Integrating parametric design with robotic additive manufacturing for 3D clay printing: An experimental study

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Abstract –

This paper presents an ongoing work in relation to the development of a parametric design algorithm and an automated system for additive manufacturing that aims to be implemented in 3D clay printing tasks. The purpose of this experimental study is to establish a first insight and provide information as well as guidelines for a comprehensive and robust additive manufacturing methodology that can be implemented in the area of 3D clay printing, aiming to be widely available and open for use in the relevant construction industry. Specifically, this paper emphasizes on the installation of an industrial extruder for 3D clay printing mounted on a robot, on toolpath planning process using a parametric design environment and on robotic execution of selected case studies. Based on existing 3D printing technology principles and on available rapid prototyping mechanisms, this process suggests an algorithm for system's control as well as for robotic toolpath development applied in additive manufacturing of small to medium objects. The algorithm is developed in a parametric associative environment allowing its flexible use and execution in a number of case studies, aiming to tentatively test the effectiveness of the suggested robotic additive manufacturing workflow and their future implementation in large scale examples.

Keywords –
Parametric design; Robotic additive manufacturing; Robotic control; Toolpath planning; 3D clay extruder

1 Introduction

The term Additive Manufacturing (AM), also commonly known as three-dimensional (3D) printing, is used to describe the process of material deposition in layers, leading to solidified products. The technology of AM has gained considerable attention the last few decades and today has succeeded to be a rapidly growing field worldwide with a number of technologies available for public use. This direction of investigation has been thoroughly explored and various methods have been introduced and discussed [1]. To name a few, these might include Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Inkjet Powder Printing, etc. [2, 3]. A number of advantages have led the manufacturing industry to introduce such technologies into daily production, which include the freedom to create any morphology without the application of molds [1], the minimization of material waste, etc.

Today, we have reached a stage where AM technologies are available for industrial and household applications in reasonable prices or even are available for reproduction through open source platforms and mechanisms [4]. Nevertheless, any selection of specific technology and its application contains particular limitations and constrains. These might include limitations in regard to the size of working area, leading to print results in small scales, constrains in regard to the type of material used, the type of mechanisms as well as the methods applied.

When tasks refer to the 3D printing of small to medium scale objects, these can be largely solved with available industrial technology. However, an area that faces limitations in large extend in terms of AM implementation is the construction industry, where the necessity for manufacturing building parts or even complete structures in actual scale, demands more thorough and comprehensive procedures that take into account actual construction parameters. In addition, due to the multiple and complex tasks involved during the construction of a building, including the need for specific technique and materials implementation [1], the introduction of open source and custom platforms for additive manufacturing is more than a necessity in order to allow direct and flexible intervention of automated mechanisms according to the large scale objective under investigation.

Large scale AM and particularly its application in construction industry is an area that is rapidly growing with many examples attempting to introduce techniques derived from 3D printing principles for the production of houses in full scale, for instance the 3D Print Canal House in Netherlands [3]. Towards this direction several attempts to provide such technologies have been conducted, especially in the area of concrete printing. Such works date back to the well-known Contour Crafting (CC) technique [5] and later to the introduction of other techniques, for instance D-Shape [6], Concrete Printing [7], Additive manufacturing of concrete [8], CONPrint3D [9], and so on. Although, similarities can be found in the abovementioned technologies in regard to their objectives, differences can also be observed, mostly it terms of material deposition and control automation processes. The techniques of Concrete Crafting and Concrete Printing as well as similar directions of investigation are based on the layer-by-layer deposition of concrete materials with the application of gantry and mounted nozzles [5, 8, 10], while technics like D-Shape follow principals similar to the Inject Powder Printing [6]. Beyond the obvious opportunities that innovations in large scale AM can bring to the construction industry, numerous advantages might be offered, which include reduction of construction cost and time, minimization of errors during construction, etc. [11]. Also, might allow issues related to the local and ecological aspect of material use to come to the fore [12, 13, 14], an area that lies within the broader field of sustainable construction, currently under consideration. This direction, together with the introduction of digital fabrication, for instance 3D printing in large scale, can reduce the environmental impact of structures [15].

In addition, recent attempts towards the introduction of advanced technology in Architecture, Engineering and Construction (AEC) industry, for instance, the use of digital design and modelling tools including Building Information Modelling (BIM) and parametric associative design or the application of robots and automation mechanisms in fabrication process, open new opportunities for integrating design to production processes. This might allow a more thorough and complete investigation, both in terms of the selected designs to be realized due to the ability of BIM and parametric tools to allow their real time control and modification prior to their actual construction according to a number of criteria (environmental performances, constructability, etc.). Also, this might include a more flexible and customized processes for controlling output data for construction of non-standard morphologies and later on their physical execution using automated and robotic construction systems [16, 17, 18]. In addition, advanced tools and mechanisms allow a more productive and open source approaches [19], which can be applicable to the construction industry, advantages that are necessary to be acquired during an AM process in actual scale.

However, in order to complete a fully operable system for 3D printing, knowledge in regard to the software and hardware installation are necessary, an area that is not always accessible by the majority of architects or constructors. In this paper, an attempt to overcome such limitations is conducted by introducing a robotized method for hardware installation and toolpath planning process that can be easily available and can be adopted by people involved in similar research directions. Further prospects are, by using similar principles, to extend the scale of additive construction, aiming at their implementation in various scales with emphasis on large scale manufacturing, an area that currently is in the forefront of the research conducted in our laboratory for sustainable robotic construction [12].

Within this framework, and by following similar principals [16], this paper presents a methodology for integrating parametric design and robotic additive manufacturing, aiming to be applied in, both small/ medium and large scale 3D clay printing tasks [13, 14]. The process aspires to promote the sustainable aspect of the material evolved but also to stress the advantages carried out in the design and construction industry by integrating parametric tools with automated construction technics.

The structure of the paper is as follows; in the next section the methodological framework is briefly explained; then, analytical descriptions in regard to the installation process of the industrial 3D clay extruder and the robotic calibration are given; afterwards, the toolpath planning development process, the robotic control and finally the robotic execution are demonstrated by testing a number of case studies; and finally, conclusion is drawn.

2 Methodological framework

As it has been mentioned, the aim of this ongoing study is to develop a robust and reliable methodology that will allow the integration of parametric design with robotic additive manufacturing mechanisms for 3D clay printing. This, in combination with the application of clay material, which promotes the ecological aspect of the suggested methodology, aspires to provide a sustainable and custom/open source platform that can be applied in different case studies. Such cases might include printable objects range from small/medium to large ones, using them as individual building elements in the construction industry.

Analytically, the proposed methodological framework considers all necessary actions required to embed the selected automated mechanisms for 3D clay printing in the overall automated construction system. Also, is designed to include all necessary steps required for a complete workflow procedure from design to production with emphasis on toolpath planning process and robotic control.

Initially, the installation of an industrial 3D clay extruder, and specifically the Clay Kit with LDM Wasp Extruder by WASP [20, 21] is embedded in the construction system and particularly is mounded at the end of an industrial robot ABB 600-20/1.65 with IRC5 controller. The industrial extruder consists of two main parts, the clay pump that extrudes the material and the 3D clay extruder that is responsible for the deposition of material in layers. The installation of the mechanisms as well as the robotic system calibration are necessary parts for an accurate and effective 3D clay printing procedure. This, in combination with the need for an inseparable workflow that achieve the parametric development of the objects to be built, the toolpath planning generation and subsequently the robotic control for robotic execution, consists all necessary steps towards a complete and integrated methodology.

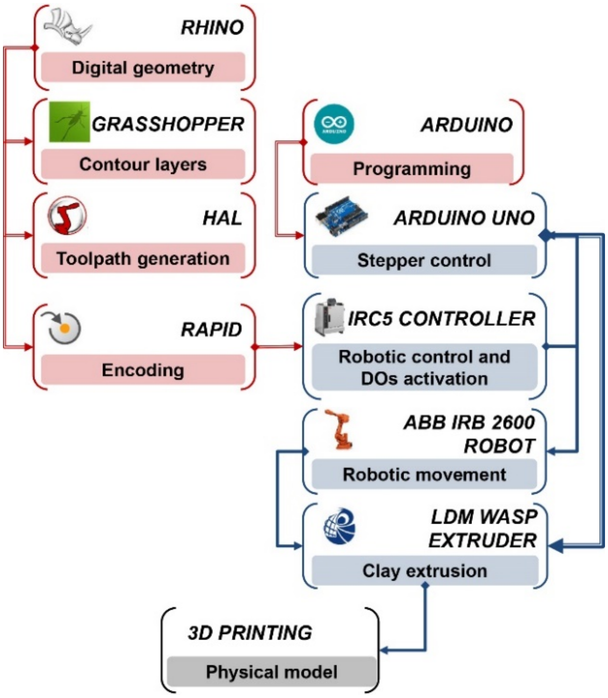

Figure 1. Methodological framework in the form of diagram for the 3D clay extrusion system development

In regard to the installation of the industrial 3D clay extruder, a number of sub-components consisting the overall system are studied and carefully mounted on the robotic arm. These include the clay pump that is responsible for continuous clay material feed to the clay extruder (nozzle) and the 3D clay extruder with nozzle that is responsible for extruding clay material and for layer deposing according to predefined width and height. As regards the toolpath planning process, similarities with other conventional [22] or advanced parametric tools and platforms [23] used for toolpath planning, which are introduced in additive manufacturing can be found. In this case, due to the parametric nature of the customized/open source platform that is introduced, the implementation is achieved in the parametric design environment of Grasshopper software [24] (plug-in for Rhino [25]). This enables the development of various morphologies in digital form that can be easily modified and parametrically control, offering large number of design possibilities. After the digital geometry is developed in the parametric environment, this is sliced based on contour-layer development algorithm, leading to the toolpath generation. Simultaneously, 3D print parameters are embedded to the digital geometry related to the width and height of each contour (filament) and according to the clay material mixture applied. Then, the HAL software [26], a robotic control plug-in for Rhino, is used to produce all necessary data in RAPID code and in turn to be executed by the ABB robotic arm. The following sections describe, in detail, the main steps of the suggested workflow procedure (Figure 1).

3 Installation of 3D extruder and robotic system calibration

3.1 Overview of the automated construction system

The robotic system consists of four main parts, where its synchronization aims at creating a process that will allow 3D clay printing of various complex and non-standard shapes. The system consists of the following parts:

1. The cylindrical tank for clay feed connected with the industrial clay extruder.
2. The industrial clay extruder that consists of one stepper driver that rotates an auger in the form of a rotating helical screw inside a cylindrical chamber, extruding the clay through 1mm nozzle.
3. The on-off switch and flow rate control board for the industrial 3D extruder that is run through an Arduino board, which controls a stepper motor driver.
4. The industrial robotic arm ABB 600-20/1.65 with IRC5 controller.

As it has been mentioned, the automated system is run in the parametric environment of Grasshopper in conjunction with HAL, which allows parallel control of robotic arm movement and activation of the industrial 3D clay extruder. As a result, clay is fed to the extruder at the edge of the robotic arm through the provided clay tank. Important aspect towards a seamless printing process is the accurate/functional design and programming of the automated clay printing control system.

3.2 Design and installation of 3D clay extruder system

Initially, an acrylic base functioning as the supportive system of the industrial 3D extruder is designed, fabricated and finally mounted at the end of the robotic arm. The suggested design solution allows undisturbed ventilation of the stepper motor, easy connection with the industrial clay extruder system, and simple assembly and disassembly of the mechanism for maintenance purposes. The acrylic base is attached to the robotic arm through a supportive steel blade with four screws, which also encloses the industrial 3D extruder fixed with two screws. Figure 2 shows the tool adjusted on the robot.

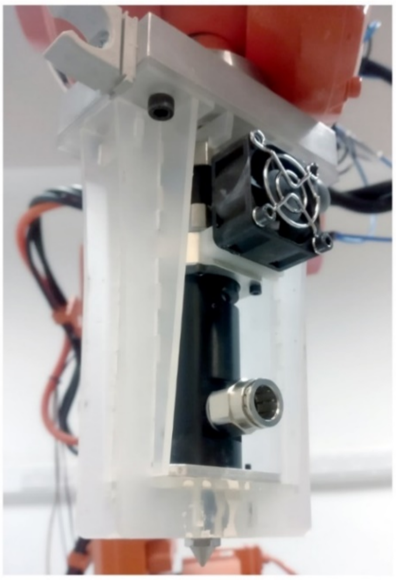

Figure 2. The industrial extruder with the supportive system mounded on the robotic arm

In order to feed with material the extruder at the end of the robotic arm, the cylindrical tank is filled with clay that is provided by the manufacturer [27]. By pushing air pressure into the tank, the piston is activated and pours the clay that is inside. The clay is passed to the cylindrical chamber of the industrial 3D extruder through a plastic pipe. In order to activate the industrial 3D clay extruder through its stepper motor, a stepper controller is used for rotation movement. The programming of stepper controller (CNC Single Axis 4A TB6600 2/4 Phase Hybrid Stepper Motor Drivers Controller) is achieved in Arduino environment using an Arduino UNO board. The programming allows pulse rate control in order to adjust the rotational direction and speed of the stepper motor. For powering the Arduino UNO board and the stepper driver, an external power supply is used. With the use of a Siple Pole Double Throw Toggle Switch (SPDT), it is possible to activate the Arduino UNO directly from the power supply or through a relay connected to the power supply and controlled by the IRC5 robotic controller. The use of switch allows manual preparation of the system for printing and automatic control through the control of robotic arm. Finally, the board for system's control is placed on the robotic arm (Figure 3).

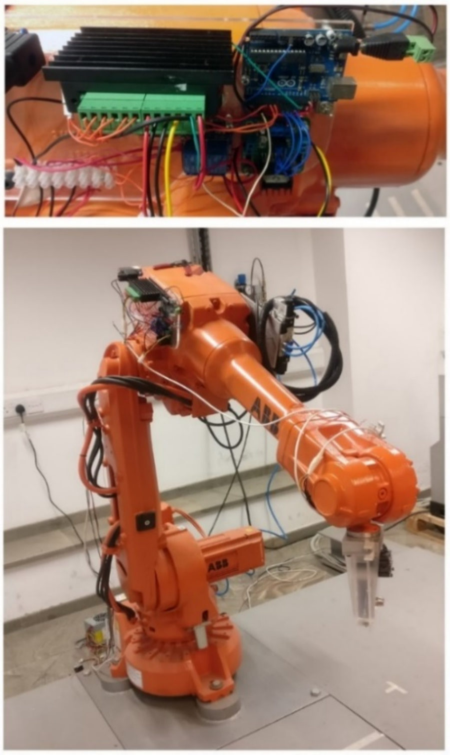

Figure 3. The 3D clay printing control system mounted on the industrial robot

3.3 Robotic system calibration

In order to achieve accurate and automated 3D clay printing process, the control of material flow from the pneumatic piston to the nozzle is important to be examined. The Arduino UNO board is programmed to control the rotation of the stepper motor at a constant and continuous rotational speed, which achieve the movement of clay material into the chamber and then its exit from the nozzle. As it has been mentioned, the Arduino board is powered by an external electrical source that is connected to a relay on the robotic arm controller. By activating the relay, the Arduino operates and controls the flow of clay. When the relay is switched off, the clay funneling stops. The on/off control of relay occurs in real time using the HAL plug-in. The activation or deactivation of nozzle funneling is based on the generated toolpath that is derived according to the digital shape under investigation.

A significant aspect in the printing process is the calibration of the robotic arm movement with the clay extrusion speed. This is done by observing the results derived from initial case studies, where several changes in robotic movement speed occurred. During the case studies execution, the robotic movement is controlled using the Teach Pendant, allowing determination of its right speed. Figure 4 shows results of calibration: under extrusion print (A) using 15 mm/s speed; over extrusion print (B) with TCP velocity of 5mm/s, and calibrated extrusion print (C) with a robotic movement speed of 9 mm/s.

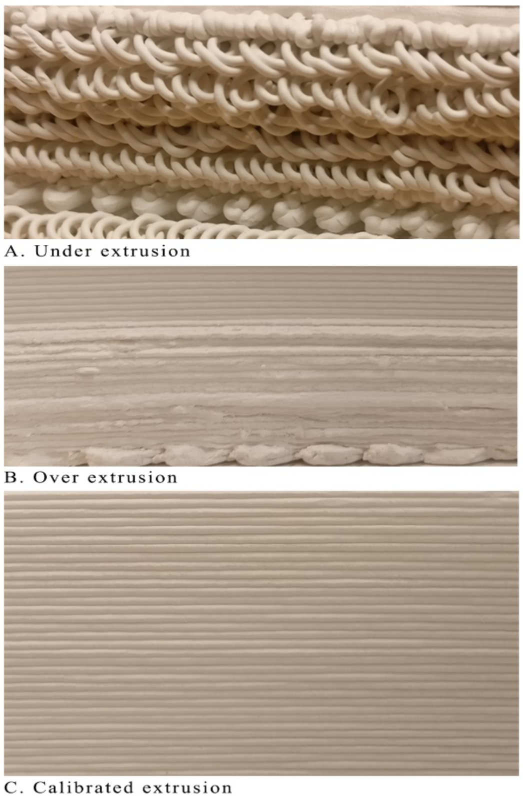

Figure 4. Results of 3D printing speed calibration. A. Under extrusion speed, B. Over extrusion speed, C. Calibrated extrusion speed

Finally, for the correct deposition of material on the base of working area, the height calibration of the nozzle in relation to the base is required. This is done by placing the nozzle perpendicularly to the corner of the base with an approximate distance of 0-0.2mm. For the correct positioning of nozzle, this is repeated three times, as many as the rest of base's corners. Using the HAL plug-in, the point of nozzle placement is recorder, updating the point in the parametric environment and then associating this with the base. In addition, for the right deposition of material, two initial layers of the geometry are added to the base with 5mm offset from the perimeter in accordance with the first layer of the shape. The form is printed on a solid layer, providing results of uniform clay layers.

4 Toolpath planning, robotic control and execution

4.1 Parametric design and control

In a 3D printing process, important parameters determining the end result are the layer height that defines the distance between the sections in the contour process, the line width that is influenced by the filament width of the extruded materials and the wall thickness that determines the number of polylines per layer, calculated based on the width of extruded materials. These parameters are introduced into the Grasshopper parametric environment in order to identify the robotic toolpath.

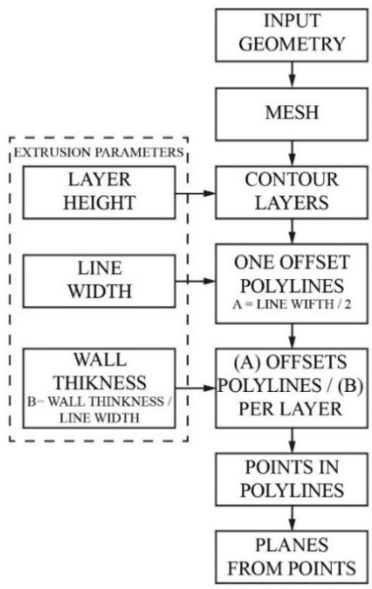

Figure 5. Flowchart of the contour geometrical configuration algorithm

The purpose of the parametric algorithm is to receive and process any digital geometry (BREP), by converting this into mesh object. Then, it generates contour layers in the form of consecutive polylines. The users can determine the print precision by varying the layer height up to 2mm. In this phase of experimentation and for case study purposes, the layers are defined with a height of up to 1mm. Subsequently, the sequential sections of layers are offset with inward direction and with value 0.5mm that is determined by the line width, which represents the filament of the extruder material (in this case 1mm/0.5). Moreover, the wall thickness is defined by the user, by specifying an integer number of required offsets in order for the extruder to print the expected width. The integer number is described by the roundness reduction of the thickness/line width relationship and also it calculates the group of polyline assigned in every layer height. Finally, polylines are divided into successive points, which create the toolpath of the robotic arm (Figure 5).

4.2 Toolpath planning

The development of toolpath for robotic motion behavior is based on the successive points of contour polylines generated in the parametric environment. Also, in the same algorithm the digital output (DO) activation control connected to the relay is used to activate the Arduino board, resulting in the rotation of stepper motor, and hence in the extrusion of clay material.

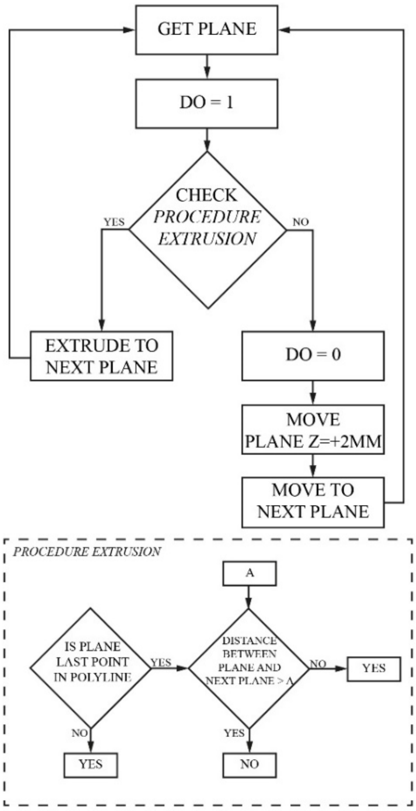

Figure 6 Flowchart of the toolpath development process

The robotic movement commences at the starting point of toolpath that is assigned outside the geometry at the corner of the base, and at the same time the clay extruder is actuated. Then, the deposition of filaments on the two thick layers of material on the base are executed. This process is based on the geometry of the initial contour layer (polyline), whereas the contour is offset 5mm and it is filled with radial lines from the center of the polygon in outwards direction. After the two layers on the base of the object are generated, the process of toolpath development is taken place.

The toolpath development process (for material extrusion) is based on the point-to-point motion driven by each contour layer, geometrically defined as polyline. The algorithm compares the distance between previous polyline's end point and next polyline's start point. If the line being created does not belong to the previous polyline, then the extruder is deactivated. In off state, the nozzle is disabled and is raised 2mm from the printed layer (from previous polyline's end point to the next polyline's start point) at a height of 2mm.

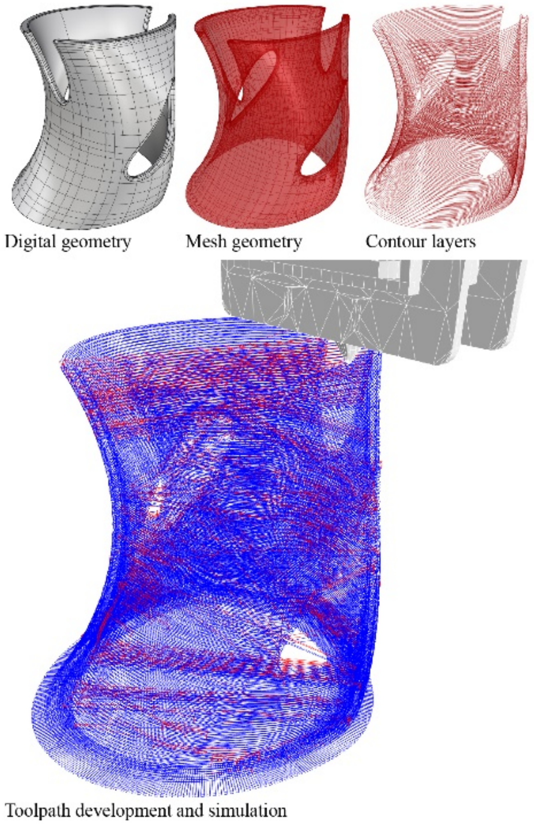

Figure 7. Toolpath development results. Blue colour shows the DO activation and red colour shows the DO deactivation

Subsequently, the nozzle approaches the next polyline's start point and the clay extrusion is activated. By turning off the nozzle at a height of 2mm ensures that the object is properly printed, as the movement of the nozzle does not touch or collide with the printed structure or does not deposit material in undesirable areas of the geometry. Finally, the toolpath development process is repeated in each sequential group of polylines for each contour layer in order to develop the overall toolpath. This is sent to the robotic controller for printing execution. Figure 6 shows the flowchart that describes the toolpath development process and figure 7 the toolpath generation in the parametric environment. Several case studies have been conducted, as shown in figure 8, in order to investigate results and draw useful conclusion for evolving printing process and for improving the functionality of the integrated platform.

In the first case study, a compact geometry is used to investigate the toolpath for clay extrusion. In this case, clay material waste is observed because there is no interruption and removal as well as deactivation of the extrusion process. Also, the layer height range is investigated, resulting in 1mm being the ideal one. Figure 8 (A) shows the second case study, where the appropriate layer height is defined and the speed of the robotic arm relative to the extrusion speed is investigated. In this case, as mentioned above, the speed of the robotic machine (TCP velocity), relative to the rotation of the stepper motor, is set at 9 mm/s. Finally, in the third case study (Figure 8B) a more complex form that consist of openings is tested, and specifically the ability of the methodology applied to automatically activate/deactivate and remove the nozzle in cases of open hole patterns is explored. Also, results in terms of the quality of printing (smooth surface resolution, etc.) are derived, which are influenced from the layer width and height.

Although, the experimental case studies introduced in this paper are in small scale, our attempt is to apply the suggested methodology in medium scale printing, but most importantly, in large scale tasks that can be revealed in construction industry. An experimentation in all scale levels with the parallel examination of appropriate clay material mixtures [27] will allow thorough and comprehensive results to be derived, evaluating in parallel the feasibility of the suggested platform to be introduced in construction industry in a future stage.

5 Conclusion

Currently, there is a tendency towards parametric design incorporated within platforms for performance evaluation of buildings, offering opportunities for design optimization and selection of the best results that can be realized in actual scale. Also, there is an increased interest among educational establishments towards automated construction processes, mainly by using industrial robotic arms for the manufacturing of complex and non-standard morphologies. However, little work has been observed in regard to the coherent and robust integration of such advanced digital design tools with automated construction processes. In this paper, the methodological framework and the initial results of experimentation in regard to the integration of a parametric design environment with a robotic additive process is presented. The aim is to develop an open source/customized platform that offers an alternative and ease solution for 3D clay printing in robotic construction tasks.

The methodological framework includes all important steps for a complete and effective integration that can achieve a smooth and seamless workflow from digital parametric design investigation to robotic production. The main pillars of this investigation include; the installation of industrial 3D clay extruder and robotic system calibration; the toolpath planning and the robotic control process, incorporated into the parametric environment; and finally the robotic execution, initially through small scale 3D clay printing studies. Within this framework, results in term of automated construction system calibration including extruder's stepper motor and robotic speed are obtained. Also, results in terms of toolpath planning process including layers' width and height of filament are obtained, offering all necessary data required for robotic execution in actual scale.

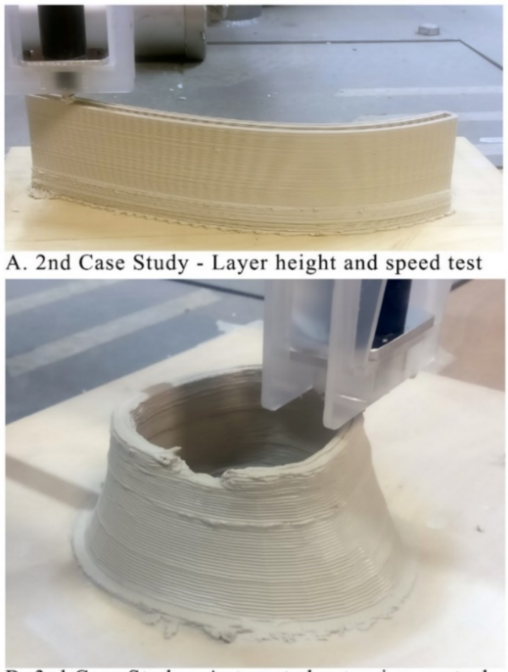

Figure 8. Two case study experiments using the 3D cay extruder mounted on the robot

In conclusion, this investigation has demonstrated a first attempt to integrate design and manufacturing tools within an open source platform. This allows an ease and effective development of robotic-driven automated system for 3D clay printing that can be potentially available for further implementation and use. Although, the first results are quite promising, further studies are required in order to test the feasibility of suggested methodology, together with a more thorough examination in regard to the use of clay mixtures and their application in different scales. Simultaneously, further studies in robotic AM need to move beyond experimental stage towards application in real construction scenarios taking into consideration sustainability criteria.

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