HYBRID DIGITAL CRAFTS WITH COLLABORATIVE ROBOTICS

New Methods in Artisan Patternmaking Using Collaborative Robots and Augmented Reality

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Abstract. Bespoke manufacturers that fabricate for architecture and design rely on skill artisans such as patternmakers to remain profitable. Collaborative robotics and augmented reality (AR) offer new technological options and approaches that integrate with existing artisan techniques. Can these technologies provide productive and practical assistance to skilled handcraft artisans? This research presents an original approach to robotic fabrication using AR robot control, and artisan techniques to fabricate an original design. The method includes documenting artisan ethnography, designing a custom cutting end effector and an AR control interface, utilising the capabilities of the robot fabricating system. The research outcome is a hybrid digital craft approach to collaborative robotic patternmaking and handcrafting. The fabrication system reduced the amount of time and physical exertion of designing and cutting out patterns from various materials. This demonstrates that robotic tools can expand rather than replace the capability of existing artisan occupations, helping to strengthen resilience in local industries and promote new innovations.

Keywords. Collaborative Robotic Fabrication; Hybrid Digital Craft; Artisan Manufacturing; Augmented Reality; SDG9.

1. Introduction

Industries that design and manufacture bespoke, one-of-a-kind products must adopt work practices that allow them to be agile and adaptable. Small-scale, bespoke, and artisan-driven modes of production are a feature of many small to medium-sized enterprise (SME) manufacturers, therefore supporting this kind of manufacturing will be vital to achieving the UN's sustainable development goals. SMEs that fabricate bespoke items rely on skilled artisans to remain profitable hence have high costs per

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unit, due to the need for specific manufacturing requirements, specialised resources, and skilled labour (Stepputat et al., 2021). The use of robotic fabrication promises to alleviate some of these pressures with a need for approaches that are adaptable for small scale manufacture to retain the skilled input of human artisans. Crucially, robotics should not be seen as a simple technology-fix to replace existing artisan skill but should be approached as means by which human work can be assisted and supported. Compared to large scale industrial robotic arms, emerging collaborative robot platforms are an attractive proposition for bespoke manufacturing because they are typically less expensive, can be adapted to different tasks with the addition of custom end effectors, and are easier to integrate into human workflows. To achieve sustainable industrialization (SDG9), it is imperative that researchers working at the intersection of design, manufacturing, and robotics engage with end-users to understand existing practices and design processes to appropriate to end-user needs for robotic adoption.

In this research, a local art manufacturer, UAP, that produces art and architectural fabrications was analysed for retrofitting technology innovations within an existing workflow of their patternmaking department. The company manufactures custom-designed products and employs many skilled local craftspeople, including patternmakers who primarily produce templates and moulds for a metal foundry. Patternmaking as a profession is changing – with less reliance on trade-based apprenticeship for learning skills and towards an exploratory 'hands-on' craft-based practice that includes mixed techniques from sculptors and artisans. A component of the exploratory approach shows that craft-based activities like patternmaking are poised to quickly evolve from predominately analogue workflows into a hybridised digital craft that includes emerging technology (Loh et al., 2016; Xia, 2017).

This paper argues that industries and professions based around creative fabrication methods have the expertise, skills, and agility in practice to customise collaborative robot arms and augmented reality (AR) as assistive tools. Instead of diminishing as an industry, patternmaking – like similar artisan industries – will continuously evolve by including emerging technology into new hybrid and digital crafts (Bernabei & Power, 2018). As these professions evolve, they will create new relationships between humans, technology as a tool, and application upon physical materials (Gramazio et al., 2014; Kolarevic, 2003).

These new factors can aid in supporting the United Nations' Sustainable Development Goals by developing new digital infrastructure that supports traditional manual activities in design and fabrication. The long-term effects promote and sustain local manufacturing development and help innovation when using new digital tools that can be retrofit into established industries. This paper contributes to the CAADRIA 2022 conference theme of Post Carbon by examining the UN Sustainable Development Goal #9 to build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. We present a 4-step framework for conceptualising the design of collaborative robotic fabrication and illustrate this with a novel solution for robotic support of patternmaking practices, thus promoting sustainable industrialisation and resilient infrastructure by retrofitting a local industry.

2. Robotic Fabrication and Augmented Reality in Hybrid Digital Craft

There is a growing body of research into robotic fabrication in craft-related manufacturing that traditionally uses highly skilled artisans. Past theories proposed that increased industrialisation creates increased automation in design (Kolarevic, 2003; Negroponte, 1995). However, there is evidence that digital fabrication methods can also form new links between robotic tools, craftsmanship, and local building traditions (Shaked et al., 2020). Digital fabrication, when implementing industrial robotics and AR can shift the focus from automation towards opportunities for human and robot interactions in assisting or augmenting daily work tasks such as making manufacturing patterns (Lavallee et al., 2011; Verma & Epps, 2013).

An industrial robot can transfer a digital design into physical material (Gramazio et al., 2014). Furthermore, other capabilities of industrial robots are demonstrated through manipulating rigid materials (Verma & Epps, 2013), precision in robot construction (Bonwetsch, 2012), and data-driven robotic fabrication to produce complex forms (Gandia et al., 2019; Menges & Knippers, 2015).

Studies have also demonstrated the practicality of using AR in design and construction that provides assembly documentation to visualise where to place components (Jahn et al., 2019). Further research has used AR to guide analogue skills such as points for welding and helping assembly of fabrication components (Bottani & Vignali, 2019). Studies have also analysed human skillsets have used motion capture, force sensors, and robotic vision to establish how robots can replicate human actions through force, speed, and motion (Brugnaro & Hanna, 2017; Shaked et al., 2020). However, analysis of traditional craft techniques has often been undertaken for aiding robotic automation, rather than providing insight into how the technology can be used as a part of the crafting process (Brugnaro & Hanna, 2017; Schwarzmann, 2020). In this study, we are using the robot as a tool for digital craft fabrication to replicate a precise transfer of digital patterns into the material at various scales.

3. Research Method

This paper presents a novel method of using a collaborative industrial robot to assist in cutting and perforating materials into 2D patterns. The research study utilises an AR head-mounted device (or headset) as a method of interaction between the digital pattern, the customised robot tool, and the materials used. In the context of patternmaking and robotic fabrication, this paper uses an ethnographically informed case study to investigate suitable craft techniques to augment and design a proof of concept with the capacity to use a robotic tool and an AR headset as part of a workflow to create an original design. This research is presented in four stages: Ethnography & Case Study, Robotic Tool, AR Headset Interaction, Fabricating a Design.

3.1. ETHNOGRAPHY AND CASE STUDY

At its core, a patternmaker's job is to create the original 'patterns' that are used in later fabrication processes such as metal casting of sculptures. However, at UAP the patternmaking department is also involved in final fabrication of elements for sculptural artworks and is involved in researching and developing new fabrication processes. An ethnography was undertaken within the UAP patternmaking department over a period of three months to observe the patternmaker's work and identify potential opportunities for developing robotic fabrication techniques to support them. The patternmaking technique identified for analysis was used in cutting patterns for a public art installation designed by Richard Sweeney, who is renowned for folded papercraft designs. Sweeney produced a small-scaled maquette of the intended final design in cardstock as seen in Figure 1.

Figure 1. (left) Maquette of folded cardstock, and the final Installation for the artwork 'Cloud' (image credit: Richard D'Souza/UAP).

The challenge for the patternmakers was to recreate the aesthetic of thin, lightweight paper with a robust material suitable for public display. The UAP patternmakers settled on using compressed PVC foam sheets. The cutting technique transferred the flattened forms onto the PVC material. The 2D patterns of Sweeney's maquettes were used as the reference and scaled up to the dimensions of the installation

Patterns were hand cut and scored referenced from design documents. Metal rulers and templates guided craft knives that cut directly into the foamed PVC sheets. The knives also marked dimensions as pen and pencil would smudge. The patternmaker attempted to make curved cuts in one motion, requiring focus and steady application of force to cut accurately into the material. Shortcomings of the technique required the PVC to be debossed or perforated so it would not crack and split when the material was manipulated by hand.

The observations revealed a physically demanding and focussed approach to cutting materials - with the motto of 'measure twice, cut once' applied to precisely measuring and making patterns. Cutting the PVC remained a manual task as digital tools like CNC laser cutters burn the PVC releasing hydrochloric acid and toxic fumes. In contrast, waterjet cutters soften and disintegrate the material and change its composition. The shortcomings of recreating analogue patterns while rescaling included introducing potential inaccuracies and the amount of time, concentration, and physical exertion of cutting rigid materials – particularly with patterns that measured metres in their dimensions.

The ethnographic observations revealed the identified workflow for creating the pattern, that is summarised as creating an analogue 2D pattern from an unfolded 3D pattern, digitising the 2D pattern for documenting and reference, manually rescaling and applying the 2D pattern to the material. Individual elements of the art installation took up to a week to complete – with transferring the pattern, debossing, and creasing required days per item. Within this workflow, an opportunity was identified from this analysis that robotic fabrication could be applied via an assistive system that a solo person could operate to rescaling and cut patterns into the foamed PVC. The workflow variations are shown in Figure 2.

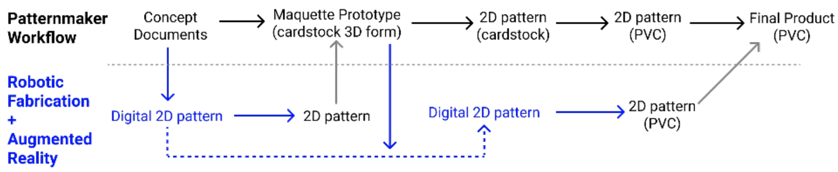


Figure 2. Diagram showing workflow between handcrafted techniques (black) and techniques using robotic fabrication and the AR interface (blue).

3.2. DESIGN TO ROBOTIC FABRICATION WORKFLOW

Based on the ethnographic observations, the research produced a proof-of-concept system of robotic fabrication that would assist patternmakers in cutting and perforating cardstock and compressed foamed PVC. A custom-designed and fabricated end effector tool was made for the robot, a Universal Robots UR10. The tool consisted of a utility knife with replaceable blades and a 'spiked' tracing wheel, shown in Figure 3, which is common in clothes patternmaking to transfer patterns to cloth. A modified workbench allowed the patternmaker to position cardstock for the robot and access to the material, also shown in Figure 3.

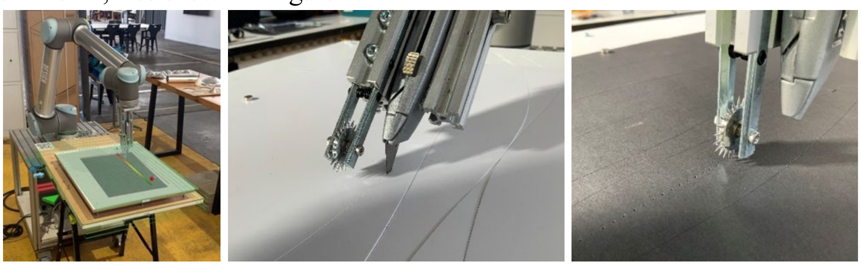


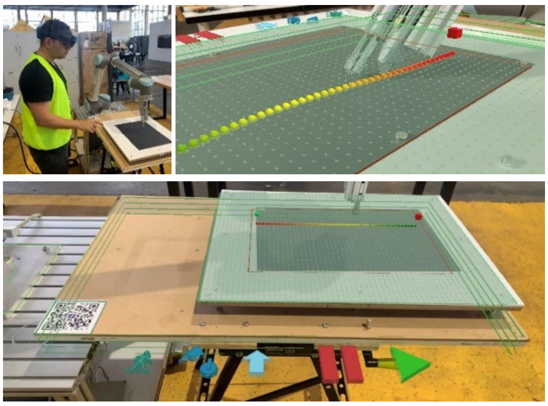
Figure 3. (left) Workbench and UR10 robot set up for fabrication (AR interface visible), (middle) craft knife end effector cutting into foamed PVC, (right) tracing wheel end effector perforating 600gsm cardstock).

The objective of the custom robot tool was to replicate the cutting technique and introduce a perforation technique that allowed the material to be creased on either side of the sheet material. The robot tool cutter used craft knives with blades that can easily be replaced – like those already used by patternmakers. A tracing wheel was also attached to make perforations on the material, which meant the material could be folded in either direction, unlike debossed folds that favour one direction. The UR10 robot was controlled using Grasshopper components and the Robots plugin. The patternmaker's approach was followed to place and nest the location of the patterns on the material, and experimental prototype forms were made using cardstock (250 and 600gsm) and a compressed PVC sheet (1mm). A user interface for interacting with the robot was designed using Fologram (Jahn et al., 2019) (see next section). The final set up was arrived at through a process of iterative design where problems with the fabrication technique were progressively uncovered and resolved.

3.3. AR HEADSET INTERACTION

To enhance the patternmaker's perception of visualising, placing, and controlling action pathways for robot action, an AR user interface was implemented using a Microsoft HoloLens2 headset or an Apple iPad tablet. The patternmaker could use these devices to visualise and interact with the projected pathways via the AR user interface buttons displayed next to the workbench and within the work environment. In this context, AR provides a bridge for supplementing digital craft skills by allowing the patternmaker to visualise, plan and control the cutting and perforating toolpaths close to the material.

The development of an AR interface aimed to encourage easy adoption of robot fabrication techniques for patternmakers or craftspeople to make 2D patterns. The AR interface minimised the need for the patternmaker to access the Grasshopper application to control the pattern or robot and allowed direct human contact to the work area and material being cut and perforated. Figure 4 shows the frequently used robot tool commands implemented in making the patterns were designed to be accessible via the HoloLens2 AR headset, or Apple iPad. The advantage of the headset device freed both human hands to interact with material or environment. Rhinoceros 3D and Grasshopper used the Fologram plugin to create the user interface and display the AR



visualisations as presented in Figure 4.

Fabricating Figure 4. (top left) Setup configured to use the HoloLens2 with the UR10 robot, (top right) AR display of the toolpath projected over the cutting surface. (bottom) Interface buttons to command the UR10 located along the edge of the workbench, from left to right: (a) switch toolpath direction, (b) swap tools, (c) cycle to next toolpath, (d) pause, and (e) start task.

Commands necessary for controlling the robot tool were designed as buttons located parallel to the edge of the workbench. The AR button locations was customised to suit the patternmaker's approach. The button commands included: changing the toolpath, flipping toolpath direction, switching between cut or perforate tools, starting, and pausing the robot action. The AR interface used a QR code marker to calibrate and anchor the projected visuals to the environment and toolpath to the cutting bed of the workbench and aid the patternmaker in aligning the robot, workbench, and the material. A physical safety 'e-stop' button was kept close to user as per safety protocol.

3.4. THE TEST DESIGN

A lampshade was designed and created as an object that would reflect complexity in form and assembly and that would prove difficult to recreate completely by hand. Design sketches created a form reminiscent of a segmented seashell requiring curved adjoining panels. Two shell forms, similar in pattern shape, but with different sizes would require eight panels each to complete the shell forms.

Early prototypes were hand-made with cardstock to develop a method of adjoining panels. Once an approach was established, forms were developed as 3D CAD drawings in Rhinoceros 3D and were then unrolled into 2D patterns. Initially the patterns were made as adjoined panels, but these occasionally produced unwanted and unpredictable creases in the denser materials. Therefore, a decision was made to separate panels, as shown in Figure 5. The edges of the panel pattern took an elliptical form and used perforation toolpaths along one or two edges to allow for guidance in panel curving, and creation of creased tabs for affixing neighbouring panels.

Patterns were input to grasshopper as NURBS for the toolpaths along a 2D plane. Multiple iterations of card maquettes were produced to find a form that combined rigidity and uniformity in curve, along with aesthetics of each panel within the assembled form. The panels were assembled first by hand using 600gsm cardstock maquettes to test the final designed form. The final design was cut, perforated and hand assembled using 1mm foamed PVC sheets within three days, and required minimal finessing or recutting by hand.

Figure5. (top left) Partially assembled shells for fabricated panels, (bottom left) completed shells joined with Kevlar fibre and tested for maintaining structure, (right) Finished lamp design.

4. Discussion and Conclusion

This paper explored the potential of using robot fabrication and AR in an evolving, niche patternmaking industry for bespoke products. Despite the industry showing capacity for increasing use of digital technology as assistive tools – custom, skilled, physical tasks are still frequently performed by hand. Even tough prevalent assumptions that digital fabrication methods will replace human activities such as skilled craftwork, this study presents that there are aspects of handcrafting that can integrate with digital tools. Elements of handcrafting are time-consuming, repetitive, fatiguing, and as shown in patternmaking, require focus and precision for the best production outcomes. Using robot tools can create a disconnect between the crafting person and the material – physical touching of material is diminished as humans are always removed from the active robot for safety reasons. Collaborative robots reduce that barrier by allowing a human closer to the material, and with enough safeguards applied, could allow a human to touch the material while the robot is acting upon it. Providing visual data via AR also reduces the barrier further by trading interaction and robot control from behind a computer screen, towards a level of interaction and communication taking place to the point of action in the work environment.

To produce a tool that allows a sole practicing patternmaker to utilise robotic fabrication, this paper presented a four-step framework which included: (a) an ethnographic case study, to document and specify a patternmaking technique that could be augmented, (b) designing a custom end-effector and cobot workflow to cut and perforate material, (c) a AR user interface to provide visual data and interaction to the patternmaker in their working environment, (d) a workflow that integrates robotic fabrication with handcrafting skills to design and make a customised novel product.

This research highlights the need for ethnographic case study observations when developing robot fabrication systems to assist and augment custom, high-skill industries. The experience gained by patternmakers on the job develops with their exposure to different materials and design outcomes. In parallel to this knowledge are the skills in using different tools and sometimes customising existing equipment or making new tools for specific activities. The shift from manual analogue work to digital techniques poses a query about how humans can maintain a physical link to materials which is a key element of crafting (Pye, 2008; Sennett, 2008).

Allowing the user to closely monitor the robot acting on the material minimised errors, but also initiated explorations for a better flow of work. Alterations to patterns, and predicting material curling helped with the outcome quality of panels and allowed for easier assembly. The patterns could be accurately cut by the UR10 robot and perforations would provide guidelines to aid with handcrafted assembly and finessing. Future research will document other professions, techniques, materials, and other augmented interactions with collaborative robots in 3D environment, not limited to 2D planar actions.

Industries with a foundation in creative and practical skillsets are well positioned to adopt and customise new technologies. The capacity of such innovation displays a positive approach for SMEs that are early adopters of technology and can promote agile and sustainable support to reaching United Nation Sustainable Development Goals. The effects of fostering innovation are not only received locally but interconnected globally. While full economic impact analysis is beyond the scope of this paper, we know from research regarding the implementation of industrial robots in UAP's manufacturing process led to additional jobs, savings in time and material consumption, and returns based on 'localising' the manufacturing process. Therefore, we believe that the process using cobots for patternmaking would create efficiencies in terms of time savings, economic costs, human health and job satisfaction. More research is required to quantify these figures, examine the financial aspects and human benefits of cobotics in manufacturing.

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