Adaptive Substrate for Enhanced Spatial Augmented Reality Contrast and Resolution

Markus Broecker* Ross T. Smith† Bruce H. Thomas‡

Wearable Computer Lab
University of South Australia

Abstract

This paper presents the concept of combining two display technologies to enhance graphics effects in spatial augmented reality environments. The appearance of the projected light images and text are enhanced by using an ePaper display as the substrate. The ePaper display employed does not emit light but provides a high resolution greyscale display surface that can dynamically change the appearance of the projected light pixels. We demonstrate graphics techniques that leverage this novel approach to provide an improved spatial augmented reality appearance. Our results are an improved black level that results in greater contrast and several image and text enhancement methods.

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

1 Introduction

This paper explores the concept of enhancing the displayed appearance of Spatial Augmented Reality (SAR) graphics by combining two display technologies, a digital projector and an ePaper[1] display. Our technique enhances both the resolution and the contrast ratio of projected objects. Using this method, we have explored a range of techniques such as image enhancement, text enhancement and texture effects that leverage both display technologies working in synergy to provide an optimized appearance.

Augmented Reality (AR) systems commonly employ hand-held displays or head-mounted displays with optical or video see through technologies to present computer generated graphics. SAR employs projected light to present computer graphics that directly illuminate physical objects to enhance their appearance [7]. To achieve this, a simple substrate is constructed with the desired shape, for example a small white rectangular box for a mobile phone mock-up, with the appearance and interactive functionality provided by the SAR system.

There are two limitations with this approach that can be improved with a composite display. Firstly the black appearance is limited to the performance of the projector and the underlying substrate. With projection technologies, black is achieved with the absence of projected light and the colour of the underlying substrate. Achieving a "true black" representation using projected light is impossible with a white substrate. Secondly, the resolution of SAR objects is limited to the number of pixels provided by the projector. Both these aspects are limitations for the appearance fidelity since with these technologies we are unable to develop fine grained details on SAR objects such as small text and intricate surface textures.

Our solution to this problem is is to exchange the traditional white substrate with an ePaper display to provide a controllable, high-resolution display surface. The combination of display technologies allows us to leverage their different capabilities simultaneously. In particular, we are interested in display technologies that have different dynamic ranges, resolutions, colour spectrum, and refresh rates. The use of ePaper combine with projectors has been previously explored [5] for the express purpose of constructing an HDR display device. The research presented in this paper explores this combination for the purpose of darker blacks, finer resolution displays, augmenting ePaper with colour, and augmenting ePaper with animation effects.

Using our display method, we envision physical substrates will be covered with ePaper displays to provide regions of the user interface with the high resolution functionality. The adaptive surface regions will be used to simulate lighting effects, surface structures and compensation for overlapping areas of projector frustum. The models our SAR system is illuminating are tracked by a 6 DOF tracking system. While support for fully dynamic and constantly moving objects is possible solely in SAR, we support for our combined display technique the common case that an object gets moved to a new place, examined and moved again. This accommodates and compensates for the low refresh rate of current ePaper displays, as the new lighting or compensation masks have to be recalculated and displayed only after a change in position.

This scenario describes how ePaper displays will be used as adaptive substrates in SAR environments and the advantages they provide. Contrary to TFT and other digital displays, they are lighter, smaller and flexible, so they are able to be fixed to even limited curved surfaces. As they are requiring power only on state change, only simple electronic control hardware is required, and new surface descriptions would have to be "uploaded" to the device only on demand. As the ePaper display is still a display, it allows changes to the displayed content during runtime, contrary to paper paper printouts. Finally, the ePaper surface substrate is not light-emitting and has reflection properties close to the white paint we used earlier for our models in our SAR system.

The following paper describes a hybrid display using a projector and an eInk display for the implementation. Section 2 discusses related works including existing composite displays, spatial augmented reality systems and previous projector-based display systems. Section 3 describes the theoretical framework for our concept where the theory and properties of this hybrid display are discussed. The following section presents a variety of appearance techniques based on the theory such as image enhancement and image contrast improvement. Section 5 discusses the implementation, using an LCD projector and a Kindle ebook reader[2] as a technology demonstrator. This section also discusses techniques for registration and calibration of the two displays. Finally, Section 6 discusses the limitations of the current systems and Section 7 describes possible

*e-mail:Markus.Broecker@unisa.edu.au
†e-mail:ross@r-smith.net
‡e-mail:Bruce.Thomas@unisa.edu.au

[1]We refer to ePaper as generic electronic paper, and eInk as the product from www.eink.com.

[2]http://amazon.com/Kindle

The 21st International Conference on Artificial Reality and Telexistence
November 28-30, 2011, Osaka, Japan
ISSN: 1345-1278

future work, as well as new research directions as the capabilities of ePaper technologies advance.

2 Related Work

SAR enhances the physical world with perspectively correct computer generated graphics using digital projectors [19]. This is in contrast to other AR display technologies, such as Head Mounted Displays (HMD) which place augmentations on an image plane in front of the user's eyes, and hand-held devices which show augmentations on a hand-held display [2]. SAR requires physical surfaces to project onto. These surfaces can consist of any objects in the environment that are of interest to the user; projections are not limited to walls or purpose built screens.

Unlike projection-based CAD displays and other AR display technologies, SAR allows users to physically touch the virtual information. The surfaces provide passive haptic feedback and all stereoscopic depth cues are naturally provided by the physical substrate. Previous virtual reality research has shown that the ability to touch virtual objects and information enhances user experience [14], and can improve users' performance [21]. This physical nature of SAR makes it a compelling choice for industrial design applications since the designers can physically touch the mock-up prototypes and leverage the flexible computer controlled appearance. Hare et al. [13] describe the importance of physical prototypes in the design process. Using SAR, designers can naturally interact with design mock-ups, without having to hold or wear display equipment. As SAR places computer generated information directly onto objects in the real world, groups can view and interact with the system. This makes SAR an ideal choice for collaborative tasks.

Objects that are augmented with projected imagery are either custom built props with ideal projection properties or they are existing entities. For the second case, research has been undertaken to investigate how to best project onto non-optimal surfaces taking into consideration their colour and geometry. Grossberg et. al describe a camera-projector method in which the colour response of the surface is taken into account [12]. A compensation image is created which allows the projection on any kind of coloured surface without any degradation in image quality. Bimber et al. also compensated for the irregular shape of the projection surface as well as inter-reflection properties of non-planar geometries and light-transport differences [3, 6, 22].

SAR systems are increasingly used in museums and other public spaces. Implementing a projector-based system instead of regular displays allows the seamless integration into existing exhibitions. In paintings, for example, certain details can be highlighted, explanations can be projected directly in place and previous restoration and cleaning processes can be displayed on the object of interest [4]. Aliaga et al. [1] describes a camera-projector system that is able to fix damages to a sculptures' surface, as well as relight it under virtual lighting conditions.

The lack of dynamic range of projectors is a well known challenge and a few attempts have been made to create a high-dynamic range display device using projectors. Stürzlinger and Pavlovych combined projectors with LCD displays, in effect replacing the light source of a TFT display with a projector or a custom-built, addressable LED display [18, 20]. They describe image splitting functions for both created displays, that split a high-dynamic range (HDR) input image into a subimage for the light-providing display (the projector or the LED wall) and the modulating display (the LCD screen). Bimber [5] created a composite high-dynamic range display using a projector and a projection surface as well. The projection surface could be any kind of display, from a TFT display, to a printed paper and also an ePaper display. His work extends Stürzlingers in that it extends and generalises the HDR image splitting function. The focus of both papers was to create a HDR capable composite display. Special care was taken to transform the input HDR image into the increased dynamic range of the new display. Our work however works with low-dynamic range data and does not focus on creating a HDR device, but rather on preserving a darker black.

While modern LCD projectors offer a high resolution, these projected images suffer from different problems up close. As the distance between projector and projection surface increases, the local resolution or pixel density of the projected image decreases. Additionally, fine darker lines between individual pixels become visible, the so-called "screen-door effect". This effect can be compensated if multiple projectors are used to illuminate a single surface. Due to small spatial differences in the projections, images don't overlap perfectly. If the rendering pipeline takes into account these differences, and compensates for it, local *Super-resolution* can be achieved [9, 10]. These overlaid images enhance each other and provide a natural anti-aliased image.

Another solution for the low local resolution of projection-based displays are composite displays. Olwal [17] et al. described different methods on how to interact with mobile, tracked, high-resolution devices to enhance local areas of the overall projection, thereby *replacing* one display locally with another, more suitable one. Contrary to this concept of employing two separate displays, we are seeking to combine the properties of two display technologies into one composite display.

Electronic paper displays are commonly used for ebook readers and low power application, such as supermarket price displays. eInk is a company and line of display products using their proprietary implementation of an electronic-paper display. The workings of electronic paper is described by Comiskey et. al [8]; the *sheet* of electronic paper consists of microcapsules, filled with electronically charged, white and black particles. A current can be applied to either the upper or lower side of this microcapsule, thus separating the particles and changing the apparent colour of the microcapsule to either black or white. To drive these sheets of paper like a display, a matrix display controller is used [11], and groups of microcapsules are addressed together, so that a pixel raster is created. One of the fundamental differences to regular displays is that electronic paper displays are passive and only need control commands (or applied voltage) when a display change is required, thus making them very energy efficient when compared to LCD technologies. Finally, the high resolution and contrast offer a legibility similar to traditional paper printouts [16].

3 Combining Display Technologies

This section provides a description of the properties of interest for the two display technologies employed in this paper, digital projectors and ePaper. A discussion on the current technology challenges is presented followed by the theory of how a hybrid display surface can be employed to improve display performance for SAR environments.

3.1 Technology Challenges

Currently the image contrast in projection-based environments is not sufficient to provide realistic blacks compared to a physical black object. When projecting black on a large area this problem is not so significant, however blacks are very important for defining details in images to highlight edges and require a good implementation to achieve this well. The current limitation is a technical challenge with the method used to create black with current projector systems. Black content is achieved with the absence of projected light, where the darkest perceived colours are produced by the underlying material colour alone and whites are achieved with the maximum light from the projector. One technique used to improve the perceived darkness of projected blacks is to use a grey screen in a darkened room. Using this technique blacks appear to be darker compared to when a white screen is used. However, the range between the darkest and lightest appearance (or contrast) remains unaffected since with a grey screen the projected white appears to be darker. This poses a problem with SAR systems since they are used to support presentations in rooms with ambient light. For example designers developing SAR prototypes for clients. This task requires high contrast images to provide optimal realism so as to maintain the fidelity when compared to physical prototypes and presented in a room with enough ambient light to allow a meeting to be held.

Ambient light significantly affects the appearance of projected light displays. Even if a room could be made completely light-absorbent, inter-reflections of the projected light between projection surfaces on models or "bounced" light from the observer's physical body will illuminate the scene and reduce the accurate representation of black. Achieving darker colours and black allows the operation of the projection system in much brighter ambient light environments without losing details of the projected textures. One solution to this challenge is to use a custom built dark room that prevents all ambient light from entering the room. This approach does improve the projected appearance but still does not overcome the limitation of the image contrast that is fixed to the performance of the projectors specifications.

The *effective resolution* is determined by the distance between the projector and the projected surface, the surface shape and the area used. Unlike simple planar displays, SAR systems are often projecting on objects that are not employing the entire projector frustum area. This leads to a lower effective resolution on the models' surface. Although the projectors can be moved closer to the surface to increase the resolution, this is limited by the minimum focal distance and the size of the objects to be projected on. These requirements decrease the effective resolution which reduces the detail of the projected information. Artefacts such as aliasing and texture filtering appear, and this effects the visual outcome such as reducing the readability of text.

3.2 Hybrid Display Theory

This paper presents our investigations into overcoming these challenges by replacing the single coloured projection surface of SAR objects with an adaptive substrate. By incorporating a projected display and a surface display, both technologies will work in synergy to improve the contrast and resolution.

3.2.1 Adaptive Substrate

Projection surfaces for traditional planar displays and SAR systems are usually a uniform colour and have an evenly reflective surface, such as a timber substrate painted white. We propose the concept of an adaptive adaptive substrate that is a projection surface capable of changing its base colour to influence the appearance of projected images. In our implementation we are using an ePaper display to provide the functionality of the adaptive substrate although other technologies could be put in its place.

One supporting argument of this method is the increasingly flexible nature of ePaper displays. Currently ePaper substrates are either rigid, as seen in ebook readers, or they are flexible allowing some limited bending around a surface or rolling up on itself. We envisage that future ePaper displays will go beyond flexible substrates that can be wrapped around simple shapes such as a cylinder, to allow elastic properties that will allow them to be wrapped around almost any organic shape. However, until this technology is invented and made commercially available, the hybrid display surface that uses both a projector and ePaper technology can provide much of the future functionality. For example consider a car dashboard where the entire surface is a display. Using our approach, the majority of the dash area will be textured using the projected light to provide simple colour details. While the instrument panel would use ePaper in conjunction with the projector to allow the fine annotations and details to be displayed.

The refresh rate of ePaper displays is currently much slower ($\sim 1Hz$) compared to projection technologies. Although this is a limiting factor, there are two reasons our approach is viable. Firstly, animated details can be provided by the projection system for animation while the ePaper is only used for static and non-time critical details. Secondly, we have already seen ePaper displays improve their refresh rates and it is likely they will continue to improve as the technology advances.

3.2.2 Contrast

Display contrast is defined as the ratio between the darkest and the brightest achievable colour. In projection displays, black is achieved by projecting no light at all. However, this leaves the pixel at the surface colour, which is usually a white surface, and is then lit by ambient light.

The adaptive substrate is able to turn individual pixels or regions to darker shades of grey and finally black. This reduces the amount of reflected light and makes the surfaces appear darker. By keeping other parts of the surface at a neutral "white" colour the maximum amount of light is reflected there, therefore increasing the contrast ratio of this display.

Image 2 highlights the difference between contrasts. On the left, the projector alone is displaying the colour black, and as a result the darkest achievable colour is the colour of the projection surface. Image 2b shows the contrast of the combined display. The ePaper display darkens the pixels that should appear black, while keeping the white pixels in the checkerboard at a neutral setting.

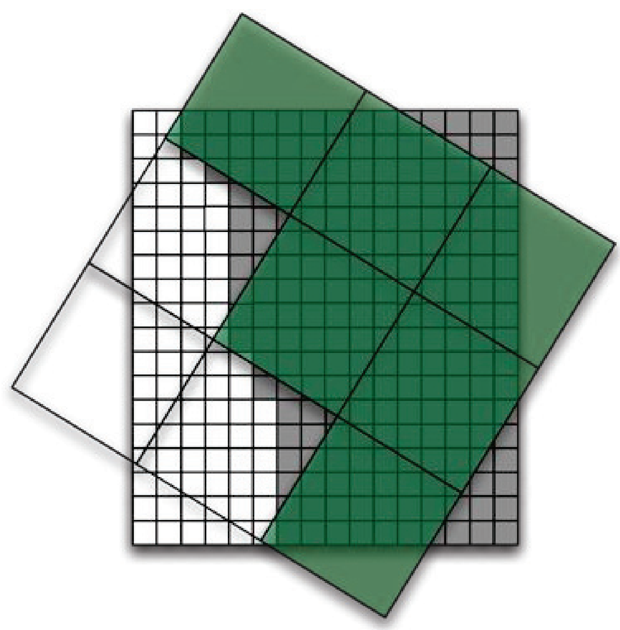


Figure 1: Comparison of different display resolutions. Let the big grid represent the projected pixel size of projectors, while the smaller grid represents the resolution of the substrate. The shaded projector pixel highlights how many smaller pixels are covered and can, on the other hand, influence the appearance of the projector pixel.

3.2.3 Local Resolution

In a SAR context, projectors usually use only parts of their display to illuminate surfaces, that may also be oriented at an oblique, non-optimal angle to the projector. With increasing distance between projector and projection surface, these pixels are also growing bigger in size (and dimmer in light). With a fixed projection surface, an increased distance means less projected pixels on this surface. We can therefore define the effective resolution of a projection surface as the actual count of pixels that are illuminating this surface. While the effective resolution decreases, the information we want to display on the same surface patch, a texture for example, stays the same.

Compared to the projector, the adaptive substrate has a much higher effective resolution on the same surface patch. It will also never decrease since the adaptive substrate is the projection surface itself. The much higher resolution allows modulation of projected light on this surface on a much finer scale than the resolution of the projected image. Controlling such fine details allows to preserve, enhance or even simulate image features and details that would have either been lost or invisible due to the low resolution of the projected image. Finally, the resolution and display of the ePaper device is projection and perspective independent. Where a projected texture would have to be interpolated to project correctly, and therefore is subjected to texture interpolation, the ePaper displays its information flat and perspective independent on the substrate.

A particularly useful aspect of the combined display technologies for SAR systems is the concept of employing an adaptive substrate for specific areas on an object. Using this approach, sections on an object that only require a low resolution may use only the projected technology for most of their appearance while areas such as interactive controls may employ the hybrid display surface to provide optimum performance and detail. Areas of interest can also be defined in this manner, drawing the user naturally to certain surface areas.

3.3 Discussion

Table 1: Comparison of display systems

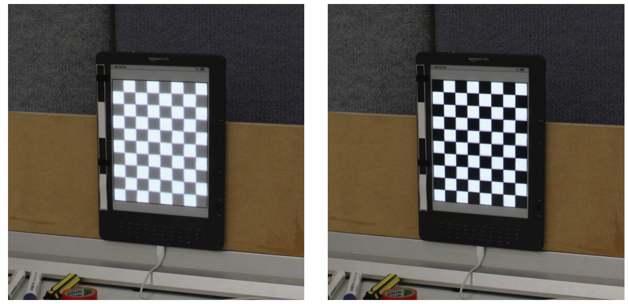
	Advantages	Shortcomings
ePaper	High contrast “True” black High local resolution	No colour Slow refresh rate Limited flexibility
Projector	Colour output High refresh rate Project on any surfaces	High black level Low effective res. Requires line-of-sight
Projector+ ePaper Composite	Colour output High dynamic range Local superresolution True black	Requires registration Inhomogenous refresh rate

By creating a composite display of two very different displays, we are utilising the strengths of each system and at the same time compensating the weaknesses (See Table 1). As can be seen, the ePaper compensates for the projector display in areas of high contrast, true black, and resolution. Project on the other hand compensates for colour range, refresh rate, and ability to conform to complex shapes. The combined effect is an overall improved visual outcome.

4 Appearance Techniques

This section describes techniques that demonstrate how the theory of using an active ePaper substrate can be employed to enhance the contrast and sharpness of projected imagery. All photographs presented in this paper were taken with a high-resolution digital camera at room ambient light. We measured the ambient light in the room with a Digitech QM1586 light meter to be about 200 lx. Preprocessing of the photographs was restricted to cropping and slight distorting, so that they would fit a rectangle. They were not colour processed.

4.1 Improved Contrast and Black Level



(a) Checkerboard projected only

(b) Checkerboard on the composite display

Figure 2: Comparing the black level of a projector alone (2a) with the black level of our composite display (2b).

In Figure 2, the black levels of a projector and our composite display are contrasted. On the left, the projector alone is displaying black; the darkest achievable black is therefore determined by the ePaper colour and the ambient light at that point. On the right, the ePaper is also displaying black at the required pixels, achieving a much darker shade of black. Both images were taken at ambient light levels.

4.2 Image Enhancement

In Figure 3, we display the “Lena” image on both the projector and the ePaper substrate. The left column shows the projector-only output, while the right column shows the same output on the composite display. A close-up of the eye in the second row highlights that details like the exact shape and details of the iris or the eye lashes that have been preserved using the composite display. The last row shows an interpretation on how the various pixel sizes and colours are interacting to form the final image. Details, such as fine details in the iris, are preserved in the composite image.

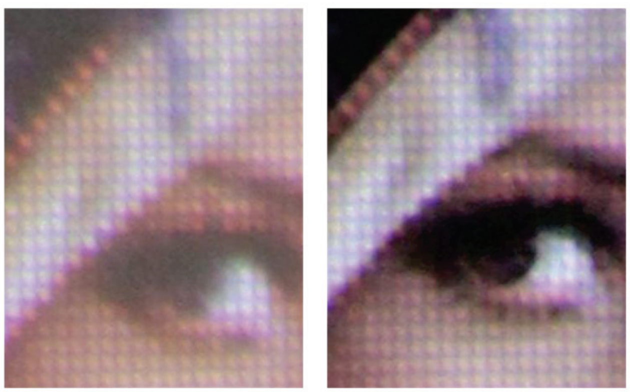
4.3 Text Enhancement

In many SAR applications, there is a need to display small legible text on a surface. This is usually done by displaying a texture which contains the text. However the density of projected pixels is often not adequate to display characters sharply. Additionally, texture filtering limits the details we can effectively reproduce. The ePaper substrate overcomes this problem by providing a very high local effective resolution. Rather than depending solely on the substrate for displaying text, we used a combined rendering techniques to display both black and coloured text using the projection system for colour and the ePaper display for improved sharpness and contrast.

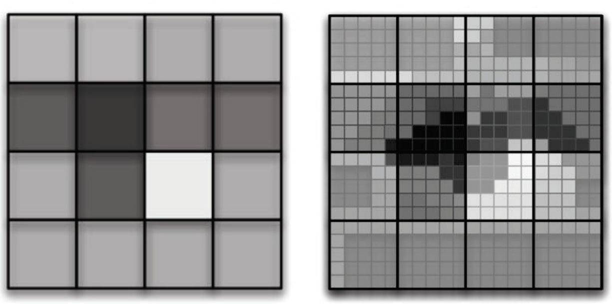
For black text on white and coloured background, high-quality images of the text are drawn on the ePaper substrate. A higher resolution on the substrate allows for smaller and sharper text. Depending on the text size, the projector might “fill in” the letters of the text as well, although it usually is concerned with providing the colour of the text background.

Figure 4 demonstrates this approach in practice. The left column shows the text texture, as it is displayed by the projector. The text is too small to be effectively rendered at that resolution and parts of letters are missing. By displaying the same texture on the ePaper

(a) Lena projected (b) Lena on the composite display



(c) Close-up of the eye in the photo (d) Close-up of the eye in the photo



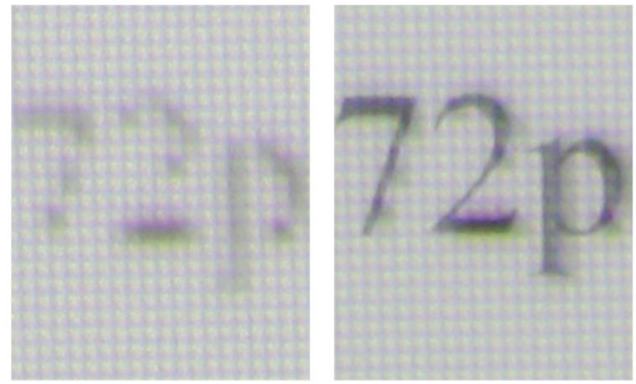
(e) Projected pixel sizes (f) ePaper pixel size

Figure 3: Contrast and detail enhancement for images, demonstrated on Lena.

underneath it, the higher resolution of the ePaper display provides crisp outlines and makes the text readable with much smaller font sizes.

4.4 Animated and Static Displays

The concept of augmenting static images can be further developed using the composite display. Static parts are augmented with the ePaper substrate and dynamic parts are displayed using the projector alone. For example Figure5 demonstrates a simulated instrument display that employs the hybrid display to create an animated instrument gauge. The frame and most details are present in the projected details and also in the ePaper substrate, thus increasing detail and sharpness. Animated parts, such as the needle, are displayed with the projector alone.



(a) Projector close-up (b) Composite close-up

Figure 4: Text enhancement.

With the composite display a compromise must be reached between lower image quality for some parts of the display and the ability to animate such a simulated instrument. However, only the currently very low refresh rate of an ePaper display prohibits us from implementing a fully augmented dynamic instrument.

4.5 Texture effects

The final appearance of the augmented surface can be altered by displaying static textures on the ePaper substrate. The combination of this static texture and the projected image provides an enhanced version of the final image output. This section describes two techniques, detail textures and detail shading.

4.5.1 Detail Textures

An effective example of the hybrid display technology is texture effects that leverage the high resolution of the substrate display to provide the fine-grained details. A projector illuminates the surface with a very low effective or "local" resolution, as most of the projected image falls on other surfaces, the background and so on. Small details, such as fine surface structures and high resolution textures can not be projected as their detail gets lost during due to the low resolution and texture filtering.

A solution is to use the high-resolution substrate display to present the *detail texture* information. This provides detail information of the surface at close distances. Traditionally, these textures were multiplied with the original texture. In our case, we provide this texture on the ePaper substrate surface, while the projector is illuminating with the original image. When the substrate is viewed up close, these details add an extra layer of surface information.

4.5.2 Detail Shading

The idea of detail textures can be extended to include variable lighting. Surface details on the texture are visible because a light source illuminates and shades irregularities on this surface. If the scale of these irregularities get larger, we are able to simulate the general shading of surfaces using bump maps.

In Figure 7 this idea is explored using prerendered bump map images. A virtual light source is moved across the display, and the shading thereof changes accordingly. The ePaper display is responsible for showing the shading, while the projector is displaying an orange tone, simulating the colour of an orange. If specular reflections are required, the projector would display them as well.

(a) ePaper only

(b) Projector only

(c) Composite display

Figure 5: An example of an animated display. (5a) shows the ePaper displays output, (5b) the projector output and (5c) the final image on the composite display.

(a) Concrete

(b) Canvas

Figure 6: Demonstration of concrete and canvas detail-textures employing the high resolution ePaper display for details and projector for colour information.

(a) Frame 1

(b) Frame 2

Figure 7: Two bump mapping frames using the composite display. The light source moves from left to right.

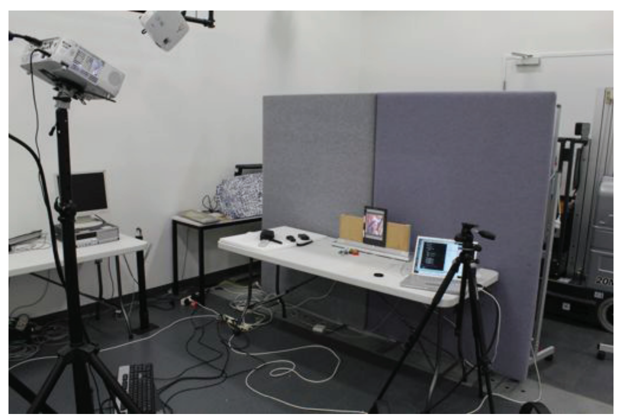


Figure 8: The experimental setup showing a projector on the left mounted at a distance of 2.5-3 metres from the ePaper display.

5 Implementation

We implemented a prototype by using an off-the-shelf ebook reader as one possible implementation of an adaptive surface substrate. A python script, responsible for aligning a displaying a textured quad, was running on a computer, attached to a projector. Projected images were generated with OpenGL.

5.1 Prototype Display

We used an Amazon Kindle DX with an eInk "Pearl" display. Its display has a physical size of 10.4" by 7.2" and a physical resolution of 825x1200 pixels. Each pixel can display 16 shades of grey; intermediate values are displayed using dithering. The Kindle's operating system displays PDF documents rasterised and has a built-in image viewer. The display itself has has very low reflectiveness, similar to painted wood we use for the construction of our other prototypes for SAR objects. The projector we used is a NEC 501W LCD projector with a resolution of 1280 x 800 pixels. It is driven by a computer over a DVI connection.

This setup is used as a technology demonstrator and early prototype and we intend to update as more feature rich hardware is available. In this setup the Kindle has some shortcomings, for example it is not a directly controllable display. The image and PDF viewer are able to display data on the screen although direct access to the display would be more optimal. Using this technique, images get stretched if they are not the correct resolutions. The refresh rate for full screen images was lower then 1 Hz.

5.2 Setup

We built a solid stand to which the Kindle was firmly attached using double-sided tape. The stand and Kindle was placed on a desk at roughly 2.5 metres distance from a projector (see Figure 8). This represents a typical case of *Desktop SAR*, in which a model is placed on a desktop and lit on all sides by projectors mounted on a frame or gantry around it. The projector was controlled by an attached computer, while the Kindle display was controlled by uploading generated images into an "ebook" representation and viewed in the Kindle's image viewer.

To create a usable composite display, the projectors image requires registration with the eInk display to ensure that the pixels of the different output devices overlay each other. As described in Section 5.1, using the image viewer is problematic, as we found it to be unreliable in clearing and refreshing the screen and displaying series of images with similar grey tones. Through experimentation we found out that only some images at a certain resolution are displayed correctly. We therefore defined a "valid" area inside the Kindle's display, and drew a border around it. This area's resolution was 800x1000 pixels, and it was framed by a 5 pixel black border. All of our generated images had this black border, allowing easy alignment between the eInk and the projector image.

To align a projected quad to this valid frame a quad was projected. Its four corner vertices were then aligned using mouse selection and keyboard commands and their positions can be stored in a file. As long as neither the projector nor the Kindle moves, the coordinates can be read from the file and the alignment step therefore has to be performed only once.

Images are displayed by texturing this aligned quad. For animated displays, the texture is created by rendering the animation into a framebuffer object and binding it as a texture. It must be noted that the effective resolution of the projector in this valid area usually quite low and even textures of the size 512x512 pixels have to be filtered.

5.3 Contrast

We measured contrast in an ambient lit room, with a ambient light of roughly 250 lx. For contrast measurements, we were displaying the ANSI contrast pattern, a 4x4 black-and-white checkerboard pattern. The illuminance of all the white and all the black areas was measured and averaged using a calibrated spectrometer in absolute irradiance measurement mode. Based on those values, the final display contrast is calculated by dividing the average white by the average dark illuminance. All the measured values were rounded to the next integer. Table 2 shows the results of the calculations.

In the first instance, we measured the contrast of the projector alone projecting on the empty Kindle surface, in the second we projected the ANSI pattern on a displayed ANSI pattern. The comparatively low contrast ratio in the first case can be explained by the display surface of the Kindle. It is not perfectly diffuse white but rather grey, this lowers the amount of reflected light.

Table 2: Contrast measurements for a single projector and a combined adaptive substrate display.

	Avg. black	Avg. white	Contrast
Projector alone	269 lx	3722 lx	$\sim 14:1$
Kindle + Projector	50 lx	3720 lx	$\sim 74:1$

6 Limitations

One shortcoming is the ePaper we employed does not provide direct access to the display. We are using an eBook reader (with an unsupported image viewer) to display our images. However, we have little control over how the images are being displayed. Image scaling, cropping and dithering were the results of incompatible images. As previously mentioned, we have no direct control, displaying a series of images meant creating an image series in advance and manually flipping to the next entry in this series. Manual operation might move the device however, which could invalidate the projector - eInk display registration.

Secondly, our current prototype has a very limited refresh rate of about 1Hz. It is not possible to display moving or animated images. While the sixteen grey levels are appropriate for many applications, they lack the finer control needed to compensate for complex lighting problems, like overlapping projection areas.

One of the major advantages of using SAR for early prototyping is the ease and low cost to build models to project on. Incorporating eInk devices as surface replacements would possibly increase the complexity and price of such prototypes. A solution would then be to use eInk displays only on selected, important parts of such a model. Finally, all these displays would be wired up to a central controller, requiring additional cable connections and control or video outputs. Fortunately, ePaper displays have a very low power requirement, so expensive and heavy power equipment is not required.

7 Future Work

7.1 Adaptive Projection Screens

Spatial Augmented Reality and multi-projector display walls have areas, in which multiple projections are overlapping. In these overlapping areas, the brightness is increased as multiple projectors, instead of one, are illuminating a surface. Using adaptive substrate, one could compensate for this over-illumination, by lowering the brightness of the surface in this intersection area only. These overlapping areas can be determined through matrix decomposition (if the projector's extrinsic and intrinsic matrices are known) or through camera-projector systems. The current limitation of only 16 shades of grey prevents our system from creating effective compensation levels. Additionally, as we can only control the blackness for now, we cannot compensate for different projector white balances, as each projector might contribute a different colour to this overlapping area.

7.2 Subpixel Antialiasing

A composite display could have an inter-display look-up-table, that maps pixel coordinates from one device to another (for example through automatic, structured light registration techniques). Having now subpixel-correct control of the higher-resolution display, we are able to perform antialiasing by decreasing the darkness level of single pixels. Text, lines or silhouettes can be smoothed using this method. This also requires direct control of the ePaper display.

7.3 Improved eInk

Our description of the composite display is a RGBK display system. We were using a greyscale ePaper display for our prototype. However future versions of eInk displays will be coloured and possible provide RGB control.

Using RGB control to describe the surface of an object allows us to reformulate the surface description of the rendering system. While we now split between colour and brightness (RGB and black), it will be possible to split the rendering in surface description (colour + black) and a lighting description. The surface description will contain the diffuse texturing and the black detail shading, while the coloured lighting by the projector will describe the lighting, the specular effects and so on. Part of the rendering equation[15] will take place by shining coloured light onto the coloured surface substrate.

Finally, an eInk display with a higher refresh rate does not change the techniques we presented so far. It might be interesting for displaying animations, as the surface change of the display can be synchronised with the refresh rate of the projection display, thereby creating a high-dynamic range composite display.

7.4 Adaptive Substrate Props

In our SAR environment, we are exploring methods of projecting on simple props and how add detail to these models by intricate surface simulation. For example, instead of creating detailed physical models of control panels, we build simple, almost box-shaped models and use SAR to enhance their surface so that the end result looks like a real control panel.

Although these models are currently painted matte white for best projection properties, we envision that bendable eInk displays will be used as surface coating for future models. They have many advantages compared to traditional displays, like their reduced power consumption, lower weight and their flexibility. For a future SAR system, a number of geometrically simple shapes, like boxes, cylinders or cones could be built using eInk surfaces as adaptive substrates instead of simply painting them white.

8 Conclusion

This paper described a new form of hybrid display using both a digital projector and eInk together to create a single composite display surface for use in SAR systems. Replacing the commonly employed uniform white projection surface of SAR objects with our composite display has allowed us to develop a series of theoretical approaches that define how this form of display can be employed. This approach significantly enhances the contrast ration and sharpness appearance of SAR objects. We have implemented image enhancement techniques that are built around two core concepts provided by this new method: effective resolution and a lowered black level. The results we achieved by controlling the adaptive substrate to work in synergy with a digital projector have significantly improved the SAR object appearance.

References

[1] D. G. Aliaga, A. J. Law, and Y. H. Yeung. A virtual restoration stage for real-world objects. In *ACM SIGGRAPH Asia 2008 papers*, SIGGRAPH Asia '08, pages 149:1–149:10, New York, NY, USA, 2008. ACM.

[2] R. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre. Recent advances in augmented reality. *Computer Graphics and Applications, IEEE*, 21(6):34–47, 2001.

[3] O. Bimber. Multi-projector techniques for real-time visualizations in everyday environments. In *ACM SIGGRAPH 2006 Courses*, SIGGRAPH '06, New York, NY, USA, 2006. ACM.

[4] O. Bimber, F. Coriand, A. Kleppe, E. Bruns, S. Zollmann, and T. Langlotz. Superimposing pictorial artwork with projected imagery. In *ACM SIGGRAPH 2005 Courses*, SIGGRAPH '05, New York, NY, USA, 2005. ACM.

[5] O. Bimber and D. Iwai. Superimposing dynamic range. In *SIGGRAPH Asia '08: ACM SIGGRAPH Asia 2008 papers*, pages 1–8, New York, NY, USA, 2008. ACM.

[6] O. Bimber, D. Iwai, G. Wetzstein, and A. Grundhöfer. The visual computing of projector-camera systems. In *SIGGRAPH '08: ACM SIGGRAPH 2008 classes*, pages 1–25, New York, NY, USA, 2008. ACM.

[7] O. Bimber and R. Raskar. *Spatial augmented reality: Merging real and virtual worlds*. AK Peters Ltd, 2005.

[8] B. Comiskey, J. D. Albert, and J. M. J. H. Yoshizawa. An electrophoretic ink for all-printed reflective electronic displays. *Nature*, 394:253–255, July 1998.

[9] N. Damera-Venkata, N. Chang, and J. DiCarlo. A unified paradigm for scalable multi-projector displays. *Visualization and Computer Graphics, IEEE Transactions on*, 13(6):1360 –1367, nov.-dec. 2007.

[10] N. Damera-venkata and N. L. Chang. On the resolution limits of superimposed projection. In *In Proc. IEEE International Conference on Image Processing (ICIP*, 2007.

[11] H. Gates, R. Zehner, H. Doshi, and J. Au. 31.2: A5 sized electronic paper display for document viewing. *SID Symposium Digest of Technical Papers*, 36(1):1214–1217, 2005.

[12] M. D. Grossberg, H. Peri, S. K. Nayar, and P. N. Belhumeur. Making one object look like another: Controlling appearance using a Projector-Camera system. In *Computer Vision and Pattern Recognition, 2004. CVPR 2004. Proceedings of the 2004 IEEE Computer Society Conference on*, volume 1, pages I–452–I–459 Vol.1, 2004.

[13] J. Hare, S. Gill, G. Loudon, D. Ramduny-Ellis, and A. Dix. Physical fidelity: Exploring the importance of physicality on Physical-Digital conceptual prototyping. In *Human-Computer Interaction – INTERACT 2009*, pages 217–230. 2009.

[14] H. Hoffman, A. Hollander, K. Schroder, S. Rousseau, and T. Furness. Physically touching and tasting virtual objects enhances the realism of virtual experiences. *Virtual Reality*, 3(4):226–234, 1998. 10.1007/BF01408703.

[15] J. T. Kajiya. The rendering equation. *SIGGRAPH Comput. Graph.*, 20(4):143–150, 1986.

[16] F. M. Meyer, T. L. Trissell, D. L. Aleva, S. J. Longo, and D. G. Hopper. Readability evaluation of an active matrix electrophoric ink display. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 6225 of *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*, June 2006.

[17] A. Olwal and S. Feiner. Spatially aware handhelds for high-precision tangible interaction with large displays. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, TEI '09, pages 181–188, New York, NY, USA, 2009. ACM.

[18] A. Pavlovych and W. Stuerzlinger. A high-dynamic range projection system. In *Photonic Applications in Biosensing and Imaging, Proceedings of SPIE 5969*. SPIE—The International Society for Optical Engineering, 2005.

[19] R. Raskar and K. Low. Interacting with spatially augmented reality. In *Proceedings of the 1st international conference on Computer graphics, virtual reality and visualisation*, pages 101–108, Camps Bay, Cape Town, South Africa, 2001. ACM.

[20] H. Seetzen, W. Heidrich, W. Stuerzlinger, G. Ward, L. Whitehead, M. Trentacoste, A. Ghosh, and A. Vorozcovs. High dynamic range display systems. *ACM Transactions on Graphics*, 23:760–768, 2004.

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

[22] G. Wetzstein and O. Bimber. Radiometric compensation of global illumination effects with projector-camera systems. In *ACM SIGGRAPH 2006 Research posters*, SIGGRAPH '06, New York, NY, USA, 2006. ACM.