

# Validating Constraint Driven Design Techniques in Spatial Augmented Reality

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## Abstract

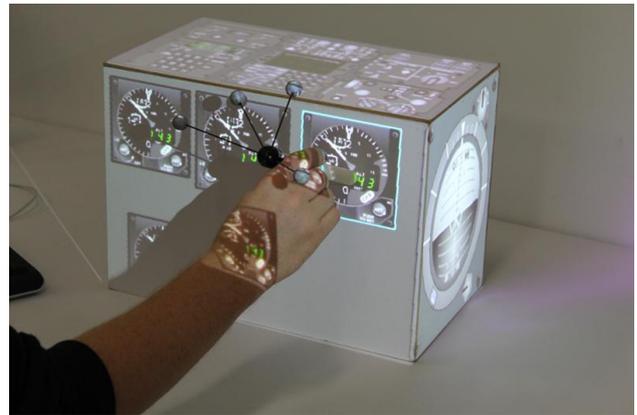
We describe new techniques to allow constraint driven design using spatial augmented reality (SAR), using projectors to animate a physical prop. The goal is to bring the designer into the visual working space, interacting directly with a dynamic design, allowing for intuitive interactions, while gaining access to affordance through the use of physical objects. We address the current industrial design process, expressing our intended area of improvement with the use of SAR. To corroborate our hypothesis, we have created a prototype system, which we have called *SARventor*. Within this paper, we describe the constraint theory we have applied, the interaction techniques devised to help illustrate our ideas and goals, and finally the combination of all input and output tasks provided by *SARventor*.

To validate the new techniques, an evaluation of the prototype system was conducted. The results of this evaluation indicated promises for a system allowing a dynamic design solution within SAR. Design experts see potential in leveraging SAR to assist in the collaborative process during industrial design sessions, offering a high fidelity, transparent application, presenting an enhanced insight into critical design decisions to the projects stakeholders. Through the rich availability of affordance in SAR, designers and stakeholders have the opportunity to see first-hand the effects of the proposed design while considering both the ergonomic and safety requirements.

**Keywords:** Industrial Design Process, Spatial Augmented Reality, Tangible User Interface.

## 1 Introduction

**The Industrial Design Process,** Traditionally, the industrial design process involves six fundamental steps, providing guidance and verification for performing a successful product design (Pugh 1990). These steps guide the design process from the initial user needs stage, assist in the completion of a product design specification (PDS), and onwards to both the conceptual and detail designing of the product. When the product is at an acceptable stage, which meets all the requirements set out



**Figure 1: The combination of SAR with a TUI to provide an interactive workflow for use within the design stages of the current industrial design process.**

within the PDS, the process follows on into manufacturing and finally sales.

This incremental development process encourages total design, a systematic activity taking into account all elements of the design process, giving a step-by-step guide to evaluating and producing an artefact from its initial concept through to its production. Total design involves the people, processes, products and the organisation, keeping everyone accountable and involved during the design process (Hollins & Pugh 1990). Each stage of the process builds upon knowledge gained from previous phases, adhering to a structured development approach, allowing for repetition and improvements through the processes. This methodology of total design shows what work is necessary at a particular point within the stream of development, allowing a better-managed practice to exist. During each stage, stakeholders within the project hold meetings reviewing the goals and progress of the project. These meetings allow a measurement of success by comparing the current work with the initial system's goals and specifications. These reviews allow for early detection of design flaws and an opportunity for stakeholders to raise concerns based on outside influences.

Throughout the development cycle of the product, the PDS is used as the main control for the project. As the product moves through each phase, the PDS evolves with new information, and changes to the original specifications. This process has been widely employed and a proven effective practice for producing designs, however the opportunity for collaborative, interactive designs are not available until the later stages of the

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process flow, after a majority of the underpinning design decisions have been decided upon.

**Augmented Reality**, is an extension to our reality, adding supplementary information and functionality, typically through the use of computer graphics (Azuma 1997). Generally AR is confined to projections through either headsets or hand-held screens. Spatial Augmented Reality (SAR) is a specialisation of AR where the visualisations are projected onto neutral coloured objects by computer driven projectors (Raskar, R. et al. 2001). This variant in design compared to the more traditional means for visualisation allows the viewer to become better integrated with the task at hand, and less concerned with the viewing medium. Due to SAR's rich form of affordance, special consideration is needed to allow for the effective utilisation of interaction techniques within the setting.

Tangible User Interfaces (TUI) are concerned with designing an avenue for interaction with augmented material by providing digital information with a physical form (Billinghurst, Kato & Poupyrev 2008; Ishii & Ullmer 1997). The goal is to provide the users of the system physical input tools, which are both tangible and graspable, to interact effectively and subconsciously with the system as if it were ubiquitous in nature. Previous efforts have been conducted in combining TUI and SAR technologies to benefit the outcome of the research (Bandyopadhyay, Raskar & Fuchs 2001; Marner, Thomas & Sandor 2009; Raskar, Ramesh & Low 2001).

**Collaborative Tools**, Previous work has been investigated into utilising SAR as an interactive visualisation tool for use during the design phase of the design process (Akaoka, Ginn & Vertegaal 2010; Porter et al. 2010). Currently, this research consists of the arrangement of pre-determined graphics within the SAR environment. SAR itself is not currently involved in the actual design process, only being utilised as a viewing medium, with all prototyping being done at a computer workstation before being transferred into the SAR environment. Interactions with these systems were pre-defined, only allowing a constant but repeatable interaction to take place.

Current detail design offers either flexibility or affordance, but not both at the same time. Flexibility is offered using a computer aided drawing package, allowing changes to texturing, detailing, and layout through the click of a button. Being computer generated however the model only exists within a two dimensional space on a monitor. Affordance is available through the creation of a physical model, which can be detailed up to suit, however this avenue does not offer for quick modification of textures and layouts. Using SAR as the visualisation tool offers affordance, but thanks to the visual properties being produced by a computer, flexibility is also available to alter and amend the design in real-time.

The means for interaction with the virtual world through physical objects is accomplished through a TUI. Tangible, physical objects (sometimes referred to as phicons), give users the avenue for interaction with augmented elements.

TUI have been used by both Marner et al. (2009) and Bandyopadhyay et al. (2001) to allow for the dynamic drawing of content within a SAR environment. Both examples allowed live content creation through the use of tangible tools. These examples present an opportunity for further investigation into SAR being used as more than solely a visualisation tool.

### Contributions

- We provide new techniques for introducing constraint based design primitives within a SAR environment. Our ideas aim to provide designers with an avenue for direct interaction with the physical projection prop, allowing for an intuitive means for performing the work.
- We present a tangible toolkit for allowing the designer to perform both selection and manipulation of projected content, the addition of shape primitives and constraints between primitives within a SAR environment.
- We provide a validation of our work using SAR as an architectural / industrial design tool. This validation has allowed us to highlight key areas where SAR offers valuable areas of utilisation within the current industrial design process.

## 2 Related Work

Augmented reality has grown to involve many varying areas of study, all actively pursuing advancements within the field. Industrial Augmented Reality (IAR), a particular area concerned with the improvement of industrial processes attempts to provide a more informative, flexible and efficient solution for the user by augmenting information into the process (Fite-Georgel 2011). This inclusion intends to enhance the user's ability to produce quality and efficient work while minimising the disruption on already implemented procedures. Early Boeing demonstrated this benefit by creating an AR tool to supplement their installation of wire harnesses in aeroplanes (Caudell & Mizell 1992; Mizell 2001).

Prior to the aid of augmented instructions, workers would need to verify the correct wiring layout from schematic diagrams before performing their work. The diagram would only provide the start and end points for the wire, with the worker required to work out their own route across the board. This would then result with inconsistent installations of wiring across varying aircraft, dependent on which engineer performed the wiring. By introducing AR instructions to the workers process, uniform routing would be performed by all engineers, standardising the wiring across all aircraft while also allowing the isolation of the particular wire being routed, removing cases where non-optimal routing were performed. This improved the current installation process while also having an effect on the repairing process, contributing to an easier framework to be followed if any issues arose down the track (Caudell & Mizell 1992; Mizell 2001). Further work has continued this approach into augmenting instructions into the worker's work process (Feiner, MacIntyre & Seligmann 1993; Henderson & Feiner 2007). The ARVIKA project has

also demonstrated a strong focus towards the development, production and service of complex technical products through its AR driven applications (Friedrich 2002; Wohlgenuth & Triebfurst 2000)

Examples of current research in industrial AR show a general direction towards providing an information rich solution for workers carrying out their respective roles. With any emerging technology from an industrial perspective, the solutions need to be financially beneficial, scalable and reproducible in order to become a part of daily processes (Fite-Georgel 2011).

Current IAR uses either video or optical see-through HMD's or video screen based displays. Another area of AR which shows promise to industrial application is spatial augmented reality

Raskar et al. (1998) highlighted the opportunity of superimposing projections, with correct depth and geometry, of a distant meeting room onto the surrounding walls, where people within each room would experience the two meeting rooms as one large collaborative space. This idea spawned the current field of SAR; using projectors to augment information onto surrounding material removing the intrusiveness of a hand-held or head-worn display.

Currently, prototyping within SAR consists of the arrangement of pre-determined graphics or free-hand modelling (Bandyopadhyay, Raskar & Fuchs 2001; Marnier, Thomas & Sandor 2009; Raskar, R. et al. 2001). Prototyping is generally done on a computer screen and then transferred into the SAR environment as a method of visualising the final design. The actual design phase exists outside of the SAR environment.

The goal of tangible bits (Billinghurst, Kato & Poupyrev 2008; Ishii 2008; Ishii & Ullmer 1997) is to bridge the gap between the digital world and the world that we exist in, allowing the use of everyday objects as a means to interact with the virtual world. Tangible user interfaces attempt to make use of the rich affordance of physical objects, using their graspable form as a means for interaction with digital content. The human interaction with physical forms is a highly intuitive interface, removing the need for displays to see-through, buttons to press and sliders to move (Raskar, Ramesh & Low 2001).

The metadesk allowed the control of virtual content through the use of phicons (physical icons) within the physical space (Ullmer & Ishii 1997). Ishii also developed the Urban Planning Workbench (URP) to further emphasise the concepts behind a TUI. In this scenario, phicons were used to depict buildings, with projections showing the effects of weather, shadowing, wind, and traffic congestion from the phicon positions (Ishii 2008).

Combining the use of TUIs within a SAR environment has given the idea of using the two tools together as a means for aiding the design process, allowing designers to partake within a collaborative prototyping environment (Akaoka, Ginn & Vertegaal 2010; Porter et al. 2010).

Constraint driven modelling is a key area in industrial design, conforming a design to uphold required

dimensional and neighbouring constraints (Lin, Gossard & Light 1981). Constraints allow "rules" to be introduced into a design so that the fixed parts of the design are locked. This allows the user to be creative in the areas they can be without violating design requirements. Applying the key ideas of a constraint driven model user interface into a SAR environment would provide a designer with an enhanced experience.

Three dimensional co-ordinate constraints should allow both implicit and explicit constraints to be viewed within the design. Lin, Gossard & Light (1981) devised a matrix solution to uphold these neighbouring constraints within a three dimensional space. By introducing relationships between constraints, a designer would be able to follow a set of 'rules' which upheld the design requirements.

The city planning system (Kato et al. 2003) devised an AR table-top design, using head-mounted displays, to view the results of placement of architectural components. The designer could place components across the site, rotating, scaling and moving them about until an acceptable solution was found. The design session however did not cater for any relationships between elements positioned within the system. Planning systems should implement constraints to disallow elements from being constructed in close proximity to certain landmarks or other placed components.

Spatial augmented reality systems have been produced where designs could be projected onto their physical sized prototypes (Akaoka, Ginn & Vertegaal 2010; Porter et al. 2010). These demonstrations showed the power of SAR as a viewing medium. These designs however constrained the user to only pre-determined interactions with the content.

Free-hand modelling has been demonstrated as a means for interaction with SAR material (Bandyopadhyay, Raskar & Fuchs 2001). Physical, tangible tools have given the user the ability to paint onto the representation (Marnier, Thomas & Sandor 2009). The use of a stencil to mask parts of the model gives the user a higher accuracy with achieving desired results. The placement of the stencil however is still free-hand, and does not rely on any constraints for use.

Previous research has shown promise in merging SAR with the design process (Porter et al. 2010). By introducing a physical design which incorporates interactive content, quick modifications can be applied to gain further understanding and knowledge to potential design choices. Our investigations extend this research by bringing the design aspects into the SAR environment, bringing with it opportunities for designers to make amendments during the visualisations. SAR is a powerful visualisation tool which allows collaboration with affordance. The goal of this research is to show that SAR can also improve the design process by using an intuitive interaction metaphor to allow SAR to become the design setting itself.

### 3 Implementing our SAR based approach

The prototype has been designed to explore the potential behind utilising SAR as a design tool during an industrial

designer's process. To allow this examination, the solution incorporates the use of a SAR prototyping system, a tangible user interface, involving a toolkit of designing markers, and some simple geometric constraints to apply dynamically into the SAR scene. The TUI is tracked using an optical tracking system, allowing continuous knowledge of all tangible markers in use within the design area. The design session is explored by allowing the user to dynamically alter the physical position of projected content across the physical prop through the use of our TUI, while also allowing the application of geometric constraints between selected objects. This section describes the design of our system, breaking down the computer driven aspect of our solution. The following section details our tangible user interface techniques.

The system has been designed in a modular fashion, allowing blocks of constraints to be applied to expand the functionality. The construction is essentially divided into three stages:

**Constraint Logic:** This incorporates our application of constraints. Our constraints utilise vector floats, allowing the use of vector maths for calculating varying geometric measurements within our design scene. This stage considers the implementation of each constraint, and how the combination of their effects will be handled by the system.

**Scene Logic:** This area involves the ideas presented in Shader Lamps (Raskar, R. et al. 2001), involving the creation and application of textures, colours, and physical models into the scene. The scene logic also applies the calibrations between projectors, physical models and tracking software, aligning all coordinate systems.

**Tangible Interaction:** This stage involves the design and implementation of a tangible user interface, to allow an intuitive avenue for designers to access both the dynamic selection and alteration of projected content. The interactions can only be fine-tuned after the scene logic has been prepared and configured, requiring a calibration between tracked and projector coordinate systems.

### 3.1 Constraint Logic

The following section will provide an outline of our proposed constraints, and the vector maths involved to produce our results. Due to the complexity of producing an exhaustive computer aided drawing functioning system, some limitations were decided upon to better serve our exploration of the proposed amendments to the design process. We limited the inclusion of four

constraints; distance, angle, parallel, and grid, with each constraint being limited in application to a set number of objects.

As discussed earlier, all of our constraint logic is based on vector geometry. This design choice allows access to an abundant amount of vector theory for calculating distances, rotations, relationships in three dimensions. We utilise a three element vector for both location and directional properties of all projected content.

Information formulas allow the designer to gain an understanding of the current layout of the scene. The distance knowledge tool would allow the designer to learn the physical distance between two elements within the scene. Likewise, through the use of the angle knowledge tool, the designer would be granted the knowledge of the internal angle between three elements.

Change formulas utilise user input to alter the physical layout of the scene. To alter the distance between two elements, the designer would first select two elements, apply the distance constraint, and enter the required distance. This sequence of events would result in the objects moving the required distance apart.

Distance is an important facet to a designer, as it describes the positional relationships between elements in a scene. The role of distance can be used to determine the space between two objects, the length of a line, or the distance between a line and object. To determine the distance between two points, the two known positions are plugged into equation 1. The returned value is a float describing the distance between the two points.

$$|xyz| = \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2} \tag{1}$$

To illustrate our design solution, we also have allowed the changing of distances between elements. We have implemented this in an 'as is' basis. We initially calculate the current trajectory between elements A and B as seen in equation 2.

$$\vec{AB} = B - A \tag{2}$$

This direction is then used within equation 3, along with the designer's input distance, to provide a new point the required distance away from point A.

$$B(origin) = A(origin) + distance * \frac{\vec{AB}}{|\vec{AB}|} \tag{3}$$

The parallel constraint is described in Figure 2. The first row in the hierarchical table allows parallelisation on an arbitrary axis, rather than constrained to either X, Y or Z planes. The parallel tool will always conform the

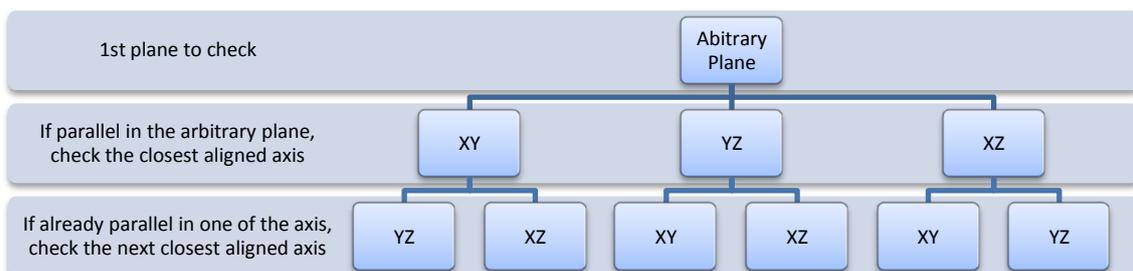


Figure 2: Parallel constraint logic flow

$$\begin{pmatrix} t * up[x] * up[x] + c & t * up[x] * up[y] - up[z] * s & t * up[x] * up[z] + up[y] * s \\ t * up[x] * up[y] + up[z] * s & t * up[y] * up[y] + c & t * up[y] * up[z] - up[x] * s \\ t * up[x] * up[z] - up[y] * s & t * up[y] * up[z] + up[x] * s & t * up[z] * up[z] + c \end{pmatrix} \quad (4)$$

projection objects exist on the face of the projection prop using the up vector, before checking further planes for parallelisation. After each application, the tool will apply the next closest axis for parallelisation; however this will not be completed if the resulting constraint moves both objects to the same point in space.

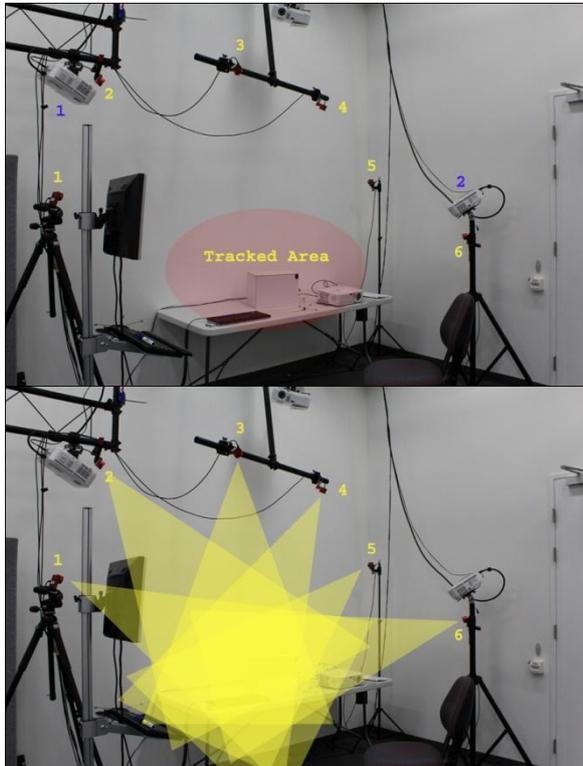
To learn the inner angle between two lines, or three objects, a dot product can be applied to the two known vectors. For the case of objects, vectors b and c are the direction vectors (equation 2) between shapes AB & AC. By plugging these two vectors into equation 5, the returned value is given in radians, requiring a conversion to degrees for use by the designer ( $radians \times \frac{180}{\pi}$ ).

$$\vec{b} \cdot \vec{c} = |\vec{b}| |\vec{c}| \cos(\theta) \quad (5)$$

$$\vec{up} = \vec{AB} \times \vec{AC} \quad (6)$$

$$\vec{c} = R \times \vec{b} \quad (7)$$

To provide the same functionality to the designer as provided with the distance constraint, a change constraint is also provided for use. Our implementation uses a rotation matrix to allow for the change of an inner angle between projection elements. The matrix, as seen in (4) is 3x3 and uses values determined by the input user angle. The chosen angle is converted to radians (from degrees) and is used to produce both c (cosine\*angle) & s (sine\*angle).



**Figure 3: The tracked workspace, illustrating projector and optiTrack camera layouts.**

The value t is the remainder of c subtracted from 1, while up represents the up vector of the plane of objects (calculated through the cross product of vectors b & c (equation 6)). This matrix is produced and then multiplied against vector b, to produce a new vector c (equation 7).

### 3.2 Scene Logic

The implementation of our prototype system incorporates the use of 2 x NEC NP510WG projectors to provide a complete coverage of all prop surfaces. Our tangible input tools are tracked in the working area by 6x OptiTrack Flex:V100R2 cameras. The TrackingTools software generates 6DOF coordinates for each tracked object, and sends the information across the network within VRPN packets. The SARventor system then converts each received message on an object basis into projector coordinates and applies the required alterations. Our prototype is run in OpenGL within the WCL SAR Visualisation Studio, making use of a single server containing 4 x nVidia Quadro FX3800 graphics cards. Our physical prop is created in a digital form and loaded into the SARventor framework. The digital vertices of the model are used to assist in complying constraint logic with the physical representation of the model

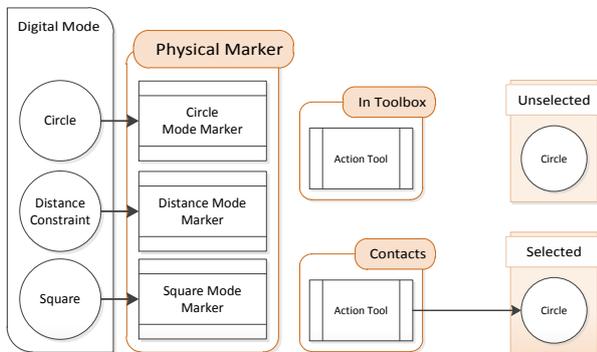
### 3.3 Tangible Interaction

With the motivation of this research aiming to create a design solution, which will allow designers to adaptively create a visual design within a SAR environment, our tangible user interface has been constructed with an aim to allow free-hand movement whilst also allowing the rigid application of constraints into the scene. The TUI will remove the need for a keyboard as the primary source of interaction, while still allowing further development and additions to take place.

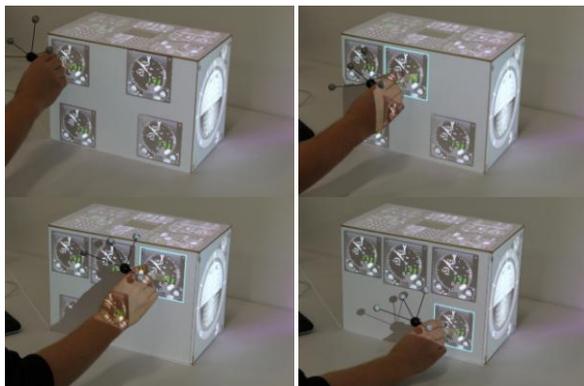
During the development of the interface, a number of requirements were deemed necessary to achieve our goals. The requirements are based around the interactions within each varying mode, also considering the numerical data entry for constraint values. Most desktop applications are touted as having an easy to use and intuitively designed interface for user interaction. This key area of design will ultimately impact largely on the users' experience of the system. Over the years, a considerable amount of research has been conducted into investigating various approaches of user interaction within three dimensional spaces (Bowman et al. 2005; Forsberg et al. 1997; Ishii & Ullmer 1997). Although within a three dimensional space, the visual experience can vary considerably, the underlying principles of an interface are present regardless of the medium. For this reason, it is essential to the goals of the system that an interaction paradigm be selected which both presents a suitable application to the design while meeting performance measurements.

By creating a three dimensional user interface, inherent characteristics can be utilised to better provide a collaborative experience. The solution uses the mental model from many fundamental 'hands-on' trade occupations, using a toolbox approach for all the interface tools. Within a designer's toolbox, individual jobs require particular tools. By removing a single point of contact, multiple interaction points between the user and the system can exist concurrently. Just as a carpenter would carry a hammer, nail and ruler within their toolbox, we foresee a designer having tools which offer the same variety of needs. By considering the most important facets of a design solution, we categorised our tangible markers into three varying functions; Mode markers, Action markers, and Helper markers.

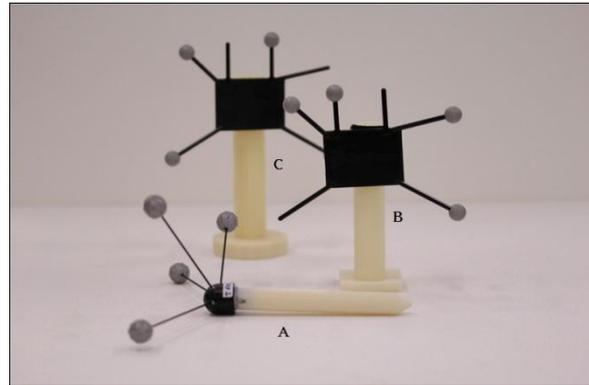
Mode markers are the most abundant tool. We use the term *mode* to describe this group of markers because of their singular functionality. Each different function is digitally assigned to an individual mode marker (Figure 4). Mode markers are executed by stamping them onto the physical prop. Each successful stamping would result in the execution of the digital representation of the marker. Action markers are our primary interaction marker within the setting, controlling the selection and manipulation of content within the scene (Figure 4). Helper markers are essentially action markers, but provide additional functionality when combined into the setting with another action marker. This would allow rotation or scaling to be done without needing to grab a special tool, as required by our mode markers.



**Figure 4: Digital representations of our TUI (left) and Action Tool functionality (right)**



**Figure 5: Selection and Manipulation**



**Figure 6: Our Tangible markers. Action marker (A) distance constraint mode tool (B), circle mode tool (C)**

Our tangible markers are displayed in Figure 6. Each marker has optical balls attached to allow tracking by our tracking system. Our action marker is designed like a stylus, drawing upon known mental models from touch screen devices. An example of our action marker in use can be seen in Figure 5, where a user can select and manipulate projected content through a point and drag technique. Our mode markers are designed like a stamp, with a larger handle for easier grasping, again drawing upon a known mental model. Each mode marker is physically designed to assist the user in visually recognising their digital representations. Our distance mode tool has the letter 'D' moulded to its base, while the circle mode tool is shaped like a circle.

#### 4 Expert Analysis

A qualitative review process was conducted with three experts within the area of architecture and industrial design who were not involved in the research. Each reviewer has over ten years experience within his or her individual areas of expertise. The review was conducted using an interrupted demonstration of our SARventor prototype system. The process that was adopted was to provide a theoretical background of the work, before moving onto an interactive demonstration of the system. Interruptions and questions were encouraged throughout the process to ensure that first impressions were recorded.

Three examples were demonstrated to encourage a broad understanding of the applicability of our system, and its potential uses in the industrial design process.

##### Texturing:

The first example provided an illustration to the power that SAR offers through its visual and physical affordance. Changes to both colour and textures can be quickly altered to allow fast and effective visualisations of potential colour schemes. Each colour and texture was demonstrated to the experts, giving a baseline understanding of the visual properties that SAR offers.

##### Tangible User Interface:

The second example explained our TUI, demonstrating both selection and manipulation with our action marker, illustrating our proposed interaction techniques. This example also exemplified our proposed interaction with mode markers, allowing quick and easy addition to primitive shapes onto the model. Each use case was

demonstrated, giving the expert reviewers an understanding of our proposed interaction metaphors.

#### Constraints:

Our final example made use of both previous examples to show an example for applying geometrical constraints between projected elements on our physical prop. This allowed a simple scenario of a very simple design begin to grow through the placement and constraining of projected content.

The demonstrations were provided to give the reviewers a wide understanding of our implementation. The information provided was practical in nature, with an emphasis on the resulting discussion on how particular elements would be affected by particular scenarios. Essentially, the prototype was used as a springboard to further discussion on more advanced elements, and the resulting repercussions from chosen design characteristics.

At the conclusion of our review session, a discussion was held on our proposed amendments to the current Industrial design process. During this time, the reviewers were given free use to experience our prototype. A particular emphasis was given on the areas where we foresaw an improvement through the use of SAR, allowing greater affordance to designers through the use of a physical prop. Our proposed improvements were relayed in questions, encouraging a detailed response from each reviewer's opinions, allowing for an opportunity to discuss areas which were not considered by the researchers.

## 4.1 Results

Reviews show that our SAR based approach does offer an opportunity to be leveraged into the current design process. The initial use for the prototype being aimed around the designer was seen as potentially viable, however the use of a computer was seen as an integral part of our reviewers work, with the ability to manage designs and models. Allowing models and parts to be dragged across into the design was seen as an important feature to help streamline the use of SAR into their current workflow. They felt that there was no need to completely remove the computer from their workflow, and were happy to conduct some of their work on a computer workstation.

The idea of being able to visually organise a design with the affordance of SAR was intriguing to the reviewers however the lack of a visible toolkit was noted as a problem. The issue with a menu based approach in a 3D environment requires it to exist either on the tabletop or on the floor around the design medium. It also raises further issues with orientation, and whom it should orientate towards.

The biggest limitation with the proposed SAR based approach was its inherent property of being a surface based medium. Both the user interface and the design space were inherently attached to a surface, disallowing the true manipulation of volume. This was seen as an issue with certain design cases, and areas of use within the design process.

It was agreed however that SAR itself is not a tool to replace current applications within the industrial design process, but to complement them instead. By looking beyond the designer as the sole user of our SAR based approach, further opportunities arise.

Allowing dynamic alteration of content during meetings, and allowing the annotations of reasoning for the changes would allow SAR to become much more than just a tool for designers to utilise, it would become a marketing medium to be used throughout the entire industrial process. Our constraint based approach would allow structured changes to be applied during these meetings, further providing an opportunity for structured reasoning for changes.

The key areas noted during the expert review of our SAR based approach are as follows:

- The prototype system was seen as a viable design solution, capable of being of benefit to designers during the conceptual and detail design stages of the process, with some further additions to assist in the logging of information, change and reasoning.
- The designers felt that the prototype could work as a designer's tool; however its inability to work with volume limited its uses.
- A strong case towards being used as a collaborative tool for use in feedback sessions between designers and stakeholders.
- Being used as a collaborative tool would assist in a healthier, more creatively immersive design by the enhanced view received from feedback sessions.
- With the added ability to manipulate content on the projection model, stakeholders would be able to make minor design changes during the feedback session, and allow for an updating of content based on these decisions.
- SAR has a valuable role in the industrial design process. An emphasis was seen on the communication stages, Market/User Needs & Sales as a strong area for application. The use of SAR within the other areas of the process would also assist in producing a more complete design, with each stage benefiting from its use in various ways.
- These communication stages have a high stakeholder involvement, and can benefit from the high fidelity SAR offers. Users will have a more realistic mental representation of the final product as they have seen a prototype that has the same form as the final product rather than a small rendered image on a screen.

Due to the successful response from our review, the following areas for focus would be to investigate further expansion of the system to include the ability to log and adapt changes during design and visual feedback sessions and produce quantitative testing of our interaction techniques. From the review process, it was found that SAR has an effective use within the current industrial design process. The affordance SAR offers and the transparency that a TUI gives its users demonstrates an approach that can have a greater success in driving superior levels of feedback between designers and stakeholders. With the added ability to annotate and track

changes within our SAR setting, we would have a tool which would provide an indispensable opportunity for designers to take advantage of during the duration of the process.

#### Market/User Needs

Information gathering is an important facet of this stage of the process. Through the use of SAR, visual designs can be presented to stakeholders with improved feedback and responses. This is achieved through controlled choice, allowing users to interact transparently with the system, while gauging their reception of each choice. Being a collaborative medium, SAR offers the opportunity to mix subjects from different backgrounds during the one session, offering a further in-depth analysis of the proposed designs. This was unanimously seen as a valuable role for SAR.

#### Product Design Specification

Using SAR throughout other stages of the development process, an enhanced understanding of the design scenario can be realised resulting in a much more information rich Product Design Specification (PDS). With SAR being a digital format, an opportunity arises for the PDS to be updated as changes and amendments are made. Social constraints can be applied to a PDS, and team reviews can be conducted agreeing or rejecting the proposed changes. Timestamps for particular changes can be automatically recorded, as well as the participants involved. Automatic updating of the PDS would help to minimise the risk of human errors.

#### Conceptual / Detail Design

Contributing to our approach, the reviewers see the strength of SAR also being used as a tool for feedback during these stages. Incorporating experts, focus groups and key users, further improvements can be quantified through these feedback sessions. Individuals would be able to interact and move around the model, getting an appreciation for the intended impact of design decisions. The ability to apply changes to the model would further assist in the updating of changes during these feedback sessions, with proposed changes being logged within the PDS.

#### Manufacturing

SAR can be used to quantify the accuracy of manufactured goods compared to the proposed digital model. SAR also offers the ability to have an animated and functional model before being sent off for manufacturing. This allows for the checking of interactions to be performed before a prototype is produced. This also offers the final opportunity for feedback from stakeholders before the financial outlay of a working prototype.

#### Sales

Sales was seen in the same light as Market/User Needs and unanimously seen by the reviewers as a valuable role for SAR. With the finished product, SAR offers an interactive medium to demonstrate its benefits. For kitchen appliances, SAR can replace particular products within the same space, saving on the space requirements of bricks and mortar stores. Customers are able to select the product which interests them, then alternate the

surface textures from the predefined selection. This would provide a much more complete and satisfying shopping experience for buyers, gaining a better understanding on the products that interested them. Building a house requires decisions to be made on wall colours, bricks, taps, handles, counter tops, cupboard designs. This is all done from pictorial books and demo products glued to a wall. The owner is required to use their imagination to realise the ramifications of their decisions. Using a mock room, SAR allows owners to see their ideas come alive and allow a better understanding of their choices.

This application of SAR also offers an opportunity for Market/User needs to be included within a Sales application. Including conceptual ideas within the above mentioned sales approaches would allow market research to be conducted on the intended market users, during their sales decisions, allowing for more informative responses.

#### SAR Conceptual Rapid Design

Our proposed area of improvement in the industrial process was seen as a strong influence with the inclusion of SAR. Allowing for the rapid experimenting of various physical and digital designs could be very accommodating during the conceptual phase of the design process. The opportunity to learn of factors not considered until later in the process, while having an opportunity to gain feedback from stakeholders over multiple models would improve the quality of understanding during focus groups. Being of a digital nature, SAR's inclusion would allow the reuse of previous designs, colour schemes, and layouts, further improving knowledge during this idea driven phase of the process.

SAR's transparency allows a project's stakeholders, people who the designers are required to communicate with, the opportunity to offer their feedback and opinions in a much more complete fashion. By offering a prototype which has affordance and interaction, people will be more willing to offer a personal opinion, instead of blindly accepting what is being shown from not actually understanding what is being presented to them. It also allows stakeholders to utilise the space and role-play the use of the product more effectively, assisting in alerting designers to any mistakes within their design.

Through the use of SAR, the high fidelity functionality of the model encourages a higher degree of interaction from the stakeholders, ensuing with a greater assessment of the design. One of the compelling features of the SAR based design is that stakeholders (designers and customers) are literally able to walk around in the design.

## **5 Conclusions and Future Work**

This paper has presented new techniques for supporting constraint based product design within a SAR environment. A TUI was produced which gives the designer a toolbox of tangible items to allow a structured approach for amending a design through interaction with the physical prop. Geometric constraints have been designed for use within our prototype system to allow the validation of our proposed amendments to the industrial

design process. Designers are able to add projected elements onto the physical prop, dynamically alter their position and apply structured constraints between fellow projections.

The prototype was evaluated by professional designers through a qualitative expert review. Initial results show promises to SAR becoming incorporated into the current industrial design process. Our SAR Conceptual Rapid Design phase offers designers an early window of opportunity for experimenting with potential designs offering affordance and interaction between themselves and stakeholders. This is seen as an integral part of improving the communication process. They felt that the initial thought of designing the prototype for use solely by designers, limited its potential. By offering collaborative measures, including annotations and the logging of changes, it would help the tool to become a more applicable solution for industrial application. This would provide an ability to apply social constraints to the session, offering higher security, accuracy, and accountability during collaborative sessions.

Future work would consider these collaborative measures, with an emphasis on providing a communication medium between stakeholder and designer throughout all stages of the design process.

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