Employing AR/MR Mockups to Imagine Future Custom Manufacturing Practices

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Versatile augmented reality (AR)/mixed reality (MR) technologies align with custom manufacturers' resource constraints and support their requirement for agility in responding to unique Industry 4.0 challenges. However, for Australian custom manufacturers, AR/MR uptake remains low. This modest-sized case study seeks to support resource-constrained custom manufacturers by exploring current AR/MR adoption challenges and potentials. Underpinned by a Research-through-Design (RtD) methodology and building upon Situated and Participative Enactment of Scenarios (SPES) methods, we reflect on using novel Microsoft HoloLens 2 AR/MR mockups to support in-situ enactments with domain experts to collaboratively imagine and design more productive and efficient augmented fabrication and assembly practices. In exploring new ways of making and doing through AR/MR, we find promising pathways for Australian custom manufacturers to add value across a product's lifecycle. Our findings identify five key areas for further research, which will be explored and developed through workshops around each identified AR/MR application area.

CCS CONCEPTS • **Human-centered computing** • Human-computer interaction • Field studies • Mixed/augmented reality • Interaction design process and methods • Interface design prototyping

Additional Keywords and Phrases: Research Through Design, Participative, Scenarios, Manufacturing

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1 INTRODUCTION

Within an Industry 4.0 and current geopolitical context, a competitive Australian manufacturing sector is essential to the nation's resilience and prosperity. At its core are advanced small-to-medium enterprises (SMEs) producing highly customised, low-volume and bespoke products to service niche sectors of the global supply chain [23]. To increase viability, ambitious custom manufacturers seek productivity and efficiency enhancements to their labour-intensive fabrication and assembly processes. For custom manufacturers', accessible, affordable and versatile technologies which improve these processes are needed to improve agility in responding to diverse consumer preferences [22].

The relatively low cost and versatility of augmented reality (AR)/mixed reality (MR) technologies align with Australian custom manufacturers' resource constraints and their need for agility in responding to unique Industry 4.0 manufacturing challenges [22]. However, AR/MR uptake remains low, despite increasing attention from researchers and practitioners across the many facets of manufacturing [15,18], such as product design [12], design prototyping [11], training [7], integration [6], maintenance [13], and assembly [19]. More recently, the commoditisation of hands-free AR/MR hardware with gestural interfaces, such as the Microsoft HoloLens 1, released in 2016, and the HoloLens 2 in 2019, provides smaller custom manufacturers with access to potentially more efficient methods of making and doing. However, given the rapid rate of AR/MR development, integration advice is lacking for custom manufacturers seeking to utilise this technology in their production processes [22].

This paper reports on a case study exploring how AR/MR applications can support custom manufacturers to fabricate and assemble products more productively and efficiently. This research contributes to the Connected Creativity theme of OzCHI2022 by exploring the creative application of AR/MR mockups to engage participants and further demonstrates how AR/MR can provide creative and impactful applications within custom manufacturing processes. Given the high degree of domain expertise required in custom manufacturing work settings, this paper uses AR/MR mockups to help researchers bridge understanding with domain experts to comprehend their contextual work practices better. In response to our research question, *"How can AR/MR mockups support custom manufacturers to imagine better ways of making and doing?"* we introduce AR/MR to the employees of a custom manufacturer through introductory mockups to help familiarise them with the technology. We further employ AR/MR mockups to facilitate a collaborative reimaging of users' current practices and discover new ways of doing through Situated and Participative Enactment of Scenarios (SPES) [9].

SPES provides users with low-fidelity mockups of future products to help them imagine new products, features, and services by acting out use scenarios in response to contextual situations that arise during normal daily activities [5]. Inspired by SPES, we employ a similar approach and provide custom manufacturers with low-fidelity AR/MR mockups to enact future augmented fabrication and assembly scenarios. AR/MR mockups help us engage participants to contribute their creative ideas, open discourse, evaluate their points of view, and discover potential new scenarios. Our findings identify five key areas for further research. These include: 1) augmenting the machine, 2) training, 3) auxiliary tasks, 4) assembly and quality control, and 5) specific operations. These five areas will be explored through workshops around each AR/MR application area. The results from this case study add practice-based insights regarding the integration of AR/MR for Australian custom manufacturers. Further, we aim to foster a discussion around the potential and limitations of this novel study to refine it for future case studies.

2 LITERATURE REVIEW

2.1 Custom manufacturers and AR/MR technology

Custom manufacturers design and manufacture products to meet customers' needs across industry sectors, for example, customised agricultural equipment, recreational vehicles, and bespoke architectural elements. Custom products are typically designed and manufactured by a small team of designers, engineers, and fabricators to the customers' specific requirements. Producing differentiated and bespoke products means that custom manufacturers must demonstrate expertise across extensive fabrication and assembly processes. Moreover, custom manufacturers operate within highly competitive business environments requiring agility and responsiveness to unique manufacturing challenges. These challenges include adopting advanced technologies and innovative processes, managing complex digital data sets, improving stakeholder collaboration, upskilling, and attracting new staff. In parallel, Australian custom manufacturers face skilled labour shortages, increased sustainability requirements and the need to deliver competitive customised projects on time and within constrained budgets [23]. Operating as SMEs, custom manufacturers are typically time-poor. They lack the resources to explore productivity enhancements such as AR/MR technology in their product development process [22].

In this paper, AR/MR is defined as spatially anchored virtual imagery that can interact with the physical world and is manipulated through gestural inputs afforded by the HoloLens 2 see-through optical display. Currently, there is ambiguity in defining a clear delineation between AR and MR technologies [17]. Many define MR as a superset of AR, encompassing all modes of the virtuality continuum between the real environment and entirely virtual, as defined by Milgram and Kishino [14]. Other authors make a clear distinction between the two, with only MR enabling interaction between digital and physical elements in the scene compared to AR, whilst other authors employ MR as a synonym for AR [17]. We seek to reduce confusion around our use of terminology and employ combinatory AR/MR terminology in line with usage across related publications [18].

2.2 AR/MR potentials and challenges in custom manufacturing

AR/MR technologies improve component fabrication and product assembly by helping users bridge the gulf between digital definitions and physical processes. In addition, immersive technologies improve user productivity by reducing cognitive load and increasing the perceptibility of complex structures, which is correlated to the nature of the human mind being hardwired to experience objects and environments in three dimensions [8].

Adopting AR/MR is expected to generate new fabrication, assembly practices, and value-adding opportunities for custom manufacturers. For example, the simulation of assembly processes can assist in the earlier identification of potential fitment issues, reducing costly rework and resulting in less waste and resource usage [15]. Several studies outline AR/MR potentials for fabrication and assembly activities. For example, Goepel & Krolla [5] employ virtual guides to assist novice workers in constructing complex assemblies through the intuitive sorting of complex task information afforded by the HoloLens' gestural interface. Moreover, AR/MR training experiences can educate novice workers in vocations requiring high degrees of tacit knowledge, such as welding and, in the process, reduce consumables, physical risk and costs [16].

AR/MR allows for augmented fabrication workflows which markedly reduce construction time compared to 2D drawings and physical templates [5]. Such an example is the AllBrick and UTAS project by Fologram, shown in Figure 1, where two bricklayers collaboratively assembled a complex curved wall in several hours, assisted by virtual guides and templates [24]. Given each brick's unique location and orientation, this type of task would be challenging to construct efficiently with traditional 2D documentation.

Figure 1: Wearing Microsoft HoloLens 2 headsets, two bricklayers follow virtual guidelines provided by the Fologram software to assist them in constructing a complex brick wall. Photograph by Fologram [Public domain], via Fologram.com. (https://fologram.com/)

In “Making in Mixed Reality”, Jahn et al. [10] describe how novice workers can fabricate and assemble complex tube structures assisted by augmented tube bending machinery. Following overlayed virtual 3D guides, workers create each bend, assess potential tool collisions, and evaluate each part’s fit against the final assembly, helping reduce accumulated errors, subsequent rework, and waste.

Several commercial AR/MR solutions can provide benefits for custom manufacturers. For example, applications such as Microsoft Dynamics 365 Guides, indicated in Figure 2, can help users create contextualised virtual work instructions [25], while Fologram software provides users with interactive virtual instructions that translate 3D design models into intelligent processes in place of traditional 2D drawings and physical templates [10].

Figure 2: A worker wearing a Microsoft HoloLens 2 headset is guided by virtual work instructions created in Microsoft Dynamics 365 Guides to place assembly components. Photograph by Microsoft [Public domain], via Microsoft.com. (https://dynamics.microsoft.com/en-us/mixed-reality/guides/capabilities/).

Most cases require expertise with Computer-Aided Design (CAD) and parametric optimisation software such as Rhino and Grasshopper 3D. Expert users also develop custom AR/MR applications to suit specific contexts using Unreal Engine, Unity, AR-Kit for Apple and AR-Core for Android. Despite these advances, implementation remains inconsistent, suggesting further knowledge is necessary to overcome AR/MR adoption obstacles in manufacturing.

Currently, various issues limit the broader adoption of AR/MR use in custom manufacturing, such as registration accuracy, user interface (UI) design, adaptability to site conditions and multi-user synchronisation [2]. From an organisational perspective, despite having lower upfront costs than technologies such as robotics, investment is needed in preparation and planning, staff training, support and ongoing costs of multiple devices [4]. Moreover, given the dynamic nature of fabrication and assembly processes, there is a need to build the manufacturers' in-house AR/MR development capabilities or, conversely, onboard specialist skillsets to develop robust solutions

AR/MR technologies have been extensively studied in manufacturing and related fields for several decades [1]. However, many manufacturers remain unaware of the technologies' potential for their specific processes and require support to identify use cases and effectively integrate AR/MR into their practice. This study uses a Research-through-Design (RtD) [21] methodology to create AR/MR mockups to foster a shared understanding with domain experts around possible future practices in a modest-sized custom manufacturer.

3 METHODOLOGY

RtD is a system of scholarly research that draws on the design practices' methods, processes, and reflective techniques to foster rich knowledge creation, *"RtD asks researchers to investigate the speculative future, probing on what the world could and should be"* [21]. This case study uses design development's iterative and reflective nature to garner insights and inform new perspectives and proposals to the complex challenges custom manufacturers face through making and critiquing AR/MR mockups. Although closely aligned, RtD is more systematic and explicitly reflective than design practice and is concerned with how design actions produce new knowledge as opposed to the pursuit of designing a successful commercial outcome [21].

The RtD methodology is essential to this case study, as digital artefact creation can provide new perspectives on complex problems, such as using AR/MR to fabricate and assemble customised products for which limited theory currently exists. Cross [3] argues that knowledge resides in designers, their practices and the products they manufacture. This study utilises RtD to uncover these insights and disseminate findings to the broader academic community. Carrol and Kellogg [1] note that in human-computer interaction (HCI), artefacts typically proceed with theory instead of theory generating new artefacts, such as the need for the computer mouse to be invented before its effectiveness as a design solution could be studied [21]. This research study actively constructs design solutions for AR/MR applications to generate new theories and reflect on current theories in their creation. Thus, continuing the dialogue between what currently is and what may be [21] in efforts to advance custom manufacturers' ability to handle future challenges.

In collaboration with custom manufacturers, this study endeavours to understand current adoption barriers and explore the possible benefits of using AR/MR technology. A helpful approach to obtaining a shared understanding of the potentials and challenges of emerging technology is the use of Situated and Participative Enactment of Scenarios (SPES). According to Iacucci et al. [9], SPES includes following users in their natural context and providing low-fidelity mockups to help imagine possible futures, if a product or service could do what they needed. SPES aims to consider real-life concerns responsively, help users engage in discourse and contribute creative solutions, walking through the motions of activity as if one were using the technology in situ. Further, mockup generation is typically formulated around interesting situations that arise by shadowing the user during everyday activities. The specific theme of mockup and scenario enactment can be either led by the researcher or the user; the critical function is to capture contextual insights on possible applications [9]. Unlike traditional lab-formulated scenarios, SPES allows acting out a possible future for a particular context and collaboratively shaping solutions.

Complimenting RtD's generative nature, we adopted an approach inspired by SPES to garner contextual insights from domain experts by exploring how AR/MR mockups can be used to prototype in-situ and real-world contexts. Within this study, each manufacturer's fabrication and assembly processes constitute the bounds of a single 'unit' of analysis or 'case'. Drawing on the case studies from Yin [20], we employ semi-structured interviews, informal discussions, observations, and conduct SPES with stakeholders involved in fabrication and assembly processes. Applying several methods helps develop a broader understanding of the custom manufacturers' environment and is valuable to determining future research paths.

The primary author was embedded in the manufacturing environment where the research was conducted and employed a series of data collection methods, depicted in Figure 3, in three parts to address the research question and examine 1) key information regarding the current state of manufacturing processes, 2) the opportunities for implementing immersive technologies, and 3) the interest of the current staff to adopt new technologies into their processes. The methods employed included n=6 semi-structured interviews and n=2 SPES using AR/MR mockups.

3.1 Participant recruitment and equipment

To conduct SPES, the primary author chose a Queensland-based custom manufacturer that extensively modifies vehicles to meet customer requirements. The manufacturing company updates existing vehicle platforms with enhanced capabilities and functionality requiring high levels of customisation and specialised manufacturing skills. Like many manufacturers in Australia seeking to participate in Industry 4.0 by adopting advanced manufacturing technologies, the company is challenged by a lack of time and resources to invest in the research and development necessary to integrate new technologies into its manufacturing workflow [23]. Therefore, this research set out to develop a shared understanding of AR/MR with the custom manufacturer keen to explore the technologies' potential.

Two visits to the custom manufacturers' workplace were undertaken in this study. The first sought to recruit them as a case study partner, whilst the three-day field study in April 2022 was conducted on the subsequent trip. The initial site visit revealed an understanding of the company's immediate and long-term AR/MR technology goals. The custom manufacturer described AR/MR technology as a longer-term objective following robotics and additive manufacturing, with AR/MR implementation seen as potentially improving quality assurance processes. During this initial site visit, a one-hour exploratory site tour was undertaken to garner a high-level understanding of the company's design-to-fabrication processes. Learnings from this initial site visit informed the development of the data collection strategy discussed in this paper. An exploratory and flexible approach was taken in expectation of on-site access and coordination of observation tasks around the manufacturers' dynamic project schedules.

After the initial site visit, a three-day field study, including semi-structured interviews, defined a strategy to recruit and engage participants. As outlined in figure 3, this strategy consists of the following steps:

1. during introductory conversations and at the start of semi-structured interviews, users from several departments of the company were shown a simple AR/MR model to help familiarise themselves with the technology
2. as a baseline, this gauged user interest in AR/MR applications and sought other activity suggestions to augment
3. reflecting on these discussions, AR/MR mockup 1 was developed
4. engaged through the AR/MR mockup 1, users, such as the lead fabricator and other fabrication staff, were shown mockup 1 on the shop floor. The feedback from this exercise informed the development of mockup 2 in response to newly identified potentials,
5. mockup 2 was shown to the lead fabricator and other fabrication staff, and
6. with the lead fabricator, we enacted scenarios in-situ around various equipment and processes in the factory to imagine future custom manufacturing practices.

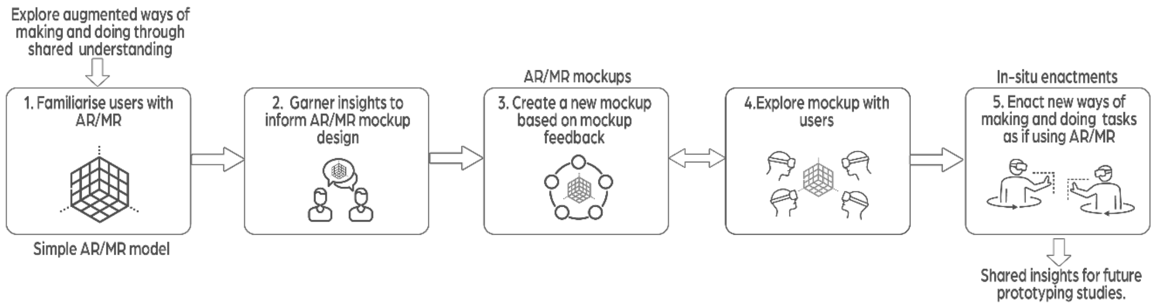

Figure 3: A diagram outlining the process of developing shared insights with users during the case study.

Researchers found that using mockups as a data collection tool:

1. created engaging discussions, allowing users to feel comfortable sharing their ideas
2. made recruitment easier, as employees were drawn into the technology by witnessing other staff's experiences
3. helped in understanding and evaluating stakeholder points of view around the technology's integration
4. removed barriers in understanding the contextual requirements of prospective AR/MR approaches, and
5. focused the SPES study on pertinent future AR/MR application scenarios.

Essential hardware used in the study included a Microsoft HoloLens 2 headset, whilst Grasshopper 3D and Fologram software was used to develop AR/MR mockup applications by the lead author as part of the in-situ exploratory field study. Fologram was chosen due to the primary authors' previous experience developing AR/MR mockups and prototype applications using the software. The AR/MR mockup applications were low-fidelity and rapidly developed in response to data collected during the field trip. In the following sections, this paper reports on the in-situ exploratory field studies conducted in April 2022 at the manufacturer's premises.

3.2 Data collection

The data collection method discussed in this paper has been designed to address limitations accessing Australian custom manufacturers experienced with AR/MR and constraints around site access with study participants. We describe the rapid design and demonstration of AR/MR Mockups in situ to help researchers and participants collaboratively imagine new ways of making and doing. We reflect on combining AR/MR Mockups with in-situ exploratory studies to evaluate AR/MR potentials alongside a manufacturer's current processes and how these impact and shape future research goals.

This paper analyses the development of AR/MR mockups and initial findings according to the following aspects. First, around AR/MR mockup design through a process of reflecting on insights gathered through informal discussions, direct observation of processes and semi-structured staff interviews. Second, we discuss the process of providing users with a firsthand experience of the AR/MR mockup demonstrations from directly within the HoloLens 2 headset. Third, we describe and discuss AR/MR mockup observations of users from our standpoint outside of the experience as facilitators. Lastly, we list five main application areas of future research pathways as collaboratively imagined through SPES. The five application areas sort prospective new practices based on similarity and their situatedness within manufacturing operations.

4 AR/MR MOCKUPS

After an initial day of observations and interviews with key organisational staff, knowledge about the company's processes was forthcoming. Furthermore, through informal discussion with engineering and fabrication staff, they appeared enthusiastic about the potential of the technology after experiencing the introductory AR/MR experiences, which involved viewing a static model of a vehicle at full scale in context on the factory floor. Through these initial activities, we learned that users intuitively understood the capability of the technology and were eager to identify processes where it would bring the most immediate value to them. During the day, a journal was used to make notes of interesting concepts and help inform the rapid development of AR mockups to demonstrate on day two.

4.1 AR/MR mockup design

During the reflective process, it became apparent that an AR/MR mockup around vehicle cutting would be a useful starting point as an example of a different approach to the manufacturer's existing process. The application around the vehicle cutting process was chosen to demonstrate the potential of the AR/MR technology and provoke further discussions on application areas. This unique process appeared to be a critical task with a high degree of preparation and manual markup of complex surfaces, possibly making it a good candidate for AR/MR. Moreover, there were significant financial risks for the company if done incorrectly, so improving this task could benefit the company.

The vehicle cutting application (mockup 1), shown in Figure 4, was created over a few hours using Fologram software and McNeel's Grasshopper plug-in for the Rhinoceros 3D CAD program. An interactive value slider provided by the software allowed the user to alter the distance of the cut line through the vehicle's cabin to the proposed datum through the centre of the front wheels, a nominal reference location in automotive design. This distance was represented through virtual text between the datum and cut line and was dynamically updated through a gesture-controlled virtual value slider.

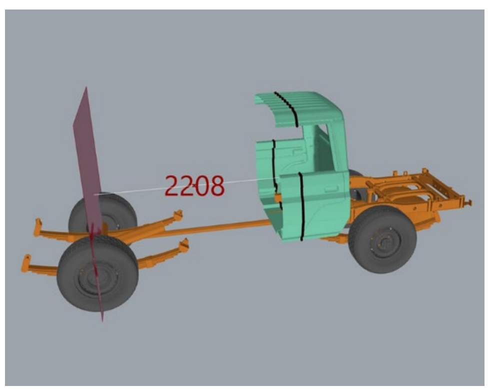

Figure 4: Mockup 1 of the vehicle cutting application shown in the Grasshopper 3D/Fologram desktop viewport.

4.2 Mockup 1 demonstration

Initially, mockup 1 was viewed by the engineering supervisor at the participant's workstation. Viewing the participant with the headset on and gesturing in the air piqued the interest of two coworkers, who subsequently used the application. Following this initial session, five additional staff members viewed mockup 1 before their semi-structured interviews: two CAD engineers, one business development manager, a lead engineer, and the fabrication lead. Further, the fabrication lead viewed the vehicle cutting example in the factory space and invited six more fabrication members to view the prototype. Finally, two more fabricators viewed the mockup during brief informal discussions during the day.

4.3 Mockup 1 participant observations

All participants experienced initial difficulties interacting with the AR/MR gestural interface. In particular, there was some uncertainty and frustration around how to press virtual menu buttons. However, most users became accustomed to gestural input after a relatively short familiarisation time (five to ten minutes) with guidance from the researcher. Observing and talking to users once they had familiarised themselves with the AR/MR experience, there appeared to be an intuitive understanding of how the technology worked, along with some early identification of applications in their work activities. However, it is helpful to note that using gestural inputs is potentially embarrassing for some users and may have detracted from some staff taking part as they seemed hesitant to participate in front of coworkers. Moreover, using a single AR/MR headset was somewhat limiting when guiding users through their experiences. Alternatively, casting a live feed from the headset to a local monitor or screen would improve the researcher's understanding of each user's experience and potentially increase bystander engagement and participation.

During these initial demonstrations, the lead fabricator was excited to show the staff and championed its use. The lead fabricator helped coworkers fit the headset correctly, walked them through the user interface menu selections and unpacked their experience by asking them about their sentiments around the technology's utility for specific processes. Of particular interest was the discussion around developing an area in the factory where they could have QR codes set out for datuming and placing the actual vehicle in the exact location each time they conducted the process in future. Further, they mentioned cutting processes on different vehicle parts. An interesting point made by another staff member was that viewing the cut line allowed them to see how its location would impact wiring and internal components, which could reduce potential errors and speed up the process.

The primary target audience for mockup 1 was fabrication staff, including the lead fabricator (who also oversees the company's CAD programming), who would be interviewed later in the day and participate in the situated enactments the next day. Based on the information gathered from these further interviews and discussions with staff during the mockup 1 demonstration on day 2, the research team reflected on which mockups to develop and display on the final day of the field trip before the situated enactments. Staff had described some key areas where AR/MR might be helpful, such as improving their quality processes and manual machining tasks. Armed with this new information, a second virtual mockup was developed that showcased four different scenarios within one experience.

4.4 Mockup 2 design

With a deeper understanding of potential application areas for AR/MR, an ambitious second mockup was developed, which displayed four separate processes virtually overlayed on the organisation's physical factory floor. This second application (mockup 2) had four stations where users could walk through and view potential alternative fabrication, assembly, and quality inspection methods. Each station had a large sign to indicate what was being displayed. The first station, shown in Figure 5, was called Assembly and displayed a full-scale representative vehicle chassis. Each chassis member was individually coloured for ease of identification, and key information on assembly components was shown, as well as information on assembly sequence and where components needed to be welded. Welds were shown according to size and length with embedded 2D drawing callouts to help the welder understand each weld type.

Figure 5. The colour-coded virtual vehicle chassis is viewed through the HoloLens 2 HMD.

The second station Folding, shown in Figure 6, was informed by discussions with staff about their sheet metal folding operations. Our virtual mockup displayed an indicative sheet metal part, identification number, dashed angled fold line, and orientation direction arrow to indicate the correct face, orientation, and insertion direction on the pan brake machine.

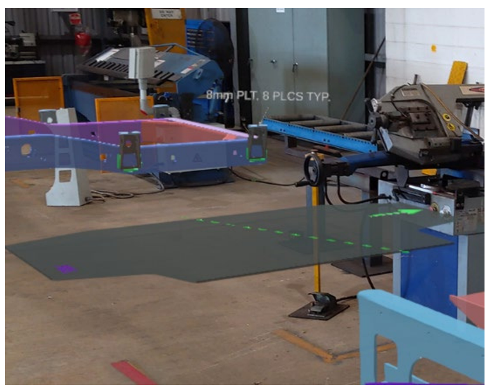

Figure 6: A virtual 3D overlay informs the worker on sheet orientation, part number and fold line in a future folding process.

The third station, Inspection, shown in Figure 7, displayed two large sheet metal parts. The intention was to discuss the possibility of overlaying a digital model over a physical one to detect deviation errors and improve quality assurance processes.

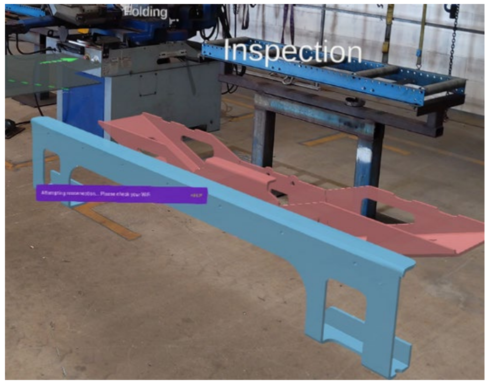

Figure 7: A virtual representation of generic folded sheet metal parts used to discuss quality inspection.

The final station, Intersect Cut, described in Figure 8, was devised from a brief conversation with staff about their development of roll-over protection systems (ROPS) and the difficulties of marking up, cutting, and welding complex curved piping. At present, successful task outcomes are highly reliant on a welder's experience and skill. Given this, the virtual overlay seeks to enhance less experienced welders' confidence to tackle this complex operation and further optimise the location of weld joints.

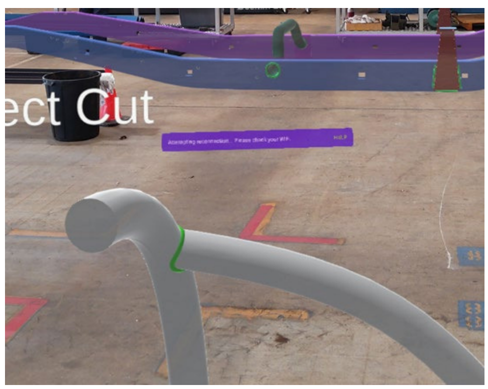

Figure 8: A virtual green line is displayed to help welders assess the feasibility of a future welded assembly.

4.5 Mockup 2 demonstration

Mockup 2 was initially shown to the lead fabricator and an apprentice fabricator on day three of the field study. During this process, we demonstrated how Rhinoceros 3D and Fologram's computer-based interface directs what is displayed within the HoloLens 2 headset—for example, viewing newly created geometry in Rhino, such as curves, surfaces, and large volumes. This real-time functionality was a potential area of interest for the two staff. We explored this area of interest by creating two large spheres to display aspects around scale and position in their factory environment. This creative experience engaged staff to imagine the further potential of the technology.

4.6 Mockup 2 participant observations

Observing and talking to staff as they viewed the four separate virtual stations, they were noticeably more comfortable exploring virtual content at their own pace with minimal guidance. Time was spent interrogating the various aspects described at each separate station, and users were immersed in their experience. It was noted that users approached components at each station as if they were in a physical workspace, bending down, looking over components, poking and pressing, trying to interact and move virtual objects to see if objects could move or be picked up. Moreover, the participants began to relate aspects of the stations that would be useful for their existing processes.

The lead fabricator/CAD supervisor was eager to understand how the application was created and operated during the coworkers' exploration of the augmented workspace. During this time, discussions focussed on hardware requirements, interoperability with the manufacturers' current CAD software and the specific skills required for integration into their design-to-fabrication processes. The participant also described a desire to try other hardware, such as Mobile AR devices, as an intermediary step to understanding AR/MR technology and the Vuxiz M400 Smart Glasses for key personnel to wear during quality inspection procedures.

4.7 Findings from using AR/MR mockups in the field

AR/MR mockups allowed participants to understand and appreciate the technology's nuances and experience firsthand how it works. Having an improved understanding of the type of information AR/MR provides allowed users to describe how they would use the technology in considerable detail. Their ideas rapidly outstripped our initial mockup applications in ways we could not have envisaged. Our AR/MR Mockups painted broad strokes initially around aspects of production we felt were valid based on our limited understanding. These initial mockups stimulated discussion with the users about potential new application avenues. Additionally, exploring tangent discussions through creative explorations proved helpful in understanding the broader context of technology integration.

5 IN-SITU ENACTMENTS OF SCENARIOS

Following the demonstrations of mockup two, a two and half-hour in-situ exploratory session was conducted by the on-site researcher and lead fabricator, who had also participated in both mockup demonstrations. Both participants did not use AR/MR technologies during the enactments but walked through the various scenarios as if they were. We approached this session with two aims:

1. to learn more about how the company currently fabricates and assembles products and
2. run through possible scenarios of how AR/MR would be used across these and adjacent processes.

For context, the on-site researcher has an industrial design background, having worked in various similar manufacturing environments over the past two decades. The lead fabricator is an experienced fitter, turner, and lead CAD Supervisor and is currently undertaking further study around industry 4.0 advanced manufacturing. Five preliminary AR/MR application area themes arose from our shared exploration. These included augmenting the machine, training, auxiliary tasks, assembly and quality control, and specific operations. The following sections describe the processes analysed, some of the common issues encountered by the fabricator and shared discussions between the participant and researcher around applying AR/MR to improve future manufacturing practices.

5.1 Augmenting the machine

The in-situ exploratory study began with the participant keen to explore using AR/MR to improve manual machinery processes. Manual machining processes rely heavily on operator experience and skill instead of computer control. Some examples include presses, lathes, bandsaws, grinders, and milling machines. Borrowing aspects of the SPES method, we observed the participant use offcut pieces of flat sheet metal to demonstrate existing folding processes on two different presses, a manual pan brake, and a 2-axis numerically controlled (NC) press brake. Following this initial overview, the participant and researcher enacted a scenario imagining the same process as if using an AR/MR headset. The lead fabricator stated, "*one of the things where I think AR could really help out is taking an old manual machine like this pan brake and being able to essentially make it semi-automatic".* It was observed that it is difficult and time-consuming to set up the machine for each fold and ensure correct sheet alignment every time; Lead fabricator, *"I have got a mark it, put it in, measure it up, trying to make sure my lines are going to be where they are"*. Exploring how AR/MR could be used, potential benefits were immediately identified, such as eliminating the need for laboriously transcribing 2D drawing information onto sheet metal through manual scribing—manually scribing limits the feasibility of carrying out complex folding operations and is prone to human error and, consequently, significant waste.

Another key consideration would be the application of fiducial markers such as QR codes and ArUco markers to sheet metal parts and presses. Doing so would allow for the accurate alignment of virtually overlayed CAD information such as a representation of the machine itself, part fold lines and orientation information to help the operator efficiently locate, orient and fold sheet metal parts. Moreover, the virtual CAD overlay can display each step in the fold sequence as the operator requires and be used to validate the folded part's accuracy upon completion. By simulating the folding process in situ, AR/MR would alert the operator to inconsistent folds and potential tool collisions earlier in the fabrication process. Moreso, limiting the need for physical prototyping and hence reduces consumables.

AR/MR also provides enhanced levels of visual feedback for NC machinery, potentially unlocking dormant capabilities for the manufacturer, as discussed regarding the manufacturer's larger NC press brake. Lead fabricator: *"on this machine, all it shows you is the profile of the bend. It does not show you anything else. So, if I've got a weird bend sequence, or if I put this in upside down, if it's not square, you know, it has got contours, I put it upside down and press it, I have just pressed it wrong, and you cannot unpress it"*. A significant limitation of this manufacturer's existing NC press brake machine is a lack of 3D visual feedback for the machine operator compared with more expensive NC presses. Using AR/MR to view real-time virtual 3D feedback would increase the capability of the fabricators' existing 2-Axis NC press brake machine to rival costly 7-Axis NC machines.

When exploring the potential returns on investment for integrating AR/MR with their existing NC press brake, the lead fabricator identified several key considerations: "*you can take a $60,000 machine and add in a, let's say, $10,000 headset for ease of math, add in another 10 to 15 grand for somebody to program, or teach somebody how to program it. Then essentially, you got a $750,000 machine for under $100,000.* Providing the machine operator with real-time virtual 3D feedback and simulation visualisations of fold processes allows the manufacturer to fabricate more accurate and complex folded components. For example, AR/MR would allow the manufacturer to design more sophisticated conical-shaped parts that are currently not feasible due to the manual scribing or folding accuracy required.

Following the initial twenty-minute exploratory study around augmenting press-brake machinery, other manual machinery scenarios were enacted, including on a nearby milling machine and lathe. The participant demonstrated using the existing milling machine, which is not NC and has no digital readouts. In viewing the user demonstrate milling operations, it was apparent that a high degree of tacit knowledge is required to coordinate axis feed accurately. A virtual overlay in this context would prove beneficial as it would allow novice users to observe a common reference point during the entire activity and reduce the need to accurately mark out 3D parts before milling. Motioning to the lathe, the lead fabricator points out that even having a virtual overlay to get the operator somewhere close to the finished part would reduce time *"without having to keep measuring it, even if I got to within a millimetre of what I need, then I can start measuring. It is still going to speed it up, I'm still going to cut that time down"*.

5.2 Training

AR/MR technology was seen as valuable for training novice operators across most manual machines, particularly the lathe operation, due to the numerous levers, dials and buttons required to operate it safely and productively. Moving from the manual machinery, we sat inside a nearby completed vehicle where the lead fabricator described how AR/MR would be preferred to their current method of supplying customers with paper-based training manuals. Motioning and pointing to various features within the vehicle stating, *"we are not there with them to operate it. So, to have that ability to put it on and visualise what's going to happen. Go through all the buttons"*. Enhancing interactive training is a potentially important area to investigate to improve the customer experience.

5.3 Auxiliary tasks

At this study stage, the researcher kept the participant engaged and willing to explore further possibilities and sought out a walk-through of other factory areas. During the walk from the fabrication area to the assembly area, the researcher prompted the fabricator in a rather opportune fashion upon seeing a potential for AR/MR stock material identification. The fabricator saw little value in visualising material in stock. The more significant potential was seen in using an AR/MR headset to identify parts when walking through their warehousing section, as now it is difficult to find particular items, and time is lost searching.

This action of probing the user around other tangent potentialities was instrumental in spotting other opportunities for the technology. For example, the fabricator motioned to the overhead crane deliberating on the operators' potential to see the crane's pendant with AR/MR during operation as it is typically obscured, but this was seen as a low priority. Moreover, upon seeing a vehicle serviced for a customer, the fabricator mentioned the difficulties of carrying out maintenance tasks. Servicing this particular vehicle is a complex operation demanding a high degree of information recall. An AR/MR headset could help walk the user through tasks, ensuring equipment is serviced correctly. Sometimes, it can be challenging to recall the correct sequence of events in maintenance tasks by following paper-based work instructions, which can be limited or outdated in the type of information they provide.

5.4 Assembly and quality control

Moving to the assembly area, the participant described the assembly process for a particular vehicle platform. Mentioning that a similar assembly had an error that, luckily spotted just before completion, would have led to significant reputational damage for the company. A minor misalignment caused the error in a part, which accumulatively could cause later features to be installed incorrectly. When asked whether this would impact downstream events, the lead fabricator stated, *"absolutely and the rework costs a lot of money as well. You have to either unpick the whole thing and lower it, or you got to cut sections out and then re-reinforce it"*. In this instance, AR/MR was seen as being vital to prevent similar incidents from occurring in the future. Several more discussions occurred when viewing existing assemblies in the workspace. We discussed how AR/MR could help workers better understand how components fit together and its usefulness in checking part alignment before welding.

Virtual work instructions would also prove helpful in ensuring all steps of a maintenance or assembly procedure are conducted correctly, consistently, and able to be verified and validated. For example, ensuring components such as bolts are appropriately torqued when installed and wiring harnesses are fitted correctly. This information is currently manually photographed, documented, and entered into a report database. This process could be streamlined using the AR/MR headset to allow technicians to create annotations in context and audio-visually document progress for later review.

5.5 Specific operations

In this instance, a core business task is precisely cutting vehicles to allow for significant modification and application of various platform packages. As discussed in the first mockup and revisited in the exploratory study, vehicle-cutting operations are core to the business. The exploratory studies allowed the investigation of the various cuts employed in different areas of vehicles. Exploring AR/MR in cutting scenarios would improve worker confidence, help de-risk the task, and ensure contextual factors are considered and anomalies spotted before cutting. Moreover, the headset's telepresence capabilities allow workers to be remotely assisted by expert staff placed off-site, ensuring that production runs smoothly. Also discussed in mockup 2 was the welding of complex tubed parts, a task requiring a high degree of tacit knowledge that could potentially benefit from AR/MR. As explained by the lead fabricator*, "you have to mark it up, make sure it is in the right place, at the right angle. A lot of times it is just by feeling, you guys get it"*. In discussing the benefits of AR/MR for this process, the lead fabricator felt it provides *"that confidence, accuracy, repeatability"*. AR/MR was seen to help improve worker confidence in welding complex tube assemblies and ensuring higher quality parts.

6 DISCUSSION AND CONCLUSION

In response to our research question, *"How can AR/MR mockups support custom manufacturers to imagine better ways of making and doing?* We discuss how AR/MR mockups were strategically employed during a three-day on-site case study. The case study sought to help users familiarise, engage with and better understand the capabilities of AR/MR technology for their particular context. We reflect on the rationale behind adopting our approach to collect the specific data required to conduct future workshops in this area, combat time and accessibility constraints, and how the interaction of users with our virtual mockups helped guide and focus an in-situ exploratory study.

Building on the SPES approach [9], AR/MR mockups help foster collaborative discourse on imagined future practices. During the field study, discussions rapidly moved toward creating new AR/MR applications around specific challenges. For example, the low fidelity of mockup 1 provided a high-level understanding of earlier error detection in vehicle cutting operations. Future studies will employ higher-fidelity AR/MR mockups and prototypes that extend and improve on this approach and explore the intricacies of each process. Interestingly, users discussed dedicated workspaces with pre-installed fiducial markers for overlaying virtual 3D models on vehicles and machinery, indicating an appreciation of how the technology works and a marked shift away from current approaches.

In observing staff explore mockup 2, there was a greater focus on understanding the broader aspects of the experience. Participants began comfortably using the headset, delving deeper into the mockup construction, and playfully exploring virtual content. Users desired further interaction than our virtual mockup provided, seeking to pick up, rotate and move objects and cycle through animations of the sheet metal folding process.

AR/MR mockups provided a standard reference to foster insightful discussions and helped bridge the divide between domain expertise and the technology's application. For example, during the enactment of augmented sheet folding, the lead fabricator frequently referred to mockup 2 as an example of how AR/MR would assist the process. Providing users with virtual mockup examples in the days prior helped focus the in-situ enactments. As a result, users began to quickly understand the technology's capability and how it could integrate across fabrication, assembly, and adjacent operations. Throughout the in-situ enactments, participants did not use HoloLens 2 headsets but instead imagined their use. Future studies will look to record users' interactions, comments and gaze whilst wearing AR/MR headsets during scenario enactments and employ multiple headsets and mobile AR devices to invite broader participation and richer discussion.

This case study was limited by size and accessibility; however, it allowed five future research areas to emerge, including augmenting the machine, training, auxiliary tasks, assembly and quality control, and specific operations. Across the identified areas, there is potential for productivity and efficiency gains by enhancing existing manual machinery processes to rival high-end equipment, reducing error, rework and waste, quality improvements and adding value through enhanced worker and customer training. For example, in the sheet metal folding process we enacted, AR/MR merges distinct activities such as part markup, identification, orientation, location, and fold sequence into one digital application. Having several tasks in one experience can improve users' understanding of the relationships between the activities and intended outcomes, potentially leading to reduced handover errors between departments and other workers.

Building on the work of Iacucci et al. [9] and informed by an RtD methodology, we iteratively generate AR/MR mockups through reflection and collaboration with domain experts to harness the knowledge residing in users and their practices [3]. Based on initial insights from in-situ enactments of scenarios, we describe five areas for further AR/MR application development and research. In future research, we will thematically analyse the in-situ enactments of scenarios and semi-structured interviews to inform the development of a series of workshops to assess and explore the potentials around each identified AR/MR application area.

In conclusion, this paper outlines the value of using AR/MR mockups to collaborate with domain experts to imagine and design AR/MR applications which can facilitate more productive and efficient manufacturing practices. In exploring potential new ways of making and using AR/MR technology, we find promising pathways for Australian custom manufacturers to add value across a product's lifecycle. AR/MR has been extensively researched across the manufacturing sector [15]. However, industry examples of AR/MR use in custom manufacturing are limited. Therefore, this modest-sized case study sets out to understand current adoption challenges to support resource-constrained manufacturers to remain viable, competitive and resilient in a complex geopolitical and Industry 4.0 business environment [23].

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