

Supporting Freeform Modelling in Spatial Augmented Reality Environments with a New Deformable Material

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Abstract

This paper describes how a new free-form modelling material, Quimo (Quick Mock-up), can be used by industrial designers in spatial augmented reality environments. Quimo is a white malleable material that can be sculpted and deformed with bare hands into an approximate model. The material is white in colour, retains its shape once sculpted, and allows for later modification. Projecting imagery onto the surface of the low-fidelity mock-up allows for detailed prototype visualisations to be presented. This ability allows the designer to create design concept visualisations and re-configure the physical shape and projected appearance rapidly.

We detail the construction techniques used to create the Quimo material and present the modelling techniques employed during mock-up creation. We then extend the functionality of the material by integrating low-visibility retro-reflective fiducial markers to capture the surface geometry. The surface tracking allows the combined physical and virtual modelling techniques to be integrated. This is advantageous compared to the traditional prototyping process that requires a new mock-up to be built whenever a significant change of the shape or visual appearance is desired. We demonstrate that Quimo, augmented with projected imagery, supports interactive changes of an existing prototype concept for advanced visualisation.

Keywords: Spatial Augmented Reality, Industrial Design, Deformable Surface, Quimo.

1 Introduction

This paper describes how our new material, called Quimo (Maas et al. 2011), is used to support freeform modelling for industrial designers working in a Spatial Augmented Reality (SAR) (Raskar & Low 2001) environment. This builds on our previous investigations into how SAR can be integrated into the industrial design process (Marner & Thomas 2010, Marner et al. 2009). We have also been investigating organic interfaces through the use of Digital Foam (Smith et al. 2008a,b). Quimo is a base material for prototyping that combines the natural sculpting properties of clay-like substances with intricate detail properties provided by SAR. Both the clay-like and intricate detail properties work in concert to provide real-time

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physical-plus-virtual feedback to the designer.

Quimo (Quick Mock-up) is an innovative free-form modelling material designed for use with SAR. The key application for Quimo is to support a novel prototyping technique, allowing industrial designers to generate reusable low-fidelity mock-ups early in the design process. Quimo is a white malleable material that can be moulded with bare hands to produce low-fidelity physical prototypes (Quimo mock-up shown in Figure 1(a) (right)). Unlike clay, Quimo comes in sheet form allowing hollow physical models to be constructed by cutting and bending the material into shape. Employing SAR to project imagery onto these low-fidelity mock-ups allows for complex surface appearances to be presented. Figure 1(b) shows a high detail physical car model painted white and using SAR to provide the visual coloured appearance details. Figures 1(c) and 1(d) show a physical car model sculpted using Quimo; the visual appearance is also projected using SAR for details. Using our new modelling process both the virtual surface appearance and the physical shape of the mock-up can be independently customized in real-time. Quimo allows the designer to create concept visualisations during the early stages of development that are physically reconfigurable with multiple visual appearances on one physical model.

This paper makes contributions to the following

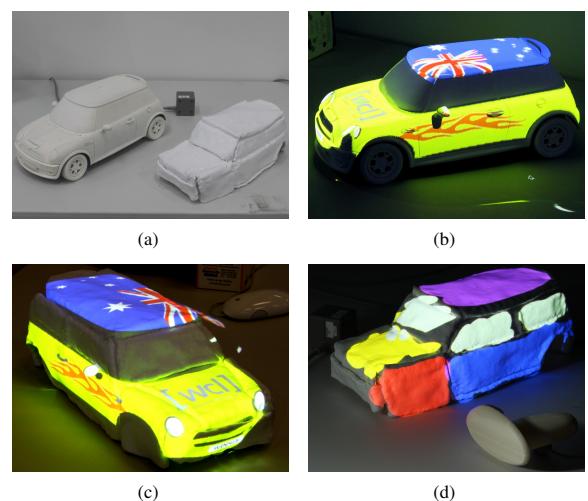


Figure 1: Modelling a Quimo prototype based on a physical model. (a) Comparison between original model and Quimo model. (b) Projected graphics on original Mini Cooper model. (c) Projected graphics on Quimo prototype. (d) Virtual spray paint on Quimo prototype.

fields: industrial design prototyping, human-computer interaction, marker-based tracking, and spatial augmented reality. This paper has the potential for a large impact due to the fact every commercial product goes through an industrial design process, and Quimo has the potential to radically improve the concept development phase of that process. In particular the following four concepts are novel contributions:

1. The creation of a new material, Quimo, which supports free-form modelling and has a suitable SAR projection surface.
2. Extending the concept phase development methodology of industrial design by allowing the presentation of feature rich information using Quimo and SAR.
3. A reproducible process for constructing the Quimo material.
4. The integration of retro-reflective fiducial markers using glass beads into the surface of the Quimo material, which allows Quimo's surface shape to be capture in real-time.

Sections 2 and 3 of this paper begin by presenting the related work, focusing on SAR and design process methodologies. In Section 4, we describe the concept design phase in the industrial design process and motivate the need for Quimo, our new modelling material. Following this, Section 5 describes conceptually how a designer uses Quimo to create low-fidelity physical mock-ups. Section 6 described three methods of how the low-fidelity mock-up can be transformed into a high-fidelity concept visualisation using SAR. Following this we describe the technical considerations and implementation aspects of the Quimo material and the SAR environment. We conclude by summarizing the contributions presented in this paper.

2 Concept Mock-ups in the Industrial Design process

Designers select a design methodology according to the design variables of the task at hand. Pugh's Total Design Model (Pugh 1991) and Pahl and Beitz's model of design (Pahl et al. 1984) are two examples of commonly applied methodologies. Whichever design methodology is chosen, concepts need to be generated that provide solutions to the design specification. This phase of design is called the concept stage. The typical process during the concept stage is to: 1) generate ideas, 2) create concepts that embody the ideas, 3) evaluate the concepts, and 4) select the most promising concepts. Using CAD and design applications to express conceptual ideas is common place. Creating physical mock-ups to assess the viability of a concept is also a common practice during the industrial design process. In practice, a combination of materials is needed to create mock-ups with diverse features. Since the model itself is still in the concept stage, the dimensions and appearance of the model are often not well defined. The designer explores different materials, colours, textures and dimensions repeatedly to find the best way to visualise a concept. We are investigating two aspects of the concept visualisation process: the techniques and materials used to create the physical prototypes, and the procedures used to augment the visual appearance of the mock-up.

2.1 Visualising a Mock-up

The appearance of the mock-up surface is an important aspect of the physical mock-up. Designers use paint and inks to colour and annotate their mock-ups. A disadvantage with this approach is when changing a design, either

a separate mock-up needs to be constructed or the initial mock-up must be re-painted. Although clay and polymer plasticine are able to change shape continuously, this is not possible once painted. The painted surfaces become less malleable. We consider these to be limitations of the current practices of mock-up creation in the industrial design process.

An alternate approach we are investigating is to use SAR with Physical-Virtual Tools (PVT) to alter the surface appearance by projecting virtual textures directly onto a physical mock-up (Marner & Thomas 2010, Marner et al. 2009). This technology overcomes the second limitation by allowing multiple appearances to be projected in succession onto one mock-up. The designer may digitally paint directly onto the model by interactively modifying the projected texture to alter the appearance. The texture can be saved and recalled later for further evaluation.

Although features in the concept stage are created, the actual dimensions are often not well defined. Finding the correct dimensions, shape, and appearance to visualise a concept is therefore an iterative process, moving back and forth between visualisations until the result is satisfactory. A material that facilitates this process is considered a requirement. As previously mentioned, traditional mock-up materials and techniques require a new mock-up to be built after the shape is significantly changed or the visual appearance is changed, adding to the total time and material involved in the concept stage.

SAR can also leverage any preliminary concept sketches, textures and design ideas that are created in the early concept stage. SAR provides the ability not only to generate a new appearance, but also present the initial ideas by projecting them directly onto the physical models. This functionality is inherently provided by the SAR system and intended to maximize the visual information and presentation to the designer.

2.2 Current Mock-up Materials

Industrial designers can utilize several techniques for constructing a physical mock-up and visualising a concept. In this section we examine three major materials and techniques: rigid materials, 3D printing, and malleable materials. With the exception of very high end colour enabled 3D printers, these techniques are used to construct the physical mock-up only, and do not focus on the appearance. Mock-ups need to be painted to provide a finely detailed surface appearance.

Rigid materials such as urethane foam, cardboard, timber, and plastics allow for the quick creation of mock-ups. The level of detail is limited by the skill of the designer and the time spent on the creation of the mock-up. Although the level of detail of the mock-up may be quite high, the shape of the models are difficult to change once created.

3D printing technology is now available to industrial designers for use in mock-up construction. The mock-up design is expressed using CAD software. The design is then printed to create a physical object. 3D printers are a very powerful tool for creating high fidelity mock-ups, however there are a number of limitations. The rigid nature of the material limits physical reworking. Reprinting designs in order to correct mistakes is a common occurrence. A second limitation is the long printing time, which requires hours before the design can be assessed and further reworked. Finally, CAD modelling is typically limited to keyboard and mouse interaction. The designer is unable to feel the properties of the material during development. By removing tactile feedback, designers create their digital models based only on their familiarity with the physical materials. In particular modelling of organic shapes without tactile feedback is difficult, especially dur-

ing the concept stage where dimensions are often not well defined.

Malleable materials such as clay and polymer plasticine are well suited for the creation of organic shapes by employing free-form modelling techniques. Designers manipulate these materials with their fingers to form the mock-up. The flexibility of the material allows the designer to change the shape of the model after its initial creation. Clay and polymer plasticine overcome the problems of remodelling a design that are apparent in the previously mentioned materials and techniques. A drawback to using clay or polymer plasticine is that it is impossible to change the shape after colours have been applied. In addition, clay and polymer plasticine both suffer from a lack of structural strength, limiting their ability to create large flat suspended sheets or large hollow objects. The disadvantage to this is large clay models are particularly heavy and not appropriate for many prototype mock-ups. To overcome this, a common practice is to use them in conjunction with cardboard or timber to create the underlying structure which the clay or polymer plasticine is applied to. However, combining materials further limits the extent to which the shape can be changed afterwards making it difficult to iterate the design without constructing a new model. Combining materials may also cause problems with producing a finish on the prototype that is consistent across the different materials that are used.

3 Related Work

Research in the field of industrial design has captured commonly used techniques and structured their flow into methodologies that assist designers in structuring the product development (Andreasen & Hein 1987, Pahl et al. 1984, Roozenburg & Eekels 1995, Ulrich & Eppinger 1995). There are differences between these design methodologies, but a common step is that promising concepts meeting the design specification will be generated in the concept stage. The concept phase is where the idea becomes a tangible reality with the first construction of a prototype. These mock-ups allow initial evaluation of the design to be performed (Wall et al. 1992).

Augmented Reality (AR) has shown potential to enhance product design, construction, and evaluation for industrial designers. Wang et. al (Wang et al. 2009) describe an AR system for the design and evaluation of functional assemblies. AR has been used for industrial building acceptance tasks (Schkolne et al. 2001), and for comparing automotive parts with the reference designs (Nolle & Klinker 2006). AR is also used in the design process; for example Augmented Foam (Lee & Park 2005) uses a head worn display to overlay material properties on a foam mock-up of a product.

We are particularly interested in SAR (Raskar & Low 2001), where perspective correct computer graphics are added to surfaces using projectors placed in the environment. SAR is useful to industrial design, compared to other AR display technologies, as the designer is not required to wear or carry equipment. SAR requires physical surfaces to project onto, which can be readily found in design prototypes.

SAR has been used to digitally paint onto physical objects (Bandyopadhyay et al. 2001, Marner et al. 2009). WARP (Verlinden et al. 2003) projects onto rapid prototype models, allowing a designer to preview the appearance of different materials. Piper et. al (Piper et al. 2002) describe a projector based system where the user can sculpt and analyze landscape forms using clay. Our Augmented Foam Sculpting (Marner & Thomas 2010) allows a designer to produce 3D virtual models by subtractively sculpting from foam.

Interacting with physical objects is the goal of tangible user interfaces (Fitzmaurice et al. 1995), and has been shown to enhance user interaction (Hoffman et al. 1998, Ware & Rose 1999). Our Quimo prototype draws from this concept by providing a tangible material that is incorporated directly with projected information.

Our investigations are also concerned with the application of tracking technologies for AR. A well employed approach is to use black and white fiducial markers such as those used with ARToolkit to provide a 6DOF tracked location. A number of researchers have extended the implementation to hide the visibility of the fiducial markers. Invisible markers have been created out of transparent retro-reflective tape (Nakazato et al. 2008, 2005a,b), paint (Nota & Kono 2008) and IR fluorescent ink (Park & Park 2004). Each of these provide a fixed shape marker which can be grouped for capturing a simple surface.

There has been research with applying ARTags (Fiala 2005a) to capture organic shapes with multiple markers (Fiala 2005b). Our work differs in that the organic shape can change in real-time. There have also been investigations into flexible fiducial markers (Pilet et al. 2005, 2008), and this work focused on tracking a number of markers that follow the contour of a non-planer shape. Unlike these systems, the tracking in this paper assumes the material that the markers are printed on can be cut.

4 Quimo in the Design Process

This paper explores a new mock-up material and the corresponding techniques employed during mock-up creation. Our primary goal has been to explore how the concept phase of the modelling methodology can be enriched by using SAR technologies to allow designers to visualise their concepts with higher detail and be provided with a more flexible modelling environment. The existing industrial design concept phase modelling process is described in Figure 2(a). We can see that significant design changes require a new prototype to be constructed. In comparison, when using Quimo and SAR for concept development both the physical model and appearance can be altered (Figure 2(b)) without requiring a new prototype to be constructed. Table 1 provides a feature summary that highlights the significant features we are investigating for free-form prototype development. Here we have identified how our approach provides benefits of existing techniques that are specifically relevant for the concept development phase.

5 Creating Mock-ups with Quimo

This section describes the Quimo material and how it can be used by designers to construct physical models before projected images are used to change the appearance in a SAR environment.

Quimo is constructed using a sheet of aluminium mesh wire coated with white silicone to create a hybrid mod-

Table 1: Features of material modelling

Technique	Malleable During Modelling	Malleable after Appearance Applied	Appearance Swapping
3D Printer	No	No	No (paint) Yes (SAR)
Rigid Materials	No	No	No (paint) Yes (SAR)
Malleable Materials	Yes	No	No (paint) Yes (SAR)
Quimo with SAR	Yes	Yes	Yes

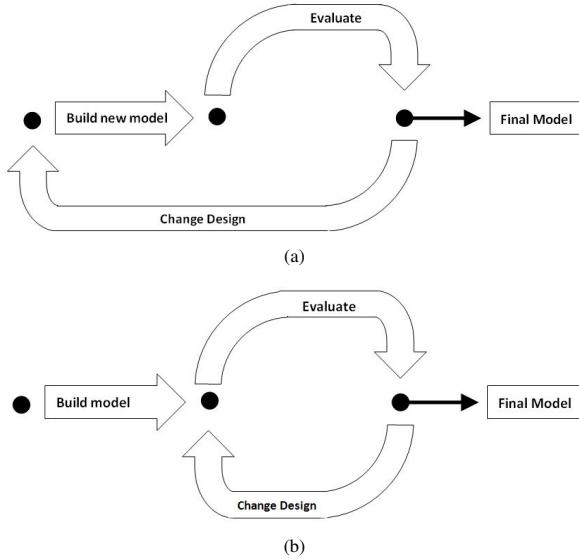


Figure 2: Concept modelling process: (a) Traditional mock-up flow (b) Updated mock-up flow using Quimo and SAR for modelling.

elling surface. The mesh wire is used for its shape preserving property; the white silicone coating is malleable and can be moulded into shapes with a smooth finish which makes Quimo a good projection surface.

Modelling with Quimo involves three basic processes; cutting, bonding and sculpting. Cutting Quimo is performed using regular scissors. This allows both curved and straight cuts to be easily performed. An example of cutting Quimo with scissors is shown in Figure 3(a).

The silicone material repels most types of glues and tapes, so we have looked into techniques for bonding the material. When joining two pieces of material together, we found stapling pieces to be a robust technique, since the staples wrap around the inner aluminium mesh (see Figure 3(b)). Another successful approach for tight corners is the use of cable ties (tie-wraps) to join pieces together (shown in Figures 3(c)) and 3(d). It is also possible to glue two pieces of Quimo together by using liquid silicone as a bonding material.

Sculpting the shape of Quimo can be easily achieved using either bare hands or tools. A bare hand technique that can be used is draping the material over an object and forming around it with your hands (see Figures 3(e) and 3(f)). Pinching the material allows a ridge to form that is useful for building up features (shown in Figures 3(g)). As with clay sculpting, tools are also very effective in shaping Quimo. A ruler can be used to create straight folds by bending it around the ruler's edge (Figure 3(h)). We also noticed that when handling Quimo, talcum powder can be used to prevent dust or dirt from sticking to the silicone surface. Since the talcum powder is white it is also suitable for projected images and slightly reduces the reflective surface of the silicon.

6 Three Modes of Modelling with Quimo

This section describes three methods of modelling with the Quimo material. The first demonstrates how a designer can construct a physical mock-up, and use a predefined virtual graphical model for projected graphics. The second method demonstrates how the designer can use PVT to paint projected imagery onto the physical Quimo prototype without a predefined virtual model. Finally, we describe how the embedded fiducial markers are used in a real-time sculpting and painting process allowing both



Figure 3: Modelling techniques used to form Quimo. (a) Cutting Quimo. (b) Bonding Quimo with staples. (c) Using cable-ties to join the material. (d) Result of a cable-tie join. (e) Draping Quimo over a hand. (f) Draping formed material into hand shape. (g) Pinching to create feature. (h) Employing a ruler to create a crease.

physical material sculpting and virtual painting to be performed for concept creation.

6.1 Modelling with Quimo and a Predefined Virtual Model

This method allows a high-fidelity mock-up to be created by using Quimo in conjunction with projected imagery of a predefined virtual graphical object. Our demonstration consists of a physical and virtual model with the appearance of a Mini Cooper (shown in Figures 1(a) and 1(b)). The Mini Cooper models were reused from a previous SAR study (Marner et al. 2009). The physical Mini Cooper model (Figure 1(a) (left)) was replaced with a sculpted Quimo version (seen in Figure 1(a) (right)). During sculpting we gained a greater understanding of how the material properties affect the sculpting process. Since we are interested in creating an approximate model quickly to simulate the design process in the concept stage we did not measure the exact dimensions. Instead, the shape was estimated and continually changed until the desired form was obtained. This process required constant comparison between the original physical model and one sculpted from Quimo. Once an approximate model is obtained, the digital appearance of the virtual model is applied using projected SAR images. Since the original Mini

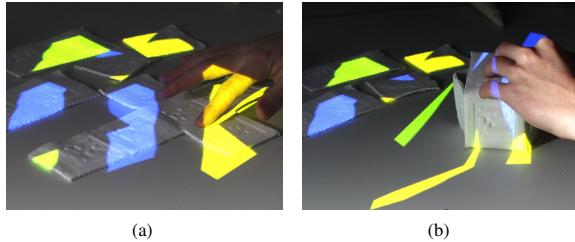


Figure 4: Deforming the Quimo material with projected images attached to markers. (a) Sheet of Quimo with projected images. (b) Folding material into a cube shape.

Cooper model and the one constructed from Quimo have different dimensions, we also applied the existing SAR calibration technique to optimize the alignment of the projections. This process requires the user to select a series of predefined points using a cursor. Figure 1(b) shows the projected imagery on the original Mini Cooper model. Figure 1(c) demonstrates how a low-fidelity mock-up created out of Quimo is transformed into a high-fidelity representation by leveraging the projected imagery.

6.2 Painting on Quimo Prototypes Without a Virtual Model

Projected imagery can still be used on a Quimo mock-up, even without an accurate, underlying virtual model. Digital Airbrushing (Marner et al. 2009) with PVT can be used to interactively create different appearances on the mock-up. An example of this technique is shown in Figure 1(d), where the surface of the Mini has been sprayed with virtual spray paint. This was accomplished using a bounding box as a stand-in for accurate virtual geometry. As the “paint” is applied using a projector, it appears to fall at the correct locations on the mock-up. Although this visualisation application supports the designer in changing the projected imagery iteratively, the model is required to remain stationary and in the same shape for the visualisations to remain accurate.

6.3 Simultaneous Physical and Virtual Modelling

In the first mode we have made the assumption a virtual model with the correct visual appearance exists before the physical material is sculpted. During concept visualisation a virtual model may not be available, to address this situation we have considered how the Quimo material can be used in conjunction with projected graphics when no pre-existing virtual model is available. Our example also considers how the material can be iteratively deformed, digitally painted and re-deformed while maintaining a correct registered projected appearance. We have addressed both these aspects by incorporating a customized tracking solution into the Quimo material. Our tracking solution employs low-visibility markers that are integrated with the material surface of Quimo. The location of each marker is tracked and used to update the digital information to compensate for the physical deformations.

For this example, we have created a 300mm x 400mm sheet of Quimo with twelve low visibility markers integrated into the surface. The markers are arranged in a 4 x 3 grid so a simple cube can be constructed. The designer starts the modelling process by digitally spraying a coloured appearance onto the surface. Using scissors, the designer cuts away the unwanted sections of the material allowing the material to be folded into a cube shape. During the folding process, the location of the markers changes from being on a planar surface to the faces of the cube. The projected graphics that were initially sprayed

onto the surface are now correctly displayed on the faces of the cube. The steps of this cube example are shown in Figure 4. It is possible to erase and change the virtual annotations or to save and switch between virtual paint appearances.

Further design alterations are also possible using digital paint and textures with PVT to further annotate the model. One advantage of this approach is the process of changing the visual appearance and the shape of the object does not require the designer to build additional prototypes as is often required when using traditional materials. The goal here is to reduce the time and material needed during concept visualisation while also increasing the functionality to maximize the visualisation possibilities.

With markers integrated in the surface we have been able to maintain the ability to cut, and bend the material into the desired shape. In the current implementation the designer is limited to bend and cut the material only on the edges between the markers to prevent destroying the marker and compromising its tracking. When the resolution of the camera increases and the algorithms used to track a bent marker are improved, the size of the markers can become smaller, allowing for a finer deformation of the material.

7 Surface Capture Techniques

Capturing the geometry of physical objects in real-time is a difficult problem. Several existing technologies were considered for implementing a tracked Quimo surface. However, we have been unable to find one solution that meets all of our requirements. This section describes our requirements and the path we followed to achieve a modified tracking system that makes it possible to project registered images on a deformable surface.

The following is a list of requirements we identified in order to determine what technique to use or develop for surface capturing:

1. The designers need to be able to cut and bend the material by using a pair of scissors.
2. The outside surface area is white. Any tracking of the shape and position may not interfere with the ability

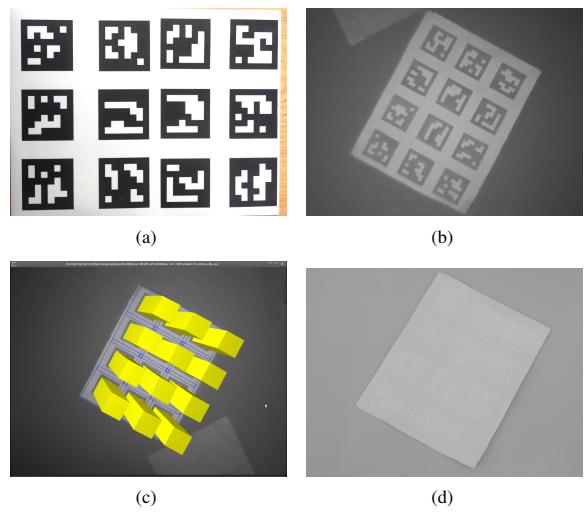


Figure 5: (a) Traditional ARToolkit fiducial markers printed in black and white. (b) Quimo material with embedded low visibility IR markers shown with IR light. (c) Virtual cubes being projected directly onto the Quimo material. (d) Quimo material shown as seen by the human eye (without IR light).

to project accurate colours and textures.

3. Real-time tracking of position and shape.

We observed the following limitations of existing technologies for our application. Electronics can not be easily integrated into the material since it will be cut regularly during use. This limits the use of embedded touch screens in the material. Commonly employed fiducial markers, such as those used in ARToolKit, provide a promising solution. However in their unmodified form the black and white markers compromise the ability to project onto that surface. Structured light and laser scanners can be used to capture the shape of an object, but are unsuitable when the object is being deformed in real-time.

To overcome these boundaries we have integrated low-visibility fiducial markers into the Quimo material. Low-visibility markers can be constructed using infra-red or ultraviolet light sensitive materials.

Low visibility IR and UV markers are made up of a material that fluoresces in the IR or UV spectrum. A camera that is sensitive to these wavelengths can then distinguish the markers that are not visible to the human eye. Since UV light can cause health problems we have chosen to use IR for our implementation. However, IR markers are normally made out of paint or tape which can not be applied to the Quimo surface. We developed a novel technique for implementing the IR markers on the Quimo surface.

We incorporate a pattern of glass beads into the silicon material while it is curing. The glass beads create a retro-reflective surface, where incident light is reflected back towards the light source. The markers are identified using a camera with an IR light source mounted close to the camera lens. Figure 5(d) shows how the markers appear under visible light and Figure 5(b) demonstrates the view under IR light.

8 System Implementation Details

This section describes three aspects of the Quimo system implementation. Firstly, we describe how the physical-virtual SAR tools are used to provide virtual spray painting on Quimo. We then discuss the tracking solution and how it was applied to create a deformable surface from grouped fiducial markers. Following this, we describe the hardware details of our SAR environment.

8.1 Physical-Virtual Tools

We have previously demonstrated how physical objects can be augmented with digital paint using our Physical-Virtual Tools (Marner et al. 2009). A major limitation of this and other SAR systems is the need for 3D virtual geometry to represent the physical objects being projected onto. To combine free-form sculpting using Quimo and digital airbrushing, we have extended our airbrushing system (Marner et al. 2009).

We expanded the previous implementation to provide support for Quimo modelling. In the update implementation physical objects are digitally painted using a bounding-cube texture map. The physical object is placed inside this volume, and the designer paints as normal. The nature of projected light ensures the virtual paint is placed in the correct location on the object, even without a corresponding virtual model. Figure 6 shows how the textured bounding box, when drawn from the point of view of the projector, correctly maps digital paint onto the mock-up. This works well when the bounding box closely fits the sculpted model, but projections would not align as well if the bounding box was significantly larger than the model. Figure 1(d) shows the result of airbrushing on the car prototype. Using the same cube map texture, the paint could

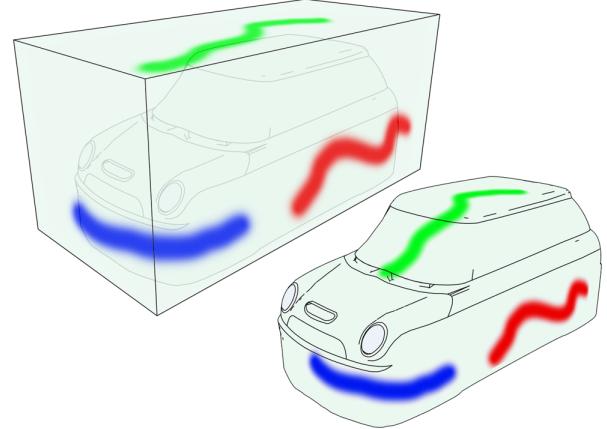


Figure 6: Left: The virtual bounding box, drawn from the point of view of the projector. The location of the physical mock-up is shown inside the bounding box. Right: The projected textures map correctly onto the physical mock-up.

also be applied to a CAD model of the design at a later stage of development. However, the goal of this technique is to preview different material properties early in the design process, before CAD models have been created.

8.2 Deformable Surface Implementation

The embedded fiducial markers are used to support more complex interactions. At the simplest level, Quimo designs are tracked, allowing the projection to be updated as the design is moved. A benefit of embedding fiducial markers into the material is the shape of the surface can be modelled. This provides a more accurate projection. In the case of the airbrushing tool, the digital paint is registered to the physical surface rather than the bounding box region, even as the material is bent, cut, and sculpted.

A naive approach to implementing the deformable surface would be to simply treat each fiducial marker as a tile that can be painted. However, the reliability of the tracking is reduced by the low contrast in the images obtained from the camera using the embedded markers. This is exacerbated by the user obscuring the camera's view of the markers with their hands or tools. This results in a projected image that flickers and is unusable to the designer.

To overcome this, we treat the entire sheet as a deformable polygon mesh, with vertices placed between each fiducial marker. The position of each vertex is determined by its neighboring markers. During tracker updates, each visible marker contributes a position for each vertex it affects. These positions are then averaged for each vertex to obtain its final location. This approach means there are four markers that can contribute to each of the inner vertices, two markers for each edge vertex, with the corners the only vertices without this redundancy. If we constrain the types of deformation that can be performed, we can add redundancy to these markers using more distant neighbors. Figure 4 illustrates our deformable surface implementation.

8.3 SAR Environment

Our environment is based on a growing framework designed to support large scale, interactive SAR systems. This framework is written in C++, using OpenGL for 3D graphics. The applications described in this paper employ a generic desktop PC with Nvidia Quadro 3800 graphics hardware. Two projectors are used, each at a resolution

of 1280x800. The PVT are tracked using a Polhemus Patriot¹ magnetic tracking system. The embedded markers on the Quimo material are tracked using a Sony XCD-X710CR Firewire camera and the ARToolkitPlus (Wagner & Schmalsteig 2007) tracking library.

The projector calibration algorithm we employed is described by Bimber and Raskar (Bimber & Raskar 2005), and involves manually finding known 3D points in the projector image. Details for the digital airbrushing algorithm have been described in our previous paper (Marner et al. 2009).

9 Quimo Material Implementation

We have previously described the materials used to construct Quimo (Maas et al. 2011). This section describes the techniques used to actually build a sheet of Quimo. Quimo is constructed using two materials: Smooth-On EcoFlex 30² and Amaco Wireform (aluminium mesh wire). The mesh wire is regularly used for freeform modelling, but lacks the white surface that is required for SAR. EcoFlex 30 fulfills this requirement. It is lightweight, will cure into a smooth surface area and can be stretched at least as much as the meshwire can. It also allows for integrating the markers in the material.

A variety of construction techniques were explored to coat a sheet of meshwire with the Ecoflex material. Our best results were achieved by using a three-layer approach. Figure 7 illustrates the layered structure of Quimo.

First, two flat sheets of EcoFlex are created, by pouring the Ecoflex liquid in an open topped box of the desired dimensions (shown in Figure 8(a)). The height of the box defines the thickness of the sheet. A thickness of 1.3 mm per sheet balances meshwire visibility, weight and flexibility. After mixing the two components of Ecoflex it takes approximately 4 hours to cure. It is then possible to work with the created sheets.

Next, liquid Ecoflex is added on top of one of the two sheets and distributed evenly (Figure 8(e)). A flat sheet of meshwire is then added to this liquid layer of Ecoflex (Figure 8(f)). The liquid layer of Ecoflex and the meshwire will create the middle layer of the material. The top layer of Quimo is made with the second sheet of cured Ecoflex that was created before. The liquid Ecoflex in the middle layer will bond all pieces together. To squeeze out excess liquid we added weight on the top layer. After another 4 hours the middle layer will be cured and the Quimo material is ready for use.

9.1 Embedding Low Visibility Fiducial Markers

The description above creates the material itself, it does not yet incorporate the low-visibility fiducial markers. The glass beads that make up the markers can be added during or after the creation of Quimo.

Adding the glass beads during the creation of Quimo will result in markers that are integrated in the material and are difficult to remove. However the glass spheres become partially submerged in the silicon, which reduces the retro-reflectivity.

Adding the glass beads after the creation of the Quimo material will result in beads that are stuck on top of the material. The problem with this approach is the glass beads can be rubbed off with firm finger pressure, however the retro-reflectivity property is well maintained with this process.

The glass beads have to be added to one of the two initial silicon sheets when it is still curing. We wait 45 minutes after mixing the liquid silicone starts to change from

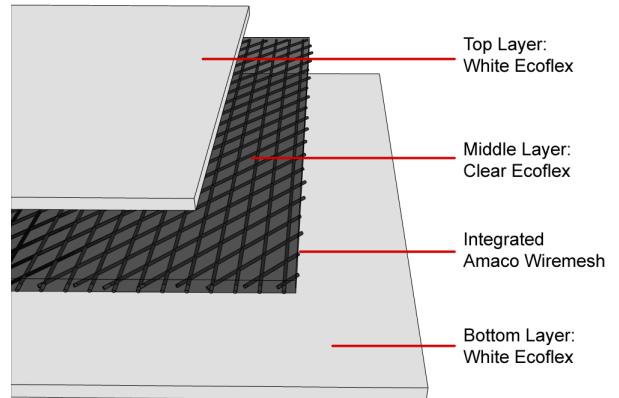


Figure 7: Cutaway showing the layers that comprise Quimo. The layers are bonded while the center Ecoflex layer is liquid.

liquid to solid. Add the beads too early and they are absorbed and lose all retro-reflectivity, add them too late and they stick on top of the Quimo, which makes them easy to rub off. The correct timing is determined by testing the viscosity as shown in Figure 8(b). When it no longer sticks, the template and the beads can be added. In addition to correct timing, the beads need to form a recognizable marker pattern that can be used with ARToolkit+. We used a 3D printer (Dimensions uPrint plus³) to construct a template which was used to form the marker shape. The template can be removed once the material has cured.

10 Limitations

There are a few limitations that we have observed during our investigations. Firstly, during sculpting we noticed the embedded aluminium mesh wire experiences some metal fatigue. Bending Quimo back and forth in the same place will result in the wires breaking. When this occurs, it is not noticed on the outside of the material since it is still covered in silicone, but the broken mesh wire does reduce Quimo's ability to retain its shape.

Our tracking solution uses a grid of ARTToolkit markers to allow the surface shape to be captured. This is intended to demonstrate the feasibility of embedding low-visibility fiducial markers into the Quimo material. A more advanced approach would be to use random dot markers (Uchiyama & Saito 2011), which have been extended to support tracking of deformable surfaces (Uchiyama & Marchand 2011).

11 Conclusion and Future Work

In this paper we have presented Quimo, a malleable modelling material allowing traditional hand modelling and projected digital imagery to be combined. We have described how the concept design phase, used by industrial designers, can be enriched using Quimo and SAR allowing for continuous changes of the visual appearance and shape without the need to build new mock-ups. We also describe the interaction techniques we explored by creating two physical prototypes to demonstrate tracked virtual projections on Quimo's surface. The final technique presented allows a user to deform the shape of the material while the digital projected graphics are updated to maintain the correct visual appearance. Finally, the implemen-

¹<http://www.polhemus.com>

²<http://www.smooth-on.com>

³<http://www.dimensionprinting.com>

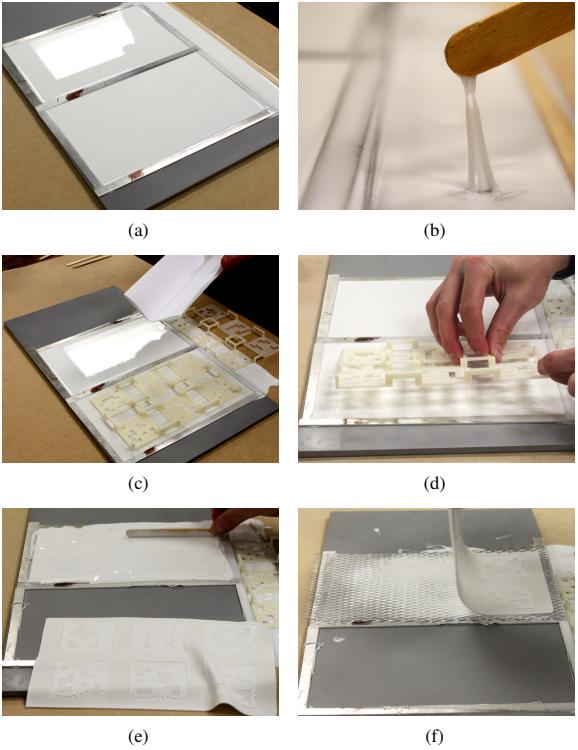


Figure 8: Material implementation. (a) Mould used to form the silicon sheets of the Quimo material. (b) Correct viscosity reached before adding glass beads for markers. (c) Adding glass beads using a template to form marker shapes. (d) Removing the template after curing. (e) Adding a layer of Ecoflex to join the sheets. (f) Add the aluminium mesh wire layer, to provide rigid property and add the top sheet.

tations details of Quimo are presented to describe how the material is fabricated and how retro-reflective glass beads are embedded directly into the silicon material to create fiducial markers.

The primary use of Quimo is for creating mock-ups in the concept design phase of the industrial design process. However, since Quimo allows for continuous surface capture and reconstruction, it is possible to save the entire process of mock-up creation. A designer can then improve their skills by watching the process in retrospect. Saving the process of mock-up creation also allows for the comparison of the design process between novices and experts. The difference can then result in instructional guidelines. Additionally, the virtual models obtained from the deformed Quimo surface can be saved and imported into CAD software for later use in the design process. This reduces the effort involved in recreating concepts in CAD software that have already been evaluated with Quimo.

References

- Andreasen, M. M. & Hein, L. (1987), *Integrated Product Development*, IFS Publications, Springer, NY.
- Bandyopadhyay, D., Raskar, R. & Fuchs, H. (2001), Dynamic shader lamps: Painting on movable objects, in 'IEEE and ACM International Symposium on Mixed and Augmented Reality', pp. 207–216.
- Bimber, O. & Raskar, R. (2005), *Spatial Augmented Reality: Merging Real and Virtual Worlds*, A K Peters, Wellesley.
- Fiala, M. (2005a), Arttag, a fiducial marker system using digital techniques, in 'Proceedings of the 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'05) - Volume 2 - Volume 02', CVPR '05, IEEE Computer Society, Washington, DC, USA, pp. 590–596.
- Fiala, M. (2005b), The squash 1000 tangible user interface system, in 'Proceedings of the 4th IEEE/ACM International Symposium on Mixed and Augmented Reality', ISMAR '05, IEEE Computer Society, Washington, DC, USA, pp. 180–181.
- Fitzmaurice, G. W., Ishii, H. & Buxton, W. A. S. (1995), Bricks: Laying the foundations for graspable user interfaces, in 'Proceedings of the SIGCHI conference on Human factors in computing systems', ACM Press/Addison-Wesley Publishing Co., Denver, Colorado, United States, pp. 442–449.
- Hoffman, H., Hollander, A., Schroder, K., Rousseau, S. & Furness, T. (1998), 'Physically touching and tasting virtual objects enhances the realism of virtual experiences', *Virtual Reality* 3(4), 226–234. 10.1007/BF01408703.
- Lee, W. & Park, J. (2005), Augmented foam: a tangible augmented reality for product design, in P. Jun, ed., 'Mixed and Augmented Reality, 2005. Proceedings. Fourth IEEE and ACM International Symposium on', pp. 106–109.
- Maas, E., Marner, M. R., Smith, R. T. & Thomas, B. H. (2011), Quimo: A deformable material to support freeform modeling in spatial augmented reality environments, in 'Poster Sessions: Proceedings of the IEEE Symposium on 3D User Interfaces', Singapore.
- Marner, M. R. & Thomas, B. H. (2010), Augmented foam sculpting for capturing 3D models, in 'IEEE Symposium on 3D User Interfaces', Waltham Massachusetts, USA.
- Marner, M. R., Thomas, B. H. & Sandor, C. (2009), Physical-Virtual tools for spatial augmented reality user interfaces, in 'International Symposium on Mixed and Augmented Reality', Orlando, Florida.
- Nakazato, M., Kanbara, M. & Yokoya, N. (2008), Localization system for large indoor environments using invisible markers, in 'ACM Symposium on Virtual Reality Software and Technology', pp. 295–296.
- Nakazato, Y., Kanbara, M. & Yokoya, N. (2005a), Localization of wearable users using invisible retro-reflective markers and an IR camera, in 'Proc. SPIE Electronic Imaging', Vol. 5664, pp. 1234–1242.
- Nakazato, Y., Kanbara, M. & Yokoya, N. (2005b), Wearable augmented reality system using invisible visual markers and an IR camera, in 'IEEE International Symposium on Wearable Computers', pp. 198–199.
- Nolle, S. & Klinker, G. (2006), 'Augmented reality as a comparison tool in automotive industry', *Mixed and Augmented Reality, 2006. ISMAR 2006. IEEE/ACM International Symposium on* pp. 249–250. article.
- Nota, Y. & Kono, Y. (2008), Augmenting real world objects by detecting invisible visual markers, in 'UIST'.
- Pahl, G., Beitz, W. & Wallace, K. (1984), *Engineering design: A systematic approach*, Springer.
- Park, H. & Park, J. (2004), Invisible marker tracking for ar, in 'International symposium on mixed and augmented reality', pp. 272–273.

Pilet, J., Lepetit, V. & Fua, P. (2005), Augmenting deformable objects in real-time, in 'Proceedings of the 4th IEEE/ACM International Symposium on Mixed and Augmented Reality', ISMAR '05, IEEE Computer Society, Washington, DC, USA, pp. 134–137.

Pilet, J., Lepetit, V. & Fua, P. (2008), 'Fast non-rigid surface detection, registration and realistic augmentation', *Int. J. Comput. Vision* **76**, 109–122.

Piper, B., Ratti, C. & Ishii, H. (2002), Illuminating clay: a 3-D tangible interface for landscape analysis, in 'Proceedings of the SIGCHI conference on Human factors in computing systems: Changing our world, changing ourselves', ACM, Minneapolis, Minnesota, USA, pp. 355–362.

Pugh, S. (1991), *Total Design: integrated methods for successful product engineering*, Addison-Wesley.

Raskar, R. & Low, K. (2001), Interacting with spatially augmented reality, in 'Proceedings of the 1st international conference on Computer graphics, virtual reality and visualisation', ACM, Camps Bay, Cape Town, South Africa, pp. 101–108.

Roozenburg, N. F. M. & Eekels, J. (1995), *Product design: Fundamentals and methods*, Wiley, NY.

Schkolne, S., Pruitt, M. & Schrder, P. (2001), Surface drawing: creating organic 3D shapes with the hand and tangible tools, in 'Proceedings of the SIGCHI conference on Human factors in computing systems', ACM, Seattle, Washington, United States, pp. 261–268.

Smith, R. T., Thomas, B. H. & Piekarski, W. (2008a), Digital foam interaction techniques for 3D modeling, in 'VRST '08: Proceedings of the 2008 ACM symposium on Virtual reality software and technology', Bordeaux, France, pp. 61–68.

Smith, R. T., Thomas, B. H. & Piekarski, W. (2008b), Tech note: Digital foam, in 'IEEE Symposium on 3D User Interfaces', Reno, NV, pp. 35–38.

Uchiyama, H. & Marchand, E. (2011), Deformable random dot markers, in 'Poster Sessions: Proceedings of the 10th IEEE International Symposium on Mixed and Augmented Reality', Switzerland.

Uchiyama, H. & Saito, H. (2011), Random dot markers, in '2011 IEEE Virtual Reality Conference (VR)', IEEE, pp. 35–38.

Ulrich, K. T. & Eppinger, S. D. (1995), *Product Design and Development*, McGraw-Hill, NY.

Verlinden, J., de Smit, A., Peeters, A. & van Gelderen, M. (2003), 'Development of a flexible augmented prototyping system', *Journal of WSCG*.

Wagner, D. & Schmalsteig, D. (2007), ARToolKitPlus for pose tracking on mobile devices, in 'Proceedings of 12th Computer Vision Winter Workshop (CVWW'07)'.

Wall, M. B., Ulrich, K. T. & Flowers, W. C. (1992), Evaluating prototyping technologies for product design, in 'Research in Engineering Design', Vol. 3, pp. 163–177.

Wang, Z., Shen, Y., Ong, S. K. & Nee, A. Y. (2009), Assembly design and evaluation based on Bare-Hand interaction in an augmented reality environment, in 'CyberWorlds, 2009. CW '09. International Conference on', pp. 21 –28.

Ware, C. & Rose, J. (1999), 'Rotating virtual objects with real handles', *ACM Trans. Comput.-Hum. Interact.* **6**(2), 162–180. 319102.