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Towards a Digital Repertoire: Design and Fabrication of a Robotically-Milled Brass Chandelier

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Abstract. The paper described the design and fabrication of a robotically-milled brass chandelier using a bespoke vertical axial revolving material holder as a robotic fixture. While the technique described is for a chandelier design, it has potential architectural applications, as demonstrated by architects such as Barkow Leibinger. The significance of this research lies in the increased flexibility of the technique performed using a robotic arm compared to the current industrial method using tubematic laser cutter. In addition, the paper outlined the design of the robotic fixture and the computational workflow to create an integrated design-to-fabrication workflow. The research highlighted robotic systems as a potential design environment through reflection on Material Engagement Theory (MET) framework. Critically, the workflow constructed design feedback as robotic agencies that provide affordances through the fabrication setup. Such affordances contribute to the designing process and refine craftsmanship by creating transactional relationships between tools and material as a digital repertoire. This emerging design environment extends robotic research into design practice.

Keywords: Robotic fabrication · CNC milling · Agency · Robotic workflow · Material engagement

1 Introduction

Computer Numeric Controlled (CNC) metal tube cutting techniques used in the manufacturing industry predominantly utilised an axial revolving material holder coupled with a solid-state laser or plasma cutter, sometimes known as tubematic cutter with a range of up to 1500 mm in tube diameter [1]. Alternatively, CNC tube cutting can be performed using an industrial robotic arm with a plasma or oxyfuel cutter end-effector on a horizontal axial revolving holder [2]. While an industrial tubematic cutter is typically designed to produce effective tube fabrication, it also means that it is a piece of single task machinery and is often limited to specialist engineering and infrastructure projects.

The research project explores a novel setup using a robotic arm with a milling router and a vertical axial revolving holder to fabricate a brass chandelier. The advantage of the setup using a robotic arm with a more common end-effector, such as a milling spindle,

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allows designers and architects to better access the technique for flexible and small-batch manufacturing [3] without compromising the fabrication quality.

The technique and outcome of the research, while limited to the design and fabrication of a chandelier, have a more comprehensive architectural application, as demonstrated by Barkow Leibinger [4, 5]. The practice has explored using such techniques to develop architectural applications such as lighting fixtures, spatial installation, sunscreens and façade rainscreen. The primary interest is in the ornamental quality that such technique provides as a serial effect as an outcome. However, their material research in ornamentation is merely the aftermath of the method without intervening in the fabrication process.

This research extends Barkow Leibinger's material research to understand better how the affordances provided by the technique (the ornamental quality) can be productive in the design and fabrication process. The key contribution is exploring how feedback from the robotic setup provides design agency–moving away from using the CNC technique as a means to an end. The research questions: How can aesthetic quality through digital fabrication bring about a transactional relationship with robotic agency towards a productive digital repertoire? A form of hybrid intelligence.

The following section outlines the design intent, research objectives and critical theoretical framework of the research. In Sect. 3, the paper outlines the technical setup of the robotic system–particularly the robotic fixture for the material and the design to fabrication workflow. Section 4 identifies the robotic agency and discusses the transactional relationship between tools and material as affordances for design.

2 Background

The brass chandelier consists of 37 brass tubes individually trimmed using a 7-axis robotic arm at the Architectural Research Lab (Fig. 1) in Melbourne, Australia. It is a bespoke commission installed in a double-height space for a private dwelling. The design intent that emerged through dialogue with the client was to create a sculptural object that would act as a focal point to the space and provide background lighting. Brass is chosen to complement the interior finishes of the room, but more importantly, it is soft and can be milled, unlike steel. The research takes place over 12 months, from initial material exploration to the design and fabrication of the brass chandelier.

2.1 Design of the Brass Chandelier

The primary structure of the chandelier consists of a hanging frame–composed of a steel rod hanger with top and bottom plates, which the pipes hook onto (1e). A set of LED lights is positioned in the centre of the cluster (1f). The tubes are arranged so there are 20 mm gaps between them to allow light to spill out. There are four sets of cutting operations performed on each pipe as illustrated in Fig. 1: the top (1a) and the bottom (1b) cut, three openings facing the LED light on the inside (1c) and up to 3 openings facing towards the outside of the chandelier (1d). The pipes' top and bottom (1a and 1b) were trimmed diagonally to reveal fluid sections that bundled together to create an illusion of tubes suspended in space. Three openings face the hanging structure (1c).

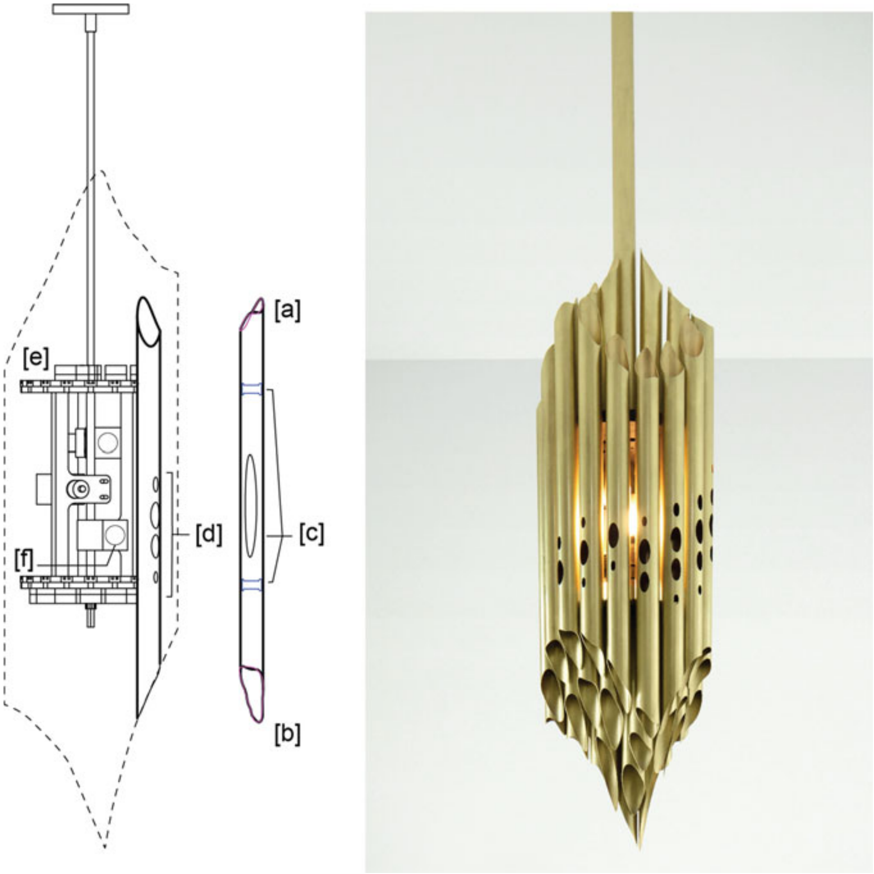

Fig. 1. Robotically fabricated brass chandelier. Left, Diagram illustrating the overall design with the hanging frame structure and a typical pipe with the various openings. Right, the installed final outcome. Photography by Ben Hosking.

Two of them are for hanging the pipe onto the frame, and a larger hole allows the LED light to illuminate the inside of the tube. The openings in the middle sections of the tube (1d) create visual interest and will enable the light to spill out sideways.

2.2 Research Objective

The objectives of the research are:

- To explore the feasibility of an alternative robotic revolve cutting using the milling technique.
- To design and prototype a robotic fixture to enable flexible manufacturing using a robotic arm.

- To examine the agency of robotics in designing. In other words, to use the robotic setup as both a fabrication and deigning tool through an integrated design and fabrication workflow.

2.3 Theoretical Framework: Material Agency as Craftsmanship

The research is informed by Material Engagement Theory (MET). Malafouris [6–8], hypothesis a design environment where the designer enters a level playing field with the tools, material, and techniques deployed during the fabrication process. In this environment, they are all actors or agents of the system whose agencies are relative to the fabrication tasks.

Centred in the discussion of MET is the agency of material. Malafouris argued from an archaeological perspective that it is a quality that is not limited to humans and can be satisfied by an object in-so-far as the object (tools and technology included) can become an extension of the person. Malafouris [6], (pp. 169–177) highlighted material agencies by examining the cognitive intent of knapping hand axe. He demonstrated that the act of knapping flint is an exercise of multiple agents at work, including the hand of the knapper, the knapping stone, and the stone being knapped. Each subsequent strike of the flint determines the angle of the next strike.

This idea of iterative negotiation of agencies shifted our understanding from the traditional concept of a preconceived image of an axe head within the flint toward one where design is a negotiation between the human action, material and tool. He states, ‘There are no fixed agentive roles in this process; instead, there is a constant struggle towards a “maximum grip” ([6], p. 176)’. As the maker actively engages with the material to produce the form, the process of Making is an enacted embodied engagement. Malafouris suggests the form of an intended object is not external but learned and sustained as an idea and developed through the Making process as an explicit ‘sense of agency’ ([6], p. 176). Similarly, David Pye stipulated that the Making process contains the intentionality of the maker expressed through the agency of tools and material [9, 10]. Malafouris ([6], p. 140) posits, ’intention no longer comes before action, but it is in the action’.

MET hypothesised that the formal outcome (as an artefact) does not result from preconceived ideas. Instead, the design intention is developed through the experience of Making or ‘directly embodied and realised in the hybrid space of situated action’ [11]. In other words, through the act of designing, prototyping and Making. It is not a total surrender of the designer’s role to material effects but rather a careful and measured sense of agency. Critically, this is not just an interaction of agents but a transactional relationship, where the outcome is not merely a by-product of the exchanges between agents but transformed by their agency; Ihde and Malafouris [11] rightly termed this “becoming”.

The following section will examine the robotic fabrication before returning to discuss the robotic agency and the transactional relationship evident in the fabrication process.

3 Robotic Fabrication

The brass tubes that make up the chandelier are trimmed using HSD 18 kW milling electrospindles attached to a Kuka KR120 robotic arm coupled with a turn-table. A bespoke robotic fixture design to hold the tube for milling is anchored to the 7th axis turn-table. Geometric design and robotic programming are performed through McNeel Rhino with Grasshopper 3D and Kuka PRC.

3.1 Robotic Fixtures Design

There are several challenges in designing the robotic fixture. First, unlike most tubematic cutter setups where the revolving axial is horizontal and typically pinned on both ends, the 7th axis turn-table conditions the axial revolving holder to be vertical and anchored at the base only. This produces a situation where the vibration from the milling process would cause the tube to oscillate, resulting in inaccurate trimming.

Second, the brass tube must be easily replaced for subsequent milling to ensure an efficient fabrication procedure. As described in Sect. 2.1, each tube is trimmed on both ends with a series of hole cut-outs. Through prototyping process, we observed that the further we cut the tube from the base of the fixture, the greater the oscillation. For the final version of the fixture design, the maximum acceptable distance from the base for any trimming operation must be within the 900 mm range. To avoid accessive oscillation for longer tubes (with a length greater than 60% of the acceptable distance), the researcher decided to flip the tube at mid-point to reduce the distance between the milling and the base of the fixture. Therefore, each tube must be removed from the fixture and manually flipped after the initial cutting procedure.

Figure 2 illustrates the design of the vertical axial revolving holder with a wide base (2b) anchored to the turn-table (2a). The tube holder (2c) is designed to be extended to accommodate a longer tube (2d) which could increase the range of the trimming operation. A steel tube (2e) is bolted to the holder (2c) to hold the brass tube (2f). In addition, a set of solid MDF blocks is required to infill the core of the brass tube to reduce vibration caused by the tool during the milling process (2g). The solid MDF blocks (2h) are inserted into the steel tube (2f), and they can be added or removed depending on the length of the tube to be cut.

These challenges inform the fixture's design, but more critically, the outcome as a series of test prototypes (successes and failures) inform the development of the repertoire. Three fixtures were developed, each incrementally refining the workmanship of the technique by reducing the vibration caused by the milling process. A smaller version of the chandelier with eight tubes (Fig. 2) is developed as a proof-of-concept for the hanging structure and testing of the robotic workflow in generating the design constraints. These developments allowed the research team to design the automated workflow using affordance produced from the technique.

3.2 Design Workflow

Figure 3 outlined the chandelier's computational and robotic workflow from design to fabrication within a single visual script using Grasshopper 3D. The workflow integrates a

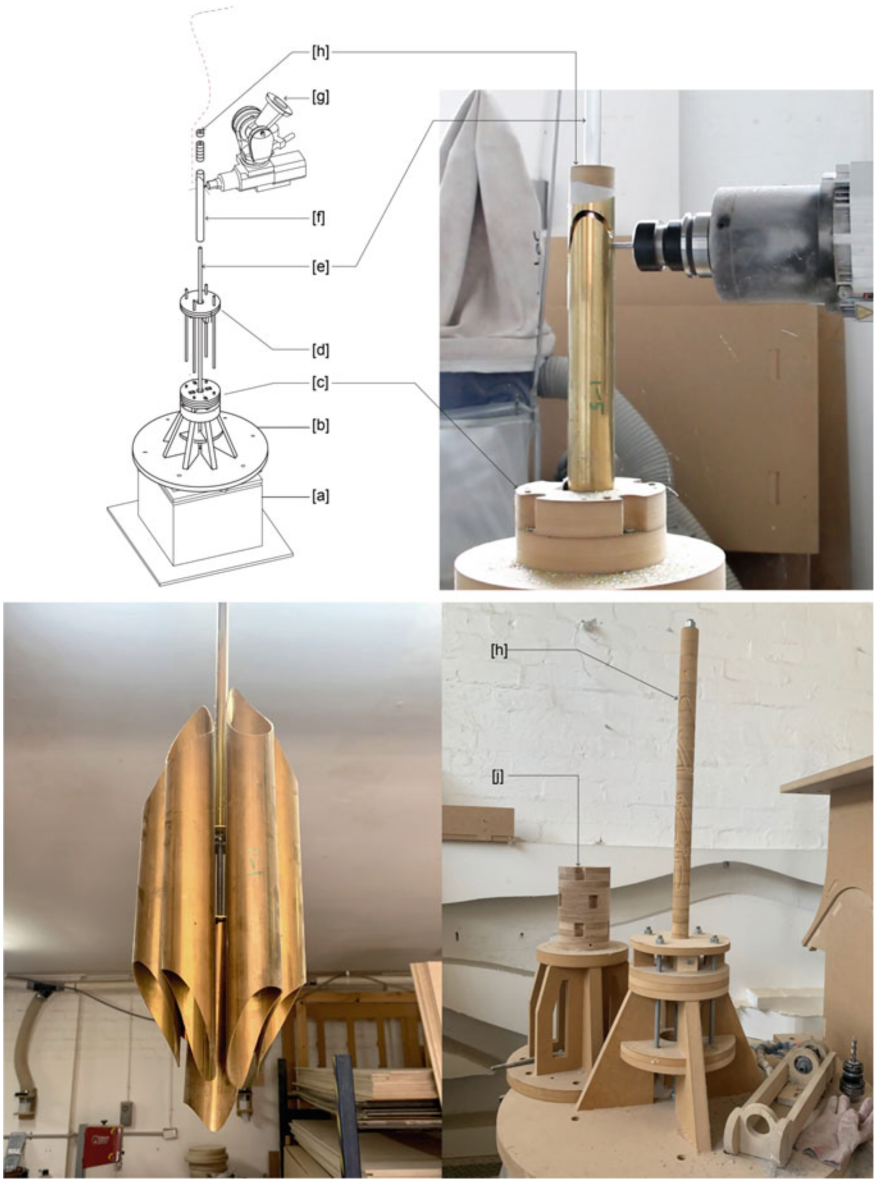

Fig. 2. Top left: Design of the fixture holding the metal tube. Top right: Milling of the brass tube using the fixture. Bottom left: 8-tubes chandelier prototype. Bottom right: Robot fixtures indicating the solid MDF block [h] infill to the brass tube and early fixture prototype [j].

seamless data flow scripted from the basic design parameters (3A) consisting of the plan layout, where the length of each pipe (L_T) considers the structural frame height (L_F), a constant gap around the frame (2x) and the trimming curve ($y \sin \theta$). The optimisation process (3C) considers the range of the robotic trimming operation discussed in Sect. 3.1.

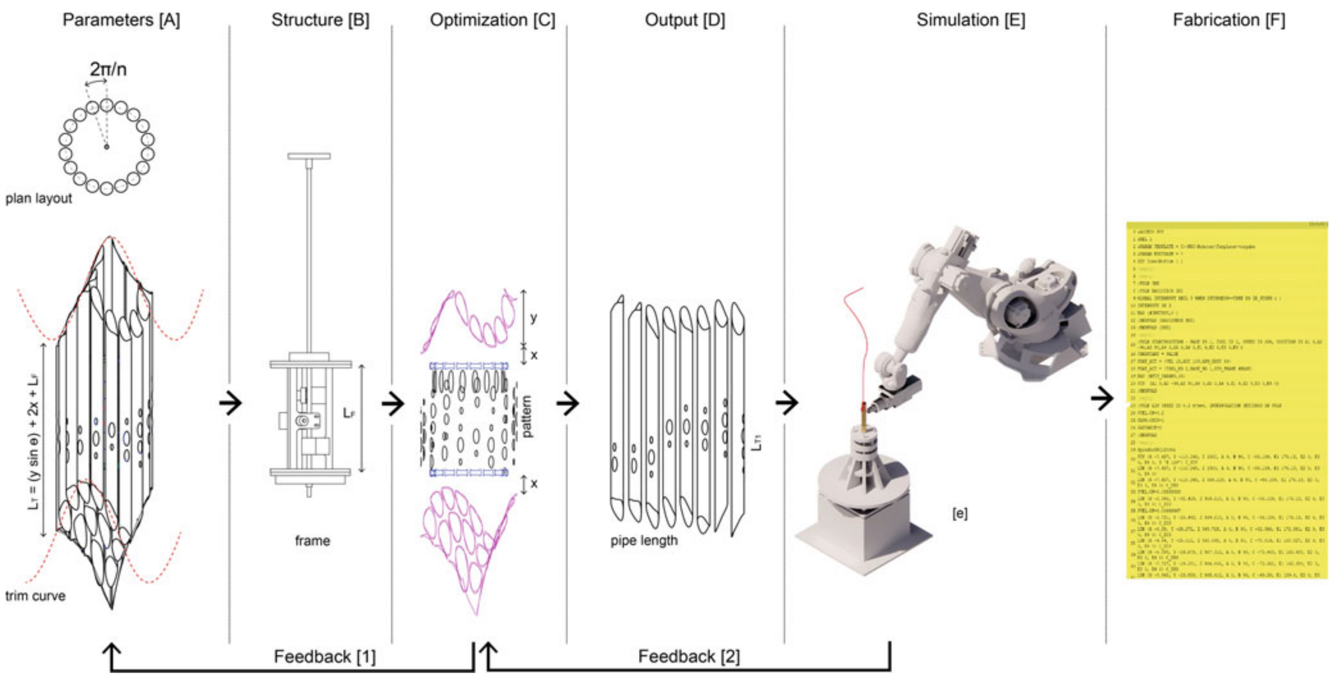

Fig. 3. Computational workflow for the brass chandelier from design to fabrication. The workflow integrates design parameters, including the structural framing within the workflow. These parameters interact with the robotic process to provide feedback in the designing process.

Again, this is constrained by the length of the structure frame as it contains the main LED fixtures, which condition where the openings in the middle sections of the tube could be placed (see Fig. 1d).

4 Towards a Digital Repertoire with Robotic Agency

The research begins to identify the transactional relationships between tool and material as affordances in the designing process. This section discusses the contribution of robotic agencies toward the design process and the concurrent refinement of craftsmanship.

4.1 Feedback as Robotic Agency

The workflow diagram reveals at least two moments of interaction between the scripting process and the tooling. The first feedback (Fig. 1) process occurs when designing the pattern (Fig. 3c) to provide side illumination to the chandelier. This is related to and conditioned by the second feedback (Fig. 2), which occurs when the robotic trimming is simulated using Kuka PRC. The simulation allowed us to check for clashes with the robotic arm and conditioned a zone where the pattern could be placed. This is, in relation to both ends of the pipe, as each tube varies in length. Subsequently, the simulation informed the amplitude of the sine curve that is used to trim the top and bottom edges.

4.2 Designing with Robotic Agency

The robotic fixture, technique and workflow provide affordances for designing on three levels.

First, affordances are generated by producing aesthetic quality as values for the design and evaluation of craftsmanship. The development of the robotic technique and physical prototypes allowed the designer to evaluate craftsmanship through the tooling process. The objective is to align the design intention with the physical outcome [10] using the constraints provided by the techniques to condition the design, including the form and pattern distribution. The desire to bring design intention closer to the outcome as a form of refinement of workmanship through robotics demands a transactional relationship between the various agents. Here, traditional static design is replaced with designing through agencies–a negotiation between the tools, material, and technique. The robotic agency replaces preconceived forms through the making activity to create an emerging effect. This is evident in the 8-pipe chandelier and the fixture prototypes. Within this exchange of agencies, nothing is fixed but in a constant state of negotiation [6]. In doing so, the robotic agency begins to shape the design.

Second, the robotic fixture and workflow function as an extension of the designer toolset. The technique becomes part of the digital repertoire where its application can extend beyond the design and fabrication of a chandelier. This research setup a concurrent design and robotic parameters to create a dialogue between design and fabrication. This is different from Barkow Leibinger's exploration of the tubematic technique, where design is an after-effect of the system.

Third, creating design feedback within the robotic system develops a transactional relationship between the tooling and the material, transforming the robotic agency into an emerging design environment. The design of the robot fixture is evidence of such a transactional becoming. It acts as a jig for the robotic process to counteract forces enacted by the robotic arm to hold the material in position for shaping. Thereby transforming the material (a brass tube) into an artefact guided by the design intention and sustained through a cumulative set of aesthetic values. The emerging aesthetic values generated through the trimming procedure maintained the design intention and allowed the designer to act and modify the outcome by incrementally refining the technique.

4.3 Future Exploration

The robotic agency described above is embedded within the workflow and fabrication process. Here, we have only explored the automated agency through constraints and in-build parameters within a design environment. The next steps will be to develop a learning environment within the ecology to allow self-population of the patternation at the individual tube and global level using Artificial Intelligence.

5 Conclusion

The paper outlined a design to fabrication workflow and setup to robotically milled tubular brass resulting in a chandelier design. While the technique described is used for prototyping a chandelier, it has potential architectural applications. In this research, we further the design research by Barkow Leibinger using the tubematic technique by examining the relationship between fabrication and its affordances. The study explored the technique's feasibility and outlined the design of a robotic fixture to enable flexible manufacturing using a robotic arm. Feedback is constructed within the computation workflow to condition the final design outcome in form and pattern distribution. The paper reflects on Material Engagement Theory (MET) to explore how robotic systems can create agency for designing through affordances generated through the transactional relationship between robotic fixture, technique and workflow. The emerging aesthetic quality provides design value for evaluating workmanship by negotiating between the tools, material, and technique to create ornamental effects. The robotic fixture and workflow form a digital repertoire that extends the designer's toolset. Doing so extends the potential of the method beyond the current application. Last, in an emerging design environment, the feedback within the robotic system develops a transactional relationship between tooling and material. This transformational process impacts the designing process, which incrementally refines the technique. As an emerging design environment, the robotic system extends robotic research into architecture practice.

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