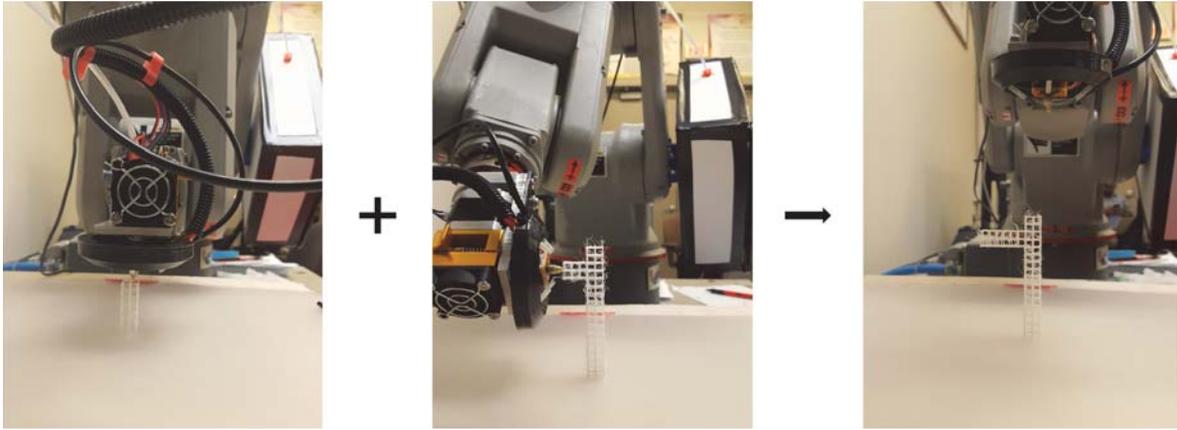


Fig. 9. 3D Lattice Structure Printing Process

material to solidify with the assistance of forced air cooling from compressed air at the nozzle outlet. The diameter of each strut is 0.48 ± 0.02 (mm). The length of the strut is 5 (mm).

4. LESSONS LEARNED

In this section we summarize the knowledge gained in designing, building, and testing the MotoMaker additive manufacturing system.

4.1. The Extruder

During the initial setup for the MotoMaker platform, a Bowden style extruder feeder motor was implemented. The Bowden style extruder system utilizes a separate setup for the extruder heating element and the extruder feed motor. The filament is fed through a tube from the extruder feed motor to the heating element. With the separation of the extruder heating element and the feed motor, the load on the end effector of the robot is reduced. However, the Bowden style extruder system jammed the filament several times during the printing process. The MotoMaker platform was then adjusted to utilize a direct feed motor, where the feed motor was attached directly on top of the heating element. The total mass attached to the end effector for the Bowden style extruder setup was 465.4 (g) and it was 616.9 (g) for the direct feed setup. The added mass to the end effector did not negatively impact the performance of the arm.

4.2. Extrusion Calibration

For the MotoMaker platform to have successful 3D prints, process planning parameters were calibrated. A successful 3D print is defined by the extruded filament adhering to the printed surface while maintaining the desired geometrical shape from the output toolpath motion of the robot arm. The process planning parameters that were calibrated were the printing temperature and the printing speed. For the 3D lattice structure printing process, these two parameters are important in order to make the extruded layer able to withstand its own weight without deflection. These parameters were verified through a calibration print. The length of the extrusion, E , for the extruding layer was calculated using Equation 1, where d_n represents the nozzle diameter, d_f represents the filament diameter, x_1, y_1, z_1 represent the starting point coordinate, and x_2, y_2, z_2 represent the end point coordinate.

$$E = \frac{d_n^2}{d_f^2} \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (1)$$

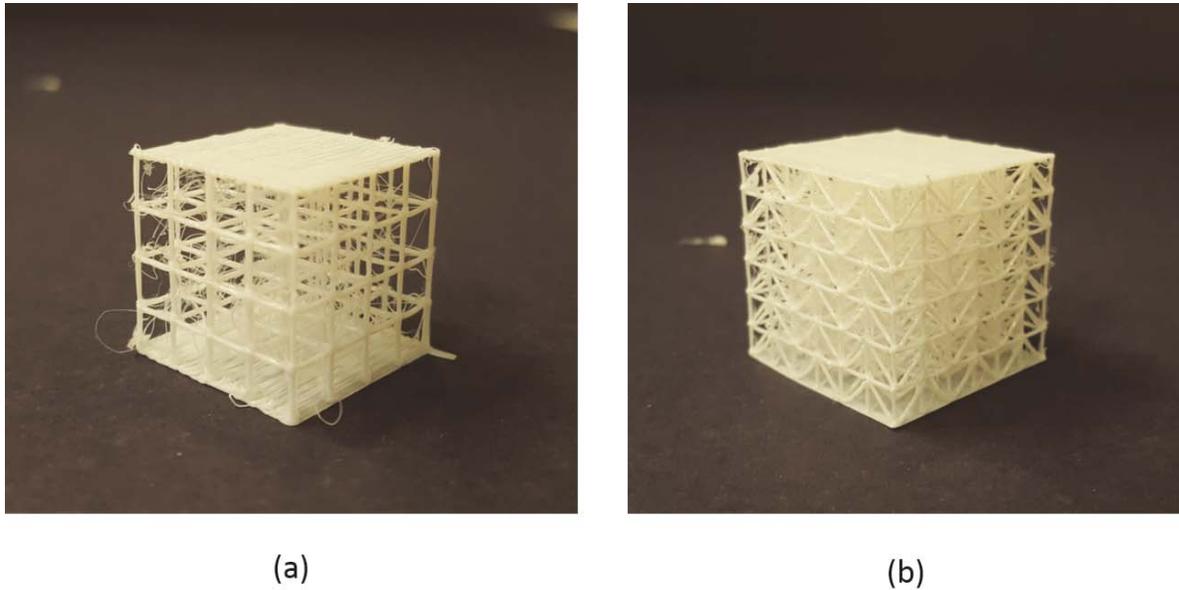


Fig. 10. Different 3D Lattice Structure Prints

For the application to generate 3D lattice structures, the printing speed and the printing temperature were calibrated by printing a single line of filament on a bridge gap structure, see Figure 11. The filament was printed across two structures while varying the printing speed, temperature, and with and without air assisted cooling for each run test. The gap between the two structures was 10 (mm). Performance of the printed filament was evaluated by checking the deflection of the printed filament through an image processing program by measuring the distance between a virtual straight line drawn on top of the two structures and the printed single line filament. From the extrusion calibration process, 220 (deg. C) printing temperature, and 1 (mm/s) printing speed with air assisted cooling were found to be the acceptable parameters for the 3D lattice structure printing application. The calibration between the printing speed and temperature was crucial in order to print and solidify the single line filament with an acceptable deflection. The diameter of the extruded filament was 0.48 ± 0.02 (mm). The printing parameters with 220 (deg. C) printing temperature and 1 (mm/s) printing speed enabled horizontal bridge gap printing with a length of up to 15 (mm) within an acceptable 0.24 (mm) deflection in the middle with air assisted cooling.

5. CONCLUSIONS

This article presented lessons learned in the conceptualization and realization of a novel platform for additive manufacturing named MotoMaker. It detailed the knowledge gained and lessons learned in deploying the MotoMaker system to fabricate multi-plane parts with overhanging structures as well as three-dimensional lattice structures.

The MotoMaker system provides a platform for researchers studying three-dimensional additive manufacturing using fused deposition modeling techniques. Ongoing research is focused upon advancing the toolpath planning algorithms for multi-plane, lattice structure, and free-form three-dimensional additive manufacturing applications. In addition, planned future work includes adding the capability to extrude multiple materials to the MotoMaker system. It is our hope that the information reported here will benefit others seeking to advance the state of the art in three-dimensional FDM additive manufacturing.

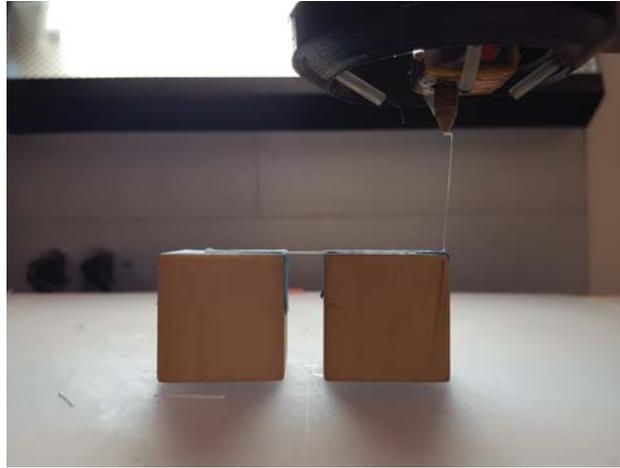


Fig. 11. Single Line Filament Printing Calibration

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