CLAY ROBOTICS

Tool making and sculpting of clay with a six-axis robot

RACHEL TAN and STYLIANOS DRITSAS
Singapore University of Technology and Design, Singapore
{rachel_tan, stylianosdritsas}@mymail.sutd.edu.sg

Abstract. The objective of the project is to design a reproducible clay sculpting process with an industrial robotic arm using parametric control to directly translate mesh geometry from Computer Aided Design (CAD) environment into a lump of clay. This is accomplished through an algorithmic design process developed in Grasshopper using the C# programming language. The design process is enabled by our robotics modelling and simulation library which provides tools for kinematics modelling, motion planning, visual simulation and networked communication with the robotic system. Our process generates robot joint axis angle instructions through inverse kinematics which results into linear tool paths realised in physical space. Unlike common subtractive processes such as Computer Numeric Control (CNC) milling where solid material is often pulverised during machining operations, our process employs a carving technique to remove material by displacement and deposition due to the soft and self-adhesive nature of the clay material. Optimisation of self-cleaning paths are implemented and integrated into the sculpting process to increase pathing efficiency and end product quality. This paper documents the process developed, the obstacles faced in motion planning of the robotic system and discusses the potential for creative applications in digital fabrication using advanced machines that in certain terms exceed human capability yet in others are unable to reach the quality of handmade works of art.

Keywords. Design computation; digital fabrication; architectural robotics.

1. Introduction

The rapid evolution of Computer Aided Design and Manufacturing (CAD & CAM) in parallel with digital fabrication technologies, in particular industri-
al robotics (UNESCE, 2005), has influenced design research work in the field of architecture in recent years. Robotic technologies have been employed in the past for a wide range of applications (Siciliano and Khatib, 2008) including automation of on-site building construction (Cousineau and Miura, 1998; Gambao et al, 2000). Recently, robots have been deployed for creative investigations of the capabilities of design and fabrication processes that are beyond human aptitude. Robots have been used for both additive processes such as assembling brick walls (Gramazio and Kohler, 2008; Willmann et al, 2012) and extrusion 3D printing (Leach et al, 2012; Jokic et al, 2012; Peters, 2013; Van Herpt, 2014; Sun et al, 2014); subtractive applications such as machining material stock (Brell-Cokcan et al, 2009; Schwinn et al 2012; Dritsas and Goulthorpe, 2013); and forming processes such as folding (Lavelle et al, 2011; Pigram and McGee, 2011).

Amongst those fabrication processes, the work presented in the paper may be classified as forming and/or subtractive. In particular, the use of wet clay in our project is closer to such traditional processes of carving and sculpting where material is both imprinted, displaced and deposited. The objective of the project is to experiment and explore the possibilities and limitation of applying advanced fabrication technologies to traditional, culturally loaded and environmentally sustainable material.

2. Digital and physical process overview

The preliminary goals of the still ongoing study are to design and produce a large-scale ceramic artefact using a computational strategy informed by the material and robotic fabrication processes. The project is thus organized in the following research and design tasks: (a) Understanding the Material, (b) Tool-Building for Clay, (c) Parametric Computation Geometry Design, (d) Motion Planning for Robotic Fabrication, (e) Ceramic Firing and Assembly.

2.1. UNDERSTANDING THE MATERIAL

Clay has numerous advantages in terms of material properties such as its low embodied energy in unfired form; it is readily available at a low cost in a wide variety of mineral compositions and colours due to its abundant natural sourcing; it exhibits certain desirable mechanical characteristics such as high compressive strength in fired form which is typical to ceramics; as well as excellent weathering resistance attributes which are desirable for outdoor building applications. However, clay has also both material property limitations such as high density, porosity and fragility well as some severe fabrication challenges due to its wet processing pre-fired, shrinkage due to firing
and hardness after firing, inconsistent composition, even though more controllable compared to other natural material resources such as timber.

In addition, we note that clay is extremely sensitive to physical damage during processing, characteristic of soft types of materials such as foam (Figure 1). Its self-adhesive properties further complicate shaping as there is the need for careful planning of material debris extraction in order to achieve high quality surface finish. Therefore, the process is unlike milling where the subtracted material is typically chipped, pulverized and evacuated from the work piece by the tool shape and external extraction systems. We therefore embarked on a custom tooling design and development process with the starting point being, the techniques and tools used in traditional pottery.

![Figure 1. Initial prototypes of robotic clay sculpting demonstrates the difficulty of material.](image)

### 2.2. TOOL-BUILDING FOR CLAY

We developed prototype tools by adapting traditional wheel throwing clay hand-tools purchased off-the-shelf as the robot’s end-effector. The design was a clamping mechanism to accommodate various tool handle shapes and cutting edge profiles. It was fabricated using laser cutting plywood and featured details for mechanical fastening and support of the cantilevering tool (Figure 2). While the interchangeable characteristics of the end effector allowed for quick tool centre point (TCP) offset calibration and rapid prototyping with various tool shapes, it proved limiting in terms of overall stiffness. Robotics generally is less stiff or positionally accurate compared to CNC mills. Extended tool lengths tend to produce vibration-induced imprints on the work piece. Nevertheless, with this study it became evident that these traditional hand tools are designed for two armed sculptors with one hand available to collect excess material before it reattaches to the artefact. We thus moved to CNC-inspired reinterpretation and redesign of our tool set.
Figure 2. First iteration of robotic end effector based on traditional clay hand tools.

For the second tool design iteration, we used waterjet cutting to fabricate a stiffer clamp from aluminium sheet metal. The tool holder was designed as an interlocking set of plates centred directly axially above the Z-axis of the robot’s flange with shorter protruding tools of various edge profiles. This allowed for both easy tool changes as well as faster calibration of the TCP offsets. Even though the performance of the second generation tooling greatly improved, we observed that hollow tipped tools were difficult to use because residual clay tended to block the cavity. Clay parts would thus fall directly behind the processed part, encumbering the cleaning process. Solid tipped tools designed in the third iteration were more predictable as they laterally displaced material that was scooped by a follow up cleaning pass. In addition, we experimented with techniques used in machining and turning where small bevels and tapers are ground into the tool’s side edge to assist material guidance evaluation. The benefits of these were nominal (Figure 3).

Figure 3. Second and third iteration of robotic end effector made of aluminium.
2.3. PARAMETRIC COMPUTATIONAL GEOMETRY DESIGN

The design objective for the large scale prototype was to create a decorative tiled surface with a regular layout and parametrically varied interior pattern; something desirably reminiscent of traditional ceramic wall tiling qualities but revisited with computational geometric and digital fabrication techniques.

The initial intent was to inform the design pattern from the sequence of tiles sculpted such that material continuously displaced towards the edges of the wall and ensured end product finish clarity. We used regular triangulation to organise and segment the design into manageable sizes for fabrication. To achieve visiting each part of the triangulation once in centre-out fashion, we employed graph analysis, namely the breadth first search sequencing (BFS). Furthermore to minimize the travel length of the robot tool, we employed a shortest path logic embedded in Dijkstra’s path finding algorithm. The result of the analysis produced an outward centripetal tree structure which we then classified such that tree edges would become the conduits of displaced clay from the interior triangles discharged to the artwork’s boundary (Figure 4).

![Figure 4. Overall tiling pattern and detail of material displacement pathing.](image)

Individual triangular faces were shaped using a fan-shaped geometric pattern with gradient characteristics identifiably produced by computational methods (Figure 5). The desired outcome was to create a wall surface with haptic, visual and lighting characteristics due to varied three-dimensional texturing.

The parametric geometry was developed in Grasshopper using components created in C# programming language. The graph analysis and optimization methods were based on the Jeneratiff library which is being developed by the team and is currently available online for download.
Figure 5. Triangular face material removal pathing and finished geometry.

2.4. MOTION PLANNING FOR ROBOTIC FABRICATION

The project was developed with the Universal Robot (UR10) in combination with the Jeneratiff digital fabrication library developed by our team that enables translation of geometry from CAD to the Pythonesque programming language understood by the machine. The benefits of this approach is the integration of the design modelling, simulation and direct over the network communication with the robot, which enables rapid experimentation cycles by eliminating technical details that demand time away from understanding the design, material and the formation process (Figure 6).

Figure 6. Robot programming and control interface based on visual programming.

Motion planning for robotic clay fabrication process includes translating design geometry to machine operations taking into account such properties as machine acceleration, travel speed and breaking which are relevant to the rate of material extraction and quality of surface finish. In addition, the main challenge was to define pathing such that residual material would be com-
pletely removed from the processed surface without reattaching onto the part.

The first iteration attempted a conventional machining inspired strategy of multi-pass processing which included a roughing phase that removed the majority of material followed by a surface finishing phase at lower speeds. To overcome the vibration of tool due to robotic stiffness issue explained as well as ensure sufficient time for the trapezoidal speed profile, we used also a strategy originating in machining, namely extended paths at the entry and exit points of the workpiece. The results were somewhat successful yet the remaining parts of material required multiple additional finishing passes.

The second iteration adapted the above logic to the material behaviour by introducing interim tool cleaning operations. Initially approached with the amusement of having the robot clean itself periodically; the idea proved to be effective in that it actually reduced the total fabrication time compared to extensive processing (Figure 7). The logic was finally fused with the design using the pathing conduits for material evacuation within the pattern and the sequencing of triangular fan indentations was organized such that subsequent passes would always push the material towards the edge gutter.

![Figure 7. Damp sponge cleaning apparatus experiment improved surface finish.](image.jpg)

2.5. CERAMIC FIRING AND ASSEMBLY

As we have not concluded the project, we have only some initial insights of the firing and assembly process. The selection of the clay material used was made with the kind advice of the local Chinese pottery gild master such that it would not require temperatures too far above 1000°C to achieve minimal shrinkage due to vitrification of clay particles. The initially fired parts did however shrink and as such these results will inform the upstream design segmentation and detailing logic. This will direct the approach to creating an interface for assembling the parts into a bigger wall which is currently based
on applying a uniformly imprinted roughing pattern on the back side of the tiles using a textured mat such that mortar or engineered adhesives can create mechanical attachment to a substrate.

Figure 8. Final results of prototypes prior to firing process.

3. Conclusions

The characteristics of artisan operation upon material are driven by cycles of skilled hand operation, acute visual evaluation and dynamic adaptation of planned actions towards end goals. In contrast, the process studied here is a computational approach that is virtually modelled and then executed off-line on top of material domain without direct or online understanding of actions and reactions of the material or feedback mechanisms.

In this fashion, it is evident that there is a qualitatively fundamentally different approach and aesthetic in the both the process and end products which should not be confused as an attempt of replacing or even simulating human action. Nevertheless, we had trouble convincing otherwise the Chinese pottery gild master as he was evidently upset when he realized the artefacts he fired for us were made by a robot. In popular culture, robotics are often perceived as immensely more capable compared to humans even though in reality we can only achieve modest results such as those presented. Arguably there is room for advanced digital fabrication for cultural heritage conserv-
tion we explored in the past (Dritsas and Yeo, 2013) especially in the light of the extinction of artisan techniques due to modernity.

Perhaps robotics can be deployed for capturing and reproducing human behaviour using vision systems and advanced closed loop control algorithms. Yet for the purposes of attempting to expand the realm of digital design and fabrication it is questionable if this would make sense or there are more fruitful opportunities for exploring the singularity points of machine capability and aesthetic.

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