IN-SITU ROBOTIC MANUFACTURING
AN APPROACH TO FABRICATING NON-STANDARD JOINERY DETAILS

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Figure 1 In-situ robotic fabrication motion capture.

Abstract

The introduction of digital design tools has increased the ability to fabricate intricate one-off design elements, becoming a focal point of interest for Architecture, Engineering, and Construction (AEC) practitioners and researchers. However, during the construction process of complex elements, various problems arise, which require immediate resolution in an in-situ application. Nowadays, AEC practitioners utilize other forms of technology to streamline the construction process, such as 3D printing for complex geometry, utilizing robotic arms for constructions, and developing Artificial Intelligence (AI) algorithms to automate fabrication tasks. This research is interested in using robotic arms in construction to develop a methodology to fabricate architectural details in situ with multi-axis robotic additive and subtractive manufacturing techniques developed for industry. Industrial robots using these manufacturing processes implement a form of flexibility in geometry constraints by introducing the ability to print in-situ.

However, the lack of a universal standard for robotic language programming and experimental replication has proven problematic across different platforms. To address the former, this project contributes general guidance for the use of RoboDK for additive and subtractive manufacturing, evaluation of current large-format additive manufacturing tools with custom nozzles, and various examples of architectural joints only manufacturable by multi-axis additive and subtractive manufacturing techniques.

Keywords: In-situ, 3D Printing, Architecture, Additive Manufacturing, Subtractive Manufacturing, Multi-planar, FDM, Robotic Fabrication, Programming

1 Introduction

Multi-Axis robots have been used for industrial applications for decades. The first industrial robot could be found as early as the mid-1950s and over the last 60 years. As technology has advanced, so have the processes and uses of industrial robots. Industrial robots are used for various purposes such as welding, pick and place, palletizing, and machine tending, but more recently, robotic systems are finding new uses for experimental purposes, particularly in Architecture, Engineering, and Construction (AEC) fields. Many AEC practitioners are starting to utilize these robots for purposes that they were not designed to do.

Today, you can find industrial robots in universities and research facilities used for experimental design. The use of multi-axis industrial robots introduces new opportunities for flexibility in the fabrication process. For example, robotic systems can be outfitted with custom tool heads such as grippers and extruders for Additive Manufacturing (AM), or spindle motors for subtractive manufacturing (CNC machining). With the introduction of AM and CNC tool heads, new research documentation has become prevalent as new opportunities are explored; however, these processes have introduced new challenges. While most industrial robots are generally similar across several manufacturers, one key difference is how each robot is programmed. To streamline the programming process, researchers have developed tools and plugins for parametric designing software such as Rhino3d and Grasshopper. However, each robot's propriety features make programming and experimental replication difficult across different platforms.

The aim of this project is to highlight the lack of a universal standard between languages from different robot manufacturers. Furthermore, it provides a potential roadmap for others to replicate multi-axis AM and CNC processes with industrial robots with a project that emphasizes the ability to fabricate joints in-situ.

The contributions can be summarized in the following points.

- The general guidance for using RoboDK and documentation of critical roadblocks and solutions.
- An evaluation of off-the-shelf large Format FDM extruders and a designed solution for Multi-axis printing.
- Examples of various architectural joints are only manufacturable by Multi-axis CNC and AM processes.

The article is structured as follows: In section 2 describes related work with an emphasis in AM ad CNC processes. Section 3 explores the current approach to In-Situ Robotic manufacturing and its limitations and introduces the methodology applied in this research. Section 4 lists the results and presents a discussion of the former to conclude with Section 5 conclusion and outlook for future work on this subject.

2 Related work

This section contains a summary of work that explores the process of AM and CNC manufacturing using 5 degrees of freedom (DOF) and the process of parametrically programming robotic tool paths. The incorporation of a robotic system as the primary motion system for digital fabrication has opened possibilities of complex tool paths such as multi-planar and non-planar toolpaths and a new approach to complex one-off designs.

2.1 5 or more axis 3D printing

Multiple axis motion systems such as robotic arms and 3+2 degree of freedom gantry platforms allow for either machineable element or tool head reorientation to dynamically translate tool path orientation. The use of a robotic arm as a multi-axis motion platform uses a process defined by a fixed base and a mobile tool. Fixed base manufacturing can be found in *Print paths key-framing* [Mitropotlou et al., 2020]; the project elaborates on a process of analyzing and processing targets on a surface to interpolate non-planar toolpaths. The researcher used a tool head orientation on the end of a robotic arm to overcome the necessity of support on overhangs. Contrary to mobile tools, a mobile platform could be fixtured to the end effector and orbit a stationary extruder found in *Compound Fabrication* [Keating & Oxman, 2013]

2.3 Robot Programming

The most complicated feature of multi-axis fabrication with industrial robots is programming. Two main categories of robot programming are online programming, where the robot is taught positions individually with an operator, and offline programming uses secondary software and computers to virtually program the robot before use. [Biggs & MacDonald, 2003]. Design applications are becoming more computer-aided design (CAD) dependent, and most CAD packages don't natively integrate robotic control in them. In the last 10 years researchers at ETH Zurich, have developed a series of software environment for robotic fabrication eg.a Python module to integrate Rhinoceros and Grasshopper to parametrically control and program robotic functions [Gramazio et al., 2013]. The wor of Gramazio et al. (2013), primarily focused on Uarm robots. Unfortunately, robotic programming languages are system-specific and not cross-compatible. In response to the former, *Parametric Robot Control* illustrates an additional Rhinochreos and grasshopper plugin called Kuka|PRC, developed to control Kuka robots with KUKA Tobot Language (KRL) [Braumann et al., 2013). These new plugins develop a workflow to seamlessly integrate Robotic control with CAD and CAM packages.

Robot programming plugins have made designing and fabricating intricate and one-off design elements more obtainable. With the incorporation of robotics in design projects such as *Timber structure of the Future Tree* [Apolinarska et al., 2019], ICD/ITKE Research Pavilion 2016-17 [Menges, 2017], ICD/ITKE Research Pavilion 2013-14 [Menges, 2014] have become possible. Furthermore, new research with the possibility of 3D printing and robotic fabrication means that AEC practitioners can start to think differently about material assemblages and processes.

3 Methodology for Robotic Manufacturing

3.1 Overview

As designs processes become more complex with the aid of digital design, the design and construction industry is researching custom solutions for fabrication. As 3D printing technology is becoming more prevalent in fabricating one-off and intricate solutions, this project takes this process one step further in asking if there could be a new logic between the joint of materials. While researching this topic, a common subject of robotic control became prevalent. Due to the complexity of robotic control, researchers primarily focus on one robotic system and develop tools to optimize the workflow. Unfortunately, this tends to make experimentation challenging to replicate. The methodology of this project consists of the following parts: AM and CNC toolpath robotic programming utilizing RoboDK (section 3.2), the customized AM extruder modifications(section 3.3), and architectural material joints(section 3.4).

3.2 RoboDK

The first step in this project was designing the robot work cell. The robot manufacturer for this project was Denso Robotics. However, at the time of this article, Denso is not a primary manufacturer used for architectural research such as Kuka, Abb and UArm. Due to this circumstance, Denso has not had proprietary software developed for complex robot programming such as Grasshopper plugins HAL Robotics, Kuka|PRC, and Taco for ABB. Thus, the software utilize was RoboDK as the section 2.3 covered that RoboDK is a robotic programming software with a robot library supporting over 50 different robotic manufacturers and 500 robot platforms, including the Denso platform.

The Robotic work cell was comprised of a Denso VS-087 fixtured to a Certiflat Mini block fabrication table (Figure 2). The fixturing table allows the flexibility to mount numerous different flanges and mounts to position elements accurately while securely mounting the robot with minimal movement. The work cell was replicated in Rhino3d and imported into the RoboDK using.STEP files [1] and the robotic connection were established using a robot's designated IP address.[2]

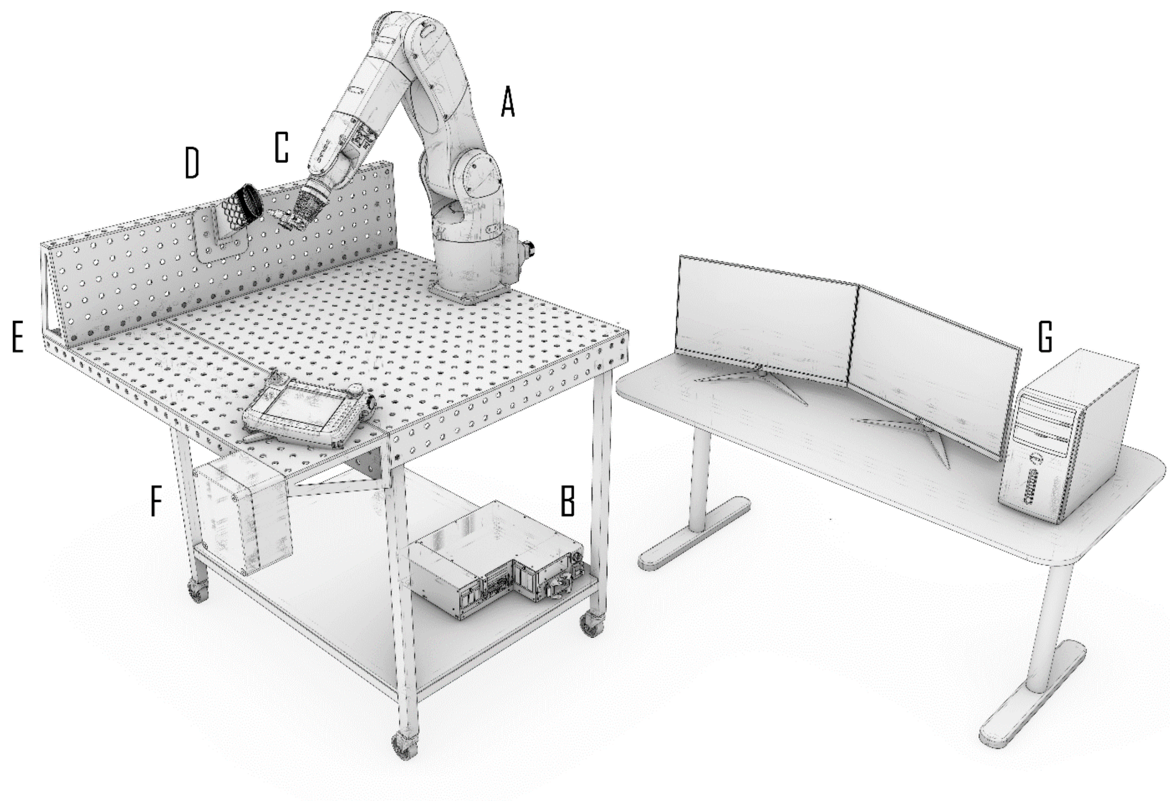

Figure 2 Schematic representation of fabrication process. (A) Six-axis robot arm. (B) Robotic Control system. (C) Extruder tool head. (D) In-situ element and 3d printed structure. (E) Fabrication Table. (F) Extruder control box. (G) Control system

3.3 Extruder

The AM tool head used in this project uses an off-the-shelf high-flow 3D printer extruder. The extruder is composed of 4 main parts. First, a BondTech 3.00mm QR Extruder mated to an

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[1] https://robodk.com/doc/en/Getting-Started.html#LoadObject

[2] https://robodk.com/doc/en/Robot-Drivers.html#UseDriver

E3D V6 heatsink. Then a SuperVolcano heater block and 2.00mm nozzle. Section 3.3 covered various layer techniques utilizing multi-axis printing properties. The experiments highlighted several concerns regarding the tool head, such as angular clearance and pocket penetration depth. This called for a custom nozzle solution that enables more flexibility for multi-axis manufacturing. Figure 3 (A,B) shows a comparison of angular clearance between the stock SuperVolcano nozzle and the custom nozzle produced for this experiment. The custom nozzle features steeper wall angles, extended reach from the heater core to eliminate collisions, and thicker thermal mass for temperature stability. Thermal calculations were calculated using Autodesk Fusion 360 to ensure that even thermal meting occurred, and design alterations were considered. The nozzle was manufactured using 3/8" brass hex stock and polished and reamed with precision accuracy. (figure 3(C,D)) Extruder control was based on an Arduino control with parameters to control temperature, flow rate, and retraction triggered by analog toggle states.

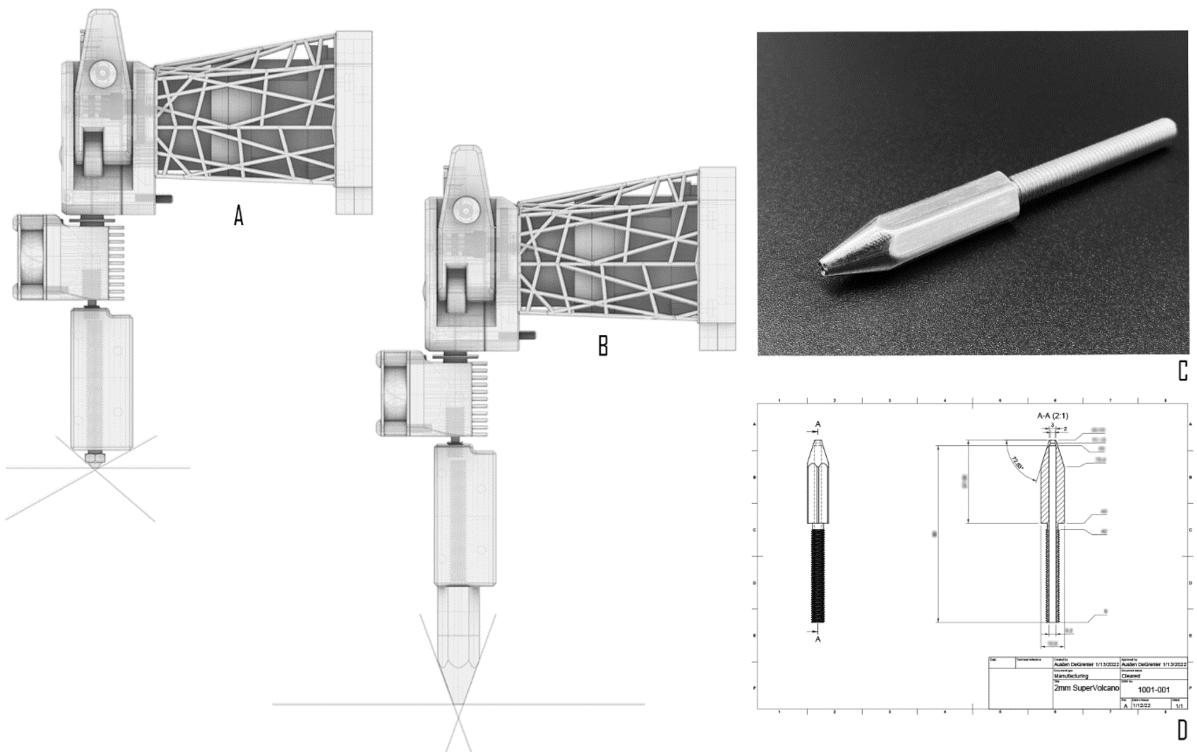

Figure 3 Custom extruder and nozzle design. (A) Stock E3d Super Volcano collision angle. (B) Custom E3d Super Volcano collision angle. (C) Manufactured nozzle. (D) Manufacturing drawing

3.4 Curve follow toolpath

Once connection and robotic control were established, the first experimentation was to create curve follow paths in Rhino3d and import the settings into RoboDK[3]. The process of curve following programming is the foreground for toolpath generation. Simple cubes with a

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[3] https://robodk.com/doc/en/Robot-Machining.html#CurveFollow

measurement of 2^3 in were designed in Rhino 3D for robotic calibration. Using Grasshopper scripts, parametric layer conditions were established to tune print attributes to the current setup.

Layer orientation and tool orientation are crucial applications to successful prints. Therefore, various layer conditions were tested below to calibrate and establish a ground plane for Joint design:

3.4.1 Horizontal layer offset. RoboDk's curve follow program will follow open and closed curves perpendicular to the normals or the directional face of the reference plane. A grasshopper scrip was generated to control layer attributes in horizontal orientation parametrically. The first test series was for the first layer of horizontal offset extrusions. Figure 4(A) illustrates the optimal horizontal offset toolpaths, projected extrusion, and test results. The test resulted in a horizontal offset of 2 mm with an extrusion rate of 10 mm/sec. Vertical tests resulted in an optimal layer height of 1.4 mm and extrusion width of 2.0 mm. The test results indicated that external cooling was necessary, and two radial blower fans with 40 CFM of flow were introduced. The external cooling solidified the layers before a new layer was deposited above.

3.4.3 Layer Overhang Degree. Layer overhang tests were performed to test the max overhang for material adhesion to the substrate. A series of tests ranging from 0° to 60° using PLA and external cooling. The results indicated that the maximum overhang with vertical print orientation is 30° without significant slumping. Figure 4(B-E) illustrates 0°, 15°, 30°, 45°, 60° overhang toolpaths and projected extrusions followed by corresponding results.

3.5.4 Non-planar Print orientation. A Grasshopper script derived to contour complex lofted isocurves. This feature on non-planar allows toolpaths to transition from complex curved or angled surfaces to planar surfaces. The test shown in figure 4(G) enables complete control of multi-axis 3d printing and a step toward complex toolpaths. The test starts with a standard base and simple vertical layers that progressively orient towards 45°. Once 45° is achieved, extrusion progresses horizontally. This test was utilized to achieve transitions from vertical to horizontal print orientation. With the understanding that overhangs greater than 45° are not achievable, the orientation of the tool head needs to orient to match the direction of the normals on a curve. This enables consistent layers to have material overlap and bonding axially and vertically. With ambient cooling, substrate layers solidify in under 5 seconds, enabling rapid z offset heights.

3.4.5 Multi-Planar. Using techniques to overcome overhang slump. A process of using Multi-planar printing tool paths was used. The test examines the possibilities of printing overhangs greater than 45° and explores the possibility of printing horizontally with no supports and minor tool orientation changes. This test included splicing multiple planar toolpaths with normals normal opposing the core structure. The ability to orient the tool head in any one direction allows for the ability to simplify travel moves.

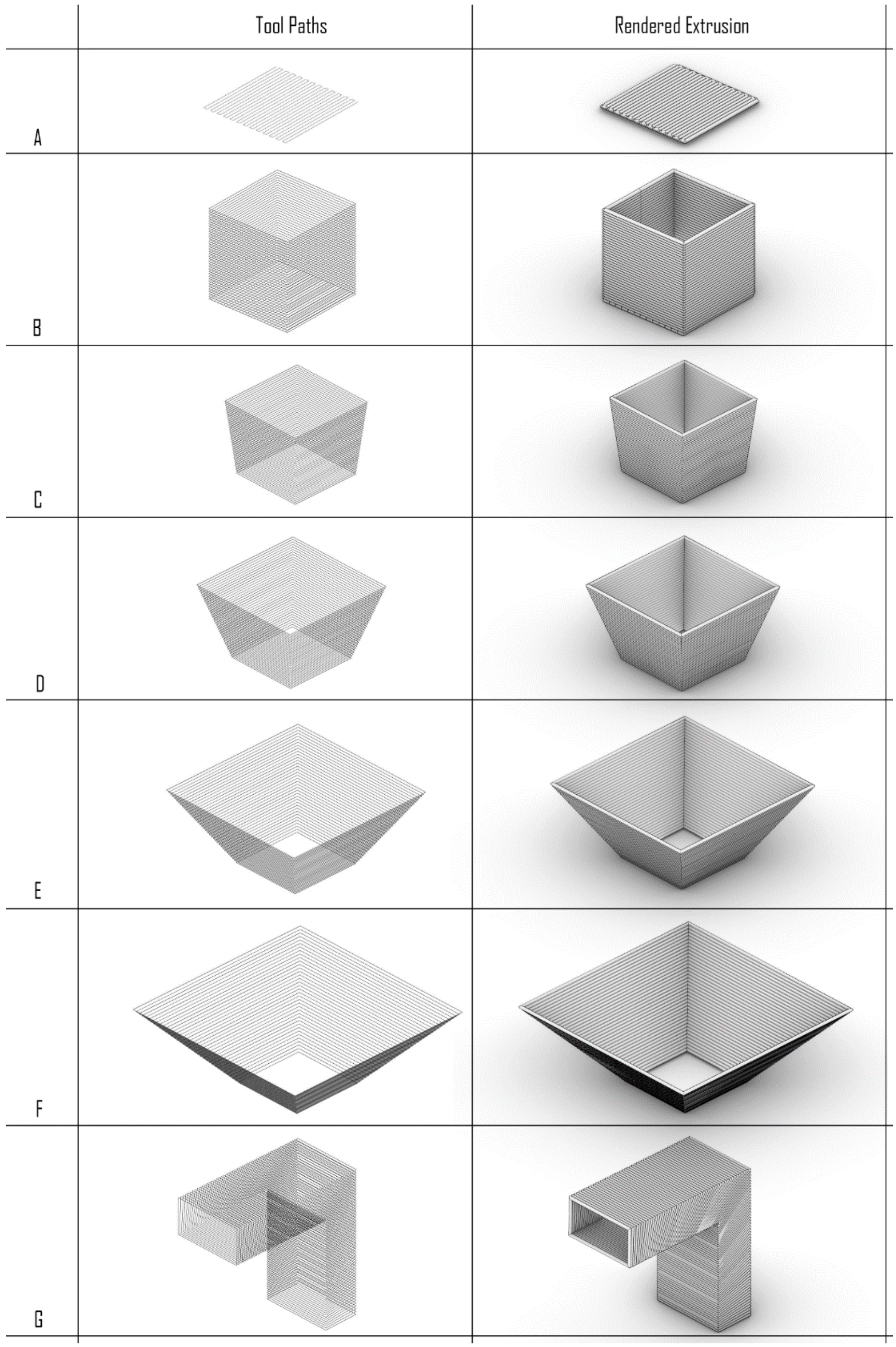

Figure 4 (A) Horizontal layer offset. (B) Layer Overhang Degree 0°. (C) Layer Overhang Degree 15°. (D) Layer Overhang Degree 30°. (E) Layer Overhang Degree 45°. (F) Layer Overhang Degree 60°. (G Non-planar Print orientation.

3.4 CNC Manufacturing.

Subtractive manufacturing is the process of using a rotating blade called an endmill attached to a spindle motor to remove material from an object. This process is most commonly used with 3 and 5-axis gantry mills. With projects becoming more complex and opportunities for more extensive fabrication processes, industrial robots have been outfitted with spindle motors and utilized for subtractive manufacturing. The Subtractive manufacturing process and toolpath generation for 3 and 5 axis is readily available. In addition, most CAD packages offer computer-aided manufacturing (CAM) programs. RoboDK also integrates these CAM packages into their software. This project utilized the Autodesk Fusion360 CAM suite [4] for subtractive manufacturing. Toolpaths were generated using a multi-planar approach with adaptive and contour clearing techniques.

4 RESULTS AND DISCUSSION

In this section, two in-situ fabrication approaches are presented. These experiments are only possible utilizing multi-axis fabrication techniques and could not be fabricated using other methods due to part orientation and work holding. The presented experiments also demonstrate a potential new logic for joints in architecture. The added flexibility of multi-axis robotics enables designs to explore new toolpaths with fewer constraints. However, in-situ still has design constraints due to collisions between the robot as well as singularities between robotic joints and physical constraints of the robot to reach positions with correct tool angles.

4.1 Fabrication Cell.

The fabrication cell consists of a Denso Vs-087, a custom extruder and nozzle with a diameter of d_n =2.0 mm and 3.00 mm Polylactic Acid (PLA) filament, and lastly, a 1Kw spindle motor and a 1/8" Up cut endmill. A fabrication table was used to ridge fixturing the robotic system while also allowing for a flexible mounting solution for elements. Additionally, 3d printed locating fixtures were fabricated to align and calibrate elements in this experiment due to limitations of resources.

The experiments displayed were carefully analyzed and pre-processed for current fabrication techniques. Unfortunately, the current robotic solution does not offer external motor control. Therefore, two different controllers were developed for the project. An AM extruder controller and a CNC controller:

4.1.1 AM controller. The AM controller is composed of an Arduino Mega, DM542E driver, and a PID temp controller. Layer width and height were held at a constant rate of L_h = 1.40 mm and L_w = 2.00 mm. Additionally, extruder flow rate and tool center point (TCP) speed and acceleration were held constant: E_{fr} = 10 mm^3/s, TCP_s = 15mm/s, TCP_a = 1500 mm/s^2. These values were calculated utilizing the calibration techniques in section 3.4.

[4] https://robodk.com/doc/en/Plugin-Fusion360.html#AFManualInstall

4.1.2 CNC controller. The CNC controller is composed of an SW55-220S BLDC controller a 1Kw Spindle motor, 1/8" Upcut endmill. The spindle was operated at a fixed 9200RPM with a 0.10" depth of cut (DOC) and ½ Dia tool engagement.

4.2 Experimental Results

4.2.1 Fabricated Prototypes. Two fabrication techniques were tested for the design and manufacturability of architectural joints without fasteners in situ. Both experiments started with a base element. In the case of this project, a standard 2"x 4" lumber was used. The decision to use standardized elements at this stage of the project was used for the ability to test multiple different toolpaths.

4.2.1.1 Inverted Dovetail. The inverted dovetail was a derivative of traditional Japanese joinery. AS the former uses features to interlock two different materials. A particular interest in the dovetail was expressed due to the overlapping surface area and the ability to revolve around the cross section. However, the traditional dovetail makes CNC and additive manufacturing difficult due to a narrow aperture expanding to a broader base. Furthermore, even with the ability to manufacture with a five-axis of freedom, the dovetail would be practically impossible to 3d print the interlocking feature.

Inverting the dovetail to having a wide aperture and a narrow base enables multiple benefits to manufacturability. The first benefit to the inverted dovetail was the ease of manufacturing subtractively. Secondly, one key factor is collision avoidance when additive manufacturing approaches are considered. Finally, the nozzle of the extruder needs to be inserted into a pocket, depending on the exterior wall angle's characteristics. The wall taper for the pocket was decided based on the tip angle shown in figure 5.

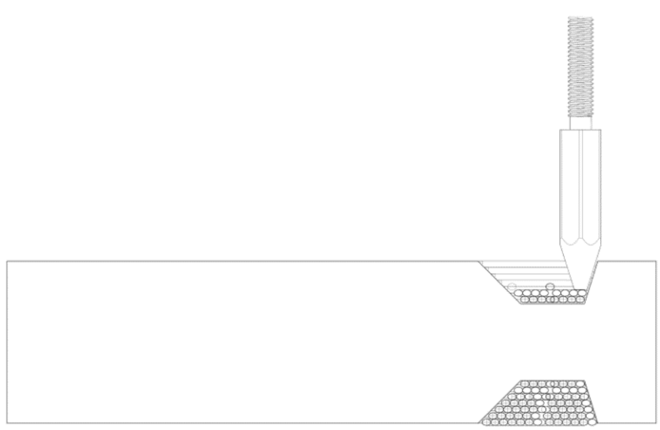

Figure 5 A detailed drawing of the nozzle, showing the wall taper

The machining approach for the pocket was generated using the Autodesk Fusion360 manufacturing feature. The toolpaths generated were generic adaptive pocketing and contours, selecting the internal contours of the walls. However, for additive manufacturing, a grasshopper scrip in Rhino was generated to automate the toolpaths. First, the inverse of the dovetail was split into four different faces. The segments were then contoured at the segmentation of 1.4mm for the layer height towards the face normal. The contours were then offset and unified to make a single spiraling toolpath for each layer. Figure 6 illustrates the robotic printing orientation and layer quality of insertion into the dovetail.

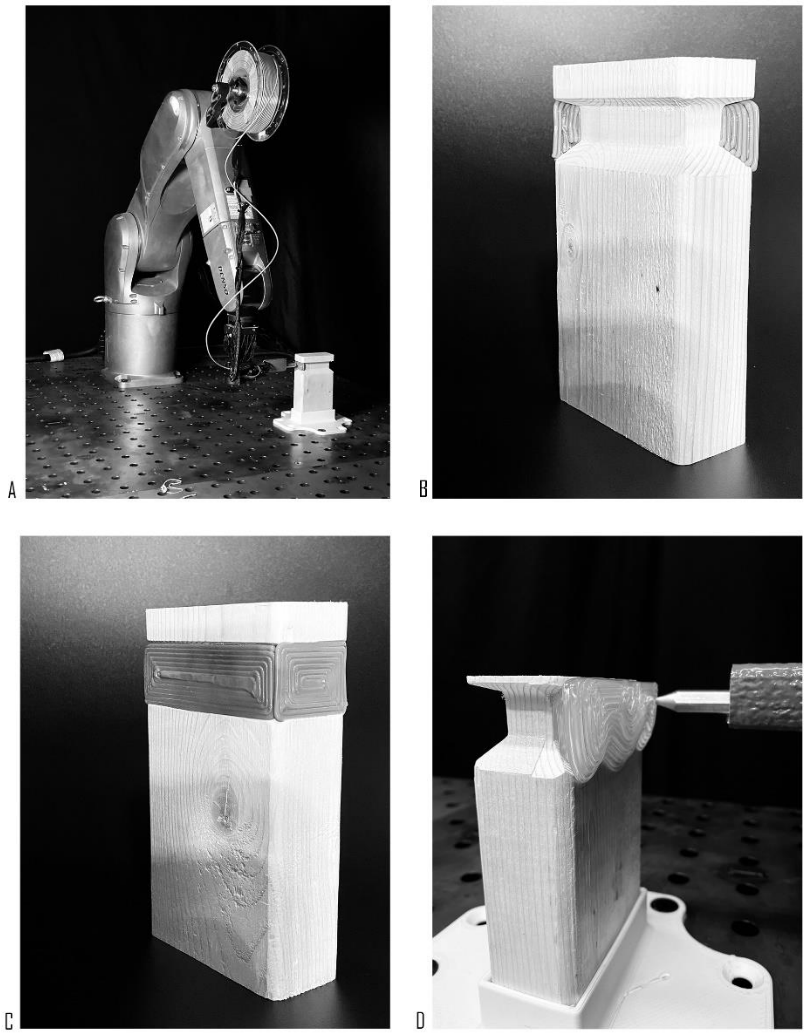

Figure 6 (A) Inverted dovetail robotic fabrication. (B) Partial completion of 3D print. (C) Completed Inverted dovetail print. (D) Detail image of 3D print.

4.2.1.2 Hach Attractor. The hatch attractor is an experiment to parametrically control a user's design preference to graft two different elements. A process of progressively scaling a base feature such as a square, diamond, hexagon, etc., and progressively lessening the scale of each feature towards the end of the base material where continuous extrusion of new material can extend beyond the limitations of the base material.

A grasshopper scrip was generated to scale a base feature parametrically. Figure 6 (A) illustrates the toolpath generated by Grasshopper. The narrowest section of the hatch pattern is 4mm, the width of two extruder passes. The gap between two hexes enlarges to 10 mm as the hatch pattern progresses. Figure 6 (B-D) illustrates the process throughout manufacturing.

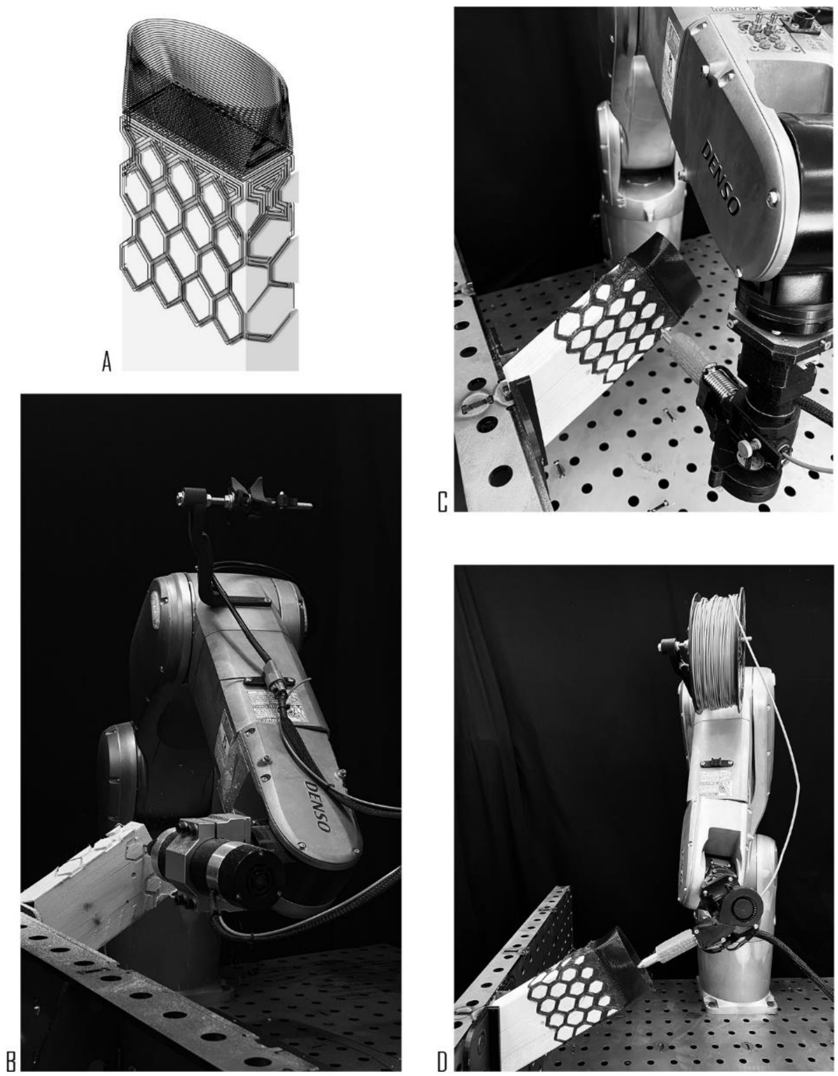

Figure 7 (A) Rhino generatedTool path (B) Robotic CNC Milling hatch. (C) Robotic 3d Printing hatch. (D) Robotic 3d printing.

4.2.2 *Comparison with static printing*. The presented results could not be fabricated with typical three-axis machines. The novelty of this experiment is the possibility to adapt, modify and build upon existing elements. Static prints are confined to a flat work surface where a part or feature grows from the base and continues outward, whereas the element in situ allows a process to grow in any direction as long as there is adequate clearance.

4.3 Discussion and Future work

The work presented in this article is part of ongoing research on the application of in-situ robotic manufacturing for AEC applications. Summaries below are various concepts that need further exploration.

4.3.1 *Hardware.* The current AM tool head with improved nozzle design was a significant step toward successful multi-axial 3d prints. The extended nozzle with a shallow tip angle provided excellent reach while minimizing collision errors. However, the current heat block proved to show significant signs of fatigue and instability. With only one point of contact for the entire rigidity of the hotend, light collisions or significant backpressure would cause the nozzle to bow and warp, showing signs of poor layer alignment. Additionally, the heater cartridge is not optimal due to the shape and thermal stability at the flow rate. The lack of thermal stability required lower than desired print speeds. Future work will include an AM tool head with a larger heater core for a more stable flow rate, integrated nozzles, and a larger tip angle for more angular clearance.

4.3.2 Point cloud. The complexity of manufacturing in-situ requires a high degree of accuracy and precision. The current project uses generic and known elements such as a 2x4. The initial intent of this project was to utilize 3D point cloud scans for two primary roles. The first use for a 3d point cloud scan would be the ability to use the scan to mesh and calibrate the work cell. Utilizing Artificial Intelligence techniques, the point cloud could be used to accurately determine the positional offsets and provide feedback to work with scanned coordinate systems. Secondly, 3D point clouds will allow the ability to alter and fabricate complex geometries. With the inclusion of CAD software in the programming process, point clouds will be able to create precise 3D models of complex geometries and work environments and allow the user to alter and edit the base element as desired. Many elements cant be easily replicated by human control, so the use of intelligent technology is crucial for successful designs and implementation.

4.3.3 Smart sensors. Incorporating intelligent sensors such as optical tracking can enable a second level of calibration and precision. For example, using motion tracking software with indexable targets will help aid point could scans with real-time data of positional movement and spatial coordinates. With the inclusion of fixed elements in open space, calibration of the work coordinate system (WCS) with tool and robot coordinate systems is complex. Systems like Optitrack could monitor WCS and provide crucial misalignment data for AI algorithms to correct in real-time without the intervention of humans.

4.3.4 Generative design. With the incorporation of point cloud scans, AI algorithms could use object and feature recognition to aid in the design process, as the environment is precisely represented and the physical and material contained won't have to be digitally modeled but they can be extracted from the point cloud model with the help of AI segmentation algorithms. Currently, the blending process between materials is the designer's choice and handcrafted; with the aid of AI, the process could become more streamlined and optimized, by learning from various previously developed designs. Moreover, the presented methodology could be included in the design process where generative algorithms are used, as in the case of the article "Beyond typologies, beyond optimization," [Saldana et al., 2020], the authorspresented a design framework utilizing AI in different design operations, where AI was used to empower creativity, by adding fabrication to the design processes future research could investigate the potentials of manufacturing complex geometry and how that could benefit the problems encounter in-situ.

4.3.5 Material Properties. The ability to experiment rapidly with cost-effective solutions means that material properties have been excluded from the current research. New materials and deposition processes should be evaluated. Not only would different materials yield different structural properties but may also aid in print results such as layer height, slump factor, cooling ratio, shrinkage, and resistance to gravitational deformation. The material properties will aid in the design process of joint as it may relieve certain constraints.

5 Conclusion and Outlook

This article presents an in-situ multi-axis robotic manufacturing process for architectural joints. The fabricated case studies are preliminary proof that the process is a feasible solution for AM and CNC fabrication.

The impact of this research is only in its infancy. However, the research not only begins to share a process for more research institutions to explore AM and CNC processes with robotics; but opens the market to bring more cost-effective solutions as second-hand robots can be obtained at potentially significantly lower costs. Additionally, this process also questions the logic between material connections. The trials in this experiment were not optimized nor a perfect solution, but the first step in asking designers to think about the material connection.

The results of this project are very encouraging, not only providing a road map for other facilitators to start experimenting with Multi-axis AM and CNC manufacturing but also providing a first step in merging two different manufacturing techniques in a design brief, joinery. Furthermore, this project intends to contribute to the digital fabrication techniques research for details and joints.

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