

Jouke Verlinden

An abstract painting with a textured, layered appearance. The top half features a mix of green, blue, and yellow tones with some white highlights. The bottom half is dominated by a dark, almost black, angular shape on the left, with a dense network of white and light green lines and curves that seem to flow across the right side. The overall style is expressive and gestural.

**Developing an Interactive Augmented
Prototyping Methodology to Support
Design Reviews**

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Jouke Verlinden

Developing an Interactive Augmented Prototyping Methodology to Support Design Reviews

PROEFSCHRIFT

Ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,
voorzitter van het College van Promoties
in het openbaar te verdedigen
op vrijdag 17 Oktober 2014 om 15:00 Uur

door JOUKE CASPER VERLINDEN
Ingenieur Technische Informatica, TU Delft
geboren te Scheveningen

Dit proefschrift is goedgekeurd door de promotor prof. dr. I. Horváth

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Developing an Interactive Augmented Prototyping Methodology to Support Design
Reviews

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PhD thesis, Delft University of Technology, Delft, the Netherlands

ISBN: 97890-6562-3607

Published by VVSD

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Cover design, Jerome Bertrand, based on Painting "La géométrie du jardin"
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Chapter 1

Introduction

When you enter a design studio, one of the first things you'll notice is a fine collection of prototypes and mock-ups. Many of these physical models were carefully made, some of them using household materials such as paper and glue. For multiple decades, digital tools draw designers in front of the computer, where powerful CAD (Computer Aided Design) and CAE (Computer Aided Engineering) applications instantaneously offer millions of product variations. These capabilities lure designers to an abstract modelling realm, disconnected from the physical existence and human-centred use of products. As Virilio predicted, society is assimilating the digital (1994): virtual worlds, social networking, cloud services, and online teaching are currently thriving. The resulting dichotomy between physical and virtual impedes inspiration and assessment of the real world, which can lead to suboptimal product designs and delays in product development.

For these reasons, my PhD project has attempted to use Augmented Reality (AR) to reclaim the physical realm to design. At the start of this project, AR was a novel technology, enabling to combine digital information with the physical environment. The combination of AR with physical models for design has been named "Augmented Prototyping" (AP), an approach that offers multiple visual and haptic means to interact with artefact models during the design process. This approach would allow design agencies to create and adapt models within hours, possibly in an inexpensive way by standard video projectors in combination with 3D printed models. Before fixing the focus and boundaries of this project, an introduction is necessary in the current practice of prototyping as well as in augmented prototyping and its enabling technologies, as presented in the following sections.

1.1 Prototyping in industrial design engineering

Prototyping - the creation of physical and virtual models - is paramount in design, architecture and engineering. In literature, a variety of such models are described, including sight models, cardboard mock-ups, working prototypes, etc. (Hilton, 1983). According to the Delft Design Guide, three-dimensional models are used to express, visualise, and materialise product ideas and concepts (van Boeijen et al., 2013). Traditionally, physical models were hand-made of materials that reflected the intended product, sometimes aided by moulding techniques. As summarised in Table 1, prototyping has evolved to a modern technology, in the context of advanced manufacturing, modelling tools, display, and computing platforms.

With the advent of Rapid Prototyping means, physical models can be (partly) made by automated means – initially by subtractive technologies such as CNC milling, and later by stereo lithography and other additive technologies, more details are discussed in Section 1.2.3. In the meantime, computing platforms have evolved from mainframe computing to mobile computing and beyond, with an increase in processing, storage, and communication capabilities (Horváth et al., 2009). Modelling tools have evolved from Computer Aided Design to Computer Aided Engineering options that embed optimization and simulation, and Product Data Management solutions to support documentation throughout the design process, including version management and document sharing. In recent years, modelling and configuration software for non-designers users are being developed in order to facilitate co-creation and customization. In terms of visualisation means, the traditional monitor and the option to make a hardcopy have evolved to 3D displays, enabled by developments in computer graphics, encompassing photorealistic qualities such as ray-tracing/global illumination quality and fast rendering speeds by discrete graphics. Immersive 3D displays emerged such as virtual reality systems. In the past decade, image processing software and miniaturisation of computing units have contributed to combine computer graphics with the physical environment, known as mixed reality. The visualisation means can be placed among the virtuality continuum, as a combination of virtual and physical elements (Milgram and Koshino, 1994), as shown on the horizontal axis of Figure 1.

Tangible virtuality offers spatial interaction with virtual objects through volumetric or holographic displays that offer depth perception. For example, the Fog screen and Helio display (diVerdi et al., 2007). In such systems, the user can interact with the virtual objects by through specialised devices equipped with sensors and actuators. When applied in design this approach is known as *tangible virtuality*, it provides a palpable, modifiable design space.

Augmented reality combines physical models with a digital overlay, such as projection or video mixing to establish a low cost, adaptable prototype. Entitled augmented prototyping, the physical interaction allows a natural tactile and haptic dialogue between designer and artefact model that can be shared among multiple co-located people.

Augmented prototyping imposes limitations on the prototype. In contrast to tangible virtuality, scale and gravity cannot be neglected when interacting with AP. On the other hand, AP embraces existing physical prototyping methods and is compatible with existing model making traditions at design agencies. Furthermore, virtual

Table 1 Evolution of prototyping and computing technologies for design.

	1970-1980	1990-2005	2005-Present
<i>Advanced manufacturing</i>	CNC milling	Additive manufacturing (AM)	Low-cost AM
<i>Computing platform</i>	Mainframe	Personal computing	Mobile & cloud computing
<i>Modelling tools</i>	CAD	CAE, PLM	
<i>Visualisation means</i>	2D monitor, printer/plotter	Virtual Reality, Powerwalls	Mixed Reality

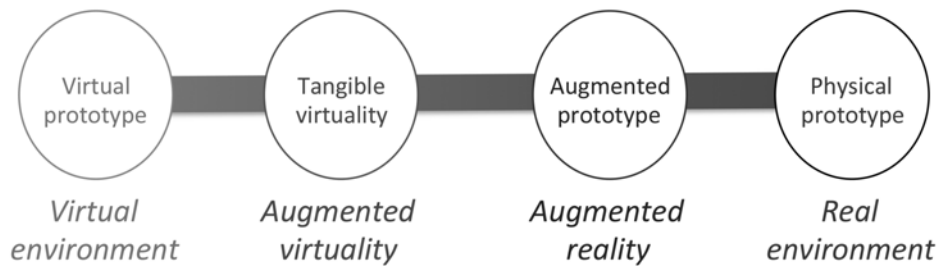


Figure 1 Prototypes among the virtuality continuum.

prototypes are limited in providing a proper perception of context, scale and proportions (Kuutti et al., 2001). With these benefits, physical objects offers the opportunity to transform passive models to a dynamic medium that simulates material, product and environment behaviour. This dynamic aspect allows the exploration of product performance, and engages stakeholders in discussing ‘what-if’ scenarios while they construct shared understanding.

1.1.1 Defining prototyping

There are no exact definitions of the concepts of prototype and prototyping. Merriam-Webster’s dictionary denotes a prototype as “a first full-scale and usually functional form of a new type or design of a construction”. According to Lim et al. (2008) a prototype is a manifestation that, in its simplest form, filters the qualities in which designers are interested without distorting the understanding of the whole. However, related design domains such as interaction design convey ambiguity, for example rapid prototyping is tied to software development (Houde and Hill, 1997). To set the stage for this project, three different perspectives are revisited to frame the objectives and roles of prototyping: design research, organisational studies, and media sciences.

1.1.2 Prototyping from a design research perspective

McGarry (2005) extensively analysed mechanical engineering student’ behaviour and their reflections on physical modelling. They found nine physical prototyping roles, ranging from “hardware as starting point” to “hardware as a medium for integration.” Although these roles illustrate the use of physical prototypes, they do not link particular design activities to possible applications or requirements. For design and engineering, Geuer identified four main intentions to prototyping, namely: exploration, communication, verification and specification (1996). These are addressed below.

1. Considering *exploration*, physical prototyping is said to “probe three-dimensional relations and proportions of certain design solutions” (Stappers et al., 1997). This can involve existing products and samples of materials as well as a physical representation of the design context, for example a scale model of a city for urban planning. Prototypes contribute to the reflective dialogue between designer and artefact (Schon, 1994). The act of creating

such models is as important as its result: new insights and solutions emerge during this process.

2. *Communication* regards sharing a product concept with other stakeholders in the design process to support decision-making. Product design is never a solitary process – fellow designers are involved often in projects, and design in collaboration with the client, prospective users, marketers, manufacturers, engineers, and other experts. Bridging the differences in knowledge, skills and attitudes among the stakeholders is essential. Smulders et al. (2008) argue that such design representations function as “boundary objects” or interfaces between the stakeholders in transition between design phases. These boundary objects encompass both product specifications and argumentation, providing a platform to create shared insight and to freeze the status of a product design for later use. A significant advantage of using prototypes is that these can be accessible to all stakeholders in the design process. It forces the designer to transform his or her thoughts and ideas into a concrete representation
3. *Verification* considers the establishment of correctness of a design, checking with design criteria and other requirements. As physical entities, prototypes are often used in tests and simulations – for example on performance, durability, and ergonomics. As Smyth (2000) claims, prototypes have an integrative character. They allow combining spatial structure with other design aspects, such as ergonomics, kinematics, and material behaviour. Furthermore, to limit superfluous effort and development time, there is a motivation to verify the performance of a design as soon as possible, before a product is produced and put on the market. This is commonly known as front-loading in new product development (Thomke & Fujimoto, 2000).
4. The fourth intention to prototyping is the *downstream process specification*. This means the use of a prototype to embody the (final) design, to remain intact during the product development process and possibly used for manuals and advertisement purposes. A typical example is found in the automotive industry, where full-scale clay models act as a unified information carrier for the shape in the detailing stage (Hoadley, 2002).

Lim et al. (2008) introduce an *economic prototyping principle* to explain and guide how prototyping happens in practice: “The best prototype is one that, in the simplest and the most efficient way, makes the possibilities and limitations of a design idea visible and measurable”. According to Liou (2007), a prototyping budget is typically limited to approximately 1% to 10% of the overall design budget. Typically, the manufacturing time of physical prototypes range from a few hours to days.

1.1.3 Prototyping from an organisational studies perspective

Organisational studies examine how individuals construct organizational structures, processes, and practices and how these, in turn, shape social relations and create institutions that ultimately influence people (Clegg and Bailey, 2008). To understand prototyping from this perspective, Critical Systems Thinking proposes four different approaches (Jackson, 2000): 1) functionalist, 2) interpretive, 3) emancipatory, and 4) postmodern. The application of this framework to design was originally proposed by

Mobach (2007), it expands traditional reasoning on prototyping to a platform that is able to find bottlenecks that bear impact to the design process. Features of these approaches are provided in Table 2.

These four offer different perspectives to consider the role of physical prototypes.

1. The *functionalist* approach deals with the problem-solving aspects of design, focused on decreasing cost or effort while increasing the quality of the resulting product as much as possible (effectiveness). Here, the prototype mainly acts as a means to obtain empirical evidence for verifying these aspects.
2. The *interpretive* approach focuses on the level of agreement and shared understanding among the stakeholders in the design process. Although design is goal-oriented, the multidisciplinary character of complex projects might easily lead to miscommunication or misconceptions among the stakeholders. An example is the use of scale models in Group Decision Rooms for urban planning to deal with interpretive aspects (Laurini, 1998).
3. The *emancipatory* approach touches the issue of power of the stakeholders. In considering users of products, this aspect covered by participatory design. For example, Sanders (1999) introduced co-creation tools with specific physical components to support participation in a playful way. However, the power balance between design team, client, product marketing, and other stakeholders is subtle and can be influenced by prototypes.
4. The *postmodern* approach gives voice to the need for pluralism and divergence in organisations. In contrast to the interpretive (which seeks consensus), postmodern philosophy acknowledges the differences as an essential ingredient towards a successful design – proliferating inspiration and lateral thinking, with little commitment to find a priori solutions. When organizations are too much focused on consensus, the postmodern approach might sense issues in pluralism and suppressing important

Table 2 Features of Critical Systems Thinking (excerpt from Jackson (2000)).

Approach	Functionalist	Interpretive	Emancipatory	Postmodern
Basic goal	Demonstrate law-like relations among objects	Display unified culture	Unmask domination	Reclaim conflict
Organisational benefits	Control, expertise	Commitment, quality of work life	Participation, expanded knowledge	Diversity, creativity
Hope	Efficiency, effectiveness, survival and adaptation	Recovery of integrative values	Reformation of social order	Claim space for lost voices
Problems addressed	Inefficiency, disorder	Meaninglessness, illegitimacy	Domination, consent	Marginalisation, conflict suppression
Method	Nomothetic science	Hermeneutics, ethnography	Cultural and ideological critique	Deconstruction, genealogy

conflicts. Prototypes can encompass this aspect in plurality in expressing design concepts and in using a variety of details and refinement.

Critical Systems Thinking offers a collection of accepted methods and tools to frame with such issues (Mobach, 2007). Many of these techniques are computerized, and offer great opportunities in combination with prototypes to solve such problems in the context of design.

1.1.4 Prototyping from a media sciences perspective

In McLuhan's work, a strong dependency between content and medium is shown ("the medium is the message", 1964). When considering the physical manifestation of prototypes, this principle holds, illustrated by architect's scale models made in materials that have an expressive quality such as solid gold, bronze or newspapers, while the final design consists of bricks and mortar. Furthermore, a medium entails specific procedures and methods to format the content, which are tailored for a specific practice that complies with a stated set of criteria.

Lim et al. (2008) characterised the manifestation of prototypes by three features: material, resolution, and scope.

1. *Material* corresponds to the substance (physical or digital) and the intrinsic means to interact with/manipulate it. For example, physical models made from foam have a different look and feel than wood. In the early stages of design, models of low-cost materials are typically used, and those which can easily provide volumes (e.g., foam, styling clay), surfaces (e.g., paper/cardboard) or structures (e.g., wires). In later stages, high-quality materials are used.
2. The *resolution* specifies the level of detail of a model, which might vary for each dimension that can be used to characterise the model. Resolution is a direct relationship with fidelity level of a prototype, where, a differentiation can be made between low-fidelity and high-fidelity prototypes.
3. Finally, the *scope* defines what aspects of a design idea were included and which were disregarded.

A framework to this interpretation is found in the theory of Media Synchronicity, which connects the media richness and parallelism to obtaining shared insight (Dennis et al., 2008). Activities encompass conveying, transmitting, and listening in the context of a set of parallel channels including physical ones. The resulting constructs are depicted in Figure 2 and include rehearsability, transmission velocity, and reprocessability. The main idea behind this theory is media appropriation: i.e., considering what type of communication best fits a situation, taking in consideration the skills and attitudes of the sender and the recipient(s), the complexity of the message, and the time available for decision making.

Physical prototypes go beyond being accessible representations – they are part of the real, physical world to engage and interact with society. Paul Dourish, influenced by phenomenologists such as Heidegger, labelled this qualification as *embodied interaction*: "Embodiment is the property of our engagement with the world that allows us to make it meaningful" (2001). A physical entity bears commitment, allows tangible and natural interaction, and can be shared with multiple people. To go even further: a physical entity has a soul, a spiritual existence far beyond anything virtual.

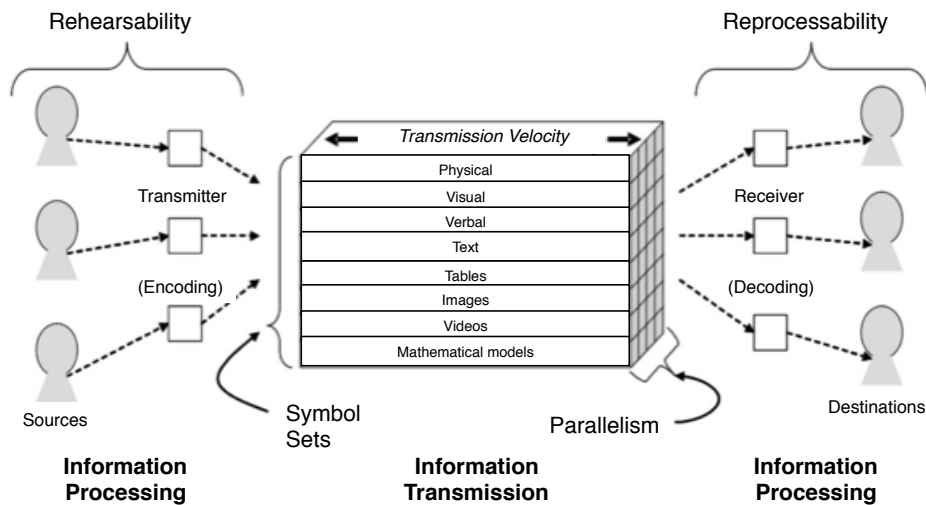


Figure 2 Constructs of the Media Synchronicity theory (Dennis et al., 2008).

1.1.5 Conclusion: shaping a medium, methodology

Based on the discussion above, I conclude the following. A prototype is considered to be the manifestation of a design solution that captures only those aspects that need addressing in a particular situation. The objective of using of prototypes is a mixture of exploration, validation, communication, and specification. With respect to communication, the technologies to manufacture and interact with the prototype govern the resulting discourse. However, prototyping is not just a utilitarian activity to capture a design. Critical systems thinking expanded this to interpretive, emancipatory, and postmodern aspects of prototyping. Its attention to emancipation and power relationships is relevant for prototypes, as these are used to convince clients or other stakeholders. Furthermore, focus on postmodernism encourages the development of new interaction and visualization means to enrich the experience of creating and using prototypes. I need to take these viewpoints into account while analysing design processes and devising support scenarios. Furthermore, in contrast to intangible, virtual models, physical prototypes establish an embodied interaction: a physical interaction that facilitates a natural, tactile, or haptic dialogue between designer and artefact. This quality needs to be explored further, and requires tools and methods.

1.2 Augmented prototyping concepts

1.2.1 Augmented prototyping design support scenarios

Since the inception of Augmented Reality (AR), a collection of design support scenarios for augmented prototyping have been devised. In literature, AP applications were proposed for several design domains, including information appliances, automotive design, architecture, and factory planning. Table 3 identifies four categories of design support scenarios based on the existing AP applications: passive presentation, altering surface qualities/texture, testing user interfaces, and changing product performance. These functions are discussed in the following sections.

Table 3 Design support scenarios, found in existing AP solutions.

Scenario	Purpose	Simulation
1. Passive presentation	Presentations	-
2. Altering surface qualities/texture	Exploration of shape related-features	Material
3. Testing user interfaces	Usability assessment	Product behaviour
4. Changing product performance	Optimize placement of features	Interaction of product & environment

1.2.1.1 Passive presentation

In the case of passive presentation, a predefined virtual model is overlaid over a physical model. The possible user interaction is limited to changing viewpoint or moving the model in space. Klinker et al. (2002) investigated the effects of presentation of (virtual) concept cars in a typical showroom, based on observing the behaviour of designers. The resulting AP system, entitled used a head-mounted display with video mixing, and rendered automotive design on a marker. In a similar fashion, I was involved in setting up a full-scale projector-based AR setup depicted in Figure 3. This result was on show at the High-Tech Automotive Campus in Helmond, the Netherlands and comprises a foam model of a racing car and 3 aligned video projections. While such presentations can host animations, for example by including dioramas (Raskar et al., 2002), they establish a passive prototype that showcases a predefined narrative.



Figure 3 Full-scale car mock-up with projection (Htas 2009).

1.2.1.2 Altering surface qualities/texture

Several AP systems have been proposed to draw lines, curves and surfaces on physical objects, with help of gloves or other tools to influence the geometry. In Cheek et al. (2002), a head-mounted camera tracked the user's index finger to create control points of curves in the air. The resulting computer graphics were superimposed on the video stream and shown on the head-mounted display. Varga (2007) proposed a system to generate and adapt free-form surfaces based on hand motion recognition, while the user had the visualised image on an auto-stereoscopic monitor. In contrast, an augmented modelling system developed by Fründ et al. displayed virtual components on a physical global shape (2003). The used modelling operations were limited to component placement (translation, orientation, scaling), and were controlled by the user with a Pinch Glove. Projector-based painting, such as the dynamic shader lamps system, highlights the natural interaction of digital drawing on physical objects (Bandyopadhyay et al., 2001). In this case, two video projectors from different angles illuminated a white object. As shown in Figure 4, the



Figure 4 Interactive painting example (Bandyopadhyay et al., 2001)

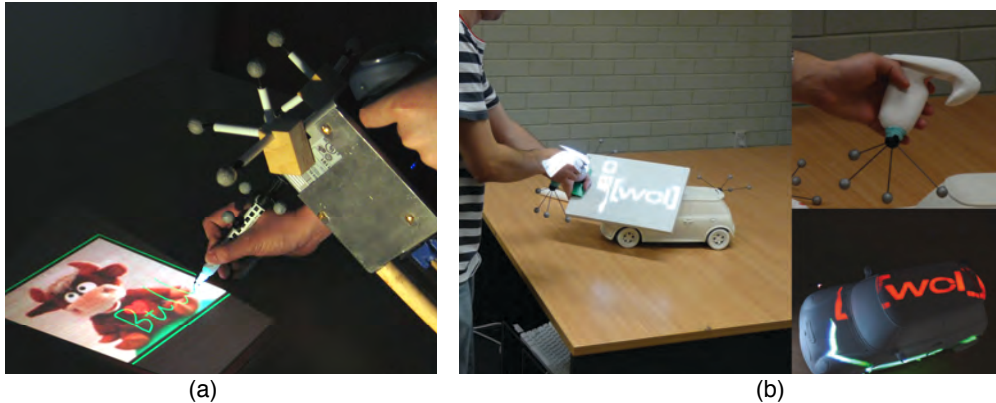


Figure 5 a) Handheld projector with pen interaction (Cao & Balakrishnan, 2006),
 b) Stencil and spray (Marner et al., 2009).

user interacts with the scene using a 3D tracked wand as a drawing tool. When the wand touches the object's surface, virtual strokes are generated and rendered with an airbrush effect. Cao & Balakrishnan (2006) presented a handheld projector and pen interface to annotate space, i.e. add decorations in line drawings. The two-handed system was able to adapt granularity, see Figure 5. Marner et al. (2009) propose a similar system with a 'stencil' as an intermediate sketchpad. The stencil is handheld and allows more control on casting sketches as texture maps on physical mock-ups. In the Skin system, 2D graphics were projected on physical objects. Physical dials and switches were used to control the texture warpage (Saakes, 2010). Although these types of AP demonstrate a natural spatial interaction, the adaptation of decoration limits the design discourse to the physical manifestation of the product.

1.2.1.3 Testing user interfaces

Augmented Prototyping can be used to overlay a virtual display on a physical mock-up to simulate the interactive behaviour of an information appliance, such as mobile phones or MP3 players. A more or less sophisticated simulation of the product's digital behaviour produces the feedback, while the user controls the interface by touching the physical object. Nam and Lee (2003) conducted a design evaluation of



Figure 6 Augmented Prototyping with head mounted display (Nam and Lee, 2003).

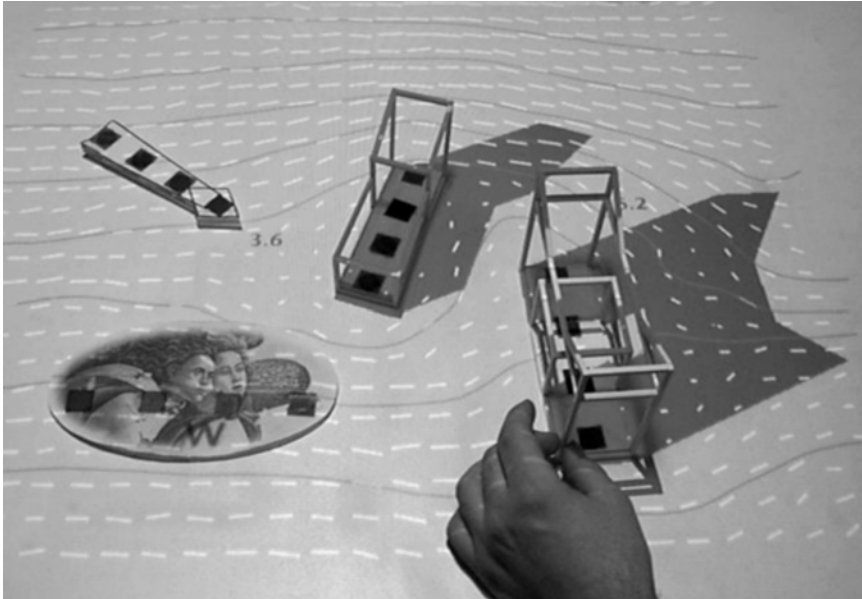


Figure 7 Interactive wind simulation (Underkoffler & Ishii, 1999).

a mobile phone (Figure 6). They employed optical tracking with a visible marker attached to the back of the object to determine position and orientation of the physical model and to render the graphics in a head-mounted or projector-based setup. Caruso and Belluco (2010) presented a system using a robotic arm that moved the tangible controls to different configurations to test large products such as dashboards. Kanai et al. (2007) developed a usability assessment tool using video projection on mock-ups. RFID tags were glued on the foam mock-up and the user wore a glove with an RF antenna. This system captured the interaction and mapped these to state transition diagrams to find mistakes during usability tests. This design analysis scenario engages consideration of both physical and cognitive ergonomics.

1.2.1.4 Changing product performance

Digital artefact models can be extended with computational simulations, this allows the user to change the environment and product properties by changing location and orientation of physical elements. This type of design support allows to brainstorm on performance, and to optimize this in “what if” scenarios. As an example, Underkoffler and Ishii presented a system with rigid physical components, representing buildings, that could be manually be reconfigured on a flat surface (1999). These components represented buildings while light reflection, shadows and wind and simulation flow fields were projected directly on the workspace (Figure 7).

The Built-it system supported the design of assembly lines: a interactive simulation of assembly data was projected on top of blocks that represented production units, while a large monitor displayed a 3D perspective rendering the resulting manufacturing plant (Rauterberg et al., 1998). Jones et al. presented a similar system that catered for stacking physical components (2010). It allowed a construction of a physical scene from blocks, which was continuously scanned in 3D. Figure 8 shows a particle flow simulation projected on top of this scene,

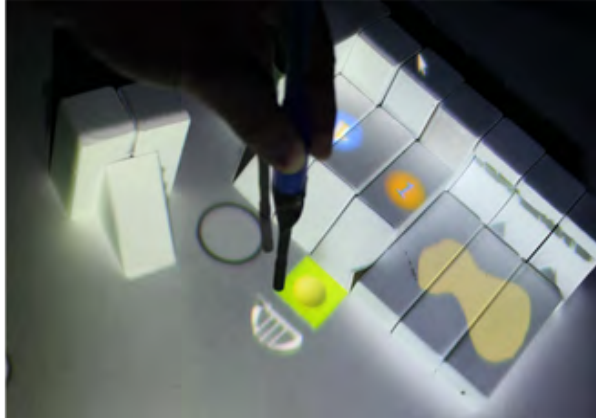


Figure 8 Reconfigurable blocks and pen to control a particle system based on a physics simulation (Jones et al., 2010).

controlled interactively with a 3D pen. This design support scenario exposes the potential combination of computational simulations with a tangible interface. AP engages natural physical spatial reasoning, while the scale and type of simulation can be tailored to the design situation at hand.

In industry, the digital and physical realms are typically bridged by rapid prototyping techniques, limiting the ability to adapt designs and detailing after the physical model is made. Augmented prototyping combines physical with virtual models and offers a natural, spatial interface where designs can be adapted continuously.

Based on literature covering AP, four design support categories have been identified, with an increasing level of interactivity: passive presentation, altering surface qualities/texture, testing a user interface, and changing product performance. However, as literature only conveys experimental systems, knowledge and procedures to operationalize augmented prototyping need to be extended.

1.2.2 Enabling technologies

Three technologies are required to establish an augmented prototype: 1) AR display technologies, 2) physical model making, and 3) 3D tracking technologies. The subsequent sections will present a state of the art of these technologies.

1.2.2.1 Display technologies suitable for AP

In the field of AR, three imaging techniques are known to merge spatial computer graphics with the physical environment (Azuma et al., 2001):

1. **Video mixing:** A camera is mounted on the product or viewer and virtual objects are rendered on the captured video frames in real time. The result is displayed on an opaque surface, for example that of an immersive Head-Mounted Display (HMD).
2. **See-through:** half-silvered mirrors are applied to superimpose computer graphics onto the user's view (as in heads-up displays of modern fighter jets).

3. **Projector-based** systems: one or more projectors cast digital imagery on the physical environment.

As Raskar and Bimber (2004) argued, a second consideration in deploying an augmented reality system is the physical layout of the image generation. For each imaging technique mentioned above, the display can be arranged between user and physical object in three distinct ways: a) head-attached, which presents digital images directly in front of the viewer’s eyes, establishing a personal information display, b) hand-held, carried by a user and not covering the whole field of view, and c) spatial, fixed to the environment.

When the AR image generation and layout principles are combined, the following collection of AP display technologies can be identified: i) HMD, ii) handheld display, iii) embedded screens, iv) see-through boards, and v) spatial projection-based AR (Table 4). Each of these options and their advantages versus shortcomings for AP will be discussed in the following sections.

Table 4. AR display technologies, suitable for AP.

Technology	Imaging	Physical layout
Head-Mounted display	Video-mixing, see-through, projection	Head-attached
Handheld display	Video-mixing	Hand-held
Embedded display	Video-mixing	Spatial
See-through board	See-through	Hand-held or spatial
Spatial projection-based displays	Projection	Hand-held or spatial

1.2.2.2 Head-mounted display

The first head-mounted display encompassed a see-through system with half-silvered mirrors to merge virtual line drawings with the physical environment (Sutherland, 1968). Since then, the variety of head-attached imaging techniques has increased and they now encompass all three imaging techniques of AR: video-mixing, see-through and direct projection on the physical environment (Azuma et al., 2001).

In a benchmarking experiment, that tested advanced display systems, HMDs performed worse than hand-held or stereoscopic monitors, and were judged them as insufficient for inspecting engineering designs (Bochenek et al., 2001). However, new developments, specifically high-resolution OLED displays and increased power of mobile platforms, yield new opportunities, specifically for entertainment purposes (Figure 9). A benefit of head-mounted displays is that they leave the hands free. Furthermore, as opposed to handheld or spatial arrangements, a head-mounted display offers a user a private view of the scene, which may include sensitive data that should not be shared.



Figure 9 Latest Head Mounted Displays (left: KABK the Hague and right: Carl Zeiss).

HMDs pose challenges to discuss a design concept during collaborative design as they limit the visibility of co-located participants and the physical workspace (Klinker et al., 2002). Another drawback is the additional weight that is attached to the human head, and that results in the increase of the inertia. It also imposes a constrained movement envelope due to cables that connect the display to workstation.

1.2.2.3 Handheld display

With the advent of powerful mobile electronics, handheld Augmented Reality technologies have emerged. Tablet PCs and personal digital assistants employ built-in cameras to enable video mixing (Schmalstieg and Wagner, 2008). The resulting device acts as a hand-held visor to an augmented experience.

0 shows an example of such a solution, a combination of an ultra mobile personal computer, a Global Positioning System (GPS) antenna for global position tracking, a camera for local position and orientation sensing along with video mixing (Schall et al., 2009). At present, such components are found in regular smartphones, exploited by mobile AR applications, often social-media based (Verlinden et al., 2012).

An advantage of using a video-mixing approach is that delay times in processing are less influential on visual performance compared to see-through or projector-based systems: the live video feed is also delayed, thereby establishing a consistent augmented view. The hand-held solutions work well for occasional, mobile use. One limitation of handheld display techniques is limited screen size and resolution (typically of 4 to 6 inches in diagonal). Long-term use can cause strain in the arms, known as the “Gorilla arm syndrome”. At present, memory, processing power and graphics processing are limited to rendering 3D scenes with a low number of polygons, although capabilities of mobile CPUs are rapidly improving.

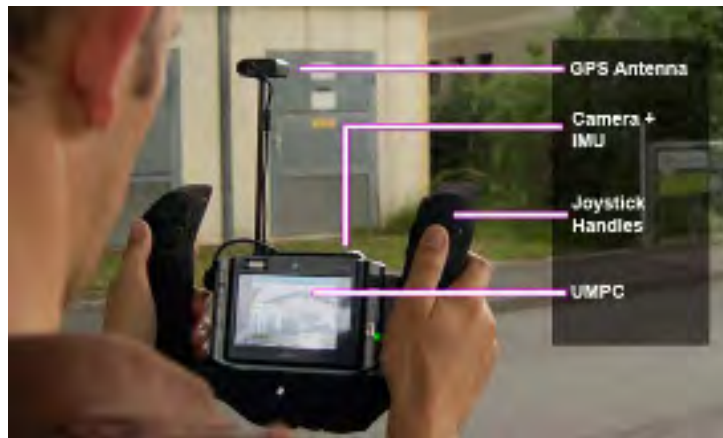


Figure 10 The Vesp'R device for underground infrastructure surveillance (Schall et al., 2009)

1.2.2.4 Embedded display

The embedding of light arrays in physical objects can be used to display virtual elements directly on its surface, establishing another AP display. Such displays are commonly applied in prototyping mobile phones and similar information appliances in final stages of design. With the advent of novel, flexible e-Paper and Organic Light-Emitting Diode technologies, parts of a physical mock-up can be covered with such screens. The Luminex material approximates this by using a LED/fibreglass based fabric, it cannot change its colours (see Figure 11). Recently, a fully interactive light-emitting fabric was presented, based on integrated RGB LEDs, with a battery and a control unit to run animations.

The advantage of this type of AP display is the unobstructedness: no separate devices are in between the user and the physical model. In that respect, it can express a high level of fidelity of a final design. However, embedding screens in physical models requires considerable effort and resources (Gill et al., 2005). Regular embedded screens can only be used on planar surfaces and their size is limited while their weight prohibits larger dimensions. At present, such displays are



Figure 11 . Impression of the Luminex material (left) and Lumalive enabled furniture (right).

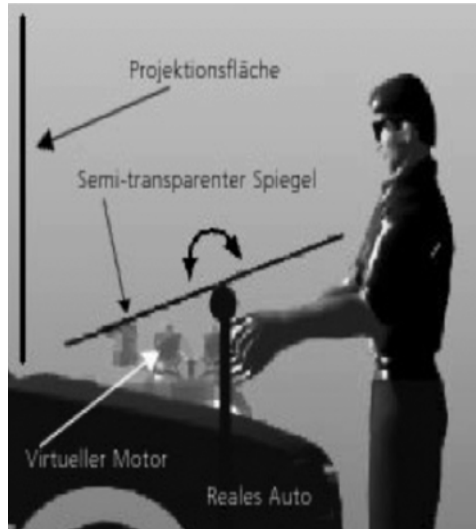


Figure 12 See-through board for car maintenance (Bimber et al., 2001)

tethered to a workstation with a cable or wireless network and currently have a low resolution (640 × 480 pixels or less). An experimental solution to this challenge was provided with “the slow display” in which a photo-chromatic paint was applied to objects and colour was changed locally by digitally controlled UV laser projection (Saakes et al., 2010). This effect only lasts for a few minutes.

1.2.2.5 See-through board display

See-through boards consist of a semi-transparent medium between the user’s hands and eyes to project digital imagery on the board, while the physical context is still visible and palpable. The augmented engineering system (Bimber et al., 2001) employed a half-silvered mirror that could swivel in one direction, while an off-the-shelf stereoscopic Virtual Reality workbench was used to track user interaction and project graphics on the mirror (Figure 12). Bordegoni and Covarrubias (2007) presented a sculpting system with a similar working principle, yet extended with a haptic feedback system.

An advantage of this technology is that the user’s hands do not occlude digital images, graphics can be displayed in front of the physical object. Furthermore, the user does not have to wear heavy equipment while using a projector array can increase the resolution of the projection. One limitation of see-through boards is that physical interaction is obstructed due to the presence of a large glass plate. Other limitations are that this solution requires careful setup and cannot be moved easily. To properly view stereoscopic graphics, the user is required to wear shutter glasses. Head tracking is required to align the virtual and physical models, because small angular inaccuracies can lead to large imaging errors. Furthermore, multiple viewers cannot share the same screen, although a curved mirroring surface can solve this if the views are split for each user (Bimber, 2002).



Figure 13 Left: projection of a cathedral interior on a church chapel in Utrecht [Hoeben, 2010], right: video of fashion designer Jean-Paul Gaultier projected on a dummy (Rotterdam, January 2013).

1.2.2.6 Spatial projection-based display

Spatial projection-based display use one or multiple projectors to cast digital imagery directly on physical objects and its context. Raskar and Bimber (2004) presented several spatial projector solutions, including projection on irregular surfaces by counterbalancing the colours and displacement of image pixels, calibrated by structured lighting. In the field of advertising and performance arts, this technology gained popularity as *Projection Mapping*, projecting on buildings, cars or other large objects, see Figure 13. Projector systems can be portable, for example iLamps: a hand-held projector that is used as a flashlight to project on the environment (Raskar et al., 2003). The Omni Touch system is a wearable projector-based AR configuration fixed to the shoulder, equipped with a laser-based projector and a depth sensor, see Figure 14 (Harrison 2011).

Figure 15 shows the principle of spatial projection-based technologies: a virtual 3D point V can be tracked to a point M on a physical screen based on the user's viewpoint, while the corresponding pixel P on the projected image can be determined by the projector's characteristics. This principle is the reverse of constructing a perspective image of a virtual object with a pinhole camera (Raskar,



Figure 14 Wearable projector with hand tracking (Harrison et al., 2011).

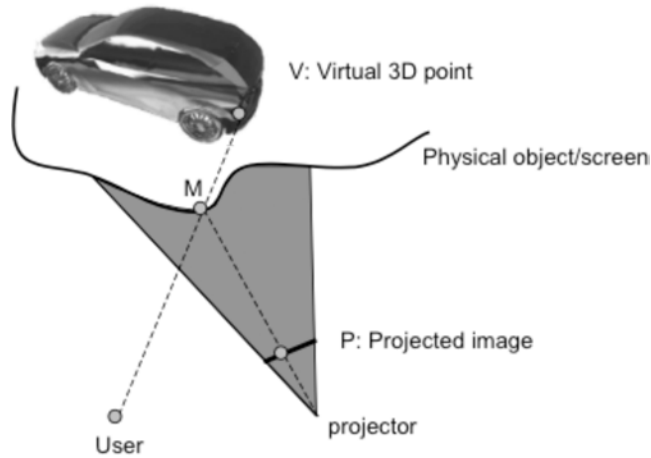


Figure 15 Projection-based display principle, adapted from (Raskar and Low, 2001).

1998). If the physical object has the same geometry as the virtual object, a 3D perspective transformation is sufficient to pre-distort the digital image in a regular rendering pipeline (Raskar et al., 2001). Reflections, which are viewpoint dependent, might introduce errors in the perception of shape details (Ferwerda et al., 2004). However, there is strong evidence that parallax - by stereopsis or by motion - “repairs” this phenomenon, resulting in the impression that highlights and reflections are glued on the geometry (Blake and Bühlhoff, 1990). If the physical and virtual shapes differ in shape or size, the projection needs image transformation and the head position needs to be tracked to adjust the perspective transformation accordingly.

The advantage of spatial projection-based technologies is that they support the perception of visual and tactile/haptic depth cues without the need for shutter glasses or HMDs. Multiple co-located users can share the display. Furthermore, compared to other AR display solutions, spatial projection requires less expensive equipment. A limitation of spatial Projector-based display technologies is that they have a restricted field of depth. Furthermore, the user can occlude the projection on the physical model, which impedes the interaction with details in the virtual model. The alignment of physical and virtual coordinate systems is more prone to

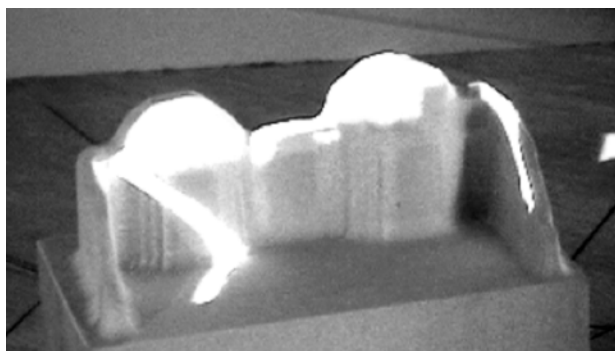


Figure 16 Projection overshoot error on the left side of the object.

perceivable errors than other display technologies. Projection overshoot, as illustrated in Figure 16, is a typical error for misaligned coordinate systems. A solution for this problem is either to include an offset (dilatation) of the physical model or introduce pixel masking in the rendering pipeline (Verlinden et al., 2003).

1.2.3 Physical model making technologies suitable for AP

The creation of physical models is found in almost all design domains, and can be manual or automated. Automated methods are also known as Rapid Prototyping (RP), and cover additive and subtractive techniques (Gebhardt, 2003).

Subtractive technologies represent a collection of automated cutting technologies (Liou, 2007), which can that operate in 2D (for example, laser cutting) or 3/5/7 D (e.g., CNC). However, the manufacturing principle imposes constraints on the geometry when compared to additive technologies.

Additive manufacturing techniques add material, layer by layer, using some a physical or chemical phenomenon to solidify material. Recently, the American Society for Testing and Materials standardized the terminology for additive manufacturing in the following categories (ASTM, 2013):

- *Vat Photopolymerisation*: formerly known as Stereolithography, a liquid photopolymer in a vat is selectively cured by light-activated polymerisation. It employs monomer resins and is known for its high surface quality and fine details.
- *Material Jetting*: similar to inkjet printing, droplets of build material are selectively deposited and immediately cured/solidified. Similar to vat photopolymerisation, material jetting uses resins. The inclusion of print heads provides the ability to mix different types of resins to create functionally graded structures, e.g. structures with gradients of flexible and rigid properties.
- *Binder Jetting*: similar to inkjet printing, a liquid bonding agent is selectively deposited to join powder materials, such as plaster or starch.
- *Material Extrusion*: material is selectively dispensing material through a nozzle or opening. A well-known commercial name for this process is Fused Deposition Modelling. Most low-cost printers such as the RepRap systems feature this technology (Jones et al., 2011).
- *Powder Bed Fusion*: thermal energy selectively fuses regions of a powder bed. This category supports fabrication in engineering plastics, metals and ceramics while the specific techniques include Selective Laser Sintering, Electron Beam Melting, and Direct Metal Melting.
- *Sheet Lamination*: sheets of material are cut and bonded to form an object. The sheets are typically of paper or low-cost plastic. This technique was formerly known as Layered Object Manufacturing.
- *Directed Energy Deposition*: focused thermal energy is used to fuse material in powder form by melting them as they are being deposited. This technique resembles numerically controlled welding and typically uses metals, allowing it to be applied on existing objects for repair.

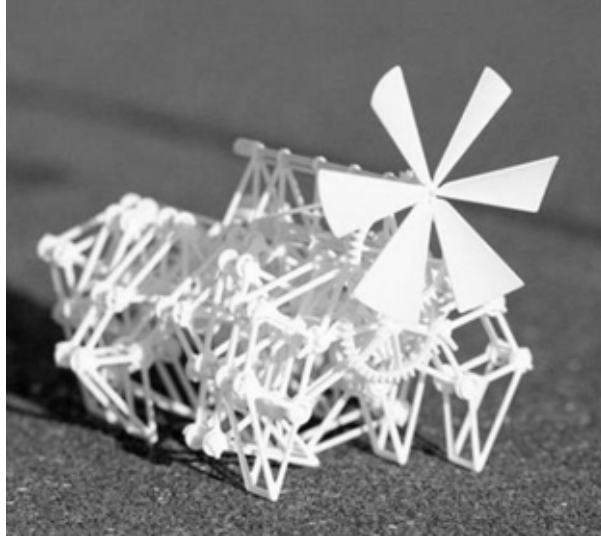


Figure 17 Nylon “strandbeest” (Janszen et al., 2014).

An in-depth explanation of these technologies is found in (Tempelman et al., 2013). In the past two decades, these additive manufacturing technologies have matured and enabled fabrication of complex geometries that include a variation of microstructures and material properties (Dobrovski et al., 2011). Furthermore, additive technologies allow the simplification of (manual) assembly through fabricating compliant or kinematical structures at once. The Strandbeest depicted in Figure 17, for example, has 74 moving components and was printed by using Powder Bed Fusion (Janszen et al., 2014).

At present, Rapid Prototyping technologies are commonly used in design practice. In a benchmark between commercially available machines, the cost of producing a PC mouse prototype varied between 60 and 130 USD, and took half a day on average (Table 5). Since the time of this benchmark, the cost and fabrication time have further decreased (Gibson et al., 2010). Service bureaus offer a collection of Rapid Prototyping technologies through web shop-based communication. This provides a competitive alternative to manual model making in most design situations, specifically when there is already a digital representation available (Engelbrektsson and Soderman, 2004). In the recent past, open-sourced and low-cost additive manufacturing machines have emerged that cost between 300 and 3000 Euros, and offer local rapid prototyping facilities to small and medium enterprises. At the moment, these have similar accuracy and build speed as commercial material extrusion machines (Tymrak et al., 2014). The proliferation of additive manufacturing as a commodity has its implications for traditional product realisation; it grants everyone access to automated manufacturing techniques at any time (Geraedts et al., 2012).

Table 5 Aspects and available characteristics of a selection of RP (Grimm, 2002).

Machine	Principle	Materials	Max dimensions (mm)	Prototype benchmark	
				Time (hours)	Cost (\$)
Z810 (Z Corp.)	3D printing (jetting binder onto powder)	Starch-based or plaster-based powder	400x500x600	3.2	75
MDX-650 (Roland)	CNC, Milling of a range of materials	Foams, wax, solid plastics and metals	650x450x115	4.1	70
Eden 500v (Objet)	Polyjet printing of photopolymer	Acrylate photopolymer resin	500x400x200	4.6	130
Thermojet (3D systems)	Multi-jet printing of Wax	Wax	250x190x200	4.8	80
Dimension (Stratasys)	FDM, Extrusion of thermoplastic filaments	ABS, Polycarbonate	600x500x600	5.6	60

1.2.4 Tracking techniques suitable for AP

In order to merge the digital and physical, an AP system needs to keep track of position, orientation, and possibly physical state of objects in the physical environment. In a comprehensive overview of tracking principles, Welch and Foxlin (2002) concluded that there is no ideal solution ('silver bullet'). A number of working principles for tracking are known: magnetic, optical passive, optical active, ultrasound, mechanical linkage, and laser scanning. I compiled a summary of commercially available technologies in Table 6.

Table 6 Summary of tracking technologies.

Tracking type	Size of tracker (mm)	Typical number of tracked items	Action radius/ accuracy	Degrees of freedom	Issues
Magnetic	16x16x16	2	1.5 m (1 mm)	6	ferro-magnetic interference
Optical passive	80x80x0.1	>10	3 m (1 mm)	6	line of sight
Optical active	10x10x5	>10	3 m (0.5 mm)	3	line of sight, wired connections
Ultrasound	20x20x10	1	1 m (3 mm)	6	line of sight
Mechanical linkage	defined by working envelope	1	0.7 m (0.1 mm)	5	limited degrees of freedom, inertia
Laser scanning	-	>10	2 m (0.2mm)	6	line of sight, update rate, object recognition

For indoors augmented reality, key tracking methods include tracker/marker size, action radius, and accuracy. As the physical model might consist of a collection of parts, the number of items that can be tracked is relevant. Magnetic, mechanical linkage and ultrasound-based position trackers are obtrusive and able to track only a limited amount of objects simultaneously. Optical tracking and laser scanning suffer from issues concerning line of sight and occlusion. Several tracking technologies can be combined with local tracking principles, also known as sensor fusion, to increase the level of tracking fidelity or response speed (Zhou et al., 2008). For example, the tracking solution of Caarls (2009) combines a slower but more robust passive optical tracking with fast sensing accelerometers to decrease the latency in sampling rotation for see-through head mounted displays.

Four tracking technologies are suitable for augmented prototyping, namely i) marker-based optical tracking, ii) markerless optical tracking, iii) laser-scanning, and iv) Phidgets. These will be briefly discussed in the following sections.

1.2.4.1 Marker-based optical tracking technologies

The addition of visual clues – markers - can reduce the complexity of recognizing objects and their location in a video stream. For example, the AR Toolkit employs rectangular black and white patterns, a web camera determines the position, and orientation, and identifies the marker (Kato and Billinghurst, 1999). Advantages are that this technology runs on a standard workstation with an update frequency of 30 Hz or higher. However, optical markers are obtrusive when markers are visible to the user while handling the object, while the visibility of the markers can be hampered by projections.

1.2.4.2 Markerless optical tracking technologies

Markerless optical tracking, also known as natural feature tracking, relies on image processing algorithms to identify objects and their position from a real-time camera feed (Prince et al., 2002). At present, the most promising is the Parallel Tracking and Mapping algorithm, which extracts a motion field with natural waypoints that is subsequently reconstructed to a point cloud or mesh (Klein & Murray, 2009). Akman (2012) refined this working principle to cater for stereoscopic images in real-time. Apart from tracking objects in space, markerless optical tracking solutions can also track the user, for example, for fingertip and hand tracking. A simple example is the light widgets system that traces skin colour and determines finger/hand position by 2D blobs (Fails and Olsen, 2002). A more elaborate example is the virtual drawing tablet by Ukita and Kidode (2004), fingertips are recognised on a rectangular sheet by a head-mounted infrared camera. Advantages of markerless optical tracking technologies is that these are unobtrusive. Furthermore, they run on standard workstations and webcams. A limitation is that these technologies require effort to train the algorithms, while the tracking fidelity is hampered by dimmed lighting conditions and projections.

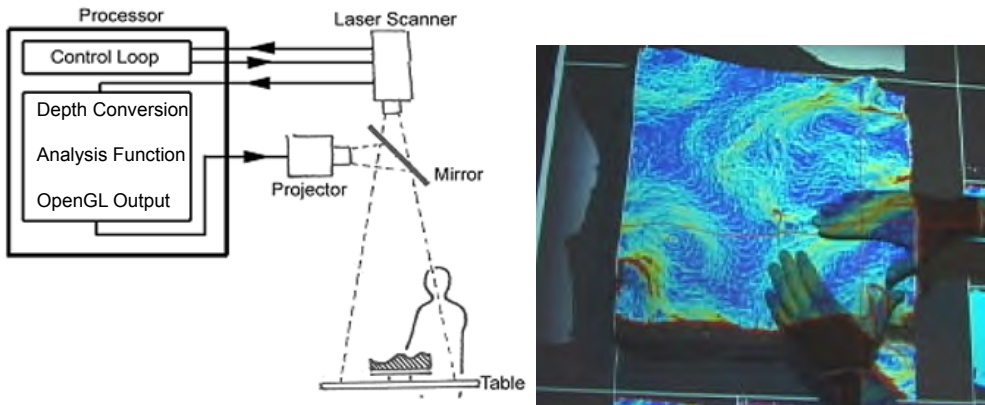


Figure 18 *Illuminating clay* system with a projector/laser scanner (Piper et al., 2002).

1.2.4.3 Laser-scanning technologies

Laser-scanning technologies are able to reconstruct 3D surfaces from large distances, such as time-of-flight measurement that determines the round-trip time of a light pulse. Figure 18 shows the *Illuminating Clay* system that established an interactive malleable surface by using a laser scanner (Piper et al., 2002). The user controlled a computational fluid dynamics simulation by sculpting a slab of Plasticine while the results were continuously projected. In the recent years, depth cameras have emerged for gaming such as Microsoft's Kinect One, enabling depth-scanning solutions with update rates of 30 frames per second less than \$150. This tracking solution could be applied in design, e.g., during sculpting. However, technology has a number of limitations when used as real-time tracking means, including the sampling rate, processing delay, resolution, as well as recognition of objects.

1.2.4.4 Phidget technologies

Electric components, such as switches can detect user interaction (events) with physical mock-ups. Greenberg and Fitchett (2001) introduced a simple electronics



Figure 19 Mock-up equipped with wireless switches that can be relocated to explore usability (Lee et al., 2004).

hardware and software library to interface PCs with sensors and actuators. Labelled “phidgets” (physical widgets), the collection includes switches, sliders, rotation knobs and sensors to measure force, acceleration, and light. Some systems have embedded switches with short-range wireless connections, allowing a greater freedom in altering the location of the interactive components while prototyping. Figure 19 depicts such an example made with the Calder toolkit that uses a capacitive coupling technique to communicate between sensor and antenna (Lee et al., 2004). Another solution is to use passive RFID systems. For example Kanai et al. demonstrated a system that lets the user wear a RFID reader on her finger, who can interact by touching the components that have hidden RFID tags while a graphical user interface was projected on a foam mock-up (2007). Advantage of this technology is that it enables local detection of events, and it provides tangible cues to interaction. However, these technologies are unfit to track position while they limit the interaction to small areas.

1.2.5 Conclusion

Three enabling technologies for AP have been discussed: display, physical model making, and tracking. Display techniques for augmented prototyping cover head-mounted, handheld, embedded, see-through board and spatial projection-based. Spatial projector-based displays seem most suitable employment in design offices and beyond, specifically if a multi-user solution is considered. Furthermore, projectors are ubiquitous in present day studios and offer a reasonably unencumbered experience. With regard to tracking, augmented prototyping applications require registering interaction with parts of the physical object, for example, to mimic the interaction with the artefact or to activate a tool. A collection of techniques is applicable in design contexts: marker-based optical tracking, optical natural feature tracking, laser scanning, and phidgets. However, there is no “silver bullet” for tracking – each application context might require a different technique.

1.3 Research design

1.3.1 Line of research

The Faculty of Industrial Design Engineering at TU Delft houses a unique blend of design, usability, ergonomics, marketing and engineering disciplines. All of these fields have built a certain tradition with physical prototyping for a wide variety of objectives as highlighted in the previous sections, for example for innovation management, styling, human-centred design, physical and cognitive ergonomics, and manufacturing. The Computer Aided Design Engineering section has a history in physical and virtual modelling, including work on natural hand motion input (Varga, 2007), vagueness in geometric representations (Rusák, 2003), and research on large-scale physical prototype creation by foam cutting (Horváth et al, 1998). My work fits in this research portfolio by its objective to develop a more natural means to interact with a design by advanced technology. In the meantime, research topics evolved on par with the growing complexity of products, including services and ubiquitous computing, to a theme now known as cyber-physical systems.

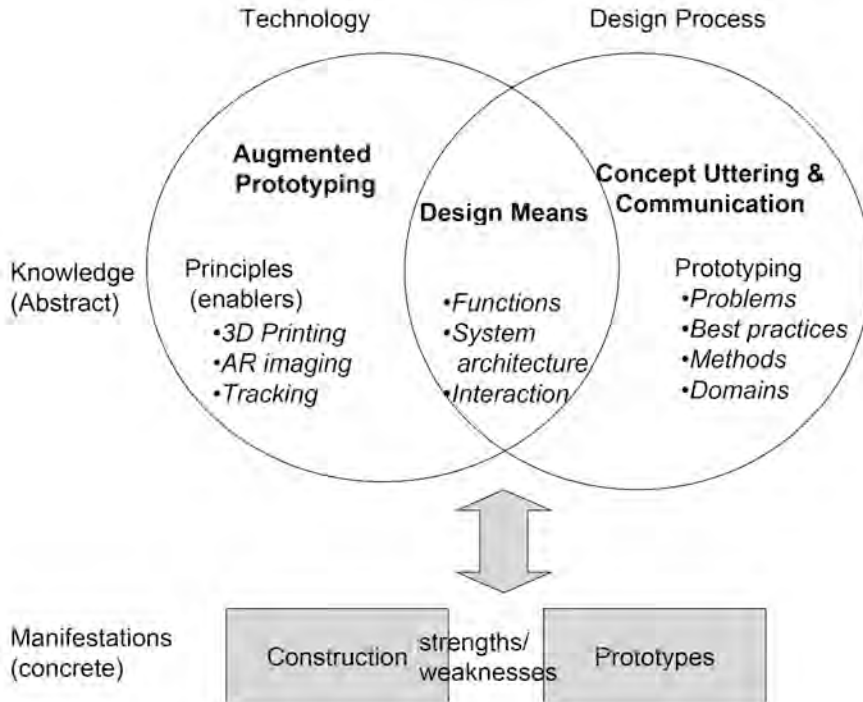


Figure 20 Overall research context.

1.3.2 Context and objectives of this project

As the title of this dissertation indicates, this research project aims to investigate how AP can be employed beneficially in design processes. A driver of this project is the opportunity to lower the threshold to creating models with a high sense of engagement to participants (stakeholders) in the design process. This engagement is crucial in the act of design, tapping into the spatial manifestation of the artefact. Traditional physical and virtual prototypes lack these to extent and are prone to misinterpretation by stakeholders. Consequently, I assumed that AP might enhance concept uttering and communication. Similar to work done in the field of participatory design in healthcare (Garde, 2013) and end user engagement by virtual reality (Thalen, 2013), such enhancement improve the outcome of the design process, creativity of designers, and innovativeness of the product.

To translate these notions into research objectives requires clarifying the problem context. The scope of the project encompasses both technology and design process, as framed in Figure 20.

As a *technology*, Augmented Prototyping offers a great deal of visualisation and interaction possibilities for designers. However, no commercial or open-source systems exist that deliver a full AP solution, including methods, recipes or procedures. At present specifically the fabrication of physical and virtual components as well as managing the interaction of augmented prototyping lack support.

With regard to the *design process*, we argue that the current knowledge on the use of advanced prototyping means in design practice is incomplete. Physical models can be considered as design media or boundary objects, yet design research presents few pointers on successful utilization in practice. This project seeks to address these issues.

Depicted in the middle of Figure 20, is the notion of a *design means*: a design medium that enhances the design process or its discourse. However, there is no reasoning framework to determine when or how novel prototyping technologies can be employed in the design process. In particular, existing literature on AP solutions are not supported by evaluations, and are at best subjected to informal test scenarios.

The objectives of this research project can then be formulated as follows:

- To identify the enabling technologies of Augmented Prototyping.
- To study the problems and best practices of concept uttering (presentation and communication) in design processes.
- To formulate an underpinning theory which guides how AP can enhance or optimize the design process.
- To develop an implemented and validated design methodology based on this theory.

1.3.3 Applying a multi-cycle multi-methodological framing

As stated in the objectives, this project requires a research approach that combines a technical (rational, system-oriented) and an empirical (observatory, activity/method-oriented) perspective. We cannot solely base our answers on empirical findings, as the opportunities that the technology offers might not address the current bottlenecks. Design and prototyping of various research means are necessary in this research project. However, a simple usability test or feasibility study will not present the necessary evidence to determine the impact of a design support solution. This requires development of AP implementations, put in a design context, to examine the strengths and weaknesses of specific solutions.

A research framework was devised that encompasses a number of research cycles, as depicted in Figure 21. As Horváth (2008) defines, a research cycle represents a principal unit of investigation, starting with knowledge exploration and ending with consolidation of knowledge. The research cycles depend on each other regarding the content of the findings.

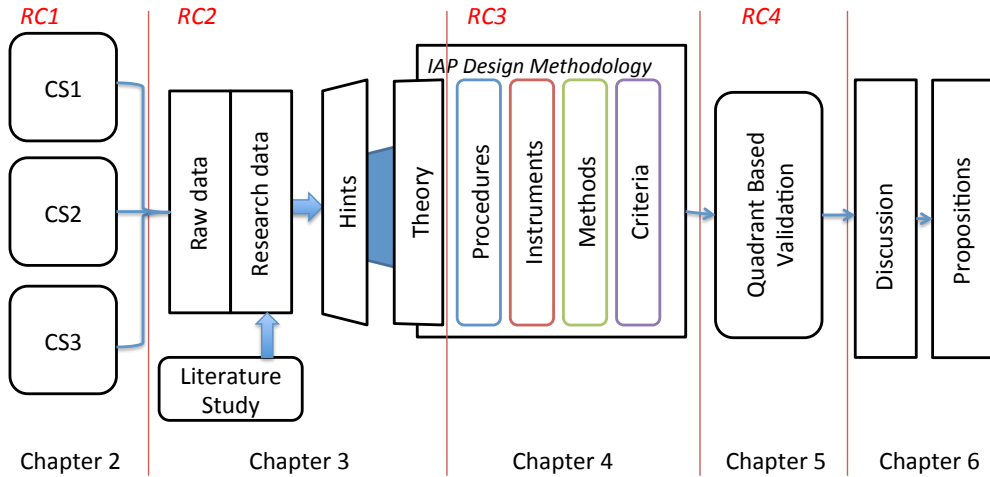


Figure 21 Research framework (RC= Research Cycle, CS=Case Study)..

1.3.4 Overall research design

I considered 4 research cycles, each corresponding to a specific research objective, depicted in Figure 21. The research cycles are done in different contexts and provide different knowledge for the follow-up research cycles.

Research Cycle 1: Case studies towards exploring bottlenecks and best practices in specific design processes

Although there exists literature on prototyping skills and technologies, the reasons why and how models are employed in design practice are lacking. The goal of this research cycle, which is framed as research-in-design Context (Horváth, 2008), is to obtain grounding from practice on how AP could be utilised in the design process. This was done by investigating three design projects in different design domains, with the objective to reveal current bottlenecks and best practices during concept uttering. The working hypothesis is that communication with other stakeholders will be the most important source of bottlenecks in concept uttering. By a cross-case study, a reference model was created to reason about the impact of including physical prototypes in the abovementioned design processes.

Research Cycle 2: Deriving indicators of the need for an efficient enabler in design processes

The second research cycle aims at conceptualising an underlying theory to develop a design support means for concept uttering. Framed as a research-in-design context approach, this cycle processes the results of the conducted case studies, in particular the bottlenecks and best practices. To do so, I have introduced the construct of hints to collect the first ideas for elements of a support system. In my interpretation, hints are focused and speculative usage scenarios, for an enabling means that can support the design process. The hints are captured as conjectures, i.e. as necessary but improvable propositions that yield a better understanding of the required support, inspired by the visionary attempts towards the support of prototyping presented in Section 1.2. Together with the reference model, they

inform about influential factors and process enhancement. I used the resulting collection of hints to generate an underpinning theory on AP in design. My working hypothesis in this research cycle was that interactive augmented prototyping (IAP) can increase the level and speed of achieving shared understanding about design concepts among stakeholders.

Research Cycle 3: Introducing IAP as a methodological solution to support design reviews

In this research cycle, the proposed IAP methodology of the previous cycle was further detailed and constituents implemented (IAP-M). To do so, the act of designing was embedded as research means, also known as design inclusive research: to synthesise and explore opportunities to generate new knowledge that cannot be derived otherwise (Horváth, 2008). The working hypothesis was that procedures, methods, instrumentation, and criteria of a design methodology could be implemented, based on the underpinning theory mentioned above.

The proposed *procedures* would identify a workflow that could be followed in applying IAP. The *methods* encompass a collection of approaches to enhance the design discourse during design reviews, e.g. how to prepare prototypes for meetings, how to capture the discussion and how to record decisions. The *instrumentation* focuses on devising an AP working principle, combining hard-and software. A number of pilot implementations were developed and verified. *Criteria* would consider inside the appropriateness to apply the methodology to a particular design situation.

Research Cycle 4: Validation of IAP-M

This research cycle aims at assessing the utility of IAP-M and its constituents by addressing the relevance and performance. In order to perform this validation, the methodology known as ‘validation square’ was adapted (Seepersad et al., 2006). The original methodology separated the merits from structural and performance points of view. This has been maintained for validating IAP. Furthermore, a distinction was made between theoretical and empirical aspects. Hence, four aspects were used in the validation of the proposed IAP-M, namely: theoretical-structural, empirical-structural, empirical-performance, and theoretical-performance. The empirical part of validation was done by examining a collection of IAP-M applications, which I called demonstrators. Improvement in terms of set performance targets was considered in the case of each demonstrator. Specific attention was given to one of the demonstrators, which resembled most an actual design situation, addressed in RC1. By a “leap of faith” outcomes of the investigation of the demonstrators were contrasted with the theoretical performance, with the goal to generalise the performance of applying IAP-M beyond the demonstrators.

1.4 Structure of this dissertation

This work’s structure follows the research design, set forth in the previous section. The empirical case studies are presented and discussed in Chapter 2. Chapter 3 presents the processing of the case study data, the reasoning behind and the concrete results of deriving hints and the transformation of the hints into a comprehensive enough theoretical underpinning of a prototyping methodology to enhance design reviews. Chapter 4, describes the constituents of IAP-M:

procedures, instruments, methods and criteria. The theoretical and application-based validation of IAP-M is covered in Chapter 5. Finally, Chapter 6 contains the conclusions and recommendations for future work. Additional data is included in the Appendices.

1.5 References

- Akman, O. (2012) "Robust Augmented Reality", Ph.D. Thesis, TU Delft.
- Azuma, R., Bailiot, Y., Behringer, R., Feiner, S., Julier, S. and MacIntyre, B. (2001) "Recent advances in augmented reality ", IEEE Computer Graphics and Applications, Vol. 21, No. 6, pp.34–47.
- Bandyopadhyay, D., Raskar, R. and Fuchs, H. (2001) "Dynamic shader lamps: painting on movable objects ", proceedings International Symposium on Augmented Reality (ISMAR), pp.207–216.
- Bimber, O. (2002) Interactive rendering for projection-based augmented reality displays , PhD dissertation, Darmstadt University of Technology.
- Bimber, O., Stork, A. and Branco, P. (2001) "Projection-based augmented engineering ", Proceedings of International Conference on Human-Computer Interaction (HCI'2001), Vol. 1, pp.787–791.
- Blake, A. Bülthoff, H. (1990) "Does the brain know the physics of specular reflection?", Nature, vol 343 (6254), pp. 165-168.
- Bochenek, G.M., Ragusa, J.M. and Malone, L.C. (2001) "Integrating virtual 3-D display systems into product design reviews: some insights from empirical testing ", Int. J. Technology Management, Vol. 21, Nos. 3–4, pp.340–352.
- Bordegoni, M., Covarrubias, M. (2007) "Augmented visualization system for a haptic interface ", HCI International 2007 Poster.
- Caarls, J. (2009), "Pose estimation for mobile devices en Augmented Reality" Ph.D.Thesis, TU Delft.
- Cao, X., Balakrishnan, R. (2006) "Interacting with dynamically defined information spaces using a handheld projector and a pen", ACM UIST Symposium on User Interface Software and Technology, p.225-234.
- Caruso, G., Belluco, P. (2010) "Robotic arm for car dashboard layout assessment in Mixed Reality environment", In 19th International Symposium in Robot and Human Interactive Communication, IEEE, pp. 62-68.
- Cheok, A.D., Edmund, N.W.C. and Eng, A.W. (2002) "Inexpensive non-sensor based augmented reality modeling of curves and surfaces in physical space ", proceedings ISMAR'02, pp.273–274.
- Clegg, S., I Bailey, J.R. (2008) International Encyclopedia of Organization Studies, Sage Publications.
- Dennis, A.R., Fuller, R.M., Valacich, J.S. (2008) "Media, tasks, and communication processes: a theory of media synchronicity", MIS Quarterly Vol. 32 No. 3, pp. 575-600.
- DiVerdi, S. Olwal, A., Rakkolainen, I. , Höllerer, T. (2007) "An Immaterial Pseudo-3D Display with 3D Interaction." In H. M. Ozaktas and L. Onural (Eds.), Three-Dimensional Television: Capture, Transmission, and Display, Springer.
- Doubrovski, E. L., Verlinden, J. C., & Geraedts, J. M. P. (2011). Optimal Design for Additive Manufacturing: Opportunities and Challenges. ASME IDETC Conference, DETC2011-48131. Washington, DC, USA. doi:DETC2011-48131

- Dourish, P. (2001) *Where the Action is: The Foundations of Embodied Interaction*, MIT Press, ISBN: 0262041960.
- Engelbrektsson, P., & Soderman, M.P. (2004) "The use and perception of methods and product representations in product development: a survey of Swedish industry", *Journal of Engineering Design* 15(2), 141–154.
- Fails, J.A. and Olsen, D.R. (2002) "LightWidgets: interacting in everyday spaces", proceedings IUI '02, pp.63–69.
- Ferwerda, J.A., Westin, S.H., Smith, R.C., Pawlicki, R. (2004) "Effects of rendering on shape perception in automobile design" In *Proceedings of the 1st Symposium on Applied perception in graphics and visualization (APGV '04)*. ACM, pp. 107-114.
- Fründ, J., Gausemeier, J., Matysczok, C. and Radovski, R. (2003) "Cooperative design support within automobile advance development using augmented reality technology", *Proceedings of CSCW in Design*, pp.492–497.
- Garde, J.A. (2013) "Everyone has a part to play: games and participatory design in healthcare", PhD thesis, University of Twente, Enschede, the Netherlands.
- Gebhardt, A. (2003) "Rapid Prototyping," Hanser publishers.
- Geraedts, J., Doubrovski, E.L., Verlinden, J.C. (2012) "Three views of Additive Manufacturing: Business, Research and Education", *proc. of TMCE 2012*, pp. 1-12. PhD thesis, University of Twente, Enschede, the Netherlands.
- Geuer, A. (1996) *Einsatzpotential des Rapid Prototyping in der Produktentwicklung*, Berlin: Springer Verlag, ISBN: 3540614958.
- Gibson, I., Rosen, D. W., Stucker, B. (2010) *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*, Springer.
- Gill, S., Loudon, G., Hewett, B., Barham, G. (2005) "How to Design and Prototype an Information Appliance in 24 Hours – Integrating Product & Interface Design Processes" in *proceedings of the 6th international conference on Computer-Aided Industrial Design & Conceptual Design*.
- Greenberg, S. and Fitchett, C. (2001) "Phidgets: easy development of physical interfaces through physical widgets", *Proceedings of UIST '01*, pp.209–218.
- Harrison, C., Benko, H., Wilson, A. (2011) "OmniTouch: Wearable Multitouch Interaction Everywhere", in *proceedings of UIST*.
- Hilton, J. (1983) "Models as an Aid to Design", in *Industrial Design in Engineering*, Charles H. Flurscheim (ed), the Design Council.
- Hoadley, F.E. (2002) *Automobile Design Techniques and Design Modeling: The Men, the Methods, and the Materials*, 2nd ed., TAH Productions, Dearborn, Michigan.
- Horváth, I. (2008) 'On the differences between research in design context and design inclusive research in the domain of industrial design engineering', *J. Design Research*, Vol. 7, No. 1, pp.61–83.
- Horváth, I., Kovács, Z., Vergeest, J.S.M. Broek, J.J. , de Smit, A. (1998) "Free-Form Cutting of Plastic Foams: A New Functionality for Thick-Layered Fabrication of Prototypes", *Proceedings of the TCT'98 Conference*, Nottingham, p. 229-237
- Horváth, I., Peck, D., Verlinden, J.C. (2009) "Demarcating advanced learning approaches from methodological and technological perspectives", *European Journal of Engineering Education*, 34(6), pp. 465-485.
- Houde, S., Hill, C.(1997) "What do prototypes prototype?", in *Handbook of Human-Computer Interaction* (2nd Ed.), Helander M., Landauer T., Prabhu P. (eds.). Elsevier Science B. V. Amsterdam.

- Janszen, B., Douvrovski, E.L., Verlinden, J.C. (2014) "Animaris Geneticus Parvus: Design of a Complex Multi-body Walking Mechanism", RP journal, vol 20(4).
- Jones, B.R., Sodhi, R., Campbell, R.H., Garnett, G., Bailey, B.P. (2010) "Build Your World and Play In It: Interacting with Surface Particles on Complex Objects", ISMAR IEEE International Symposium on Mixed and Augmented Reality.
- Jones, R., Haufe, P., Sells, E., Iravani, P., Olliver, V., Palmer, C., Bowyer, A. (2011) "RepRap - The Replicating Rapid Prototyper", *Robotica* volume 29, pp. 177–191.
- Kanai, S., Horiuchi, S., Shiroma, Y., Yokoyama, A. and Kikuta, Y. (2007) "An integrated environment for testing and assessing the usability of information appliances using digital and physical mock-ups ", *Lecture Notes in Computer Science*, Vol. 4563, pp.478–487.
- Kato, H., Billingham, M. (1999) "Marker tracking and HMD calibration for a video-based augmented reality conferencing system ", *Proceedings of International Workshop on Augmented Reality (IWAR 99)*, pp.85–94.
- Klein G., Murray, D. (2009) " Parallel Tracking and Mapping on a Camera Phone", In *Proc. International Symposium on Mixed and Augmented Reality (ISMAR)*.
- Klinker, G., Dutoit, A.H., Bauer, M., Bayer, J., Novak, V. and Matzke, D. (2002) "Fata Morgana – a presentation system for product design ", *Proceedings of ISMAR '02*, pp.76–85.
- Kuutti, K., Battarbee, K., Säde, S., Mattelmäki, T., Keinonen, T., Teirikko, T. and Tornberg, A. (2001) "Virtual prototypes in usability testing ", *Proceedings of the 34th Annual Hawaii International Conference on System Sciences (Hicss-34)*, 3–6 January, Vol. 5.
- Lee, J.C., Avrahami, D., Hudson, S.E., Forlizzi, J., Dietz, P.H. and Leigh, D. (2004) "The calder toolkit: wired and wireless components for rapidly prototyping interactive devices ", *Proceedings of DIS '04*, pp.167–175.
- Lim, Y., Stolterman, E. and Tenenber, J. (2008) "The anatomy of prototypes: prototypes as filters, prototypes as manifestations of design ideas ", *ACM Transactions on Computer-Human Interaction*, Vol. 15, No. 2, pp.1–27.
- Liou, F. W. (2007) "Rapid Prototyping and Engineering Applications: A Toolbox for Prototype Development", CRC Press.
- Marnier, M.R., Thomas, B.H., Sandor, C. (2009) "Physical-Virtual Tools for Spatial Augmented Reality User Interfaces", *8th IEEE International Symposium on Mixed and Augmented Reality ISMAR*.
- McGarry, B. (2005). *Things to think with: understanding interactions with artefacts in engineering design*. PhD Thesis. University of Queensland, School of Information Technology and Electrical Engineering.
- McLuhan, M. (1964) *Understanding Media: The Extensions of Man*, McGraw Hill, NY.
- Nam, T-J. and Lee, W. (2003) "Integrating hardware and software: augmented reality based prototyping method for digital products ", *Proceedings of CHI'03*, pp.956–957.
- Nam, T-J. (2005) "Sketch-based rapid prototyping platform for hardware-software integrated interactive products ", *Proceedings of CHI'05*, pp.1689–1692.
- Piper, B., Ratti, C. and Ishii, H. (2002) "Illuminating clay: a 3-D tangible interface for landscape analysis ", *Proceedings of CHI '02*, pp.355–362.

- Prince, S.J., Xu, K. and Cheok, A.D. (2002) "Augmented reality camera tracking with homographies ", IEEE Comput. Graph. Appl., November, Vol. 22, No. 6, pp.39–45.
- Raskar, R., Welch, G., Low, K-L. and Bandyopadhyay, D. (2001) "Shader lamps: animating real objects with image based illumination ", Proceedings of Eurographics Workshop on Rendering, pp.89–102.
- Raskar, R., Low, K-L. (2001) "Interacting with spatially augmented reality ", ACM International Conference on Virtual Reality, Computer Graphics and Visualization in Africa (AFRIGRAPH), pp.101–108.
- Raskar, R., Ziegler, R., Willwacher, T. (2002) "Cartoon Dioramas in Motion," International Symp on Nonphotorealistic Animation and Rendering, pp. 7-12.
- Raskar, R., van Baar, J., Beardsley, P., Willwacher, T., Rao, S. and Forlines, C. (2003) "Lamps: geometrically aware and self-configuring projectors ", SIGGRAPH, pp.809–818.
- Raskar, R. and Bimber, O. (2004) Spatial Augmented Reality, A.K. Peters, ISBN: 1568812302.
- Rauterberg, M., Fjeld, M., Krueger, H., Bichsel, M., Leonhardt, U. and Meier, M. (1998) "BUILD-IT: a planning tool for construction and design ", Video Program of CHI'98, pp.177–178.
- Rusák, Z. (2003) Vague discrete interval modeling for product conceptualization in collaborative virtual design environments, PhD Thesis, TU Delft, the Netherlands.
- Saakes, D.P. (2010), Shape does matter: designing materials in products, PhD Thesis, TU Delft, the Netherlands.
- Saakes, D.P., Chui, K., Hutchison, T., Buczyk, B.M., Koizumi, N., Inami, M. and Raskar, R. (2010) "Slow Display", proceedings of SIGGRAPH 2010 emerging technologies.
- Schall, G., Méndez, E., Kruijff, E., Veas, E.E., Junghanns, S. Reitingner, B., Schmalstieg, D. (2009) "Handheld Augmented Reality for underground infrastructure visualization" Personal and Ubiquitous Computing 13, pp. 281-291.
- Schmalstieg, D. and Wagner, D. (2008) "Mobile phones as a platform for augmented reality ", Proceedings of the IEEE VR 2008 Workshop on Software Engineering and Architectures for Realtime Interactive Systems, pp.43–44.
- Schon, D.A. (1994)"Designing as a reflective conversation with the materials of a design situation," Research in Engineering Design, Vol 3 New York:Springer Verlag, pp. 131-147.
- Seepersad, C. C., K. Pedersen, J. Emblemsvag, R. R. Bailey, J. K. Allen and F. Mistree (2006) "The Validation Square: How Does One Verify and Validate a Design Method?" Decision-Based Design: Making Effective Decisions in Product and Systems Design (W. Chen, K. Lewis and L. Schmidt, Eds.), ASME Press, NY.
- Smulders, F.E., Lousberg, L., Dorst, K. (2008), "Towards different communication in collaborative design", International Journal of Managing Projects in Business, Vol. 1 Iss: 3, pp.352 - 367
- Smyth, M. (2000) "Design tools as agents of disclosure", Knowledge-Based Systems, Elsevier, 13, pp. 27-35.
- Stappers, P., Hennessey, J. (1993) "Toward electronic napkins and beer mats, computer support for visual ideation skills" in Paton and Neilson (eds), Visual Representations and Interpretations, Springer, London, pp. 220-225.

- Sutherland, I.E. (1968) "A head-mounted three-dimensional display ", Proceedings of AFIPS, Part I, Vol. 33, pp.757–764.
- Tempelman, E., Shercliff, H. and Ninaber-van Eyben, B. (2014) Manufacturing Processes and Design, Butterworth-Heinemann, London, UK
- Thalen, J.P. (2013) "Facilitating User Centred Design through Virtual Reality", PhD thesis, University of Twente, Enschede, the Netherlands.
- Thomke, S., Fujimoto, T. (2000) "The Effect of 'Front-Loading' Problem-Solving on Product Development Performance", Journal of Product Innovation Management, Vol 17 (2), pp. 128 – 142.
- Tymrak, B.M. , Kreiger, M. , Pearce, J. M. (2014) "Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions" Materials & Design, vol. 58, pp. 242-246.
- Ukita, N. and Kidode, M. (2004) "Wearable virtual tablet: fingertip drawing on a portable plane-object using an active-infrared camera ", Proceedings of IUI 2004, pp.169–175.
- Underkoffler, J. and Ishii, H. (1999) "Urp: a luminous-tangible workbench for urban planning and design ", Proceedings of CHI'99, pp.386–393.
- Van Boeijen, A., Daalhuizen, J., Zijlstra, J., van der Schoor, R. (2013) Delft Design Guide, BIS Publishers.
- Varga, E. (2007) "Using Hand Motions in Conceptual Shape Design: Theories, Methods and Tools" PhD thesis TU Delft.
- Verlinden, J.C. , Roozenburg, M., Song, Y. (2012) "How it was made: a tangible replica with mobile AR", AR[t] Magazine Vol 1(2), ISSN 2213-1817, pp. 32.
- Virilio, P. (1994) The Vision Machine Trans. Julie Rose, Bloomington: University of Indiana Press.
- Welch, G. and Foxlin, E. (2002) "Motion tracking: no silver bullet, but a respectable arsenal", IEEE Computer Graphics and Applications, Vol. 22, No. 6, pp.24–38.
- Zhou, F., Been-Lirn Duh, H., Billinghamurst, M. (2008) "Trends in Augmented Reality Tracking, Interaction and Display: A Review of Ten Years of ISMAR", in proc. of ISMAR , pages 193-202.

Chapter 2

Exploring bottlenecks and best practices in specific industrial design processes

2.1 Aims, problem statement and research questions

The literature overview presented in the previous chapter indicated that there is a lack of knowledge with regards to the benefits of physical prototyping in the design process: I observed that most findings on prototyping were not representative of industrial practice because they are either based on student projects or on textbooks. Therefore, my objective was to obtain grounding from the industrial practice on how augmented prototyping had been and could be utilized in the design process.

The investigation was arranged around the following research questions:

- Why are prototypes used in design processes?
- What bottlenecks exist concerning concept uttering?
- What best practices can be found in employing physical models?

To obtain more in-depth knowledge, I chose to apply the case study method in a multiple case analysis to gain complementary knowledge in the domain of product design. As described by Yin (1988), a crucial aspect of a case study is combining multiple sources of evidence. Therefore, observations, artefact models, documentation, interviews, were considered, resulting in a collection of bottlenecks and best practices. Subsequently, a cross-case comparison needed to be executed to obtain insight in the impact of prototyping to the design process. Here, the working hypothesis was that prototypes need improvement to discuss and review concept utterances with stakeholders.

2.2 Empirical case studies of physical prototyping in industrial practice

As mentioned above, the method of multiple case studies was chosen to obtain a sufficiently deep and accurate account of all prototyping and modelling activities used at the visited companies. The criteria for the selection of the studied cases were the following:

- i) The project had to include industrial design activities,
- ii) The agency could be accessed by the researcher in terms of availability of principal designers and documentation,
- iii) The collection of the cases had to cover a variety of products, in order to cater for plurality in the body of findings.

Based on these criteria, I selected projects at three different design agencies. All three had more than five years experience with product design, while being specialized in different domains as stated in section 2.3. Table 7 specifies the coverage of the case studies in terms of interviews, recorded design reviews, and additional evidence gathered during the investigation. Case #1 (Tractor design) could be followed from the start until the end, yielding more documentation and interviews than the other two cases. Case #2 was a retrospective case study that relied on interviews with the involved stakeholders as well as inspection of all design documentation and prototypes. Due to the planned duration of three years for Case #3, only the early phases of could be covered, resulting in partial coverage of the complete design process.

Table 7 Case study coverage

Design case	Study Period		Inter-views	Interview partici-pants	Additional evidence
#1. Tractor	27-jul-2006	4-apr-2007	20	2	Models, intermediate drawings
#2. Oscilloscope	14-dec-2006	3-apr-2007	10	5	Models, design documentation
#3. Museum interior	22-aug-2006	24-apr- 2007	8	2	Models

The research questions stated in section 2.1 were converted into case study questions regarding the use and generation of concept utterances, stakeholders and group activities, and bottlenecks. Table 8 provides an overview of the structure of the case study analysis.

For each case study, its owner approved the protocol, which contained a description of analysis structures, regulations, and an introductory section to explain the objectives of the project for company representatives (Appendix A). To verify the findings in each case study, the data and interpretations were discussed with the design studio in a debriefing interview. Subsequently a formal report was made for each case study that was checked and approved by the respective case study owner.

Table 8 Structure of the case study analysis.

Case study question	Result	Data collection methods
<i>When are concept utterances generated and used in the design process?</i>	Timeline with design utterances & representation types	Observations, Interviews, Pictures
<i>What are the characteristics of these concept utterances?</i>	List of characteristics of concept utterances	Pictures (observations), Structured interviews of stakeholders
<i>Which product modelling aspects play a role in these utterances?</i>	List of aspects Specification of dependencies among aspects	Observations, Interviews
<i>What topics are dealt with as group activities? Who are involved?</i>	Timeline of topics: product modelling aspects and who is involved.	Interviews
<i>What problems occur during the creation and use of concept utterances?</i>	Description of bottlenecks, possibly related to decisions and insight.	Interviews

2.3 Description of the case studies

The following pages present each case study according to the following structure: i) case introduction, ii) stakeholders, iii) the design task, iv) the design process, and v) prototypes used.

2.4 Case #1. Tractor redesign



Figure 22 Design stages of the tractor design. Left: early 3D model, middle: sketched concept, right: picture of the null series.

The first case study was performed at a small Dutch automotive design company, consisting of four industrial designers. Their design portfolio ranges from passenger buses, specialised transportation concepts, to consumer products. Furthermore, the company has proficiency in computer-aided design (CAD) and virtual prototyping, performed on mobile workstations, often at clients' locations. The design activity observed in the case study was a redesign of the body of an imported tractor, the development of its design is summarized in Figure 22. The studio's responsibilities encompassed aspects of branding, automotive styling, detailed design, and preparation for manufacturing.

2.4.1 Stakeholders

The various stakeholders were geographically distributed. The client was a tractor dealer in the United Kingdom who first contacted a Dutch peer to refurbish the imported vehicle so as to comply with European traffic regulations. This company (manufacturer #1) acted as an overall project manager and was responsible for assembly and retrofitting the chassis. Manufacturer #2, who was contracted for the body shells, hired the design studio. Most of the communication was done by e-mail; meetings occurred only when a milestone was reached.

Within the design studio, two senior designers (#1 and #2) took part in the design activities while construction details were delegated to a junior designer (#3).

2.4.2 Design task

The assignment was the motor compartment cover (the body) and some related components such as the dashboard and panelling around the seating. The design task was focused on the body, and the designers had to address shape, construction, and material properties from the aspect of aesthetics. Traffic safety was less of an issue, as the tractor is an agricultural vehicle.

The shape of the body of the tractor was constrained by the chassis and the engineering package (engine and all related components). The body had to give room to the motion envelope of the engineering package, the axes, and the wheels. Crucial design elements were the air inlets, headlights, dashboard gauges, and steering wheel:

- Air inlets were necessary to cool the motor, but their area and placement on the hood depend on the overall body shape.
- Headlights were not included in the original (Chinese) design, but they were obligatory according to European rules.
- gauges and steering wheel of the original design needed restyling in order to match the brand of the UK-based tractor dealer.

2.4.3 Observed design process

Table 9 summarises the tractor design process, including the tasks, group activities and challenges. Designer #1 started creating a bid to the client, which was soon approved. For the remainder of this project, Designer #1 acted internally as project manager at the design studio and was in charge of the communication with the other stakeholders. Subsequently, Designer #1 performed a market analysis, collecting images and information on competing products on the Internet. The existing tractor was manually reverse engineered with rulers and callipers, specifically the motor block, a 3D model was constructed in a CAD package (Catia). Then, the conceptualisation phase started. Designer #1 and Designer #2 used Catia to make three concepts in a few days. These were presented to the other stakeholders on 5-6-2006 by means of a PowerPoint presentation containing several 3D renderings. The client responded negatively and expressed that the design lacked styling feature (“aggressive look”). Furthermore, the client insisted on using off-the-shelf headlight components. Designer #2 made modified design sketches, which included alternative motorcycle headlights in three styling concepts (“edgy”, “solid”, “cubic”). Designer #2 performed an extensive investigation into the headlights between August and September: he visited a number of car dealers to survey existing headlights, most of which were considered too expensive. Furthermore, as the tractor body was approx. 60 centimetres wide, car headlights (typically 30 cm each) were too large. The headlight were tested by probing the components in a wooden model of the front body – only one side/bottom and middle section was made with indications of the inside engineering package (coded as C1.2).

Table 9 Timeline of the Tractor design project.

	Product planning	Concepts	Detailing	Production preparation
Start date	15-5-2006	22-5-2006	26-6-2006	3-11-2006
Forms of representation	Pictures [Internet search] 3D model of engineering package [Catia]	3D renderings [Catia] 2D sketches [Photoshop, based on Catia renderings]	Pictures [visits], 3D models [Catia], 2D sketches [Photoshop& Alias Sketchbook]	3D models [Catia], construction principles [Adobe Illustrator]
Group activities/ stakeholder meetings	22-5-2006	5-6-2006 26-6-2006	1-8-2006 13-10-2006 3-11-2006	20-12-2006
Challenges	<ul style="list-style-type: none"> Reverse engineering of existing product 	<ul style="list-style-type: none"> Expressiveness of styling in 3D models (misunderstanding client) Lighting component 	Headlight unit selection <ul style="list-style-type: none"> Fit of headlight in body Dashboard & fuel cap 	<ul style="list-style-type: none"> Fit of skirts (oil filter) Blinkers

The headlight was scanned in 3D by an external firm to obtain an accurate digital model. Subsequently, Designer #3 was given the task to perform the detailed 3D specification/modelling. This included the fuel cap and dashboard dials. In this phase the model was altered to fit the headlight. The client insisted on a “flush” fit. This influenced the body geometry as well as the location and shape of the air inlets. In a final design review meeting, the result was approved by all stakeholders and Manufacturer #2 subsequently made the moulds and casts. However, the casts did not fit due to the oil filter, which was overlooked in the initial reverse engineering step.

Manufacturer #1 made several changes to the engineering structure before assembling of the null series:

- A different opening mechanism for the hood to access the motor block.
- Different material for the air vents.
- The inclusion of blinkers on the sides of the body.
- The lower parts of the front body (“skirts”) were not used to enable access to the oil filter.

These adaptations were not discussed with the designers and were made to get the null series, i.e., the final pre-production version, ready as soon as possible. The overall shape, gauges and steering wheel were not affected. The first consumer review, based on this prototype, was positive concerning both its performance and styling.



Figure 23 Left: elongated tractor chassis that was reverse engineered, right: wooden section model of the body, to select and fit the car headlights into the new shape.

2.4.4 Prototypes used

Three physical prototypes were used during this design project, for specification, exploration, and verification purposes, shown in the Table 10. During the debriefing interview, the designers expressed that the first prototype had a large impact on the design process, in that it changed the course of the rest of the design project. The other prototypes were of little significance.

Table 10 Physical prototypes used in case study #1.

	Prototype description	Primary objective	Number of prototypes	Duration (lead+lifetime)	Impact on project
C1.1	Reverse engineering of existing tractor	<u>Specification</u> of engineering package and shape constraints	1	1 week	Large
C1.2	Wooden section of part of the body	<u>Verification and exploration</u> of headlight fit.	1	1 day	Minimal
C1.3	Null series	<u>Specification</u> of shape, <u>verification</u> of body fit and construction	1	1 month	Minimal

2.5 Case #2. Hand-held oscilloscope design



Figure 24 Hand-held oscillator prototypes of case study #2 (cf. Table 12).

This case study was performed at a design department of an international electronics design and manufacturing company. Due to sensitivity of running projects, a project from the past was selected, that was well documented and key personnel were still accessible at the company. The design project was the redesign of a handheld digital oscilloscope, which involved developing new technologies for fast analogue–digital conversion, updating brand aesthetics, and optimizing ergonomics to fit the target users. This project took place between 1996 and 1999, and its resulting product, the 190 series, is regarded as one of the best in the market: it won several design prizes (IF Design award 2000) and the brand’s subsequent products are still using the same styling.

The case study protocol was adapted to a retrospective analysis, following the same procedure to include interviews with former stakeholders, an on-site inspection of the design documentation. At the time of this project, the people I interviewed functioned as product planning lead (1), industrial designer (2), user interface designer (1), mechanical engineer (2), and electrical engineer (2). That is, altogether 8 people were interviewed. Finally, I had a debriefing interview and check of the case study report with the original product planning leader.

2.5.1 Stakeholders

All stakeholders were employees of the same company and came from multiple disciplines. The product planner was responsible for the overall development process, while hardware aspects were covered by industrial designers and mechanical engineers, software aspects by user interface designer and software engineer, and electronics by technology innovators and electrical engineer. At the end of the development process, factory engineering, and packaging departments were involved, while sales representatives were involved during the whole project.

Many team members were already involved in other oscilloscope designs, but a significant difference was that previous projects were dispersed in several departments. In this project, team members were co-located in an open office environment. All intermediate prototypes and specifications were collected on a table in the centre of the office, with an emphasis on “total user experience”. The

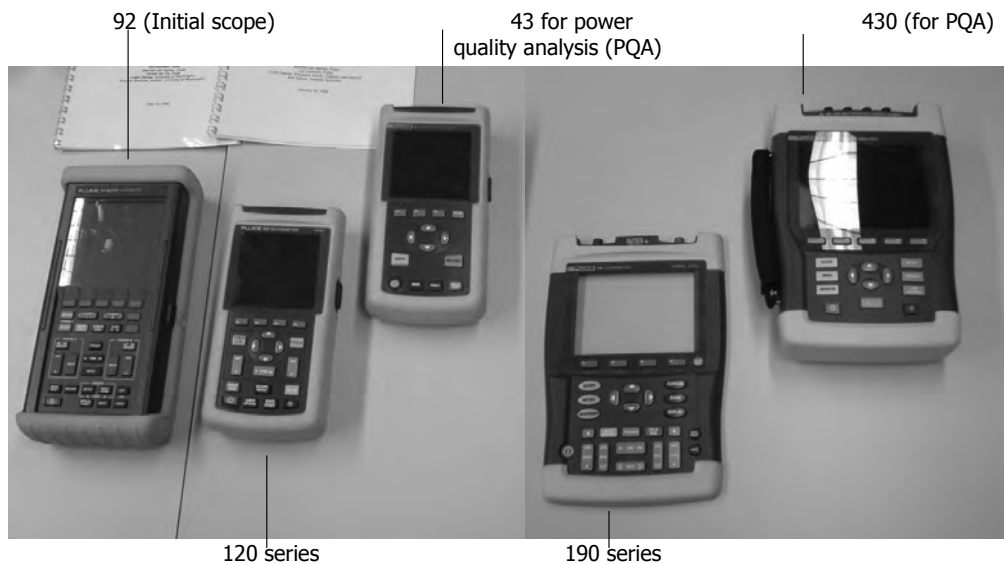


Figure 25 Chronological order of portable Oscilloscope designs.

interviewed team members claimed that this physical display had a large impact on getting support from higher management, while also serving as a sales pitch for prospective clients.

2.5.2 Design task

In contrast to the previous series, the oscilloscope was solely focused on the analysis of analogue signals that required new functions such as saving and recalling from memory.

Three design challenges dominated industrial and interaction design:

- **Display:** Between 1996 and 1999, it was not possible to select a proper liquid crystal display from a catalogue. This not only influenced product cost and development effort for electrical engineering but also the performance of the screen (field of view, contrast, resolution, colour capabilities), as well as the size and weight. Initially, a 320x240 pixel grey scale display was used, and later replaced with a colour version that required a redesign of the graphical user interface.
- **Button layout:** selection, placement, and size of the keys were a major design challenge. The buttons enabled the user to display, scale, filter, and record one or two analogue signals. They had to be used during diagnostics and repair of large electric installations (possibly while the user is wearing gloves). The final design had 35 buttons.
- **Probes:** the user had to be able to shift between various tips and clamps in order to touch contacts and pick up electric signals. Over 20 probes with different tips and voltage ranges would ship with the product. At the time, there were no standards or certifications for these probes.

Although the electronics parts (engineering package) also received a great deal of attention during development, the designers considered the resulting engineering package as given, to be built into the product.

2.5.3 Observed design process

Table 11 summarises the oscilloscope design process, including the tasks, group activities, and bottlenecks. During the product-planning phase, product ideas were devised based on the earlier handheld oscilloscopes (Figure 25). The product requirements were determined during focus group discussions with electricians in the United States. During these sessions, foam mock-ups were used to check grasping and carrying experience, as well as to test appeal of the shape. After formulation of a business plan to prove financial feasibility, product planning was finalised. During the concept development phase, the team grew to a multidisciplinary group of 8 people who focused on design and engineering aspects of the oscilloscope. At this stage, both physical (foam) and virtual (Alias Wavefront) mock-ups were made. The user interface was developed as a paper prototype, i.e., screens were sketched on pieces of paper. Intermediate designs of both shape and screen interaction were evaluated with prospective users by the product planner. He contacted users, demonstrated prototypes (both foam, paper, and later working prototypes) and tried to map their activities and preferences. Each of these visits took approximately 2 hours and was accompanied by engineering team members. The complete team received feedback from these users in monthly meetings. This continued throughout the complete development process, and totalled more than 150 visits in the Netherlands, Germany, UK and USA.

In the detailing phase, the dimensions and shape were fixed and the industrial designers focused on specifying the injection moulding details, buttons, and the accessories such as the probes and packaging. The user interface (display and button control) was implemented in a PC simulation (visual basic) to be used for

Table 11 Timeline of the oscilloscope design project.

	Product planning	Concepts	Detailing	Production preparation
Start date	March 1996	July 1997	March 1998	April 1999
Forms of representation	Sketches, mock-ups [foam], Interface sketch [paper]	Mock-ups [foam], 3D renderings [Alias Wavefront], UI design [paper]	Mock-up [wood, CNC], 3D surface model [Wavefront], interaction simulation [PC-visual basic], Navigation [State transition diagrams]	Shell model [Stereo lithography, First-out of tool/Second-out of tool] working engineering package (alpha release)
Group activities/ stakeholder meetings	Monthly internal presentations			
Challenges	<ul style="list-style-type: none"> • Team-building • Key technologies research • Obtaining user focus 	<ul style="list-style-type: none"> • GUI modelling • Team communication 	<ul style="list-style-type: none"> • Accessories (bag, packaging, probes) • Colour Version 	<ul style="list-style-type: none"> • Screen resolution • Power on-button

both usability tests as well as a specification means for software engineers. In this phase, the user interviews focused on assessment of the shape (CNC milled mock-ups), the user interface (PC simulation), and the sales pitch (packaging text). During the production preparation phase, the body was manufactured with stereo lithography to test the internal fit and some strength properties. This was soon followed by the First out of Tool and Second out of Tool models from injection moulding, which were used to tune the material composition and surface texture. This was also the first opportunity to integrate working PCBs into the physical shell. At this stage, usability problems surfaced, most notably, the access to the power on/off switch which required a different shape. Subsequently, higher management decided to alter the product to a colour version, which required changes to the display: new graphics and fonts had to be developed. Due to the imminent product launch, no field-testing could be performed on these changes. The series 190 entered the market in October 1999.

2.5.1 Prototypes used

Six physical models were used during this design project for exploration, verification, specification, and communication purposes, as shown in Table 12. During the debriefing interview, the designers expressed that the initial foam mock-up and the final null series had a large impact on the design process, while user interface mock-ups had little significance (C2.2 & C2.3).

Table 12 Physical prototypes used in case study #2.

	Prototype description	Primary objective	Number of prototypes	Duration (lead+lifetime)	Impact on project
C2.1	foam mock-up	Exploration of dimensions and overall shape.	10	1 month	Large
C2.2	User interaction prototype (PC-based simulation with physical keys on mock-up)	Verification and specification of User Interface.	1	2 months	Minimal
C2.3	User experience prototype (CNC milled)	Specification and communication of shape details and surface tuning	1	2 months	Minimal
C2.4	Mechanical prototype (Stereolithography)	Exploration of inside construction	3	3 months	Medium
C2.5	first & second out of tool injection moulded (FOOT/SOOT)	Verification in tolerancing and material finish ("feel").	2	4 months	Minimal
C2.6	Null series (moulded)	Verification of software and manufacturing	50	4 months	Large

2.6 Case #3. Museum interior design



Figure 26 Exterior of the building in which the museum is located on the ground floor (built in 2008).

The third case study was carried out at an office of a well-known Dutch furniture designer, which employs eight people with training in fine arts. The head designer emphasised innovative approaches to furniture design. The monitored project was interior and specialised furniture design of a municipal museum in The Netherlands. The case study covered the process from August 2006 until April 2007, when the detailing phase was completed.

2.6.1 Stakeholders

At the design studio, three designers shared the work from October 2006 until the museum opened in 2008. The head designer was responsible for keeping the overall vision while an experienced architectural designer managed the project, and delegated 3D modelling to an arts student. Compared to the other cases, there were more external stakeholders, including director of the museum, curators, restaurant keeper, and local government representative. The director was the key decision maker, who controlled the budget and managed practical issues. The curators had the largest influence on the interior, as they were in charge of launching exhibits to attract the public. The officer of the local government was responsible for funding and building regulations. The restaurant keeper's concerns were the logistics of serving food and drinks. Other than the representative of the local government, all external stakeholders had no experience with design projects. The interim director chose to meet every month with all stakeholders to review the progress.

2.6.2 Design task

The assignment was to design the museum’s interior, in particular, the layout of the space, as well as furniture for the particular functions, such as a counter, restaurant, and museum shop. Structural walls were predetermined, including the staircase and façade. The original design brief stated that the interior had to be flexible and easily adaptable to different layouts for exhibits and special events (the original proposal was titled “art parking”). The events would differ in audience and activities, yet all would use the same confinements of the museum. The events included: child’s atelier, exhibit, architecture cafe, lecture, dancing, auction, and workshop.

2.6.3 Observed design process

Table 13 summarises the museum interior design process, including the tasks, group activities and challenges.

Table 13 Timeline of museum interior design project.

	Product planning	Concepts	Detailing	Production preparation
Start Date	Spring 2005	September 2006	April 2007	September 2007
Forms of representation	Sketches [illustrator]	Sketches [illustrator], 2D and 3D line drawings [Vectorworks], Scale models [foam board and paper]	-	-
Group activities (design reviews)	Pitch (presentation+ book)	Monthly presentations with all stakeholders		
Challenges	Persuading other stakeholders during competition	<ul style="list-style-type: none"> • Fixing design specifications (requirements) • Curtains • Office space • Garden • Mobile kiosk 	-	-

The city invited three design agencies to develop the plan for the museum’s interior in a competition. The head designer (designer #1) created a vision in a few days that two junior designers translated into floor plans and visuals, collected in a booklet. The presentation emphasised the flexibility and identity of the future museum interior. As designer #1 stated in the interview: “The challenge is that you can think of a museum as the ultimate white box – a place in which the only objects present

are the objects of art. Yet we wanted to create something with its own visual identity that can successfully harbour different pieces”.

After the winner was announced, the project started in September 2006. A different designer at the studio, trained as architect, was appointed to lead the rest of the project, while designer #1 remained involved to preserve the underlying vision. The first task was to fix the design requirements. This proved to be a challenge, as the initial specification was a narrative of four pages were vague. This was partially due to the lack of commissioning skills of the external stakeholders – they were involved in an interior design project for the first time in their life. The studio translated the narrative into a one-page list of features and events. In a subsequent booklet, the studio proposed four design scenarios to trigger discussion during the design review. The scenarios identified a collection of solutions and implicitly encompassed the studio’s preferences, including a large curtain to flexibly separate spaces at will. A 1:50 scale model showed the fixed elements glued to the floor plan, extended by abstract elements to represent furniture (C3.2). However, during the subsequent design review, the design team had difficulties to keep the discussion focused on functions of the interior while disregarding aesthetic details. In particular, the director did not appreciate curtains used as a wall to split a room. Decisions on functional use of the space had to be postponed.

In December, alternative scenarios for office space and exhibit facilities were discussed. Designer #1 presented a booklet and an altered scale model, proposing to combine office space and the counter in a mobile unit. The curators did not accept this proposal, and demanded private office space. This proposal led to annoyance and trust issues in how the studio interpreted the assignment. The director supported his staff in this matter, while voting in favour of the designers in another disputed part of the interior, namely the design of the counter.

In 2007, a full specification of the furniture and layout plans was developed, and was labelled the “preliminary design”. It was documented in floor plans and section views, combined with a new scale model (C3.4). One of the emerging ideas was a mobile kiosk, initially imagined to solve a problem of docking and unloading transport trucks. This mobile kiosk was further elaborated to function as an advertisement opportunity of the museum that could host small-scale events. My investigation stopped in May 2007, just after the finalisation of this preliminary design specification. The Museum was opened on May 1st, 2009.

2.6.4 Prototypes used

Four 1:50 scale models and floor plans were used in this project, as summarized in Table 14. During the debriefing interview, the designers expressed that all the prototypes had large impact on the design process, in that they changed the course of the rest of the design project.

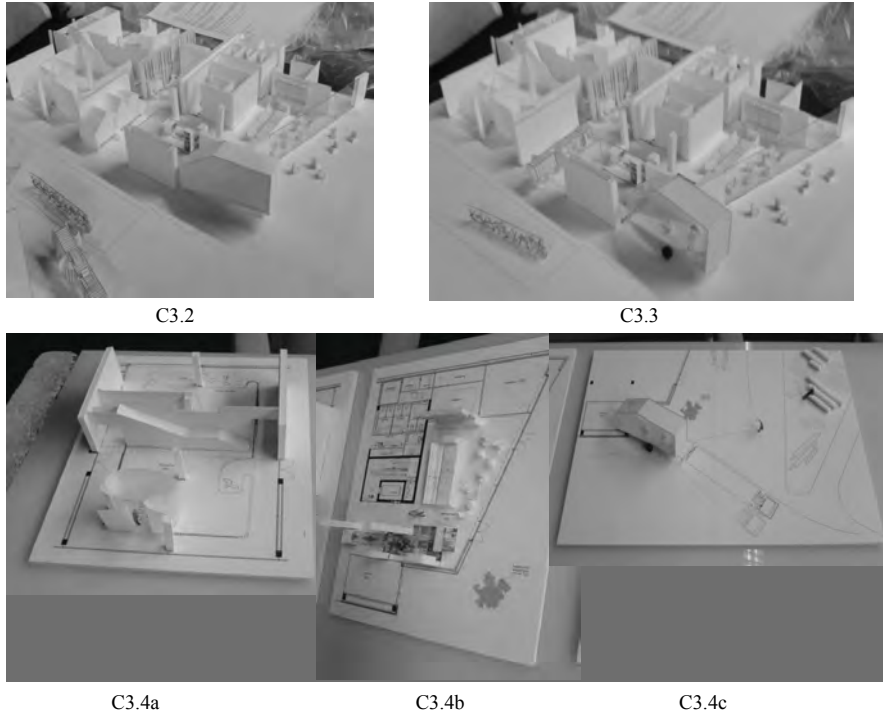


Figure 27 Scale models used in the preliminary design phase, initial (C3.2), adapted (C3.3), and final (C3.4a-c).

Table 14 Physical prototypes of case study #3.

Prototype description		Primary objective	Number of prototypes	Duration (lead+lifetime)	Impact on project
C3.1	Initial scale model (provided by museum)	<u>Exploration</u> of space, <u>specification</u> of interior-exterior interface	1	2 weeks	Large
C3.2	Draft layout (November 2006)	<u>Exploration</u> of different usage scenarios, <u>communication</u> during design review	1	Few days	Large
C3.3	Adaptations (different furniture in previous scale model) (December 2006)	Further <u>exploration</u> of furniture and <u>communication</u> during design review	1	Few days	Large
C3.4	Preliminary design freeze (April 2007)	<u>Specification</u> of final design	3	Few days	Large

2.7 Cross-case identification of bottlenecks and best practices

The cross-case study was focused on the bottlenecks and best practices considering concept uttering, to address the research questions of Section 2.1. Here, I used the ATLAS.ti software application¹, which can connect video/audio recordings to transcripts and other case documentation, and is be used to codify text selections, as shown in Figure 28. In this project, it was not feasible to validate bottleneck finding by multiple coders: the interview transcripts totalled over 700 paragraphs. As proposed as closed coding strategy of grounded theory (Glaser & Strauss, 1967), I processed the interview transcripts of the case studies by highlighting and including annotations when either challenges or best practices appeared. These were triangulated by the written documentation (presentations, emails, and design review minutes). I then identified the design challenges and best practices in three additional read cycles, focusing on communication and the effect of specific prototypes. Then, the resulting process highlights were collected and

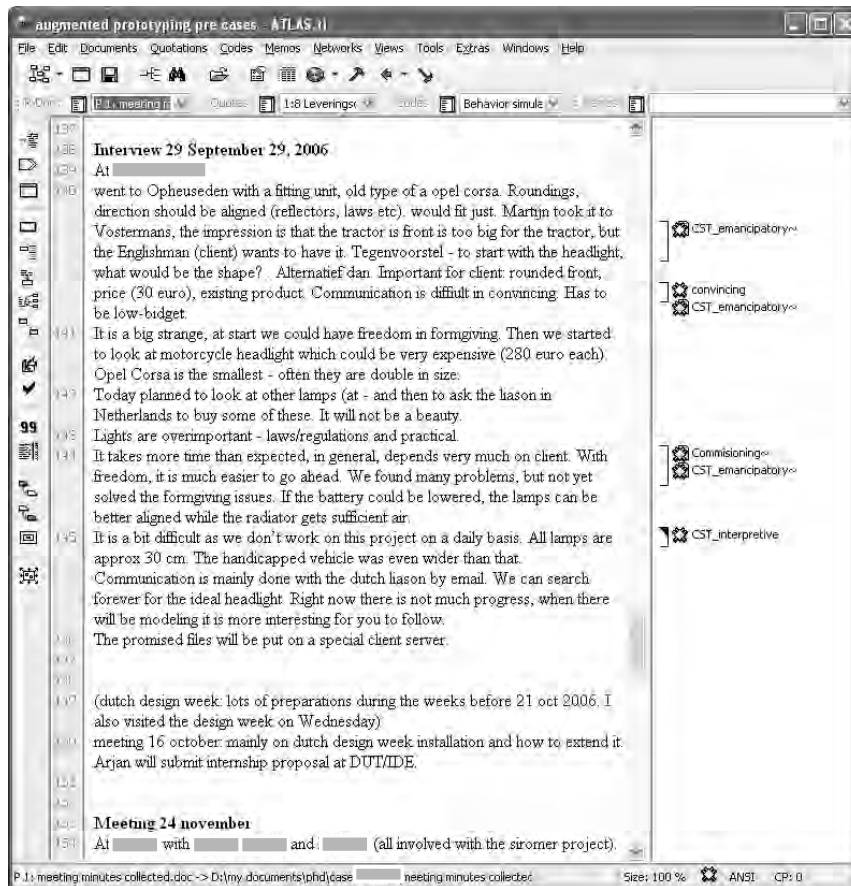


Figure 28 Snapshot of the case repository.

¹ www.atlasti.com

clustered, the full list resides in the appendix B. This collection was subsequently discussed with the original problem owners to determine their impact on the overall design process. The following sections discuss those bottlenecks and best practices that had a large impact.

2.7.1 Bottlenecks

The bottlenecks were considered to hamper the design process, could be clustered in categories related to product, stakeholders, and studio. Table 15 provides an selection of the most important, including a reference to the original document in the case repository. An account of all bottlenecks is found in Appendix B.

Table 15 Case repository of bottlenecks with a large impact.

ID	Bottleneck	Consequences/impact	Evi- dence
<i>Product</i>			
1F.1	Retrofit a fixed component (headlight) to freeform surface geometry	- Project delay - Unwished alterations of expression/style	#20
1F.2	Problems in finding headlight which would fit in the design	-Increased time and effort	#12, #19
2P.2	Crude tools to specify Graphical User Interface (interaction/navigation, resolutions)	-Limited amount of options -Incomplete specification -Superfluous communication with software engineers	#2, #3
2F.2	Button placement should consider engineering package inside (collision avoidance)	- Additional Redesign effort	#3, #10
3F.2	No tools at hand to specify dynamic behaviour of the building (use, business processes)	-Difficulties in expressing and assessing dynamic quality of interior design	#8
3I.4	Budgeting is difficult to fix (museum-specific?)	-Difficult basis for design decisions	#4
3I.5	Difficulties in fixing the design requirements	-Additional effort to translate to usable specifications	#8
<i>Stakeholders</i>			
1I.1	Priorities of the others (client, designer) concerning headlight design were not understood	-Conflict	#9, #12,#20
1I.2	Indirect contact with client – assignment came from the part builder ; unclear project structure.	-Miscommunication -Delay -Too much stress on engineering at start	#20, #22
1E.1	Client was not open to arguments of designers concerning headlight	-Too much domination in decision making -No optimal design freedom	#12,#22
1E.2	Client's requirement towards the headlight and style were not picked up from start	-Client was not taken serious. -Lack of trust	#22

3I.1	Difficulties to communicate style elements (curtains)	-Delay in design decision -Resistance in accepting parts of the designs by other stakeholders	#4, #6,#8
3I.3	Functional aspects get little attention in design reviews Client was preoccupied with form elements/aesthetics.	-Additional translation required by designers -Adjustment of agenda	#8
1E.3	Without consulting the designers, the manufacturer adapted the design for the null series (blinkers, air vents, skirts)	-Designer is not taken serious	#20, #21, #22
<i>Studio</i>			
1P.1	The inclination to use CAD and 3D renderings could have been better balanced with other representations (sketching, tape-drawing)	-No lateral thinking/emergence of innovative shapes -Neglect of visual and physical product manifestation	#20, #22
1P.2	The use of (physical) prototypes was not part of the design brief	-Threshold towards employing prototypes	#20

2.7.2 Best practices

The best practices of the design agencies were clustered into issues related to product manifestations, stakeholder communication, and studio. Table 16 provides an account of the most relevant, a full account is provided in Appendix B.

Table 16 Best practices.

ID	Best Practice	Consequences/impact	Evi- dence
<i>Product manifestations</i>			
2P.1	Many physical models throughout the design process	+ Increased inspiration	#2,#3,# 10
2F.4	Physical mock-ups were easy to make in foam and paper, had a large effect at start of process	+Decreased cost and effort of redesigns later on	#3,#8, #10
2E.1	Lot of usability studies	+User is taken seriously +Valid grounding to make decisions	#10
3P.1	The movements of people/users could be used as a base to design a floor plan/objects	+Inspiration by envisioning complex performance aspects	#1, #8
<i>Stakeholder communication</i>			
2P.4	Table with all design materials available at all times	+ Display of richness, variance + Increases shared understanding + All team members could contribute to this display + Convinced and impressed higher management and prospective customers	#8, #10
2E.3	Physical models served as a conversational piece, to access prospective users.	+Eases access to focus groups +Initiated open discussion with prospective users	#10

2I.1	Monthly confrontation of user feedback to the team	+Increased shared understanding of user context, preferences + Rapid feedback on design changes	#10
3I.2	Monthly meetings with all stakeholders, sharing meeting minutes	+Increased shared understanding +Keeping focus in long term project	#6, #8
<i>Studio</i>			
3F.1	Photoshop is used to explore colour/material textures	+Saved time	#4
3E.2	Scale models contained designs of the surrounding landscape, although these were not part of the design assignment	+Attain influence outside given design scope	#8
3P.2	During presentations, the narrative excels in framing dynamic and metaphoric aspects of a design	+Enriches the ability to share complex dependencies	#8
3E.3	Designer purposely made rough scale models, textual descriptions and sharp section views.	+Keep focus on the designer's agenda	#8

2.8 Reference model of prototyping for shared understanding

In order to convert these findings into a methodology, a reference model was made to chart the main constructs and their causal relationships of impacting each other (Blessing and Chakrabarti, 2009). The reference model, depicted in Figure 29, establishes correspondence between a project's performance and the bottlenecks and best practices. Specifically, process delays, stakeholder's trust, and product quality.

In the case studies, both design reviews and other communication with stakeholders were identified to have a large impact on the product development process. Design reviews represent a "formal documentation and interrogation instrument" in the design process. These meetings with stakeholders are aimed at assessing the intermediate design results by various criteria and to discuss sub-problems, in various ways of structured procedures (Turner, 1982). Mitchell (1994) stresses that these reviews improve the design by establishing a unique event that combines information exchange, interaction, and conflict resolution. Stompff expanded the use of formal design reviews with teams, with the importance of using physical prototypes to create shared understanding. Xijuan et al. (2002) attempt to quantify the impact and effect of a specific design review by comparing the fidelity of the design before and after. However, each design review bears different discussions, timing and procedures (Pugh, 1990). The case study owners mentioned in the debriefing interviews that the success factors were stakeholder's trust and product quality, while product delays were happening both in case #1 and #3.

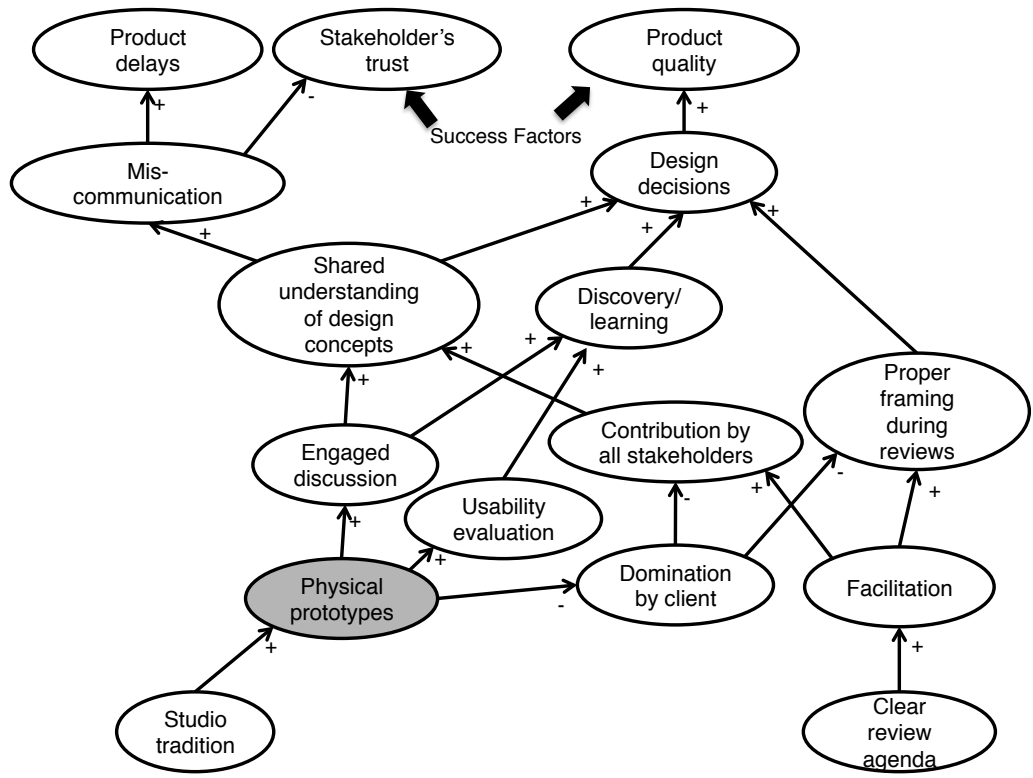


Figure 29 Reference model of prototyping for shared understanding and discovery (+ = enhances, - = diminishes).

The central construct is the *shared understanding of design concepts*, which has an impact on miscommunication (as a negative construct) and quality of design decisions. Shared understanding is affected by the personal skills and knowledge of the meeting participants (Bucciarelli, 2002). A secondary construct is the presence of *discovery/learning* during the design review: amongst others, finding errors in a design and solving these during design review meetings, denoted in Huet et al (2007). A third construct is the *proper framing of the discussion during design reviews*, which considers how the focus is kept on those topics that are essential for the current design situation. As Schon (1983) explains in his theory on reflective practice, framing is the activity to construct meaning by underlying structures of belief, perception, and appreciation. This construct is also known as external reframing (Mazhedi, 2013), this activity engages all stakeholders in addressing the action. Drawing from the observation from the case studies, I claim that these three constructs positively influence design decisions, while ill shared understanding leads to miscommunication. *Engaged discussion* denotes an active and informed debate with an intense use of all design representations. *Contribution by all stakeholders* expresses the impact of all stakeholders to the design review, some of who might be absent during design reviews but still be consulted (such as the focus group studies of case #2). The use of *physical prototypes* can diminish *domination by client*. This happened in case #3, while in case #1, the absence of models fostered domination and created issues of trust. *Clear review agenda*, *facilitation*, and *usability evaluation*

are constructs that were distilled from the case studies. The use of *physical prototypes* is determined by *studio tradition* (which contrasted between cases #1 and #2 in computer and prototyping practice).

By stipulating causal links of the bottlenecks and best practices, the reference model provided a forerunning framework of understanding communication, in particular the role of prototypes in design reviews. It is a preliminary, qualitative model that is used to set the focus and demarcate the extent of a hypothetical design support methodology in next research cycles.

2.9 Robustness of the case studies

Three case studies involved industrial design projects that illustrated prototyping objectives and deepened existing knowledge about the use of these physical representations of the design process. In considering the robustness of the findings, three concerns about the conduct need to be addressed: representativeness of the design task, limited amount of cases, and possibility of outdated practice and technologies.

2.9.1 Representativeness of the design task

In the debriefing interviews, the involved project owners with over 15 years of design experience confirmed that the investigated projects were representative of industrial design work. By nature, all three design projects were different, but the process highlights overlap in terms of bottlenecks and best practices. The tractor design project was considered different from automotive design in its manufacturing process (limited to manually made plastic bodywork).

2.9.2 Limited amount of cases

As a qualitative study with N=3, the robustness of created knowledge is limited. However, as the research questions stated, the objective of this multiple case study was to obtain grounding from design practice. Furthermore, as the principal researcher was involved in collecting, processing, and interpreting the data, an objective stance was obligatory, provided by the case study protocol and the procedures for highlighting the case repository in Atlas.ti. Although debriefing interviews helped to check the generality of three specific cases, the collected body of findings and the resulting reference model could be used as a source of inspiration, yet do not provide a solid reasoning platform for validating new design methodologies or tools.

2.9.3 Possibility of outdated practice and technologies

According to Gartner's Emerging technologies Hype Cycle, Augmented Reality has moved from being a technology trigger in 2006 to a spot in the trough of disillusionment in 2013, while Rapid Prototyping just recently appeared as an innovation trigger labelled "3D printing" (2013). However, these trends did not change the tradition of the agencies involved in the case studies. In January 2013, I visited the case study owners to reconfirm the case study findings and check the forerunning design support methodology. According to their opinion, the past projects reflected current practice in design, and the best practices still were valid,

while the bottlenecks were considered as learning experiences. They considered the use of smartphones and wireless Internet as the only major technological change, yet this was not yet fully integrated in their business processes.

2.10 Conclusions

In order to obtain insight into current industrial use of prototyping, I followed two design projects over the period of 9 months, and I investigated one past design project as retrospective case. I particularly focused on the communication with clients and other stakeholders, as well as the models and design specifications that were used internally. The case studies covered the design domains of interior, automotive, and information appliances, and included two to six different types of physical models, mainly for exploration and communication purposes. The involved project owners with over 15 years of design experience confirmed that the investigated projects were representative of industrial design work.

Coding the interview transcripts in Atlas.ti tool aided to find the bottlenecks and best practices in concept uttering. The bottlenecks explored for the particular case studies can be summarised as follows:

- Case #1 (tractor) suffered a 6-month delay due to miscommunication with a client who had no training in design. The client did not understand presentation style of the concepts: the design had to be redone by the design studio. Finally, due to some errors in the initial reverse engineering, the manufacturer adapted the final design without consulting the studio. The bottlenecks were enlarged by the fact that the stakeholders were not co-located and took limited effort for communication.
- Case #2 (Handheld oscilloscope) experienced issues in consolidating the different engineering aspects (mechanical, electric, software) to designers of hardware and software.
- Case #3 (museum interior) encompassed a large number of external stakeholders who all wanted to contribute to the design without any training. This created difficulties in envisioning functions in a spatial layout and according to the studio yielded a compromised design.

This body of findings triggered the development of a reference model, linking the use of prototypes to reaching shared understanding during a design meeting. This model hypothesises that the lack of shared understanding affects product delays, stakeholder's trust and product quality. This implies that AP should try to support the design review. The identified set of bottlenecks and best practices will be used in the following chapter to further explore opportunities of AP design support scenarios.

2.11 References

- Blessing, L., Chakrabarti, A. (2009) "DRM, a Design Research Methodology", Springer.
- Bucciarelli, L.L., (2002) Between thought and object in engineering design, *Design Studies*, 23(3), pp-219-231
- Gartner (2013) "Gartner's 2013 Hype Cycle for Emerging Technologies Maps Out Evolving Relationship Between Humans and Machines", <http://www.gartner.com/newsroom/id/2575515>, visited march 2014.

- Glaser, B., & Strauss, A. (1967) *The Discovery of Grounded Theory*. Chicago: Aldine.
- Huet, G., Culley, S. J., McMahon, C. A., Fortin, C. (2007) "Making sense of engineering design review activities", *AI EDAM journal*, vol. 21(03), pp. 243-266.
- Turner, B. (1982) "Design Audit", *Design Studies*, Vol 3(3), pp. 115-122.
- Mitchell, W.J. (1994) "Three paradigms for computer-aided design", *Automation in Construction*, July, Vol. 3, No. 2–3, pp.239–245.
- Xijuan, L., Yinglin, W., Shouwei, L. (2002) "A metrics based task analysis model for design review planning", *Design Studies*, Vol 24, pp. 375–390.
- Pugh, S. (1990) *Total Design: Integrated Methods for Successful Product Engineering*, Addison-Wesley, New York.
- Schon, D (1983) *The reflective practitioner- how professionals think in action*, Basic Books.
- Stompff, G. (2012) *Facilitating Team Cognition. How designers mirror what NPD teams do*, PhD Dissertation, TU Delft, the Netherlands.
- Yin, R. (1988). *Case Study Research: Design and Methods*. London: Sage.
- Zahedi, M. Sharlin, M., Bartus, T.J. (2013) "Framing Episodes Leading to Emergence of Shared Goals within Client/Design Team", *proceedings of IADSR 2013*, pp. 1182-1194.

Chapter 3

Deriving indicators of the need for an efficient enabler in design processes

3.1 Aims, problem statement and research questions

The case studies described in the previous chapter provided insight on the current state of including of prototypes in the design process in different domains. To use these findings as a source to generate design support scenarios for AP, I have formulated the following research questions:

- What support scenarios by AP can be generated based on these findings?
- What underlying theory can be formulated to be able to combine these scenarios into a design methodology?

My working hypothesis is that AP can support the communication among stakeholders by increasing the speed of establishing shared understanding on design concepts.

3.2 Hints

I devised the notion of a *hint* as a supporting conceptual means to speculate about AP solutions, based on the evidence from the case studies. In this project, a hint is understood as an indication of something that contains a part of a solution for a recognised bottleneck. It embodies pointers to particular low-level design support scenarios that could relieve bottlenecks or that apply a best practice. Figure 30 shows the hint's structure: first the scenario, and then a bullet list with the underlying evidence – bottleneck or best practice with reference to the case study repository presented in the previous chapter between parentheses - combined with the envisaged consequence.

Hint : <support scenario>

- ❖ <bottleneck or best practice text> (<bottleneck or best practice identifier>) → <envisaged consequence of the support scenario>

Figure 30 Hint formatting scheme.

In the “Art of conjecturing”, Jouvenel (1967) argues that the conception of future technology solutions requires considering a utopian stance in which technology assists society. In essence, hints are speculative elementary usage scenarios, for my study focused on AP. To generate hints, the bottlenecks and best practices of the case studies (cf., Appendix B) were revisited in view of the working hypotheses on IAP stated in the previous section and design support applications presented in Section 1.2.1 The resulting collection is presented below.

Hint 1: There is a need for presenting design alternatives of different aspects (interaction, electrical engineering, mechanical engineering, manufacturing).

- ❖ Physical mock-ups were easy to make of foam and paper and had a large effect at the start of the process (2F.4) → AP can enrich these mock-ups and lower the required costs & effort.
- ❖ Table with all design materials available at all times (2I.2) → AP increases shared understanding and can help integrating the – otherwise separate – design specifications.
- ❖ Challenges in finding headlight to fit the design (1F.2) → AP saves time and effort in exploring features on a fixed shape.

Hint 2: There is a need for a ”conversational piece”– projecting contexts to engage the audience.

- ❖ Physical models were used as a “conversational piece”, to access prospective users. (2E.3 & 2P.3) → AP brings about a novel stimulus to contact users, and stimulate discussion.
- ❖ Table with all design materials was available at all times (2P.4) → AP displays a plurality of ideas on a small collection of physical objects that engages stakeholders.

Hint 3: Combining existing physical models (chassis, engineering package) with virtual surface modelling offers advantages.

- ❖ Inaccuracies in initial reverse engineering of motor dimensions produced errors in the design that were recovered in manufacturing the null series (1F.3) → display of virtual designs on physical model engages natural spatial reasoning to check geometric fit of physical components.

Hint 4. Tagging or object recognition allows physical models to be linked to virtual designs.

- ❖ Fit of fixed component to freeform surface (headlight) (1F.1) → AP offers better consideration of style languages of freeform shapes.
- ❖ Challenges in finding headlight which would fit the design (1F.2) → AP saves time and effort in exploring features on a fixed shape.
- ❖ The use of (physical) prototypes was not part of the design brief (1P.2)→ AP facilitates cheap prototyping, lowering the threshold to using physical models.

Hint 5: Interactive display of digital details near or on physical prototypes improves information.

- ❖ Existing specification in preliminary design spanned many pages (3F.6) → AP enables fast retrieval of digital details using the physical parts as “bookmarks”.

Hint 6 The projection of material/textures increases the sense of reality (“Material lights”).

- ❖ The use of (physical) prototypes was not part of the design brief (1P.2)→ AP facilitates cheap prototyping, lowers the threshold to use physical models.
- ❖ The computer (Photoshop) was used to perform colour/material textures (3F.1) → Faster material exploration, larger number of materials/textures can be explored.

Hint 7 There is a need to link product models to budgeting/requirements engineering tools.

- ❖ Difficulties in fixing the design requirements & budgeting as stakeholders cannot understand their dependencies (3I.5, 3F.4, 3I.4) → Interactively calculate project key performance indicators from a augmented prototype (e.g. costs, manufacturing time, and so forth).

Hint 8 Physical models can be used advantageously as a collaborative, social medium to discuss design concepts.

- ❖ Priorities of client and designer concerning headlight design were not mutually understood (1I.1) → AP to capture priorities in design context.
- ❖ Client's wishes with regard to the headlight and style were not picked up from start (1E.2) → Better client engagement by allowing interaction with AP.
- ❖ Physical mock-ups were easy to make in foam and paper and had a large effect at start of process (2F.4) → Using low-cost AP decreases modelling cost & effort required.
- ❖ Monthly presentations of user feedback to the team (2I.1 and 3I.2) → AP allows to present design errors on top or near design alternatives, building shared understanding of user context.
- ❖ Table with all design materials available at all times (2E.2) → AP should be accessible to all stakeholders to contribute to and interact with intermediate project results.
- ❖ Other stakeholders had a different frame of reference. They typically mention existing furniture blocks, which they developed in previous function (3I.8) → AP can superimpose different artefact representations directly on spatial manifestations, speeding up shared understanding.

Hint 9 Several levels of abstraction and concreteness need to be blended.

- ❖ Functional aspects got little attention in design reviews, as the clients were often preoccupied with form elements/aesthetics (3I.3) → AP can serve to improve the topic of the discussion during design reviews.
- ❖ Sketchy scale models were used, without colour/material details (3I.6) → AP to improve the focus of the discussion during design reviews.
- ❖ The coloured doll suggested colour to the monochrome model, even though it was not part of the interior design itself (3P.5) → AP can increase richness in expression while keeping an intended level of abstraction.

Hint 10 The use of various materials enrich the design discourse.

- ❖ Various materials were used to represent furniture – not necessarily limited to those representing reality (3P.4) → AP can increase inspiration by expressing a diversity of materials.

Hint 11 Physical objects can be more expressive by including other information carriers, such as verbal, graphical animations, textual, symbolic.

- ❖ Expression of style was not understood (3I.1) → AP improves expression possibilities and allows providing better insight.
- ❖ There were difficulties to communicate style elements to other stakeholders, for example curtains (3E.1) → AP can address hesitations of other stakeholders.
- ❖ During presentations, narratives were required to frame dynamic and metaphoric aspects of a design (3P.2) → AP supports dynamic and metaphoric narratives in an interactive manner.

Hint 12 Models need to be tailored to the design review agenda.

- ❖ Sketchy scale models were used, without colour or material details (3I.6) → AP can keep the focus on important issues.
- ❖ In the final scale model, all objects were glued to the base plate to focus discussion on the agenda (3E.8) → Physical entities to express fixed elements of AP, allows focus on the variable elements in design concepts.
- ❖ Designer purposely made sketchy scale models, textual descriptions and sharp section views (3E.3)→ AP allows directing of review process in advance.
- ❖ During presentations, a number of options were shown (3P.3) → AP adds plurality in presenting style and layout of the solution space.

Hint 13: Design exploration scenarios, such as user studies and pedestrian flow, can fix focus to the design agenda.

- ❖ Client was not open to the designer's arguments concerning the headlight (1E.1) → the embodied dialogue of AP can offers better argumentation by connecting to computational simulations.
- ❖ The use of (physical) prototypes was not part of the design brief (1P.2) → Expressive AP can be made with few resources.
- ❖ Monthly presentations of user feedback to the team had a positive effect (2I.1) → AP allows presenting design errors on top or near design alternatives, building shared understanding of user context.
- ❖ Lot of user studies were executed (2E.1) → The speed of creating an interactive mock-up by AP enables more user testing.
- ❖ Sketchy scale models without colour/material details were used (3I.6) → AP can vary level of specification by alternating the level of detail.

Hint 14: A physical mock-up should be used in simulating interactive use.

- ❖ It proved to be difficult to evaluate interaction designs of a handheld product (2F.1)→ AP can integrate digital display/behaviour with physical mock-up to allow a better evaluation of the user interface.
- ❖ Only limited support existed to specify GUI with regards to interaction/navigation, display resolution (2F.3)→ AP can enable fast GUI specification changes.
- ❖ Physical mock-ups were easily made in foam and paper to make and had a large effect at start of process (2F.4) → AP can lower the threshold in cost and effort required to create an interactive mock-up.
- ❖ The feel of the button operation depended, to a large degree, on the final component selection (2F.5)→ AP equipped with phidgets allow exploration of different buttons combined with software.
- ❖ The use of the final software platform in conceptual stages posed too many constraints on UI design (2P.5) → AP can mimic embedded software and interaction of information appliances without production software.

Hint 15 Novel design solutions can be explored by considering alternate layouts and simulations.

- ❖ There were challenges in finding headlight that would fit in the design (1F.2) → AP yields alternatives in small timeframes.
- ❖ The inclination to use Catia and 3D renderings could have been better balanced with other representations, e.g., sketching, tape-drawing (1P.1)→ Interactive AP provides more inspiration for emergence.
- ❖ Button placement of the handheld product was restricted by engineering package inside (2F.2) → AP constraining design solution space based on the envelope of a physical mock-up.
- ❖ It was sometimes difficult to fit translations of labels on buttons on product screen (2F.6) → Speed up of probing dimensions and fit on AP.
- ❖ Many physical models were used (2P.1)→ AP enables to create a larger collection of models that might provide more inspiration between stakeholders.
- ❖ No tools existed to specify dynamic behaviour of the building (use, business processes) (3F.2)→ Spatial layouts, such as buildings use AP for insight in dynamic functions and test what-if situations.
- ❖ The movements of people/users could have been used as an inspiration to design a floor plan (3P.1)→ Interactive pedestrian flow to address problems and opportunities in an AP.

Hint 16 it is advantageous to combine physical models with computational simulations such as pedestrian flow simulations.

- ❖ No tools existed to specify dynamic behaviour of the building to envision use and business processes (3F.2)→ AP establishes a natural learning environment to experiment with layouts and their consequences, providing a fast and interactive medium to find the underlying principles.
- ❖ Functional aspects received little attention in design reviews; client was preoccupied with form elements/aesthetics (3I.3) → AP visualises focus of design review agenda, in particular for intangible, functional aspects of the built environment.
- ❖ The movements of people/users was used as a base to design a floor plan/objects (3P.1) → AP allows computational simulations to tangibly explore different scenarios.
- ❖ The building/landscape did not offer good provisions for (un)loading trucks (3F.3) → Logistical aspects of design can be grasped by AP.

Hint 17 Recording of the design discourse is needed, including projection state, position and orientation of physical objects, and audio/video of the stakeholder's discussion.

- ❖ Indirect contact with client – assignment came from the part builder ; unclear project structure (11.2) → AP yields transparent co-located project overview.
- ❖ Miscommunication happened during internal division of tasks (11.4) → AP builds a shared vision for a design and its subcomponents.
- ❖ Without consulting the designers, the manufacturer adapted the design for the null series, i.e., blinkers, air vents, skirts (1E.3) → AP to “freeze” the designer's rationale.
- ❖ Monthly meetings with all stakeholders were conducted (3I.2) → AP can offer a better record of the topics, alternatives, and other aspects of design reviews.
- ❖ The discussions on the usage scenarios during design reviews were redacted from the meeting minutes (3E.4) → AP creates a full record of the design review discourse.
- ❖ Initially some stakeholders were kept out of the loop (3E.5) → Using AP improves stakeholder's emancipation.

Hint 18 Record interaction with models for later use.

- ❖ Many user studies were conducted (2E.1) → AP allows the end-user to be taken seriously and provides grounding to make design decisions.

3.3 Conceptualization of the Interactive Augmented Prototyping Design Methodology

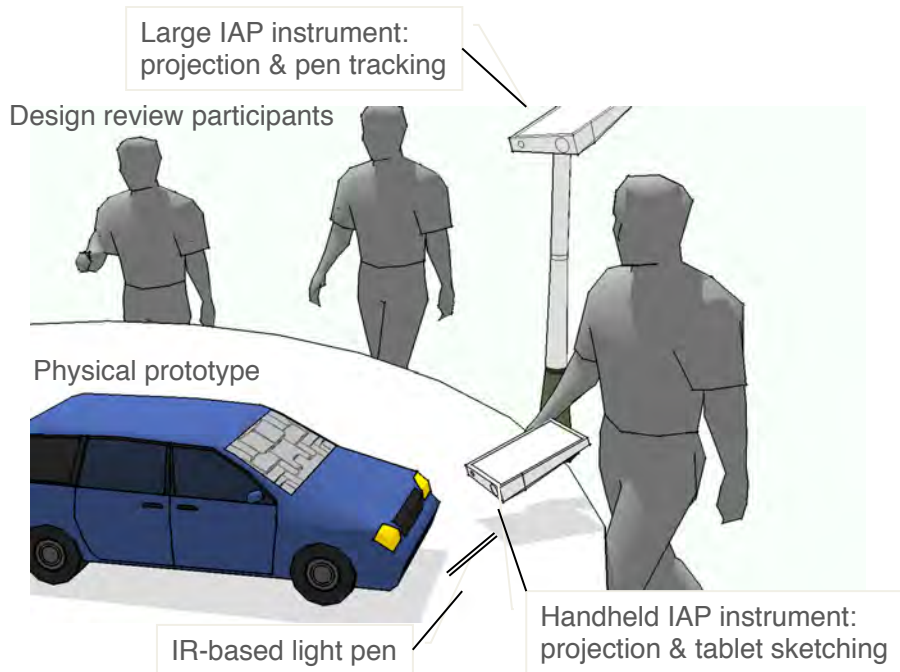


Figure 31 Impression of a design review supported by IAP.

In converting the hints to a design support means, two considerations should be made. First, the support scenarios of the previous section refer to AP-centric activities, methods, and tools. This exceeds the common understanding of a traditional AP system, which represents an instrument to merge physical and digital information as introduced in Chapter 1. Secondly, I assume that making AP more interactive opens up new prospects. The term *interactive* covers three different interpretations:

- IAP provides a *natural, spatial medium* to display multiple design aspects concurrently, accessible to multiple stakeholders (covered by hints 1-12).
- IAP allows *adaptations in the design* during use and can provide *real-time feedback of computational simulations* (hints: 13- 16).
- IAP can *capture the argumentation* of the design review through annotations/sketches as well as capture the discussion and models used during sessions (hints: 17-18).

Based these observations, I formulated the following hypothesis:

Hypothesis: Using interactive augmented prototyping as a design methodology (IAP-M) can improve the shared understanding of design concepts among stakeholders during design review meetings.

An application-sensitive methodology allows AP to adapt to a specific design situation, while its methods and procedures treat the phenomenon of interactive

augmented prototyping in a comprehensive way. The vision that feeds this hypothesis is the prospective during design reviews as depicted in Figure 31. It shows how multiple design review participants can discuss design concepts, while multiple projector-based devices establish augmented prototyping, each with its own functions that add to the current discourse. This could include a larger system with bright projection capabilities and smaller ones for handheld use.

3.4 Workflow of using IAP-M

Figure 32 depicts the envisioned information flow, presentation models, annotated models, notes, segment indices, and audio/video are indicated as information sources. The design team is supposed to be in charge of model making and review session preparation, they have to consider several presentation means, including slideshows, drawings, models and the like. After setting up the hardware, the IAP-M instrumentation is calibrated to ensure a proper 3D mapping between virtual and real world coordinate systems, and to initiate the presentation. During the presentation, the recording system captures a video feed of the instruments as well as the user interaction with the physical and virtual. These input events are stored with their segment indices. Inspection of sessions is available through a session browser. All notes and annotations can be viewed in context of a 3D scene or the 2D presentation slide. During this activity, it is assumed that the design process is affected in the next iteration of presentation models and so forth.

IAP-M will require information storage, processing and retrieval functions, which are

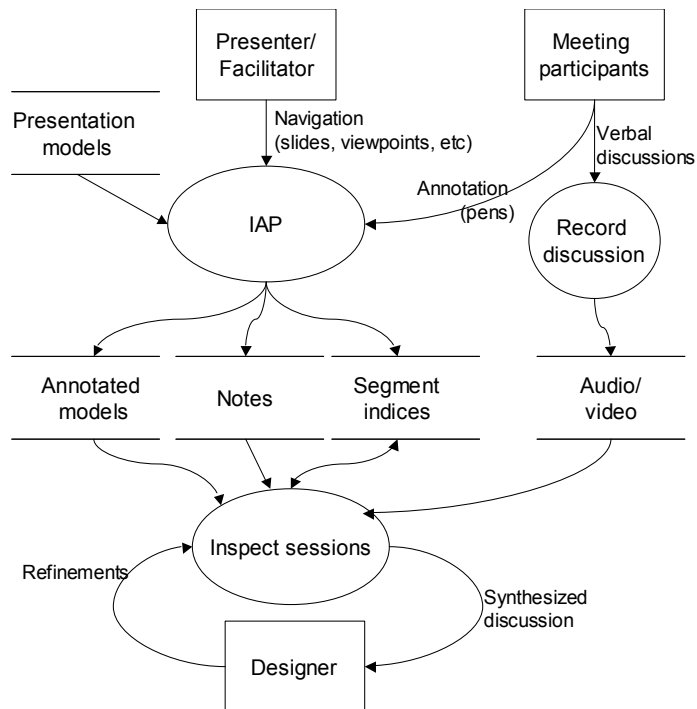


Figure 32 Information flow of IAP-M.

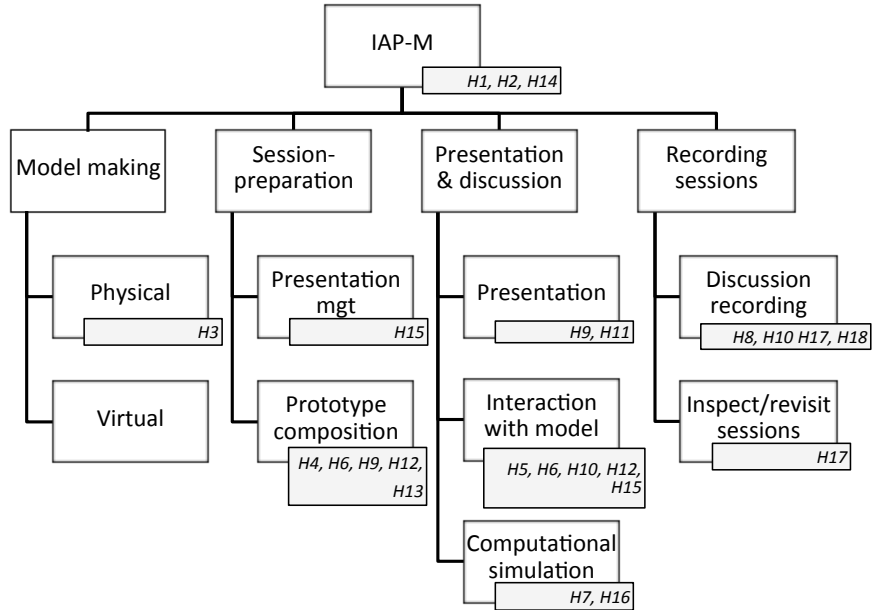


Figure 33 IAP-M function hierarchy diagram with mapping of the hints specified in the implementation chapter.

3.5 Functions of IAP-M

Table 17 briefly revisits the envisaged design support scenario from the hints to IAP-M, with an indication whether these solutions mainly cover a method, procedure, or instrumentation. These functions could be clustered in four main activities: 1) physical and virtual model making, 2) preparing the design review by arranging presentation models and other materials, 3) executing a design review, and 4) recording the discourse during meetings and revisiting these recorded results. Figure 33 depicts the subsequent function hierarchy diagram of the IAP-M with the associated set of hints.

Table 17 Envisaged IAP constituents, based on by hints

Model making		
H3	Enable the inclusion of existing physical objects and reverse engineering	Method
Presentation management		
H15	Prepare the projection of alternative component/button layouts (e.g., of older and competing products)	Method
Prototype composition		
H12	Consciously prepare the model for discussions, e.g., by fixing/filtering items and by setting a small number of configurations	Procedure
H4	Allow browsing through a selection of physical components and include some of these in a virtual global concept	Method
H5	Support browsing through a selection of virtual components/textures and include some of these in a physical global shape	Method
H9	Implement an interactive display of colours/materials in focused areas only, e.g., tied to an object representing a user in interior model	Method

	(similar to coloured doll in existing model)	
H13	Include computational simulations to control focus during discussing concepts	Method
Presentation		
H11	Build narratives by supporting animations and (text) slides	Instrument
Interaction with model		
H5	Display design details/specification close to a physical model when a part focused upon	Method
H6	Support browsing and selection of virtual components/textures on a physical shape	Method
H15	Interactively project alternative component /button layouts (also of older and competing products)	Method
H12	Support interaction with designs, and capture user interaction, reflections (annotation), and design decisions	Method
H10	Allow browsing through a collection of physical models and explore their placement in a global concept, with the ability to record/bookmark alternatives	Method
H13	Support freehand digital sketching on a physical surface (captured with author +timestamp for later use)	Instrument
Computational simulation		
H7	Include coarse budgeting calculations and design requirements capturing tools in the virtual prototype	Method
H16	Include interactive simulations, results are directly projected on the physical prototype and its environment	Method
Discussion recording		
H17	Include recording and retrieval of design review sessions (replay, overviews, etc.)	Method
H8	Support annotations	Method
H18	Capture interactive use of product design – including keystrokes and performance, (non)verbal communication of users	Method
H10	Allow browsing through a collection of physical models and explore their placement in a global concept, ability to record/bookmark alternatives	Method
Inspect/revisit sessions		
H17	Include storage and retrieval of design reviews sessions (replay, overviews, etc.), to be shared through network connections.	Method

3.6 Conclusions

The previous chapter concluded with the observation that communication among stakeholders is an essential part of design. Our working hypothesis is that *interactive augmented prototyping methodology* (IAP-M) can improve the shared understanding of design concepts among stakeholders during design review meetings. Here, interaction covers three notions: i) natural, spatial interface, ii) altering design utterances, and iii) capturing the design discourse through annotations. To convert the findings of the case studies in design support scenarios, the notion of *hints* was introduced as a speculative elementary usage scenario of a future augmented prototyping system that supports the design process. The formulation of hints, based on bottlenecks and best practices of case studies, provided grounding in design practice. In total, 18 hints were generated that mapped to 9 different functions of a novel design methodology entitled IAP-M.

between engaged discussion and sessions review. In the domain of usability engineering, a collection of interaction multimedia recording techniques has been devised to capture user-product experiences. For example, the d.tools system can connect physical mock-ups to a PC, which in turn simulates system behaviour and monitors user interaction (Hartmann et al., 2006). The user is recorded by multiple media (video, audio, application state) and the record can be accessed later with an interactive diagram.

There exist commercial 3D design review systems, for example Autodesk's Design Review, that can be used without cost. These systems enable loading a set of CAD files and to inspect and annotate (pen and text) the 2D and 3D models (AEC Magazine, 2006). In general, these systems are meant for a single-user, and have limited capabilities to capture multimedia. They do not offer procedures or interactive simulations. Most VR and AR systems offer the same functions as commercial software but in an immersive fashion through head-mounted displays or CAVE environments. For example, the IMPROVE project focuses on large displays ("powerwalls") and algorithms for photo-realistic rendering, yet its annotation facility is minimal (Santos et al., 2007). The ability to annotate 3D models is, for example, presented in Jung et al. (2002), who discern simple text comments (similar to post-it notes) from sketches in 3D. Both Kremer (2008) and Knopfle and Voss (2000) describe head-mounted display based VR system that allow users to inspect models by showing and hiding parts, obtaining dimensions and a simplistic means to add text comments. Although both systems specifically target design reviews, they don't offer tools or methods to prepare, execute or document such meetings. Similarly, Moeslund et al. (2004) and Siddarta et al. (2006) employ optical see-through Head Mounted Displays to inspect designs, yet no support is provided for the procedure of reviewing (agenda keeping, meeting minute taking, and so forth).

The Skin system was proposed to simplify the level of fidelity during brainstorming and exploration, by projecting a multitude of 2D textures on physical objects (Saakes, 2012). Greenhalg et al. (2000) proposed to support capturing all virtual events in a VR system and offer a virtual playback facility called Holovid. In this system, a miniature version of the virtual world was accessible by all virtual partners, it lacked video or audio recording. A comprehensive VR-based solution, entitled Boom Chameleon, was presented by Tsang et al. (2002). This system included an LCD touch panel on a moveable structure to act as a physical window to a virtual scene. It offered so-called spatially embedded snapshots, which showed a 3d rendered design from a specific viewpoint. These were displaced around the 3D model of the design in question and could be used to add 2D annotations with the LCD touch panel. Furthermore, the system employed a "flashlight" tool to draw directly on the 3D surfaces. Viewing and inspecting artefact models was however limited to a single user. Furthermore, no physical model could be employed to collaboratively address details or inspect the design by tactile senses. Furthermore, no record was made of remaining aspects of the design review meeting, e.g., the verbal communication.

3.8 References

- AEC Magazine (2006) "Autodesk Design Review", Issue 23 August 2006, vol 23, pp. 26-27.
- Greenhalgh, C., Purbrick, J., Benford, S., Craven, M., Drozd, A., and Taylor, I. (2000) Temporal links: recording and replaying virtual environments, in Proceedings ACM Multimedia'00, pp. 67-74.
- Hartmann, B., Klemmer, S. R., Bernstein, M., Abdulla, L., Burr, B., Robinson-Mosher, A., and Gee, J. (2006) "Reflective physical prototyping through integrated design, test, and analysis", proceedings UIST '06, pp. 299-308.
- Jouvenel, A. (1967) "The art of conjecture", Basic Books, NY.
- Jung, T., Gross, M.D., Do, E. Y-L. (2002) "Annotating and Sketching on 3D Web Models", proceedings Intelligent User Interfaces IUI'02, pp. 95-102.
- Knopfle, C., Voss, G. (2000) An Intuitive VR User Interface For Design Review, AVI 2000, pp. 98 – 101.
- Kremer, K. (1998) "A Concept For Virtual Reality Tools For Design Reviews", proceedings IEEE Visualization, pp. 205-210.
- Minneman, S.L., Harrison, S.R. (1993) "Where Were We: Making and Using Near-Synchronous, Pre-Narrative Video", proceedings ACM Multimedia '93, pp. 207-214.
- Moeslund, T.B., Storring, M., Broll. W., Aish, F., Liu, A., Granum, E. (2004) "The ARTHUR System: An Augmented Round Table", proceedings SCI 2004, pp. 277-282
- Potts, C., Jay David Bolter, A. Badre. (1993) "Collaborative Pre-Writing With a Video-Based Group Working Memory", Graphics, Visualization, and Usability Center (Georgia Institute of Technology, USA) Technical Report 93-35.
- Raskar, R., van Baar, J., Beardsley, P., Willwacher, T., Rao, S. and Forlines, C. (2003) "iLamps: geometrically aware and self-configuring projectors ", SIGGRAPH, pp.809–818.
- Saakes. D.P. (2010), Shape does matter: designing materials in products, PhD Thesis, TU Delft, the Netherlands.
- Santos, P., Stork, A., Gierlinger, T., Pagani, A., Araújo, B., Jota, R., Bruno, L., Jorge, J., Pereira, J.M., Witzel, M., Conti, G., Amicis, R. de, Barandarian, I., Paloc, C., Machui, O., Jiménez, J.M., Bodammer, G., McIntyre, D. (2007) "IMPROVE: Collaborative Design Review in Mobile Mixed Reality", Lecture Notes in Computer Science, Volume 4563, pp. 543-553.
- Sidharta, R., Oliver, J., Sannier, A. (2006) "Augmented Reality Tangible Interface for Distributed Design Review", in Proceedings of. CGIV, pp. 464-470.
- Tsang, M., Fitzmaurice, G.F., Kurtenbach, G., Khan, A., Buxton, B. (2002) "Boom chameleon: simultaneous capture of 3D viewpoint, voice and gesture annotations on a spatially-aware display", proceedings of UIST '02, pp. 111–120.

Chapter 4

Constituents of IAP-M

4.1 Aims, problem statement and research questions

The interactive augmented prototyping methodology (IAP-M) represents a design support methodology as a structured, instrumented, and systematic approach of efficiently achieving specific objectives. Like the DRM framework (Blessing and Chakrabarti, 2009), it should include a prescriptive set of means, aids, and measures that can be used to improve design. This chapter elaborates on these parts, named constituents, as they all are required and need to be considered in the full context of the design situation at hand. These constituents have been introduced in the previous Chapter, and refer to “the procedure”, “the set of methods”, “the set of means”, and “the criteria”. The research questions were therefore:

- What steps or stages should be followed to apply IAP-M?
- What methods are required to support the IAP-M procedure?
- How can the IAP instrumentation be implemented with current technologies?
- What criteria need to be met to ensure a valuable application of IAP-M?

This investigation called for a design-inclusive research cycle, as IAP-M covers a combination of physical models, hardware, software, and methods, in which one or multiple prototypes of the I/O Pad need to be implemented to explore the level of interactive prototyping in a collaborative setting.

This chapter starts with presenting the procedure in one section, followed by a collection of methods in 4.3. The development of the I/O Pad is covered in sections 4.4-4.6. In a final discussion, the appropriateness criteria of the methodology are proposed in section 4.7.

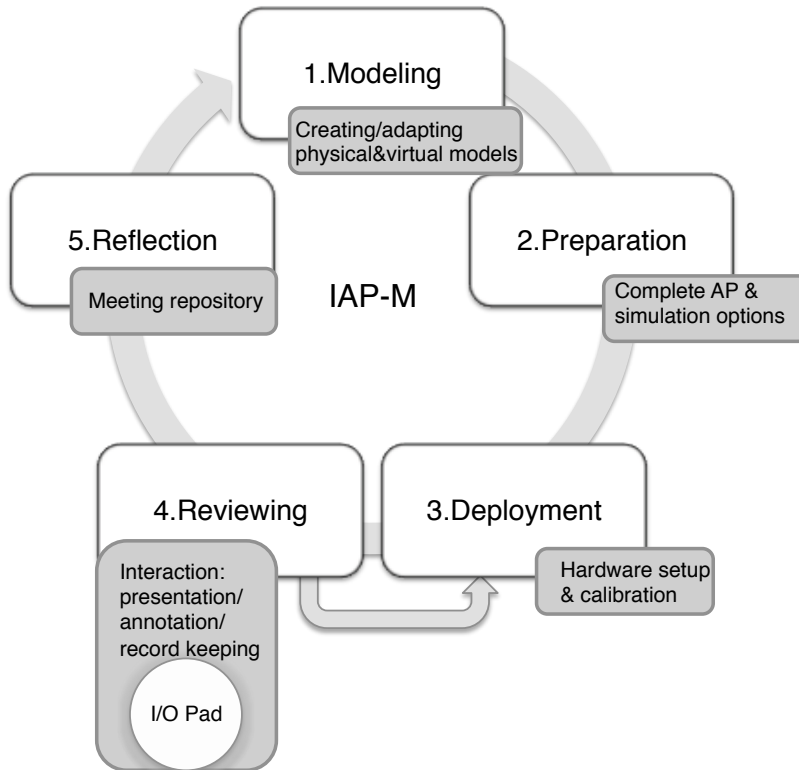


Figure 35 The IAP-M procedure, methods and instrument.

4.2 Specification of the IAP-M application procedure

Based on the function hierarchy of section 3.5, the procedure of applying IAP-M has 5 steps: modelling, preparation, deployment, reviewing a design, and reflection (Figure 35). In some cases, an identical augmented prototype is reviewed in several meetings (possibly on different locations). That is, the deployment and review can be repeated multiple times while modelling and preparation can remain the same. Furthermore, this procedure has an iterative nature: the final step can lead to a subsequent iteration with adaptations or detailed prototypes. These steps will be discussed in the following sections.

4.2.1 Step 1: Modelling

During *modelling*, the design is represented by physical and virtual models that encompass the key concepts to be addressed during stakeholder meetings. Modelling typically starts with digital models and manual model making, but might also be initiated with existing products that are collected to kick-start the discussion. When there already are physical models (e.g., competitive solutions, clay models, and so forth), reverse engineering techniques such as 3D scanning can be used to

reconstruct a digital model. As introduced in Section 1.1, this step is typically already included in a product design process, and key outputs are 3D models that will be included in the design review. Method A Mixed reality prototype fabrication, described in section 4.3.1, provides a framework and guidelines for manufacturing the models.

4.2.2 Step 2. Preparation

In this step, attention is given to the meeting agenda and setting the stage for physical/augmented components of the concepts for the design review meeting. The design team has to determine the intended interaction during the design review session. This includes generating a comprehensive collection of physical and digital models, including identifying specific parts of the model that should be addressed separately. Here, Method B Physical model making for projector-based AP can be applied.

4.2.3 Step 3. Deployment

Deployment ensures the transport, installation, and setup of the models and instrumentation in a meeting environment. During this step, calibration will have to be executed. Other preparations for design review sessions include:

- Ensuring the light conditions in the room are fit for projection.
- Tuning noise level and microphone positioning for audio recording.

4.2.4 Step 4. Reviewing

Reviewing encompasses presentation and discussion of the design concepts, while the instrumentation allows the meeting participants to interact with the model and simulations. The interaction with the design utterances in this step are determined by the instrumentation and the physical models, annotation and presentation opportunities, agenda keeping, and decision making. Participants can experience and modify the model, create annotations on the discussed concepts. Furthermore, the meeting is recorded and the design review discourse is captured through a meeting template, specified in method C recording design review sessions. This encompasses the annotated models, notes, segment indices, and audio/video as presented in Section 3.4.

4.2.5 Step 5. Reflection

During *reflection*, designers and other stakeholders can inspect previously recorded meetings to obtain a basis for prospective design decisions. If necessary, the meeting template discussed in the previous step can be extended by specifying follow-up actions.

4.3 Specification of the methods used in IAP-M

To enable a correct application of IAP-M, I devised a collection of methods. This collection is based on literature and prior findings, specifically considering projector-based AR. It covers semi-systematic techniques and approaches to manufacture AP components (Methods A & B), and to record the design review discourse (Method C).

4.3.1 Method A. Composition of physical and virtual counterparts

Essential to IAP-M is the creation of augmented prototypes, distinguishing physical and virtual counterparts. Figure 36 depicts the affordances for physical and virtual realms, based on literature and my own experience. Physical models – albeit existing products or mock-ups of novel designs - are suitable to use i) to express global shapes, ii) to probe physical ergonomics. Virtual models are suitable to project i) details that are matched to the global shape, and ii) features that are subject to change (often manifested in textures and materials). The object presence of local geometric features, like edges and rivets, is optimal when displayed in both physical and virtual models. Buttons and interactive components also work best when they are manifested in both physical and virtual models. For example, in the system of Bandyopadhyay et al. (2001) a virtual representation of a pen, indicating chosen colour or state of the system was projected on top of the physical tool.

For a particular design, these affordances can be framed to three elements. The first element is the given part in the design, which represents the context or environment for the design and provides spatial or functional constraints to a concept. This typically corresponds to global, graspable items in a prototype. The second element, the design focus, addresses both problem and solution spaces of a specific design situation. This element will change throughout the design process, and maps to virtual models. The third, crucial design elements, represents fixed features that need to be included in a design concept which can typically be changed in the physical layout of a solution. These would translate into combined physical and virtual counterparts.

This framing of a design situation in three categories provides a rationale to the design team to prepare the augmented prototype, and to determine the type of interaction necessary to address the solution space during with other stakeholders. As an illustration, this framing was applied to the empirical case studies in Figure 37. Both tractor and oscilloscope designs have a body (global shape) as design focus, while the interior design mainly deals with a more abstract notion of spatial

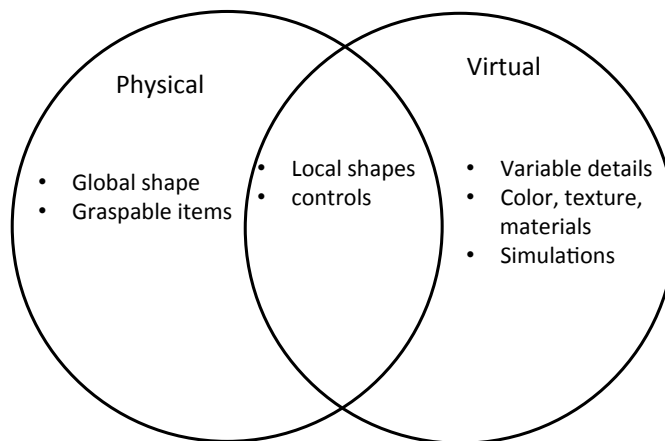


Figure 36 Affordances of physical, virtual and combined realms for augmented prototyping.

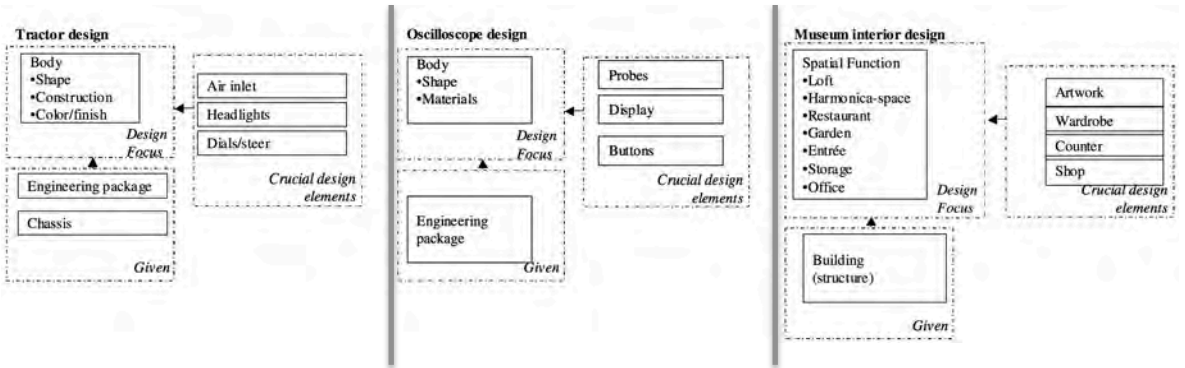


Figure 37 Major design parameters for the explorative case studies structures.

4.3.2 Method B. Physical model making for projector-based AP

In order to gain an optimal projection on physical objects, their surface needs to be neutral in terms of colour and reflective components. The latter is also known as a lambertian surface, an ideal diffuse reflection in which the apparent brightness of the object to an observer is the same regardless of the observer's angle of view (Foley et al., 1995). Figure 38 depicts an appropriate approximation of these surface properties, in a scale model of the tractor of case study 1. This model was manufactured in Polyamide by Selective Laser Sintering, delivered in 3 days after ordering online at a Dutch Service bureau.

The following trade-offs need to be made during physical model making for projector-based AP: scale, material and orientation during manufacturing, post-processing, fiducials for object registration:

- Scale – objects or their physical components should be able to fit on a

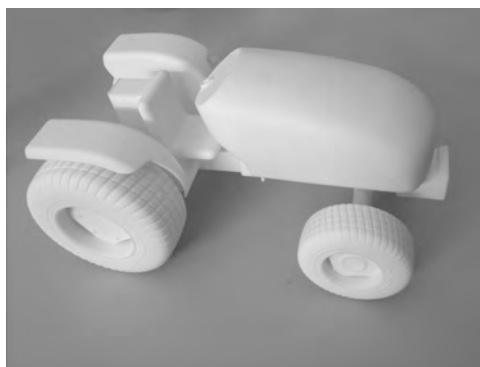


Figure 38 Rapid prototyped scale tractor model with lambertian surfaces (size: 26 x 8 x 6 cm).



Figure 39 Coloured 3D printed object with embedded marker.

regular meeting table while they should be sufficiently large to grasp and to project on. At the same time, large objects take longer to manufacture and their cost can become prohibitively expensive (given that volume determines the cost for most AM processes).

- Process parameters– when rapid prototyping is applied, parameters such as part orientation and the used material are should be considered carefully to avoid artefacts such as seams, stair casing, and reflective surfaces. Post processing, in particular using latex paint after sanding and polishing can be used to recover artefacts but takes time.
- Prototyping fiducials for object registration - in order to register the physical and digital coordinate systems for moveable, tangible objects, a calibration step has to be taken during model preparation to align origin, scale, and orientation. In the case of rapid prototyping, this preparation can be simplified by including placeholders for fiducials in the geometry or decoration (when multi-material or ink is involved). Although the initial insights is not yet implemented in an algorithm, this method should consider the following aspects; discernibility of the fiducial pattern, depending on distance and resolution of the tracking system; visibility and occlusion of the fiducials when users grasp the models (preferably bottom or top of objects); visual distraction of optical markers with regard to the physical and projected content.

4.3.3 Method C. Recording design review sessions

Recording design review sessions typically is done by minute making, as manifested in the case studies. In order to merge the annotated models, notes, segment indices, and audio/video as described presented in Figure 32, a formalism is required. On this topic, Huet et al. present a meeting capture template shown in Table 18: a tabular scheme to record topics, decisions and actions (2007).

Table 18 Huet's Meeting Capture Template (Huet et al., 2007)

#	Topic (in a few words) and Action (+name, date)	Who?	What?	Impact on design and manuf. ?	Time
1		<input type="checkbox"/> Struct <input type="checkbox"/> Sys	<input type="checkbox"/> Exploring <input type="checkbox"/> Clarifying	<input type="checkbox"/> Process	
	Action:	<input type="checkbox"/> Certif <input type="checkbox"/> Magt <input type="checkbox"/> Manuf <input type="checkbox"/> Client	<input type="checkbox"/> Evaluating <input type="checkbox"/> Decision <input type="checkbox"/> Debating <input type="checkbox"/> Informing	<input type="checkbox"/> Product <input type="checkbox"/> Tools	
2		<input type="checkbox"/> Struct <input type="checkbox"/> Sys	<input type="checkbox"/> Exploring <input type="checkbox"/> Clarifying	<input type="checkbox"/> Process	
	Action:	<input type="checkbox"/> Certif <input type="checkbox"/> Magt <input type="checkbox"/> Manuf <input type="checkbox"/> Client	<input type="checkbox"/> Evaluating <input type="checkbox"/> Decision <input type="checkbox"/> Debating <input type="checkbox"/> Informing	<input type="checkbox"/> Product <input type="checkbox"/> Tools	

I converted this meeting capture template converted into an object-oriented representation scheme shown in Figure 40. The main objects are IAPSession and IAPEvent. The first captures the meta-data of a review session, referring to an agenda, participants, and additional data (such as the materials used and links to external video and 3D scenes). The agenda topics need to be defined beforehand while the IAP-M instrumentation should support navigation between the topics with dedicated keys. The IAPEvent object represents either manually defined or automatically generated meeting items that bear importance to the session. These might be user interface actions such as topic navigation, pen strokes or the selection of different design alternatives, or post-session notes. An IAPEvent instance consists of a universal timestamp, a reference to the current state of the 3D scene, and a number of fields that are compatible with the Huet's meeting capture template. The *topic* refers to one of the IAPSession's agenda items. The *action* field refers to a predefined list (exploring, evaluating, etc.). The current user is recorded in the *who*-

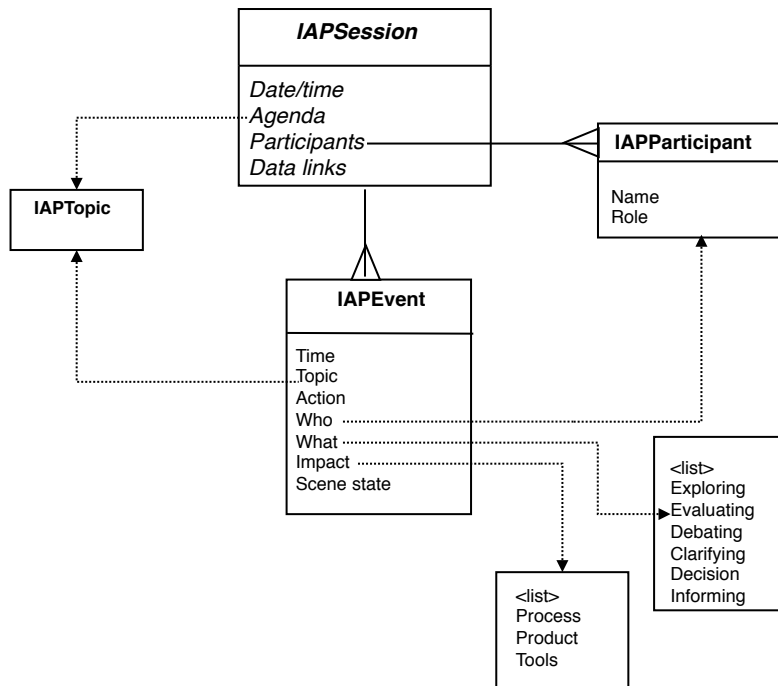


Figure 40 Representation scheme for design review sessions.

field, although recognition of the participants is only possible for pen events, other events require human intervention. Specific action information is stored in a string field called *what* – which might include automatically generated data such as pen strokes or user comments. Finally, the *impact* attempts to define the action focus by identifying process, product, or tools.

4.4 Instrumentation

As presented in the first chapter of this thesis, a vast number of Augmented Reality systems have emerged in the field of design. However, none of these proposed solutions supported interactive modelling or CAD operations, and are limited in the ability to import/export geometry. In a similar fashion, engineering simulations would be difficult to integrate and their interface would have to be hard-coded. This made employment of complex simulation (for example, injection flow-moulding, finite elements analysis or fluid dynamics simulations) tedious to implement and adapt to a particular design situation.

4.4.1 Instrumentation requirements

Based on design practice, and AR technology surveys as Azuma et al. (2001), I identified the following requirements regarding the IAP-M instrumentation:

- **Ease of mobility:** design reviews often take place at the client or some other stakeholders, the IAP apparatus should fit in two reasonably sized suitcases and should withstand unsupervised transport (by air or in the trunk of a car).
- **Installation efficiency:** time and effort of installation should be kept to minimum, with self-starting facilities. Maximum time should be 15 minutes. If the system requires calibration, it should provide step-by-step guidance.
- **Setup flexibility:** The system can relate various physical components to virtual counterparts. The user should be able to attach and detach these in an easy fashion.
- **Physical posture:** position and orientation of the projector systems should be fixed without creating hazardous situations.
- **Embodiment:** the system should be self-contained unit without loose parts, should auto-start, and should offer a number of pre-set configurations.
- **Ease of portability during operation:** during use, the projector systems could be moved and this should be achievable by one person. To enable this, the number of cables should be kept to a minimum.
- **Recording capabilities:** the system should support the recording of all input events and the corresponding 3D models. Different levels of granularity might be selected to optimise recording performance (time, level of detail, channels).
- **Time performance:** the refresh rate of the complete system must be at least at 10 Hz, with as little delay in response time as possible.

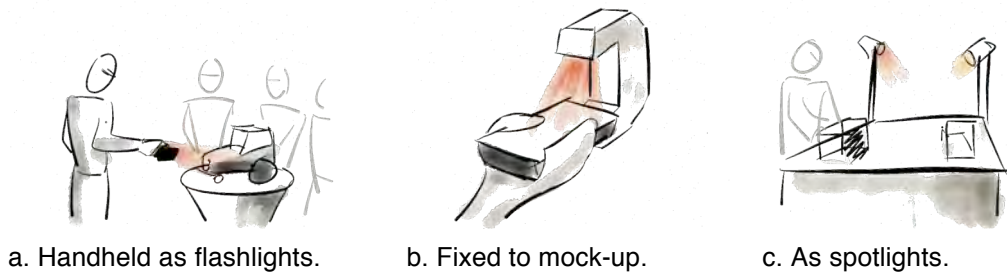


Figure 41 Embodiments of the I/O Pad.

- **Environmental interference:** IAP systems should not adversely influence environmental conditions, in particular noise and lighting condition. Projector noise should be minimised in order to support regular conversations (max 30 decibels, the level of whispering). Furthermore, although IAP systems might require a dimmed room, it should still be possible to see and interact with other people and objects at the location. A minimum level of 200 LUX is allowed (a dimmed training room).

4.4.2 Introducing the I/O Pad concept

To address these requirements, I devised a projector-based system, labelled as I/O Pad. The technical concept, patented in the US and EU as WO 2009014448, was envisioned as a single unit, its functions cover overlaying interactive 3D graphics as well as recording the design discourse. The I/O pads components would encompass input, processing, and output, specifically:

1. An ergonomic casing (lightweight, robust) with facilities to attach the device to a tripod.
2. A computer.
3. A touchscreen display, possibly supporting pen interaction as well.
4. A microphone.
5. A camera system, possibly extended by tracking sensors.
6. Projector.
7. Power unit.

I/O Pads can be handheld or larger to carry increased projection and computing power. If battery-operated, the I/O Pad is a self-sufficient, untethered device. By wireless communication, multiple I/O Pads might be used concurrently, in which each I/O Pad could perform a specialized task: e.g., modelling, simulation analysis, or annotation management. In this fashion, dedicated modules can be viewed as a physically addressable (i.e., tangible) component. Figure 41 shows some usage scenarios of I/O Pad embodiments in a design context. The left scenario depicts the system as a handheld device, being used as a flashlight to augment (parts of) a product model, in the middle sketch, the system is attached to a product mock-up to test and adapt an interface concept, while the right scenario is shows the I/O Pad as a spotlight, able to illuminate larger areas. As a working principle, this device is not bound to its application in design. Forensics, medical examination, and performing arts have been considered as possible application areas for this patent.

4.4.3 Calibration

Calibration of the I/O Pad deals with a number of elements: the transformation between camera and projector world-coordinate systems, defined by the projector internal parameters (field-of-view, centre position), the camera internal parameters, and the vector (translation/angle) between the two components. As I/O Pads are equipped with different hardware, each I/O Pad embodiment requires a different calibration method. A handheld unit typically requires a single calibration step, which can happen after the unit is assembled. Larger I/O pads, however, requires calibration during each deployment step due to the registration of the IR cameras of the motion capture system and fluctuations in both projector focal distance (zoom) and colour temperature. Based on prior research, e.g., Raskar and Bimber (2004), I developed a three-stage procedure to calibrate the projection.

Camera calibration

To employ optical tracking technology, the camera first needs to be calibrated. Most systems like AR Toolkit come equipped with predefined methods and applications to support calibration. In general, this calibration is only required once as the camera's internal parameters will not be changed. Standard cameras require no calibration, as calibration files are already provided.

Projector calibration

The second stage deals with extracting the projector's internal and external parameters, relative to a calibration object or scene. By considering a projector as a dual of a camera, projector calibration can use Faugeras Linear Camera Calibration algorithm (1993). This algorithm uses point correspondences between original x,y,z coordinates and their projected u,v , counterparts to resolve internal and external camera parameters. In general cases, 6-point correspondences are sufficient (Faugeras 1993, Proposition 3.11). Appendix C. presents an implementation. In theory, this calibration step only has to be performed once for 1 fixed focal distance of the projector (zooming in or out would necessitate recalibration). The user can operate the touchscreen of the I/O Pad to determine the projected locations (u, v coordinates) for each of the 8 vertices (x, y, z coordinates) of the test object.

Component registration

The final I/O Pad calibration stage considers the geometrical transformation between camera and projector, depicted in Figure 42. It links the AR Toolkit coordinate of the object (the transformation $C \rightarrow O$), with the model matrix of the projector ($P \rightarrow O$,

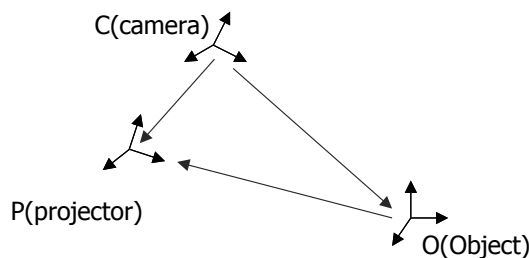


Figure 42 Relations between coordinate systems of the I/O Pad.

determined in the previous stage). The transformation between camera and projector can then be calculated by: $C \rightarrow P = C \rightarrow O \cdot (P \rightarrow O)^{-1}$

Theoretically, this component calibration has to be done only once, actually we have experienced several times that the camera was slightly moved with respect to the projector.

4.5 Pilot implementations of the I/O Pad

In this project, I developed two pilot implementations of the I/O Pad, characterized in Table 19. These iterations allowed me to target specific functions of the instrument and to use those hardware and software components that were available at that time.

Table 19 Characterisation of the I/O Pad pilot implementations.

Generation	1	2
Software platform	OpenGL	VRmeer+
Marker tracking	AR Toolkit (visible markers)	Personal Space Tracker (IR trackers)
3D prototyping material	Basic shape	3D printed Tractor
Lines of code	200 (C)	80 (python and C++)
Performance	15 frames per second	40-80 frames per second

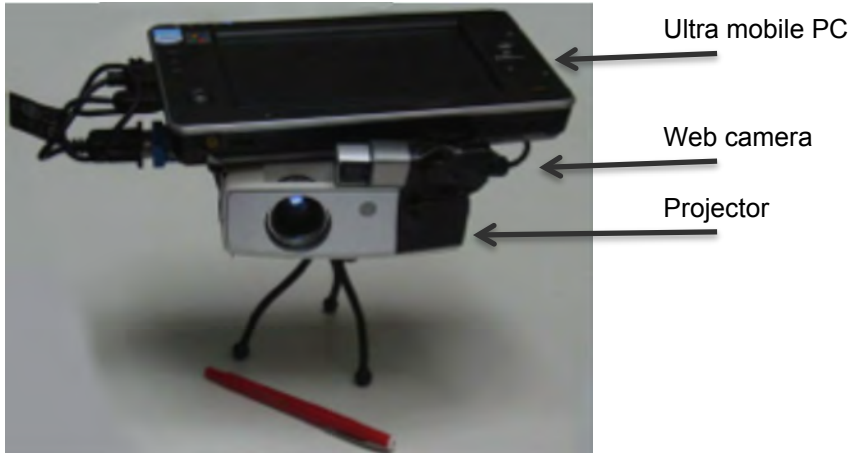


Figure 43 I/O Pad 1st generation pilot implementation, fixed to a small tripod.

4.5.1 Hardware of the first pilot

The first pilot used a lightweight embodiment of approximately 1,5 kilograms intended for handheld use, depicted in Figure 43. It included a LED-Based projector with a native resolution of 800x600 pixels, weighting 750 grams including battery (Toshiba FF-1). This projector was connected to a Tablet computer /UMPC (Asus R2H 900 MHz ULV Celeron processor, 500 MB RAM), with a 7-inch passive touch screen with a resolution of 800x480 pixels. A Microsoft NX-6000 web camera delivered video images with a resolution of 2 Megapixels per frame.

4.5.2 Software

Figure 45 shows the software architecture of the first pilot. It was based on an existing stand-alone OpenGL-based geometry viewer and supported importing a scene of VRML files and rendering these based on AR Toolkit. As discussed in Section 1.2.4.1, AR Toolkit supports optical 3D tracking and tag identification that employs flat rectangular markers. In this pilot, a multiple-marker setup was used to cope with occlusions. The scene data and VRML files defined the models, while different texture maps of the augmented prototype could be changed by keyboard interaction (i.e., joystick keys on the right of the touchscreen display). By activating another button, the rendered scenes as well as the original video streams were saved to a log file.

Following the notions of 4.4.3, I implemented a calibration procedure to determine



Figure 44 Handheld I/O Pad in use.

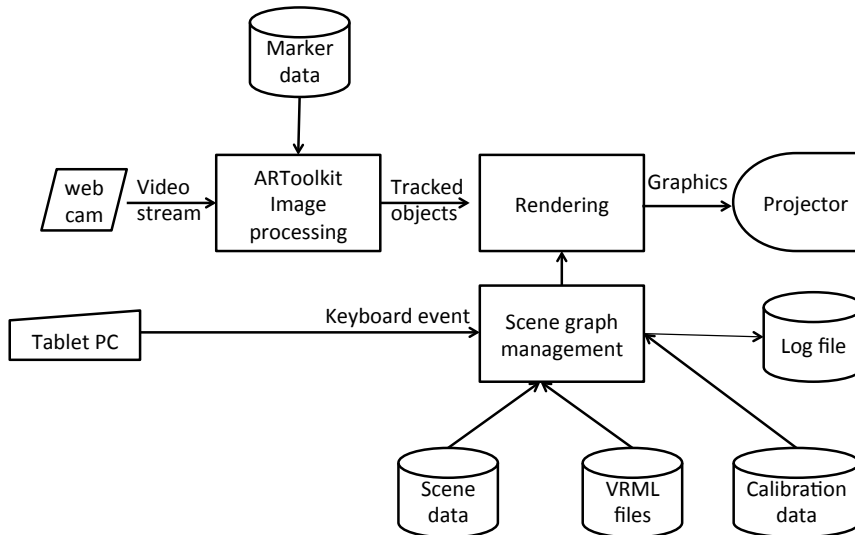


Figure 45 Data flow of first I/O Pad implementation.

internal and external parameters of the projector as well as the coordinate transformation between camera and projector. The projection coordinates (u, v) of a test object's vertices (x, y, z) had to be indicated by the user on the touch screen. The calibration application would save this calibration data to a file.

4.5.3 Augmented prototype and interaction

As test object, the pilot used a cropped pyramid of 4,5 cm, made in Nylon. Its geometry was modelled in Catia and texture maps containing arbitrary pictures and drawings were added to its faces in an xml file, readable by the renderer. Figure 44 shows the handheld I/O Pad in action with four standard AR Toolkit markers placed around the test object. The user could interact with the pilot implementation by operating the touch screen and by moving the handheld system or model with markers. Joystick keys on the UMPC were used to navigate between the different collections (left and right). The "OK" button was linked to a "Decision" event. This event did not alter the state of the application but was logged in a time-stamped file for later use

4.5.4 Testing the first pilot

The initial pilot system could be easily transported, installed, and moved while running the software. The aforementioned calibration was done in less than 20 seconds, by maximum 8 taps on the touchscreen during which setup was not allowed to move with respect to the object during this period – attaching a tripod to the I/O Pad was necessary for successfully executing this. The LED-powered projector was on and off within 2 seconds and did not produce more noise than a laptop under normal use. However, the resulting hardware created a bulky package and was uncomfortable to lift for longer than 5 minutes.

System performance

The computing power of the UMPC proved to be sufficient to support AR Toolkit tracking and rendering at 30 frames per second for a simple object. However, the system was incapable of capturing streaming video and application state. This required tapping into the OpenGL pipeline on the UMPC system and slowing the update speed down to 8-10 Hz. This either has to do with disk access for storing video or the single-threaded nature of the existing application which blocks the tracking-visualization loop at each frame. To decrease the processing burden of recording, the video resolution could be adapted both in size and update frequency depending on: camera/object movements, level of the microphone, and input events that influence the changes in the model. Furthermore, it might be preferable to employ an external application to capture the screen, possibly employing a server-based solution like VNC² to stream and combine the audio-visual channels.

Projector brightness

People can perceive the projector's images when it produces 50% to 100% more light at the surface than its environment (Sheng et al., 2011). This would equal 300 Lux at the given surface light of 200 Lux. We have to take into account that the reflectance of the polyamide test surface is approximately 80%. The small projector has a measured power of 16 Lumen; as Lux equals Lumen per square meter, the conversion has to take into account the maximum envelope of projection at a certain distance from the object. In practice, the projector brightness was acceptable on a distance 20-40 centimetres. For the furthest distance of 40 cm, the projected area is 23,1 by 17,3 centimetres or 0,04 m²; this results in approximately 400 Lux light energy at the object's surface, or 320 Lux when corrected for reflectance, which is sufficient. At the minimal distance of 20 cm., the area was 12 x 9 cm (0,01 m²), which results in 1185 Lux adjusted for 80% reflectance.

Field of depth

In exploratory tests, the projection focus on the object remained acceptable in the two ranges: between 20 and 30 cm., and between 30-40 cm. As the focus ring was difficult to reach, adjusting the manual focus was difficult. One could imagine a manual of automatic switch between these two ranges. Such an automatic option is feasible, as the distance between projector and object is constantly measured and a small linear actuator could be integrated to alter the focus ring.

4.5.5 Reflection on the first implementation

Although the first implementation fulfilled most of the requirements stated in Section 4.4.1, its applicability for IAP-M was hampered by the use of marker-based tracking, and limitations in projector brightness and computing power.

² www.vnc.org

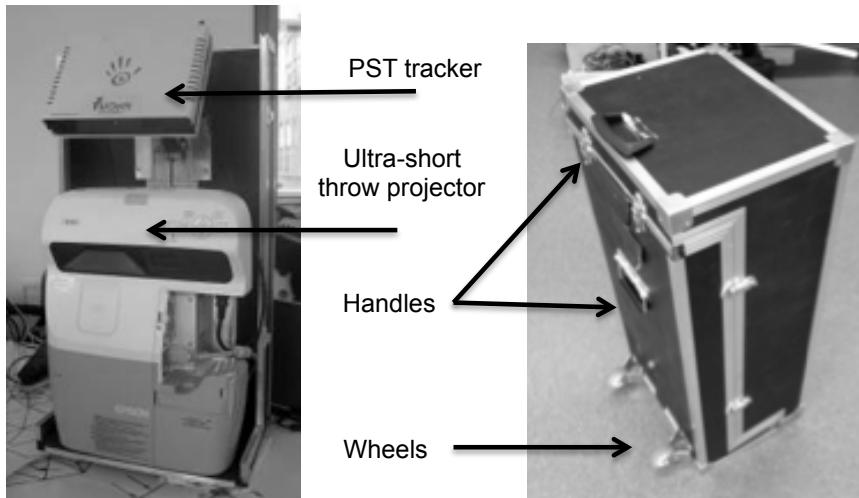


Figure 46 Embodiment of the second I/O Pad.

4.6 Second pilot implementation

To explore a more comprehensive solution of the I/O pad, a second implementation was made. It comprised on a larger yet portable setup with better tracking and graphics characteristics.

4.6.1 Hardware

The second pilot was based on using an ultra-short throw projector to project on a table (Epson Ep460i, 3000 lumen). When placed on a surface, this projector illuminates an area with a diagonal of 2 meters. The pilot included an infrared-based optical tracking and matching system, the Personal Space Tracker³(PST), which could track and identify up to 128 objects simultaneously based on random dot patterns (retro-reflective stickers that need to be applied to the physical object). This tracker had an accuracy of 1 mm and an update frequency of 100 Hertz. It was equipped with 3.5 mm optics to match the field of view of the projector. A Tablet PC with an ATI Mobility Radeon HD 4500 graphics processor was used as computing unit (HP tm2).

A custom-made flight case was made of 45 x 30 x 110 cm, the complete system weighted 7,5 kilograms, see Figure 46. The case was equipped with wheels and handles and could be transported without having to alter the layout of the devices. This allowed unpacking/installing of the projector-based AR installation in less than 10 minutes.

³ www.ps-tech.com

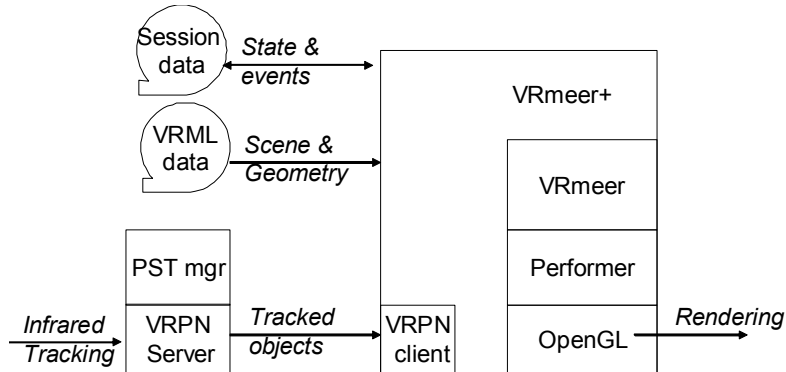


Figure 47 Software architecture of the I/O Pad.

4.6.2 Software

The software architecture, depicted in Figure 47, is based on VRmeer⁴, an open-source visualisation core specifically made for interactive scientific visualisation. This solution used the C++ OpenSceneGraph library, extended with a scripting layer (de Haan et al., 2008). The advantage of using this platform was that it supported a large variety of display/tracking hardware through a standard VRPN protocol, such as the Personal Space Tracker. The interaction was controlled in a Python scripting layer, which allowed altering the interactive behaviour on the fly without recompiling and restarting the application.

Calibration of the projector's internal parameters was done by determining the field of view and centre point of the projector. To register the transformation between PST tracker and projection, a calibration plate equipped with IR markers was created, shown in Figure 48, projected visuals could be moved by the mouse adjusted to fit the rectangles – when all were aligned the transformation between tracking and projector was determined as discussed in Section 4.4.3.

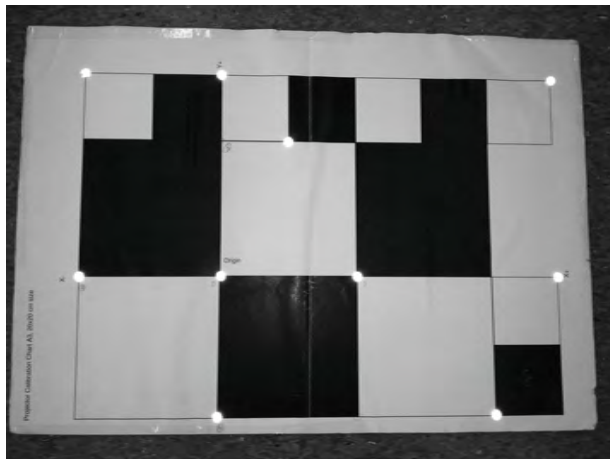


Figure 48 Calibration plate to align projector and tracking system (IR markers are highlighted).

⁴ graphics.tudelft.nl/VRmeer



Figure 49 Test objects equipped with retro reflective markers.

4.6.3 Augmented prototype and interaction

As depicted in Figure 49, the physical models to be used in this pilot were created by additive manufacturing technologies. This also included the tractor model of case #1, which was initially made in plaster (Z-Corp, Binder Jetting) while the wheels were fabricated on a polyjet system in transparent material (Objet Eden 260, Fullcure720). The resulting physical model proved to be very brittle while the transparent material generated unwanted mirror effects. An improved version was fabricated by Selective Laser Sintering in white polyamide as shown on Figure 38. Due to time limits, the dialogue was limited to moving the objects around on the table. Three original designs of the tractor's body, featuring different headlights and air inlets as well as slightly varying principal styling curves, were converted from Catia models to texture maps. These variants could be selected for projection on the physical model by using mouse buttons or a Bluetooth enabled remote control (Figure 50). Furthermore, flat cardboard pieces could be used to inspect surface curvature, by holding them close to the augmented model.

4.6.4 Testing the second pilot

The second pilot was demonstrated during at five company visits and two exhibits. Over 300 people interacted with this implementation. The interaction with the



Figure 50 Second I/O Pad in use with several 3D printed objects.

instrumentation and the models was fluent, especially due to the rapid update speed. The concealment of the ultra-short throw projector in a desk-mount surprised the audience, who were often thinking the models were physically printed in full-colour.

System performance

This system was better capable of tracking and rendering than the initial pilot (60 frames per second for scenes with approx. 40.000 polygons). The update frequency and delay was also improved by using the dedicated optical tracking system, which did not consume computing power on the host and consistently worked at 100Hz.

The 3000-lumen projector provided sufficient brightness to illuminate the objects in normal lighting conditions, while the SLS printed parts in Nylon had a proper, neutral surface for projection. In one location, the PST tracking suffered from direct sunlight, causing the IR tracking system to be flooded. The demonstration could only be continued after closing shades in the room.

Embodiment

The construction of the hardware worked well as a prototype – the system was operational in 5-10 minutes by opening 8 latches and switching on the devices. Some parts required repair or adjustment. In particular, the attachment of the tracker to the main body was not sufficiently rigid, which introduced misalignment of coordinate systems and required recalibration of the coordinate systems. Furthermore, inflatable wheels would be a better to transport the system on the street, especially on Dutch “kinderkopjes” (cobblestone walkway).

System development

The system was developed together with a student team and a computer graphics postdoc in approximately 5 weeks. The selected software architecture worked well to establish a connection between the tracker hardware and visualisation but was too complicated to be considered for further development in design support. First, the software architecture was devised for scientific visualization and incompatible with regular CAD files. Especially the inclusion of textures and bitmapped graphics required tailor-made solutions in the C++ core. Secondly, although the Python environment allowed changes on the fly, the semantics were difficult to comprehend. For example, to enable tracking of physical models, they had to be registered as “tools” – a mapping that was scattered in several configuration files and scripts. Furthermore, the alignment of the physical models and the virtual counterparts required trial-and-error. It would have been better if the placement of retro-reflective stickers was guided by indentations in the 3D geometry as the prototyping fiducials for object registration method mentioned in 4.2.3.

4.7 Criteria for applying IAP-M

Reflecting on the procedure and methods as well as the evaluation of the instrumentation, the following preconditions need to be valid to be able to apply IAP-M in a design situation:

1. The design involves a spatial realm, which can be scaled to a manageable size - e.g., an area of a tabletop - and still makes sense (design solution space).

2. The process involves multiple stakeholders, each with different skills and knowledge.
3. As a supporting design methodology it needs to fit the existing design approach at a specific agency (studio tradition).
4. The conditions of the design review's location should be able to be controlled in terms of lighting and noise to be able to augment and record the discourse.

4.8 Conclusion

Based on the underpinning theory in the previous chapter, a five-step IAP-M procedure was devised: modelling, preparation, deployment, reviewing and reflection. To support the preparation and reflection steps, three methods were proposed: a) guidelines to frame the parts of an augmented prototype between physical, virtual and mixed fabrication, based on their function during reviewing. b) a checklist for Rapid Prototyping physical models, c) a meeting minute repository to record the design review discourse.

The instrumentation of IAP-M is embodied in a system, entitled I/O Pad. This device is equipped with a video projector, optical 3D tracking, and a central processing unit. Different embodiments of this concept can be implemented, ranging from desk lamps to handheld mobile devices. Furthermore, multiple I/O Pads can be used concurrently. The proposed working principle of the I/O Pad resembles the iLamps concept (Raskar et al., 2003). Both cater to a handheld, geometrically aware projection and allow ad-hoc clustering of devices. However, the I/O Pad differs in three ways: i) each I/O Pad contains a touch screen to interactively capture and display sketches and gestures from designers, ii) each I/O Pad is equipped with recording devices (webcam) to pick up discussions and usability assessment sessions, and iii) the I/O Pad network architecture encompasses a distributed structure to facilitate data sharing, dialogue management and in particular session recording. Having been granted a patent in Europe and US for this working principle, I argue that the I/O Pad offers a novel way to deploy augmented prototyping.

The initial pilot implementation of the I/O Pad used a small tablet computer, LED projector, and a small web camera in combination with AR Toolkit markers. Although this first pilot demonstrated the feasibility of including handheld I/O Pads in IAP-M, there were limitations in its use. The computing power restricted the geometric complexity, while the brightness of the small projector had an ideal distance between 20-40 cm. Furthermore, tracking multiple objects was challenging as the visible markers overlapped easily.

To cater for these limitations, a second implementation was constructed, based on more capable hardware, including a large TabletPC with graphical processing unit (GPU), an ultra-wide projector and an IR-based tracking solution. A flight case was made to make this setup portable, and it was transported at least 300 km by public transport and car. This implementation outperformed the first pilot in terms of computing power/brightness/tracking. A set of test objects were rapid prototyped, equipped with retro-reflective markers. Nylon SLS fabrication is favoured due to its robustness and lambertian reflective properties. However, the chosen software platform proved to be too complicated to import/export CAD models and implement various types of interaction, such as 3D drawing and annotation.

These pilot implementations provide sufficient insight of the envisioned I/O Pad and their development yielded recommendations for further development and valorisation.

4.9 Recommendations for further implementation of the I/O Pad

When multiple I/O Pads are used simultaneously, synchronisation is necessary. This can be solved in several ways, for example, by application sharing (i.e., running the same synchronized instance on all pads), by model sharing among different applications (for example one pad dedicated to modelling and one to simulation), or by hosting diverse models of the same product. More investigations are necessary to determine which option is the most suitable.

Another challenge is the access and navigation through the resulting reviews. Although sessions can be replayed in a chronological order (video streams plus modelling events), it makes more sense to offer different interface techniques that cater for clustered data management. The ShowMotion Technique might be a useful extension to interact with design review data (Burtnyk et al., 2006). This technique offers navigating through “temporal thumbnails” - moving 3D cuts based on cinematic visual transitions. Such a set of animated parts of the design could enrich the inspection and comparison of several versions of a design.

4.10 References

- Bandyopadhyay, D., Raskar, R. and Fuchs, H. (2001) “Dynamic shader lamps: painting on movable objects”, proceedings International Symposium on Augmented Reality (ISMAR), pp.207–216.
- Burtnyk, N., Khan, A., Fitzmaurice, G., and Kurtenbach, G. (2006) “ShowMotion: camera motion based 3D design review”, in Proceedings of I3D '06, pp. 167-174.
- Faugeras, O. (1993) *Three-Dimensional Computer Vision: a Geometric Viewpoint*, MIT press.
- Foley, J., van Dam, A., Feiner, S., Hughes, J. (1995) *Computer Graphics: Principles and Practice, Second Edition in C* Addison-Wesley, Reading.
- Huet, G., Culley, S. J., McMahon, C. A., Fortin, C. (2007) “Making sense of engineering design review activities”, *AI EDAM journal*, vol. 21(03), pp. 243-266.
- Kato, H. and Billinghurst, M. (1999) “Marker tracking and HMD calibration for a video-based augmented reality conferencing system”, *Proceedings of International Workshop on Augmented Reality (IWAR 99)*, pp.85–94.
- Sheng, Y., Yapo, T.C., Young, C., Cutler, B. (2011) “A Spatially Augmented Reality Sketching Interface for Architectural Daylighting Design” *IEEE Transactions on Visualization and Computer Graphics* 17(1), pp. 38-50.
- Raskar, R. and Bimber, O. (2004) *Spatial Augmented Reality*, A.K. Peters.
- Wagner, D., Schmalstieg, D. (2006) “Handheld Augmented Reality Displays”, in *proceedings of Virtual Reality Conference 2006*, pp. 321- 322.

Chapter 5

Validation of IAP-M and its applications

5.1 Aims, problem statement and research questions

In this project, I conceptualised and developed IAP-M: a collection of methods, instrumentation, a procedure and criteria based on an underpinning theory. In order to demonstrate that this methodology is suitable for its intended purpose, I need to address the following questions:

- What is the scientific basis of validating IAP-M?
- What should be validated from epistemological and methodological points of view?
- Is there evidence that supports the utility of IAP-M?
- What can we conclude from these findings and how can these be generalised?

5.1.1 Method selection and anticipated results

Validating a tool or method in design is a challenging part of research as little can be predicted based on induction: each research process and outcome is unique (Eckert et al., 2004). To cater for this validation challenge, Seepersad et al. (2006) presented a reasoning framework that distinguishes between structure/performance and theoretical/empirical aspects, also known as the validation square. I will apply this framework to IAP-M through using demonstrators as empirical basis.

5.1.2 Adaptation of the Validation Square

To balance the logical empiricist validation that focuses on “a strictly formal, algorithmic, reductionist and confrontational process, where new knowledge is either true or false”, Pedersen et al. (2000) initially introduced a framework for validating engineering design methods entitled the *validation square* (VS) method. Characterized as relativist validation, the Pedersen et al. considered a semiformal and conversational treatment to testing new knowledge that includes heuristics and non-precise representations. With regard to the theoretical and methodological fundamentals, the VS framework separates the merits of a design methodology from

a structural (logical) and a performance (utilitarian) point of view. As illustrated in Figure 51, the validation square is divided into four quadrants. The left two are associated with structural validation and the right two with performance validation. The upper part of the square corresponds to domain-independent, generic validation while the lower addresses the domain-specific validation (tuned to the validity of the methodology for domain-specific cases).

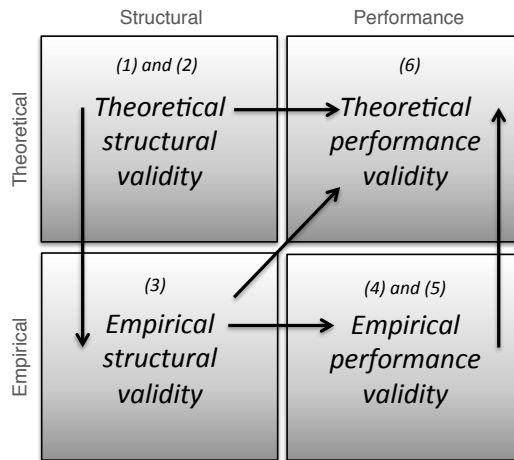


Figure 51 The scheme of the original Validation Square proposal.

To operationalize the validation square, six activities are described: (1) accepting individual constructs of the methodology, (2) investigating methodology consistency, (3) accepting example problems, (4) examining usefulness of the methodology for example problems, (5) accepting that usefulness is linked to applying the methodology, (6) recognising usefulness beyond the case studies. Du Bois (2013) applied this framework to validate a collection of software development methodologies, renaming this to a quadrant-based validation.

Figure 52 places this framework into my project context, linking the validation to the devised theory and its implemented constituents. We envisioned that the application of IAP-M brings process enhancement by creating shared understanding through engaged discussions and discovery of errors/solutions.

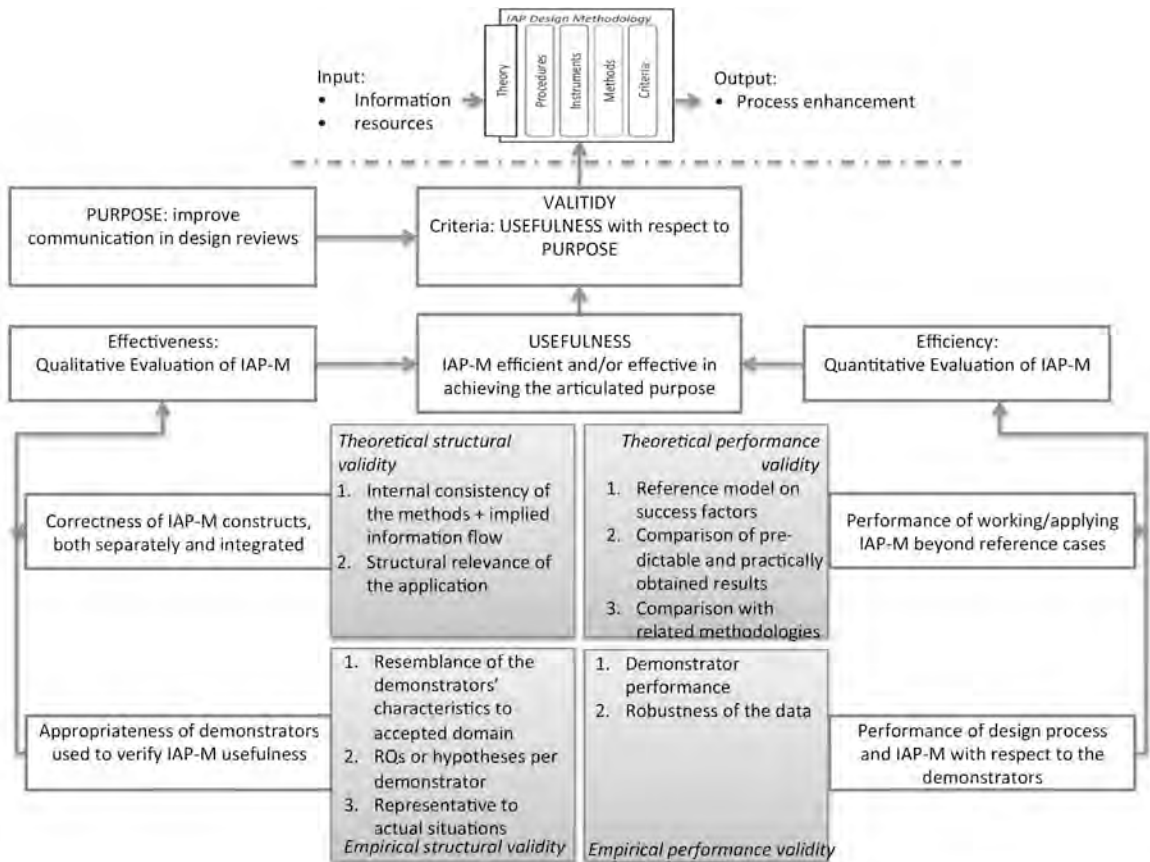


Figure 52 Quadrant-based validation for IAP-M

5.2 Theoretical structural validity of IAP-M

The theoretical structure of IAP-M needs to be validated on three aspects: knowledge, workflow, and information processing.

Knowledge

The design methodology set forth in the previous chapters and the underlying theory as framed in a reference model in Figure 29 there are no critical internal contradictions. The IAP-M concepts were derived from empirical case studies, which were representative of product design, while the bottlenecks and best practices were confirmed to have an impact on the design process.

Workflow

The procedure set forth in Chapter 4 presents a sequential application of the methods and instrumentation in 5 steps, which can be iteratively applied. The consecutive steps of modelling, preparation, deployment, reviewing and reflection match typical activities of regular design review (Pugh, 1990).

Information processing

The information flow of section 3.4 defines the high-level processes and entities during and after application of IAP-M. In the software architecture and

implementation schemes of Chapter 4, the data processing was simplified to 3D objects and calibration data, while the design review session scheme was refined to an event-based object repository with references to topic, participant, follow-up action, and impact. As these constructs are based on empirical findings, specifically by Huet et al. (2007), IAP-M offers the information that is needed for reviewing and decision-making. However, the IAP-M criteria are incomplete, due to the limited implementation of the instrumentation. This should be addressed at the theoretical performance validation to consider the true utility of this methodology.

5.3 Grasping performance targets

The main hypothesis of IAP-M was that it could improve shared understanding of design concepts among stakeholders during a design review meeting. In Chatzimichali et al. (2011), I already explored collective learning among professionals, and other phenomena such as creative conflict, consensus and spatial reasoning. Yet this exploration could not be implemented in one definitive experiment. Instead, I selected three constructs to reason about the theoretical and empirical performance, in the context of the reference model (Figure 29 in Chapter 2):

Engaged discussion – In interpreting the design review as a conversation, it should facilitate argumentation of different disciplines (with possibly different notations, models and simulations and so forth). Conversational features such as turn taking, issue counting and so forth can be used to measure the level of engagement.

Shared understanding of design concepts- Shared understanding covers both social and linguistic aspects. I attempted to narrow this down to the time necessary to understand a new design utterance by a user.

Discovery/learning – apart from generating shared insight, design reviews are meant to find errors and solutions. In this assessment, the time necessary to find an error in a design could be an indicator, although errors vary in gravity from a small imperfection to a mission critical mistake.

Table 20 presents the resulting performance indicators. An additional indicator was added regarding the ease of operation of the I/O Pad, which should not add a barrier during design reviews.

Table 20 IAP-M performance indicators.

Performance	Measurable units	Objective
Engaged discussion during the design review	Turn taking, topics discussed	↑ (more is better)
Time to obtain shared understanding during a design review	Time	↓
Discovery/learning during sessions	Time to find design errors	↓
Learnability of I/O Pad	Time to learn operation	↓

In Prototyping effort as time and resources are crucial in design processes, these influence the impact of IAP-M. This effort is reflected in the modelling, preparation, and deployment steps of the procedure.

Table 21 IAP-M Prototyping effort indicators.

Performance	Measurable units	IAP-M procedure
I/O Pad adaptation (software development)	Time	1. Modelling & 2 Preparation
Effort of manufacturing physical models	Time	2. Preparation
Effort of creating digital models/assets	Time	3. Deployment
Effort of deploying the system	Time	3. Deployment

5.4 Empirical validation through demonstrators

To obtain empirical evidence, I tested a collection of experimental applications with staff and senior design students. These tests, called demonstrators, represent application cases of IAP-M:

1. Nightclub interior design: design review exploring the match between style and furniture layout in the conceptual design phase, including pedestrian simulation.
2. UI test of a voice recorder: usability assessment of a mock-up with projected screen in the detailed design phase, compared to a traditional 2D screen version.
3. Starting with a digital model: CNC milled car with projection of material, to explore feature selection in the detailing phase of design.
4. Starting from a clay model: exploration of features on an automotive clay model, in conceptual design phase.
5. Starting from sketches: employing a sketch-based modeller and rapid prototyping to address material and feature selection of an information appliance in the concept design phase.

The first two demonstrators specifically focus on the IAP-M targets, while #3-#5 expand on the development effort. The following sections cover these demonstrators in detail.

5.4.1 Demonstrator #1. Design review of a nightclub interior

To test IAP-M in a design review, we developed an application that focused on modelling the layout and style of a nightclub. This design required considering the following elements:

- A space of 16x20 meters.
- The layout of functional regions such as bars, dance areas, toilets and entry points.
- The decoration of walls, furniture should fit an aesthetic and functional style that differs between different nightclub brands.
- Safety and routing during calamities and specific events like “happy hours”.
- Consultation of multiple stakeholders (owner, fire experts, organizers of special events and so forth).

Interactive augmented prototype

Traditionally in interior architecture, floor plans and specifications are used for such discussions. In some cases, simple scale models are made. As discussed in case



Figure 53 Picture of physical setup (left) and interactive augmented prototype (right).

#3 (Section 2.6) such representations lack focal points and hamper addressing functionality.

The interactive augmented prototype is shown Figure 53. Set in a scale of 1:40, a number of physical objects could be moved across the rectangular floor. Each of these objects corresponded to a piece of furniture: dance floors (hexagonal pieces), bars (long elements, in different sizes) and seating areas (chairs mounted on a small piece of tile). Apart from the moveable furniture, some fixed components were projected, including a main entrance, emergency exits, and toilet entry.



Figure 54 Snapshots of the different interior styles.

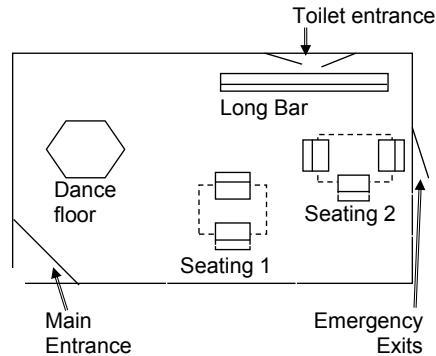


Figure 55 Initial layout of the nightclub, with furniture blocking toilet and emergency exits.

The augmentation of the model supported selection of a pre-set style, tracking the movements of the physical scale furniture models, and a pedestrian flow simulation. Figure 54 depicts the four styles that corresponded to a collection of bitmaps that are mapped to the walls, floor and pieces of furniture. The user could switch from one to another by voice command (“switch to ...”), while a hardcopy of these styles was located on the side of the system.

When not in use, pieces could be moved outside the floor plan. Similar to the urban design system discussed in Section 1.2.1.4, this demonstrator included an interactive simulation, which would display a pedestrian flow simulation as dots in the scene, each pedestrian with its own location and orientation. Based on the layout and simulation time (determined by a clock interface), they would move among the elements of the nightclub. By inserting a “fire” object, evacuation scenarios were triggered.

Review sessions

The prototype was tested in three sessions; each including a team of two senior design students (2 architecture, 4 industrial design). All participants had experience in designing, planning and coordinating festivals and exhibitions. During the sessions, the participants were given an assignment, stating the imaginary design context and the role each participant had to play (client, designer, expert).

The participants had no problems in finding out how the basic operation worked, including moving around furniture pieces and interpreting the pedestrian flows, and explored different configurations when another style was chosen (see Figure 56).

For each session, configuration “errors” were introduced at the start – a bar in front of a toilet entrance, illogical placement of a seating area (see Figure 55). One of the benchmarks was to observe whether these were noticed and fixed. In all three sessions, the errors were noticed and corrected within 1 minute. The sessions took on average 6 minutes per style – the maximum was 10 minutes. This included discussion, reconfiguration and evaluation. The participants remarked that the augmentation added an engaging factor that stimulated discussion



Figure 56 Discussion on one of the layouts during a session.

Implementation details

The physical models were made by hand from polystyrene slabs and wood. A large I/O Pad on a corner of the table, facing down with a 35-degree angle. This presented a complete projection of floor and walls that allowed collaborative use of the setup.

The furniture components were modelled in SolidWorks and converted to VRML files. We used a Wizard of Oz technique for object tracking. To enable this, the software was based on an Open Inventor example. A human operator monitored hand motions of the users and propagated the changes in style, furniture position/rotation and time of the virtual clock by mouse and keyboard. Furniture movement was supported with by Open Inventor's concepts of draggers and engines, which we constrained to a 2D plane in space.

The pedestrian flow simulation was based on magnetism-type attraction and propulsion forces (Matsushita and Okazaki, 1993). Pedestrians and blocking objects were represented as positive particles while target objects were negative. For each time slice, Coulomb's law is applied to calculate the magnetic forces:

$$F = \left(\frac{k \cdot q1 \cdot q2}{|r|^3} \right) \cdot r$$

Where F is the magnetic force (a vector), k is a constant value, q1 is the intensity of magnetic load of a pedestrian, q2 is the intensity of another magnetic pole, r is the translation vector between the two particles. The standard workstation limited the number of simulated pedestrians (Pentium III PC). 25 visitors would result in an update rate of 20 Hz. Round objects had one force in the centre, rectangular pieces such as the bar had 2 forces at their ends. Pedestrians all had the same magnetic load (2) while the forces of the furniture pieces depended on the virtual time to allow different scenarios like 'happy hours' (between -2 and -20). The fire object was given a very large positive value (200) to propel all virtual visitors.

Lessons learned from this demonstrator

The Wizard of Oz setup worked surprisingly well; participants adapted to the limited speed of picking and moving elements. However, there was confusion about the

interactive components with no or little physical means: the clock and the style selection. Although the pedestrian flow simulation was considered useful, the dynamic visualization sometimes distracted the participants when they switched to another style.

As all had a background in organizing and designing dance parties, they suggested enhancements. This included adding lighting effects, more styles and furniture pieces (or possibilities to use scanners and cameras to create new ones), to include air circulation, sound isolation, and the logistics of beverages.

Table 22 Performance indicators of demonstrator #1.

Performance indicators	Value	Remarks
Time to obtain shared insight during a design review	Design concepts were optimised by two stakeholders within 6 minutes	Role playing by pairs of experienced festival planners
Discovery/learning during sessions	Design errors were found within 1 minute.	
Learnability of Instrumentation	1 minute	
Engaged discussion during the design review	yes	Constant discussion while moving elements and inspecting the pedestrian flow.
I/O Pad adaptation	3 weeks	Software implementation including pedestrian flow simulation
Effort of manufacturing physical models	2 hours	Abstract wooden objects, painted white
Effort of creating digital models/assets	1 hour	Selecting bitmaps and music styles.
Effort of deploying the system	n.a.	

5.4.2 Demonstrator #2. UI test of a voice recorder



Figure 57 Voice recorder system (left), projection (middle) and 2D screen prototype (right).

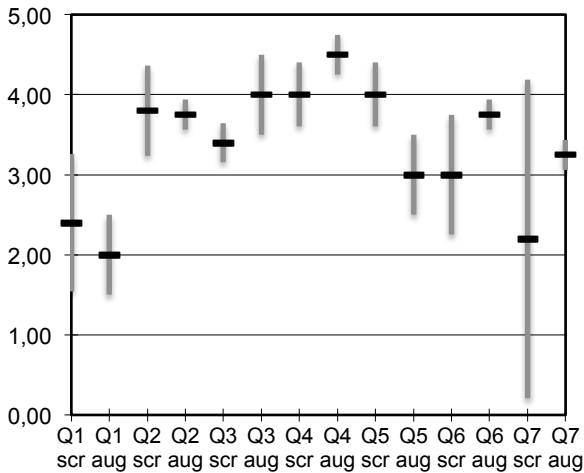
The second demonstrator focused on assessing the usability of a handheld information appliance, in this case a voice recorder. In the design of such products, both physical and cognitive ergonomics play an important role in assessing the quality of a product proposal during design reviews. The design was a handheld product of 11 x 7 x 2 cm, and contained a speaker, a microphone, a power switch, and a small screen at the front. On the right side were three buttons for control. The ideated product only offered a limited set of functions: recording, playing, navigating, and removing spoken messages. The operation architecture of the recorder was divided into two screens (Figure 58). A main menu displayed nine message slots, which could be empty or filled (the latter indicated by an asterisk). When a message slot was selected, a submenu offered options to play/record/clear the message.

To test the discovery of errors, some annoyances were introduced in the design:

- A filled message slot should be cleared before another message could be recorded on that lot.
- The submenu offered no possibility to navigate directly to a previous/next message (the user had to use the 'back' menu option).



Figure 58 Voice recorder main menu (left) and submenu (right), to be projected on mock-up.



Q1	Can you hold the voice recorder comfortably in your hand?
Q2	Is the control/operation of the voice recorder understandable?
Q3	Are the buttons logically placed if you would control the real product?
Q4	Can you imagine what the actual product will be like?
Q5	Is the display legible?
Q6	Do you think the prototype is a good replica of the real product?
Q7	Does the prototype offer enough information for a decision to buy the product?

Figure 59 Questionnaire results for both screen (“scr”) and augmented (“aug”) conditions.

Interactive augmented prototype

The interactive augmented prototype used a wooden mock-up, on which the screens showed above would be projected. The mock-up was mounted on a Microscribe 3D arm (Figure 57 on the left). The I/O Pad would render and project a texture-mapped polygon that represented the product’s screen, while position and orientation were constantly following the Microscribe 3D arm. Separate bitmaps had to be produced for each screen state, resulting in 584 permutations (main menu: 9 filled/clear slots, 9 message menus: each filled/cleared and 4 different active states). The bitmap file names corresponded with the respective permutation, `m<bbbbbbbbb>.gif` for the main menu and `9<bbbb>.gif` for the submenu where `b` is either 0 or 1. In the I/O Pad’s software would load the proper bitmap files based on button presses, which in effect established a finite state machine to reflect the dialogue state. The I/O Pad would also play pre-recorded audio messages - recording of sound was not supported in this prototype. The buttons on the physical mock-up were not connected; an observer monitored the actions of a user and updated the state machine accordingly (wizard of Oz). A 2D version was developed as well, running on a laptop and mouse. This reflected the traditional way of prototyping of handheld concepts (Section 0), and was used to compare the design review with the interactive augmented prototype.

UI Test sessions

In the product assessment sessions, 9 participants, senior design students and staff members, were first given a short introduction and then a number of assignments they had to perform. These assignments included the following tasks: i) searching for particular messages, ii) recording new ones, and iii) having to cope with memory full exceptions. Four participants started with the 2D screen prototype while the remaining started with the interactive augmented prototype.

The time to finish the assignments didn’t differ much among the test group (all participants took around 9 minutes). The participants found more design flaws using the augmented prototype than in the screen version. During the sessions, five

subjects remarked that the red power button confused them; this could also be observed as the button was occasionally pushed by accident in both prototype versions. Two participants mentioned the unfriendly features during the assignments (the illogical navigation and the inability to record a message without clearing it first). While using the augmented prototype participants stated more detailed remarks, e.g., three participants indicated that the placements of the buttons on the side should be improved, as it was difficult to control them by thumb while holding the product in their hand. After the assignments, the participants filled in a questionnaire, which included questions concerning comfort, understandability, legibility, and significance of the prototyping method, scored on a 5-point scale (1=strongly no, 5= full agreement) (see Figure 59).

Lessons learned from this demonstrator

The tests indicated that the participants had a higher sense of engagement in the augmented condition – for example, one person was observed to move the physical mock-up closer to his mouth during recording. Although not statistically sound, it suggests that IAP-M performs better in assessing combinations of physical and cognitive aspects.

Unfortunately, the Microscribe tracker introduced an additional strain. It had a limited movement envelope with 5 instead of 6 degrees of freedom. Furthermore, it added weight and inertia, occasionally resulting in situations where arm and wrist posture was sometimes tense. To guarantee correct illumination among the complete action radius of the Microscribe, the projector was located at 2 meters distance. This resulted in a low resolution of the bitmapped polygon, reducing legibility of the projected screen (200x200 pixels at most). A final observation with this demonstrator was that we could perceive noticeable delays in update speed when the physical mock-up was swiftly moved or turned. Surprisingly, this was due to the latency in the LCD-based projector.

The development of the interactive augmented prototype took 1 week. This included creating the content (screen bitmaps and audio clips) and the adaptations to the I/O pad to connect to the Microscribe tracker and the implementation of the state machine discussed above. The 2D screen prototype was implemented in 1 day, by reusing the same screens and graphics of the augmented prototype.

Table 23 Performance indicators of demonstrator #2.

Performance indicators	Value	Remarks
Time to obtain shared insight during a design review	9 minutes	Completion of a set of assignments
Discovery/learning during sessions	yes	More design flaws were found than in the screen-based prototype
Learnability of Instrumentation	1 minute	In the traditional prototype, all participants had issues with mouse control.
Engaged discussion during the design review	n.a.	
I/O Pad adaptation	3 days	Software development
Effort of manufacturing physical models	2 hours	MDF wood sawing /sanding and 2 layers of paint.
Effort of creating digital models/assets	1 day	Bitmap of screens & setting the dimensions of the screen)
Effort of deploying the system	n.a.	

5.5 Demonstrators that considered the preparation procedure

The reference model indicated that the prototyping effort plays an important role in the inclusion of specific prototyping technologies, thus to test the utility of IAP-M, the modelling, preparation, and deployment procedure should be addressed.

5.5.1 Demonstrator #3. Starting with a digital model

The fictitious context of this demonstrator was the configuration of a car design, with the objective to explore the following features: i) the colour/material of the car body (including reflection), ii) continuity of the surface geometry, and iii) location and shape of headlights, windows and rims.

In a situation like these, regular practice would employ handmade sketches or computer-based renderings based on a CAD model. As these lack spatial cues, they are challenging to comprehend as a whole product rather than a series of sketches or renderings.

Interactive augmented prototype

In this demonstrator, an existing 3d model of a car was used. This model was scaled down to 20x10x10 cm, CNC-milled in polyurethane foam, and coated in white latex paint. In the virtual model, three components were selected for alter material properties (car body, wheels, wheel frames). Together with a student team, a set of menus was developed, offering the following configurations:

- Material: palettes of materials were shown, grouped in three categories (plastics, metals, and woods). Each material corresponded to a bitmap for texture mapping and a reflectivity index.
- Environment: a separate selection of images could be used as reflection maps and backdrops. This included bitmaps with white lines on a black background, which acted as a zebra striping effect to inspect the continuity of the car surface.
- Lighting: spotlight position and colours could be adapted.
- Presets: offers the possibility to store and retrieve material/lighting setting to explore alternatives.

A regular computer mouse was used to interact with the menus, which were selectable as four tab sheets. The resulting interactive augmented prototype is shown in Figure 60.



Figure 60 Setup, with turntable (left) and material dialogue (right).

Implementation details

The physical model was CNC-milled and painted. To track the orientation, a wooden turntable was built equipped with an encoder to read the angle (3200 pulses per full turn, connected to the workstation with a phidgetEncoder highSpeed⁵).

The I/O Pad was mounted on a tripod, 45 degrees tilted off the vertical axis. From the point of view of a standing or sitting user, this setup allowed illuminating a large area of the model. The material dialogue was projected on a wooden board, adjacent to the turntable.

Lessons learned from this demonstrator

This interactive augmented prototype was evaluated by a focus group involving 4 senior industrial design students and 2 automotive design teachers. After a short introduction, each participant was asked to reconstruct six pre-rendered images, presented on a hardcopy in an order of increasing difficulty. These assignments involved setting material, reflection, and light properties as well as physical positioning of the prototype. Participants had to verbally indicate when they felt satisfied with their work. A screenshot of their projection was saved.

All participants could immediately operate the turntable and predict its operation. However, the material menu required some guidance, as not all subjects could predict which parameters could be set in each of the tab sheets. The selection of the product part (by using the arrow buttons above the tab sheets) had to be introduced and demonstrated before the users felt familiar with the interface. Participants with no 3D modelling experience took longer to finish the tests, 37 minutes on average compared to 18 minutes for those with experience.

The ability to check the surface continuity was not tested by the participants. Limited by the use of a scale model, a detailed inspection of shapes was impossible.

⁵ http://www.phidgets.com/products.php?product_id=1057

Configuring the I/O Pad, including the menu layout, took approximately 3 weeks. In this case, the interactive visualisation was developed in Macromedia Director, a multimedia-authoring package that supported real-time visualization of and interaction with 3D models. This enabled the design students without programming skills to create and maintain the menu options and projection settings.

CNC-milling and painting took in total less than 1 hour. The calibration was done manually in by tweaking the field of view and the translation & orientation of the virtual camera in the 3D scene.

This system demonstrated the opportunities of augmented prototyping, based on a digital model. Below, the IAP-M targets are revisited for this demonstrator.

Table 24 Performance indicators of demonstrator #3.

Performance indicators	Value	Remarks
Time to obtain shared insight during a design review	3-6 minutes/concept	Time necessary to adapt model
Discovery/learning during sessions	n.a.	
Learnability of Instrumentation	2 minutes for CAD users, 4 for novices	
Engaged discussion during the design review	n.a.	
I/O Pad adaptation	3 weeks	Software development
Effort of manufacturing physical models	1 hour	CNC-milling and painting model white (latex)
Effort of creating digital models/assets	1 hour	Converting 3ds file
Effort of deploying the system	n.a.	

5.5.2 Demonstrator #4 Starting from a clay model



Figure 61 Clay model (Scale 1:5).

The fourth demonstrator was linked to an automotive styling course at the faculty of industrial design. The students were working on a physical model based on sketches that they made earlier in the process. In the clay modelling stage, the basic shape is already defined. I selected a car model that was made in about 3 weeks by Mr Jacob Lammers, representing a redesign of a Fiat Multipla– measuring 80 by 40 centimetres at scale of 1:5 (see Figure 61). The model did not contain details and no finish had been applied. In traditional model making, the clay model would have to be elaborated by using paint/foils in which components and material expression have to be fixed to a single, comprehensive model. This is a tedious process that will take at least 2 weeks, and requires expensive materials such as dinoc foil (Hoadley, 2002). In exploratory discussions, we concluded that the augmentation could be



Figure 62 Snapshot of the illuminated clay car.

beneficial by skipping this process, and to support the exploration of car details such as window shape and material studies.

Interactive augmented prototype

After studying automotive design textbooks, the following design parameters were selected: shape of the windows, headlights, tail lights, grilles, contour lines and accents on the body, and wheels (rims). All of these can be related to areas on the scanned 3D model. For each parameter, a collection of bitmaps was made. Figure 62 shows a snapshot of the system.

Implementation details

The intention was to project on the clay model without any physical modifications. However, preliminary tests showed that it was impossible to project imagery on brown clay - only fluorescent, saturated colours could be rendered as intended. The physical model was painted with simple household white latex and wooden wheels were added.

A Minolta Vivid 700 scanner was used to make a 3D scan of the car model. This required seven scans from different viewpoints, which were combined and simplified in the accompanied software. The scan was then imported into Kinetix' 3D Studio Max for further editing. This editing consisted of removing unwanted floating polygons/vertices, adding surfaces and objects where needed, creating surfaces for texture mapping, and adding texture mapping coordinates to these surfaces. The surfaces that would be used to render components in-place were created by selecting the appropriate polygons on the model and using them to create a new surface, positioned slightly above the original polygons to avoid interference during rendering. In the modeller, the UVW mapping modifier was used to define texture-mapping coordinates on the new surfaces.

As with demonstrator #3, a regular computer mouse was used to interact with the menu. The projector was located approximately 3 meters away from the turntable.

Lessons learned from this demonstrator

Three focus group discussions were held, with automotive design tutors, senior design students, and a group of CAD researchers. In each session the system was demonstrated, and the participants were allowed to work with the system themselves as well. This was followed by a semi-structured discussion to collect opinions and suggestions. The topics included clay sculpting, the experimental setup, and other opportunities for augmented prototyping. Most participants were surprised by the effect of rotating the turntable, but found its operation natural. The participants judged the illuminated clay to be useful for design. However, in their opinion, it could not replace the presentation of a finished, painted model. Automotive design already has an accepted standard of physical model making with visual detail that is hard to compete with.

Furthermore, straightforward 3D scanning that was done in the preparation phase of this demonstrator is insufficient: additional effort is required to reconstruct the underlying surface. Furthermore, the resulting shape needs post processing to split the resulting mesh into components that make sense for the design process. In this case, these components were the car features such as headlights, window contours and so forth.

The participants suggested opportunities for augmentation in design:

- Zebra striping projection for surface continuity testing during sculpting.
- Supporting sketching on the 3D surfaces during design reviews, preferably directly on the clay model with some sort of virtual paintbrush tool. This could be used to set the styling lines and relevant contours.
- 'Interactive sculpting': use a 3D scanner and projector configuration as a sculpting assistant by projecting physical changes that have to be made manually.

The reverse engineering took approx. 1 week, which included painting the model white. The implementation itself took 1 day.

Table 25 Performance indicators of demonstrator #4.

Performance indicators	Value	Remarks
Time to obtain shared insight during a design review	3-6 minutes/concept	Time necessary to adapt model
Discovery/learning during sessions	n.a.	Presentation quality worse than traditional models, but satisfactory for exploration.
Learnability of Instrumentation	1 minute	
Engaged discussion during the design review	n.a.	
I/O Pad adaptation	6 days	Turntable hardware, software development
Effort of manufacturing physical models	3 weeks	In automotive clay course
Effort of creating digital models/assets	2 hours	Laser-scanned point cloud reverse engineering (complicated)
Effort of deploying the system	2 hours	System required to be moved.

5.5.3 Demonstrator #5. Starting from sketches

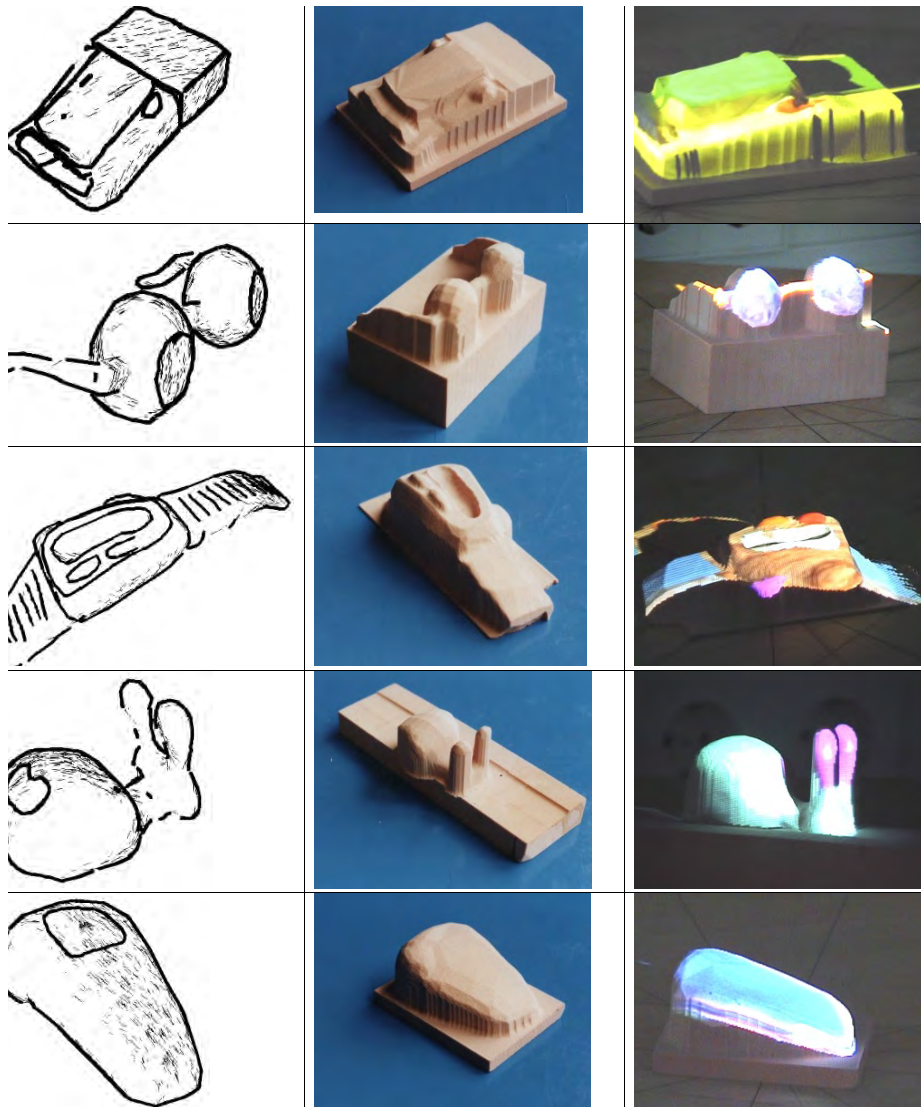


Figure 63 Screenshots and pictures of design cases in the demonstrator, as Teddy model (left), as CNC-milled mock-up (middle), and interactive augmented prototype (right).

In this demonstrator, the focus was on the modelling and preparation of IAP-M Five design students were invited to select an existing sketch or idea for a product they already had designed, and to re-model it using the augmented prototyping system. The designs were a letter balance, digital see-through goggles for nightclubs, and a number of portable cash registers. The test took place in two sessions: modelling and reviewing.

Modelling

In the first session, the participants used a sketch-based 3D modeller called Teddy to create a 3D model of their idea. The students' actions were timed and they stopped drawing when they were satisfied.

Reviewing the interactive augmented prototype

The second session was held when the virtual and physical models were manufactured and calibrated. In this session, the interactive augmented prototype was used to perform a colour and material study. The participants were asked to press a save button when they were satisfied with the result. Figure 63 shows a summary of the intermediate results.

Implementation details

Teddy, a sketch-based 3D modelling application was used to generate a 3D geometry (Igarashi et al. 1999). It is a simple modeller that required less than 10 minutes instruction. Its result, a wavefront OBJ file, was converted to STL format in preparation of the physical prototyping. Deskproto (2003) was used for scaling and alignment and to create milling paths for the Roland CAMM-3(PNC-3000). The material used was polyurethane foam (pink colour). For its virtual counterpart, the obj model was imported in a simple 3D modeller (Shapeshifter) to split the mesh into a collection of parts, to be addressed in the interactive augmented prototype.

The turntable hardware and I/O Pad combination of the demonstrator #3 was reused, to select materials and textures which are projected on parts of the model. The I/O Pad was moved close to the turntable and tilted to 60 degrees cast downwards from a height of approximately 1.30 meters.

Lessons learned from this demonstrator

The main objective of this demonstrator was to probe the workflow speed of IAP-M when starting without digital or physical model. This took on average more than one hour, although the actual milling was done unattended (50 minutes on average-corresponding to 60% of the time). Manufacturing the augmented prototypes took on average 82 minutes, a breakdown is shown in Table 26.

Table 26 Average performance of participants and technical support.

Activity	Time (minutes)	
	Designer	Operator
Modelling in Teddy	25	
Conversion and alignment of Teddy model		10
CNC machine preparation & milling		50
Creation of virtual model		7
Calibration on turntable		15
Using the AP for colour and material selection	25	
Total (minutes)	50	82

After the final session, the participants received a questionnaire that focused on usability and applicability of the method. Not all subjects were satisfied with the prototyping system. Key elements that lacked were a larger selection of colours and materials and more accurate prototyping means. Significant differences were found

in the quality of the prototypes. In particular, designs 2 and 3 (Figure 63) posed serious challenges to the augmented prototyping calibration. The participants expressed that the sketch-based modeller was too limited to express product shapes, in particular when coping with symmetry or using specified dimensions.

Table 27 Performance indicators of demonstrator #5.

Performance indicators	Value	Remarks
Time to obtain shared insight during a design review	n.a.	
Discovery/learning during sessions	n.a.	
Learnability of Instrumentation	within 1 minute	
Engaged discussion during the design review	n.a.	
I/O Pad adaptation	1 day	Software development
Effort of manufacturing physical models	82 minutes	CNC milling
Effort of creating digital models/assets	50 minutes per model	obj file conversion. Complex task: calibration (15 minutes per model).
Effort of deploying the system	n.a.	

5.6 Empirical structural validity of IAP-M

The demonstrators were introduced to obtain empirical evidence. As design domain and design challenge abridged in Table 28 show, the demonstrators are representative to product design. Furthermore, the demonstrators fit three of the appropriateness criteria for IAP-M: i) the design involves a spatial realm, ii) the application scenario fits the tradition of that specific design, and iii) the conditions of the design review's location can be controlled in terms of lighting and noise as to track and record the interaction and discussion. The fourth IAP-M criterion, the involvement of multiple stakeholders, is only evident in demonstrator #1.

Table 28 Structural characterisation of the demonstrators.

	#1	#2	#3	#4	#5
	Nightclub interior	Voice recorder	Car	Car	Handheld form study
Design domain	Interior design	Information appliance	Automotive	Automotive	Information appliance
Design phase	Concept	Detail	Detail	Concept	Concept
Design challenge/ topic	Furniture layout & calamities	Usability assessment	Visualization of Material/ feature selection	Articulation of features	Visualization of Material/ feature selection

The demonstrators covered different parts of IAP-M, Figure 64 charts the focus on either the review and preparation procedure. Furthermore, the demonstrators also represented the three different starting points for establishing a prototype of the IAP-M modelling step: digital (#3), physical (#4), and sketching (#5).

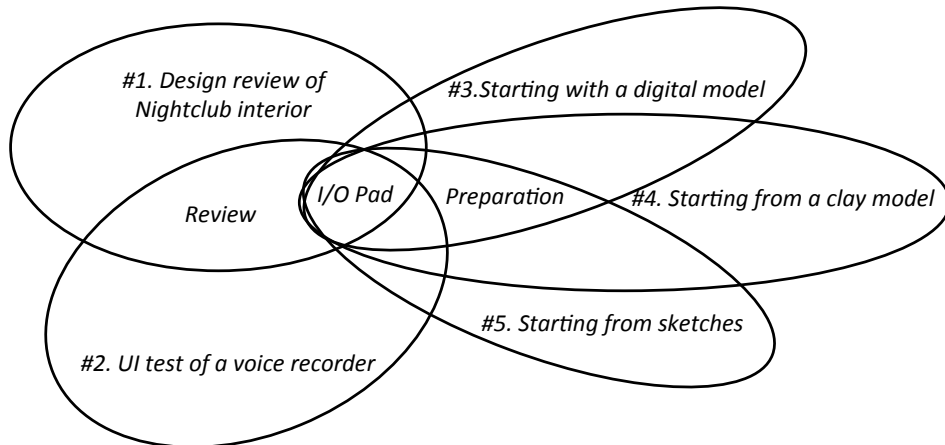


Figure 64 Coverage of IAP-M constituents by the demonstrators.

With regard to instrumentation, all demonstrators included an interactive augmented prototype. However, an incomplete I/O pad implementation was used:

- In all demonstrators, calibration of the projected image was performed manually instead of using the proposed algorithm in the previous chapter. This worked for the setups, as it had to be done only once by setting standard parameters as (virtual) camera position/orientation, field-of-view, and scale. Furthermore, the physical components had simple, convex geometries, which were quite tolerant of inaccuracies in the projections.
- In demonstrators #1 a “Wizard of Oz” workaround was used to support tracking, while a similar solution was used for #4 to track user interaction. During the evaluation, the participants were not aware of a human link between them and the system.

Taking in consideration both the design situation and the coverage of IAP-M constituents, demonstrator #1 is the most representative application case. This was the only design review setting that involved multiple participants and used interactive computational simulation. This demonstrator was used as a ‘reference case’ to reason on the empirical performance.

5.7 Empirical performance validity

5.7.1 Fulfilment of the targets

Empirical performance of IAP-M focuses on the effectiveness of the demonstrators – in particular demonstrator #1 as the reference case. Here, the targets defined in Section 5.3 will be revisited

Engaged discussion

The participants continued taking turns in the discussion while both adapted the scene as well. Here, the pedestrian flow simulation gave an additional level of engagement and was found useful during exploration of calamities.

Additional findings from other demonstrators:

- However, the visual detail of the interactive augmented prototype of demonstrator #2 and demonstrator #4 were insufficient. This quality requires careful planning in the preparation phase.

Shared understanding of design concepts

In contrast to regular interior design reviews such as found in case study 3, IAP-M delivered a better way for fast exploration. In the Demonstrator #1 the review of a layout required approx. 6 minutes. This interactive augmented prototype yielded a large collection of design variants for the four different styles.

Additional findings from other demonstrators:

- For all demonstrators, the learning time of IAP instrumentation was less than 1 minute (except for the sketch-based modelling approach of demonstrator #4).
- In Demonstrator #2: a comparison between screen-based and augmented prototype shows that the latter presents a higher confidence in assessing the physical and cognitive ergonomics.

Discovery/learning

In the nightclub interior design review application, the participants discovered all errors in the presented concepts throughout all evaluation sessions.

Additional evidence from other demonstrators:

- Demonstrator #2, UI annoyances were tracked in greater detail in the augmented prototype.

Development effort of the demonstrators

In order to reason on the development effort, the complete collection of demonstrators should be considered. We should distinguish between adapting the I/O Pad instrumentation (hardware and software, done by me) and the creation digital and physical models for a particular demonstrator (done by student teams).

- *I/O Pad adaptation* Development of an I/O Pad configuration, in the case of demonstrators #1 and #2, took three man-weeks. Adaptations to an existing platform took a between 1 day or less (demonstrators #3 to #5).
- *Effort of manufacturing physical models & digital models/assets* Excluding the clay modelling of demonstrator #4, the manufacturing of physical models took 1-4 hours. The creation of the virtual models varied, ranging from 30 minutes for calibrating CNC milled models to 1 week for reverse engineering the clay model of demonstrator #4.
- *Effort of deploying the system* Only demonstrator #4 included the deployment procedure, which was limited to indoor transport and installation.

5.7.2 Robustness of the data

With the assistance of design students, I developed five demonstrators. This action-learning approach allowed for creating a wide palette of solutions and lessons from one demonstrator could be applied to subsequent developments. All demonstrators were evaluated by prospective end users, in many cases design students – in total 36 people tested the setups and gave feedback on the quality of the result. The

involved senior students and design teachers had a sufficient frame of reference to judge the impact on regular design practice.

In conclusion, the demonstrators did show that IAP-M yields engaged discussion and improves establishing insight, while in some cases the quality of the augmented prototype suffered and would require improvement to get accepted.

5.8 Theoretical performance validity

The collection of demonstrators presented empirical evidence in the application of IAP-M with regard to the previously defined targets. The validation square offers a scheme to reason on the theoretical performance by inspecting the limited empirical findings through a “leap of faith” (Seepersad et al., 2006).

5.8.1 Comparison of predictable and practically obtained results

To complement the empirical findings and lessons learned from the demonstrators, three follow-up activities were performed:

- 1) Design professionals at 16 Dutch Design agencies were surveyed, with regard to the utility of interactive augmented prototyping. A detailed report on this investigation is found in Appendix D.
- 2) A critical reflection on the IAP-M constituents, specifically I/O Pad and the reflection method by the three original case study owners. A subsequent publication is found in appendix E.
- 3) IAP-M has been brought to market – an account of this valorisation effort is presented in Appendix F. The resulting techno starter has realised augmented prototyping solutions for customers in aerospace, automotive and real estate development.

The accumulated evidence is charted in Table 29.

Regarding the *survey*: the design professionals considered the IAP-M most applicable in interior and automotive design. Their envisioned benefits of IAP-M, emphasizing a significant improvement of external communication and improving insights. Although all reflections were positive with regard to the opportunities of AP, the technical implementation was considered too time-consuming for daily practice.

Regarding the *critical reflection*: the second implementation of the I/O Pad was deployed and demonstrated with the 3D printed tractor, next to two other projector-based systems. The designers discussed the use of these devices during design reviews, also with respect to the design project that was followed. In all three agencies, a different I/O Pad application was preferred, and specifically method A. mixed reality fabrication needs further attention to cater for studio tradition and design domain. With respect to the Method C. recording design reviews, the repository scheme was discussed and refined.

Regarding the *valorisation*: the I/O Pad was patented (US and Europe) and an IDE alumnus founded a start-up company with a computer science student. This enterprise, Delight Interactive Solutions B.V., initially worked on extending the technologies to a portfolio of products. Due to the economic crisis, the company's target group of design engineering had to be broadened to domains that have an explicit attention towards increasing the user experience, i.e. museums and real

estate sales. However, the intended workflow still resembles IAP-M procedure. Their clients include BMW, TNO and the Delft Science Centre.

Table 29 Practically obtained and predictable findings regarding performance.

IAP-M constituent	Demonstrators	Additional evidence
<i>Procedure</i>		
• <i>Modeling</i>	#5	
• <i>Preparation</i>	#3, #4, #5	Pilot implementation (Chapter 4)
• <i>Deployment</i>	-	<ul style="list-style-type: none"> • Pilot implementations (Chapter 4), • Critical reflection (Appendix E).
• <i>Review</i>	#1	
• <i>Reflect</i>	-	Critical reflection (Appendix E)
<i>Instrumentation: I/O Pad</i>	All	<ul style="list-style-type: none"> • Pilot implementations (Chapter 4), • Critical reflection (Appendix E). • Valorisation (Appendix F)
<i>Methods</i>		
• <i>A. Mixed reality prototype fabrication</i>	All	Pilot implementations (Chapter 4).
• <i>B. Physical model making</i>	#3	Pilot implementations (Chapter 4).
• <i>C. Recording design review sessions</i>	-	Critical reflection (Appendix E).

5.8.2 Quadrant-based validation of IAP-M

To validate the utility of IAP-M, I was faced with the challenge that the implementation was limited and it would be very difficult to obtain statistical proof. I adapted the framework of the validation square to a quadrant-based validation of IAP-M, by separating the structural and performance aspects, a relatively small body of findings could stipulate sufficient evidence to support usefulness of the methodology. As an empirical basis, I used five IAP-M demonstrators for specific design situations. All these were made, tested, and results were peer-reviewed. Although they individually only partially cover IAP-M, the collection contains a reference case (demonstrator #1) which represents a proper design review situation and suggests that the I/O Pad helps in obtaining shared insight. The findings of these demonstrators were complemented by a survey with 16 design agencies, a critical reflection on the IAP-M constituents by the three original case study owners, and valorisation through a techno starter. The design professionals indicated the usefulness of the principle of IAP-M, but the present implementation too cumbersome for industrial application.

5.8.3 Propositions

Based on empirical studies and the development and validation of the Interactive Augmented Prototyping Methodology, I formulate the following propositions:

1. The use of prototypes during design reviews supports an engaged discussion and discovery/learning, which eventually minimises delay in product development, improves product quality, and increases stakeholder's trust (*Section 2.8 Prototyping for shared understanding – reference model*).

2. Augmented reality techniques are insufficient to enhance the design process (*Chapter 4 Constituents of IAP-M*).
3. Current studio tradition in design is too analogue and needs to be adapted to apply IAP-M (*Section 4.9 Criteria for applying IAP-M*).
4. The iPad can only become a truly useful design tool when it includes a tracking system and a projector (*EU & US patent PCT/NL2008/050515*).

5.9 References

- Chatzimichali, A.P., Gijselaers, W., Segers, M.S.R., Bossche, P.V.D., Emmerik, H.V., Smulders, F.E., Jonker, P.P., Verlinden, J.C. (2011) "Bridging the multiple reality gap: Application of augmented reality in new product development" In SMC, pp. 1914-1919.
- Du Bois, E. (2013) A designerly methodology for software development, PhD thesis, Delft university of Technology.
- Eckert C., Clarkson P.J., Stacey M.K. (2004) "The lure of the measurable in design research" proceedings of Design 2004, pp. 21-26.
- Hoadley, F.E. (2002) *Automobile Design Techniques and Design Modeling: The Men, the Methods, and the Materials*, 2nd ed., TAH Productions, Dearborn, Michigan.
- Huet, G., Culley, S. J., McMahon, C. A., Fortin, C. (2007) "Making sense of engineering design review activities", *AI EDAM journal*, vol. 21(03), pp. 243-266.
- Igarashi, T., Matsuoka, S., Tanaka, H. (1999) "Teddy: A Sketching Interface for 3D Freeform Design", *Proceedings of SIGGRAPH'99*, pp. 409 - 416.
- Matsushita, S. and Okazaki, S. (1993), 'A Study of Simulation Model for Pedestrian Movement with Evacuation and Queuing', in Smith, R.A. and Dickie, J.F. (eds.), *Proceedings of the International Conference on Engineering for Crowd Safety*, London.
- Pedersen, K., Emblemsvåg, J., Bailey, R., Allen, J. K., Mistree, F. (2000) "Validating design methods & research: The validation square" in *proc. ASME Design Engineering Technical Conferences*, Baltimore, MD.
- Pugh, S. (1990) *Total Design: Integrated Methods for Successful Product Engineering*, Addison-Wesley, New York.
- Seepersad, C. C., K. Pedersen, J. Emblemsvag, R. R. Bailey, J. K. Allen and F. Mistree (2006) "The Validation Square: How Does One Verify and Validate a Design Method?" *Decision-Based Design: Making Effective Decisions in Product and Systems Design* (W. Chen, K. Lewis and L. Schmidt, Eds.), ASME Press, NY.
- Shapeshifter <http://xtras.tabuleiro.com/products/shapeshifter/>, September 2003.

Chapter 6

Achievements, conclusions, and recommendations

I conclude this dissertation by highlighting the major findings of this project, providing a critical analysis of the project, and ending with recommendations and future work in the field of Interactive Augmented Prototyping.

Augmented reality- superimposing digital information on the physical world – creates opportunities in spatial interaction and in merging the abstract (computational) with the concrete (physical). AR is being applied in a variety of domains, from the creative arts to forensic sciences, from medical diagnostics to assembly instruction. However, when I started this project, little was known on using of this display technique to design. The main objective of this work was to propose a methodological solution for interactive augmented prototyping.

The selected research approach included exploration of technologies, empirical studies, development of design methodology, and finally an intertwined set of development (demonstrators) and critical reflection.

The main contributions of this thesis are:

- AP supports an improved concept utterance that relates to both embodied interaction and object presence.
- Design errors can be found in the early concept phase by the ability to merge physical and cognitive ergonomics.
- A design methodology, entitled Interactive Augmented Prototyping (IAP-M), which utilizes AP as an instrument to support design reviews.
- The concept of I/O Pad, a patented portable projection and recording unit that can improve shared understanding during design reviews.
- The use of hints to provide a scheme to convert empirical findings to novel design support by elaborating on bottlenecks and best practices.

Based on the resulting I/O Pad patent (European and US), techno starter Delight Interactive Solutions adopted IAP-M.

Section 6.3 presents the resulting body of knowledge of 9 conference papers, 10 journal articles, 3 book chapters and an international patent. The original WSCG article of 2003 was cited more than 60 times, while the corresponding YouTube video was viewed over 14,500 times. Public audience experienced the

demonstrators and I/O Pad implementations, with over 20000 people during the Dutch Design Week (Eindhoven, 2006) and several other exhibits throughout the Netherlands.

6.1 Reflection on the research framework followed

I originally selected the topic based on my recognition of a real-life need combined with a personal curiosity: how could augmented reality be of any use to design processes in industry? At that time, some appealing AR systems were reported in literature, but it was not fully embedded in design practice.

There were two challenges:

- 1) None of the proposed AR systems were flexible and portable to be used in a real project,
- 2) To truly support the design process, it would be insufficient to only propose a tool—it would require a design methodology that includes procedures and methods.

The research approach of this work required both technology development and empirical study. The project was procedurally and methodologically framed in four research cycles. In this case, the multi-methodological research approach could be considered as bricolage. The investigator ('bricoleur') selects the best next building block that fits the accumulated knowledge at that moment (Denzin and Lincoln, 2003). Sometimes, the constructed blocks had to be reshuffled to end up in the current reasoning framework. The resulting approach is eerily compatible with new insights from constructive design research: covering work done in the lab, the field, and the showroom (Koskinen et al., 2011).

The empirical studies at the start of this project helped me to get to know design practice and the diversity in scale, functions, and speed of the work done. I followed three individual design projects in industry, more or less from cradle to manufacturing. On conducting the case studies, it was very useful to stick to Yin's guidelines regarding setting up a case study protocol, a case study database and a case study report for each individual case. Finding the collection of cases was a challenge, which relied on personal networking skills. At that time, it certainly helped that my project involved advanced technologies such as projection and 3D printing.

It was difficult to convert the empirical findings into a design methodology – although bottlenecks and best practices during these design project served as a basis, it was first unclear how these could be clustered. I introduced the notion of a hint as an indication of something that contains a part of a solution for a recognised bottleneck. It embodies a pointer to particular design support scenario. This resulted in a design methodology entitled Interactive Augmented Prototyping (IAP-M) that encompasses an instrument, methods, and procedures to enhance design reviews with AP to increase the shared understanding among stakeholders. How I interpreted the hints changed during this: from a categorised list of functions for a tool to conjectures for procedures, methods, instruments, and criteria. The amount of effort for these reinterpretations seems out of proportion to the solution at hand, a set of simple procedures and a tool entitled the I/O Pad.

The limitations of a PhD project have meant that not all I/O Pad's implementations could be explored. I developed two pilot systems, each generation had a different embodiment in terms of size, computing and projection power. The second used a larger collection of objects to test the calibration and interaction routines.

I valorised the project's vision of the I/O pad by filing a patent, guiding student groups, and advising a techno-starter based to bring IAP-M to practice. Although these actions were not necessary for the academic reasoning on IAP-M, they constituted exciting learning exercises in which patent attorneys, venture capitalists, entrepreneurs, and launching customers had to be introduced into the field of IAP. It also enabled me to request funding to buy parts necessary to implement the pilots and the demonstrators. This worked out better than I expected: the patent went international and the Delight Interactive Solutions B.V. still exists today. Such valorisation provides some proof that there is value in the concepts, brought about in this thesis.

It was difficult to validate IAP-M. Eventually, I adopted the validation square approach to separate the structural and performance aspects of assessing validity of the methodology. Here, I used the development, usage and reflection of five demonstrators as empirical evidence, one of which counted as 'reference cases'. In this development, over 50 IDE students assisted in ideating and constructing interactive augmented prototyping setups, which was instrumental in devising these pilot systems. To aid the 'leap of faith' in generalising the utility of IAP-M, 16 industry experts were interviewed. They were shown examples of interactive augmented prototyping and were interviewed on the benefits and weaknesses of IAP-M. Their replies confirmed that IAP-M could be useful in their practice, yet that the ease of establishing an augmented prototype needs to be improved before the IAP-M can be applied in industry.

Much has changed since the inception of interactive augmented prototyping: the I/O Pad was developed long before a certain fruit company⁶ launched a product with a similar name, while at the same time the first mobile phones and tablets with built-in projectors have emerged. Furthermore, novel software technologies such as parallel tracking and mapping have improved optical tracking capabilities than the implemented in the pilot systems. This may, to a degree, undermine the novelty of the technical part of this thesis, that was built on simplistic tracking libraries such as ARToolkit. The other parts of the methodology still hold and can be extended. Furthermore, low-cost 3D printing options help AR Toolkit reality even more now than ever before.

6.2 Recommendations and future work

While investigating this project, new challenges emerged. Researchers interested in this field should consider the following three activities:

1. A complete implementation of the IAP-M with a fully functional I/O Pad

With the current software and hardware solutions, it is feasible to fully implement the I/O pad and its capability to record design reviews. This will allow a more robust validation of IAP-M. Furthermore, IAP-M can then be used to capture design reviews for new empirical studies.

⁶ Apple, Inc.

2. Field studies to assess IAP-M in different design domains

The type of design support will differ for each design domain. In my case studies, covered in Chapter 2, were restricted to automotive, interior, and information appliances design. Within these domains, the case studies provided insight into the differences of stakeholder complexity, prototyping tradition, and communication. Exploring other domains will uncover specific semantics in the using prototypes and other design representations. Only then can we develop better design methodologies that focus on communication.

3. Consider deformative technologies

In comparison to manual prototyping or additive/subtractive methods, deformative solutions have the potential to reduce the time of physical prototyping to minutes or even seconds. Several projector-based AR solutions have been presented that use deformative materials such as clay, beads (Ratty, 2005), and specialised composite sheets (Ou et al., 2014) and thereby extend the natural interface to physical malleability. For over a decade, automatic deformation tools have been explored, often labelled as actuated surfaces. Through some kinematical structure, a surface is distorted in 3D. Within certain boundaries, this manufacturing technique – also known as ‘active deformable sheets’ – offers a direct coupling between physical and virtual geometry. One example is the Feelex apparatus (Iwata et al., 2001), which consists of a grid of small linear pneumatic actuators and sensors which establishes a $50 \times 50 \times 18$ mm surface that serves as input and output. Together with Daniel Saakes and Rob Luxen, I devised a similar apparatus. Figure 65 shows the resulting interactive 3D display that operates at 10Hz. When the resolution of such deformative techniques is increased, they can certainly contribute to future design review systems.

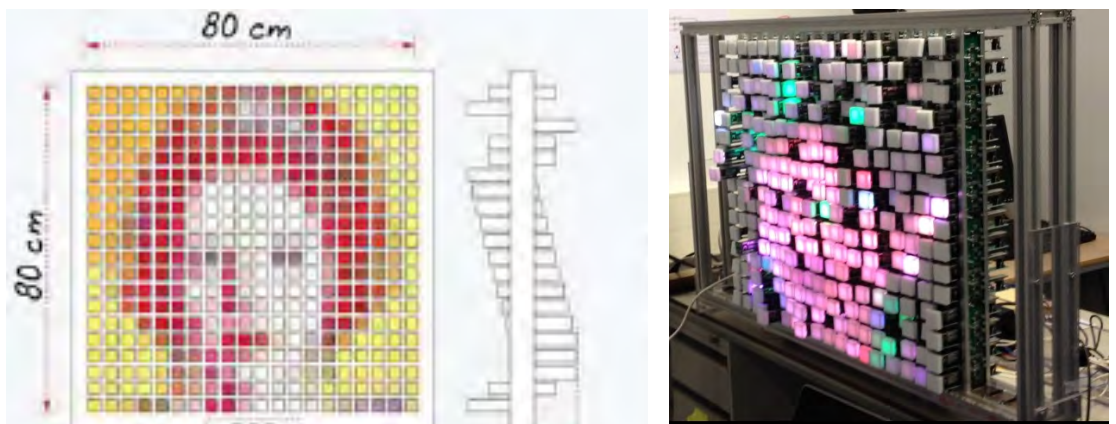


Figure 65 Kinect Mirror setup (left) and implementation (right).

6.3 Related publications by the author

The work of this dissertation has been archived in the following *book chapters* and *journal articles*:

1. Verlinden, J.C., de Smit, A., Peeters, A.W.J. and van Gelderen, M.H. (2003) "Development of a flexible augmented prototyping system ", *Journal of WSCG*, Vol. 11, No. 3, pp.496–503.
2. Verlinden, J., Nam, T-J, Aoyama, H., Kanai, S. (2006) "Possibility of applying Virtual Reality and Mixed Reality to the Human Centered Design and Prototyping for Information Appliances", *Research in Interactive Design – Vol. 2*, Springer.
3. Verlinden, J., & Horvath, I. (2006). Framework for testing and validating interactive augmented prototyping as a design means in industrial practice. In *Research in Interactive Design* (Fischer, X., & Coutellier, D., Eds.), Vol. 2. Berlin: Springer.
4. Verlinden, J., Suurmeijer, C., & Horvath, I. (2007) "Which prototype to augment? A retrospective case study on industrial and user interface design", *Lecture Notes in Computer Science*, Berlin: Springer-Verlag, Vol. 4563, pp. 574–583.
5. Verlinden, J., Horvath, I. (2008)"Enabling interactive augmented prototyping by portable hardware and a plugin-based software architecture" *Journal of Mechanical Engineering, Slovenia*, Vol 54(6), pp. 458-470.
6. Verlinden, J.C., Horvath, I.(2009) "Analyzing opportunities for using interactive augmented prototyping in design practice", *Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AI EDAM)*, volume 23, issue 03, pp. 289-303.
7. Verlinden, J.C., Horvath, I., Nam, T-J. (2009) "Recording augmented reality experiences to capture design reviews", *International Journal on Interactive Design and Manufacturing*, Volume 3, Number 3 / August, 2009, pp. 189-200.
8. Verlinden, J.C., Horvath, I. (2010)"The enablers for interactive augmented prototyping", *Int. J. Product Development*, Vol. 11, Nos. 1/2, 2010, pp. 62-88.
9. Verlinden, J.C., Kanai, S. (2010) "Product and Interaction Design Environments for the Future", *Research in Interactive Design*, vol 3.
10. Verlinden, J.C., van Duijnen, F., Horvath, I. (2010) "Validating the strengths and weaknesses of Interactive Augmented Prototyping in Industry", *Research in Interactive Design*, vol 3, Springer.
11. Verlinden, J.C. (2012) "pixels want to be freed! Introducing augmented reality enabling hardware technologies", *AR[t] Magazine*, vol 1(1), ISSN 2213-1817, pp. 42-59.
12. Verlinden, J.C., Roozenburg, M., Song, Y. (2012) "How it was made: a tangible replica with mobile AR", *AR[t] Magazine Vol 1(2)*, ISSN 2213-1817, pp. 32.
13. Verlinden, J.C. (2012) "Augmented Prototyping – Augmented Reality to support the design process", *AR[t] Magazine Vol 1(2)*, ISSN 2213-1817, pp. 62.

The working principle resulting from this PhD research was registered as Dutch patent nr. 2000778 “Projectie en registratie installatie”, filed as European & USA patent WO2009014448A1, “projection and registration device”.

Intermediary results were discussed in the following *conference papers*:

1. Verlinden, J.C., de Smit, A., Horváth, I., Epema, E. and de Jong, M. (2003) “Time compression characteristics of the augmented prototyping pipeline “, Proceedings of Euro-uRapid’03, p.A/1.
2. Verlinden, J., de Smit, A. and Horváth, I. (2004) “Case-based exploration of the augmented prototyping dialogue to support design “, Proceedings of TMCE 2004, pp.245–254.
3. Verlinden, J., van den Esker, W., Wind, L. and Horváth, I. (2004) “Qualitative comparison of virtual and augmented prototyping of handheld products “, Proceedings of Design 2004, pp.533–538.
4. Verlinden, J., Kooijman, A., Edelenbos, E. and Go, C. (2005) “Investigation on the use of illuminated clay in automotive styling “, Proceedings of CAID/CD’05 Conference, pp.514–519.
5. Verlinden, J., Horvath, I., Edelenbos, E. (2006) "Treatise of Technologies for Interactive Augmented Prototyping", proc. of Tools and Methods of Competitive Engineering, pp 523-536.
6. Verlinden, J., & Horvath, I. (2007) “A critical systems position on augmented prototyping systems for industrial design”, proceedings ASME-CIE ’07, Paper No. DETC2007-35642.
7. Verlinden, J.C., Horvath, I. (2008) “Enabling interactive augmented prototyping by a plugin-based software architecture”, proc. of Tools and Methods of Competitive Engineering, pp. 245-256.
8. Stellingwerff, M., Verlinden, J.C. (2011) "Projecting spaces with Augmented Reality", in Lengyel Toulouse (eds) Projecting Spaces, Eckart Richter & Co, ISBN 978-3-942411-31-8, pp 147-152.
9. Verlinden, J.C., Doubrovski, E.L., Horvath, I. (2012) “Assessing the industrial impact of interactive augmented prototyping on several abstraction levels”, proc. of Tools and Methods of Competitive Engineering, pp. 1205-1215.

6.4 References

- Ratti, C., Wang, Y., Piper, B., Ishii, H. and Biderman, A. (2004) “PHOXEL-SPACE: an interface for exploring volumetric data with physical voxels “, Proceedings of DIS ’04, pp.289–296.
- Denzin, N. K., & Lincoln, Y. S. (2003) “Introduction: The discipline and practice of qualitative research” In N. K. Denzin & Y. S. Lincoln (Eds.), *Strategies of qualitative inquiry* (2nd Ed.) Thousand Oaks, CA: Sage, pp. pp. 1 – 45.
- Iwata, H., Yano, H., Nakaizumi, F. and Kawamura, R. (2001) “Project FEELEX: adding haptic surface to graphics “, Proceedings of SIGGRAPH2001, pp.469–475.
- Koskinen, I., Zimmerman, J., Binder, T., Redstrom, J., & Wensveen, S. (2011). *Design research through practice: From the lab, field, and showroom*. Elsevier.
- Ou, J., Yao, L., Tauber, D., Steimle, J., Niiyama, R., Ishii, H. (2014) “jamSheets: Thin Interfaces with Tunable Stiffness Enabled by Layer Jamming”, in proceedings of TEI’2014.

Acknowledgements

This promotion has been a long and tedious project, yet never without inspiration. I owe this to so many people, within and outside Delft University that it is simply undoable to name them all. First, I would like to thank my promotor, **Imre Horváth** to keep the faith and in helping me to construct something that can be called scientific. Then, I would like to thank the members of the section of Computer Aided Design Engineering who all contributed to this work in one way or the other: **Joris Vergeest, Han Broek, Bram de Smit, Adrie Kooijman, Fabian Mulder, Niels Moes, Eliab Opiyo, Zoltan Rusak, Wolf Song, Ernest van Breemen, Edit Varga, Wilfred van der Vegte, Regine Vroom, Tjamme Wiegers**, and all PhD students of the past and present. Thank you for supporting me!

The faculty of Industrial Design Engineering is such a great place to start (and get!) your PhD project – such a diverse set of experts was consulted during the course of my work. I owe much to **Pieter Jan Stappers**: for showing me the way to virtual reality when I was a young student and for keeping a link to academia while I was embedded in industry. Others that provided invaluable help during this project include **Jo Geraedts** (let's go beyond advanced manufacturing), **Henri Christiaans** (especially when on a different continent), **Heimrich Kanis** (still not sure we reached something reliable), **Peter Vink** (darn, I didn't address comfort), **Daniel Saakes** (what should we do now?), **Frido Smulders** (consider this as a boundary object), **Bruno Ninaber-van Eyben** (I need your prototypes), **David Peck** (that Norfolkian accent shouldn't become a scarce material), **Rene Weever** (propositions can always be improved), **Erik Tempelman** (let's manufacture music now), and **Zjenja Doubrovski & Argun Cencen** (now I can formally contribute to your PhD project).

I am grateful of the active participation and constructive feedback of my promotion committee. This work would never be possible without the support by fellow researchers within and outside the Netherlands. First of all, I am comforted by the coaching I received by the couple **Claudia Eckert** and **Martin Stacey**: what a great gift to have met you in Glasgow so many years ago! Same kudos go to **Martijn Stellingwerff** whom I shared so much in both education, research and beyond. **Gerwin de Haan** provided great support while developing the second implementation of the I/O Pad. Furthermore, it was great working at the ARLab at the academy of Arts in The Hague with **Yolande Kolstee, Hanna Schaffenberger, Wim van Eck** and all others. Cheers to my friends: **Mark Mobach** in Gruning, to **Monica Bordegoni** and **Maura Mengoni** in Italy, to **Tek-Jin Nam** in Korea, and **Satoshi Kanai & Yoshiyuki Shiroma** in Japan. I hope we will continue to collaborate on exiting stuff in the near future!

Parts of this project have been funded by NWO, STW, SurfNet, KOSEF, and SenterNovem. Important gifts in this venture were my patient and exiting contacts with industry: **Arjan Steketeer, Christian Suurmeijer, Han Hendriks, Jurgen Bey, Martijn Pennings**, and all your colleagues: thank you so much. Furthermore, I have deep respect for the guys who are trying to bring parts of my work to the market: **Frans van Duijnen, Rene Elsgeest** & the complete team at Delight Interactive Solutions. I hope my work is not in vain and you can really make it work in Industry!

This work was not possible without the dedicated support, love, and understanding by my family. My dear **Simone** and daughters **Noor** and **Nouschka**, I feel blessed and let's celebrate this! **Marion & Rob, Martijn & Zoe, Maaïke, Nina & Meynald** – now we can move on when discussing academic life!

This work is dedicated to all the students that helped my research on Interactive Augmented Prototyping. Some of them already appeared as co-authors in publications, others weren't mentioned yet:

Aernout Peeters
André Weenink
Anne Lien van der Linden
Astrid Heijnen
August Eckhardt
Bas Linssen
Ben Streek
Bjorn Luik
Bram de Leeuw
Celeste Go
Charlotte Vanhoutte
Christiaan Uythoven
Christiaan Karsen
Daan Janssen
Diederik van der Steen
Edwin Branbergen
Edwin Edelenbos
Elizabeth Berghuijs
Elselien Epema
Emma Heijerman
Frans van Duijnen
Hanneke Jacobs
Harish Karakat
Hironori Yoshida
Inge van Bruinessen
Ioanna Tziouvara
Jaap Sybenga
Jan Asmus
Jasper Verhagen
Jitender Pritipalsingh
Joep Steenbeek

Kenneth van Kogelenberg
Koen Rotteveel
Koen Wijffelaars
Koos Looijesteijn
Liesbet Wind
Lucas Jaspers
Lunni Huang
Luuk Langenhoff
Lotte de Reus
Man-Wai Shing
Mariet Sauerwein
Marlou de Jong
Martijn Klitsie
Martijn van Gelderen
Mauricio Martínez
Naveen Sethia
Nick Noordam
Olaf Dijkgraaf
Otmar Klaas
Pim Spiekermann
Reinout de Kraker
Rik Rooijen
Sanne Aarts
Simon Jaspers
Simon Gamme
Sofieke Jagtman
Thijs Kuipers
Thomas Fritz
Tsubasa Maruyama
Willem van den Esker

Appendix A

Case study protocol template

For each of the case studies, the following protocol template was tuned by the text fields, indicated between chevrons.

Interactive Augmented Prototyping – Case study protocol
Version 0.1 (21 Jul 2006)

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1. Introduction
2. Field procedures
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3. Case study research questions
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1. Introduction

This case study is part of a research project entitled “Interactive Augmented Prototyping as a Design Means for Industrial Design Engineering”. It is executed by Jouke Verlinden (MSc) and promotor is prof. Dr. Imre Horváth, both from the Faculty of Industrial Design Engineering, Delft University of Technology.

Interactive Augmented Prototyping (IAP) represents an emerging field of using augmented reality technologies to prototype product designs. More details can be found in the two attached scientific papers (WSCG’03 and TMCE’06). Our general research questions are formulated as follows:

- Q1. Where in the design process is it advantageous to use which type of IAP?
- Q2. To which design phase offers IAP most value?
- Q3. Given a phase of design, how do the benefits depend on the technologies?
- Q4. How does this value vary per product domain?
- Q5. To what degree influences IAP the overall design process?

For our work, it is crucial to gain a deep understanding of the design process and the roles of physical models/prototypes among a number of typical industrial design engineering companies. At present, there is simply a lack of knowledge on these topics in academia. We will have to go beyond a simple interview or survey. Field observations will be most applicable, as formulated in the methodology of a “case study”. This case study protocol contains the procedures and general rules that will be followed during the study.

We believe that <Company name> is a representative match and excels in the field of <Design Domain>. Therefore, we would like to observe a particular product development project from early start to its detailing phase. As the case study research questions reveal, our objective is to track the process, the documentation and design-related discussions as much as possible.

2. Field procedures

After the selection of the particular design project that to be followed (called project S), the case study encompasses in the following activities during the entire design process:

- A. Keeping an activity diary by key product developers.
- B. Interview(s) with the key product developers at <Company>.
- C. Inspection and capturing of design specifications, sketches, prototypes and related representations of project S.
- D. Observation of key product development discussions of project S.
- E. Discussions and presentations by the investigator on the findings.

Table A1 Data recording template.

Phase	Product planning	Specifica-tion	Idea phase	Concept phase	Detailing	Prototype& validation testing
A. Diaries		daily	daily	daily	daily	t.b.d.
B. Interviews	once	weekly	weekly	weekly	weekly	bimonthly
C. Inspection			weekly	weekly	weekly	weekly
D. Observation		once	t.b.d.	t.b.d.	t.b.d.	t.b.d.
E. Discussions and presen-tations	once				once	once

These data recording activities are scattered during this process, schematically shown in table A1.

2.1 Assistance and guidance

Although this investigation is an independent research activity by Jouke Verlinden, a minimal level of assistance and guidance would be required from <Company>. Main contact person for the investigation is <Company contact>. During the process, we will communicate by email and phone when necessary and we will have at least three meetings concerning the progress of the research project (at start, intermediary, at finalization).

When there are changes in the availability of interviewees or changes in the mood and motivation of the case study investigator, this will be directly be exchanged by email.

2.2 Privacy and sensitivity

The investigator and its employer, the Delft University of Technology, greatly appreciate the willingness of the <Company> to contribute to this project. It is our mutual understanding that this Interactive Augmented Prototyping project creates a win-win situation for both partners

As the research questions of the introduction indicate, the primary interest of this investigation is not the product but the process. However, we will need to gain and capture as much empirical evidence as possible in terms of interviews, design representations, pictures and documents. All raw data will be kept on location at <Company> only, while the case study report will be written for the <Company> representative. All scientific (or other) publications will be sent to the main contact person, <Company contact> before publication.

2.3 Workplace

The investigator has to be present at a project of <Company> for at least half a day each week during the execution of the investigation. A fixed schedule will be preferable, yet this might be changed depending on project S's progress. What is required is at least a table desktop and some (electronic) storage facilities, if possible not too far away from the work on project S.

2.4 Activity Diaries

To track the design process, the project's team is asked to fill in a simple electronic diary. This instrument is not meant to be an extensive monitoring means, but rather a minimal way to capture important design events and to provide interesting issues for interviewing.

2.5 Interviews

At least the <Company> employees that collaborate on project will be interviewed for the study. After an introductory interview, this will probably happen every week or whenever an important design milestone has been reached. It would be preferable if other key stakeholders in the project could be interviewed (including client, subcontractors etc.)

2.6 Observations

Observations of key meetings will be done with minimal intrusion (voice recording). The openness for the observation of each of those meetings has to be discussed on beforehand.

3. Case study research questions

In short, we are trying to find problems in concept uttering. The case study questions are presented in Table A2.

Table A2 Decomposition of case study research questions.

Case study question	Data collection methods	Result
When in the design process are concept utterances generated and used?	Observations, interviews, pictures	Timeline with design representations
What are the characteristics of these concept utterances?	Pictures (observations), structured interviews of stakeholders (repertory grid)	List of characteristics Collection
Which product modelling aspects play a role in these utterances?	Observations, interviews	List of aspects Dependency specification between aspects and
What topics are dealt with as group activities? Who are involved?	Diaries, interviews	Addition to the timeline of topics: product modelling aspects and who is involved.
What problems occur during the creation and use of concept utterances?	Diaries, observations	Description of bottlenecks, added to the timeline to pinpoint their relevance. Possibly related to decisions and Insight.

The measurements that will be used as a basis are specified below.

3.1 Quantitative measurement units

These can be obtained by inspecting project information, the prototypes and other forms of representation (CAD models, drawings etc.) The data can be double checked with interviews of key persons in the project.

- Time of “birth” (design phase)
- Investments (cost/time/..)
- Type, details
- Objectives (relating to a project plan)
- Context (relationship to other forms of representation e.g. sketches etc.)

3.2 Qualitative measurement units

Some units concerning the employment of physical models are less quantifiable yet shared by all stakeholders in the design process. Specific interviewing techniques will be used to obtain those and to check resemblance among the stakeholders, in particular semantic differencing and the repertory grid technique. Furthermore, additional sources are team meetings and presentations to clients, covering the following topics:

- Model(ing) aspects
- Sense of engagement/expressiveness/interactivity

3.3 Design process and its bottlenecks

Investigating the impact of physical models cannot be done without capturing personal experiences of the stakeholders of the design process. To obtain this evidence, frequent semi-structured interviews and diaries will be used. This will lead to the following topics that can be charted among the timeline.

- Insight

- Decisions
- Problems and issues

4. Guide for the case study report

The data of this case study will yield a concise report. It builds upon the reporting techniques of Michael Soderman, to depict the process and results in a number of tables and graphs as shown below. It will include descriptions, a timeline (Gant chart), and a table grouping insight/decisions per physical model and per phase in the design process. Conclusions will be drawn on concept uttering problems and requirements concerning Augmented Prototyping systems.

Table A3 Tabular description of design representations and effects.

		Product planning	Specifi- cation	Idea phase	Concept phase	Detailing	Prototype & testing
Forms of repr.	which						
	how						
Purposes 2 nd cat: tests 3 rd cat: insights							
Effects 3 rd cat: insights 4 th cat: decisions							

Appendix B

Bottlenecks/best practices from the case studies

The impact of the physical design means is difficult to determine in a single characteristic. Apart from utilitarian purposes, physical design supports shared understanding or insight. In searching for a reasoning model to support our early findings, we found the extensive work on Critical Systems Thinking by Jackson (2000), which to our knowledge, has not been applied to the field of engineering design. The only similar work we found focuses on interior architecture of public spaces (Mobach, 2007). As Mobach explains, four different perspectives can be enforced on the process of design: utilitarian, interpretive, emancipatory, and postmodern views each have their existence in judging the management and the subsequent methods & tools of a design process [2006].

Prototyping is often seen as a way to enhance insight, but as shown in the empirical case studies, it also has the potential to enforce decision making (emancipatory) and to enrich the design process with different type of design probes (postmodern).

Case 1. Tractor

ID	Impact	Element	Role/consequences	Source
1F.1	Large	Fit of fixed component to freeform surface (headlight).	- project delay - unwanted alterations of expression/style	#20
1F.2	Large	Challenges in finding headlight which would fit in the design	-increased time and effort	#12, #19
1F.3	Small	Inaccuracies in initial reverse engineering of motor dimensions.	- unwished alteration of design by manufacturer -project delay	#20,#2 2
11.1	Large	Mutual priorities (client, designer) concerning headlight design were not understood	-conflict	#9, #12,#2 0
11.2	Large	Indirect contact with client – assignment came from the part builder ; unclear project structure.	-miscommunication -delay -too much stress on engineering at start	#20, #22
11.3	Small	Expression of style was not understood.	-decreased trust of client on designer's artistic skills	#8,#22

1I.4	Small	Miscommunication by internal division of tasks	-not a shared vision on the design	#22
1E.1	Large	Client was not open to arguments of designers concerning headlight	-too much domination in decision decisions -less optimal design freedom	#12,#22
1E.2	Large	Client's wishes towards the headlight and style were not picked up from start	-client is not taken seriously	#22
1E.3	Large	Without consulting the designers, the manufacturer adapted the design for the null series (blinkers, air vents, skirts)	-designer is not taken seriously	#20, #21, #22
1P.1	Large	The inclination to use CAD and 3D renderings could have been better balanced with other representations (sketching, tape-drawing)	-little lateral thinking/emergence of innovative shapes -little attention to visual and physical product manifestation	#20, #22
1P.2	Large	The use of (physical) prototypes was not part of the design brief	-threshold towards employing such prototypes	#20

Case 2. Oscilloscope

ID	Impact	Element	Role/consequences	Source,
2F.1	Large	Difficult to evaluate combination of physical and interaction designs	- suboptimal evaluation of GUI (errors) - increased costs	#1,#2, #3,#7, #8, #10
2F.2	Large	Button placement should consider engineering package inside (collision avoidance)	- redesign effort	#3, #10
2F.3	Large	Crude tools to specify GUI (interaction/navigation, resolutions)	-incomplete specification -superfluous communication with software engineers	#2
2F.4	Large	Physical mock-ups in foam and paper are easy to make and had a large effect at start of process	+decreased cost and effort	#3,#8, #10
2F.5	Small	The feel of the button operation is very much depending on the final component selection	-suboptimal fidelity of interaction	#1,#2
2F.6	Small	Internationalisation of labels on buttons and on screen sometimes difficult to fit.	-time	#3
2I.1	Large	Monthly presentations of user feedback to the team	+good shared understanding of user context, preferences + immediate feedback on designs	#10
2I.2	Large	Table with all design materials available at all times	+ shared understanding	#8,#10

2E.1	Large	Lot of user studies	+user is taken seriously +valid grounding to make decisions	#10
2E.2	Large	Table with all design materials available at all times	+ all team members could contribute to this display + convinced/impressed higher management and other prospective customers	#8,#10
2E.3	Large	Physical models serve as a conversational piece, to access prospective users.	+access (openness)	#10
2P.1	Large	Many physical models, also per stage	+ inspiration	#2,#3,#10
2P.2	Large	Crude tools to specify Graphical User Interface (interaction/navigation, resolutions)	-limited amount of options	#2,#3
2P.3	Large	Physical models serve as a conversational piece, to access prospective users.	+discussion	#10
2P.4	Large	Table with all design materials available at all times	+ display of richness, plurality	#8,#10
2P.5	Small	The use of the final software platform in early stages constrains UI design too much	-constraining interaction techniques	#7

Case 3. Museum interior

ID	Impact	Element	Role/consequences	Source
3F.1 *	Large	The computer (Photoshop) is used to perform colour/material textures	+saves time	#4
3F.2 *	Large	No tools at hand to specify dynamic behaviour of the building (use, business processes)	-difficulties in expressing and assessing dynamic quality of interior design	#8
3F.3*	Small	Building/landscape outside did not offer good provisions for (un)loading trucks	-more time/effort necessary -constraints in design	#8
3F.4*	Small	Difficulties in fixing the design requirements	-delay	#8
3F.5	Small	Limited time to finish competition	-quality of presentation	#5
3F.6 *	Small	Specifications in preliminary design span many pages	-large effort to create	#8
3I.1 *	Large	Difficulties to communicate style elements (curtains)	-delay in design decision	#4, #6,#8
3I.2 *	Large	Monthly meetings of all stakeholders, sharing meeting minutes	+shared understanding +keep focus in long term project	#6, #8
3I.3 *	Large	Functional aspects get little attention in design reviews ; client is preoccupied with form elements/aesthetics.	-additional translation required by designers -adjustment of agenda	#8
3I.4*	Large	Budgeting is difficult to fix (museum-specific?)	-difficult basis for design decisions	#4

3I.5 *	Large	Difficulties in fixing the design requirements	-additional effort to translate to usable specifications	#8
3I.6 *	Small	Employment of sketchy scale models, without colour/material details	+keep focus on important issues	#8
3I.7 *	Small	Specifications in preliminary design span many pages,	-difficult to create overview -easy introduces misunderstanding	#8
3I.8 *	Small	Other stakeholders have other frame of reference. They typically mention existing furniture blocks ("Armando Balie"), which they have developed in previous function.	-additional effort to translate -trust	#8
3I.9	Small	Open cabinets and public offices were also not appreciated at start by future users (privacy)	-trust	#8
3I.10	Small	Scale models have to look good, flimsy ones are misjudged	-misjudgement of design idea -trust	#3
3E.1 *	Large	Difficulties to communicate style elements (curtains)	-resistance in accepting parts of the designs by other stakeholders	#8
3E.2 *	Large	Surrounding landscape is done by others, with no consultation of the museum. Scale models contain suggestions of surrounding landscape.	+more influence on outside landscape	#8
3E.3 *	Large	Designer purposely made sketchy scale models, textual descriptions and sharp section views.	+steering of process by designers	#8
3E.4 *	Small	The discussions on the usage scenarios during design reviews were skipped from the meeting minutes.	-usage scenarios were not honoured by others	#8
3E.5 *	Small	At time of competition, some stakeholders were kept out of the loop	-resistance to accept outcome of competition	#8
3E.6	Small	Future visitors are not involved in design process	+less complex decision structure	#8
3E.7	Small	Architect of building worked in parallel with no mutual consultation.	-less influence on structural aspects of interior	#8
3E.8 *	Small	In the final scale model, all objects are glued to the base plate	+express that design is frozen	#8
3E.9	Small	Open cabinets were also not appreciated at start by future users (privacy)	-danger in keeping vision of interior	#8
3E.10	Small	We lost the battle for the room as public space	+leverage to get acceptance for other parts of the plans	#6

3E.11	Small	Current interim director will not be the final 'owner', is more focused on facilitation than own vision	-lack of vision in commissioning	#6,#8
3P.1 *	Large	The movements of people/users can be used as a base to design a floor plan/objects	+inspiration by uncovering this aspect	#1,#8
3P.2 *	Large	During presentations, the narrative excels in framing dynamic and metaphoric aspects of a design	+richness of expression	#8
3P.3 *	Large	During presentations, a number of options are shown	+richness of solution space	#8
3P.4 *	Small	Use of various materials to represent scale furniture	+inspiration (diversity)	#1
3P.5	Small	The coloured doll gives colour to the whole (monochrome) model, while it is not even part of the design itself.	+richness of expression	#8

Unmappable bottlenecks/best practices

Additional bottlenecks that did not map to hints

Case #1

N.A.	Large	Designers only had part-time involvement in the project	-lack of continuity	#12
N.A.	Large	Client not trained in design or commissioning design.	-explanation not always understood	#22
N.A.	Small	Some construction principles were not adopted by manufacturer due to complexity	-project effort	#22
N.A.	Large	No one specifically was in charge of art direction	-detailing was not fully in line with initial concept	#22
N.A.	Small	Stubbornness of client (in combination with miscommunication) delayed the project	- leadership is missing	#20

Case #2 additional bottlenecks that did not map to hints

N.A.	Small	Over 150 user visits	- increased costs	#10
N.A.	Small	At start : hesitation from engineers	- shared vision	#8,#10
N.A.	Small	Customer was internal, less formal communication and pressure on budgeting/deadlines than with external customers.	- decision making pace	#9
N.A.	Small	At start : hesitation from engineers	- shared vision	

Appendix C

Linear Camera Calibration Source code

The developed C++ source code is as follows:

```
// Calibration algorithm, Jouke Verlinden, based on code from Thomas
Willwacher
/* inputs:
   nPointsFound
   aPointsFound[0..n][0.4] second index 0 & 1 corresponds to (u,v) and 3-5 to
(x,y,z) coordinates of the control points.

// Step 1: Fill Matrix that covers the constraining equations
Matrix lhs(2*nPointsFound, 12); // lhs=LeftHandSide

for (int i = 0; i < nPointsFound; i++) {
    // odd rows
    lhs(2*i+1, 1)=aPointsFound[i][2];
    lhs(2*i+1, 2)=aPointsFound[i][3];
    lhs(2*i+1, 3)=aPointsFound[i][4];
    lhs(2*i+1, 4)=1;
    lhs(2*i+1, 5)=0; lhs(2*i+1, 6)=0; lhs(2*i+1, 7)=0; lhs(2*i+1, 8)=0;
    lhs(2*i+1, 9)=-aPointsFound[i][0]*aPointsFound[i][2];
    lhs(2*i+1, 10)=-aPointsFound[i][0]*aPointsFound[i][3];
    lhs(2*i+1, 11)=-aPointsFound[i][0]*aPointsFound[i][4];
    lhs(2*i+1, 12)=-aPointsFound[i][0];

    // even rows
    lhs(2*i+2, 1)=0; lhs(2*i+2, 2)=0; lhs(2*i+2, 3)=0; lhs(2*i+2, 4)=0;
    lhs(2*i+2, 5)=aPointsFound[i][2];
    lhs(2*i+2, 6)=aPointsFound[i][3];
    lhs(2*i+2, 7)=aPointsFound[i][4];
    lhs(2*i+2, 8)=1;
    lhs(2*i+2, 9)=-aPointsFound[i][1]*aPointsFound[i][2];
    lhs(2*i+2, 10)=-aPointsFound[i][1]*aPointsFound[i][3];
    lhs(2*i+2, 11)=-aPointsFound[i][1]*aPointsFound[i][4];
    lhs(2*i+2, 12)=-aPointsFound[i][1];
}

// Step 2: Find u-vector corresponding to smallest singular value (S)
(=Solution)
DiagonalMatrix D(12); // output of function SVD()
Matrix U(12,12); // output of function SVD()
```

```

SVD(lhs.t()*lhs, D, U);

int smallestCol = 1;          // Column containing smallest sing. value
// find smallest
for (int j = 1; j < 13; j++)
    if ((D(smallestCol)*D(smallestCol)) > (D(j)*D(j)))
        smallestCol = j;
ColumnVector S = U.Column(smallestCol);

// Step 3: write 12x1-Vector S as 3x4 Matrix (row-wise)
Matrix ProjMV(3, 4);
for (int k = 0; k < 12; k++)
    ProjMV((k / 4)+1, (k%4)+1) = S(k+1);

// Step 4: decompose ProjMV in Proj- and MV-matrices
double scale = sqrt(ProjMV.SubMatrix(3, 3, 1, 3).SumSquare());
ProjMV /= scale;

if (ProjMV(3,4) > 0) ProjMV *= -1;

ColumnVector Q1 = (ProjMV.SubMatrix(1,1,1,3)).t();
ColumnVector Q2 = (ProjMV.SubMatrix(2,2,1,3)).t();
ColumnVector Q3 = (ProjMV.SubMatrix(3,3,1,3)).t();

double q14 = ProjMV(1,4);
double q24 = ProjMV(2,4);
double q34 = ProjMV(3,4);

double tz = q34;
double tzeps = 1;
if (tz > 0) tzeps = -1;

tz = tzeps*q34;
RowVector r3 = tzeps*Q3.t();
double u0 = (Q1.t()*Q3).AsScalar();
double v0 = (Q2.t()*Q3).AsScalar();
double a = crossNorm(Q1,Q3);
double b = crossNorm(Q2,Q3);
RowVector r1 = tzeps*(Q1.t() - (u0*Q3.t()))/a;
RowVector r2 = tzeps*(Q2.t() - (v0*Q3.t()))/b;
double tx = tzeps*(q14 - u0*tz)/a;
double ty = tzeps*(q24 - v0*tz)/b;

// create Rotation Matrix and Translation Vector
Matrix RotMatrix(3,3);
RotMatrix = r1 & r2 & r3; // concatenation of 3 vectors to rotation matrix.
ColumnVector t(3); // translation.
t << tx << ty << tz;

// Step 5: Expand found matrices to 4x4 matrices
// Projection
Matrix IntMat(4,4);
IntMat(1,1)=-a;   IntMat(1,2)=0;   IntMat(1,3)=-u0;   IntMat(1,4)=0;
IntMat(2,1)=0;   IntMat(2,2)=-b;   IntMat(2,3)=-v0;   IntMat(2,4)=0;

IntMat(3,1)=0;   IntMat(3,2)=0;
IntMat(3,3)=-(gfFarPlane+gfNearPlane) / (gfFarPlane-gfNearPlane);
IntMat(3,4)=-2 * gfFarPlane*gfNearPlane/(gfFarPlane - gfNearPlane);

IntMat(4,1)=0;   IntMat(4,2)=0;   IntMat(4,3)=-1;   IntMat(4,4)=0;

```

```

// External parameters: Rotation&Translation
Matrix ExtMat(4,4);
RowVector nulleins(4);
nulleins << 0.0 << 0.0 << 0.0 << 1.0;
ExtMat = ((r1 & r2 & r3) | t) & nulleins;

// Step 6: Set matrices as Current MV/Proj-matrices
for (int l = 0; l < 16; l++) {
    MVMat[l] = ExtMat((l%4)+1, (l/4)+1);
    ProjMat[l] = IntMat((l%4)+1, (l/4)+1);
}

// Step 7: Save matrices to file ("IntMat0.dat"/"ExtMat0.dat")
ofstream lfInt, lfExt;
lfInt.open("IntMat0.dat", ios::out); lfExt.open("ExtMat0.dat", ios::out);
for (i = 0; i < 16; i++) {
    lfInt << IntMat(i%4 + 1, i/4 + 1) << ((i%4-3)?" ":"\n");
    lfExt << ExtMat(i%4 + 1, i/4 + 1) << ((i%4-3)?" ":"\n");
}
lfInt.close();
lfExt.close();

```


Appendix D

Survey of viability of IAP-M in Industry^{*}

In order to validate the underlying theories of IAP-M in industry, we selected a semi-structured interview approach (Lindhof, 2002). This would provide the opportunity to visit design agencies and discuss topics in an arbitrary order. We could visit 13 offices, scattered across the Netherlands and representing various product domains and core activities. Table D1 shows the characteristics of the market study participants, varying in business size from a few employees to multinationals. This subset includes well reputed and studios that won several international design prizes. All of the participants had more than 10 years experience in their work, and had a good understanding of their daily practice as well as the impact of various prototypes – digital and physical. The largest group covered product design and engineering, with a diverse portfolio of products that are mass-produced for consumers, such as car seats, thermostats, mobile phones, and copiers. The automotive domain covers mobility products, including mopeds and passenger busses, while aerospace included the development and assembly of large VIP aircraft. Furniture designers with an arts background represented the interior domain, with several specializations such as kitchens or retail design. Participant #11 was coming from the area of web design, communication and branding – this interview proved to be less relevant for our survey as the end product of this company was less tangible and considers different manufacturing and engineering aspects than all other.

The semi-structured interview was performed at the studio premises. A 60-90 minutes time slot was reserved for a session with a senior employee, if possible the director or project manager. Notes were taken, and all data was processed in a questionnaire sheet that followed the topic guide. The presentation material was limited to a non-functioning mock-up, a demonstration video and a two slides. These introduced the technology, function, and envisioned benefits. In particular, the video showed how a handheld projector setup could be used to project materials and features on a 3D printed tractor (an actual design case).

^{*} *Excerpt from Verlinden, J.C., van Duijnen, F., Horvath, I. (2010) "Validating the strengths and weaknesses of Interactive Augmented Prototyping in Industry", Research in Interactive Design, vol 3, Springer.*

Table D1 Profile of the market study participants.

#	Position	Employees	Domain	Core activity
1	Sr. Designer	<50	Products	Engineering
2	Project manager	<10000	Automotive	Engineering
3	Product manager	<100	Aerospace	Engineering
4	Engineer	<10000	Automotive	Engineering
5	Designer	<100	Products	Design
6	Director/Owner	<10	Products	Design
7	Project manager	<50	Products	Engineering
8	Designer	<50	Products	Design
9	Director/Owner	<50	Interior – Kitchens	Design
10	Director/Owner	<10	Interior – Retail	Design
11	Director/Owner	<100	Websites	Design
12	Design Manager	>10000	Products	Engineering
13	Director/Owner	<10	Interior	Design

Although all reflections were positive towards the technical opportunities of AP, any implementation was considered too time-consuming for daily practice. The quality of projection was considered most applicable in interior and automotive design.

Perceived strengths and weaknesses of IAP-M

The concept of IAP-M and the I/O pad was new for most participants, they expressed that the presentation of projector based augmentation and augmented prototyping were clear. After presenting the IAP slides and video, three of participants, covering the domains kitchen interior, large engineering department, website design, could not see how this technology could help their design processes. The other 2 interior design agencies and the aerospace engineering firm could clearly see benefits of the proposed technology, especially for exploration and to communicate with external stakeholders.

The participants were asked to give their opinion regarding the strengths and weaknesses of IAP and the I/O Pad in particular. The most prominent strengths are in line with the envisioned benefits: allowing to explore multiple design variants and to communicate with the client and other stakeholders. On the other hand, primary weaknesses signify the effort needed to realize such prototypes and the resulting quality. In comparing the respective strengths and weaknesses, we could distil the most important concerns that senior designers and engineers raised –regarding method and technology.

Concerning the method, three main issues need addressing: i) does variability in a design matches the physical – virtual division, ii) what is the trade-off between speed versus quality, iii) how does this affect the emancipation of other stakeholders. The first is related to product domain and activity – the fit with some (like website or kitchen design) is less obvious. The second concern touches the need for speed versus the need for credible prototypes, which differ based on customer and studio tradition. The last demarcates the role of the designer in the design process and the power that clients and other stakeholders have in the process to explore alternatives that might be undesirable.

Concerning the technology, the following issues are mentioned: i) application of new versus proven technologies in the design process, ii) ease of setup, iii) expression of design details by projection. The first indicates the infancy of IAP in the design process – there is no off-the-shelf system that reliably provides this. On the other hand, some agencies are keen on adopting emerging technologies. A related concern is the time needed to train, install and use the I/O pad – as with most other model making gear, this should be kept at a minimum. Training time that is allowed is 1 day for interior and product design, while engineering studios allow for an average of 5 full-time days. The third technical concern relates to the shortcomings of projector-based AR, with a limited resolution and projection coverage. The level of fidelity required touching fabric and plastic texture is of importance in interior design, and arguably be supported by projection on low-cost mock-ups. However, the augmentation does allow envisioning novel information streams (such as pedestrian flows), which might require consideration while reviewing early design concepts.

Table D2 Expressed IAP strengths and weaknesses and their occurrences.

Strength	#	Weakness	#
Strong idea, Fills a gap in current design process, different than present methods.	5	Might take too much effort to realize (labour intensive, complex) .	4
Exploring/Presenting many variations rapidly without making it costly.	4	Quality of the projection vs. regular finished models (e.g. wood finish).	3
Flexible with fabrics and layout, styling-tool.	3	Physical model is required, also needs updated when applied in a new situation.	3
Bring ideas rapidly to the customer.	3	Only 2,5 D (just a “skin”).	2
Might be spectacular – esp. with a handheld version.	1	Requires a lot of knowledge/might be difficult.	2
Good for acquisition/ marketing.	1	Tactility not the same as end version (interior).	1
Easy to use.	1	User can occlude the projection.	1
		Cannot support 1:1 scale for large products/setups.	1
		Possibly wrong perception of the product by client.	1

Then we asked about the envisioned benefits of the IAP to their own design process. The results are summarized in Figure D2. The participants mention as most important benefits: *Communication with external parties, Facilitate user testing process, facilitate concept development, improve insights, and reduce errors/mistakes.* Concerning the method, three main issues need addressing: i) does variability in a design matches the physical – virtual division, ii) what is the trade-off between speed versus quality, iii) how does this affect the emancipation of other stakeholders. The first is related to product domain and activity – the fit with some (like website or kitchen design) is less obvious. The second concern touches the need for speed versus the need for credible prototypes, which differ based on customer and studio tradition. The last demarcates the role of the designer in the design process and the power that clients and other stakeholders have in the process to explore alternatives that might be undesirable.

Table D3 Phases and activities that could benefit most from IAP.

	Definition	Concept	Detailing	Deployment
Communication among stakeholders		5	4	
For exploring styling (shape/features)	1	3	1	2
UI testing		1		
Specification (zooming into details)			1	

Application domain & design phase that might benefit most

During the interview, the participants suggested domains that could profit by IAP. The majority of statements point at a generic application in product design (5 participants) and sometimes interior design (2 participants). In particular, handheld consumer electronics and automotive were mentioned.

Furthermore, two participants put forward all product categories that involve diverse group of stakeholders, such as automotive, medical and aviation. Other domains that were mentioned are packaging design and fashion, both as to projecting prints/graphics. With regard to the specific design phase that could benefit from IAP-M, the participants mentioned concept and detailing phase, while pre-manufacturing stage was not selected at all. Table D3 summarizes the responses, linking the

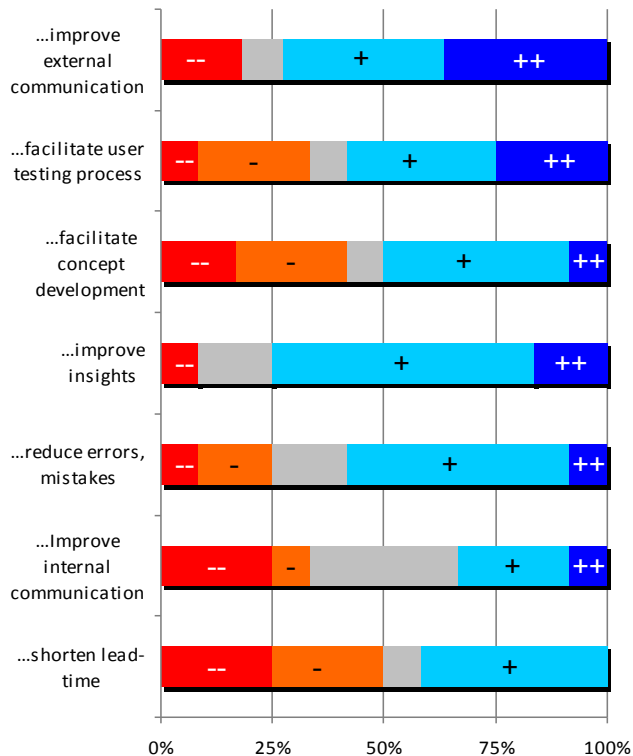


Figure D1 Envisioned benefits of IAP-M.

phase (definition, concept, detailing, pre-manufacturing) to specific activities (vertical).

The interior design agencies also suggested IAP support during the building/installation phase, as assistance to select decoration or furniture layout in a full-scale context.

Appendix E

Critical reflection on the IAP-M constituents by the original case study owners^{*}

METHOD

We selected an interview supported by a demonstration of the pilot implementation. The interview allows us to discuss future usage scenarios of IAP, and will yield several interpretations of the notion “design means”. The interaction with the pilot system during the interview establishes an embodied reflection; Söderman [12] already explored this method in concept testing, where it was clear that interaction with the physical prototypes yielded more detailed feedback on an artefact model than more abstract representations such as virtual reality-based presentations and hand sketches.

We returned to three design agencies that participated in an empirical case study, performed in 2006 and 2007 [14]. Each session would be attended by at least two participants, and would take place at the company in a meeting room or similar environment. One facilitator chaired the meeting while another investigator captured the session and provided technical backup. The agenda for each meeting contained three activities, as shown in Table E1.

^{*}Published as Verlinden, J., Doubrovski, E., Horváth, I. “Assessing the industrial impact of interactive augmented prototyping”, in proceedings of TMCE 2012

During the demonstration and discussion, the participants were introduced to the three systems described in the previous section. Then, the following questions were posed: i) could this be beneficial to your design process, if so, how? ii) Does the demonstrated system enrich communication between stakeholders? iii) What are the challenges that can be foreseen when adopting the particular IAP solution? Furthermore, the participants were individually challenged to express which type embodiment they would preferred and why.

The case review was discussed with the senior participants, who worked on the project to be revisited. A hardcopy of a list of bottlenecks and best practices was used to steer the interview. – for each the participant(s) were asked what, in retrospect, the impacts of these bottlenecks were and how IAP could serve as a means to solve these. Finally, an excel worksheet was shown during the discussion of the meeting minutes template. This was introduced and adapted by the facilitator based on input of the participant. These adaptations were kept and used in the subsequent sessions.

Three demonstration setups were prepared to allow participants in getting first-hand experience with different IAP instrumentations: I/O Pad, handheld pico-projector, and a retail projection system, shown in Figure E1. More details are provided below.

A. Desktop: I/O Pad, 2nd pilot implementation

The I/O Pad is the second pilot implementation of projector-based Augmented Reality, depicted in Figure E1. By employing an ultra-short throw projector (Epson Ep460i), the system is able to project on a table while the height of the setup is limited and is portable. When vertically placed, the selected projector would illuminate an area with a diagonal of 2 metres. The tracking system is an infrared-based optical tracking and matching system, called Personal Space Tracker⁹ which can track and identify up to 128 objects simultaneously based on random dot patterns (retro-reflective stickers that need to be applied to the physical object). The tracker has an accuracy of 1 mm and an update frequency of 100 Hertz, and was equipped with special optics to match the field of view of the projector (near mode). A Tablet PC (HP tm2) was equipped with a relatively powerful graphics processor,

Table E1 Interview outline.

Agenda	Activities	Time (min)
1. Demonstration & discussion on future use.	I/O Pad, Showwx projector, LightTouch system	30
2. Case Review	Short intro, revisit design process, opportunities for IAP	15
3. Meeting minute template	How the meeting minute scheme is fit to their practice.	15

an ATI Mobility Radeon HD 4500 and runs Ubuntu Linux.

⁹ www.ps-tech.com



A. I/O Pad



B. Showwx pico-projector
LightBlue Optics (UK)



C. LightTouch system
Microvision (USA)

Figure E1 Three different projector-based AR demonstrators used in this investigation.

The software architecture is based on VRmeer¹⁰, an open-source visualisation core specifically made for interactive scientific visualisation. This solution builds upon the C++ OpenSceneGraph library and was extended with an additional scripting layer in Python [4]. The advantage of using this platform is that it supports a large variety of display/tracking hardware, such as the employed PST tracker. Furthermore, it allows altering the interaction behaviour on the fly.

The system was encased in a custom-made flight case, equipped with wheels and handles and could be transported without having to alter the layout of the devices. This allows unpacking/installing of the projector-based AR installation in less than 10 minutes. The object that was used is a 26 x 8 x 6 cm model of a tractor, fabricated by Selective Laser Sintering in white polyamide. Three original designs of the tractor's body, featuring different headlights and air inlets as well as slightly varying principal styling curves, were converted from Catia models to texture maps. These variants could be activated by using mouse buttons or the TabletPC's keyboard.

B. Handheld: pico projector

The second embodiment of an interactive projector system is based on off-the-shelf hardware: a pico projector connected to a smartphone. The advantage of this setup is that it is relatively lightweight and small (220 grams, 12 x 6 x 2 cm). Due to the laser-based projector, a Microvision Showwx with a resolution of 840x480 pixels with 10-lumen illumination power, the image is always in focus. The demonstration mainly included viewing pictures and videos by the built-in software applications. During demonstrations, arbitrary surfaces in the environment can be used to explore various types of interaction.

C. Desk lamp: retail projection system

The final embodiment that was included in this experiment was a specialized projector with built-in touch sensor, battery and CPU. This specific system, entitled

¹⁰ graphics.tudelft.nl/VRmeer

LightTouch is manufactured by Light Blue Optics, is typically meant for use in retail environments. It is a freestanding product that casts an image on a table (400 grams, 10 x 3 x 17 cm). It functions as a desk lamp while the image is always in focus due to the employment of holographic laser projection. As the pico projector described in the previous section, this system has a low light output of max 35 lumens with a resembling resolution of 800x480 pixels, spread over an area of area 21 x 12 cm.

The software platform is Windows CE, limiting the processing and rendering capabilities to simple graphics applications. The built-in sensor is capable of tracking 1 finger when the user taps the surface. During demonstrations, we used the build-in image sorter and movie player applications.

Sampling

The sessions were held at design agencies of different design disciplines, attendance is shown in Table E2. In all cases, the principal designer was available that was part of the empirical case studies. Furthermore, additional studio members – including interns - were invited to discuss the future impact of IAP.

In terms of timing, setting up the demonstrations took 20-30 minutes (mainly setting up the I/O Pad and the video recording equipment). The actual sessions took between 60 and 90 minutes. Results are presented in the following sections.

Table E2 Attendance of the embodied reflections.

#	Design domain	Original Case Study	Attendance
1	Automotive	Tractor	2 senior designers& 1 intern.
2	Information appliances	Portable oscilloscope	3 senior designers& 3 interns.
3	Interior design	Museum interior	3 senior designers& 3 interns

Embodied Reflection findings

In all sessions, participants interacted with the demonstrators and explored projections on various surfaces. For the I/O Pad, the interaction between card and tractor was done the most often. In the case of the Desk lamp variant, all participants activated a projected keyboard. The demonstrations led to the following responses regarding the benefits and challenges of IAP-M.

RESULTS

Design support

A number of design support activities that can be done with IAP are discussed, namely client presentations, context analyses and sketching. For presenting concepts to a client, IAP might save time by just bringing white models (session #3) and allow different concepts to be shown as demonstrated with the tractor model. The participants remarked that the projections look acceptable, especially the I/O Pad, which performs as well as a 17" laptop screen. The projection of the three different concept models on the same global shape is considered to be convincing, yet one of the senior participants expressed doubts whether this would be acceptable for designers – better to have several physical models and project features on top.

Projection might also help to feel engaged in a particular context, for example medical or container logistics. Scale was mentioned by two of the three embodied candidates – in one case to use full size (automotive) and in the interior as small scale (table top).

The projection could be very useful for determining split lines (segmenting the object) (raised in session #1 and #2). Interactive sketching and projecting flow simulation to check manufacturing would be useful as well. However, every design, choosing an appropriate scale is crucial (sessions #1 and #3).

Magic factor of IAP

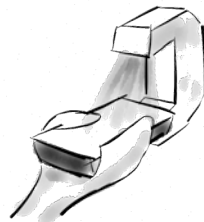
In the opinion of the participants, the projection on physical models constitutes a surprising element, especially the digital counterparts stay aligned when the physical components are moved. This point was raised in all three sessions when the cards of the I/O Pad were moved or thrown around. In session #1, some have worked with a projected keyboard device in the past, yet the demonstrators are more versatile and display color information.

Novel interaction techniques

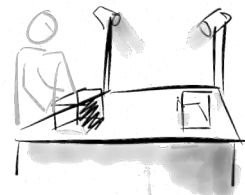
Several novel interaction techniques were invented by the participants during the demonstrations.



a. Design Review,
handheld.



b. Interaction test with
mockups.



c. Augmented photography
studio.

Figure E2 Design support scenarios proposed during the three sessions.

First, the interaction with the card and tractor allowed creating section views by pushing the card on the tractor body (interfering with the virtual geometry). This interactive “slicing” technique yields novel ways to inspect surface continuity and to probe dimensions. Second, several sketching techniques were explored with pens, paper and physical models. Specifically to cater for explanation and exploration during design reviews.

Weaknesses

The envisioned weaknesses of the IAP demonstrators concerned projection coverage, interaction and time. Projection coverage is perceived limited from both the I/O Pad and the Desk Lamp systems – both project from a single side, requiring using small physical models or forcing unnatural viewpoints when multiple stakeholders are discussing a concept. A top projection was suggested to perform better. Furthermore, the projection size of the Desk Lamp – cm2- considered to be too small in regular design cases. Participants remarked that they expect that the interaction would be similar to that of current smartphones and tablets. This led to disappointment when using the desk lamp system that only supports single finger interaction. The interaction with the I/O Pad went well, yet sometimes objects would be mistakenly moved out of bounds of the tracking region.

One hesitation that was raised at all sessions was that the time to make such a model/prototype should not take too long; otherwise it becomes a distracting factor and is not in sync with the design process. However the time to make such a model/prototype should not take too long, otherwise it becomes a distracting factor and is not in sync with the design process.

Preferred IAP embodiment

Each of the design studios had a different preference: automotive: handheld, information appliances: desk lamp (allowing hands-free use to interact), interior: table with facilities/storage/etc. in its vicinity. The preferred embodiment and design scenario are depicted in Figure 2.

For the automotive studio, portability was found very important, as the designer typically travels to the client. The handheld embodiment, as sketched in Figure 4a is preferred. Furthermore, IAP can then be combined with handheld 3D scanning for reverse engineering etcetera. Yet for other design activities it would be more worthwhile to have a full-scale projection (for example of the bus interior), similar to a more traditional Powerwall.

At the information appliances design department, hands-free operation of IAP would be preferred as the main focus is human-machine interaction, both in physical and cognitive ergonomics. The designers envisioned a scenario in which the projector/tracker unit is clamped onto a mock-up (Figure 4b).

For interior designers, the added value of IAP is perceived to be in explorative phase. A setup similar to a “photography table” with lights and props to make snapshots of interiors on small scale would work well. As depicted in Figure 4c, it could have physical tools with a library of part designs/furniture with digital counterparts that can be deployed at different scales, preserving a level of abstraction. Urban design and architecture design challenges would benefit a lot from these techniques. The other senior member immediately expresses that the setup looks like a “dark room” (traditional photographic processing lab).

Retrospective impact analysis

After the embodied reflection, a past project was revisited based on a small project overview that the principal investigator made. The bottlenecks and the possible impact of IAP were discussed, which led to an overview of past strategy, effects, and possible impact of IAP – this complete overview is presented in the appendix while particular aspects are highlighted below.

Tractor case

Regarding prototypes the senior designers answered that a physical model would have helped in the discussion about the headlight, where discussion was too abstract. In a physical model, they could have explained that using a normal headlight the tractor would “look like a frog”. The designer’s idea of using smaller lamps was not understood by the other stakeholders.

Museum case

Budgeting and budget ownership had a large influence on the further detailing/implementation of this project. Maybe the projections could have had an influence on the presentation, but mainly to seduce the people – to give insight in the motions. That could have helped in convincing the stakeholders.

Oscilloscope case

As for the impact on the past design project and similar cases in the current company: any physical mock-up is better than none. IAP could certainly have helped in making a better prototype for usability studies than the screen-based prototyping approaches that were used that time. In the current situation, design and engineering process is different, with less time available for usability assessment and optimization – instead, physical models are made mainly for technical purposes (fit of the engineering package, manufacturing tests).

Capturing design reviews

At the end of the session, an empty design review template was shown and discussed. In all agencies, the principal designers expressed that there is little attention for minute making; main limitation is time necessary to do these acts (minute making, revising etc.). In product design/engineering, it is not affordable to have an external moderator/secretary. This typically only happens on request, and often the other stakeholders have little interest in revising such records. Furthermore, when minutes are made, they tend to be in an informal structure. However, all principal designers express their eagerness to improve note taking during design review.

The role of design review meetings is different than the template implies: all principal designers express that decisions are normally not made during these events. Often, it functions as a status update and an investigation of what needs to be done- so the decisions would be focused on the process and not on the artifact.

In considering the design review template, three modifications have been suggested by the interviewees: 1) to change the meaning of the “What” to a description of the event, 2) the original meaning of this column (“what”) is renamed to a new field entitled “Type”, 3) a new column to denote follow-up actions. The resulting representation scheme for design review sessions is shown in Figure E3.

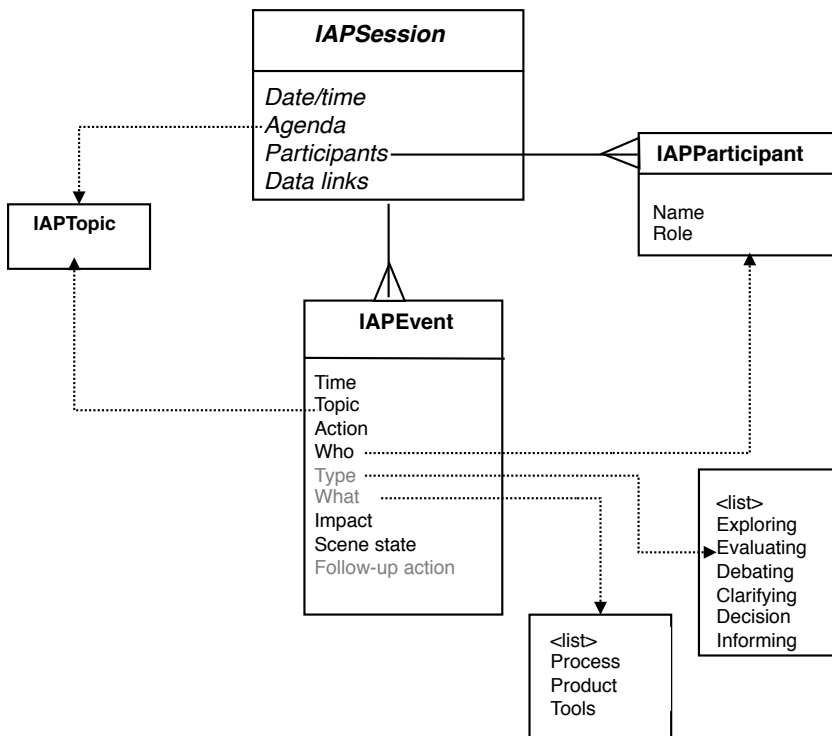


Figure E3 Improved representation scheme for design review sessions.

DISCUSSION

Technical issues

The demonstrations that we employed suffered from a number of challenges, mainly considering light and construction issues. Considering light: the two small projector systems required a dimmed room. The I/O Pad system can work in normal lighting conditions. However, in one location the tracking suffered from a lot of direct sunlight, causing the IR tracking system to be flooded. Only after closing the shades as much as possible we could continue this demonstration.

The construction of the I/O Pad needs improvement, for example the fixture of the tracker to the main body was not sufficiently stiff, which introduced misalignment of coordinate systems (registration). There were also limitations in the software architecture, devised for scientific visualization and incompatible with CAD files. Furthermore, although the python environment allowed changes on the fly, the semantics were difficult to apprehend.

Robustness

Due to pragmatic reasons, one specific embodiment type was implemented in the I/O Pad. In all sessions, the participants understood the concept of projection on physical models and could relate it to their own practice, as discussed in Section 2.3.

The past design processes that were revisited were more than 4 years ago. However the senior designers had no problems in remembering how the process went or to identify bottlenecks. In the view of the principal investigator, the timespan in-between helped in reflecting more objectively on the process.

CONCLUSION

IAP is an emerging technology that can enhance the design process. However, the actual employment of these systems is limited to academic situations. Most tests and surveys show concept of IAP in an abstract narrative. This investigation engaged a focus group with demonstrations and discussion, labelled an embodied reflection. . In total, 8 senior and 6 junior designers attended the sessions, which were performed at three design agencies.

In each session, three IAP systems were demonstrated while the focus group was invited to engage with the systems. The participants' reactions show similarities with a prior survey – however the embodied reflections presented different strengths and weaknesses, and enabled more brainstorming on new ideas on how IAP can be used in the design process. Furthermore, there is no single embodiment of IAP that is preferred by all domains – the differentiation between table, desk lamp or handheld device all can be useful and should be developed further.

In the sessions, a past design process was revisited, taking in consideration what the impact of IAP could have been in enhancing design reviews. This step ensured that we extended the earlier findings – of 3-4 years ago, with new insights and developments. These findings, combined with the embodied reflections, show that the design review is still most likely candidate to employ, with a design review template that pivots around the *IAPEvent* structure, defined in Section 5.5.

REFERENCES

- [1] Bimber, O., Stork, A., Branco, P. (2001) "Projection-based Augmented Engineering" of proceedings HCI'2001, volume 1, pp. 787-791.
- [2] Bochenek, G.M., Ragusa, J.M. and Malone, L.C. (2001) "Integrating virtual 3-D display systems into product design reviews: some insights from empirical testing", *Int. J. Technology Management*, Vol. 21, Nos. 3–4, pp.340–352.
- [3] Cross, N., Christiaans, H., Dorst, K. (1997) "Analysing Design Activity", John Wiley & Sons, ISBN 0471960608.
- [4] de Haan, G., Post, F.H. (2009) "StateStream: a Developer-Centric Approach Towards Unifying Interaction Models and Architecture" In Proc. of ACM SIGCHI Symposium on Engineering Interactive Computing Systems EICS 2009, pp.13–22.
- [5] Keller, A.I. (2005) *For Inspiration Only, Designer Interaction with Informal Collections of Visual Material*, PhD dissertation, Delft University of Technology, the Netherlands.
- [6] Lim, Y., Stolterman, E. and Tenenbergs, J. (2008) "The anatomy of prototypes: prototypes as filters, prototypes as manifestations of design ideas", *ACM Transactions on Computer-Human Interaction*, Vol. 15, No. 2, pp.1–27.

- [7] Mengoni, M., Germani M. and Peruzzini, M.(2009) “Products experience: how can Virtual Prototyping improve usability testing?” In Innovative developments in design and manufacturing - Advanced Research in Virtual and Rapid Prototyping, Ed. P.J. Bártolo et al., CRC press.
- [8] Nam, T-J, Lee, W. (2003) “Integrating Hardware and Software: Augmented Reality Based Prototyping Method for Digital Products” in proceedings of CHI’03, pp. 956–957.
- [9] Nielsen, J. (1992) “Finding usability problems through heuristic evaluation”, proceedings CHI '92, pp. 373-380.
- [10] Opiyo, E. Z., Horváth, I, and Vergeest, J. S. M. (2000) "Evaluation of Foundational Theories in the Framework of Abstract Prototyping ", proceedings TMCE 2000, pp. 349-360.
- [11] Radkowski, R. (2010)“What makes an Augmented Reality Design Review Successful?.” In proc. TMCE, pp. 499-510.
- [12] Söderman, M.(2005) Virtual reality in product evaluations with potential customers: An exploratory study comparing virtual reality with conventional product representations” Journal of Engineering Design Vol. 16(3), pp. 311–328
- [13] Verlinden, J., Horvath, I. (2008)“Enabling interactive augmented prototyping by portable hardware and a plugin-based software architecture” Journal of Mechanical Engineering, Slovenia, Vol 54(6), pp. 458-470.
- [14] Verlinden, J.C., Horvath, I.(2009) “Analyzing opportunities for using interactive augmented prototyping in design practice”, Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AI EDAM), volume 23, issue 03, pp. 289-303.
- [15] Verlinden, J.C., van Duijnen, F., Horvath, I. (2010) “Validating the strengths and weaknesses of Interactive Augmented Prototyping in Industry”, Research in Interactive Design, vol 3, Springer.

Appendix F

Valorisation of IAP-M

The working principles and embodiment of the I/O Pad has been filed as a patent on the July 25th 2008 (WO2009014448A1). The 15 claims pivot around this principle:

A projection and recording device, provided with a processing and control unit, a memory for recording images and other data, an input/output interface, a controllable camera, a touch screen for the input and display of data and images, a position determining system for determining the position of at least one object in relation to the projection and recording device, with images recorded by the camera being storable in the memory and displayable on the touch screen, and a projector for projecting an image stored in the memory onto the at least one object, wherein the cooperation between the position determining system and the projector enables the projector to project images onto the object.

Additional claims extend this with 2D/3D drawing, simulation or editing, the inclusion of a microphone and speaker to record/reproduce audio –

The original Dutch patent was later translated and filed as a PCT, subsequently filed in the EU and US. In valorising this knowledge, questions were:

- What would be a solid business case to initiate process enhancement through IAP-M?
- What domains will fit to this proposal?
- What further development of the constituents of IAP-M is necessary?

The valorisation of this patent was initiated during a student project and a techno starter, described below.

Student team

An IDE MSc design team, working on a project for an aviation company in 2009, applied the principle of IAP-M. They proposed to use the methodology for procurement and development of custom refurbishing of passenger airplanes. This context encompasses interior stylists, clients, certification agencies and different engineering disciplines that all have challenges in integrating the concept designs. The typical languages are textual (quotations, design specifications) and engineering drawings (electric, aerodynamic, mechanical). Furthermore, due to the tubular shape of the aircraft, a floor plan does not expose the spatial aspects such as height, location of windows while issues such as weight distribution and hazards need to be

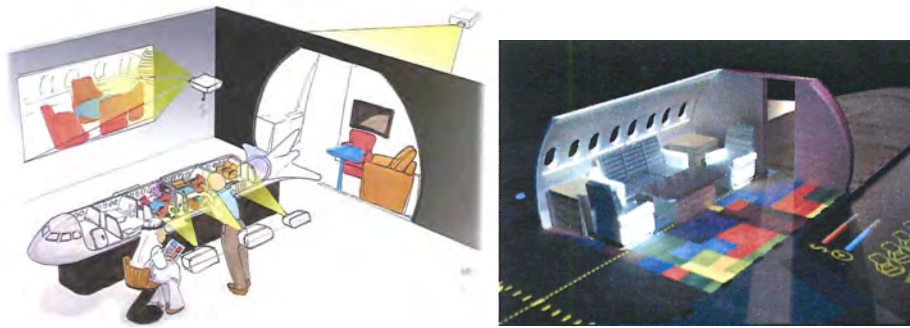


Figure F1 Artist' impression (left) and working prototype (right) of the aircraft interior design tool.

addressed for safety and certification purposes. This situation is challenging and IAP-M provides opportunities to enhance this, cf. Figure F1.

Techno-starter Delight Interactive Solutions

In 2010, then student Industrial Design Engineering Frans van Duijnen of the team mentioned above founded the techno-starter Delight Interactive Solutions B.V.” with Computer Science student Rene Elstgeest, based on this launching customer and the patent.

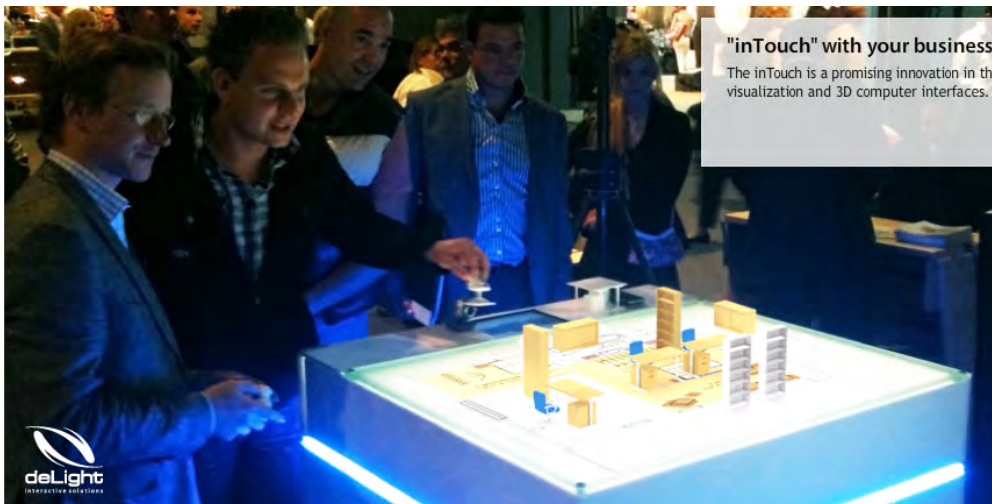


Figure F2 Impression of Delight's AR system, with projections on 3D printed furniture, marker-based tracking and floor plan projection inside the box.

This evolved to the following product portfolio:

- MARK software platform: a proprietary marker-based rendering engine with import capabilities from CAD systems. Also a free viewer (entitled “deLight player”) can be downloaded to view AR files.
- ARea Table – a table with projector and sensors embedded, which connect to the software. Both permanent and travel editions have been made.
- Projector-based solutions, built to collaborate with the ARea Table.
- AR glasses (Vuzix), either video mixing or see-through.

Their system was initially targeting interior designers and furniture shops – to support design exploration together with clients. The IAP-M procedure was adapted to the following steps:

1. *Enter your customers' room size and specifications* (=modelling)
inTouch automatically generates and projects 3D images of the empty room on the screen and on its surface.
2. *Choose the scaled models of the preferred furniture* (=preparation)
The 1:1 images will be automatically displayed on the screen. The movement of the models is automatically followed on the screen.
3. *Move around the room for a different view* (=reviewing)
Look automatically how it would look like from different perspectives.
4. *Select the textures and colours and play with them.* (reviewing)
The texture and colour changes made are immediately displayed on the screen and on the scaled models as well!
5. *Save the colour and arrangement combination* (=reflection)
and allow your customers to order the products directly.

Although it doesn't address deployment, this procedure resembles IAP-M but is tailored to exploration and selling than on critically reviewing concepts. As such, the method of capturing and reflecting on sessions was dropped. Furthermore, the instrumentation often does not employ projector-based AR: the projector in embedded in the ARea system typically projects 2D graphics, whereas separate monitors display 3D graphics for walk-through or animations. Although the company did spend effort in implementing calibrating projectors in spatial AR, the effect has little value over flat displays to urban planning/real estate, while the hassle of installing and calibrating projectors proved too labour-intensive.

At the moment, 6 people work at this start-up. As reporting on business operations is confidential, only highlights are mentioned: the company did projects with German automotive firms on in-car entertainment while the aviation stayed in their focus but suffered from the economic crisis. In the domain of real estate, the interactive display of city/floor plans and 3D views is proving as a promising business. Other projects of Delight Interactive Solutions were done in museum environments, as well as trade fairs. To summarize, business development of Delight Interactive Solutions went in a different direction that the IAP-M was originally intended – the design methodology is not necessarily applied to product design yet it still addresses communication between stakeholders.

Summary

Developing an Interactive Augmented Prototyping Methodology to Support Design Reviews

Physical prototypes and scale models play an important role in engineering design processes, especially in the field of industrial design. Such physical models are typically used to explore and discuss design concepts in various stages, from initial idea generation to manufacturing. Over the last decade, augmented reality technologies have been developed to assist prototyping in design. We can employ head-mounted displays, projectors, or handheld video-mixing solutions to “enrich” physical models with features, materials, and behaviour. In literature, such systems are known as Augmented Prototyping (AP). They demonstrate various types of interactivity in design, ranging from passively displaying presentations, through altering surface qualities/texture, and testing a product’s user interface, to changing product performance. However, few off-the-shelf software and hardware solutions exist. Scientific proposals mainly focus on the technology and not the design process. These indicate that there is a lack of knowledge on how such advanced prototypes impact design processes. This knowledge is essential to benefit from advanced design support tools.

The objectives of this project can then be formulated as follows:

- To identify the enabling technologies of Augmented Prototyping.
- To study the problems and best practices of concept uttering and communication in design processes.
- To formulate an underpinning theory which explains how AP can enhance the design process.
- To expand this theory to an implemented and validated design methodology.

The outcome of this project is a design support methodology, entitled Interactive Augmented Prototyping Methodology (IAP-M), which utilizes AP as an instrument to

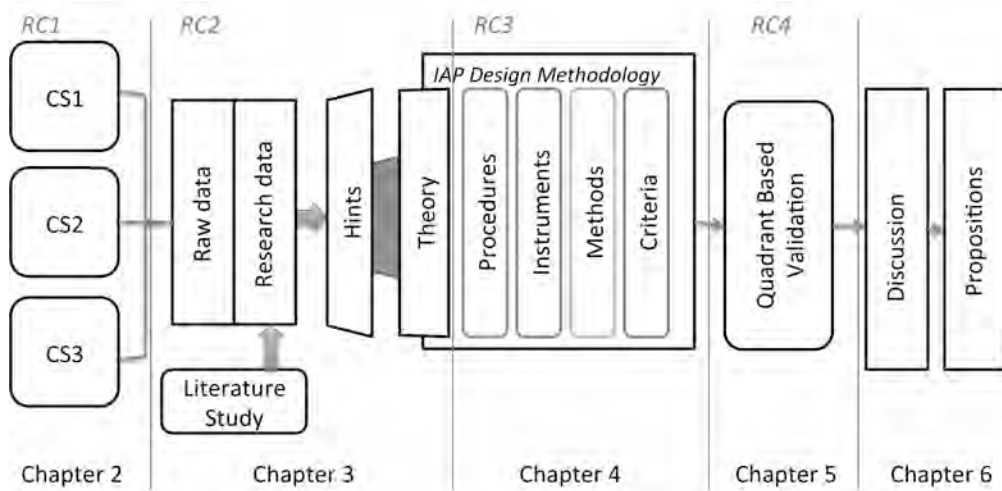


Figure 1. General outline of the research framework (RC= Research Cycle, CS=Case Study).

support design reviews. The instrument, a projection and recording unit, was patented and licensed to a techno starter for further valorisation. Two versions have been developed as research means. Although the instrumentation is central in this study, it requires procedures and methods to be applied in design processes. Hence, IAP-M was constructed as a design support methodology, applicable in several design situations as defined in its criteria. The insights that lead to IAP-M originated from empirical studies and design inclusive research, and were implemented in a collection of demonstrators.

Research design

The research approach of this work required both technology development and empirical study. The project was procedurally and methodologically framed in four research cycles, depicted in Figure 1. The first cycle, as research in design context, focuses on the current state of technology and empirical studies in design support. The second research cycle, framed as a research in design context, aims at conceptualising an underlying theory to develop a design support means for concept uttering. In this cycle, the construct of hints is introduced: a focused and speculative usage scenario of a future methodology (and system) that to support the design process. The third cycle exemplifies a design inclusive research study, devoted to the implementation of this underlying theory as a design methodology with its constituents (methods, procedures, instruments, criteria). The final research cycle addresses the utility and integrity of the devised IAP-M in a research in design context step by applying an approach entitled the validation square.

RC1. Exploring bottlenecks and best practices in specific design processes

Although existing literature covered prototyping skills and technologies, little was written on the reasons why and how models are used in design practice. To better understand this, I executed three empirical case studies in different areas of industrial design. Three design projects were followed, one retrospective, with specific focus on physical prototyping and group interaction activities. The research

questions were: i) what are the characteristics of concept utterances?, ii) which product modelling aspects play a role in these utterances?, iii) what topics are dealt with as group activities?, iv) who are involved?, and v) what problems occur during the creation and use of concept utterances? The projects covered the design of information appliances, automotive design, and interior design. In the investigation, a record of all concept utterances and their impact on group activities were collected. One outcome of this multiple case study is that improving communication in design reviews would have the largest impact on the overall design process. Given the fact that any AP system requires specific knowledge and skills before, during, and after the design reviews that designers currently lack, the findings show that there is a need for a practical AP application methodology. A reference model was constructed to describe the causal relationships between prototyping, the design process, and its outcomes. This model relates the lack of shared understanding to product development delays, decrease of stakeholder's trust, and suboptimal product quality. Furthermore, the data reveal that the roles of prototypes in current practice are not necessarily functional manifestations in a design process. For example, a prototype can be a conversational piece or a seducer to engage other stakeholders.

RC2. Deriving indicators of the need for an efficient enabler in design processes

As a subsequent step, the findings of the case studies were linked to ways to alleviate bottlenecks and learn from the best practices concerning concept uttering. The findings were filtered and interpreted by considering augmented prototyping as a technical solution principle. Then so-called "hints" were constructed, defined as elements of focused and speculative usage scenarios of a future methodology (and system) that can support specific activities in the design process. These hints were captured as conjectures, i.e., improvable but necessary propositions that yield a better understanding of the required design support.

The collection of hints indicated that communication activities, especially in design reviews, would benefit most from an interactive type of augmented prototyping. A design review is a process in which stakeholders with different backgrounds formally or informally discuss design alternatives and ultimately make design decisions. Literature of engineering and management sciences indicated that both methods and materials play a crucial role in design reviews. In design domains, such as aerospace engineering, formal methods have been devised to streamline the reviewing process and set up a clear audit trail that is required for legal issues. In order to "augment" the design discourse, the hints highlighted three activities: presenting design alternatives, keeping a meeting agenda, and capturing design decisions. In the field of computer-supported collaborative work and virtual reality, functions have been proposed that facilitate showing/hiding design components, adding text annotations, and snapshot taking. Based on these findings, a theory was developed to increase the shared understanding among stakeholders during design reviews by establishing a social and tangible medium through interactive augmented prototyping (IAP). Here, the term "interactive" has three different meanings:

- IAP provides a natural, spatial medium to display multiple design aspects concurrently, accessible to multiple stakeholders.

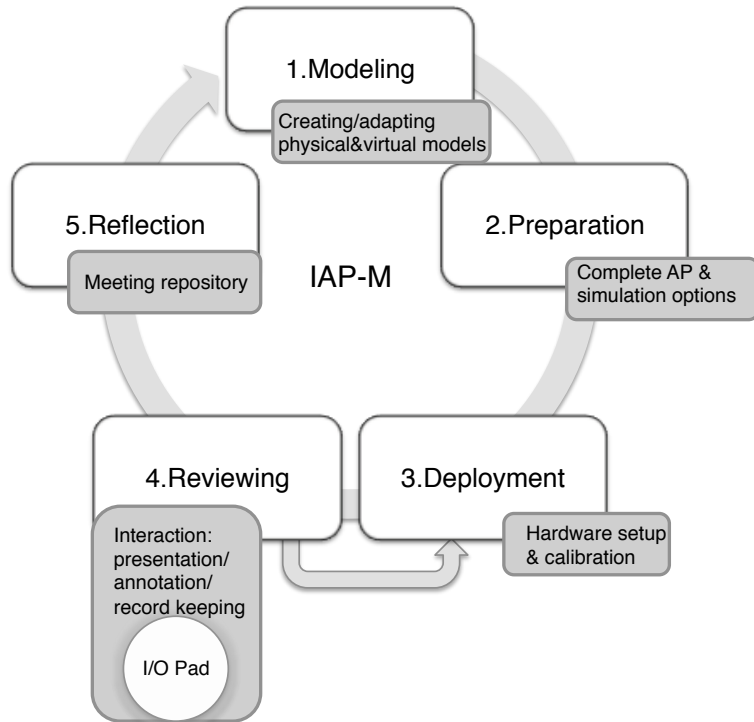


Figure 2. The IAP-M procedure, methods and instrument.

- IAP allows adaptations in the design during use and can provide real-time feedback of computational simulations.
- IAP can capture the argumentation of the design review through annotations/sketches as well as capture the discussion and models used during sessions.

A functional hierarchy decomposition and information flow was derived from the hints, resulting in the architecture of the solution that includes hardware, software, physical models, and a workflow.

RC3. Constituents of IAP-M

This underlying theory and working principle required extension to a design support methodology, entitled IAP-M. The IAP-M encompasses procedures, methods, instrumentation and criteria.

The IAP-M *procedure* applies IAP-M in a design reviews context and consists of five steps: model preparation, deployment, reviewing, and reflection. Figure 2 depicts this procedure including the methods and the related instrumentation.

The IAP-M *methods* are

- Guidelines to select between physical, virtual and mixed manufacturing of prototypes based on their function during reviewing. The guidelines use the



Figure 3. I/O Pad pilot implementations, Left: 1st implementation, right: second.

identification of design focus, crucial design elements, and given constraints.

- Guidelines to manufacture models by Rapid Prototyping (a checklist and workflow for creating physical models fit for IAP).
- A meeting minute repository (a data model to capture discussions and decisions during design reviews through video/audio/and model state and concurrently linking discourse information to the design representation, as found in the CAD files).

To enable IAP-M, I developed an *instrumentation* named the 'I/O Pad'. It combines optical tracking sensors, a projector, and computing components in a single package. Stakeholders of a design review can use multiple I/O Pads concurrently to augment a physical model, establishing a so-called occasional projector arrays. This solution was patented in the USA and Europe (NL2008/050516 "projection and registration device"). The prior empirical case studies helped in formulating requirements such as portability, ease of installation, and adaptability during use. Software requirements covered accuracy and performance, compatibility with existing CAD systems, and an open architecture for future tracking systems.

The first I/O Pad implementation used a small tablet computer, an LED projector, and a small web camera in combination with AR Toolkit markers. Although this first pilot showed the feasibility of including handheld I/O Pads in IAP-M, there were limitations in its use. The computing power restricted rendering detailed geometries, while the brightness of the used projector restricted the operating distance to 10-40 cm. Furthermore, tracking multiple objects at close distance was difficult as the markers for each object would overlap. A second implementation was constructed,

based on more capable hardware built into a portable flight case. It included a large TabletPC with discrete graphical processing unit, an ultra-wide projector, and an IR-based tracking solution. A set of 3D printed designs, equipped with retro reflective markers for tracking, served as the basis for augmented prototypes. As could be expected, this system outperformed the previous pilot in terms of computing power, brightness, and tracking accuracy. The software platform proved to be too complicated to import/export CAD models and to implement user interaction techniques such as 3D drawing and creating annotations. These pilot implementations provided sufficient insight into the envisioned I/O Pad working principles. The pilot development yielded recommendations for further development and valorisation. With regard to software architecture, I proposed a novel platform is based on plug-ins for 3D graphics updating and calibration functions for existing CAD systems. An autonomous software agent coordinates communication among the plug-ins, and allows capturing the discussions and interaction of the prototypes for later use.

A methodology requires specifying *criteria* to determine how suitable the methodology is to a specific design situation (appropriateness). Four preconditions of a design situation were formulated to be compatible with IAP-M, concerning the presence of i) a spatial realm, ii) multiple stakeholders, iii) a compatible studio tradition, iv) availability of a proper meeting location.

RC4. Validation of IAP-M and its applications

IAP-M was envisioned to bring process enhancement by creating shared understanding through engaged discussions and discovery of errors/emergence of solutions. To validate the design methodology, the validation square was adapted to a reasoning framework depicted in Figure 4. The validation square is a semiformal and conversational treatment to testing new knowledge that includes heuristics and non-precise representations. Characterized as a (so-called relativist) validation, this approach separates the merits of a design methodology in a structural (logical) and a performance (utilitarian) point of view.

Theoretical structural validity

The theoretical structure of IAP-M was validated on three aspects: knowledge, workflow, and information processing. The knowledge in terms of reference model and the IAP-M methods, deriving from the case studies and additional literature considering the design review discourse, contain no critical internal contradictions. The workflow relates to sequential application of the methods and instrumentation in 5 steps, represented as the IAP-M procedure. However, the procedure does not indicate when a set of iterations should be stopped: IAP-M should be extended to contain a finalisation criterion. Finally, with regard to information processing: the information flow of the underlying theory is in line with the subsequent software architecture and implementation of the two I/O Pad versions.

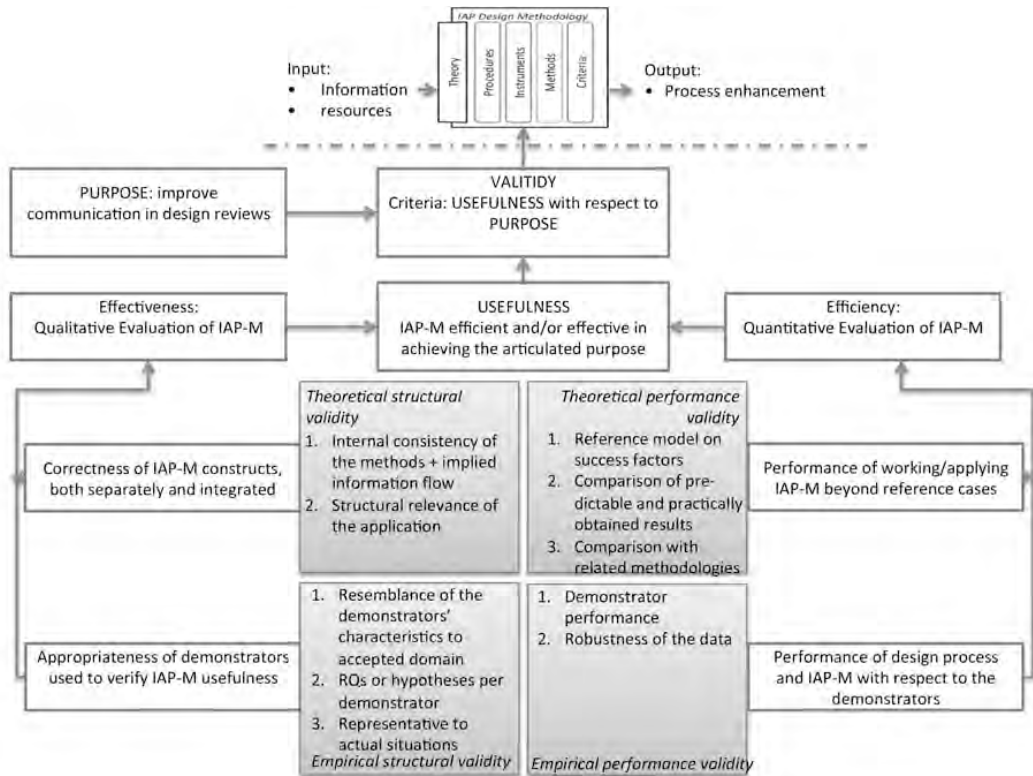


Figure 4. Quadrant-based validation for IAP-M

Empirical structural and performance validity through demonstrators

To gain empirical experience, I developed and tested a collection of experimental systems with student teams. These systems, called demonstrators, were application cases of IAP-M representative of product design and reflect a subset of the IAP-M procedure, methods, and instrumentation. The demonstrators included a CNC-milled foam car model on a turntable, a mock-up of a voice recorder, a sketch-based modelling setup with instant 3D printing and projection, a large-scale clay model of a car (scanned and projected upon), and a scale model of interior design of a nightclub. In each of the demonstrator projects, the resulting system was evaluated by prospective end users on the design performance, including the time to employ the IAP-M, the model quality, level of engagement during a design review, and the opportunity to resolve design errors. In total, 36 senior design students and design teachers tested the setups and gave feedback. For example, a benchmark between a screen-based and augmented prototype showed that the latter presented a higher confidence in assessing the physical and cognitive ergonomics. Another demonstrator, selected as ‘reference case’, established engaged discussion while participants immediately found design errors when confronted by a novel concept. In terms of development effort, the time to create physical and virtual models was equal to traditional model making. However with regard to the software platform there was a trade-off between reaching a desired level of interactivity and the time necessary to create a full implementation of IAP-M instrumentation. Consecutively the demonstrators only supported a subset of IAP-M (e.g., no automatic calibration).

Theoretical performance validity

Empirical evidence of the validity of IAP-M through demonstrators was limited to laboratory implementations. However, combined with the emergence of commercial AP solutions for design reviews, provided a sufficient body of evidence to reason on the utility of IAP-M. The performance of the IAP-M application in the reference case established engaged discussions and enabled error solving by multiple stakeholders. Furthermore, the different embodiments of the instrumentation in the demonstrators extend the validity of the approach beyond the two generations of I/O Pads. This validity can be easily extended to other of AP display types, such as head-mounted displays and handheld computing.

Conclusions and recommendations

AR is applied in a wide variety of domains, from the creative arts to forensic sciences, from medical diagnostics to assembly instruction. However, little was known on the utility of this technique in design. The main objective of this work was to propose a methodological solution for interactive augmented prototyping. The main contributions of this thesis are:

- AP supports an improved concept utterance that relates to both embodied interaction and object presence.
- Design errors can be found in the early concept phase by the ability to merge physical and cognitive ergonomics.
- A design methodology, entitled Interactive Augmented Prototyping (IAP-M), which utilizes AP as an instrument to support design reviews.
- The concept of I/O Pad, a patented portable projection and recording unit to improve shared understanding during design reviews.
- The use of hints to provide a scheme to convert empirical findings to novel design support by revisiting bottlenecks and best practices.

However, there are still unresolved issues concerning the design support scenarios and technologies that deserve further research. In particular, more field studies are necessary to assess IAP-M in different design domains, location-tracking technologies need to be refined and adapted to 3D printing.

Deliverables

The resulting body of knowledge has been published in 9 conference papers, 10 journal articles, 3 book chapters, and an international patent over almost ten years. The original WSCG article of 2003 was cited more than 60 times, while the corresponding YouTube video was viewed over 14,500 times. The demonstrators and I/O Pad implementations were presented to public audiences at several exhibits throughout the Netherlands and during the Dutch Design Week (Eindhoven, 2006) with over 20000 people.

Based on the resulting I/O Pad patent, techno starter Delight Interactive Solutions adopted IAP-M for interactive design visualisations, which it delivers as products and services. Their clients include BMW, TNO and the Delft Science Centre.

Samenvatting

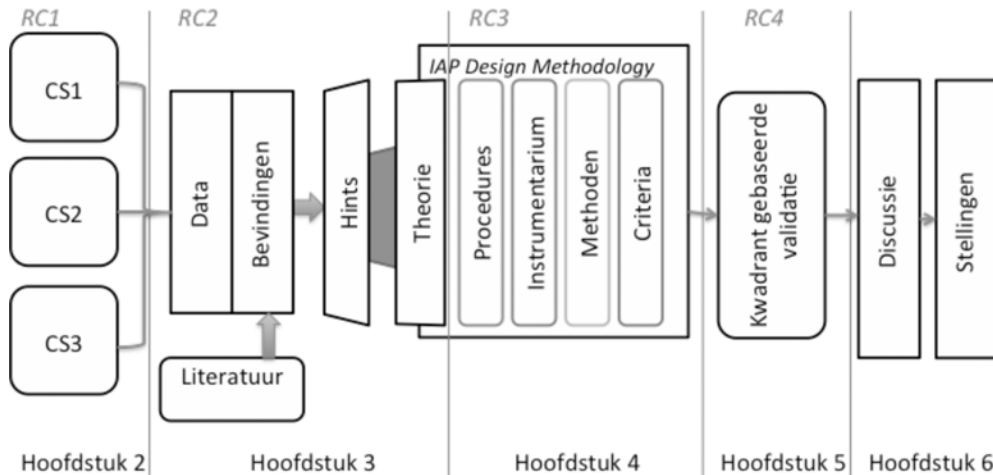
Ontwikkeling van een Interactieve Augmented Prototyping Methodiek ter ondersteuning van ontwerpbesprekingen

Fysieke modellen, prototypes en maquettes spelen een belangrijke rol in ontwerpprocessen. Dergelijke modellen worden doorgaans gebruikt om ontwerpen te verkennen en te bespreken in verschillende stadia, van idee generatie tot productievoorbereiding. In het afgelopen decennium zijn augmented reality technologieën ontstaan die het ontwerpproces kunnen ondersteunen. Head-mounted displays, beamers en video-mix oplossingen kunnen worden gebruikt om fysieke modellen te “verrijken” met functies, materialen, en gedrag. In de literatuur wordt deze technologie Augmented Prototyping (AP) genoemd. Er bestaan verschillende scenario's om AP in te zetten tijdens het ontwerpen, variërend van passief weergeven van presentaties, het veranderen van materiaal/textuur, het testen van gebruikersinterface, en het optimaliseren van productprestaties.

Wetenschappelijk onderzoek in dit domein richtte zich tot voor kort primair op de technologie. Daardoor was er een gebrek aan kennis over hoe dergelijke geavanceerde prototypes het ontwerpproces kunnen beïnvloeden. Daarnaast waren er weinig software en hardware oplossingen voor handen. Deze zaken zijn essentieel om het productontwerpen beter te ondersteunen.

De doelstellingen van dit project waren als volgt:

- Het identificeren van augmented Prototyping technologieën.
- het bestuderen van knelpunten en “best practices” in het presenteren en bespreken van productvoorstellen tijdens het ontwerpproces.
- Het formuleren van een onderliggende theorie die verklaart hoe AP het ontwerpproces zou kunnen verbeteren.
- De ontwikkeling van deze theorie in een geïmplementeerd en gevalideerde ontwerpmethodiek.



Figuur 1 Onderzoeksopzet (RC= Research Cycle, CS=Case Study).

Het resultaat van dit project is een methodiek voor ontwerpondersteuning, genaamd Interactieve Augmented Prototyping Methodiek (IAP-M), welke AP gebruikt ter ondersteuning van design reviews. Het instrument, een projectie en opname-eenheid, werd gepatenteerd en is in licentie genomen door een techno starter voor verdere valorisatie. Tijdens dit project zijn er twee versies ontwikkeld. Hoewel het instrument centraal staat in deze studie, zijn er procedures en methoden nodig om AP in het ontwerpproces toe te passen. Hierom is IAP-M als methodiek ontwikkeld, voor ontwerpsituaties die zijn beschreven in de toepassingscriteria. De inzichten die leiden tot IAP-M zijn ontstaan uit deels empirisch, deels ontwerpgedreven (“design inclusive”) onderzoek.

Onderzoeksopzet

De onderzoeks aanpak van dit project vereiste zowel technologieontwikkeling en empirisch onderzoek. Het project werd opgedeeld in vier onderzoekscycli, afgebeeld in figuur 1. De eerste cyclus, onderzoek in een ontwerp context, richt zich op de huidige stand van de techniek en empirische onderzoek naar ontwerpondersteuning. De tweede onderzoekscyclus was gericht op het ontwikkelen van een onderliggende theorie voor de inzet van AP technieken voor het communiceren van ontwerpvoorstellen. In deze cyclus werd het concept *hints* geïntroduceerd: een gerichte en speculatieve gebruiksscenario van een toekomstige methode (en/of systeem) om het ontwerpproces te ondersteunen. De derde cyclus is een voorbeeld van een ontwerpgedreven onderzoek, gewijd aan de uitwerking van de onderliggende theorie tot een ontwerpmethodiek (inclusief procedures, instrumentarium, methoden en criteria). De laatste onderzoekscyclus was gericht op het bepalen van de bruikbaarheid van IAP-M, door het toepassen van een kwadrant gebaseerde validatie.

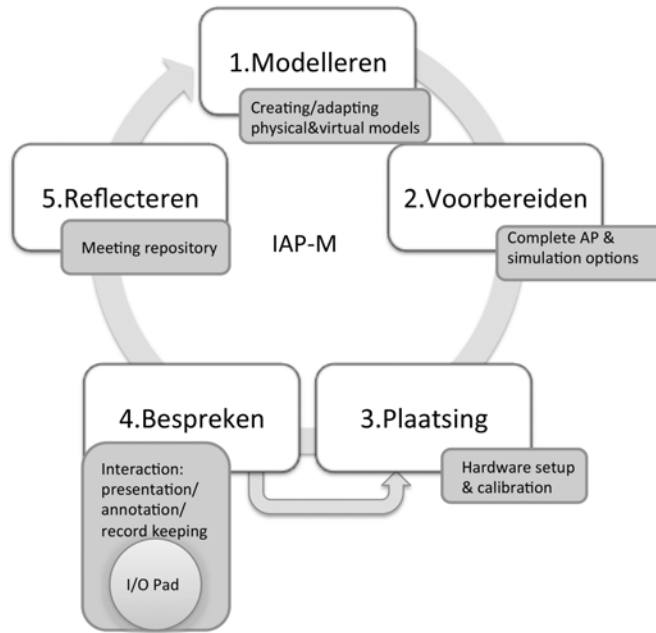
RC1. Het onderzoeken van knelpunten en best practices in specifieke ontwerpprocessen

Bestaande literatuur richt zich op prototyping vaardigheden en technologieën, er is weinig bekend over de redenen waarom en hoe modellen worden gebruikt in het ontwerp de praktijk. Om dit beter te begrijpen, heb ik drie case studies uitgevoerd in verschillende productcategorieën binnen het domein industriële vormgeving. Elk volgde een ontwerp-project, met specifieke aandacht voor fysieke modellen en hun gebruik in groepsactiviteiten. De onderzoeksvragen waren: I) wat zijn de kenmerken van het productvoorstellen, ii) hoe spelen fysieke modellen een rol in deze voorstellen, iii) welke onderwerpen worden behandeld tijdens gezamenlijke activiteiten (zoals vergaderingen), iv) wie zijn bij dit proces betrokken, en v) welke knelpunten doen zich voor tijdens de maken en inzetten van productvoorstellen? De projecten behelsden het ontwerp van handheld oscilloscoop, een tractor en een museuminterieur. Door deze case studies is er een overzicht van alle productvoorstellen en hun impact op de activiteiten van de betrokkenen verzameld. Een van de resultaten van deze meervoudige case study was dat het verbeteren van de communicatie over ontwerpvoorstellen de grootste impact heeft op het totale ontwerpproces. Voorts, omdat elk AP oplossing specifieke kennis en vaardigheden vereist, bleek dat er behoefte is aan een methode om AP toe te passen. Uit deze bevindingen volgde een zogenaamd referentiemodel, waarin de causale verbanden tussen prototyping, het ontwerpproces, en de resultaten worden beschrijven. Dit model probeert te verklaren hoe het ontbreken van een gedeeld begrip van productontwikkeling kan leiden tot vertraging, afname van vertrouwen van stakeholders, en suboptimale kwaliteit van de ontworpen producten. Bovendien bleek dat in de huidige praktijk de rol van prototypes niet noodzakelijkerwijs gekoppeld is aan een het toetsen van het ontwerp. Een prototype kan bijvoorbeeld overtuigingskracht vergroten of andere belanghebbenden zelfs verleiden tot een beslissing in het ontwerpproces.

RC2. Het bepalen van mogelijkheden tot verbeteringen van het ontwerpproces

Als een volgende stap werden de bevindingen van de case studies omgezet in mogelijkheden om knelpunten te verlichten en te leren van de best practices. De bevindingen werden gefilterd en geïnterpreteerd aan de hand van de mogelijkheden van geavanceerde prototyping technologieën. Hieruit werden zogenaamde "hints" geconstrueerd, gedefinieerd gerichte en speculatieve gebruiksscenario's van een toekomstige methode (en systeem) welke specifieke activiteiten kan ondersteunen tijdens het ontwerpproces. Deze hints zijn vermoedens, dat wil zeggen: onbewijsbare proposities om beter te begrijpen welke aspecten van het ontwerpproces we kunnen verbeteren.

Uit de verzameling van hints rees het vermoeden dat communicatie, vooral tijdens design reviews, het meest zouden kunnen profiteren van een interactieve vorm van AP. Een design review is een bespreking waarin ontwerpvarianties door betrokkenen van verschillende achtergronden, formeel of informeel bespreken en waar uiteindelijk ontwerpbeslissingen in worden genomen. Literatuur in de technische en organisatie wetenschappen beschrijven dat zowel gespreksmethoden als gebruikte



Figuur 2. IAP-M procedure, met vermelding van methoden en instrument.

materiaal een cruciale rol spelen tijdens het beoordelen van (ontwerp)voorstellen. In ontwerp domeinen, zoals lucht & ruimtevaart, zijn formele methoden bedacht om de bespreking te stroomlijnen en om het dossier aan beslissingen vast te voor juridische kwesties. De hints omvatten drie activiteiten: de presentatie van het ontwerp alternatieven, het bijhouden van een agenda van de vergadering, en het vastleggen van ontwerpbeslissingen. In het domein van computer-supported collaborative work en virtual reality zijn design review functies voorgesteld voor het tonen of verbergen van ontwerp onderdelen, het toevoegen van annotaties en de ontstane ontwerpvariatie vast te leggen.

Op basis van deze bevindingen is een theorie ontwikkeld om het gedeelde begrip tussen belanghebbenden gedurende design reviews verbeteren door de middel van interactieve augmented prototyping (IAP). Hier verwijst de term "interactief" naar drie verschillende betekenissen:

1. IAP biedt een natuurlijk waarneembare, fysieke verschijningsvorm om meerdere ontwerpaspecten gelijktijdig te tonen welke toegankelijk is voor alle belanghebbenden.
2. IAP ondersteunt het maken van aanpassingen in het ontwerp en kan direct terugkoppeling van berekeningen/simulaties projecteren op deze veranderingen.
3. IAP kan de argumentatie van de ontwerpbeslissingen vastleggen door middel van annotaties/schetsen, tevens kunnen de bespreking inclusief de modellen die gebruikt worden tijdens de sessies digitaal worden vastgelegd.

De oplossing die IAP ondersteund omvat hardware, software, fysieke modellen en een werkvolgorde. Een functionele hiërarchie decompositie en informatiestroom zijn afgeleid uit deze hints.

RC3. Onderdelen van IAP-M

Deze achterliggende theorie en werkingsprincipe dient te worden uitgewerkt tot een ontwerpmethodiek, getiteld IAP-M. De IAP-M omvat procedures, methoden, instrumenten en criteria.

De IAP-M procedure past IAP toe in een design reviews context en bestaat uit vijf stappen: model voorbereiding, implementatie, evalueren, en reflectie. Figuur 2 laat deze procedure zien, inclusief van de methoden en de bijbehorende instrumentatie.

De IAP-M methoden zijn

- Richtlijnen om te kiezen tussen fysieke, virtuele of gecombineerde productie van prototypes op basis van hun functie tijdens de bespreking. De richtlijnen maken gebruik van de identificatie van het focus, cruciale elementen in het ontwerp en gegeven beperkingen.
- Richtlijnen om modellen te vervaardigen door Rapid Prototyping zoals 3d printing of CNC frezen. Desbetreffende checklist en workflow zorgen dat de resulterende modellen geschikt zijn voor IAP.
- De opzet voor vergadernotulen tijdens design reviews. Dit in de vorm van een datamodel om overleg en besluitvorming vast te kunnen leggen tijdens, waarin middel van video/audio en 3D model gekoppeld kan worden aan de design review agenda en kan worden teruggevonden indien nodig.

Om IAP-M mogelijk te maken, ontwikkelde ik een instrument genaamd de 'I/O-Pad'. Het combineert optische plaatsbepaling, een beamer en computer onderdelen in één apparaat. Betrokkenen kunnen gelijktijdig gebruik van meerdere I / O-Pads om een fysiek model te verrijken met digitale informatie. Deze oplossing werd gepatenteerd in de VS en Europa (NL2008/050516 "projectie-en registratie-apparaat"). De eerdere empirische case studies zijn gebruikt bij het formuleren van eisen aan het instrument, zoals draagbaarheid, gemak van installatie en flexibiliteit tijdens gebruik. Software eisen waren hadden betrekking op accuratesse en snelheid, alsook compatibiliteit met bestaande CAD-systemen en een open architectuur voor toekomstige ontwikkeling.



Figuur 3. I/O Pad implementaties, Links: eerste uitvoering, rechts: tweede.

De eerste I/O-Pad implementatie bestond uit een kleine computer met aanraakscherm, een LED-beamer en een web camera in combinatie met AR Toolkit barcode stickers. Hoewel deze eerste pilot liet zien dat een handheld I/O-Pad kan worden gerealiseerd met de huidige stand der techniek, waren er beperkingen in het gebruik. De rekenkracht is beperkt waardoor geen gedetailleerde geometrie kan worden gevisualiseerd, terwijl de helderheid van de gebruikte beamer alleen werkt in een bereik van 10-40 cm afstand tot het te belichten object. Tevens is plaatsbepaling van meerdere objecten moeilijk op zulke afstanden, omdat de barcodes van elk object elkaar zouden overlappen. Een tweede uitvoering werd geconstrueerd, voorzien van krachtiger componenten en ingebouwd in een draagbare en verrijdbare flightcase. Deze implementatie omvatte een TabletPC met aparte grafische verwerkingseenheid, een ultra-wide beamer, en een infrarood-gebaseerd plaatsbepalingssysteem. Een set van 3D-geprinte ontwerpen diende als basis voor augmented prototypes, welke werden voorzien van retro reflecterende stickers voor de plaatsbepaling. Zoals kon worden verwacht was dit systeem beter dan de vorige uitvoering in het gebied van rekenkracht, helderheid en plaatsbepaling. Echter het gebruikte software platform bleek te ingewikkeld om CAD-modellen te importeren, en de interactie van de gebruiker technieken zoals 3D-tekenen en het maken van aantekeningen kon niet worden ondersteund. Desondanks geven deze twee implementaties voldoende inzicht in de beoogde I/O-Pad werkingsprincipes. De ontwikkeling leverde aanbevelingen voor verdere ontwikkeling en vermarkting. Met betrekking tot software-architectuur, heb ik een

nieuw platform voorgesteld, gebaseerd op een plug-ins architectuur op basis van bestaande CAD-systemen.

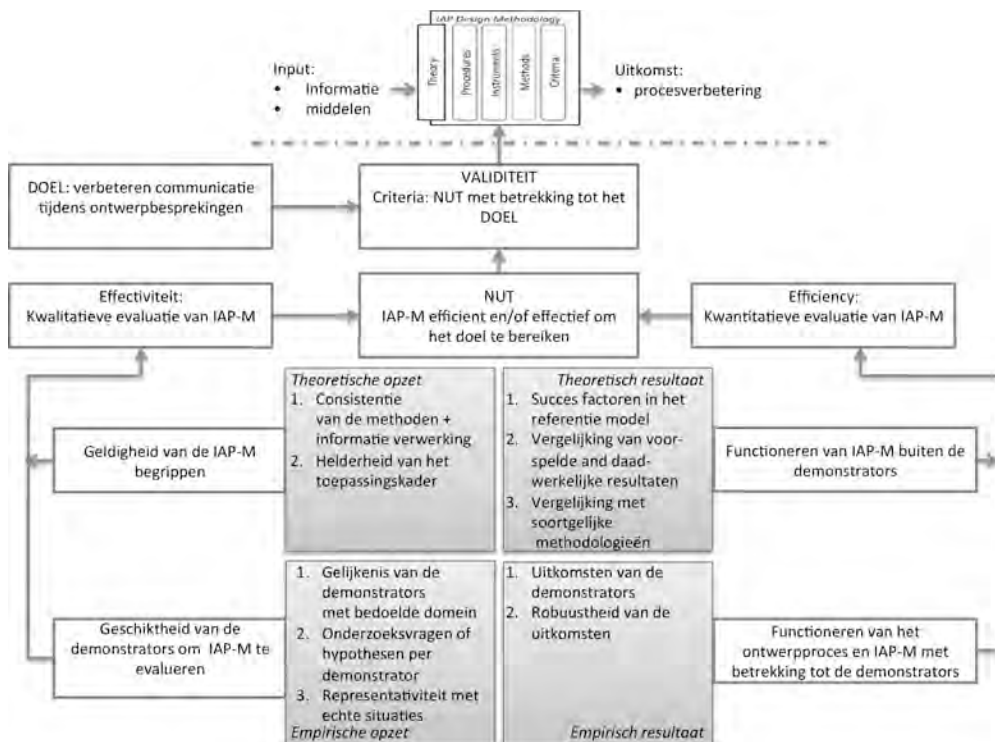
Vier criteria zijn geformuleerd op te bepalen of IAP-M kan worden toegepast op een ontwerpsituatie, en wel met betrekking tot de aanwezigheid van i) een ruimtelijke element in de ontwerpogave, ii) verschillende belanghebbenden, iii) een compatibele studio traditie, iv) de beschikbaarheid van een geschikte vergaderlocatie.

RC4. Validatie van IAP-M

IAP-M werd ontwikkeld om tijdens ontwerpbesprekingen het gedeeld begrip (“shared understanding”) te verbeteren en de ontdekking van fouten/vinden van oplossingen te versnellen. Om het nut te valideren, werd het zogenaamde “validation square” aangepast in een kwadrant-gebaseerde redenering, weergegeven in figuur 4. Gekarakteriseerd als een (zogenaamde relativistische) validatie, splitst deze benadering de verdiensten van een ontwerpmethodiek op in een structureel (logisch) en een resultaatgericht (utilitair) kader.

Validiteit van de theoretische opzet

De theoretische opzet van de IAP-M werd gevalideerd op drie aspecten: kennis, werkvolgorde en informatieverwerking. De begrippen uit het referentiemodel en de IAP-M methoden, die uit de case studies en aanvullende literatuur volgen, bevatten geen kritische interne tegenstellingen. De werkvolgorde heeft betrekking op achtereenvolgende uitvoering van de methoden en instrumenten in 5 stappen.



Figuur 4. Kwadrant-gebaseerde validatie van IAP-M

Echter, de procedure geeft niet wanneer een set van iteraties moet worden gestopt: er dient een afrondingscriterium te worden toegevoegd aan de IAP-M procedure. Tot slot, met betrekking tot de verwerking van informatie: de informatiestroom van de onderliggende theorie is in lijn met de in dit project ontwikkelde software-architectuur en de van de twee I/O-Pad implementaties.

Empirische validatie door middel van demonstrators

Ter verkrijging van empirische bevindingen heb ik een verzameling van experimentele IAP systemen ontwikkeld en getest met studententeams. Deze systemen, demonstrators genaamd, vertegenwoordigen elk een toepassing van IAP-M en komen overeen met een deelverzameling van de IAP-M procedure, methoden en instrumenten. De demonstrators omvatten een CNC-gefreest schuim automodel op een draaitafel, een mock-up van een dictafoon, een opstelling waarin schets-gebaseerde modellen werden CNC-gefreest, een omvangrijk kleimodel van een auto (met 3D scanning gedigitaliseerd), en een maquette van het interieur van een nachtclub. Bij elke demonstrator werd het resulterende systeem geëvalueerd door potentiële eindgebruikers over de werking, en werd er gekeken naar de kwaliteit van het prototype, de mate van betrokkenheid tijdens een (fictieve) ontwerpsituatie, en de mogelijkheid om het ontwerp fouten op te lossen. In totaal waren er 36 senior ontwerp-studenten en -docenten betrokken bij de tests. Zo bleek in een vergelijking tussen een scherm-gebaseerd en augmented prototype dat de laatstgenoemde beter was om zowel fysieke en cognitieve ergonomie van een ontwerpvoorstel te kunnen beoordelen. Een andere demonstrator, geselecteerd als 'referentie casus', lokte actieve discussie uit tussen de participanten, terwijl de men ingebouwde ontwerpfouten onmiddellijk vond wanneer ze met nieuwe ontwerpvoorstellen geconfronteerd werden.

Tevens werd per ontwikkeltraject gekeken naar de inspanning om de IAP-M toe te passen

De tijd om fysieke en virtuele modellen te maken was min of meer gelijk aan gelijk aan de traditionele modelbouw voor desbetreffende ontwerpsituaties. De demonstrators boden slechts een subset van IAP-M functies (bijvoorbeeld geen automatische kalibratie). Hier gold dat er een afweging moest worden gemaakt tussen het bereiken van de gewenste interactiviteit en de tijd die nodig is om het IAP-M instrument volledig te implementeren

Theoretische haalbaar resultaat

Het empirisch bewijs voor de geldigheid van de IAP-M is beperkt tot laboratorium evaluaties middels de demonstrators. Echter, in combinatie met de opkomst van commerciële AP oplossingen voor design reviews, is er voldoende materiaal om te redeneren over het nut van de IAP-M. Tijdens de test van de referentie casus was er actieve discussie en groot fout oplossend vermogen van de proefpersonen door de IAP-M. De variatie in instrumentatie van de demonstrators illustreert naast de twee bovengenoemde implementaties van de I/O-Pad de veelzijdigheid van IAP-M. Deze instrumentatie kan eenvoudig worden uitgebreid tot andere van AP-display types, zoals head-mounted displays en handheld computers.

Conclusies en aanbevelingen

AR wordt toegepast in een breed scala van domeinen, van de kunsten tot forensische wetenschappen, van medische diagnostiek tot assemblage handleidingen. Er is echter weinig bekend over het nut van AR binnen de ontwerpdisciplines. Doel van dit project was om een methodiek te ontwikkelen voor de interactieve inzet van augmented prototyping. De belangrijkste bijdragen van dit proefschrift zijn:

- AP ondersteunt als medium voor ontwerpvoorstellen zowel sociale als een fysieke interactie.
- Ontwerpfouten kunnen worden gevonden in de vroege conceptfase door ontwerpvoorstellen te kunnen beoordelen op zowel fysieke als cognitieve ergonomie.
- Een ontwerpmethodiek, genaamd Interactieve Augmented Prototyping (IAP-M), die AP gebruikt ter ondersteuning van design reviews.
- Het concept van de I/O-Pad, een gepatenteerde draagbare projectie en opnamesysteem om gedeeld begrip tijdens design reviews te verbeteren.
- Het gebruik van hints, welke kunnen worden ingezet om empirische bevindingen uit de ontwerppraktijk om te zetten naar nieuwe ontwerpondersteuning, door het identificeren van knelpunten en best practices.

Er zijn echter nog steeds onopgeloste kwesties met betrekking tot het ontwerp ondersteunen scenario's en technologieën die verder onderzoek verdienen. Meer veldonderzoek is noodzakelijk om IAP-M te beoordelen in verschillende ontwerp-domeinen. Daarnaast dienen plaatsbepaling-technieken nog verder worden verfijnd en aangepast aan 3D printing.

Resultaten

In de looptijd van tien jaar is de kennis uit dit project gepubliceerd in 9 conference papers, 10 tijdschrift artikelen, 3 hoofdstukken uit wetenschappelijke boeken, en een internationaal patent. Het oorspronkelijke WSCG artikel uit 2003 werd meer dan 60 keer geciteerd, terwijl de bijbehorende YouTube-video meer dan 14.500 keer werd bekeken. De demonstrators en I/O-Pad implementaties werden aan publiek gepresenteerd op diverse exposities in heel Nederland, waaronder tijdens de Dutch Design Week met meer dan 20.000 inwoners (Eindhoven, 2006).

Op basis van het I/O-Pad octrooi is in 2009 het bedrijf Delight Interactive Solutions opgericht door oud-TU Delft studenten. Dit bedrijf levert producten en diensten op gebied van Augmented Reality en interactieve ontwerpvisualisatie, o.a. bij BMW, TNO en het Delft Science Centre..



About the author

Jouke Verlinden (1969) received his M.Sc cum laude in computer science at Delft (1993). He graduated on exploring story telling in virtual reality at the Graphics Visualization, and Usability Center with prof. Jay Bolter and prof. Jim Foley at the Georgia Institute of Technology, Atlanta. He worked in industry as project manager and senior interaction designer for 7 years before returning to academia.

In 2000 he was appointed assistant professor at the section of Computer Aided Design Engineering at the Faculty of Industrial Design Engineering, Delft University of Technology. The ambition was to develop new, accessible design media for industrial designers that respect current practice. This resulted in over 70 scientific publications. Furthermore, Jouke is co-founder of a full semester curriculum, entitled *minor on Advanced Prototyping*. With over 240 alumni and 15 articles in 5 years, it is one of the undergraduate courses that demonstrate how research and education can be combined in a multidisciplinary setting.

Follow-ups on his PhD research on augmented prototyping evolved to a larger field where bits and atoms meet, entitled *Augmented Matter in Context*. Current topics include 3D printing, robotics, and the emancipation of stakeholders. This field has found successful applications in cultural heritage, performing arts, advanced manufacturing and sports. Furthermore, it resulted in a number of patents and spin-off companies, while these projects are supported by various national and international grants. In this field, he is often consulted by Dutch media and governmental agencies/ministries.

Propositions

Accompanying the thesis:

“Developing an Interactive Augmented Prototyping Methodology to Support Design Reviews”

1. Using prototypes during design reviews supports engaged discussion and discovery/learning that eventually minimises delay in product development, improves product quality, and increases stakeholder’s trust (this thesis).
2. Augmented reality techniques are insufficient to enhance the design process (this thesis).
3. Current practice of design studios relies on analog approaches, but it has to be adapted with regards to using IAP-M (this thesis).
4. An iPad is a truly useful design tool if it includes a tracking system and a projector (EU & US patent PCT/NL2008/050515).
5. Interactive augmented prototyping will play an important role in bringing the past to the present* and designing our future
6. Exhibitions and YouTube should be obligatory media of science communication.
7. There should be a bibliometric indicator that counts the citations of patents in patents.
8. Academic design curricula should include research towards improving prototyping technologies.
9. The best place to make a phone call on a train is the silence zone (“stilte coupe”).

These propositions are regarded as opposable and defensible, and have been approved as such by the supervisor prof. dr. I. Horváth.

*M. Roozenburg “Smart Replicas — Bringing Heritage Back To Life” Augmented Reality, Art and Technology, 2012, vol 1(2), pp 28-31.)

STELLINGEN

Behorende bij het proefschrift:

“Ontwikkeling van een Interactieve Augmented Prototyping Methodiek ter ondersteuning van ontwerpbesprekingen”

Stellingen

1. Tijdens ontwerpbesprekingen zorgt het gebruik van fysieke modellen voor een ruimtelijk gefundeerde discussie en het vinden van fouten/oplossingen. Dit leidt uiteindelijk tot het verkleinen van de kans op vertragingen tijdens het product ontwikkelproces, betere producten, en meer vertrouwen van de belanghebbenden (dit proefschrift).
2. Augmented reality technieken bieden te weinig aanknopingspunten om het productontwikkelproces te verbeteren (dit proefschrift)
3. De huidige ontwerptraditie is te analoog en dient te worden aangepast om IAP-M te kunnen toepassen (dit proefschrift).
4. De iPad is een goed ontwerp middel als deze wordt uitgerust met een adequaat 3D plaatsbepalingssysteem en een beamer (EU & US patent PCT/NL2008/050515).
5. Interactieve augmented prototyping zal een belangrijke rol spelen in het tot leven brengen van het verleden* en het vormgeven van onze toekomst.
6. Tentoonstellingen en Youtube moeten verplichte communicatiekanalen zijn voor de wetenschap.
7. Er ontbreekt een bibliometrische index die citaten van octrooien naar octrooien telt.
8. Onderzoek naar het verbeteren van prototyping zou een vast onderdeel moeten zijn in academische ontwerpopleidingen.
9. De beste plaats om in de trein te telefoneren is de stille coupé.

Deze stellingen worden opponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotor prof. dr. I. Horváth.

*M. Roozenburg “Smart Replicas — Bringing Heritage Back To Life” Augmented Reality, Art and Technology, 2012, vol 1(2), pp 28-31.)



Developing an **Interactive Augmented Prototyping Methodology** to Support Design Reviews

PHYSICAL PROTOTYPES and scale models play an important role in engineering design processes, especially in the field of industrial design. Such models are typically used to explore and discuss design concepts in various stages, from initial idea generation to manufacturing.

OVER THE LAST DECADE, augmented reality technologies have been developed to assist prototyping in design. We can employ head-mounted displays, projectors, or handheld video-mixing solutions, as well as 3D printing to “enrich” physical models with features, materials, and behaviour.

The outcome of this project is a design support methodology, entitled **INTERACTIVE AUGMENTED PROTOTYPING METHODOLOGY (IAP-M)**, which utilizes augmented reality as an instrument to support design reviews. The instrument, a projection and recording unit, was patented and licensed to a techno starter for further valorisation. Although the instrumentation is central in this study, it requires procedures and methods to be applied in design processes.

The insights that lead to IAP-M originated from empirical studies and design inclusive research, and were implemented in a collection of demonstrators.

Jouke Verlinden