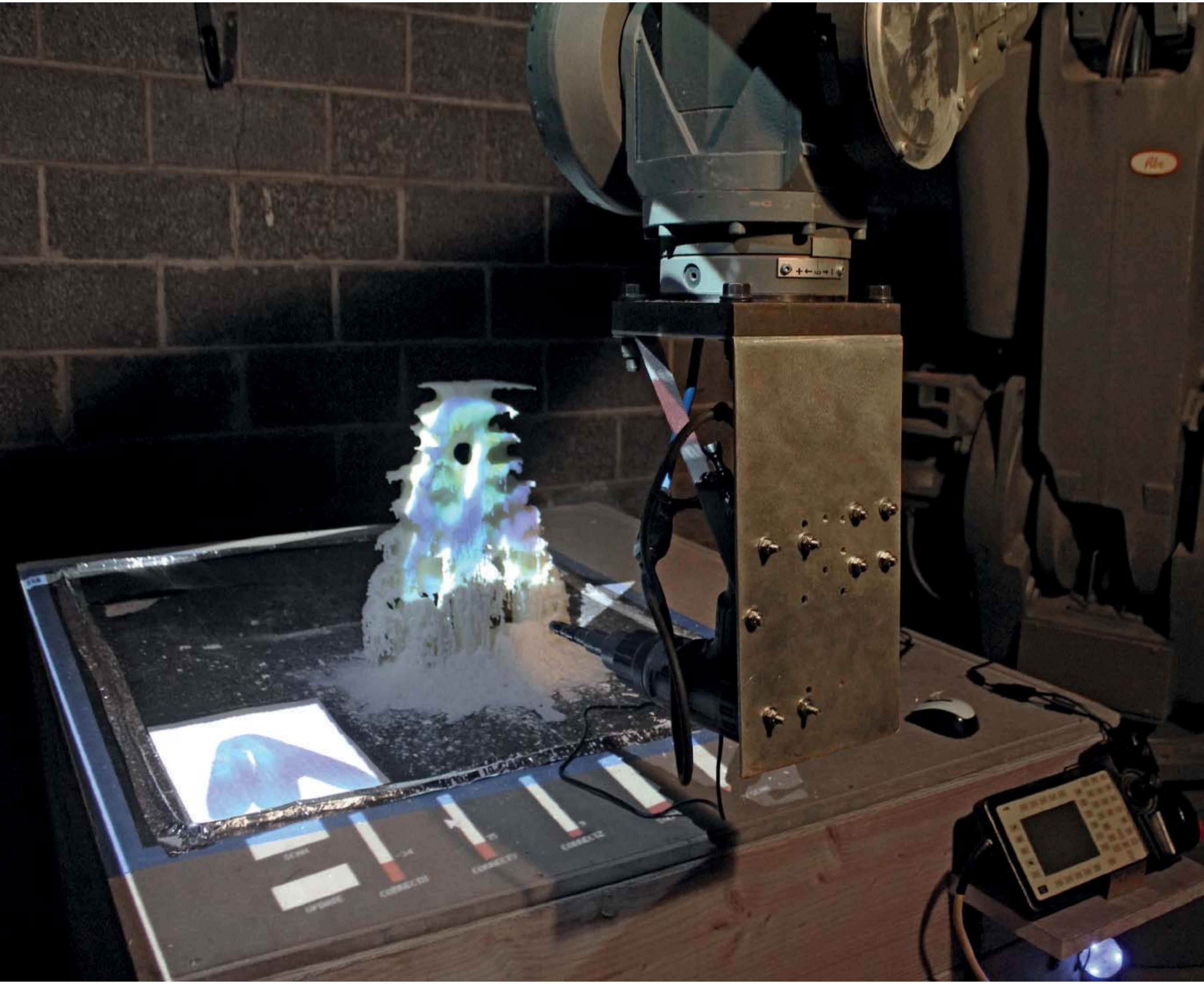
Fig. 1: Mixed reality modelling: prototypical set-up for recursive wax forming.



AUGMENTED MATERIALITY: MODELLING WITH MATERIAL INDETERMINACY

RYAN LUKE JOHNS (GREYSHED AND PRINCETON UNIVERSITY, UNITED STATES)

The digital revolution has instigated numerous changes to the architectural design process, which have distanced physical and intuitive material exploration from the standard procedures and protocol of the discipline. By combining augmented reality technologies with real-time computer simulation, sensory feedback and robotic fabrication tools, new workflows enable the architect to design spontaneously and intuitively with seemingly stochastic material processes while managing the complex performance criteria associated with 'highly informed' design. This paper presents a prototypical design process to these ends and discusses this approach and its implications in relation to alternative workflows as practised in architectural design and fabrication.

INTRODUCTION

With the advent of CAAD (computer-aided architectural design) and CAM (computer-aided manufacturing) technologies, both design and construction processes tend to unfold at abstract scales, effectively dissolving any organic link between human metric and material production. The current paradigm, characterised by the massive influx of digital design and computer-aided fabrication tools, could easily be mistaken for a shift solely towards architectural automation and, in turn, a move away from human intuition. New forms of digital mediation, however, provide the potential to bridge the gap that has divided human sensibilities and material properties in the design process, thus ushering in a new kind of craft that is both materially responsive and 'highly informed'.[1]

As movement between each side of the digital/physical dichotomy becomes easier with the development of fabrication and digitisation technologies, a multitude of other bilateral relationships are being called into question. Recognising that the once resolute distinctions between digital/physical, man/machine, design/construction, and stochastic/deterministic dichotomies are fading, this research explores how the simultaneous occupation of multiple realms, or all of these realms, might benefit architectural design. Borrowing from the principles of computer threading, the aim of this project is to break up and interlace these previously distinct elements of the architectural design and fabrication process in order to render once linear and differentiated components concurrent.

This research commenced with the application of this design-threading strategy to a simple milling exercise. By sending only one movement command at a time to the robotic manipulator, the computer software provides a real-time visualisation of the robot's toolpaths, and allows the designer to modify these toolpaths (and thus the design) at any stage of the machining process. Drawing closer to the intent of the research, the project evolved into a recursive design-fabrication exercise which combines physical human input with the robotic manipulation of a stochastic material process (melting wax). By rapidly scanning a physical object while also melting it, the system attempts to achieve a topologically optimised result based on the given wax volume and user-placed loading conditions. A multitude of constantly communicated variables give simultaneous control to the human operator, the computer simulation, the robotic manipulator, and the material process. These elements become inseparable, and their individual import becomes indistinguishable from that of the global system.

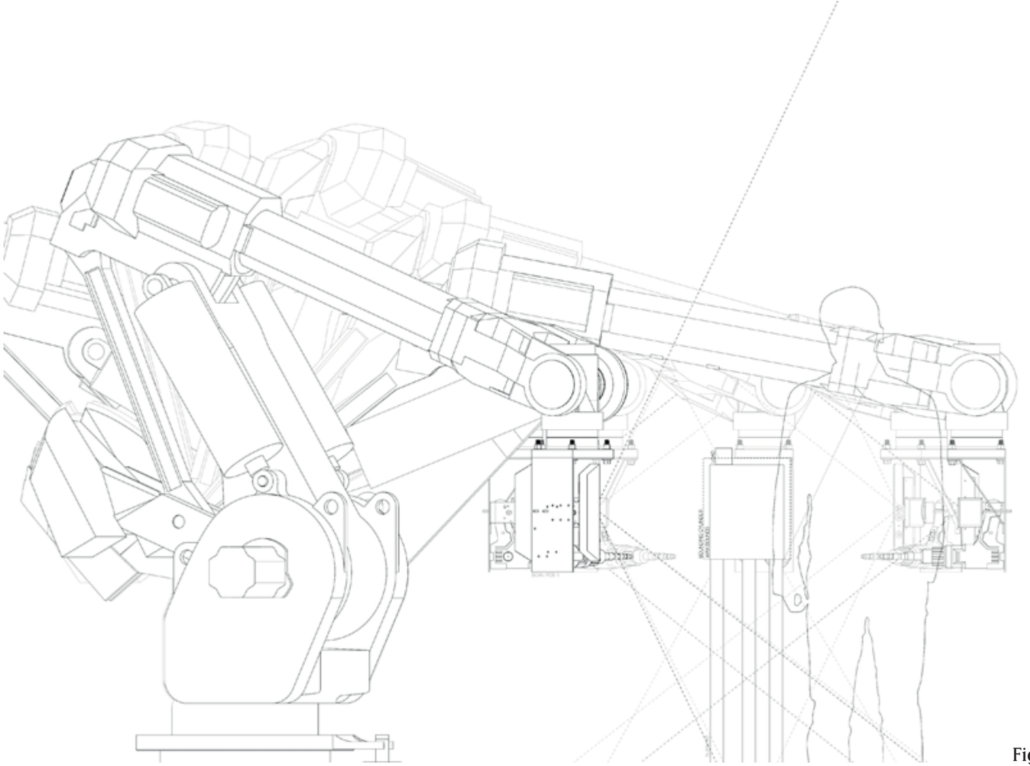


Fig. 2: Set-up elevation.

RELATED WORK

The use of bidirectional computational models and recursive (or circular) explorations is discussed at some length in Kilian's thesis, *Design Exploration through Bidirectional Constraints*,[2] while 'the premise that material, structure, and form can become inseparable entities of the design process' is presented by Neri Oxman.[3]

Mixed reality systems that link a physical interface with a digital architectural model can be found in the early experiments of John Frazer[4] and in a variety of more recent projects.[5] A number of research papers have engaged gestural design, augmented reality[6] and interactive fabrication.[7]

The use of robotic manipulators to procedurally inform computationally indeterminate material processes has been explored in Roxy Paine's Erosion Machine[8] and the Procedural Landscapes project of Gramazio and Kohler.[9]

Recognising the wide array of precedents for the individual components behind this research, this paper seeks not to explore any singular innovation, but rather to investigate the potential for combining a variety of existing technologies and principles in the early stages of design and fabrication. This amalgam fosters an intuitive control of digital fabrication tools, and in turn provides the potential to recursively manipulate stochastic material systems.

INITIAL RESEARCH: INTERACTIVE MILLING

Intuitive interaction with digital fabrication tools is severely limited by the lack of communication between the operator and the tool. While CNC (computer numerical control) mills and robotic manipulators excel in realising the digital, they cannot easily convey the complexity of their actions during the fabrication process. As fabrication procedures become more highly informed, the human operator becomes less informed of the global significance of any given operation. If the designer is to have real-time influence upon the fabrication process, he must be capable of recognising what the robot is doing at any given moment so that he may immediately grasp the role of that action in the larger and more complex narrative of the overall design.

In order to experiment with live manipulation of a design during the fabrication process, a prototypical milling technique was developed that allows the operator to see and modify the robot's toolpaths in real-time. In this set-up, an augmented reality interface provides the operator with a live preview of the robot's projected toolpaths, and allows the user to modify those toolpaths by tapping on the screen in the area where he would like to focus the mill (fig. 4).[10] Rather than sending the entire milling operation as one predetermined batch of commands, the software running on the tablet sends only one movement command to the robot at a time. This allows the user to insert new movements at the front of the buffered command list at any time, ensuring that the system essentially operates on the scale of 'byte to robot' rather than 'file to factory'.

Fig. 3: Detail of wax model: indeterminate accrual.

Fig. 4: Interactive milling: The robot's toolpaths are overlaid with live video of the milling operation. Touching an area of the screen causes the robot to immediately move to and mill in that area.

DYNAMIC MATERIALS

The prototypical milling set-up helped to establish a communication protocol with the robot and represented a shift towards both *informed-operator* and *operator-informed* fabrication. However, the determinacy of milling seemed to restrict its potential to convey interesting iterative communication between the physical material and the digital model. The subtractive result of the milling operation is always in direct parallel to the simulated Boolean operations of the computer model. This research, however, is specifically interested in the use of digital fabrication tools to allow informed control and design using materials that are not entirely predictable with computer simulations. To this end, it was necessary to experiment with a stochastic material process that engaged computationally difficult properties, such as fluid or thermodynamics, erosion, organic growth and decay, chemical reactions, etc.

Considering the realistic limitations established by current processing capability and the slight delays associated with the established communication protocol, wax-melting was selected as an intermediate material process for further experimentation. Wax is relatively indeterminate when heated, but cools rapidly enough to enable momentary lapses in the process. It thus affords time, when necessary, for contemplation and re-calculation.

This material process was also of interest because it occupies a space between *subtractive* and *additive* fabrication that is not precisely or predictably *formative*.[11] Much of the heated wax flows into new areas, cooling and accruing, while some falls from the work object or is vaporised.

SET-UP

This project represents a prototypical design/fabrication process that demonstrates the concurrent coordination of digital simulation with stochastic material properties, human design decisions and robotic manipulation. It thus encompasses a wide array of variables of varying complexity, which prove desirably difficult to convey as a linear narrative. While the elements of the project are presented below sequentially, in reality, they frequently operate simultaneously or are interspersed with one another. These are the primary components of the experiment:

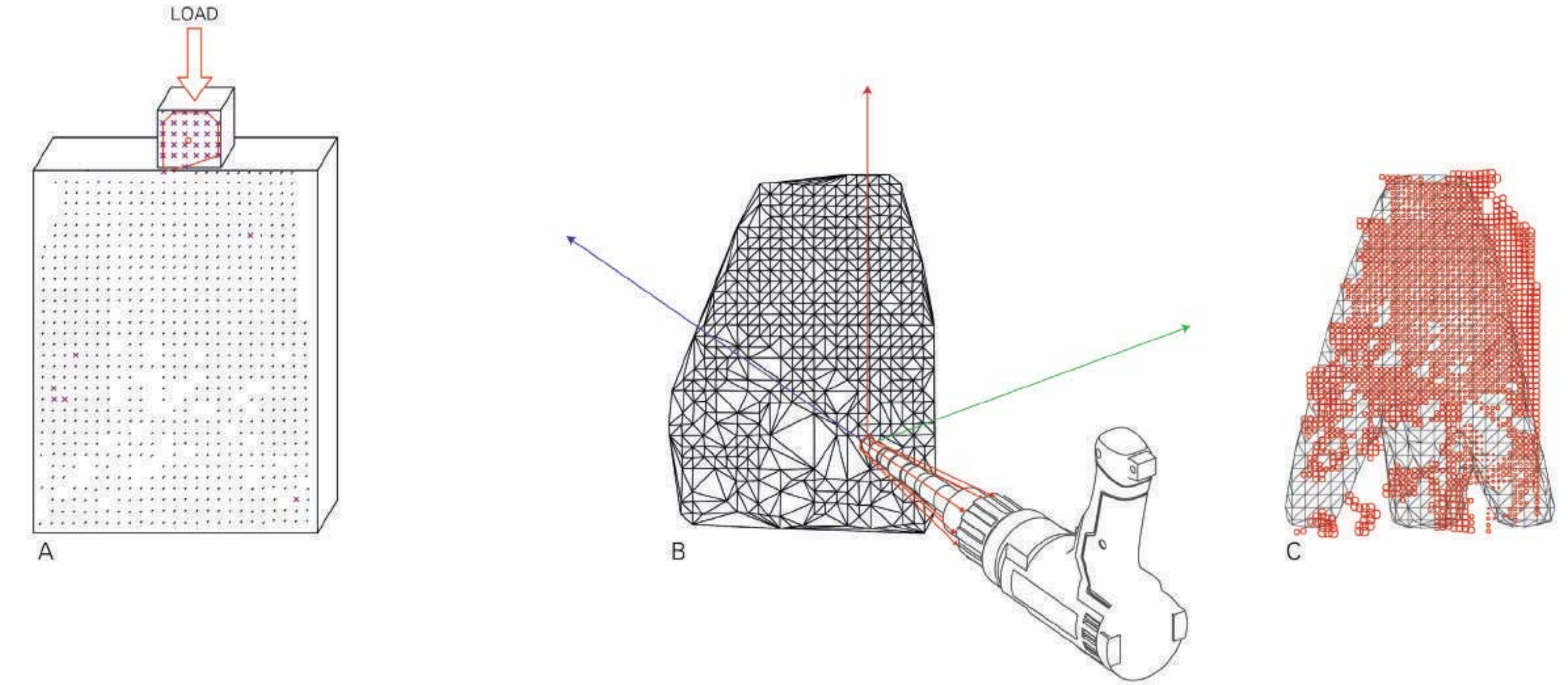


Fig. 5: Select software operations: a) Separate specifically coloured points (purple) and isolate clusters of a given size. Find centroid of convex hull and place virtual load. b) Triangle mesh created from Kinect scan for ray-based collision test. c) Sort scan points by distance to nearest vertex.

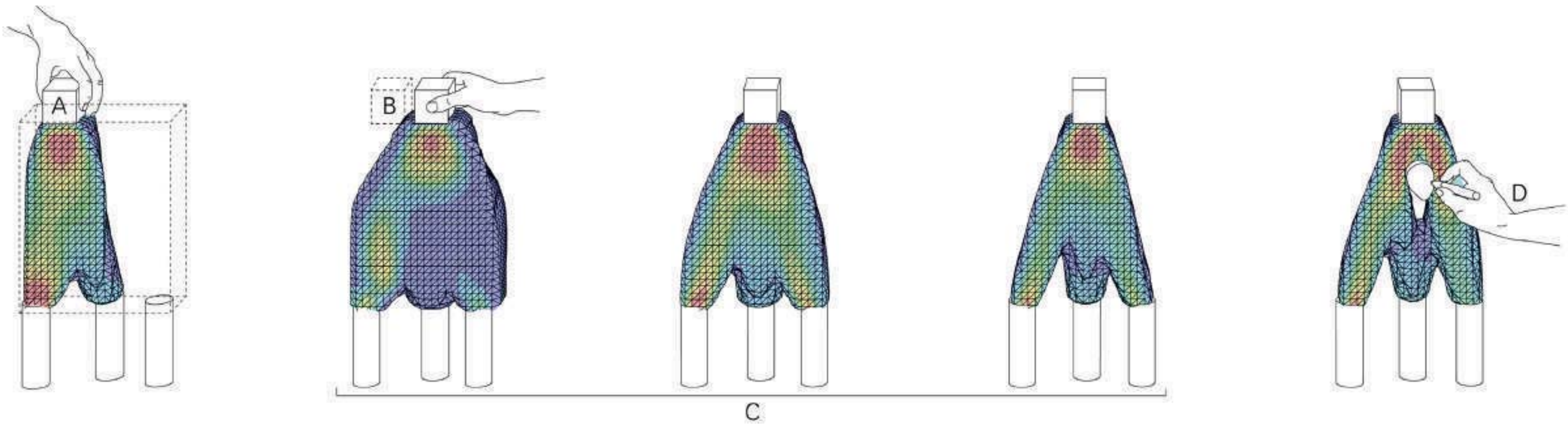


Fig. 6: A simple modelling narrative illustrated. a) Load is placed and forces are calculated. b) User decides to shift load. c) Reduction of volume. d) Void area indicated with a coloured marker.

– The process begins when the user places a wax block upon any number of supports and within the working range of the robotic manipulator.
– The human operator has access to coloured wooden blocks that represent downward load forces, and he can place any number of these upon the wax in any desired configuration.
– The robotic manipulator is equipped with an end-effector consisting of an electric heat gun and a Kinect scanner.[12] It moves to an initial scanning position, where the Kinect provides a coloured 3D point cloud of the wax block, its loads and supports.
– The computer software (written in Processing, a programming language) communicates constantly with the robot's controller and the Kinect.[13] The local coordinates of the scanned Kinect point cloud are transformed into the world coordinate system of the robot and the digital scene using the position and orientation values of the end-effector.
– The software locates the physically placed load blocks within the digital model by first sorting all points of a given colour (in this case, purple) into clusters. By finding the area of the convex hull of these clusters and checking if this area corresponds to that of the wooden block, it finds which 3D points represent load forces.[14] A virtual load-block is then placed at the centroid of each qualifying cluster (fig. 5a).
– Considering the wax volume and its corresponding support and load conditions, the software calculates the regions of material that are most (and least) essential for structural performance using topological optimisation.[15]
– The software sorts the digitally scanned points, which represent the physical wax volume, by their distance to the result of the topological optimisation calculation, or rather, in order of structural necessity (fig. 5c).
– Following this calculation, the robot proceeds to heat a given number of these points for a duration proportionate to their distance from the structural core. It thus melts or vaporises the wax around each location.
– At any point in this process, the user can draw with a coloured marker to indicate desired void areas in the wax volume. Employing the same strategy used to find loading conditions, the software removes these areas from the topological optimisation calculation, thus routing the structure around the opening and thickening it where possible to compensate for this change.
– The user can shift the load conditions, remove some or add others at any point in the process (fig. 6).
– As with the interactive milling experiment, an augmented reality interface informs the user of the digital model and the projected movements of the robot. Using a digital projector,

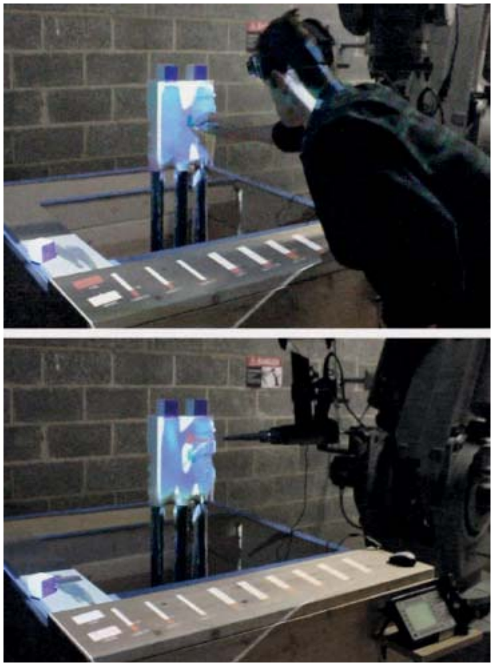


Fig. 7: Above: Desired void areas are physically indicated using a coloured marker. Below: The virtual model is automatically reconfigured around the indicated opening and the robot proceeds to melt away this area.

Fig. 8: Toolpaths are projected in real time, providing indication to the human operator where the robot will move next (path weight and colour) and how long it will melt in a given location (sphere radii).

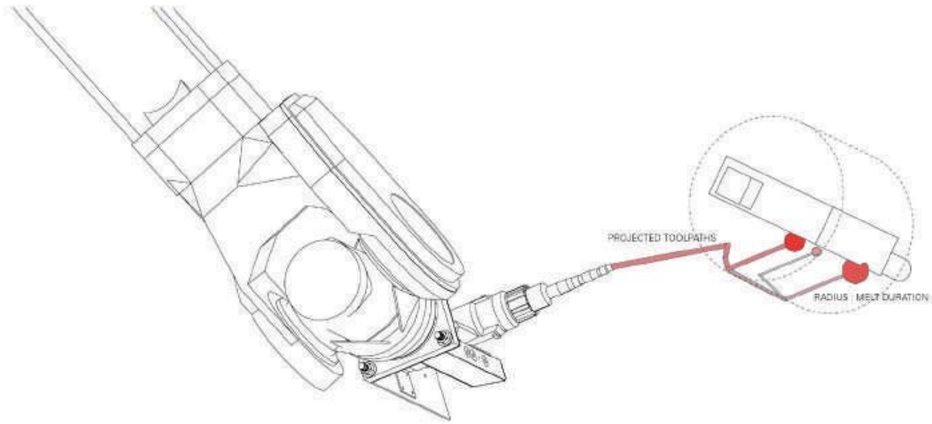


Fig. 9: Wax model. The result of the operations illustrated in figure 8.

Fig. 10: Wax model. Two downward loads and asymmetric supports.

the virtual information is mapped (fig. 7) directly onto the wax surface.[16] It illustrates not only the future toolpaths of the robot, but also the duration of each melt position (as spheres of varying radii) (fig. 8), the topological optimisation model, the visible scan points, and the digitally referenced support and load geometries. A second stationary Kinect tracks the user's head position and aligns the virtual camera with this location so that, from the perspective of the user, the projected information is visually aligned with the physical world and the movements of the robotic manipulator. This removes the need to hold a cumbersome tablet, though it has the necessary limitation of being optimised for a single user.

– By triangulating the scanned point cloud and mathematically testing a ray-based approximation of the end-effector for intersection with these triangles, the software prevents physical collisions between the robot and the wax volume (fig. 5b). This allows the robot to melt the wax from the closest desirable distance without fearing collisions.

– Assuming that the melted wax generally flows downwards, the software recognises over-melted areas and is capable of prioritising points above these locations so that the dripping wax helps fill the problematic cavity.

DISCUSSION

Rather than developing design in a linear progression from idea to computer-simulated model to fabrication tool and material result, the process allows these elements to operate concurrently or in rapid and recursive succession. This allows each component of the design process to inform the other from the onset. Recognising the co-dependency of these elements, the process cannot proceed without the simultaneous cooperation of its four players: the human designer, the robotic manipulator, the computer simulation, and the material reaction. This allows the designer to engage physical materials in the modelling phase and to learn from this interaction, just as one gleans scalable structural problems from an unstable architectural model. Furthermore, by employing both computer calculation and robotic execution, it becomes possible to integrate highly informed articulation and advanced material dexterity with the more traditional components of the initial design process.

While this process used the computer simulation for structural optimisation and melting wax as the material system, these components are merely placeholders for potential relationships with higher degrees of complexity and variance. On the side of computer scanning and calculation, for example, the process could be expanded to account for site-specific building codes or program requirements. These factors would make themselves apparent among the earliest design decisions, thus ensuring that they would not jeopardise the original design intent. With regard to the material system, the advent of safer, faster, lightweight and purpose-built robotic solutions coupled with developments in software and processing capability (providing, for example, faster-than-real-time calculation of fluid dynamics) could enable control over larger and more indeterminate material relationships. This project imagines a future in which real-time modelling with stochastic physical systems such as erosion, insect behaviour, plant growth, or lava flows might be not only possible, but intuitive. Just as the material properties of hanging-chain, clay, or paper models link them with certain formal typologies, so might these developments in physical modelling inform a new variety of formal variation.

ACKNOWLEDGEMENTS

This research owes much to the faculty of the Princeton University School of Architecture who advised the project during my thesis semester (Axel Kilian, Elizabeth Diller, Ryan Neiheiser, and Jesse Reiser) and to the friends and fellow students who provided the support necessary to complete such an endeavour.

NOTES

1 For an examination of digital craft, see Malcolm McCullough, *Abstracting Craft: The Practiced Digital Hand* (Massachusetts: The MIT Press, 1996); For 'highly informed' design, see: Tobias Bonwetsch, Fabio Gramazio and Matthias Kohler, 'The Informed Wall: Applying Additive Digital Fabrication Techniques on Architecture', in Gregory A. Luhan, Phillip Anzalone, Mark Cabrinha and Cory Clarke, eds., *Synthetic Landscapes: Proceedings of the 25th ACADIA Conference, October 12–15, 2006, University of Kentucky, Louisville, Kentucky* (Mansfield: Association for Computer-Aided Design in Architecture, 2006), pp. 489–95.

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10 The interactive milling software was written in Processing, a programming language. Accessed 30 September 2013: http://www.processing.org. It uses the *NyARToolKit Library* to track a printed marker on the work surface, and thus aligns the virtual camera of the digital scene with the live video feed from the tablet's rear-facing camera: *NyARToolKit*. Accessed 30 September 2013: http://nyatla.jp/nyartoolkit/wp/.

11 Branko Kolarevic, *Architecture in the Digital Age: Design and Manufacturing* (New York: Spon Press, 2003).

12 The robotic manipulator is an ABB IRB 6400/2.4-150 with an S4C controller.

13 The software makes much use of the *toxiclibs* library, namely the vector and mesh utilities: Karsten Schmidt, *toxiclibs*, 2012. Accessed 30 September 2013: http://www.toxiclibs.org; Kinect communication implemented using the *Simple-Openni* library for Processing; Max Rheiner, *Simple-Openni*. Accessed 30 September 2013: https://code.google.com/p/simple-openni/.

14 The convex hull is calculated using the Mesh library; Lee Byron, *Mesh – A Processing Library*. Accessed 30 September 2013: http://www.leebyron.com/else/mesh/.

15 The topological optimisation calculations are currently processed using a custom Python script which communicates with Sawapan's Grasshopper plugin: Panagiotis Michalatos and Sawako Kaijima, *Millipede*. Accessed 30 September, 2013. http://www.sawapan.eu/.

16 Ixagon, *SurfaceMapper for Processing*, 22 December 2012. Accessed 30 September 2013: http://www.ixagon.se/surfacemapper/.

Fabricate 2014

Editors: Fabio Gramazio, Matthias Kohler, Silke Langenberg

This edition published in 2017 by
UCL Press
University College London
Gower Street
London WC1E 6BT

Available to download free: www.ucl.ac.uk/ucl-press

First published in 2014 by gta Verlag.

A CIP catalogue record for this book is available from The British Library.

ISBN: 9781787352148 (PDF)
DOI: https://doi.org/10.14324/111. 9781787352148