3D Projection on Physical Objects: Design Insights from Five Real Life Cases

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ABSTRACT
3D projection on physical objects is a particular kind of Augmented Reality that augments a physical object by projecting digital content directly onto it, rather than by using a mediating device, such as a mobile phone or a head-mounted display. In this paper, we present five cases in which we have developed installations that employ 3D projection on physical objects. The installations have been developed in collaboration with external partners and have been put into use in real-life settings such as museums, exhibitions and interaction design laboratories. On the basis of these cases, we present and discuss three central design insights concerning new potentials for well-known 3D effects, dynamics between digital world and physical world, and relations between object, content and context.

Author Keywords
Design, projection, 3D, cultural heritage, exhibitions, architecture, visual effects, Augmented Reality.

ACM Classification Keywords
H.5.1 Multimedia Information Systems.

General Terms
Design.

INTRODUCTION
3D projection on physical objects is a nascent field of study, and engineers, designers, artists, and researchers have just started to explore the potential and characteristics of this type of technology. 3D projection may be construed as an evolutionary rather than a revolutionary technology, in that it is a further development and combination of existing technologies. Many of the uses of 3D projection borrow from more well-established forms of visual media, sometimes employing specific means of expression, sometimes tweaking them slightly and at yet other times, using juxtapositions of traditional visual expressions and 3D projection to create spectacular effects. As stated by Manovich: 'We will see that many of the principles [of new media] are not unique to new media, but can be found in older media as well.' [10:p50].

Broadly speaking, 3D projection on physical objects may be defined as a type of mixed reality [12], which refers to systems or installations that blend physical elements with digital, virtual elements. Milgram and Kishino [12] present a reality/virtuality continuum, with real environment at one end of the spectrum, on through augmented reality, augmented virtuality, and, eventually, virtual environment. With reference to this continuum, 3D projection is best defined as Augmented Reality (AR), since it consists of digital information that is projected onto physico-spatial structures. As such, 3D projection is related to an increasingly widespread type of visualization technology, namely AR that captures images of the physical environment and represents it, with added layers of data, on displays such as mobile phone screens [5]. This is used, for instance, by route-finding and locative services that combine video feeds captured by a mobile phone camera with information about nearby sites, by employing GPS data from the phone [15]. These systems can be construed as a further development of principles explored in see-through head-mounted AR displays [2].

3D projection on physical objects is distinct from these types of systems, since they display the virtual layer on top of the actual physical surroundings, and not on a representation thereof. As such, it falls within the category of spatial AR [13]. Since 3D projections rely on precise mapping of the physical spaces onto which they are projected – as opposed to 2D projections, which typically can be projected onto most flat surfaces – using Manovich's terminology [11], these installations may also be described as *augmented spaces*, which are defined as involving the embedding or overlay of layers of data onto the environment. In this respect, 3D projection on physical objects shares a number of traits with CAVE installations where the user is surrounded by projection surfaces [6]. This eliminates the need for mediating devices and places the spectator within the augmented environment. However, CAVE installations are closed, highly specialized stand-alone systems that use flat surfaces for projection, whereas the installations we introduce in this paper are positioned in other contexts (e.g. exhibition spaces) and use irregular projection surfaces that have been modeled in digital 3D.

In this respect, some 3D projections are also related to new kinds of displays integrated into the physical environment, such as media façades [7] and urban screens [17], insofar as 3D projections are sometimes employed to augment or transform the built environment.

In this paper, we present five cases in which we have developed installations that employ 3D projection on physical objects. These cases concern installations developed in relation to *The Mejlby Stone, Holger the Dane,* the *Architectons, Loop City* and *Expo 2010*. The installations are the outcome of three years of ongoing research and development into the field of spatial AR and 3D projection. The installations have been developed in collaboration with external partners and have been put into use in real-life settings such as museums, exhibitions and interaction design studios. On the basis of these cases, we discuss three central design insights concerning *new potentials for well-known 3D effects*, *dynamics between digital world and physical world*, and *relations between object, content and context*. The primary contributions of this paper are thus 1) the cases that exemplify how 3D projection can be used for various purposes and in various domains and 2) the design insights, which are a condensation of our findings from working with the cases.

RELATED WORK

During the past two decades, several research teams have been investigating 3D projections on physical objects from a technical perspective, in contrast to our interest in using the technology to support engaged communication. At an early stage, Raskar and his co-researchers [14] explored the use of projectors to graphically animate physical objects, and address technical issues such as the projection in relation to the physical object, intensity correction, and edge blending. In a related paper [13] Bandyopadhyay, Raskar, and Fuchs present an AR system, enabling the interactive painting and texturing of three-dimensional objects, and Lee et al. [9] have developed a setup that enables projection on a two-dimensional, handheld surface, which can be can be moved in physical, three-dimensional space. In continuation of the above-mentioned contributions, Bimber and Raskar [5] provides a thorough overview of the general principles and techniques of spatial AR.

Beyond such explorations of 3D projection, which primarily focus on the technical aspects of the technology, the most prominent examples of 3D projection are, arguably, the works of Pablo Valbuena. His series of installations entitled *Augmented Sculptures* [18] has been displayed at venues such as Ars Electronica, and has also attracted many views on Internet video services. Valbuena's installations are typically composed of very angular and clear-cut geometrical shapes that are camera tracked, and in conjunction with which 3D technology is used to create the illusion of light sources moving across the faces of the installations. There are also a growing number of installations that employ 3D projection to mimic the third dimension on a 2D surface. *555 Kubik* [16] is an example of such an installation. Projected onto the façade of Hamburg Kunsthalle, the installation employs visuals that in various ways create a sense of depth: the façade's tiles appear to move in and out of the façade, the interior of the building is revealed in perspective, and so forth. AntiVJ's installation, *Enghien* [1], employs similar forms of expression, but takes further steps to both underline and break down the illusion. Projected onto a building façade, the installation first mimics moving light sources to emphasize the 3D effect; then, starts copying and apparently moving the physical, architectural features, such as windows and balconies; finally, it deconstructs and eventually explodes these features of the building. Several other projects have used projections on buildings, but without fusing the projections and the forms of the buildings, for instance, *L.A.S.E.R. Tag* [8] and *The Climate Wall* [7]. These installations are either developed to explore technological potentials or for artistic reason. The artistically oriented installations primarily explore new means of expression, and may be defined as staged events for audiences. In relation to these installations, the work we present in this paper may be characterized as more functionally oriented, in the sense that the five systems we describe have been developed to support communication (in the cases of The Mejlby Stone, Holger the Dane, 3XN, and the Loop City project) or design practices (in the case of the Expo project). Furthermore, several of the systems also incorporate interactive elements that, to some extent, allow users to influence or control the content of the projections.

INSTALLATIONS

During the past three years, our research lab has developed a series of installations that explore the potential of projecting digital content on physical objects. The installations have been developed as parts of full-scale experimental projects, in collaboration with external partners, including museums and architectural firms.

In the main part of this paper we combine and condense the insights obtained from working with these installations, in order to establish a general understanding of the challenges and potentials of designing 3D projection on physical objects. In the following sections, we present five of these cases, which are also presented in the short video that accompanies this paper. The first example, The Mejlby Stone installation, in fact used 2D projection on a physical rune stone. We have chosen to include this installation because it was our first full-scale project using projection on physical objects and the findings from the project have informed the subsequent four installations and encouraged our use of 3D projection.

The installations are presented on the video accompanying this paper, throughout the paper we will refer to specific instances in the video in the following manner (video 2.35).

The Mejlby Stone installation

The Mejlby Stone installation is an augmentation of a Danish rune stone [4]. Rune stones are part of the cultural heritage from the Viking age in Scandinavia. More than 2300 stones tell of life in Scandinavia during the Viking Age period (AD 950–1050), through images and writing in the runic alphabet, which can only be read or understood by specialists. At museums, it is common practice to use exhibition labels to communicate the story told by the rune stones, but in the case of The Mejlby Stone, we have added a digital layer to the stone in the form of a projection, thereby fusing the physical artefact and the communication of information about the stone.

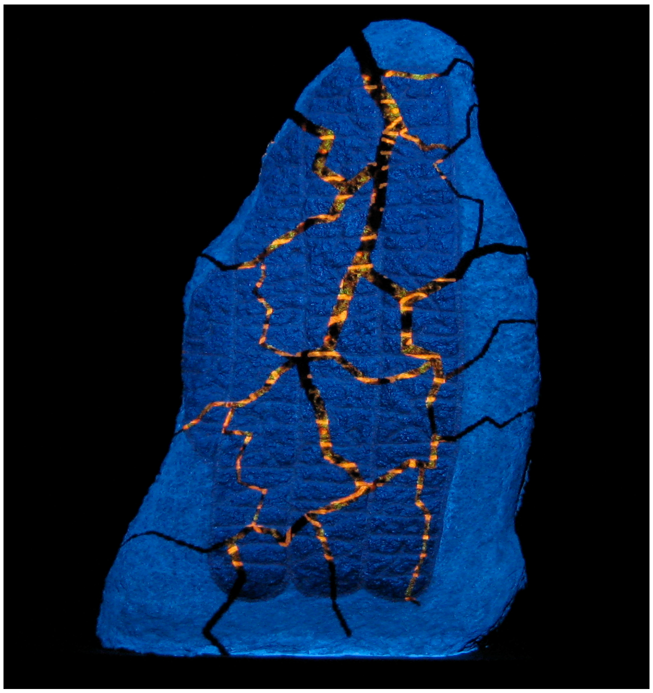

Figure 1. The Mejlby Stone Installation.

As reported in more detail in [4], the projection consists of five different elements presented cyclically: 1) when no visitors are near The Mejlby Stone the runes are lit up in red for about two seconds, at twenty-second intervals; 2) when someone passes within a few metres of the stone an animation appears on the stone. The animation tells the story of the events that led to the erection of The Mejlby Stone; 3) next the runes appearing on the stone as they are carved; 4) when all the runes are carved into the stone the passage of time is illustrated by visually exposing the stone to different kinds of weather. Rainstorms, frost, and lightning progressively efface the runes from the surface of the stone, see Figure 1; 5) in the final element, the runes first reappear on the stone in strong neon colours, then appear to tumble to the floor in front of the stone. Now the audience is supposed to kick the runes back onto the stone. When all the runes are back on the stone, they transform into Roman characters, legible to a present-day audience. The inscription reads: 'Åne erected this stone for his son Eskil who found death with Thore in Øresund'.

Since early 2009, The Mejlby Stone installation has been part of the exhibition at Randers Cultural Historical Museum in Randers, Denmark. Through a study in terms of interviews and observations we have investigated the effect on museum visitors. First of all, 34% of the recorded visitors spent between five and ten minutes in front of the stone. This indicates that the installation is capable of attracting attention and sustaining awareness of itself. We have observed extensive person-to-person interaction in terms of adults explain to children what happened in the story and in some instances people talk about subjects such as death and grief. Our study seems to suggest that the shift from passive watcher to interactively kicking the runes is difficult to decode. Moreover unintended use also emerged in the form of girls bringing themselves into the projection so that the projection falls directly on their bodies [4].

Holger The Dane installation

Holger The Dane is a mythical Danish figure, a statue of whom is found in the Castle of Kronborg, Denmark. Kronborg, also known from Shakespeare's *Hamlet*, is a renaissance castle close to 400 years old, and 100 years ago a statue of Holger The Dane was placed in one of the casemates in the cellar of Kronborg, see Figure 2. According to one of the myths about Holger The Dane, he will awaken and defend the country when an enemy from without threatens the kingdom of Denmark.

When visitors approach the statue the embers behind the feet of Holger The Dane gloves stronger and his life is told in terms of narrative segments. One of six fairies, which according to the legend gave special power to Holger The Dane, appears floated in front of the statue. The illusion is supported by a shadow of the fairy on the sculpture and by magic dust lighting up a part of the sculpture. Among the myths, we also read that he was held captive by *Karl den Store* (English: Charlemagne), that Holger The Dane is lawless, that fairies granted him magical powers, and that he fought the giant Burmand. The myths are visualized by abstract references to the myths: for instance, Holger The Dane's fight against Burmand is visualized by a shadow slowly covering the statue, to illustrate Burmand approaching Holger The Dane, followed by sounds illustrating the fight between the two, then a fairy arrives, giving Holger The Dane extra strength, enabling him to split the shadow, after which blood appears to sprinkle the shield and one of the feet's of the statue. In a final sequence Holger The Dane seems to have falling asleep indicated by the upper part of his body slowly moving in the rhythm of his breathing.

The statue is a very popular photographic subject and when a flash photographing is detected the visual style of the projection is changed.

Since October 2010 the installation has been in operation at the Castle of Kronborg and an initial study supplemented by interviews of visitors indicate that the installation creates an engaging experience. Most visitors who arrive at the room where the status is placed view the entire sequence, but only few notices the effect of flash photographing. Visitors' spontaneous exclamations indicate that visual effects make sense for them, for instance "now he is locked up" when grilles are projected on the statue (video 2.25). In particular the effect of splashing blood and the sleeping sequence triggers reaction from visitors. The interviews reveals that people are quit split when it comes to the overall concept and visual style: some find the installation a bit little too much Disney Worldish whereas others appreciated the mood and atmosphere created by the installation and also pointed out that the installation is powerful way of making younger generations interested in the myth of Holger the Dane. The manager of the Castle and the person in charge of cultural heritage communication were initially in the design process in favor of a more direct retelling of the myths but when seeing the final result found the atmosphere of the installation quit amazing.

Figure 2. The Holger the Dane Installation.

Loop City

Loop City is an installation presenting a proposed plan for a large-scale urban project that spans Copenhagen and Southern Sweden. The installation uses three projectors to present visuals on two walls set at a 90-degree angle in the corner of an exhibition room. Additionally, the installation presents visuals on the floor and on a solid elongated bridge volume that extends into the room from one of the walls.

The presentation is composed of three parts. The first part uses the two rear walls as a canvas for an introduction to the urban planning challenges, and the solution proposed by the architectural firm BIG. This part employs traditional 2D visuals, such as animated maps, diagrams, and text. At the end of this part, the visuals outline a future metro line, which suddenly extends onto a triangle that was previously in the dark. This initiates the second part, which employs 3D visuals centered around the bridge volume. Now, the walls serve as a backdrop, with additional information presented in 2D, but attention centers around a bridge volume, which displays both diagrams and specific proposals for metro lines. The floor is also brought into play, for instance when tiny images of people exit the metro lines and pour into the city, while buildings rise around them, see Figure 3. When these more specific instantiations have been visualized, the third part begins. This part returns to a 2D presentation, but now also incorporates the floor, to show a roller-coaster-inspired ride through Copenhagen on the new public transportation line.

Figure 3. The Loop City Installation.

Loop City was from August to November of 2010 part of the Danish Pavilion at the 2010 Venice Architectural Biennale in Italy. Through a study consisting of on-location observations and interview we investigated how the visitors reacted and responded to the installation. Since the installation was a kind of movie showed in an on-going cycle most of the visitors encountered the installation in the middle of the storyline. Out of 131 people 13% saw the movie from when they came in and until the narrative ended. 24% of the visitors saw the movie from when they entered the room and then saw it again from the beginning of the narrative till the point in the storyline, they saw when they arrived. 31% of the visitors entered the room and left immediately after only a short glance. Several of the visitors found it a very good idea to spatially communicate the spatial topic of urban planning but others did not pay particular attention to the 3D effects as such.

The Architecton installations

The Architectons are two digitally augmented sculptures that represent iconic features and façade elements of prominent buildings designed by 3XN Architects. We collaborated with a 3XN project team to develop 3D projections for the Architectons, which represented the headquarters of Saxo Bank, and the domicile of the Horten law firm. Both Architectons represented the buildings' distinct façades, which are composed of triangular and parallelogram-shaped elements assembled in a 3D structure, see Figure 4.

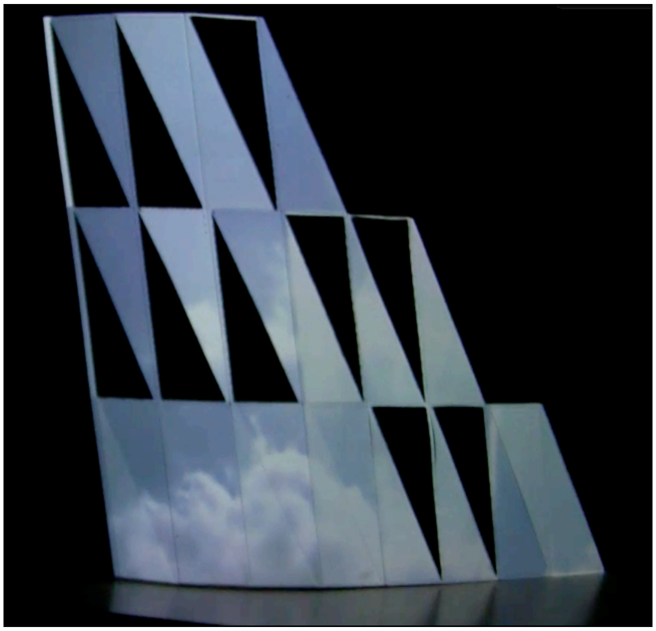

Figure 4. Scale model (1:4) of The Saxo Bank installation.

The Architectons were both approximately six meters wide, three meters tall and one meter deep. The two Architectons had different content projected onto them, but both had interactive zones in which the content would switch between three different loops, depending on viewer distance. The content projected on the first Architecton, that of the Horten firm, employed shifting positions of light sources, in order to emphasize the particular way in which elements of the façade appear to be either flat or protruding at various times of day, depending on the positions of the sun and the viewer. The content of the second Architecton, that of the Saxo Bank, emulated the context of the bank's headquarters, which has a glass façade and is positioned in the open; for these reasons, it often reflects the sky, see Figure 4. The three interaction zones therefore showed clouds, first moving across the sky in black and white, then in colour, and finally, to those standing in the innermost zone, the reflected clouds were supplemented by the reflection of the sun moving across the mirrored façade.

From February to May 2010, the Architectons were part of an exhibition at the Danish Architecture Center, entitled *Mind Your Behaviour*. The exhibition was composed of wall-mounted posters and scale models of buildings, as well as five Architectons, of which we worked with augmenting the two mentioned above. Our studies of the two Architectons in use both during the hectic launch event and on subsequent occasions, combined with feedback from the architects, revealed that the 3D visuals were only vaguely perceived by users, and consequently they did not explore the interaction zones as intended. In large part, we consider this to be a result of a late decision to increase the general lighting level in the exhibition area. Since we relied on projectors, this caused the visuals to fade in comparison to other elements of the installation. We thus consider the Architectons case to be the least succesful in regards in to using 3D projection to augment the experience and perception of the physical objects. A central finding that sprang from this case is therefore that designers must ensure that lighting conditions are adequate if 3D projection installations are to be effective.

The Danish Pavilion at Expo 2010

The Danish Pavilion at Expo 2010 (see Figure 5) is part of the world exhibition in Shanghai in 2010, during the period from 1 May to 31 October.

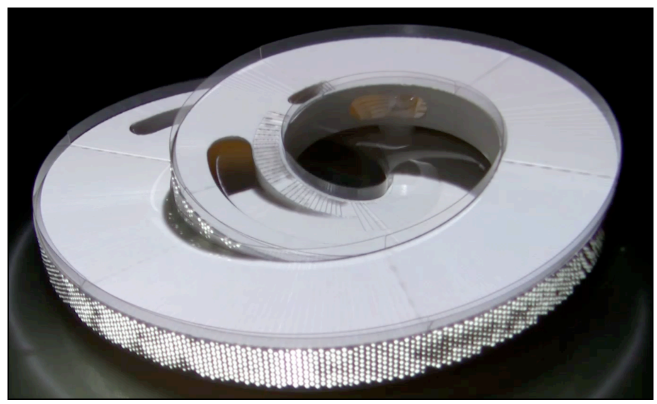

Figure 5. Scale model (1:100) of Expo Pavilion.

Its organic architecture was created by Danish architects at BIG, and our research laboratory participated in the design and implementation of the pavilion's media façade. The building is double-spiral, steel construction with an almost three-hundred-metre-long façade, see Figure 5.

The façade itself is perforated by 3600 holes of varying sizes, each containing a semi-translucent tube. With the addition of LED lighting fixtures behind each tube, the

	Rune stone	Holger the Dane	Architectons	Expo 2010	Loop City
Domain	Cultural heritage	Cultural heritage	Architecture	Design process	Urban planning
Object	Archaeological artefact	Statue	Model of façade element	Scale model of building	Walls, floor and bridge volume
Size (l,w,h) cm	80x50x170	110x110x190	600x100x300	60x60x40	340x340x200
Object structure	Organic	Organic	Complex, Planar	Complex, Non-planar	Simple geometry
Content	Animation Visual effects Narrative sections	Visual effect Narrative sections	Simulation of façade appearance	Simulation of façade appearance	Animation Text and graphics Narrative sections
Context	Museum exhibition	Castle casemates	Architectural exhibition	Design laboratory	Architectural exhibition
Interaction	Limited	Limited	Limited	Complex	None
Period	Permanent	Work in progress	3 months	4 months	2 months

Table 1. Overview of the installations.

façade becomes a large, low-resolution display, with tube-like pixels in an elongated, curved configuration. Because each pixel is a tube, they are less visible when viewed from the front than from an angle. In order to develop and test potential content for such a non-standard display integrated into a building, several custom-made design tools were developed. One such tool was a white, 1:100 scale model, combined with a projection setup, which enabled the visualization of potential content directly on the physical model.

Our evaluation of the installation is based on interviews with the interaction designers who used it during the design process. The installation was used by the design team on a regular basis - at least once a week, and often more frequently - for six months during the process. It was first intended to function as a simulation of how the final façade would appear; however, it turned out that the renderings of the interactive façade elements on the model were somewhat imprecise compared to how actual façade LEDs appeared in real life. For this reason, subsequent alterations had to be made on the Expo site. In spite of this, the installation turned out to be a useful instrument for the designers in several ways: first, it presented a way of visualising content on the very complex building structure which was not otherwise possible; second, it offered an straightforward way of understanding the coupling of the physical space with interactive content; third, it presented the designers with a tool for making on-the-spot alterations and experiments and see the immediate outcome; and fourth, it served as a pre-eminent boundary object for communicating with outside partners in the project.

Summary

Table 1 provides a structured overview of the five installations. The installations are diverse, both with regards to the domains for which they have been designed, with regards to their content, with regards to the size and complexity of the object onto which the content is projected, and with regards to the particular use situation that the installations affect.

ALIGNING DIGITAL MODELS AND PHYSICAL OBJECTS

Before we present and discuss our central design findings, we will give a brief overview of our strategies concerning the alignment of digital models and physical objects. In four of the five installations we had specific physical objects as our starting points for the installations, and in two of these four installations, The Mejlby Stone and Holger the Dane, we projected directly on the original object. In the case of the Architectons, we projected on full-scale models of fragments of two existing buildings, and in the case of The Expo Pavilion, we projected on a 1:6 scale model of a building under construction. The Loop City installation is different, in that the projection space is the corner of an exhibition room, together with a section of a bridge volume.

For Holger the Dane, no digital model was readily available, so a scanning company assisted us in creating a digital model, which was subsequently used to create a 3D print in a scale of 1:4, enabling us to develop and test the installation without going to the castle. In all cases except that of Holger the Dane, we used more than one projector, creating a need for handling edge blending.

In the case of the Architectons, two existing buildings were the starting points for the process. First, a digital 3D model of a section of the façade was created, and from this, a physical model of the façade element was created. The content to be projected was produced using the 3D imaging software, and projecting the content on the physical model is simple in theory, but not in practice; several circumstances pose challenges, here. First, the physical model does not perfectly match the digital model, and the lenses in projectors are not perfect lenses, which causes distortion of the image; even small inaccuracies can be detrimental to the final result, since just a few pixels that 'spill over' their designated positions may be very obvious, depending on projection and viewing angles. To enable the match-up of the digital and the physical models, two custom-made tools were developed. The automatic calibration tool applies a heuristic algorithm that tweaks the position, rotation, field of view, and aspect ratio of the virtual camera, in order to compensate for the corresponding parameters of the projector, as well as discrepancies between the digital and physical models (video 3.26). The calibration process is initiated by informing the software tool of the positions of eight to ten predefined points on the physical model, coordinating and associating each of these points with the corresponding points in the digital models. Through a process that may last from 30 minutes to several hours, depending on the mismatch between the digital 3D model and the physical model, the camera's view of the digital model is tweaked, to compensate for the differences between the parameters of the virtual camera and those of the projector.

In addition to our automatic calibration tool, our lab has developed an interactive tool which works by selecting a portion of the physical area on the model where the projection of the digital 3D model does not match the physical model, then stretching the digital model to make the projection match the physical model (video 3.48).

The necessary calibration very much depends on the quality and complexity of the physical model. Both of the Architectons were made of cardboard glued together in a fairly complex and somewhat shaky structure, with some of the elements only connected to the rest of the model by a single edge, making the model vulnerable to physical stress. The Expo 2010 model, despite its organic form, was much more simple and physically stable, but both in this case and in that of the very plain model for the Biennale 2010, calibration is needed, when setting up the installation.

DESIGN INSIGHTS

In the following, we will present and discuss central findings from our work in the five cases with a particular emphasis on issues that may be of relevance to designers who wish to employ 3D spatial AR. Our presentation of these insights are based on our analysis of the cases in conjunction. Generally speaking, the use of 3D projection in spatial AR opens up for a range of effects and illusions that designers can make use of. Some of the effects are generic and may be employed in most spatial AR setups that make use of 3D, for example, variable light sources, particle systems and the introduction of virtual elements in the projection space. Other effects are highly context-specific, drawing on the physical properties of the place and projection surface, as well as on the ways in which people normally perceive the space that is being augmented. We will not offer a complete overview of these effects, but instead focus on three themes that we find particularly salient for the future design of 3D projection on physical objects: new potentials for well-known 3D effects, dynamics between digital world and physical world, and the relation between object, content and context.

New potentials for well-known 3D effects

In the five cases, we have to a large extent made use of standard visual effects that are part of existing 3D software (we have primarily used 3D Studio Max, but most the following techniques are available in other applications). Our findings from the five cases indicate that a number of these existing 3D techniques offer designers relatively straightforward means of creating intriguing effects and illusions when used in 3D projection of physical objects.

One of the most basic techniques afforded in 3D software is to establish the perception of depth by creating and moving light sources in the world of a digital model. This effect can be used in many installations involving 3D spatial AR and can be used to achieve a variety of illusions. For example, in the Architecton project, this effect was used to simulate the sun's movement across the sky, within a time frame of seconds; this caused the geometrical shapes of the Architectons to stand out, and visualized the way in which the buildings represented appeared at different times of day (video 4.00). Similarly, one of the reasons for employing spatial AR in the Expo 2010 project was that it allowed us to explore how the façade of the pavilion would appear at different times of day, as some parts of it would be in direct sunlight, and others in total shade (video 5.54). A related effect is the introduction of virtual objects casting shadow on the physical object causing them to appear in front of the physical object, like in the case of the fairies of the Holger the Dane installation (video 1.48).

Another common technique that can we have successfully worked with is the use of various particle systems, which can simulate for instance fire. Such particle systems can be placed in front of a model and create quite realistic effects, for instance in terms of reflections on the complex geometry of the physical object itself. In the Holger the Dane installation, particle effects such as fire are used extensively, for instance to animate the fairies that fly around Holger the Dane and grant him his magical powers (video 2.43).

A third technique that we have also used from 3D software is to employ various filters normally confined to the digital 3D world to create visual effects on the physical model. For instance we use the twirl filter to create he illusion that Holger the Dane is sleeping indicated by having the upper part of his body slowly moving in the rhythm of his breathing (video 3.06).

A fourth standard procedure that takes on new potentials is that of unwrapping the digital 3D model, thereby producing a digital 2D object corresponding to the surface of the digital 3D model, a process similar to that of making a 2D map of the world from a 3D globe. The 2D object may be processed in any 2D tool and wrapped back on to the 3D model. In this way, for instance, animations on the 3D model may be created, or video may be used as texture, which in turn transforms the surface of the physical object when projecting the digital model onto the physical model. In the case of the Expo model, we created custom software in order to map an elongated video feed onto the 3D models.

Although our focus here is on visual effects, we must emphasize that the use of audio can be a highly effective means for designers to achieve their intended objectives. For instance, when the runes on The Mejlby Stone are carved out, this is supplemented by the sound of a hammer striking a metal artefact on the stone (video 0.21), and when lightning illuminates the stone, peals of thunder complement the visual effects (video 1.06).

Dynamics between digital world and physical world

A second central insight from our work is that one of the most potent effects that designers can make use of is the interplay and dynamics between the digital world and the physical world.

One of the drawing powers of 3D spatial AR is that it has the potential to alter viewers' perceptions of physical structures. A visual effect that plays on this perception is that of shifting between 2D and 3D projection. In the Loop City project, we used this effect in the transition between two phases (video 4.29): the first phase, which employed traditional 2D visuals on the rear walls of the augmented space, and the second phase, which added 3D visuals to the presentation on the floor and the rectangular ramp in the centre of the space. In the first part, the floor and the bridge volume were not illuminated, and the viewer's gaze was attracted to the walls, until a red line denoting a metro line was suddenly projected onto the ramp, tracing the edges of the shape and connecting the 2D and 3D spaces (video 4.39). In this segment, the outline of the bridge is followed by projecting a series of arches on the solid bridge volume, which enables the illusion that cars can drive under the bridge through the arches and onto the floor in front of and behind the bridge volume (video 4.55). In this case, the introduction of a physical object in the augmented space (in the very simple form of the triangular bridge volume) proved highly effective. A related visual effect afforded by 3D projection is the ability to pick out and alter specific areas of a model, which can be used to demarcate or highlight designated areas of the physical model. This means that projections do not 'spill over' onto surrounding areas but can be concentrated on the physical objects or even specific parts of the object. In the case of the Architectons, which were both brought to life using two projectors, this emphasized the effect of moving light sources since this visual effect only appeared on the Architectons (video 4.00) and not on any other surfaces in the room; to the audience, this gave the perception of installations that stood out since they seemingly bended the laws of physics.

Operating in the digital 3D world also enables the designer to virtually project on specific elements of the physical model and thus pick out special areas that can augmented. In the case of Holger the Dane, this meant that we could focus the attention of the audience on the shield on the statue by isolating this in certain sequences (video 2.59). In the Expo case, we employed this effect to mimic the grid of embedded LEDs that made up parts of pavilion surface, while leaving other parts unprojected (video 5.45).

A further way of playing on the dynamics between the virtual and physical world is to emphasize the physical properties of the object(s) being augmented. This may be accomplished, for example, by tracing the outline of an object, as is done with the rectangular bridge volume in the Loop City installation (video 5.29). Often, this may be used to achieve spectacular results when combined with another visual effect, the transformation of physical properties, such as the textures or shapes of objects and surfaces. Often, these two effects are related to designers' intentions to emphasize or transform the semantic properties of objects in the augmented space. The Holger the Dane installation offers a good example of how the use of visual effects to emphasize and transform the physical properties may be combined with the emphasis or transformation of semantic properties: by the public, the Holger The Dane statue is perceived as rock solid, both literally, being cut from stone, and in terms of representing a firm and unyielding mythological warrior. In the installation, we emphasized this general perception by initially projecting an image of the statue onto the statue. The result is an increased contrast that emphasizes the physical properties, and makes it appear even more solid. However, at a later point in the unfolding narrative, we employ a visual filter on the projected image, which makes the statue appear to move and twist ever so slightly (video 3.05). This illusion plays into the viewer's perception of the physical structure, as well as the permanence of the mythological figure that now comes to life. The Mejlby Stone presents a different way of emphasizing and transforming the content of an augmented object: in several phases, the runes carved into the stone are highlighted. For example, at one point the stone is in darkness, but the runes are carved out, one by one, and appear in fiery red, underscoring the power of written language (video 0.21); later on, sets of runes are highlighted and visually transformed into translations, so they may be understood by present-day spectators .

An important point that arises in this presentation of visual effects and illusions is that spatial AR may be used to visualize both the actual and the imaginary; or in other words, it may be used to create the illusion of something real on a 'blank' object, or to create the illusion of something imaginary on an object that has specific properties. In the Expo 2010 project, our motivation was to simulate the real by approximating how the planned interactive façade would appear; in the Architecton projects, we sought to visualize in the exhibition space how the actual building façades would appear. In other cases, such as Holger the Dane and The Mejlby Stone, we employed spatial AR effects to visualize imaginary phenomena, such as the fairies that grant Holger the Dane his powers, or the story of the people mentioned on The Mejlby stone.

Relations between object, content and context

A unique challenge when designing projection-based, spatial AR is the development of content that is suited to the specific physical object or environment onto which it is projected. Therefore, this content must be developed with the complexity of the physical object in mind. Moreover, the context into which a 3D projection installation is placed is also a concern. Thus, the third central insight from our work concerns the connection and balance between object, content and context.

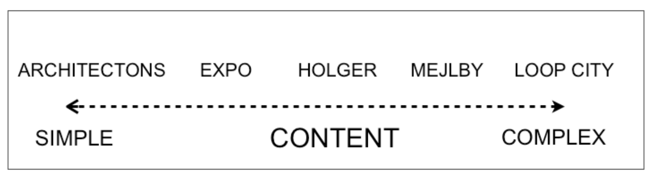

Figure 6. Complexity of content.

With regard to complexity of content, we have experimented with different communication strategies in the five projects. The projections in the Architectons case represent the simplest content of the five cases, in that they consist primarily of shifting light sources and intensities, as well as imagery of the sky's reflection on a façade. At the other end of the scale, we have very information-intensive projections, in the case of Loop City, in which both 2D and 3D graphics are used in combination with text and sound, to narrate the history of urban planning in the Copenhagen area, and envision the city's future. Between these two extremes we have Holger the Dane and The Mejlby Stone installations, which primarily employ visual effects and animation for communication, see Figure 6. In all five cases, excepting the EXPO 2010 case, the intention has been to use the installation to create awareness of the physical installation and the story behind it.

When developing content for 3D projection, designers must address the major design challenge posed by the geometrical complexity of the physical object onto which the content is to be projected. As illustrated by Figure 7 the objects may be positioned on a scale from simple to complex. Of our cases, the Loop City projection space represents the least complex physical projection surface, while The Mejlby Stone and the Holger the Dane statue are positioned at the other end of the spectrum. With regard to the relationship between content and object complexity, we have found that the very simple geometry of the Loop City projection space created an opportunity for quite complex content, whereas the organic forms and physical textures of the two cultural heritage objects (The Mejlby Stone and Holger the Dane) seemed better suited to visual effects that are less information-intensive. This is not to say that complex projection objects must rely on solely such effects – for example, animation and text have been employed with good results, in the case of The Mejlby Stone – but this information must be carefully integrated to fit the shape and expression of the object.

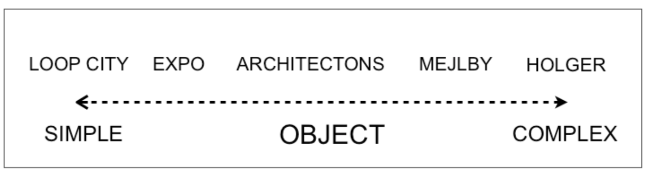

Figure 7. Complexity of projection objects.

An additional consideration in this regard is the complexity of the context of the projection space. In the five cases presented here, the complexity of the contexts has been quite diverse, as illustrated in Figure 8. The EXPO 2010 installation was set up in our laboratory, where we had full control over lighting conditions, and it was intended for use by a limited group of designers and stakeholders with the particular goal of evaluating and discussing specific design solutions. The two Architectons were parts of an architectural exhibition in which they competed for attention with other elements of the exhibition, such as back-lit, wall-mounted posters, which gave off so much light that they almost ruined the intended effect of the projections. The Loop City 2010 installation was also part of an architectural exhibition, but this space not as 'busy' as the setting of the Architectons case. The projection space for The Loop City installation was situated in the corner of a room, the entrance to the which led people quite naturally to the 'sweet spot' providing the optimal position for viewing the 3D effects. In contrast to The Mejlby Stone, which is positioned in a room that contains a number of other exhibition objects, the Holger the Dane Statue has its own confined space in the casemate of the castle, which provides a much more tranquil context for the installation.

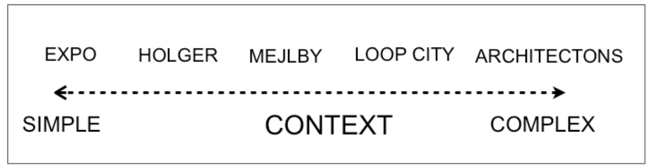

Figure 8. Complexity of context.

CONCLUSIONS AND FUTURE WORK

Recent years have seen a significant upswing in the presence of AR that layers digital information over representations of the physical environment', as smart phones and handheld devices now have sufficient processing power to support this technology [15]. Spatial AR, on the other hand, is still a nascent field for both practitioners and researchers. In the five projects discussed in this paper, we have begun to explore the potential and challenges of 3D projection within this field, through installations that have been implemented in real-life settings. In addition to general findings concerning the characteristics of 3D projection on physical objects, this approach has yielded valuable insights for the design of future systems that employ 3D projection on physical objects. We have focused in this paper on insights concerning new potentials for well-known 3D effects, dynamics between digital world and physical world, and relations between object, content and context.

In comparison to 'traditional' AR, such as that used by handheld devices, spatial AR using 3D projection presents interaction designers with unique opportunities as well as specific challenges, which are different from those encountered in AR using a mediating device like for instance a mobile phone. The most prominent advantage of using 3D projection on physical objects is, arguably, that it offers viewers an experience of immediacy and physical presence, which is different from what may be achieved with traditional AR using a screen as the mediating layer. 3D projection removes the screen as mediating layer and presents the virtual layer directly on top of the physical surroundings. This manoeuvre enables an experience of presence that is qualitatively different from screen-mediated AR, as explored in more detail by Zahorik & Jenison [19].

In addition to adding information to the physical environment, the use of various visual effects enabled by 3D projection allows the designer to alter the perception of physical structures. For this purpose, designers may employ standard visual effects that are included with 3D software, for example moving light sources and particle systems.

However, 3D projection on physical objects is also a complex process that presents the designer with a number of challenges. First, the process of developing a precise 3D model of the physical environment may be complicated, particularly when dealing with complex structures, such as the Holger the Dane statue. Second, content must be custom-developed for the specific environment; although standard effects from 3D software may be employed, other types of content must be carefully aligned with the physical environment. Third, successful implementation of 3D projection requires a large degree of control over the physical location in which the technology is employed. The projectors must be calibrated very precisely, the lighting conditions have to fall within specific parameters, and the physical environment must not be altered. This set of challenges is most likely the reason that related examples of spatial AR [1,13,14,18] are set up within controlled environments, either in lab settings or designated exhibition areas.

Given the emergent state of the field, there is a range of interesting research questions to pursue in future work. Extending the discussion of employing this technology in controlled settings, and technological explorations of how to accommodate shifting environments (e.g. continuous calibration of 3D models with moving physical objects, or calibration of light in accordance to changing light conditions in outdoor settings) might mitigate obstacles to implementation. Another topic, which we have only begun to explore, concerns which modes of interaction are particularly suitable to different types of 3D projection. In the cases we have explored, the interactive elements are limited. The EXPO 2010 case is an exception in this respect; however, the high level of customization of this installation is dependent on users being acquainted with 3D software. A related topic for future research is the exploration of which types of content are particularly suited to 3D projection. In many cases, the technology so far employed has presented relatively abstract visual imagery [1,18] or generic effects [14]. In cases such as The Mejlby Stone and Loop City, we have begun to explore more informative types of content; however, these are initial efforts that require further exploration.

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