Spatial Augmented Reality for Interactive Rapid Prototyping

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Abstract

This paper investigates the use of Spatial Augmented Reality for industrial design. We have implemented a prototyping system that augments low fidelity physical models with projected images. These enhanced prototypes are used to create and evaluate the design of a product. The traditional method of interactive prototyping involves building a physical model of the device with working components such as buttons. Virtual versions of these components are directly projected onto the low fidelity prototype with Spatial Augmented Reality. The user's fingers are tracked to allow interactive SAR buttons to be fully functional. This enables the user to manipulate the virtual components in real-time, saving the time and cost of manually installing them. We discuss our implementation of this prototyping system and how it integrates with the design process. In addition, we have evaluated our method of interacting with Spatial Augmented Reality prototypes. The results indicate that users can interact naturally with projected control panels, and that the system provides a useful tool for designers.

Keywords: Spatial Augmented Reality, Rapid Prototyping, Industrial Design.

Index Terms: H.5.2 [Information Interfaces and Presentation]: Graphical User Interfaces—Input Devices and Strategies; I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction Techniques

1 Introduction

We are investigating the use of Spatial Augmented Reality (SAR) for interactive rapid prototyping. This paper presents our concept for employing SAR to aid designers in the development of prototypes by advancing the detail design phase of the modelling process. We are particularly focused on developing the ability to quickly add interactive behaviour without significant time or cost investments.

Current industrial design processes are widely employed to optimize product development in automotive, home appliance, aerospace, and other industries. A strong benefit of this modern approach is the iterative aspect of the engineering, design, and construction phases. Characteristics such as aesthetics, ergonomics, and usability are addressed through several iterations to improve a product's design. Recently, 3D printing technology have been incorporated into the industrial designer's toolkit. This technology provides designers with a rapid approach for evaluating the usability and ergonomics of a design by using a tangible prototype rather than a virtual 3D model alone. This process reduces the design time, provides superior feature complexity compared to hand constructed designs, and in particular, enables the physical shape and size to be altered rapidly, allowing multiple iterations of a physical prototype to be produced.

Pugh's Total Design methodology [21] consists of six iterative stages: market (user need), product design specification, conceptual design, detail design, manufacture, and sales. Of these, we are interested in the detail design phase. The designer and client iteratively evaluate the functionality of a prototype during this process. A common part of the detail design process is to install electronics such as buttons, dials, screens, and control systems to provide the interactive functions of a device. Implementing the electronic components includes schematic design, Printed Circuit Board (PCB) layout, PCB production, and installation into the prototype. The integration of these electronic components adds time to this prototyping phase. During the industrial design process we have observed that once the electronics have been installed for functionality, the reconfigurability of the physical design is reduced. The designing, manufacturing, and installing of electronic components is costly and time consuming. Once they are manufactured and installed it is more difficult to reconfigure the physical design. If the designers are not happy with the position of a button, they must justify the time and cost involved before developing another iteration of the physical prototype with electronic parts.

This project is part of a collaboration between the Wearable Computer Laboratory and the School of Art, Architecture and De-

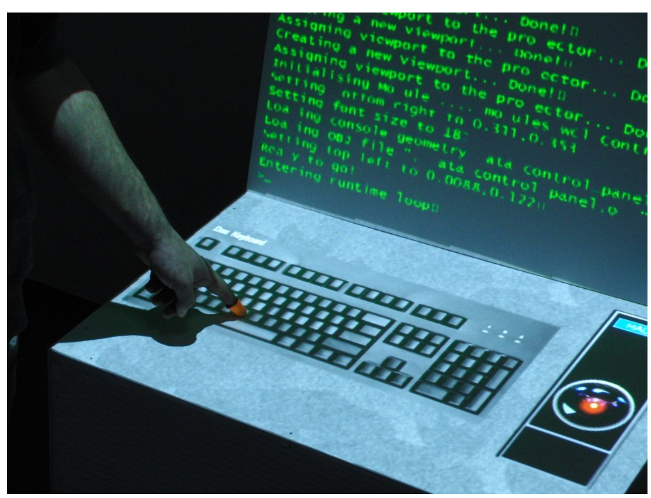

Figure 1: A user interacts with a virtual control panel. The panel is painted white, with the visual appearance and interactive functionality provided by the SAR system.

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sign at the University of South Australia on the use of SAR in the design process. Our collaborative efforts are focused on developing tools to provide interactive design functionality early in the detail design process. To achieve this, the SAR system projects the functional components such as buttons, screens, sliders, and dials onto the prototypes to provide visual feedback. These virtual components are made interactive by incorporating a tracking system and software control logic into the SAR environment. The tracking system captures a user's finger location in real-time which allows the SAR prototype (for example, Figure 1) to be used in the same manner as a prototype equipped with electronics and physical controls.

To support the process of SAR interactive rapid prototyping, there are three main artifacts to be considered: 1) the physical prototypes that designers, clients, and stakeholders can interact with and make judgments concerning the design; 2) a complete toolset to allow designers to create interactive SAR prototypes; 3) and the technology infrastructure to support the development and presentation of the SAR prototypes. This paper presents our initial implementation and evaluation of the these artifacts in order to show that the prototypes have an acceptable visual and interactive representation. We have constructed the necessary infrastructure to support the development and presentation of these SAR prototypes.

Our hypothesis is that a SAR system can be used to provide interactive rapid prototyping that is dynamically configurable and supports interactive functions. To demonstrate this, we have constructed six physical prototypes. Three incorporate electronics for their interactive functionality, and three employ a SAR environment to provide the same interactive functionality. An evaluation has been conducted to investigate aspects of the physical prototypes equipped with electronics and the prototypes that employ SAR. The goal is to see if participants can understand and interact with the SAR prototypes.

2 Background

Physical mock-ups and prototypes are an important part of the industrial design process. They allow designers and clients to grasp relationships between components of the design and test human factors that are difficult to understand from drawings and CAD models alone [9]. Hare et al. [6] further elaborate on the need for physical prototypes at various stages of a design. Four prototypes of increasing complexity were built, and an evaluation was conducted to measure users' performance in operating the prototypes. They show prototype fidelity has little effect on performance, and even low fidelity prototypes can be used to gain valuable feedback on designs. One limitation of their prototypes is that visual feedback was provided on a standard computer monitor, rather than the prototypes themselves. By using SAR projection technology, our work aims to improve the ability to rapidly and iteratively prototype not just the physical design of a device, but also the user interface.

Several toolkits have been developed for quickly creating high fidelity prototypes of physical interfaces. Phidgets [5] provide a variety of input controls and sensor modules that can be combined to create complex physical interfaces. The Calder Toolkit [12] builds on this concept with wireless input modules that can be attached to product design mock-ups. Pushpin Computing [14] provides wireless input modules that are pushed into a foam substrate, with power pins connecting to conductive planes beneath the foam. This makes the placement of the nodes very simple, but their size and shape cannot be dynamically changed. Additionally, a flat plane for the foam substrate is required, which limits their use on complex surfaces.

Spatial Augmented Reality [3] augments surfaces and objects in the physical world by projecting perspectively correct computer graphics onto them. Previous virtual reality research has shown the ability to physically touch virtual objects, and interact using physical handles can enhance the user experience [8, 31]. This is a positive finding for SAR, as the nature of the display technology requires physical objects to project onto. One potential downside to SAR is the shadows that are cast onto objects by the user. However, a study by Summet et al. [25] shows users are quickly able to adapt to occlusions. The introduction of a second projector eliminates the change in behavior users exhibit to cope with these occlusions.

Most of the SAR research is based on the concept of Shader Lamps [22]. Using calibrated projectors, arbitrary physical objects can have their appearance modified with computer graphics. Interactive Shader Lamps [2] allows a user to digitally paint onto a physical object. CADcast [18] projects assembly instructions in-situ with the components to be assembled. Laser projectors have been used for interactively programming motion paths for industrial robots [32] and marking welding points for products on a production line. SAR technology has been used to aid in medical surgery by projecting directly onto the patient [23], and as an instructional aid for learning to play billiards [24].

SAR applications have also been developed for the industrial design domain. WARP [30] uses SAR technology to allow designers to experiment with different material properties and finishes for a design prototype by projecting onto a foam model of the object. Augmented Foam Sculpting [15] allows designers to create 3D models by sculpting with foam, and uses SAR to project visualizations onto the foam. The HYPERREAL design system [7] uses SAR to emulate deformations of the surfaces of objects. The physical surface is unaffected with this technique.

DisplayObjects [1] moves from using SAR to project materials and graphics onto a physical mock-up, to projecting prototype user interfaces. DisplayObjects uses a Personal Interaction Panel [26] style interface and allows a user to place controls onto design mock-ups. While no evaluation was performed, this work shows the potential benefits of using SAR to improve the ability to iteratively design the visual aspects of the interfaces.

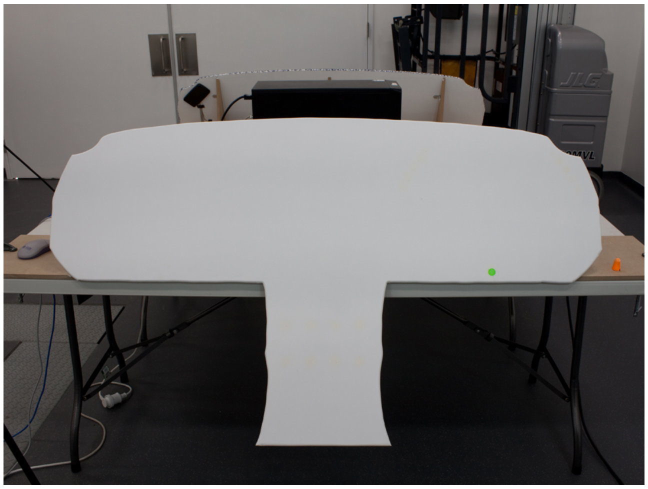
SAR applications are also related to Tangible User Interfaces (TUI). Graspable User Interfaces, as described by Fitzmaurice et al. [4], use physical handles for interacting with computer systems. This is built on investigations by Ullmer and Ishii [28], who developed physical analogues to standard graphical user interface components. TUI's have been used in applications such as urban planning [29], 3D landscape analysis [19], and for tabletop gaming [13]. Tangible User Interfaces attempt to replace virtual interaction with physical interaction. Our work is a hybrid of these two approaches. We use physical prototypes of devices, and project a virtual user interface onto them. Ideally, interacting with the interface should be the same as with a physical interface, even if the physical controls are absent.

3 Design Process, User Interface, and Environment

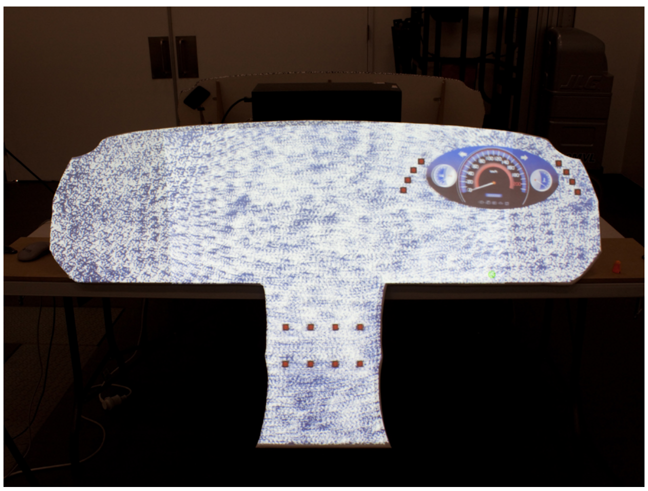
This section describes three aspects that support the use of a SAR prototyping system for the industrial design process. We first describe how the current design process has been extended through the use of SAR for iterative, interactive prototyping. Following this, we consider the interface requirements for allowing a designer to employ functional widgets in their prototypes. Finally, our large scale SAR system is described. This environment can be used by design houses for developing new concepts.

3.1 Spatial Augmented Reality in the Design Process

In the design of complex products there are many factors that need to be addressed. For example, in the design of an automotive interior, factors such as manufacturing, meeting safely standards, satisfying ergonomic constraints, styling and branding requirements need to be considered. The development of a successful design requires a balance of all of these factors. As a consequence, design



(a)



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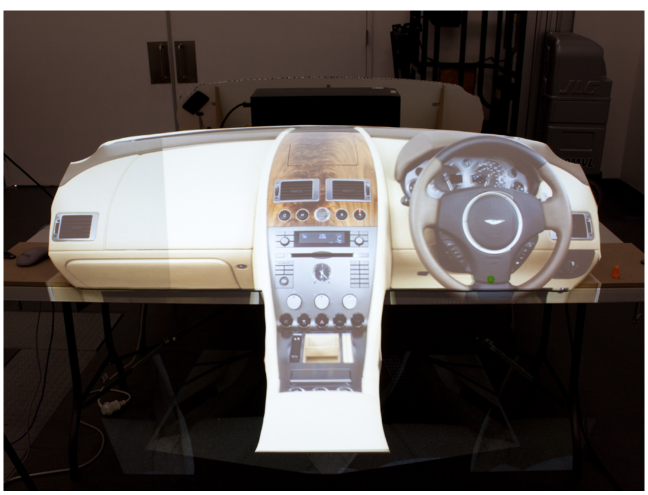


(c)

Figure 2: (a) A blank dashboard prototype that can be enhanced with SAR. (b) The dashboard prototype with a simple projected texture. (c) The dashboard prototype using a photograph to provide a fully featured projected appearance.

is a collaborative process requiring input from a range of multidisciplinary areas such as industrial designers and electrical engineers [10, 11, 17]. The coordination of these groups in creating a forum for sharing knowledge and ideas is vital to the success of the project.

The ability to make changes to the design early in the design process is beneficial, as this is the best opportunity to develop a common understanding of possible issues and make cost effective changes to the layout of components. Using traditional methods, it becomes more difficult to change the significant aspects design once prototypes are built. The advantages of using SAR in the design process are the high speed of production and low cost of development. A low fidelity model can be made from inexpensive materials in a small amount of time, so it is easy to make changes to the physical shape of the prototype at this stage in the design process.

An example of using SAR for design is shown in Figure 2. We have constructed a low fidelity model of a car dashboard which is shown in Figure 2(a). We can project components that commonly appear on a dashboard directly onto the prototype. In addition, changes to the layout of components are quick to make on a prototype enhanced by SAR. Figures 2(b) and 2(c) show different designs that can be displayed on the dashboard prototype at the touch of a button. The design in Figure 2(b) shows an early iteration of a design which is used to explore different button layouts. Figure 2(c) uses a photo (instead of a 3D model) to show a realistic car dashboard that represents what a fully featured dashboard may look like using SAR. This allows a designer and client to sit down and experience how the car will feel before a final design is manufactured. The designs shown in Figures 2(b) and 2(c) have different purposes, but both can be easily displayed with SAR.

A prototype such as the dashboard is viewed in an immersive full scale SAR environment by stakeholders to evaluate and provide feedback on the positives and problems of any proposed layout. Additional problems can be addressed at this stage, such as the arrangement and location of onboard computing or controls. As the design develops, the detail of the SAR physical and virtual models increase, and the focus changes from overall layout to detailed styling and ergonomic decisions.

As the physical form of the prototype is refined, the model develops from a low fidelity surface to a contoured body that is CNC machined. The versatility of the projection system allows appearance changes to be made and evaluated immediately in full scale by stakeholders. In conjunction with ergonomics specialists, the usability of control placements and the interaction design is evaluated and refined with a live interactive model, allowing for changes to the arrangement and functionality of components.

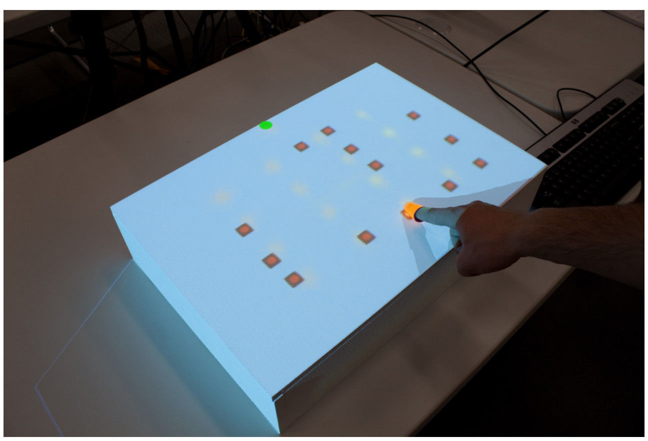
3.2 User Interface Support for the Design Process

As previously described, there are a number of design tasks that can be enhanced with our SAR rapid prototyping system. Once a designer has a physical substrate and its geometric model, the designer can dynamically develop the appearance and functionality of the prototype. One method is to develop textured skins in a traditional 3D modeling package to create a number of alternate appearances. The designer imports the geometrical model and applies the textures to the model as desired. The designer can rapidly swap between the different textures allowing a visual comparison between each design to be conducted. This functionality is a useful feature when presenting the various designs to the clients. During this process, annotations can be placed on the SAR prototype. To support this function we have previously developed a tracked stylus system [16] to allow free hand drawing on the 3D surface. These annotations can be captured and played back later as required by the industrial designer.

A second method for developing the design is to interactively

(a)

(b)



(c)

Figure 3: A user interacting with a virtual slider (a), and dial (b). A user changing the layout of several virtual buttons (c).

place and modify SAR design elements (buttons, displays, sliders, and such) onto the physical substrate. The designer is given a selection of design elements to place on the prototype. The designers may also develop their own elements with traditional graphics applications. Once placed on the prototype, editing operations such as, translation, rotation, scale and deletion can be performed. Figure 3(c) shows a user creating a custom layout for a set of buttons. The user relocates each button by dragging them with their finger. This function allows the designer to rearrange the elements as required.

Functionality of the SAR controls is activated using the finger tracking system. Designers and clients are able to operate controls on the prototype in a similar way to a traditional prototype. For example, when a SAR button is activated through touch, it can be illuminated in the same manner as a traditional backlit button to provide visual feedback. A variety of different widget controls can be implemented using this technology. To explore some of these possibilities we have implemented an interactive SAR slider (shown in Figure 3(a)) which is operated using the same technique as a physical slider. Additionally we have implemented an interactive SAR dial (shown in Figure 3(b)) that can be operated by moving your finger around the outside of the dial.

When designing large prototypes such as control rooms, the location of multiple physical objects can be changed to evaluate new layouts. Traditional prototypes support this functionality, but is also possible when using SAR projected images to enhance the appearance of the prototype. For example, consider designing three control panels that are to be positioned in a submarine. Once the features of each panel have been designed and projected onto the physical models, the client could decide that their location needs to be changed to accommodate another control panel. The SAR system supports this functionality by capturing the physical location of each model and applying the offset to the projected virtual controls. This functionality allows the client and designer to easily explore different layouts to find a desirable solution.

As the prototype design matures, its functionality is iteratively increased, providing an accessible means of testing conceptual designs without significant financial outlay. This functionality provides a very effective tool for the design process and we envision it can be extended as more widgets and features are added to the SAR design toolkit.

3.3 Spatial Augmented Reality Environment

We have an established large scale SAR laboratory in the Mawson Institute at the University of South Australia. This laboratory was custom built to provide a flexible SAR environment. The physical size of the laboratory gives designers the flexibility to work with a range of prototype sizes from small to large. The space is 14 metres long by 8.5 metres wide with a 4 metre high ceiling; a full size automobile can be driven into the laboratory and its entire surface can be enhanced using projected images. The automobile manufacturing and industrial design sectors are intended end users of the laboratory.

Flexibility is a major design feature of the laboratory. The ceiling is fitted with rigging for mounting projectors, cameras, and other equipment, with additional power and data points placed every two metres. A digital video matrix switch allows quick reconfiguration of projector and computer combinations. The new laboratory incorporates the following: forty sets of projectors with mounting systems, high powered computer systems, and an IS1200 wide area tracking system to support two people. We also use tracking software [27] provided by Simon Taylor from the University of Cambridge to track the user's fingers. The tracking software analyzes images from two Firewire cameras and reports 3D positional data of the fingers which are used to interact with the SAR prototypes. Our SAR infrastructure is built on a software framework written in C++, using OpenGL for 3D graphics, running on Linux.

4 Evaluation

We have performed a user evaluation in order to investigate our hypothesis that a SAR system is effective in supporting interactive rapid prototyping. The following sections provide the full experiment details and discussion of results. A preliminary summary of these results was previously published [20].

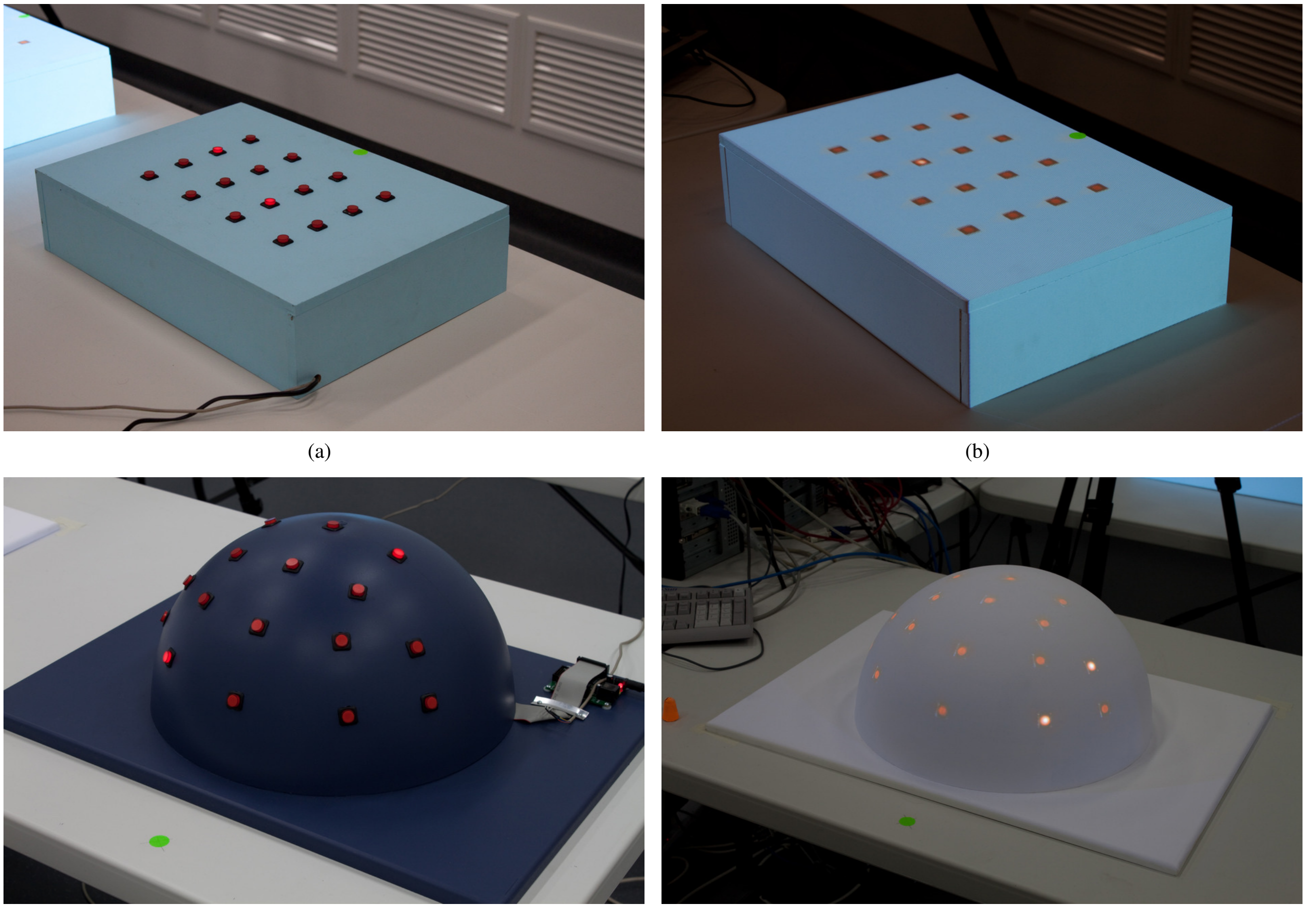

(a) (b) (c) (d)

Figure 4: (a) Physical box, (b) virtual box, (c) physical dome, (d) virtual dome.

4.1 Method

The aim of the study was to evaluate the use of SAR in creating user interface and control panel prototypes. For SAR to be a useful tool, users must clearly understand the projected graphics and be able to interact with virtual controls. To evaluate the use of SAR in place of physical prototypes in the design detail phase, we constructed physical prototypes and matching SAR versions, and compared the results of a simple task.

The experiment was a 2 x 3 repeated-measures design. The independent variables examined were interaction method (physical and virtual) and device (box, dashboard and dome). We are interested in the dependent measures of task time and button press time. Advice from the industrial design experts suggested that an increased delay for interactive components would be acceptable during operation. It was suggested that a latency of one second would not affect the understanding of the concept since they are not usually concerned with speed performance at this stage of prototyping.

4.2 Participants

Results were gathered from 24 participants comprised of students and staff at the University of South Australia and the general public. Of the participants, there were 19 males and 5 females; 2 left handed and 22 right handed; mean age 26.83 years (SD 7.60).

4.3 Apparatus

Three control panel designs were developed for the evaluation: a button box, a simplified car dashboard, and a dome. Our aim was to investigate interfaces that could not be replicated on a large touch screen. Each control panel contained 16 buttons. The box's buttons were evenly distributed in a 4x4 grid on its top face. The dashboard had two rows of buttons on the center console, with the remaining located to the left and right of the instrument panel. The seating position for the dashboard was on the right, since the study was conducted in Australia. The dome had buttons evenly distributed on its front half.

For each design, a version with physical buttons with embedded electronics was built, and a matching SAR version was created. The SAR versions have the same dimensions of the physical versions, with the details projected onto them. Participants wore an orange thimble on their index finger that was tracked to detect button presses for the SAR control panels.

The physical prototypes used pushbuttons with embedded LEDs. The buttons were controlled by an MSP430 microcontroller on a pre-made Olimex development board . Each LED and button was wired to one of the I/O pins provided by the development board. Button states were detected by the MSP430 and registered the event with the control software.

The control panel designs for the box prototypes are shown in Figure 4(a) and Figure 4(b), the design for the virtual dashboard is shown in Figure 2(b) and the design for the dome prototypes are shown in Figure 4(c) and Figure 4(d).

4.3.1 Limitations

Accurately detecting a button press using 3D tracking technology is a difficult task. Virtual button presses are detected when the user's tracked finger moves within a certain distance of the virtual button's position. This distance matches the size of the physical buttons. However, a user can inadvertently activate a button if their finger moves too close. To reduce this problem a simple de-bouncing algorithm is used. The software requires five collisions in a row before a button press is be triggered. The user must hold a button for at least 0.16 seconds before it registers. The frame-rate of the cameras also affect the quality of the tracking. If a user moves their finger too fast, the tracking software is not able to track the orange marker in the camera image. These problems could be alleviated with higher resolution cameras, or an adaptive intersection algorithm that recognized if the finger is stationary and 'close enough' to the button. Finally, there are problems inherent with attempting to use camera based tracking in a SAR environment where the object being tracked is also being projected onto. In the future we would like to investigate the use of infrared markers with the same tracking software, in the hope of improving performance.

4.4 Procedure

The evaluation consisted of six conditions, one for each control panel. The procedure for each condition was identical, and consisted of the following:

1. Participants began with their finger resting at a home position, identified by a green circle in front of the control panel.

2. Two buttons on the control panel would activate. One of these would flash repeatedly, and the other glowed solidly.

3. The participant pressed the flashing button, then the remaining illuminated button, then returned their finger to the home position.

4. The system would pause for two seconds.

5. Steps 2-4 were repeated for a total of eight training button pairs. Data from these training pairs was discarded.

6. Steps 2-4 were repeated again for a total of 32 additional button pairs where data was collected.

The order of control panels was randomized for each participant to compensate for any learning effects. All participants received the same button pairs, but in a different order. This was done to ensure participants had to move their hand the same distance to reach the buttons, and times could therefore be meaningfully compared.

Participants used their dominant hand to press buttons on the box and dome control panels. All participants were required to use their left hand for the dashboard so they could reach all the buttons comfortably. Participants were seated for the dashboard and dome, and standing when operating the box prototypes.

Training sessions for each condition took approximately one minute, with the data collection at each control panel taking approximately three minutes. An overall experimental session lasted approximately 40 minutes.

4.5 Data Collection

For each button pair, the time between button presses was recorded, as was the total time taken to complete each condition. The operation of each condition was automated by a control program. Once a participant had completed all six conditions, they completed a questionnaire asking about their experience operating each of the prototypes.

Table 1: Total task completion time

	Mean	Std. Dev.	Min.	Max.
Physical Box	114.15	8.17	104.66	135.91
Virtual Box	184.17	26.98	147.93	246.01
Physical Dashboard	130.72	10.02	117.84	159.22
Virtual Dashboard	182.38	31.19	139.15	252.46
Physical Dome	119.13	9.85	107.79	147.32
Virtual Dome	181.68	33.92	134.94	283.68

Table 2: Mean button press times

	Mean	Std. Dev.	Min.	Max.
Physical Box	0.47	0.10	0.34	0.68
Virtual Box	1.38	0.27	0.83	1.91
Physical Dashboard	0.59	0.09	0.44	0.73
Virtual Dashboard	1.32	0.33	0.82	1.90
Physical Dome	0.54	0.12	0.40	0.80
Virtual Dome	1.37	0.33	0.72	2.15

5 Results

5.1 Quantitative Results

The total time for each condition was taken from the first correct button press to the last. This measure includes the two second delay between each pair of buttons. The mean total time across all six conditions was 152.04 seconds (SD 38.41). The physical control panels had a mean total time of 121.33 seconds (SD 11.60), while the virtual control panels had a mean total time of 182.74 seconds (SD 30.41). The mean total times for all conditions are listed in Table 1.

In ANOVA (Analysis of Variance) models, we determined the following: there was a significant effect from interaction method on total task time, $F(1,23) = 234.65$, $p < 0.05$. The results show that total task time was not significantly affected by device, $F(2,46) = 2.26$, $p > 0.05$. There was no significant interaction effect between interaction method and device on total task time, $F(2,46) = 3.12$, $p > 0.05$.

The time between button presses was recorded for each button pair (see Table 2). The mean button pair time across all control panel configurations was 0.94 seconds (SD 0.47). For all physical control panel configurations, the mean button pair time was 0.53 seconds (SD 0.11). The mean button pair time for all virtual control panel configurations was 1.35 seconds (SD 0.31).

In ANOVA models, we determined the following: there was a significant effect from interaction method on mean button pair time, $F(1,21) = 263.49$, $p < 0.05$. The results show that mean button pair time was not significantly affected by device, $F(2,42) = 0.42$, $p > 0.05$. There was no significant interaction effect between interaction method and device on mean button pair time, $F(2,42) = 2.97$, $p > 0.05$.

5.2 Qualitative Results

Each participant answered a questionnaire after completing all six conditions. Four common questions were asked for all six prototypes. Responses for each question were on a 5 point Likert scale (5 Agree - 1 Disagree).

Table 3: Mean scores for questions 1, 2, 3 and 4

	Physical Box		Virtual Box	
	Mean	Std. Dev.	Mean	Std. Dev.
Q1	4.95	0.20	4.71	0.46
Q2	4.83	0.38	4.46	0.72
Q3	4.96	0.20	2.83	1.05
Q4	4.88	0.34	4.13	1.12

	Physical Dashboard		Virtual Dashboard	
	Mean	Std. Dev.	Mean	Std. Dev.
Q1	4.88	0.34	4.54	1.02
Q2	4.29	0.81	4.46	0.66
Q3	4.88	0.61	3.29	1.27
Q4	4.92	0.28	4.50	0.83

	Physical Dome		Virtual Dome	
	Mean	Std. Dev.	Mean	Std. Dev.
Q1	4.92	0.28	4.54	0.72
Q2	4.63	0.88	4.46	0.88
Q3	5.00	0.00	2.96	1.12
Q4	4.88	0.34	4.33	0.92

The questions 1, 2, 3, and 4 are as follows:

Q1 I could easily identify the buttons on the <device>
Q2 I was able to easily tell which buttons I needed to press
Q3 The system was quick to detect which buttons I was trying to press
Q4 The lighting conditions were satisfactory

The participants indicated that visually (Q1, Q2, Q4), in all six conditions it was easy to identify the buttons, tell which button needed to be pressed, and that the lighting conditions were satisfactory. As supported by quantitative data, the participants felt the physical devices were quick to detect which buttons were pressed (Q3). Table 3 shows that the physical devices were perceived to be able to quickly detect a button. For the virtual devices, the participants did not perceive the detection to be quick or slow. The mean scores for Questions 1, 2, 3 and 4 are shown in Table 3.

The questions 5, 6, and 7 were asked for the virtual prototypes only and are as follows:

Q5 The lack of physical buttons did not affect my interactions with the virtual <device> prototype
Q6 The shadows did not affect my interactions with the virtual <device> prototype
Q7 The virtual <device> prototype closely resembled the physical <device> prototype

Question 5 explores the passive haptic nature of the SAR surfaces emulating a pushbutton. About two thirds of the participants felt the passive haptics were sufficient for the tasks required of them, and around one third reported that not having a physical button affected their interactions. The result for Question 6 indicates the shadows caused by the projectors did not adversely affect the participants' actions, while the result for Question 7 supports our premise of SAR providing good visual representations of the physical device. Although not a perfect replication of a physical pushbutton, our results support that this form of interaction provides a useful mechanism for rapid prototyping of physical devices. The mean scores for Questions 5, 6 and 7 are shown in Table 4.

Table 4: Mean scores for questions 5, 6 and 7

	Virtual Box		Virtual Dash		Virtual Dome	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Q5	3.67	1.17	3.63	1.35	3.79	1.35
Q6	4.13	1.12	4.50	0.83	4.33	0.92
Q7	4.13	1.15	4.46	1.14	4.21	1.18

6 DISCUSSION

The results show that our SAR prototyping system is usable as a tool to assist designers. The users were able to understand what they were interacting with and they were able to interact with the buttons in a timely manner. This shows that designers can create an interactive prototype with understandable components.

The system described is useful for presenting a concept to a client or a stakeholder. Participants are able to interact with controls that are projected onto the prototype. Firstly, every participant was able to complete the task. This shows that the system is usable. Although the results show that there is a slight delay when interacting with a virtual button compared to a physical button, this did not adversely affect the user's ability to understand and complete the required tasks. On average the difference between the response times is less than one second. These SAR prototype devices are not designed for precise human factors evaluations, but they are intended to aid people in understanding the visual and interactive components of a design. Although the delay of the SAR system is greater compared to the physical prototypes, this will improve with better tracking technology. We have also informally discussed the use of SAR prototypes with ergonomic experts and they have suggested that it is promising for measuring certain fatigue factors. The evaluation clearly demonstrated this capability.

SAR prototyping also provides a reduction in the time it takes to design a device. For example, we built two prototype dashboards for this evaluation, one with physical buttons and the other for SAR projection. We were able to design and build the dashboard shape out of MDF in two days each. One of these was then painted with a textured color and had push buttons and a control system installed. The other was painted matte white ready for SAR projection. The simple white prototype took two days to construct compared to the one fitted with electronics which was built in five days. This method of developing and evaluating integrates well with Pugh's Total Design methodology. In particular, the SAR prototyping system is well suited to the details design phase. The users can also evaluate the design of these interactive prototypes. This could be useful for client or stakeholder meetings where the designer can change the layout of the components based on the input from other parties.

6.1 Participant Feedback

Common suggestions from participants included a need for additional feedback for the virtual buttons. Many users had trouble determining if they had successfully pressed a virtual button. The only feedback provided in the evaluation was visual feedback. If the correct button is pressed, the light turns off. Since the button light flashed every 400ms, users sometimes moved their finger away from the button prematurely. They assumed that the button light had been switched off, when it was actually still flashing.

Several participants suggested that audible feedback would be useful to determine if they had successfully pressed a virtual button. One participant also suggested to highlight around a pressed button as a form of visual feedback. This could be useful for small components, since a user's finger can occlude the component that they are operating.

7 Conclusion

We have presented a technique that supports the industrial design process by allowing re-configurable interactive functionality for use with the detail design phase of Pugh's Total Design methodology. The SAR system presented allows designers to implement interactive functionality before electronics are incorporated into their prototypes. The interactive functionality aspect of the SAR system has been evaluated. We have demonstrated that with our current technology performance, clients can evaluate the interactive aspects of a prototype allowing them to contribute and change the design. The performance of the virtual controls is currently slower compared to the physical console (mean: 1.35 seconds compared to 0.53 seconds respectively). Although slower, this was a positive result as it is considered suitable performance for a prototype in the earlier design phase. Also, for the purposes of evaluating a prototype before the electronics are integrated there are two advantages that make SAR useful for prototyping. Firstly, designers are able to maintain a rapid iterative process with interactive functionality, and secondly, once the initial environment is setup the cost and time required for design using SAR is reduced compared to reproducing new electronics for a prototype.

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