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Irregular Substrate Tiling

The Robotic Poché

Abstract The poché, or the mediation between one surface geometry and another, becomes increasingly important as architects continue to expand their design vocabulary with the aid of digital tools. Likewise, as the environmental and economic advantages of renovating and retrofitting existing structures become more apparent, fitting precise and digitally designed models to the imprecise surfaces of an existing edifice becomes more necessary. In this paper we present an in-progress report on the development of a surfacing technique which utilizes a robotic manipulator as reconfigurable formwork for laying ceramic tiles over an imprecise structure. Whereas the human tileworker must rely on a steady substrate for lack of a steady hand, the robot is capable of holding tiles in their designated position and orientation indefinitely (namely, until the bonding material sets). The process involves creating a digital model of a tile surface which is loosely offset from a low-resolution or irregular substrate surface. Tile positions are taken from the digital model, and are placed sequentially by a robotic manipulator equipped with a vacuum gripper. Each tile is held steadily in position while polyurethane-based expanding foam is sprayed to fill the gap and create the bond between the tile and the existing surface.

Keywords: Cladding, Digital Architecture; Formwork; Poché; Robot Programming.

Introduction

Figure 1 Prototypical robotic poché surface.

The poché, or the mediation between interior and exterior surface geometries, is an inherent concern in architectural design and construction. Differentiation between "shape, position, pattern and size" (Venturi, 1966) of inside and outside surfaces enables specificity in design, but this contradiction also results in unused void space and the challenge of interfacing two dissimilar surfaces. The construction techniques used to address these design challenges can be broadly divided into two methodologies: that of creating surfaces from a structure contained within the poché (Fig. 2a) and that of casting or aggregating surfaces from a temporary external formwork or scaffold (Fig. 2b). With the advent of digital fabrication and demands for "informed" (Kolarevic, 2003) surfaces in architectural design, the former category has yielded the necessity of creating finely tuned and precisely machined framework to support cladding elements within given tolerances: materialising complexity requires a close bond between architects, data consultants, engineers, frame and cladding fabricators, contractors and surveyors (Scheurer, 2010). Likewise, formwork-based construction techniques require similar coordination, but the temporary nature of the scaffold confers the advantage of isolating production constraints: the precision of the final surface is contingent upon lost forms rather than embedded within the structure. Accordingly, the structure of the poché is given the potential of meeting other functional requirements. With these principles in mind, we propose a hybrid of these processes: one which utilizes a robotic manipulator as a reconfigurable formwork for creating precise surface connections to a loosely defined structural framework (Fig. 2c). Panels are robotically placed in an *additive* technique but also serve as a *formative* (Kolarevic, 2003; Bonwetsch et al., 2006) boundary for the cast poché which binds them to the framed substrate.

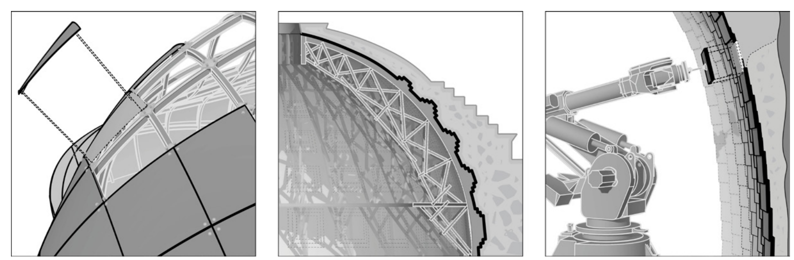

Figure 2 From left: A) Cladding relying on digitally fabricated framework. B) Pantheon section: formwork with graded aggregate fill. C) Robotic poché.

Related Work

Previous work in robotic cladding in construction has focused primarily upon increasing safety and efficiency during the construction of tall buildings (Gassel et al., 2006). Robotic strength is used to lift heavy façade panels into position, generally under the guidance of a human operator (Yu et al., 2007) (Fig. 3). Rather than exploring the design potential of robotic fabrication however, prior work has been motivated by a desire to automate the construction processes of conventional designs.

In the vein of the reconfigurable formwork, the recent "Procedural Landscapes" research at the chair of Gramazio and Kohler, ETH Zurich uses both additive and formative processes to create "informed" surfaces for concrete casting by impressing sand with a robotic manipulator [1]. Use of polyurethane foam has precedence in robotic architectural fabrication in the "Foam" project, also at the ETH (Gramazio and Kohler, 2008), however these were procedural explorations which utilized the material logic of expanding foam coupled with precise paths to inform the creation of acoustic diffusers—in our research, the material (while also engaging acoustics to some extent) is used for the more traditional purpose of filling and binding.

Figure 3 The KAJIMA "Mighty Hand" panel-holding construction robot.

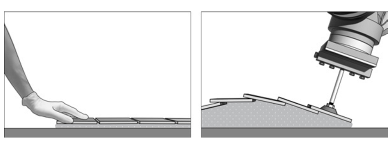

Figure 4 Human versus robotic tiling capability.

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Overview

Appropriating traditional means of construction for robotic processes enables not only the possibility for aesthetic complexity (Oesterle, 2009), but also enables a re-evaluation of the potential of processes which have evolved around human capabilities and ineptitudes. For lack of a steady hand, the human tiling process requires a firm substrate to configure and support tiles during the construction process. The patience and stamina of the robotic manipulator, however, allows for an inversion of this process: the robot can hold tiles precisely in position for extended periods without fatigue. In essence, the manipulator becomes the substrate (fig 4).

The precision and variability of the robotic manipulator in this process enables "highly informed" (Bonwetsch et al., 2006) surface geometries. While most current digitally informed cladding techniques rely on a finely tuned structural frame, our process embraces and is enhanced by loose tolerances between surface panels and the structure to which they are attached. As the robot provides the calibration of the surface by holding it in the appropriate position, any ad hoc technique can be used to bridge the poché space and adhere the panel to the opposing frame/surface. Variation of these filling-and-adhering materials has the potential of increasing the utility of the void space. While this simple concept has a multitude of potential manifestations, our in-progress research explores one prototypical iteration.

Prototype Design Evolution

The evolution of our in-progress prototype was guided by the desire to explore techniques of slow robotic fabrication while responding to the practical requirements of our workspace—an imprecise existing ceiling structure with poor insulation properties. In order to decrease heat loss during winter research while reducing the noise transmission associated with our work, we focused on materials which had the potential of providing both thermal insulation and acoustic dampening. While expanding polyurethane foam met the thermal requirements, we required mass in order to reduce sound transmittance: ceramic tiles provided a cheap and easily accessible option. By utilizing expanding foam as both the means for filling the void space and adhering the tiles, we create a soft connection between the mass of our inner surface and the structure of the outer membrane—theoretically increasing the effectiveness of acoustic dampening by decoupling the surfaces [2].

As the interior surface is both robotically assembled and will remain within the context of the research facility, we elected to inform the geometry of our simple test-case by the bounding envelope of the robot's movement. The tile layout was generated in Rhino Python such that tile angles were individually oriented by the surface normal at the closest point of the robot's reach envelope and aligned to point towards its origin (Fig. 5). Tiles were placed recursively such that the distance between them was mapped based on the angle of their orientation, enabling a shingled appearance. The surface therefore serves both as an insulator for the space and a visual cue to the capabilities of the robot's movement within it.

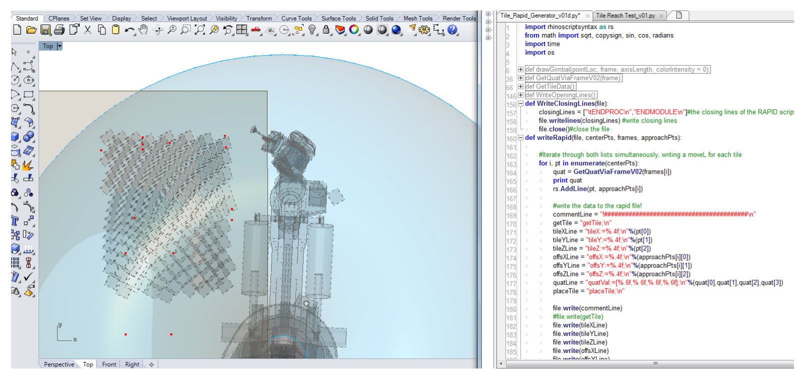

Figure 5 Tile positions and RAPID generated using Rhino Python.

The large tolerances allowed by this process did not require a resolute model of the pre-existing conditions, but simply a general understanding of its key points (primarily for the purpose of avoiding collisions). We utilized our robotic manipulator as a digitizer, sending a handful of coordinate values to Rhino Python via serial interface and referencing them during the modeling process to generate our surface within a loose range (~25 cm) of the existing structure.

Fabrication

For the construction of this prototype, we created a custom vacuum gripper for our 6-axis industrial robot (an ABB IRB 6400) using a salvaged mini-fridge compressor and off-the-shelf components. The I/O system of the robot controller is wired to a relay which controls power to the compressor and to a solenoid valve which can be opened to release the vacuum.

We use 11.0 cm square ceramic tiles for an adequate balance between resolution and construction speed (Bonwetsch et al., 2006). Guided by its native RAPID language (ABB, 1997), converted from the data of the digital model using Rhino Python, the robot moves the suction cup to the loading position and turns on the vacuum pump. It then carries the tile to its designated position and raises a prompt on the controller's teach pendant notifying the user to manually apply the expanding foam. As the robot can maintain this position indefinitely (and can be shut down during a pose), the time it must wait until its next movement is determined entirely by the cure time of the filling and adhering material. In our case, we use primarily store-bought expanding polyurethane foam, which we have found to require 40-60 minutes of cure time (at 20-30 °C) before the tile can be released by the robot. In an attempt to increase production speed, we experimented with a professional two-part polyurethane

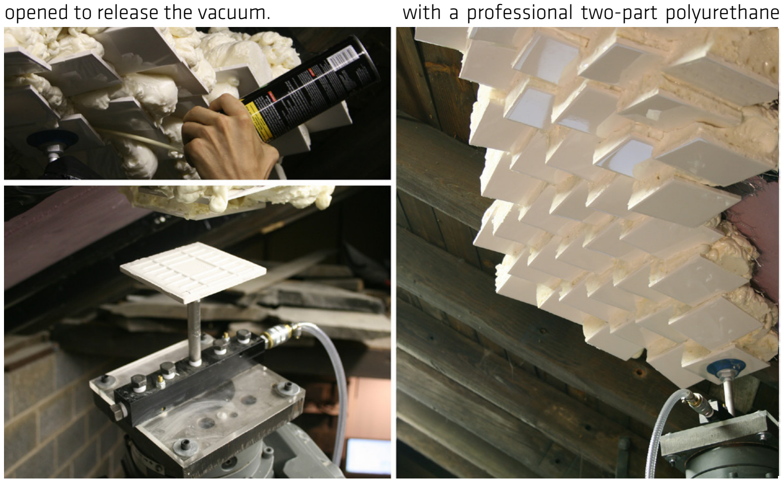

Figure 6 Prototype build process.

system, and though the rapid cure time allowed the tile to be released in 2-4 minutes, it accordingly exacerbated nozzle-clogging issues to the extent that it became infeasible for continued use. The products we tested listed a suggested gap-filling ability of 7.5 cm, but we found we could fill larger volumes with careful application and the use of ad hoc filler materials (scrap styrofoam, wire mesh, dowels, etc.). The presently constructed one-square-meter section of our prototype contains 63 tiles and required approximately 70 hours of build time (Fig. 6/7).

Discussion and Conclusion

Our process effectively demonstrates a technique for using a robotic manipulator as a reconfigurable formwork, while clearly indicating that opportunities exist to streamline the foam-tile manifestation of the concept. Simple improvements to the foam delivery system, such as automated spraying, faster curing, and a self-cleaning nozzle, could improve the process speed tenfold. Further efficiency gains could be achieved through an end effector capable of orienting and placing multiple tiles in one movement. It is worth noting, however, that our primary intention is not to maximize efficiency, but to examine the design potential of this method. Indeed, the idea of maximum efficiency is in many ways at odds with the concept of the poché: as Venturi (1966) states, the residual space created by contradiction between interior and exterior geometries is "sometimes awkward" and "seldom economic."

Beyond our prototypical example which engaged thermal insulation and acoustic isolation, simple variations in material and technique present an array of available performative qualities: aesthetic complexity, light deflection, directional acoustics, and economy of material. Perhaps this process's greatest potential is its ability to produce composite surfaces which tailor the physical properties of the each element of cladding and filling to specific program requirements, creating "functional gradient materials" (Hirai, 1996).

In a production environment, accessing the full potential of this process to reduce the complexity and tight tolerances demanded by current freeform cladding systems requires mobilizing the robot for on-site construction. Mobile construction robots—like the Echord robot of ETH Zurich [3]—could be located within a working zone using not only pre-placed registration markers, but by scanning and calibrating their own previously placed tiles: effectively employing precise placement as a dynamic

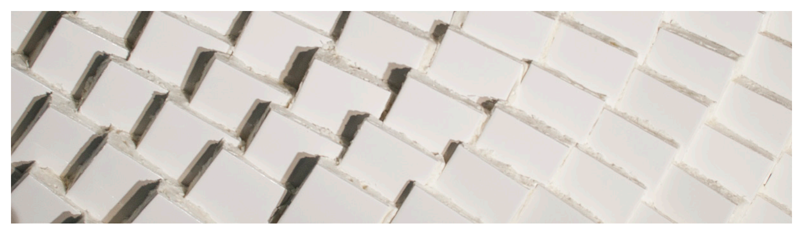

Figure 7 Prototypical irregular-substrate tile surface.

datum for growth. While the tight tolerance requirements of recent digital architecture have resulted in the need to register “the entire building…from one zero point” in place of the more traditional “ruler and tape [run] offsets from specific points” (Kolarevic, 2003), such mobile robotic paneling and re-positioning systems would afford the potential of a return to the flexibility of utilizing local origins in construction.

The precise reference system afforded by this prototypical robotic construction process encourages a reexamination of existing construction methods and implies a potential for reimagining construction order. Whether dealing with new construction or retrofitting existing structures, the loose tolerances of the architectural poché, when combined with the accuracy of industrial actuators, allow a greater liberty in producing highly informed surfaces within relatively imprecise construction constraints.

Acknowledgements

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[2] http://www.tmsoundproofing.com/decoupling-explained.html.

[3] http://www.dfab.arch.ethz.ch/web/e/forschung/198.html.