
KUKA

Free Form Clay Deposition in Custom Generated Molds

Producing Sustainable Fabrication Processes

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Abstract In a context of free fab printing, this research explores a series of investigations into the potential of 3D printing with clay that address the problems of viscosity, tool paths and setting times. The material of clay is explored here in order to simulate architectural building processes that use both subtractive and additive methods of construction that cannot be performed by a gantry style model of robotics. The use of clay deposition on a robotic tooling path enables a continuous and sustainable adaptation process due to the fact that clay is reusable, can mimic other materials in viscosity and is compatible with a range of sustainable aggregates through to firing stages. This paper describes ongoing research into a two-step robotic fabrication of free form clay printing; namely, as (a) the robotic milling of a sustainable formwork; and (b) as controlled deposition of liquid clay into a form or mold.

Keywords Robotic free form · 3D printing techniques · Sustainable tool path processes

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1 Introduction

3D printing processes are an area of robotic fabrication that enables architectural building processes through additive manufacturing techniques. Free Form Fabrication (FFF) or Extrusion 3D printing processes rely on the extrusion of a material in a pattern determined by an STL file. In FFF, material is extruded successively onto a work bed or plate, whereas in 3D printed robotic processes, only the robotic reach, and the work bed limitations limit the object size. While studies have been conducted in a diverse range of material from polymer to plastics and clay, specifically the area of robotic clay printing has significance since the material characteristics of clay such as viscosity, tool paths and setting times present a challenge to robotic manufacturing, but also offer the benefit of sustainable adaptation processes.

The research builds on ceramic material and delivery methods as an ideal approach for large-scale 3D printing, due to the properties and material specifications. The unique property held by clay is that it combines the strength of a solid with the fluidity of a liquid, with plasticity in terms of slide or 'shear' as initial response to pressure, and strength attained by a mix of particle sizes and thixotropy, which holds fine particles in a strong network (Hamer 2004). Ceramics or clay in a raw state change consistency, and can mimic other materials through the addition or reduction of water, defloculant, sodium silicate, alcohol and a range of up-cycled industry waste aggregates (crushed materials added to a body to deliver different properties of strength, moisture absorption and refractory qualities). Aspects of dissolvability allow for the use of clay specifically in robotic manufacturing where machinery and equipment are sensitive to material blockage. Furthermore, robotic 3D clay printing in a customizable mold support new work methods that are highly sustainable because the subtractive continued shaping of molds enables reuse and refinement.

This paper describes preliminary results from an ongoing research into a two-step robotic fabrication of free form clay printing; namely, as (a) the robotic milling of a sustainable formwork; and (b) as controlled deposition of clay composites into a mold. The research investigates a series of robotic precedents and commercialized 3D printing techniques in order to develop a framework for material and fabrication techniques. It focuses specifically on multi-functional processes including robotic arms while also addressing material sustainability in the 3D printing process, and the potential of up scaling for free form printing.

In the following, a background overview is presented. A second part describes the present framework for the research (including technical components of pump, setup of robotic arm and work envelope, limitations of aggregate clay body, and customized end effectors). The paper concludes with a report on ongoing exemplary studies into the custom manufacturing of a mold and slip cast in clay, free form deposition of clay, and robotic deposition of clay within a mold.

2 From Commercialized 3D Printing to Robotic Applications

The medium of ceramics has a long tradition of forming techniques such as wheel throwing, hand building or casting, but has seen some recent research into robotically controlled investigations into free from deposition and scale adaptations that test the material limits. Ceramics is used in industry and design in a range of modes from slip casting injection molding and wheel forming to 3D printing, which differ in terms of techniques and strategies, use of material body, and deposition techniques. 3D ceramic printing is currently commercialized on a small scale by companies such as Figulos and Shapeways, production costs are high, and there exist quality and stability issues with material shrinkage or cracking that is typical for ceramic or porcelaineous materials.

In a context of free form robotic fabrication, research has been undertaken into three- dimensional depositing of plaster within the work envelope of an industrial robot of ‘Morpheaux’ (Bard et al. 2012). ‘Robosculpt’ (Schwartz and Prasad 2012) shapes molds for fibre-glas chairs by robotically subtracting from a manual packed clay solid. ‘Objects of Rotation’ (Dickey et al. 2014) uses different clay shaping tools in a collet chuck attached to a robot arm that are used to mark or shape columns of clay secured on a clay throwing wheel, and which enables digital automation and up-scaling for clay modeling techniques. A significant research for combination of subtractive and additive combinations of formwork has been undertaken by ‘Woven Clay’ (Friedman 2014). Here, a styrene formwork is created using a router subtracting material, and additive robotic fabrication is applied. The porcelainous clay is deposited by robotic extrusion of a paste style of clay into a woven pattern onto an undulating foam bed, so that the material is set to dry within the formwork. This set an interesting precedent for the combination of different sets of robotic applications within one work process. Furthermore, material processes of ceramics can be exploited through robotic manufacturing for serial tests of surrogate or compounds, such as waste or up-cycled aggregates that address sustainability in large scale 3D printing.

3 Framework for Subtractive Robotic Milling and 3D Printing

Using a robot to rout out plaster molds and subsequently to deposit material selectively into the mold can be significant because this reduces several steps from a traditional ceramic fabrication workflow, and advances the potential of free form ceramic deposition by utilizing the full range of movement available with a 6 axis robot. A continuous trajectory from the subtractive cutting of molds towards the additive deposition of material allows for a simplified workflow, and more importantly demonstrates a two-fold robotic process where one single machine is

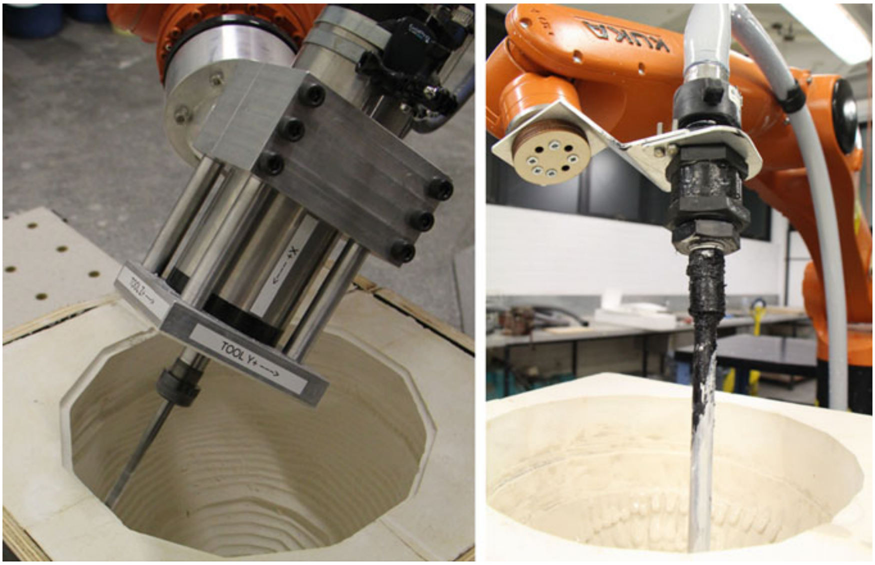

Fig. 1 Plaster Milling for Slip Cast mold (*left*), and clay deposition (*right*)

deployed for multiple fabrication steps (Keating and Oxman 2013). The research developed these considerations into a series of material and robotic path studies into free form clay deposit. Several aspects were included: designing with time; viscosity of material, placement, and hardening; three-dimensional deposit of material (in space); velocity as aspect between tool path and material sedimentation; 3D printing as gestural tracing in material, equivalent to drawing, a comparison of different 3D printing materials and techniques; studying differences between material bodies using clay as a composite material combined with different aggregates. These considerations were tested against the project brief that explores robotic fabrication of a mold, and consecutive clay deposition as a two-step processes that combines additive and subtractive techniques (Fig. 1).

In order to derive a framework, the research tested these criteria through a series of prototyping experiments, including:

1. Subtracting material to shape details by testing the fabrication of molds for slip casting that are fabricated using a spindle router from a block of pottery plaster. While the creation of a mold traditionally requires a master object to cast from, here, sequences of subtractive cutting of forms of the mold can be pre-determined digitally, and continuously removed with completed stages of fabrication.
2. Exploring different aggregate conditions of a material body in order to understand requirements for robotic deposition process of liquid material bodies.
3. Using a robotically controlled extruder end effector to lay material first in a repeating, incrementally stepped up 2D pattern, then at angles, speed and precision unachievable by hand slip trailing or by a simpler gantry frame setup.

4 Workflow and Robotic Free Form Clay Printing

Several technical elements further contributed to the framework, such as the fine-tuning of the pump setup, hoses and deposition bed; the limitations of aggregate body of the clay material; and the development of a customized end-effector, which are discussed in the following.

4.1 Setup and Work Envelope of Robotic Arm

The 3D clay depositing process is prototyped here on a KUKA KR10-R1100 with a working envelope of approximately 1 m^3, using the robot as a 3D clay printer. A remote pump draws material from a reservoir, attached to the robot arm with a 6 m hose to utilize the full range of robot reach and axis movement. The extrusion system is configured to work with a volume of material vastly beyond a traditional robotic payload. The KUKA KR10-R1100 is stationed at a standard workbench height of 900 mm on a portable, custom fabricated steel base. Initially a series of intuitive tech pendant movements to test appropriate speed and height for tool-paths was conducted, followed by extrusions for various material clay aggregates with high control in KUKA|prc (Fig. 2).

4.2 Technical Components of Pump, Hose and Depositing Bed

The research used a Moineau or Progressive cavity pump with a marine grade stainless steel core or driver for deposition. It draws from a plastic reservoir (20–200 L) connected by a flexible hose that feeds the printing material into the

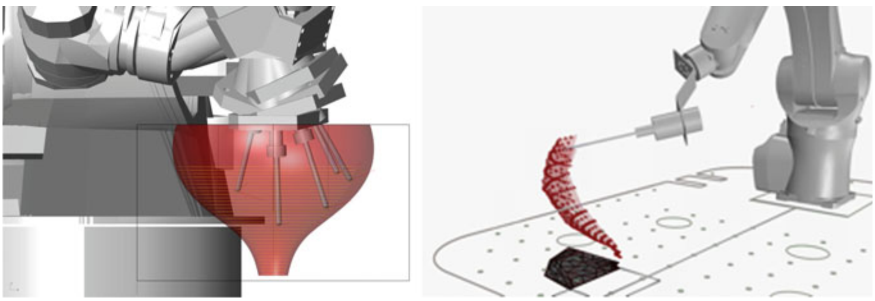

Fig. 2 Milling (*left*) and Testing tool path for robotic deposition in sections on custom bench (*right*)

Fig. 3 Robotic work envelope, material storage and accessibility, flow of clay depending on viscosity and speed of the pump and raw and fired test samples

chamber of the pump, and into a hose (diameter 25 mm) attached to the robot end effector for extrusion (Fig. 3). The extruder setup utilizes an aluminum coupling which holds several "off the shelf" irrigation components to act as the extrusion nozzle during the material testing phase. The current configuration enables researchers to experiment with a range of materials of various viscosities as well as aggregates in an accurate, repeatable and documentable way. In addition, there are a series of control valves to ensure safety of operation, maintenance and cleaning of the equipment, including one valve at reservoir outpoint, one in the pump cavity, and a third attached to the nozzle or end effector. At a later stage, this setup will be reconfigured to incorporate an air powered piston valve capable of being synchronized with remote control of pump velocity.

4.3 Limitations of Aggregate Body of the Clay Material-Scaling up

As a specific focus of the research, different materials for robotic extrusion were tested based on white earthenware casting slip (commonly used for casting) composed of clay particles suspended in a liquid composite body, and with additives including kaolinite, crystalline silica, water, sodium silicate and polyacrylate dispersant (dispex). Furthermore, waste materials were included as aggregates to address sustainability, including recycled paper pulp and softwood sawdust. Maltodextrin and fine sugar were added to the mix to aid adhesion of the layers during deposition, while cellulose fibre and bentonite are added to provide structural integrity. Alcohol (methylated spirit) was added to decrease setting times through evaporation. Initial tests were successfully prototyped by extrusion in the closed form mold (Table 1). This is significant because it presents an alternative to common slip casting. In slip casting, liquid porcelain or clay is filled into a mold, and water is absorbed by the mold so that the material solidifies, and excess liquid can be emptied. While slipcasting can include negative aspects such as overspill, material wastage or mistimed absorption, the controlled robotic deposition can improve these aspects by selective delivery of material.

Table 1 Material mixes for robotic deposition

Material mixes	Robotic deposition consistency
(1) Earthenware casting slip (2) Cellulose fibre	Cellulose fibre stays in suspension in the material, but tends to clump in extrusion/deposition
(1) Earthenware casting slip (2) Paper Pulp, 30 % by volume water	Paper pulp is aerated through fabrication process and when added to the base creates an aerated even, lumpy texture. Tool path lines, once layered, tend to slump on corners as the tool path changes direction
(1) Earthenware casting slip (2) Maltodextrin & fine sugar added to base mix 16 % each before water (3) Paper Pulp 30 % by wet volume	Texture similar to mix 2 but sugar and maltodextin result in thickness, facilitating the layered toolpath deposits adhering to each other and the deposition bed
(1) Earthenware casting slip (2) Maltodextrin & fine sugar dry weight added to base mix 16 % each before water (3) Paper Pulp 30 % by volume (4) Methylated spirits 3 % wet	Texture changes with the addition of the methylated spirits, becomes thicker and holds its shape better. Once set, the material goes hard and is reasonably strong even in an unfired state
(1) Earthenware casting slip (2) Softwood particles 20 % by volume (3) Bentonite 5 %	Textured with some particles being up to 4 mm long and 2 mm wide. Bentonite absorbs moisture and acts to hold the materials in suspension

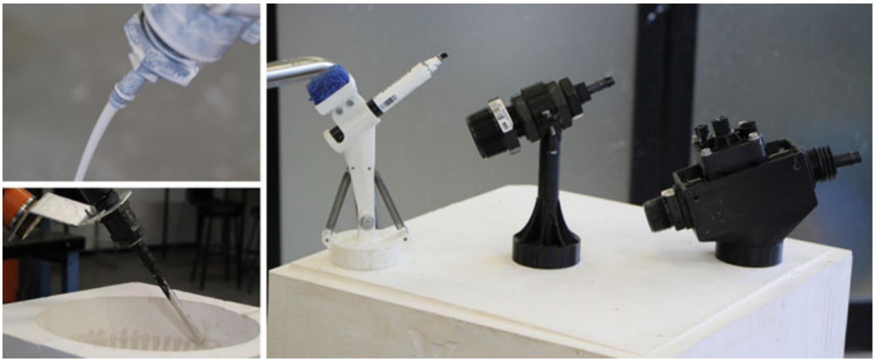

Fig. 4 Successive development of prototypes for clay deposition end effectors

4.4 Development of Customized End Effectors

In conjunction with the material composite studies, several iterations of end-effectors were produced to explore strategies for clay deposition. An electrically triggered solenoid valve with a roll plate coupling resulted in limitations of working with multiple viscosities, because maintaining a consistent pressure with water to correctly operate the valve during movement proofed difficult. Another aspect included the need for different off-the-shelf irrigation fittings to enable trials of nozzles with varying diameter. As a result, a modular end effector was developed so that individual components can be swapped for different material experiments, programs, or in the event of passages becoming clogged or damaged (Fig. 4).

In addition, once experiments moved from 2D toolpaths that either spiraled or stepped up in the Z direction to depositions within 3D forms, a nozzle 150 mm in length was added to enable placement of materials with less movement of the robotic arm, and less danger of collision with the work-piece, allowing increased velocity of movement and a more versatile placement angle.

5 Conclusion

This paper has discussed the initial stages of an ongoing research in the context of free fab printing as a series of investigations of the potential of 3D printing with clay. These initial tests that have been undertaken enable us to better understand the problem of relationships for robotic printing of clay in terms of mold, viscosity, tool path and multiple times (depositing times, liquid run times, setting times). The research discusses a robotic tooling for a two-step robotic fabrication of free form clay printing; as the robotic milling of a sustainable formwork; and as controlled deposition of liquid clay into a form or mold. The research successfully prototyped first results with the robotic milling of formmolds that have minimal waste in the production, and the consecutive deposition with different clay mixtures. The robotic deposition demonstrated an improvement of common slipcast processes and reduction of spillage and material waste, which is part of traditional practices. Furthermore, the use of waste substances from industry as a component of the deposition material was successfully tested, and thus aspects of sustainability could be associated within the context of 3D printing.

As a future research trajectory, the process could be adapted to specific site conditions by the including locally sourced materials as aggregates, and furthermore be upscaled towards architecture applications.

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