ISOMORPHISM Stylized Translations of 2D Prototype in Additive Clay Printing

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Abstract. Traditionally, the relationship between digital prototypes and fabricated entities has been explicit and stable. However, recently, the ambiguous relationship between the above is coming into our focus. This research discusses a series of methods using the industrial six-axis robot to achieve diverse stylized expressions under specific prototypes and reveals the relationship between robot-controlling and printed features in order to figure out the stylized topological relationships of digital twins. This paper begins with a consideration of the relationship between imaginary archetypes and solid entities, which leads to the possibility of hitherto unknown polysemy. Next, several methods to determine the robot motion parameters based on different style details were applied, which could examine the effect of each process according to a predefined prototype by the controlled variable method. Then, some experiments have been carried out to demonstrate the connection between robot movement and fabricated details, along with the method to generate the corresponding toolpath for specific design intent. This research shows the possibility to create diverse translations based on a targeted 2D prototype by defining robot movement, which will fundamentally improve the form-shaping capability of digital technologies.

Keywords: Stylization · Prototype · Ambiguity · 3D Clay Printing · Robotic Arm Control

1 Introduction

The concept of the prototype in architecture has a long history and can be understood simply as an initial reference. Along with the development of typology and analytical psychology, the concept of prototypes in architecture includes spatial prototypes and gradually extends to formal prototypes. In recent years, the intervention of artificial intelligence in architectural generation syntax has made it possible to quickly generate multiple spatial solutions with a specified structure. At the same time, as a counterpart, the digital fabrication paradigm, a new digital workflow, which enables precise control over the design and generation of components, dramatically facilitates the entitlement of customized and differentiated construction components [9]. Moreover, the designer's global exposure to highly differentiated design expressions has facilitated and enforced this paradigm [3]. The contemporary interest in form customization of construction

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elements [6] has two primary motivations: a qualitative, design-driven desire for novel forms or an aspiration for the quantitative improvement of building performance metrics (such as structural, thermal, or acoustic) [9]. Since then, the relationship between digital prototypes and constructed entities has become ambiguous, no longer a clear one-to-one relationship but a multiplicity of meanings.

The concepts of style are two commonly used devices for design analysis and synthesis [1]. As digital prototypes and fabricated entities are two fundamental aspects of digital twins, the "black box" brought about by rapid advances in digital technologies has prevented us from understanding the formal expression capabilities of relevant technologies. By using 3D additive clay printing as an example, this research hopes to sort out the stylization relationship matrix based on the particular 2D digital prototype, which will reflect the polysemy or ambiguity between them.

2 Background

2.1 Additive Clay Printing

Clay, the typically green and sustainable building material, just like other natural, paste-like materials, offers a potential reduction in the embodied CO_2 that the production of buildings using conventional materials emits, in addition to its excellent insulation and fire resistance properties. Due to its excellent material properties, clay is one of the most popular building materials in history, even the oldest. Early potters utilized coil-based mimicking techniques to make clay products. This method has some consistency in the logic of Contour Crafting (CC), a layered fabrication technology of additive manufacturing that can produce unique elements with complex geometric features relatively quickly without high fixed tooling costs [9]. Contour crafting (CC) seems to be the only layered fabrication technology uniquely applicable to the construction of large structures [5].

Clay 3D printing technology has advanced tremendously in recent years. Institutions like the IAAC and digital fabrication manufacturers like WASP are utilizing robotic fabrication to extrude and deposit clay at a constant rate along a linear print path [2]. Both projects, Pylos (IAAC) and Big Delta (WASP), show the potential application of clay in a time- and cost-efficient manner for large-scale construction.

2.2 Stylization

The debate on the expressive capability of digital technology has been going on since its dawn. On the one hand, digital construction technology has made possible the production and manufacturing of complex customized components, which is unimaginable before it appears. Technological advances have brought about increased productivity and a new aesthetic paradigm revolution. On the other hand, recently, blurring the original recognizable layers has often been seen as progress in the field of technology, which does away with visible traces of the manufacturing process. However, historically, construction methods in architecture and the building industry have celebrated traces of making ranging from stone cutting to log construction [8].

The design analysis and synthesis of AM utilizing the style concept is crucial since layered 3D additive printing methods leave behind endogenous signs of manufacture.

Sculptural expressions based on three-dimensional features, such as volume features and form features, and pictorial expressions based on two-dimensional features, such as material features, color features, and texture features, are two categories of stylized expressions for bespoke components.

2.3 Research Origin

Digital fabrication research on the expressive impacts of AM has been quite popular. The Janus Printing Project by Harvard GSD enables multi-material printing of clay-based materials through coextrusion nozzles (Fig. 1 Left) [10]. In the Seed Stitch Wall (Fig. 1 Right) by Ronald Rael and Virginia San Fratello, the print trajectory designed visually mimics the knitting technique known as seed stitch to create a soft texture of the building [7]. The aforementioned studies, however, only seek to evaluate the effectiveness of a single approach and do not, in a broad sense, systematically resolve the ambiguity that progressively develops between them.

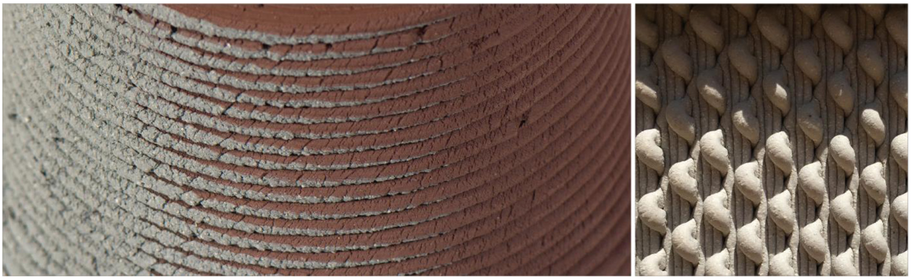


Fig. 1. Left: Janus Printing, Right: Seed Stitch Wall

Using the clay additive printing process as an example, this research aims to investigate the capability of the digital fabrication process for the physical translation of a particular 2D digital prototype under specific toolsets. It also attempts to systematically analyze the coupling relationship between the isomers and manufacturing parameters.

3 Methods

Instead of using a one-way linear conceptual model process, the research workflow (Fig. 2) for this study begins with a particular 2D digital prototype, extracts the specifics of the prototype's differential characteristics, and then determines the appropriate physical construction methods using a stylized index matrix derived from empirical generalization. The matrix is created from printing tests using various methods in specific processes, such as particular process parameters, robot commands, material properties, and associated manufacturing effects. It can be claimed that there is an ambiguity between the two based on the one-to-many relationship between the textural details of the built thing and the digital prototype.

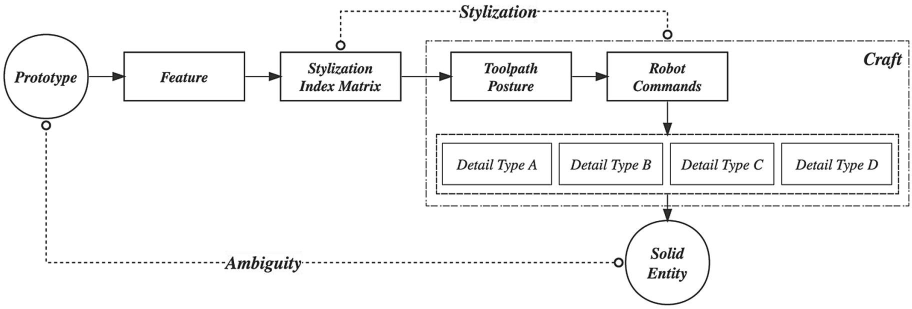


Fig. 2. Research workflow

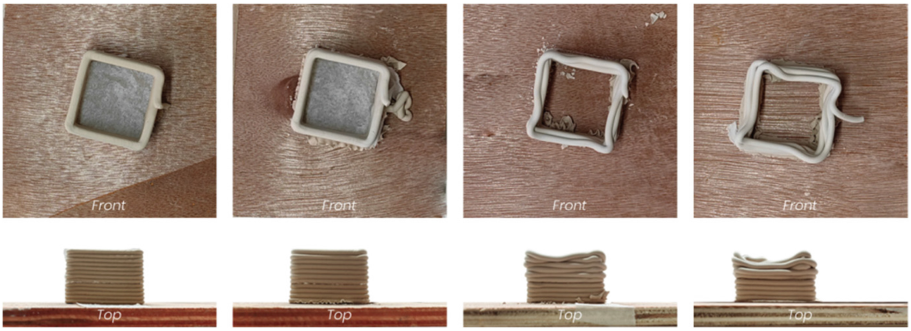
Three key parts of the experiment-based study process are carried out sequentially: the formal relationship between the continuous extrusion process and clay properties, the establishment of a transformation matrix of robotic target pose, and the influence of different movement modes of the robotic arm with a fixed toolkit on form in the printing process.

3.1 Formal Relationship Between Printing Process with Clay Properties

In contrast to other clay printing methods, this study focuses on determining the robot arm motion pattern and process parameters based on a single material, a fixed kit, and a particular digital prototype in order to investigate the continuous extrusion printing method's materialization performance limits.

The method relies on a technique called paste-based extrusion, a process in which successive beads of viscous ceramic paste are deposited on a printing surface to form a 3D object in a process similar to coil pottery [10]. The deposited material compresses the still-fresh clay at lower levels during printing due to the special material qualities of the paste-based material [4], resulting in variable degrees of micro deformation. In regard to constructing details, we can make distinct features on the print surface by varying the height and width of the extruded bead with the aid of the elastic deformation characteristics of the clay, permitting a variety of print forms. As a result, the extruded bead's width and height are direct elements in forming texture. The extrusion speed is controlled by the paste pumping system, which is made up of a stepper motor and an air compressor. During printing, we must synchronize the flow of paste and the speed of the tool head.

The height and width of the paste-based print element extrudate are frequently combined with one another. We have found that the two are adversely connected within a particular range through early experiments (Fig. 3). We used a circular nozzle with an inner diameter of 2 mm for the preliminary sub-height test, so the subdivided layer height must be kept to a specific interval during printing; otherwise, insufficient interlayer adhesion will affect printing accuracy and may even cause the component to deform overall. The printed section's width and height are constrained by a number of process variables. These elements can be broadly divided into static and dynamic parameters, such



Sub-height = 2.0mm Sub-height = 2.5mm Sub-height = 3.0mm Sub-height = 3.5mm

Fig. 3. The preliminary sub-height tests

as pumping air pressure and tool head movement velocity. Static parameters include subdivision height and tool head attitude.

Hence, starting with three common parameters—toolpath sub-height, toolpath velocity, and toolpath posture—this study will undertake a series of controlled experiments to assess the impact of process parameters on the form-shaping.

3.2 Transformation Matrix of Robotic Target Pose

Starting with static and dynamic process parameters, this experiment determines the impact of printing parameters based on various motion patterns on the shape.

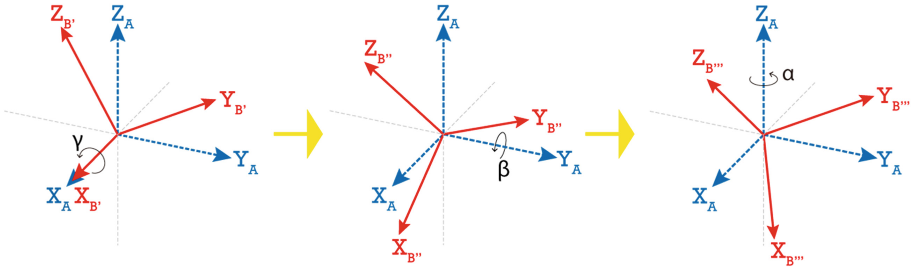


Fig. 4. TCP rotation Transformation

Although the dynamic parameters describe the rate of change of each state, the static parameters need to characterize the tool head pose and the height of the subdivision layer using six degrees of freedom: X, Y, Z for the TCP spatial position, and A, B, and C for the TCP spatial pose. By modifying A, B, C at a fixed spatial position, the figure

(Fig. 4) illustrates the spatial pose transformation of a certain target point.

$$\begin{bmatrix} 0 & 0 & 1 & X \\ 0 & 1 & 0 & Y \\ -1 & 0 & 0 & Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

A fourth-rank homogeneous transformation matrix (1) should be passed through in order to convert the robot root coordinate system to the tool head TCP coordinate system. The experiment shows the rotation transformation matrix needed to guarantee that the print head nozzle orientation is vertical and downward, while the original digital prototype of the printed object determines the TCP's spatial position (X, Y, Z).

3.3 Formal Effects of Different Movements with the Fixed Toolkit

Different movement patterns of the robot are the outcome of the interaction between static and dynamic process parameters.

- Only the Z variables can be used in the subsequent style generation session to generate variable layer height features by changing the Z variables of the tool head TCP for a specific region because the digital prototype has been established and the X and Y variables of the tool head trajectory have been constrained. The width parameters of the printed cross-section alter in accordance with the paste pumping speed, resulting in a distinct texture on the printed surface. In order to determine their mapping relationship, four combinations of subdivision layer heights are put up in the tests.
- For a given slurry pumping rate and subdivision layer height, the width of the printed cross section is less the quicker the tool head moves. In the experiment, four gradients were set up to assess how quickly clay could be shaped.
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The experimental results (Fig. 5) show that different combinations of subdivision heights based on Z variables shape the texture of the component surface in a fairly natural way, and printing formal samples enables the construction of unique prototype patterns across distinct zones of the pattern. The component texture only generates noticeable results near the edge of the transition region, regardless of whether it is based on the A or B variables. Because the change in angular velocity between consecutive TCPs of the tool head changes more dramatically during the attitude shift than the change in linear velocity, a localized buildup of material occurs at a constant pumping rate. In terms of the dynamic process parameters, varying the tool head speed directly results in varying printed cross-section widths, which is anticipated to be used for creating particular prototype designs.

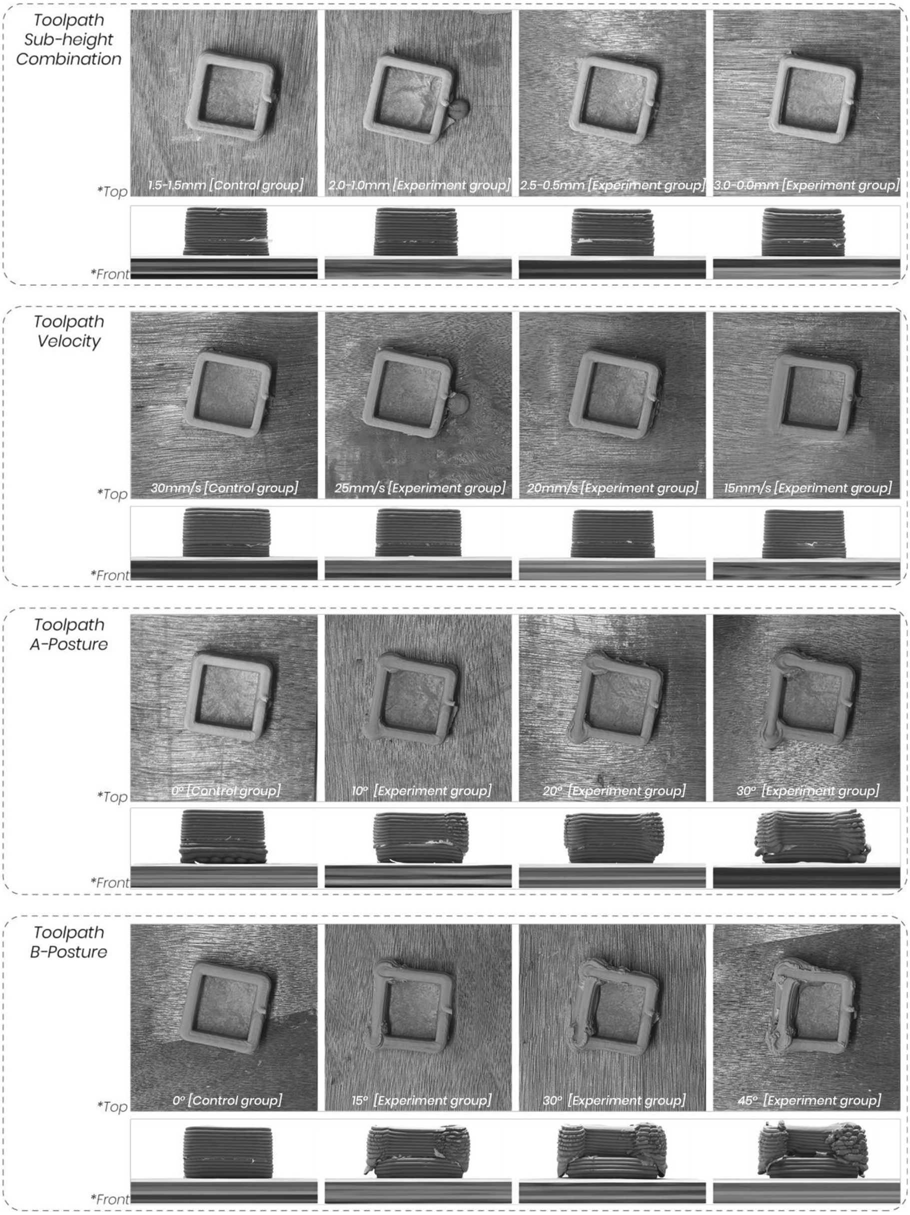

Fig. 5. Results of control tests

4 Results

4.1 Printed Entity and Original Prototype

Controlling these three printing factors will allow for the differentiating production of certain prototype designs, according to the controlled tests on subdivision layer height, printing speed, and printing posture. The print results of the subdivision layer height combination of 1.0–2.0 mm and the tool head speed of 20 mm/s produced the most controlled and smooth surface texture out of the four gradient combinations in the aforementioned series of testing. From the standpoint of stylization, the printed textures based on the A and B poses do not significantly differ from one another and can be categorized as belonging to the same style. As a result, just one pose will be used to create the arguments in the ensuing solid printing procedure. The prototype features are represented by the 15° rotation pose of the A variation during the solid printing process.

The selection of the initial prototype is based on the following aspects: first, the digital prototype can only influence the texture style and is not allowed to change the volume and form characteristics of the model; second, the selection of the digital prototype must reflect the generality for future application in the broader range of scenarios; therefore, a capital "X" in Rockwell font is selected for this experiment, which can represent the boundary characteristics based on horizontal, vertical and oblique directions; third, the graphic characteristics of the digital prototype should be translated into recognizable robot commands; fourth, the digital prototype must be unchanged to ensure its uniqueness.

Figure above (Fig. 6) displays the outcomes of the formal entity formation. With the interlayer order remaining intact and the entity's surface reflecting the texture of resolution, it can be seen that the texture performance of the finished entity depending on the variable of speed is the most moderate. The finished entity's texture performance based on the subdivision height variable is the best, and its surface exhibits clear signs of difference. The boundary region of the prototype mostly reflects the texture features of the completed entity based on the variable of tool head posture, with the most obvious aspects primarily in the vertical and oblique orientations.

4.2 Discussion and Future Work

The surface characteristics of the three produced entities and the features of the digital prototype demonstrate how different expressions of the same digital prototype may be created by adjusting the proper process parameters. In the era of the digital twin, this relationship shatter the stereotype of a rigid one-to-one mapping relationship between prototypes and entities, further enhancing the stylistic alternatives of particular prototypes and exhibiting the multitude of meanings in the context of digital production.

The term "isomorphism" accurately captures how different constructed things based on a particular archetype display a dialectical relationship of both diversity and identity to one another. The identity, in the topological sense, is that each entity responds to a particular prototype; the difference arises because each entity is the product of a particular production process. Although this method of exploration is presently restricted to the materialization of 2D prototypes, which can only translate flat features into surface

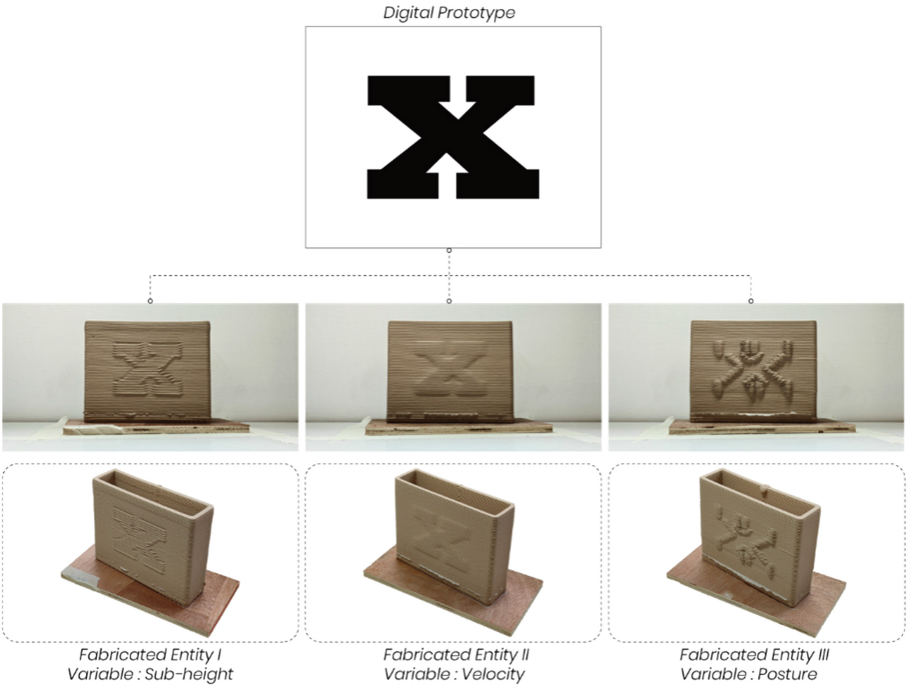

Fig. 6. Digital prototype and fabricated entities

features, the underlying technology will undoubtedly advance to higher dimensions as digital technology advances.

Further investigation of the structural and thermal qualities is not conducted in such tests, and the results are now only applied to aesthetic expression, lessening their relevance to practical concerns. In order to establish gradations that provide aesthetics and performativity throughout the volume or section of the surface, future study will expand this approach to adjust the thermal and structural qualities of clay materials.

5 Conclusion

Prototypes are traditionally thought of as the starting point for designers' new shape inspiration. This study discovered that the growth of design variety can be constrained by stable and unambiguous mapping relationships. The use of stylized tools for studying polysemy of digital prototypes, particularly employing simple tool systems with single materials, is the main driving force behind this study's examination of parametric design systems and digital fabrication tools. The other two main aims of this project, which are of more interest, are to propose a process-oriented design approach and to implement techniques for manipulating robots under specified construction specifics.

Research has proven that using the same digital prototype as a base, it is possible to define the process parameters for autonomous clay printing, which would fundamentally give robotic manufacturing new formal meaning. In order to think about "process-oriented design," which demonstrates excellent implementability and spectacular challenges in further research and application, the designer's attention will shift when faced with a design prototype from a single outcome orientation to a multiple outcome orientation and back to the motion parameters and process aspects of the robot itself.

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