# Ubiquitous Projection

## New Interfaces using Mobile Projectors


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# Abstract

The miniaturization of projection technology has enabled a new class of lightweight mobile devices with embedded projectors. Projection engines as small as a postage stamp are currently being embedded in thousands of mobile devices. Mobile projector-based devices differ in very fundamental ways from the display-based devices we commonly use. Mobile projectors can be carried with the user and project imagery into almost any space, projected content is visible to multiple users and supports social interaction, physical objects and surfaces can be augmented with projected content, and embedded projectors can enable new form-factors for mobile displays.

This research investigates the potential of mobile projectors as a new platform for human-computer interaction. I aim to demonstrate that the unique affordances created by the miniaturization of projection technology can inspire new and compelling interaction with single-users, multi-users, the environment, and projector-embedded objects. This research presents a comprehensive survey of mobile projector-based interaction – documenting interaction with historic projection devices; introducing novel interaction techniques, metaphors, and principles for mobile projector-based systems; providing implementation details of functional prototype devices using mobile projectors; presenting technical innovations, such as the development of specialized projectors and custom marker tracking algorithms; and detailing results from preliminary user testing with the prototype systems created. This research forms a systematic investigation of the past, the present, and a possible future for interaction using mobile projectors.

# Acknowledgements

The decision to undertake my Ph.D. studies at Carnegie Mellon has had an incredibly positive influence on my research, work, and life. While studying at Carnegie Mellon and collaborating with Disney Research I was immersed in the history that had been made at these institutions. It is an empowering feeling to know that your own research has the potential to reach these heights and make a small piece of history itself.

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# 1 Introduction

Throughout history projectors have been a powerful visual communications medium. Whether at human scale or at architectural scale, projectors have a profound ability to shape our visual experience. They have been used to project images of the world onto paper, glass, or film with the *camera obscura* and have brought imaginary worlds to life by projecting drawings and animations with the *magic lantern* (Figure 1). Their use has ranged from the study of science to the entertainment of the masses.

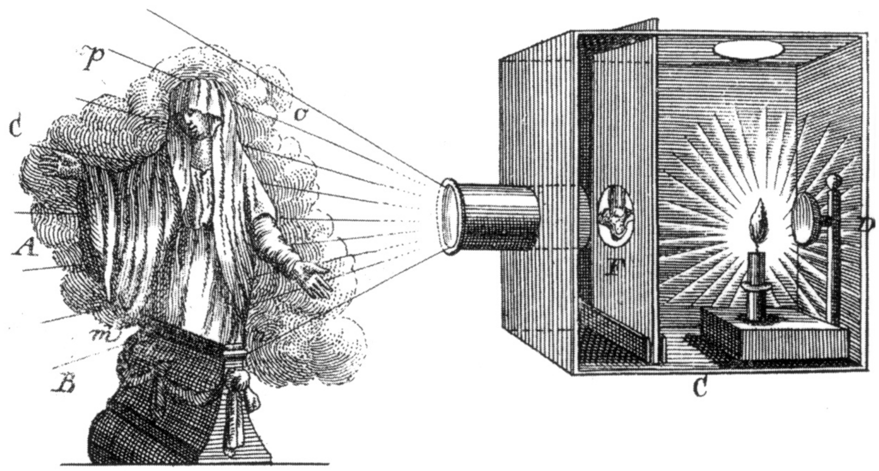


**Figure 1:** A magic lantern projects a figure on to smoke exiting a coffin. Oekonomisch-technologische Encyclopädie, 1794.

Although projectors enable us to change the visual environment in dynamic and malleable ways, their modern day use is commonly constrained to projecting rectilinear images onto a flat surface. Projectors have found a commercial niche as large-scale display devices for presentations or movies. However, unlike conventional television or computer displays, projectors reflect light off a surface and back to the viewers eye. The viewers eye is not focused on the projector itself, but the environment into which it projects. As can be seen in figure 1, almost any reflective surface imaginable can become a display.

Recent technological advances have led to the miniaturization of projection devices and signaled a new stage in the rich history of the projector. With projection chipsets no bigger than a postage stamp now available (Figure 2, right), we are witnessing a fundamental shift in how, where, and why projectors are used. Miniaturized projectors become personal projection devices that are constantly with us. For the first time, computationally controlled imagery can be projected directly from mobile phones, digital cameras, or tablet computers. Market research predicts as many as 58 million devices with embedded projectors on the market by 2015 (Pacific Media Associates, 2012). Importantly, this opens up new possibilities for the design of interactive systems.

*Ubiquitous projection* is the vision of tiny, bright, power-efficient projectors embedded into devices throughout the environment. Combined with intelligent sensing and network connectivity, these devices will be used for both work and play. As human-computer interaction (HCI) increasingly moves out from the desktop and into the environment, mobile projectors are a unique technology that can transform the surfaces around us with interactive imagery. They enable new forms of interaction, not only with computing systems, but with those around us and the environment itself.

**Figure 2:** A current generation mobile projector (left) and a current generation projection engine (right) (Source: 3m.com and microvision.com).

## 1.1 Research Outline

This research aims to demonstrate the potential of mobile projector-based systems as a new platform for human-computer interaction. I present a systematic investigation of the past, the present, and a possible future for interaction using mobile projectors. The core research activity is the design and implementation of functional mobile projector-based interactive systems. These prototype systems allow rapid exploration of the design space for mobile projector-based interfaces to prove their viability from a technical and functional standpoint. There are five major components of this research that each examine a key aspect of interaction with mobile projectors.

*A History of Mobile Projector-based Interaction.* Although the miniaturization of mobile projectors is very recent, the history of interaction with mobile projectors begins well before the invention of cinema. Technologically primitive, but creatively expressive handheld projection devices were developed and used in theatrical settings in Europe and Japan. The early use of these historic devices established important precedents for mobile projector-based interaction. In Chapter 2 I document early forms of 'interaction' with historic mobile projectors and contextualized them in relation to contemporary research. Finally I provided discussion and commentary on how knowledge of this history can inform the development of future mobile projector-based interactive systems.

*Mobile Projector-based Interaction.* The mobility of miniaturized projectors is one of the key affordances of this new technology. Their size allows users to grasp them in a single hand, attach them to their bodies, or move them from space to space. The ability to dynamically change projected imagery based on the physical movement of the device introduces new challenges and opportunities for the creation of interactive content. One of the major challenges is to deal with projected imagery that moves, shakes, and distorts with the user's every move. User gestures and device movement, however, can be utilized to interact and dynamically control projected imagery. In Chapter 3 I introduce a novel interaction metaphor, labeled *MotionBeam*, and a prototype system that uses the movement of a mobile projector to control and interact with projected characters.

*Mobile Projector-based Multi-user Interaction.* Mobile projectors allow the creation of shared interactive spaces. The relatively large size of projected images allows them to be easily seen by multiple people, making them a natural fit for collaborative interaction. Collaborative work, learning, and play are crucial elements of our interactions with other people in day-to-day life. In Chapter 4 I introduce the *SideBySide* system that enables ad-hoc multi-user interaction with mobile projectors. *SideBySide* tracks multiple independent projected images, to enable interactions that are responsive to user movement as well as imagery projected from other users in the space.

*Mobile Projector-based Interaction with the Environment.* Mobile projectors can situate projected content together with physical objects, making them a promising tool for interaction with the physical environment. They show great potential as a technology to seamlessly merge digital content into the physical environment. Mobile projectors can augment the environment with projected content that is context-aware and specially tailored to the physical location and situation. Enabling these possibilities requires the development of tracking and projection techniques that can register imagery to physical locations without extensive instrumentation of the environment. In Chapter 5 I introduce *HideOut*, a prototype system that can map projected imagery onto objects and surfaces in the environment. *HideOut* enables new mobile and tangible application scenarios including digital media browsing using available surfaces, tangible board games enhanced with projection, and story books that are brought to life with interactive content.

*Interaction with Embedded Mobile Projectors*. The ongoing miniaturization of mobile projector chipsets enables compact, lightweight projectors to be entirely embedded within interactive objects. Imagery can be projected from the inside of the object, greatly simplifying the registration of projected imagery. However, this approach relies on the design of custom optics to guide projected light and match the geometry of the object. Although fabricating custom optical elements has traditionally been expensive and impractical, recent developments in 3D printing technology have enabled the fabrication of optically clear plastics that are well suited for use with mobile projection. In Chapter 6 I present two novel techniques for prototyping with embedded projection using 3D printed optical elements: *Light Pipes* enables light to be guided from point to point in a similar manner to optical fiber and *Internal Illumination* allows internal areas of an object to reflect light for use as a display.

The next chapter begins with the historic origins of mobile projectors and a survey of contemporary research. This chapter sheds light on the history of mobile projectors and details many of the research prototypes and applications that have been developed to date. Once the stage has been set, the subsequent chapters describe prototype systems that I have developed with my collaborators to examine single-user, multi-user, environmental, and embedded interaction with mobile projectors. The specific research contributions are listed at the beginning of each chapter and summarized as a whole in the conclusion of this document. Likewise, detailed discussion of related work is provided in each chapter to clearly illustrate how this research advances the state-of-the-art. Although each chapter is self-contained, together they tell a larger story about the new interfaces we may encounter with the proliferation of mobile projectors in the era of *ubiquitous projection*.

# 2 A History of Mobile Projector-based Interaction

A stream of mobile projectors have arrived on the market as standalone devices or embedded within mobile phones, digital cameras, and tablet computers. Meanwhile, developing mobile projector-based interactive systems has been a growing area of interest in the research community. Research to date has approached the subject from a contemporary technological understanding of the 'mobile projector'. In this chapter I pursue a different approach that closely examines the historical precedents of mobile projector-based interaction. I take an inclusive view of mobile projectors, encompassing any portable device that projects animated imagery. This has the advantage of expanding our understanding beyond a single technology platform. With the growth of interest in mobile projectors, it is an ideal time to look more deeply at the broader historical context. I present the following contributions:

- A survey of the historical origins of mobile projection devices.
- A survey of the projection techniques used with historic mobile projectors and how they have been adapted in contemporary research.
- Discussion of how historical mobile projector-based interaction can inform the design of future systems.

In this chapter I juxtapose historic technology and interaction styles with contemporary equivalents from the research literature. Firstly, I document the historic mobile projection devices used in Europe and Japan, then outline their contemporary equivalents, the underlying technology, and the various form-factors currently available. Secondly, I describe the historic use of these devices in a performance context, categorize the projection techniques used by performers, and document how contemporary research and technology is being used to extend these techniques. Finally I conclude with discussion on how knowledge of historical mobile projector-based interaction can be applied to contemporary research.

## 2.1 Mobile Projection Devices

Although some 200 years separates the first mobile projection devices from their contemporary counterparts, many of the fundamental elements of projection technology remain the same. The large majority of contemporary mobile projectors still consist of a *light source*, an *image source*, and a *focusing mechanism*. How each of these elements are implemented differs greatly and is the subject of continuing research to create bright, high resolution imagery from increasingly small devices.

I now introduce historic projection devices that have a mobile form-factor and outline the technology of the time. I contrast this with contemporary technology as a means to understand the new affordances provided by contemporary mobile projectors. A broader historical perspective on current technology allows us to better understand the trajectory for future developments and in-turn design future interactions.

### 2.1.1 Historic Projection Devices

Early mobile projectors are closely linked to the magic lantern, an early projection device that was typically stationary and first described in 1646 (Kircher, 1646) (Figure 3). Housed inside a casing was a light source and a concave mirror to collect light. The light was projected through an image source, in the form of a painted glass slide, and then on through a lens focusing mechanism to project an enlarged version of the slide (Figure 4).

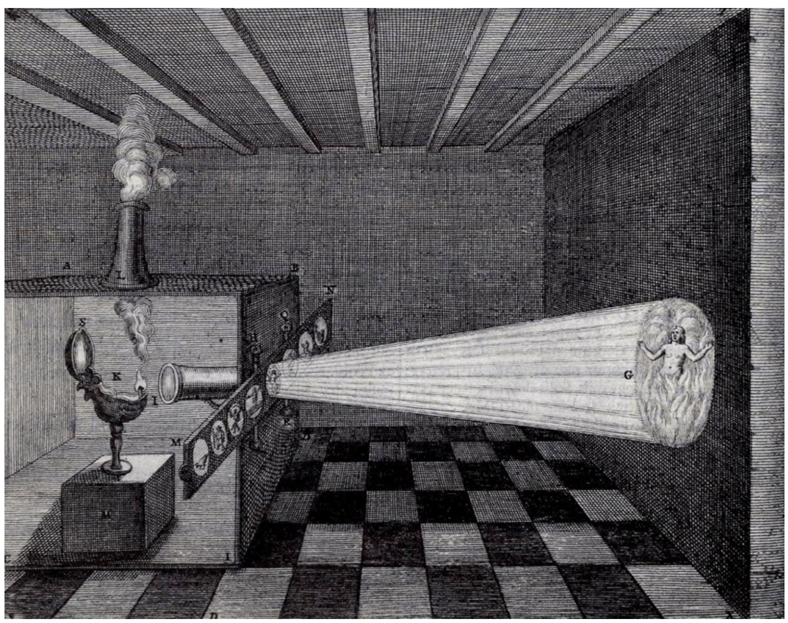


**Figure 3:** The first known illustration of a magic lantern from a later print of *Ars Magna Lucis et umbrae* (Kircher, 1646).

The type of light source used with the magic lantern was dependent on the technology of the time. Early devices used candles and oil lamps to project dim flickering images. Later developments,

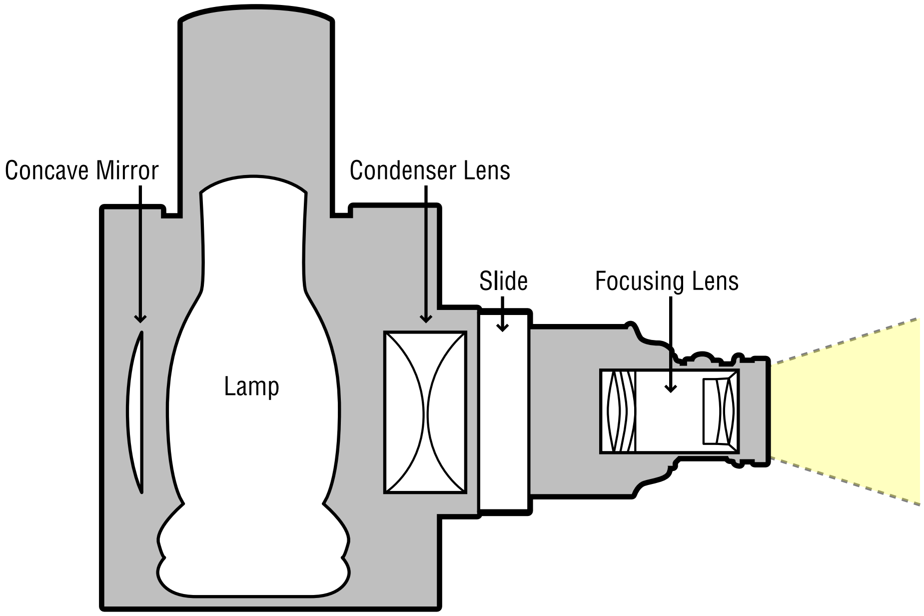



**Figure 4:** Optical layout of the magic lantern.

including the Argand lamp, the arc lamp, and finally the incandescent electric lamp, dramatically improved the brightness and size of the projected image.

A notable characteristic of the magic lantern was the creation of animated imagery well before the emergence of cinema. To achieve simple animation techniques, specialized glass slides were used that could change the image based on mechanical movement. Typically one background slide was fixed in place, while another foreground slide could be moved in front using rotation or linear movement.

Historic projection devices, such as the magic lantern, encompass a broad area of research and I will now narrow my focus to projection devices that were designed for mobile usage. Mobile projection devices can be broadly categorized into two main varieties: mobile magic lanterns from Europe, and the Japanese adaptation known as the *furo*.

## Mobile Magic Lanterns

Mobile variations of the magic lantern exist, but constitute only a very small section of the magic lantern landscape in Europe. In most cases mobile magic lanterns were constructed from metal, meaning heat emitted from the light source made holding them with bare hands impractical. This was further confounded by the need for the projectionist to use their hands to change slides and adjust focus at the same time.

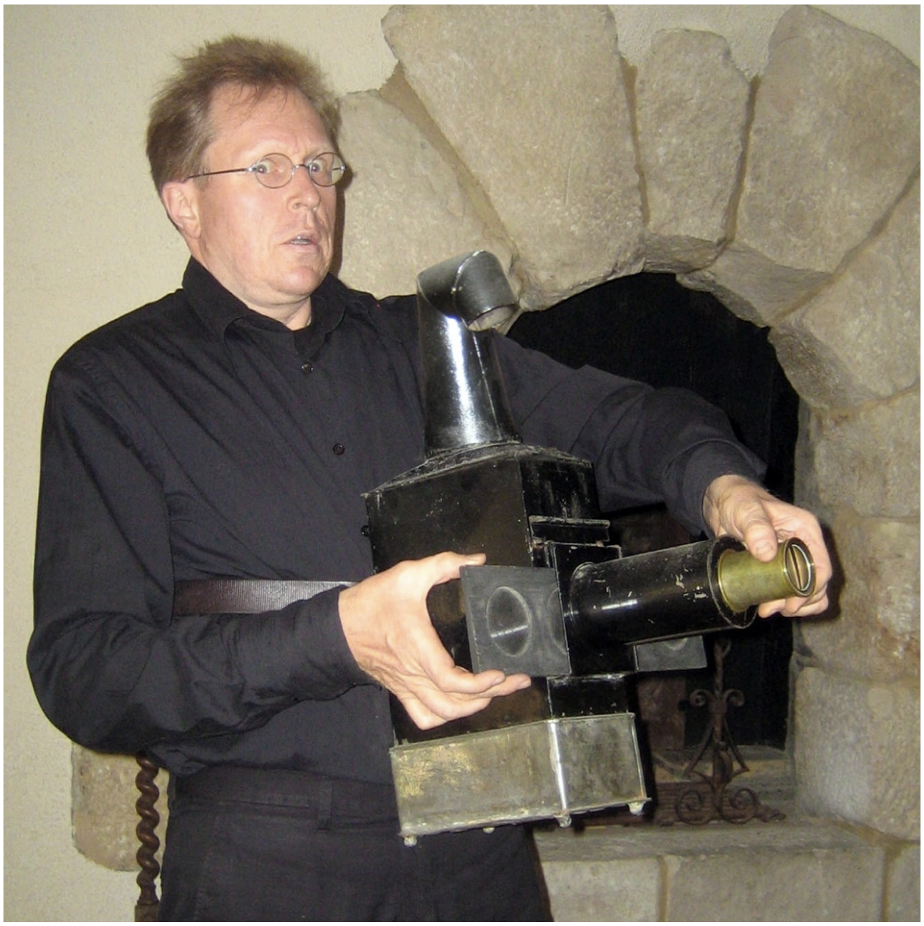


**Figure 5:** A rare belt-mounted variation of the magic lantern created by Philip Carpenter, 1823 (Source: Erkki Huhtamo Collection).

Belt-mounted magic lanterns were a rare variation that utilized a belt attached to the rear of the device to support 'mobile' usage. As the belt supported the weight of the device, the hands of the projectionist were free to change slides and adjust focus (Figure 5). To accommodate mobile usage the lantern pictured in Figure 5 has a smoke outlet that faces away from the projectionist. However, the heat generated from the light source, combined with the close proximity to the projectionist's body, would limit the duration of use and mobility.

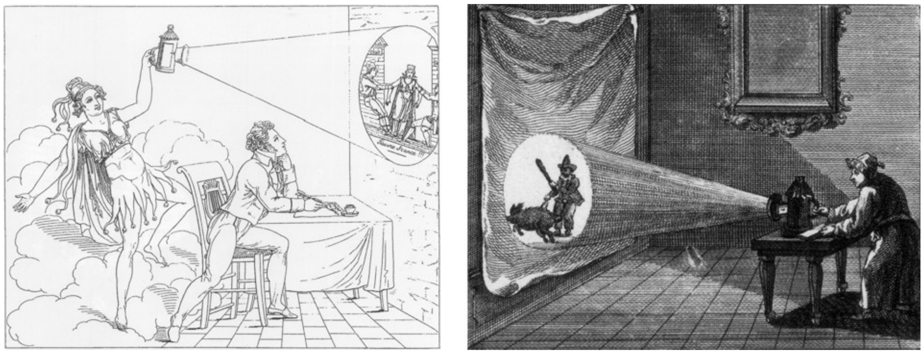


**Figure 6:** Magic lanterns with handles were depicted in use from both handheld and mounted positions. Left: Frontispiece of Les Folies du siècle, 1817, (Crangle et al., 2005) Right: Troldmandens Laterna Magica, 1780, (Mannoni and Campagnoni, 2009).

Although magic lanterns with handles were a more common sight than the belt-mounted variety, there is little evidence to suggest they were designed for mobile use. In many instances handles appear on lanterns with solid bases and legs that suggest use from a mounted position. Illustrations from the time depict their use in both handheld and mounted positions (Figure 6). The most likely candidates for handheld use are the smaller toy magic lanterns that were produced in large quantities in Nuremberg, Germany. Figure 7 illustrates two such lanterns that have a rear handle and are of suitable weight to be carried freely in one hand.

**Figure 7:** Toy magic lanterns with handles attached to the rear (Source: Jack Judson Collection).

## Furo

The vast majority of magic lanterns created in Europe were used from a fixed position. This is radically different in Japan, where the magic lantern was re-invented as a mobile device, known as a *furo*, in the early 1800s. The *furo* was used extensively in the *utsushi-e* performance to act out stories by rear-projecting images onto a rice paper screen.

Much documentation on the *furo* and *utsushi-e* has been lost due to events such as the Great Kanto earthquake in 1923 and the Second World War. Genjiro Kobayashi's Japanese language book 'Utsushi-e' is one of the main sources of information and provides detailed illustrations of how *utsushi-e* was performed (Kobayashi, 1987)[1]. Although a handful of other Japanese language publications document *utsushi-e* (Iwamoto, 2002; Minami et al., 1982; Yamamoto, 1988), English language documentation is limited[2]. I draw from the above sources to describe the *furo* projection device and later the utsushi-e performance.

A major difference between the European magic lantern and the Japanese *furo* was its construction using a light wood (Figure 8). European magic lanterns were typically constructed using metal and their casing would become very hot during use. The Japanese cedar or Paulowina used to construct the *furo* made the device incredibly light and insulated the heat from the oil lamp inside. This allowed the performer to grasp the device directly with their hands and move it in both subtle and exaggerated ways.

The size of the *furo* body ranged from 24-27cm wide, 19-24cm high, 13-15cm deep, and weighed approximately one kilogram. On its front was a slot for the slide holder to be inserted. Each slide holder had between 3-5 slides positioned side by side in sequence. The performer switched between slides by physically moving the slides back and forward. The slide is positioned right next to the condenser lens that focuses the light from the oil lamp. The light passes through the slide and on through the projection lens to enlarge the slide image.

Slides were created by painting directly onto glass and could be as small as 5cm x 5cm, making it a time consuming manual process. Approximately 100 images would be used during each story. Slides were

[1] An unpublished English translation is available in the library of the Magic Lantern Castle Museum.

[2] Several notable English language sources are Prof. Machiko Kusahara's utsushi-e website (Kusahara, 2010) and NHK World's recent documentary on *utsushi-e* (NHK World, 2010).

**Figure 8:** An exact replica of a 19th century Japanese *furo* projector, made by Fumio Yamagata (Source: Jack Judson Collection).

typically painted on a black background for use as foreground images, meaning the performer could freely move the device without drawing attention to the rectangular projection frame. The black background also enabled other imagery to be projected on top of the projection if desired.

### 2.1.2 Contemporary Projection Devices

Contemporary mobile projection devices encompass a considerably more diverse range of technologies and form-factors than their historic counterparts. I now outline the different technologies that can be found in contemporary mobile projectors and list the various form-factors that these technologies have been incorporated into.

#### Technologies

Contemporary mobile projectors typically consist of a *light source*, an *image source*, and a *focusing mechanism* housed together in a portable unit. Many of the technologies introduced here are miniaturized versions of existing standard-size projectors. Others have been specifically developed to cater for the low power consumption and small volume that a mobile form-factor requires.

### Light Sources

The most stringent requirement for a mobile projector light source is power consumption. The light source must produce as much light as possible, while consuming as little power as possible. This means the light source must be highly-efficient with limited heat dissipation. Light-Emitting Diode (LED) and laser-based light sources are currently used in a number of commercial devices.

LED-based projectors can be found in single white LED, and combined red, green, and blue LED configurations. The small size of LEDs (typically 6 x 7 x 2mm) enables a compact optical design (approx. 5.5cm$^3$) that can vary in brightness from 5 lumen to upwards of 80 lumen for a battery powered device (Figure 9). Mains powered devices can be even brighter, up to 300 lumen, but require significantly more current and a cooling mechanism such as a fan. As LED production volumes increase to replace conventional incandescent lighting, prices are expected to steadily decrease.

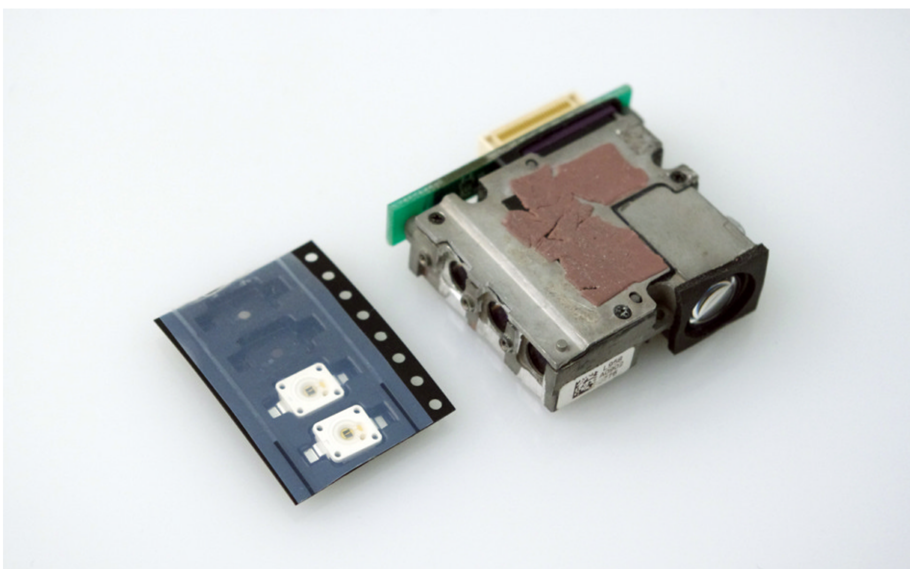


**Figure 9:** LEDs (left) are used as a light source for a Texas Instruments DLP Pico light engine (right).

Laser-based projectors use red, green, and blue lasers to produce an image that is always in focus. The recent development of 'direct' green lasers means laser-based projector modules can have an even smaller volume than LED-based designs (approx. 2.5cm$^3$). Laser-based projectors are subject to laser safety classification to reduce the risk of eye injury. Recent studies have identified the maximum laser brightness possible within each safety classification (Buckley, 2010a,b). Laser-beam-steering (LBS) projectors in particular have surprisingly low limits of 1 lumen (Class-1) and 17 lumens (Class-2) (Buckley, 2010a). Liquid crystal on silicon (LCOS) based projectors have higher limits of 20 lumens (Class-1) and several hundred lumens (Class-2) (Buckley, 2010b). Laser-based projectors can also be affected by visible 'speckle' that can degrade image quality.

### Image Sources

Mobile projector 'image sources' guide or redirect light to create colored pixels that later form an image. A number of competing technologies exist, each with its own advantages and limitations.

Digital Micro-mirror Devices (DMD), most notably Texas Instrument's Digital Light Processing (DLP) technology, work by reflecting light off a 2D array of microscopic mirrors. Each individual mirror can be rotated to an *on* or *off* state. In the on state light is reflected off the mirror to produce a light pixel and in the off state light is directed onto a light-absorbing surface to produce a dark pixel. By rapidly toggling the micro-mirrors on and off with red, green, and blue light sources, different color intensities can be created. DMDs are a mature technology, but due to their small scale and mechanical complexity, reaching higher resolutions remains an ongoing issue.

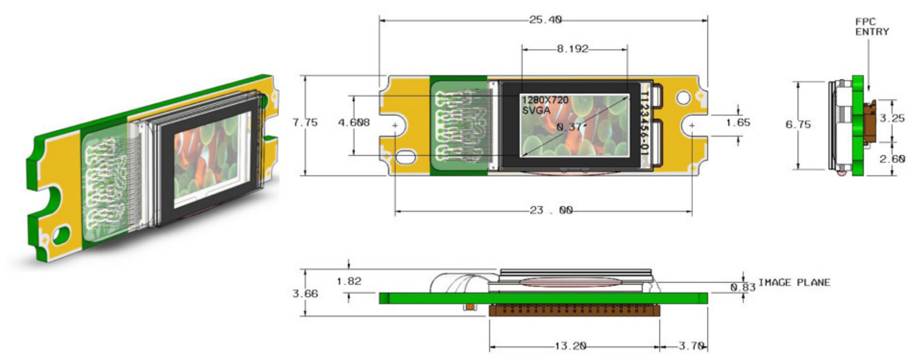



**Figure 10:** LCOS light modulation panels are used to reflect light from an LED or laser light source to create an image. Shown here is the Syndiant SYL2271. Dimensions in mm (Source: syndiant.com).

LCOS-based projectors, like DMDs, are also based on reflecting light for individual pixels (Figure 10). Switchable liquid crystal pixels are applied to the surface of a silicon integrated circuit with a top layer of reflective metal. In the on state light passes through the liquid crystal layer and is reflected back off the reflective metal to produce a light pixel, in the off state light is blocked by the liquid crystal to produce a dark pixel. LCOS pixels can be more tightly packed than DMDs, resulting in higher resolutions. Both DMD and LCOS-based projectors can use LEDs or lasers as a light source.

Laser-beam-steering (LBS) projectors use a fundamentally different approach to image generation by scanning a single 'pixel' across an entire image over time. The laser beam is directed using a bi-axial MicroElectroMechanical systems (MEMS) mirror that scans across the image using a sinusoidal pattern (Freeman et al., 2009). Persistence of vision enables us to integrate the rapidly scanning laser 'pixel' into a single image. High resolutions are achievable, but the uneven pixel distribution caused by the sinusoidal scanning results in reduced image sharpness. LBS projectors are particularly susceptible to high laser safety classification as the full intensity of the laser beam is focused at a single point rather than distributed over an entire image (Buckley, 2010a). LBS projectors also tend to produce more laser speckle when compared with LCOS-based laser projectors.

#### Focusing Mechanisms

The ability to maintain a focused image is particularly important for mobile projectors that are actively moved during usage. LED-based projectors typically use a conventional lens with a manual focusing dial. Although auto-focusing, in a similar manner to digital cameras, is possible, a commercial product with this feature has yet to be made available. Another common characteristic of mobile projector lenses is the top half of the lens is used to project the image upward. By placing the projector on a flat surface, such as a table, the image can be projected onto a perpendicular wall without having a keystone effect.

Laser-based projectors have the distinct advantage of always being in focus, even on angled or curved surfaces. LBS projectors direct the laser onto a projection surface without the need for a conventional lens (Figure 11), although some commercial devices make use of a lens/filter for reducing the amount of laser speckle in the projected image. Laser-based LCOS projectors use a lens to shape/spread the image after it reflects off the LCOS array. Due to the near zero etendue of laser light, the projected image stays in focus over a very large range.

### Form-factors

A key motivating factor behind the development of mobile projectors is the ability to provide a *large* display from a *small* device. This is aptly summed up by mobile projector manufacturer Microvision: "Pico projectors are the latest technology to prove that big things often do come in small packages"

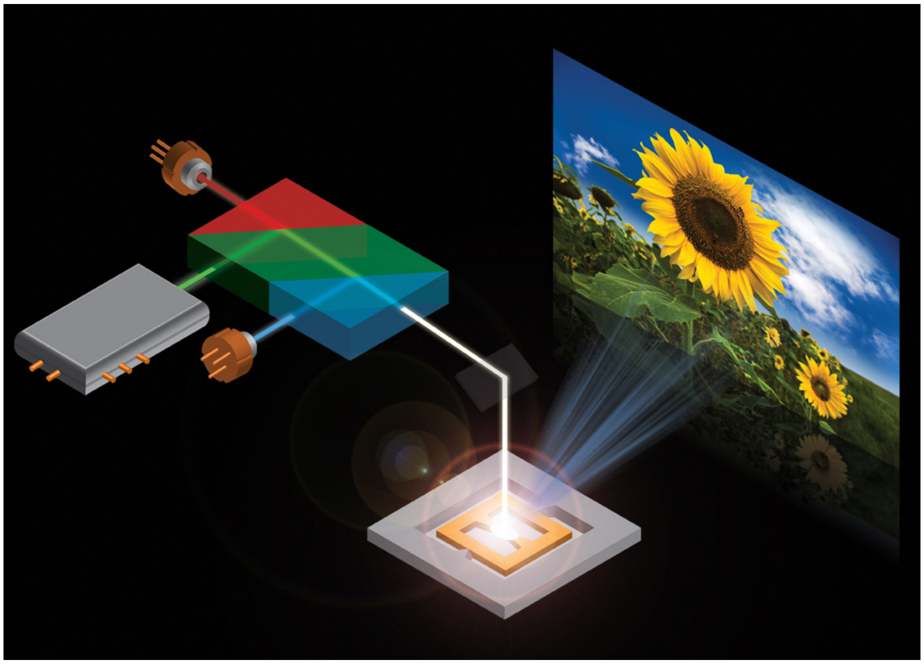


**Figure 11:** Laser beam steering projectors render an image using a MEMS mirror, without the need for a conventional lens (Source: microvision.com).

(Freeman et al., 2009). This motivation explains the industry push towards small devices that deliver a large display experience, rather than developing new forms of interaction. The research community, however, has begun to explore interaction through a range of mobile projector form-factors that build upon contemporary technology.

### Handheld Projectors

Standalone handheld projectors have been available on the market for several years, targeted as a stand-in replacement for conventional projectors and displays in a mobile setting. However, Dachselt et al. (2012) suggest "...the marketing scenarios presented in ads are disheartening: businessmen watching catch-up TV on a hotel wall, groups of executives enjoying an ad-hoc PowerPoint presentation at the watercooler". Despite the lack of a 'killer app' for handheld projectors, manufacturers continue to test the market. More recently mobile projectors have been embedded in handheld devices including mobile phones, digital cameras, and tablet computers (Figure 12).

The research community has been more imaginative in envisioning new usage scenarios for handheld


**Figure 12:** Handheld devices with embedded projectors have been released on the market, including the Samsung Galaxy Beam mobile phone (left) (Source: samsung.com) and the Nikon CoolPix S1000pj digital camera (right) (Source: nikon.com).

projectors, exploring a range of interaction methods. Device movement sensed by motion sensors, such as accelerometers/gyroscopes (Rapp et al., 2004; Raskar et al., 2003), or on-device cameras (Yoshida et al., 2010; Beardsley et al., 2005), has been used to interactively control projected imagery. By tracking the users fingers with a stereo camera, direct touch on the projected image has been used to annotate, rotate, and move digital content directly (Sugimoto et al., 2005). Pen based sketching on projected content, tracked by a commercial motion capture system, has been used for precise writing, drawing, and annotation of digital content (Cao and Balakrishnan, 2006). Interaction with shadows occluding the projection has been used for gestural interaction with digital content by way of an on-board camera (Cowan and Li, 2011) or depth camera (Molyneaux et al., 2012) for real-time tracking. The handheld projector form-factor is particularly relevant to this research and detailed discussion of related work will be introduced in each relevant chapter.

### Wearable Projectors

Perhaps the earliest example of a wearable projector is the *virtual retina display* that projects modulated light directly onto the retina of the eye to create an image (Kollin, 1993). Projectors mounted on the body to project an outward image have been researched in the fields of wearable computing (Mann et al., 2003) and mixed reality (Inami et al., 2000; Karitsuka and Sato, 2003), long before the commercial availability of compact mobile projectors. Karitsuka and Sato demonstrated a range of techniques for interacting with a shoulder-mounted camera-projector unit, such as fingertip interaction with tangible objects to control digital content and freehand sketching on arbitrary surfaces.

Wearable projector systems span across a range of form-factors and include head-mounted projectors that share the same viewpoint as the user (Kijima et al., 2002; Maeda and Ando, 2004), a simulated wrist-worn projector that uses tilt and touch gestures for user interaction (Blaskó et al., 2005), and an ear-worn projector using a camera to detect hand gestures (Tamaki et al., 2009). Wearable projectors have also been considered for use in military contexts to display information to soliders while maintaining situational awareness (McFarlane and Wilder, 2009) or to provide mixed reality-based training (Krum et al., 2012).

A number of wearable projector projects have captured the imagination of the general public by showing projected interaction on the body and everyday surfaces (Mistry et al., 2009; Harrison et al., 2010, 2011). Spatial or touch gestures are used to interact with projected imagery using camera, acoustic, or depth-camera-based sensing. The mobile projectors used with these prototypes are mounted on stable areas of the body such as the head, chest, and shoulder.

### Embedded Projectors

The vision to embed small projectors in everyday objects has existed for some time. Early on, Underkoffler et al. (1999) introduced the concept of the *I/O Bulb*, combining camera-input and projector-output into an ordinary light bulb to sense interaction and display information in future architectural spaces. Similarly, the vision of projector-based *Shader Lamps* was introduced by Raskar et al. (2001) to render dynamic textures onto neutrally-colored physical objects.

More recent research has utilized commercially available mobile and short-throw projectors to build compact prototypes. *Play Anywhere* uses a tabletop projector-camera pair to create interactive experiences with handheld devices and tangible objects (Wilson, 2005). *Bonfire* extends the desktop computing experience onto the tabletop using several mobile projectors mounted on the back of a notebook computer (Kane et al., 2009). *LuminAR* builds upon the concept of the *I/O Bulb* by embedding a mobile projector-camera pair inside an articulated desk-lamp, enabling projected interaction across the workspace (Linder, 2010). A lamp form factor has also been explored by Chan et al. (2010) to support interaction with an interactive tabletop. *Penlight* (Song et al., 2009) and *MouseLight* (Song et al., 2010) explore how a mobile projector can be used to enhance interaction with common input devices such as a pen and mouse.

A number of manufacturers have also exhibited different prototypes that use embedded projectors. Microvision and Intel have developed a 'gun projector' gaming device for navigating first-person-shooter game environments[3]. Using a Microvision projection engine, Pioneer has developed an augmented reality heads-up-display (HUD) for car navigation[4]. The mobile projector is used to project onto a transparent screen and superimpose map and navigation information into the drivers view of the road.

## 2.2 Mobile Projector-based Interaction

Mobile projectors have evolved from simple mechanical contraptions to sophisticated electronic devices. As researchers begin to explore how contemporary mobile projectors can be used for interaction, the use of historical mobile projectors for performance in the 1800s can be a valuable reference source. The role of the performer to control and 'interact' with the projector establishes numerous historical precedents for projector-based interaction.

I begin this section by describing historic interaction with mobile projectors that were used in an entertainment context, including the mobile magic lanterns in Europe and the *utsushi-e* performance in Japan. I then outline and categorize the projection techniques developed for use with historic mobile projectors, contextualize them within contemporary research, and outline how they are being advanced with contemporary technology. Understanding how and why historic mobile projection devices were used deepens and matures our knowledge of this emerging area of research.

### 2.2.1 Historic Interaction

The origins of interaction with mobile projectors arguably lie with the 'phantasmagoria' theatrical performance and the use of a wheel-mounted platform to dynamically move the projector. Phantasmagoria was a popular form of entertainment in Europe in the early 1800s where images of skeletons, demons, and ghosts were projected to frighten the audience (Robinson et al., 2001). Numerous technical innovations were developed to allow the projectionist to display multiple superimposed images, to animate the size of imagery by moving the projector on tracks (Figure 13), and to project on unconventional surfaces such as smoke and translucent screens. Although the magic

[3] Infinite Reality Gaming:
http://software.intel.com/sites/billboard/article/infinite-reality-gaming-microvisions-gun-projectorcontroller

[4] Pioneer AR-HUD:
http://www.microvision.com/displayground/vehicle-displays/pioneer-hud-nav-system-is-powered-by-microvisions-picop/

lanterns used with the phantasmagoria were not truly 'mobile', they established an important historical precedent for active physical movement of a projector to change the appearance of projected imagery.

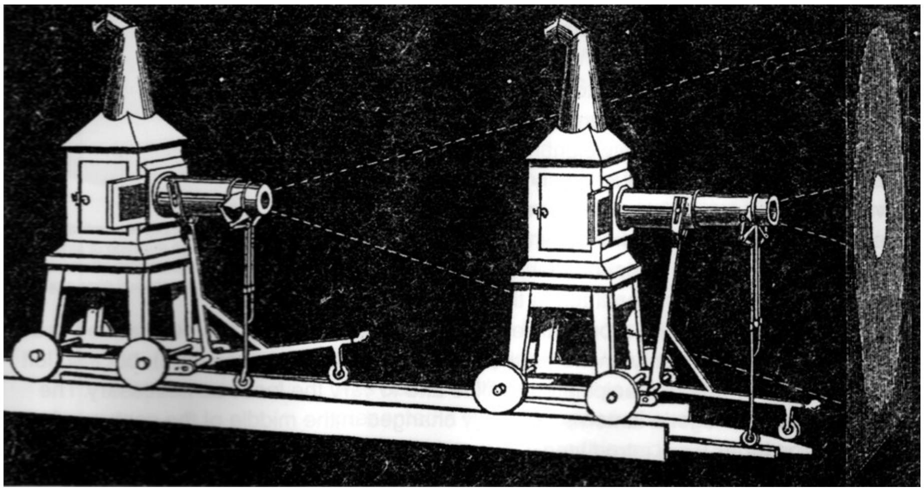


**Figure 13:** During the phantasmagoria performance the size of the projected image could be animated by moving the projector back and forward along a track. Here the magic lantern has a self-adjusting focusing mechanism to keep the image in focus (Robinson et al., 2001).

## Mobile Magic Lanterns

Mobile magic lanterns began to appear sporadically in the literature in the 1800s. Illustrations depicting their use were largely artistic impressions rather than technical explanations of how the devices were used. However, by examining artistic illustrations of 'usage', considering the affordances of the devices themselves, and understanding the broader usage of magic lanterns at the time (e.g. phantasmagoria) we can begin to infer how they were used.

Figure 14 depicts the use of the belt-mounted magic lantern to entertain a family. The rear projection screen and manual adjustment of the lens focus suggests a similar projection style to phantasmagoria to shrink and enlarge the projected image. The accompanying slides used with this projector depict a series of illustrated animals (Figure 15). The black background of the slides suggests the animals were intended to appear free-floating and subtle movements may have been used to create animation within the projection screen area.

Figure 16 depicts a mobile magic lantern with rear handle being used in a family setting. The

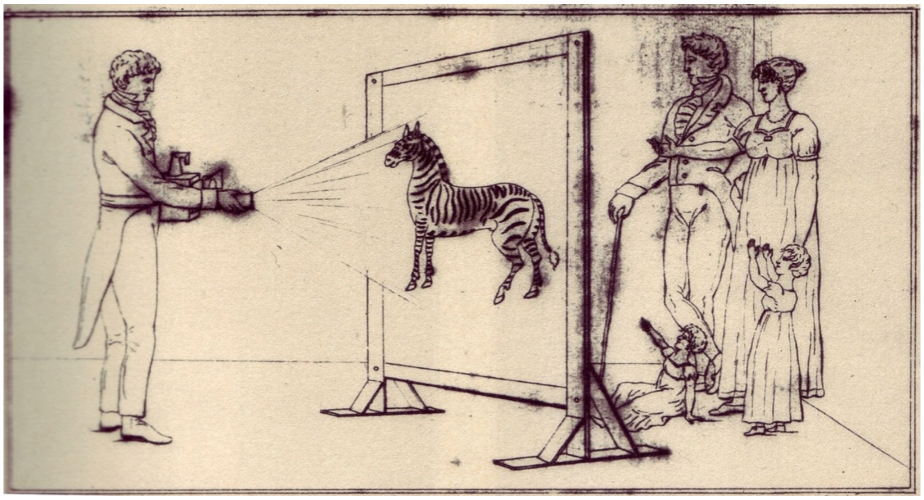


**Figure 14:** A belt-mounted magic lantern is used to entertain a family. Philip Carpenter, 1823 (Source: Erkki Huhtamo Collection).

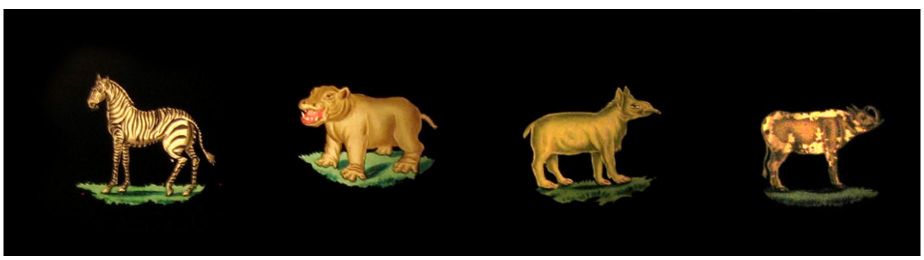


**Figure 15:** Slides used with a belt-mounted magic lantern (Source: Erkki Huhtamo Collection).

projectionist is seated and ready to change slides and we can speculate that he is about to make the character 'walk' using slide changes and movement across the screen. However, little evidence is available to concretely substantiate how the projectionist manipulated the device to perform and 'interact' with the audience.

Although these illustrations ignore many of the practical realities of magic lantern usage, such as heat from the lantern casing, smoke emission, and the size requirements of the light source and optics, they allow us to paint a preliminary picture of mobile use of the magic lantern. Unfortunately there is little reason to think that 'mobile projection' in Europe was anything more than a handful of isolated cases.

**Figure 16:** Illustration showing the use of a magic lantern with a rear handle to entertain a family (Mannoni and Campagnoni, 2009).

## Utsushi-e

In Japan, mobile projectors were the norm rather than the exception. The wooden *furo* was used extensively in the *utsushi-e* performance between approximately 1803 to 1903 (Kobayashi, 1987). *Utsushi-e* was a popular form of entertainment during that time and was influenced by earlier Japanese theater such as *kabuki*, *bunraku*, *rakugo* and *sekkyobushi*. Approximately eight performers would be involved in an *utsushi-e* performance including projectionists, storytellers, and musicians. The audience faced towards a screen that could be as large as 5.4 meters wide by 1.8 meters high. Behind the screen were as many as five projectionists (Figure 17) who each manipulated a *furo* to create one part of the overall image (Figure 18). The *furo* could be placed on stands to project static imagery, or manually moved and angled to create dynamic imagery. The musicians would play the *shamisen*, a three stringed musical instrument, and sing or narrate with the storyteller on the outside of the screen.

The stories told during an *utsushi-e* performance ranged from theatrical pieces known in other forms of Japanese story telling, to ghost stories, war epics, and short pieces demonstrating specific projection effects. For example, seasonal themes common in Japan like the budding of cherry blossoms in the spring, the changing color of leaves in the fall, or exploding fireworks during the summer. Projected imagery would include animated people, characters, and animals, as well as static background imagery

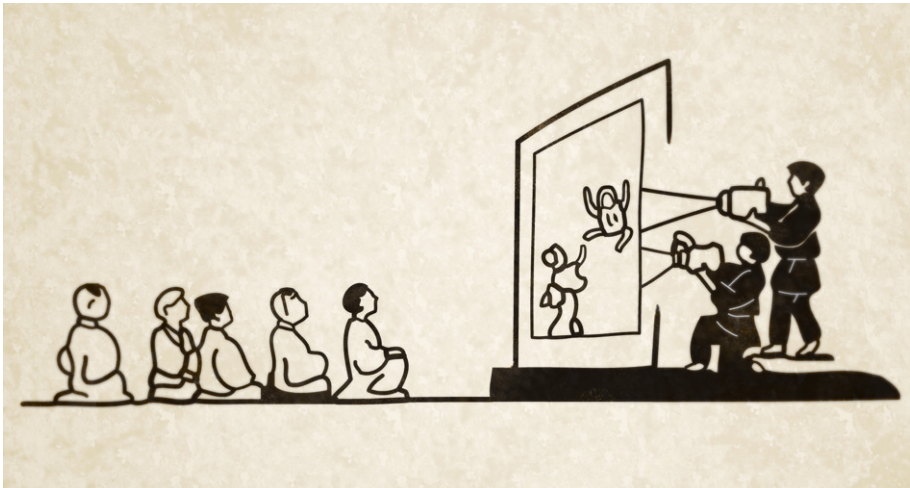


**Figure 17:** *Utsushi-e* was a Japanese performance that utilized multiple mobile projectors to act out a story from behind a rice paper screen.

such as houses, trees, and rivers. Performances would take place at theaters, temples, schools, and homes. With the arrival of cinema, the popularity of *utsushi-e* declined significantly. Today the art form is preserved through workshops and performances by Fumio Yamagata and the Minwa-za Theater Company in Tokyo, Japan[5].

The manual manipulation of the *furo* contrasted with the technical sophistication of European magic lanterns that had levers, gears, cranks, and multiple projection lenses. The affordances of these devices had a direct influence on the style of performance that later developed in Europe and Japan. The wheel-mounted magic lantern used in the European phantasmagoria show was restricted to linear movement toward and away from the screen, although more precise multiple image montage and mechanical slide movement could be used. The *furo* allowed *utsushi-e* performers to freely move the projector up, down, left and right as well as zoom in and out. Rather than use mechanics, effects were performed manually by manipulating the slides or occluding the projection.

[5] Minwa-za Theater Company: http://www.minwaza.com

**Figure 18:** An illustration depicting the audience view of an *utsushi-e* performance from 1832 (Iwamoto, 2002).

### 2.2.2 Projection Techniques

I now categorize and document the techniques used by performers to animate imagery with mobile projectors. Due to the prevalence of handheld interaction in the *utsushi-e* performance, the majority of projection techniques are drawn from *utsushi-e*. The projection techniques fall into four categories that were used in combination during the performance. After introducing each projection technique I discuss related contemporary research and outline contemporary technology that can be used to extend these techniques.

#### Device Movement

The defining feature of the mobile magic lantern or the *furo* is its mobility. Unlike cinema, in which the image frame has a fixed size, location, and shape during presentation, mobile projectors cause the image to move, shake, and distort with every movement of the device. In the case of *utsushi-e*, and perhaps with mobile magic lanterns in Europe, movement of the projector was used to animate projected imagery. The size, weight, and heat-insulating qualities of the *furo* allowed the performer to control the size and location of the image on the screen.

### Techniques

a. Translating the image by moving the device up, down, left, and right.

b. Rotating the device to project on more distant surfaces.

c. Scaling the image by moving the device toward and away from the screen.

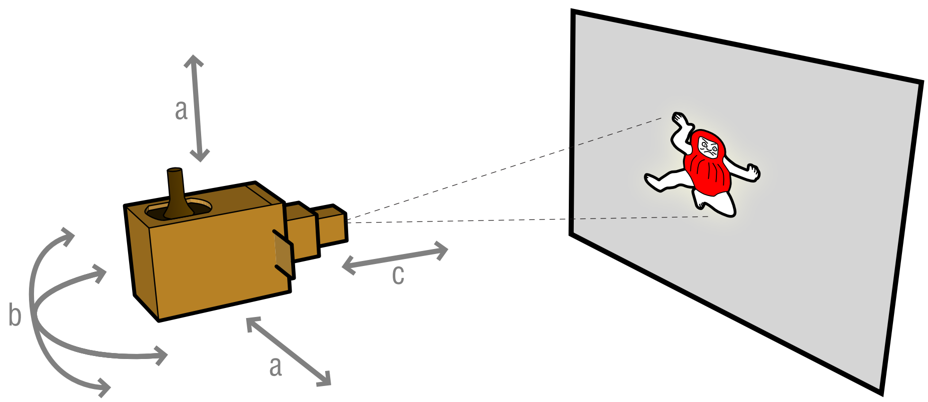



**Figure 19:** Physical movement and rotation of the device was used to position projected imagery.

### Contemporary Research

*Device Movement* is a fundamental affordance created by the miniaturization of projectors. Contemporary devices have reached such a size that they can be controlled with more ease and accuracy than their historic counterparts. Unlike projectors of the past, accelerometer enhanced or optically tracked projectors can sense device movement and dynamically change projected imagery. Automatic keystone correction is an early example used to display a rectangular image when the projector is not perpendicular to the projection surface (Raskar and Beardsley, 2001).

A number of contemporary systems leverage the movement of a mobile projection device for gestural input. Current research has taken two main approaches. The first is strongly linked to *utsushi-e*, where the image is projected into the environment based on the angle and position of the projection device (Yoshida et al., 2010; Willis et al., 2011b,a). As the user moves the projection device, the projected imagery moves with it. This approach can be implemented entirely with sensors on the device, such as inertia measurement units (IMU) with accelerometers, gyroscopes, and magnetometers. In the *Mobile Projector-based Interaction* chapter I introduce a number of techniques for controlling and animating projected characters based on user movement.

The second approach ties the image to the physical environment; when moving the projector the image stays attached to its existing physical position. This approach is known as the spotlight (or flashlight) metaphor, as the user highlights a point of interest (much like a spotlight) inside a larger spatial information space. Rapp et al. (2004) first introduced the concept of panning and zooming to navigate information with physical movement of the projection device, as well as 'clutching' to temporarily lock the projected image with a button click. Although the spotlight metaphor can be implemented roughly with in-device sensing, drift-free registration of digital content onto the physical environment currently requires more complex optical sensing. For example, Cao and Balakrishnan (2006) use a commercial motion capture system to register projected imagery onto surfaces in the environment such as tables and walls.

## Projection Occlusion

*Projection Occlusion* occurs when the performer blocks the projection of light to the screen. This was a common technique used in the *utsushi-e* performance to fade images in and out and to flicker imagery, such as fire or fireworks, by quickly waving a hand in front of the lens.

### Techniques

a. Wiping to make an image disappear using a wooden board.

b. Fading the image in and out by lowering fabric over the lens.

c. Flickering the image by waving a hand in front of the lens.

### Contemporary Research

Projectors enhanced with cameras now have the ability to sense the object occluding the projection or the shadow cast on the projection surface. Computer vision techniques can be used to extract information about the shape of the object, for example, to detect the pose of a users hand. Camera-based interfaces have been used in a number of contemporary systems to interpret the body's silhouette for gestural interaction, most notably in Myron Krueger's *VideoPlace* system (Krueger et al., 1985; Krueger, 1991). Occlusion of projected light has also been used as a pointing interface; the

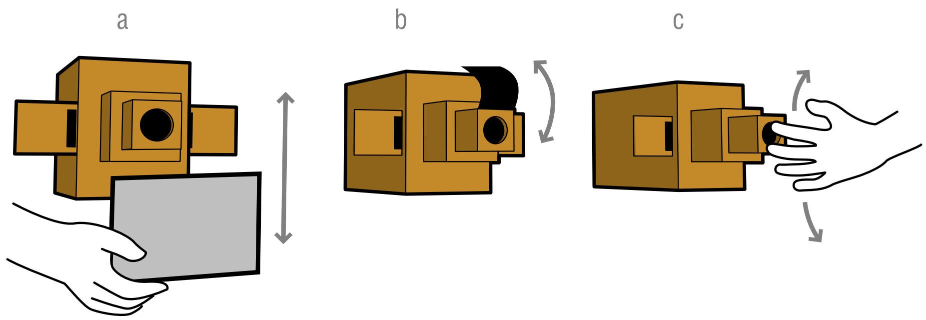



**Figure 20:** Projected imagery is occluded to create visual effects.

shadow cast in front of a fixed projector by a users hand is used to extend their reach for pointing (Shoemaker et al., 2007).

Several recent systems have begun to explore the use of projection occlusion for gestural interaction with mobile projectors. *ShadowPuppets* allows users to cast shadows with their hands for gestural input (Cowan and Li, 2011). Basic hand movements, such as opening, closing, and pointing, are interpreted by the system and mapped to panning, zooming, and selection commands to control a map interface. The *Augmented Projectors* system also supports interaction with shadows cast by the users hand onto the projection surface (Molyneaux et al., 2012). Users interact with projected physics-enabled objects that can collide and bounce off the shadow. The system also supports a similar set of hand gestures as *ShadowPuppets* for pointing, panning, and zooming projected content.

## Multiple Projections

*Multiple Projection* systems montage projected images together on a single screen. During the *utsushi-e* performance, imagery projected from each *furo* would make up one part of the overall image (Figure 18). Techniques to montage multiple images together involved aligning images side by side or on top of one another. Multiple performers, each holding a *furo*, worked in unison to animate their images so they were perceived by the audience as a single overall image. For example, using two separate projectors to depict the launching of fireworks from a boat. From the audience perspective the experience can be likened to cinema with a single screen, but from the performer's perspective multiple separate screens were manipulated simultaneously.

Techniques with multiple projections were also used with dual and triple lens magic lanterns from Europe. Although these devices were not handheld, effects such as cross fading and superimposing images were used in a similar way to Japanese *utsushi-e*.

### Techniques

a. Cross fading between two images by projecting on the same area then fading one image out and the other image in.

b. Superimposing separate images together by projecting from slides with a black background.

c. Combining image segments together to create a single image. Multiple projectors are aligned side by side or on top of each other.

d. Animating superimposed images by aligning them together then moving them apart.

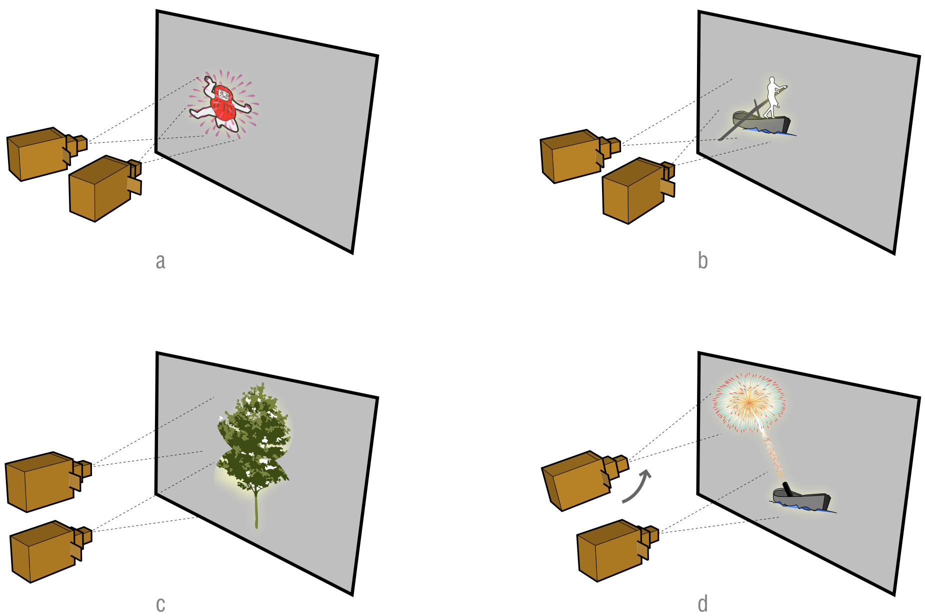



**Figure 21:** Multiple projectors were used to combine and animate imagery.

### Contemporary Research

Embedded cameras combined with computer vision techniques allow contemporary mobile projector-based systems to detect the actions of other users in the immediate environment. Wirelessly communication technologies allow information to be exchanged between multiple devices in real-time. Rather than relying on the performer to execute actions at set times, contemporary devices can receive signals or detect activity and respond automatically.

Several contemporary systems have implemented multi-projector interaction scenarios involving tasks such as passing ownership of a projected object between users (Cao et al., 2007), initializing file transfers by dragging a file onto another users projection (Sugimoto et al., 2005), tiled viewing of projected imagery to create a larger image Cao et al. (2007), game interactions to collaboratively assemble a jigsaw Cao et al. (2008), and lining up projected tiles to create a path for a robot to travel along Hosoi et al. (2007). These systems reply on fixed infrastructure, such as a motion-capture system or cameras mounted in the environment, and substantially limit where mobile projectors can be used.

Several recent projects have attempted to overcome the limitations of fixed infrastructure by using on-device sensing such as IMUs (Robinson et al., 2012) or cameras combined with visible markers (Shilkrot et al., 2011). Each approach has shortcomings, including issues of sensor drift with IMUs and the use of obtrusive markers with a camera-based approach. In the *Mobile Projector-based Multi-user Interaction* chapter I introduce a novel approach for enabling multi-user interaction by projecting and tracking invisible markers from multiple devices.

## Image Design

*Image Design* consists of the spatial layout or temporal sequencing of slide imagery. Manipulation of slides to animate imagery was prevalent with both the European magic lantern and the Japanese *furo*. Numerous techniques were developed, which proved to be one of the primary methods to animate imagery before cinema. Listed below are some of the most prominent techniques.

### Techniques

a. Switching between slides by shifting the slide piece from one slide to the next.

b. Rotating the image. For *utsushi-e* this was achieved by pulling a string to rotate a circular slide, and for European magic lanterns a crank attached to a worm drive produced the same effect.

c. Occluding parts of the image with black slide patterns to animate movement. This was achieved by pushing/pulling the entire black patterned slide or one segment of it.

d. Segmenting slides into multiple parts to animate individual movement by directly manipulating the slide.

e. Coloring an image by moving a colored slide over an outline slide.

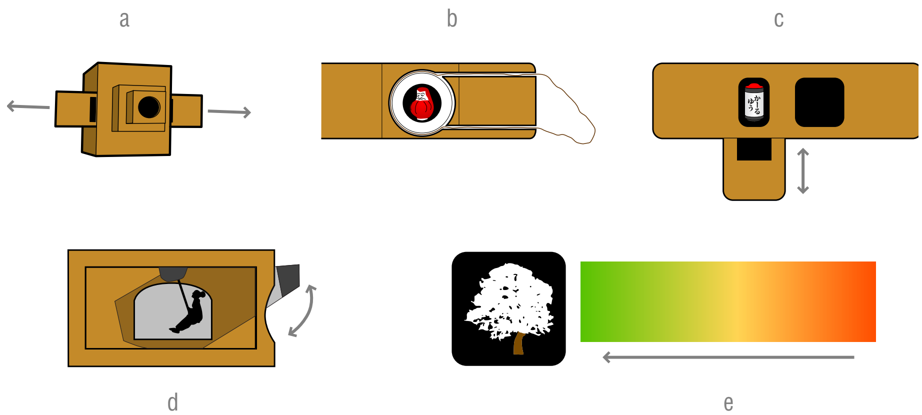



**Figure 22:** Slide images are manipulated to create animated content.

Contemporary Research

*Image Design* can be broadly considered as the treatment and effects applied to projected imagery. The technology for contemporary mobile projectors in this area has changed dramatically from the use of glass slides in historic projection devices. Instead of compositing individual pre-defined images, dynamic imagery can be created from 2D pixel arrays representing the red, green, and blue (RGB) color channels. Contemporary devices with powerful graphics capabilities can animate imagery using either 2D or 3D graphics.

*Image Design* represents a fundamental consideration for interactive mobile projector systems and encompasses the style of graphics and how they change in response to user input. Imagery can be mapped to device movement based on real-time input from motion sensors or input devices such as buttons, touch panels, or pens. In the *Mobile Projector-based Interaction* chapter I introduce a detailed exploration of mappings between user movement and projected imagery, including discussion of how staging, movement, animation, physics, and perspective treatments can be applied for convincing real-time interaction.

## 2.3 Discussion

Although technologically primitive by today's standards, the illusions and performances created with early projection devices were extremely popular in the pre-cinema era. I now discuss how knowledge of historic mobile projection devices, techniques, and performance can be used to inform the design of new mobile projector systems.

### 2.3.1 Performance

Early mobile projectors were used predominantly in a performance context. The projectionist would perform by manipulating the projection device in front of an audience. This changes the dynamics of 'interaction' when compared to a contemporary HCI scenario where a user interacts with a system. If we frame HCI as theater (Laurel, 1991), we can consider the user as the actor or performer. They interact with both the system (the projection device), other actors that share the stage, and perform for members of the viewing audience.

As mobile projectors project outward into public space, they provide a spectacle for the viewing audience. Unlike mobile devices with inward facing screens, there is little assumption of privacy and limited opportunities to conceal information. Designing the experience of the viewing audience is a key consideration in a performance context. For theater this involves the careful crafting of events on stage and the clever concealment of objects off stage. This raises several questions for the design of new mobile projector systems: Does the interaction invite audience involvement or discourage it? How does the audience interpret and react to projected content? Can new users learn the interface by observing from the audience?

### 2.3.2 Large-Scale Interaction

*Utsushi-e* performances are notable for their use of multiple projection devices combined on a large screen. Contemporary systems catering to as many as three users have been developed (Cao et al., 2008), but I am unaware of any work exploring multi-user interaction on the same physical scale as *utsushi-e*. To cover the entire screen, performers would combine angling of the projection device with body movement from one side of the screen to the other. This differs significantly from conventional computer-based interaction performed from a fixed location.

Covering a large surface area with multiple projectors requires either very bright projectors controlled at a distance with arm movement, or dimmer projectors controlled up close with body movement. Much like the projection devices used with *utsushi-e*, the current generation of mobile projectors has limited brightness. To cover a large surface area, interaction must take place relatively close to the projection surface and encompass active body movement. This poses several questions for the design of large-scale mobile projector systems: Is it necessary for each user to see and understand the entire scene? How does the audience perceive the scene – as isolated fragments or as a unified scene? How can body movement across a large area be used for gestural interaction?

## 2.3.3 Gestural Interaction

The physicality of interaction with historic projection devices offers a source of inspiration for developing gestural interaction techniques. These techniques draw upon our understanding of the physical world (Dourish, 2001) and our 'body awareness & skills' (Jacob et al., 2008) to produce more expressive interaction than the common 'window, icon, menu, pointing device' (WIMP) style interface. Projection techniques used by *utsushi-e* performers are heavily gestural, with the coordination of hand and body movement a key component in animating imagery. Examples include animating the movement of a character with a rhythmic motion, pulling on a string to spin an image back and forward, or creating a flickering effect by waving a hand in front of the projector. Although mechanically simple, these gestures allow enormous expressive range for the performer to work with.

By embedding motion sensors or cameras on the device, we now have the ability to sense gestures and map them to specific functionality. This allows considerable more flexibility than the direct mechanical mappings used with historic devices. Designers of future mobile projector systems should consider how to best utilize gestural interaction. This can range from the expressive mapping of user movement to projected imagery, to triggering functionality based on predefined gestures. Many of the historic projection techniques discussed in this paper provide a useful starting point for the exploration of gestural interaction with contemporary technology.

## 2.3.4 Naïve Optics

Movement of the projection device was a major part of the *utsushi-e* performance. To understand how movement of the device corresponds to movement of the projected image, we must draw from our understanding of 'naïve physics' (Jacob et al., 2008). This includes our naïve understanding of optics: how light, shadow, and reflection function in our day-to-day life. By pointing with a projection device, our intuition tells us where the light will be cast without a formal understanding of the geometric relationship between a light source and a projection surface.

User movement of the projection device naturally leads to a shaky and sometimes distorted image. Contemporary research has addressed these issues by dynamically correcting the image as the projector moves. Minor shaking of the image is compensated so as to appear static, and distortion is corrected so to remove the keystone effect Raskar et al. (2003). Despite what may have been a shaky and distorted image, *utsushi-e* performance was a popular form of entertainment for over 100 years in Japan. The willing suspension of disbelief may have contributed to the audience ignoring imperfections in the presentation to follow the performance. Although many contemporary systems utilize image stabilization and distortion correction, an uncorrected image may well conform better to our naïve understanding of optics. Distortion in particular is a form of visual feedback that lets the user understand the angle at which they are projecting. A future study may seek to determine the benefits achieved when these techniques are implemented or not.

## 2.4 Summary

There is a rich history of mobile projector-based interaction. I have examined the two main types of historic mobile projection devices used in Europe and Japan and compared them to contemporary technology. I documented the projection techniques used with these devices and contextualized them in relation to contemporary research. Finally I provided discussion and commentary on how knowledge of this history can inform the development of future mobile projector-based systems.

Early mobile projection devices and techniques established important precedents that are relevant to contemporary research. Understanding how and why these devices were used deepens and matures our knowledge of this emerging area of research. With the growing interest in mobile projector-based interaction, now is an ideal time to reflect upon the past so we can understand and create the future. In the next chapter I draw from the historic use of the mobile projector, and in particular *utsushi-e*, to explore gestural interaction with mobile projectors.

# 3 Mobile Projector-based Interaction

Despite the significant predictions regarding the number of mobile projectors to enter the market (Pacific Media Associates, 2012), only a relatively small amount of research has focused on developing new applications and interaction techniques for handheld mobile projection devices. One of the major challenges is to develop interaction techniques that accommodate movement. Projected imagery moves, shakes, and distorts with the user's every move. In this chapter I present a novel interaction metaphor, labeled *MotionBeam*, which uses the movement of the projection device to control and interact with projected characters (Figure 23).

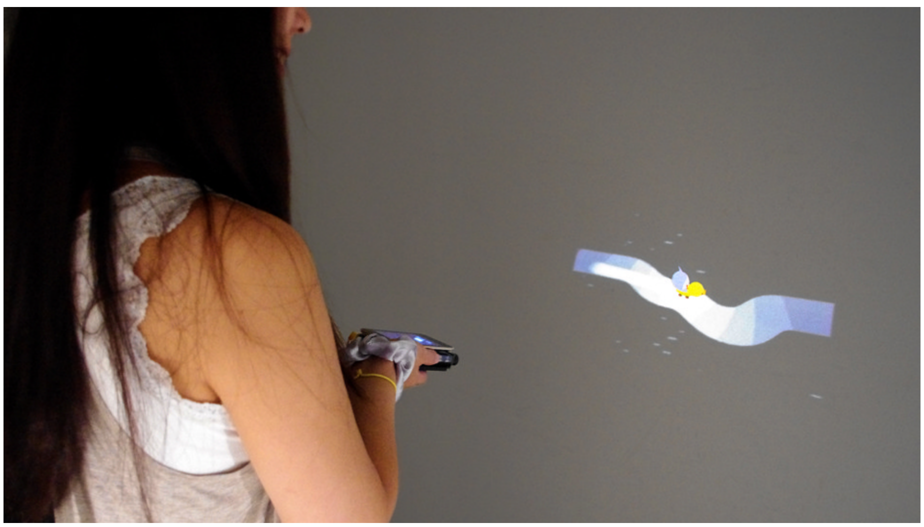


**Figure 23:** *MotionBeam* is a metaphor for character interaction with mobile projectors.

This work draws from the tradition of historic mobile projectors that use direct physical manipulation to control projected imagery. Rather than attempt to mitigate the effects of projector movement, I seek to encourage it by using the projector as a gestural input device. This creates a unified interaction style where input and output are tied together within a single device. To outline the use of the *MotionBeam* metaphor, I present a set of interaction principles, detail the implementation of several prototype applications with a custom device, and describe observations from a preliminary user study with the system.

Character interaction has applicability to a range of important domains such as games, educational software, virtual worlds, storytelling, and numerous other applications where an avatar is used to represent a user. In the long-term, the development of holographic, volumetric, and shape-changing displays will make character experiences even more convincing. Although future technologies will empower this area of research, we can build the foundations for richer interaction with projected content today. I present the following contributions:

- I introduce the *MotionBeam* metaphor and interaction principles.
- I present prototype applications running on a custom hardware device to illustrate the use of the *MotionBeam* metaphor.
- I describe observations and insights from a preliminary user study with the system.

## 3.1 Related Work

This work draws specifically from the use of historic mobile projectors, such as the mobile magic lantern and the *utsushi-e* performance, to control and animate projected characters. I extend this work using contemporary technology to dynamically change the projected content based on user movement and gestures.

### 3.1.1 Input Methods

Contemporary research with mobile projectors has explored a range of input methods such as on-device touch sensors (Blaskó et al., 2005), direct touch on the projected image (Sugimoto et al., 2005), pen based sketching on the virtual environment (Cao and Balakrishnan, 2006), acoustic sensing on skin (Harrison et al., 2010), and hand gestures (Mistry et al., 2009). In this work I focus on coupling together the movement of the projection device to the imagery projected. This approach avoids the problem of attention shift between input device and projected image by tying together input and output within a single device. Other areas with relevance to this work include research concerned with pointing-style interaction such as virtual reality ray-casting (Bowman and Hodges, 1997) and laser pointer based interfaces (Kirstein and Mueller, 1998).

### 3.1.2 Movement-based Approaches

The issue of projector movement has been approached from several directions. Early research addressed the problems of image stabilization and distortion correction (Raskar and Beardsley, 2001; Raskar et al., 2003). By dynamically correcting the image as the projector moves, conventional content can be viewed in a regular fashion. Although a static projected image is well suited to numerous applications, the mobility of mobile projectors is one of the key affordances of the technology. I believe it is important to investigate interaction techniques that are suitable for use with movement. Other approaches that explore the movement of mobile projectors include systems such as *CoGAME*, where users interact to connect projected tiles together and form a path for a small robot (Hosoi et al., 2007), and *Twinkle*, where users guide a projected character to interact with objects in the environment (Yoshida et al., 2010). These works present promising initial investigations into the use of device movement to control projected imagery.

### 3.1.3 Spotlight Metaphor

A significant portion of research has focused on the spotlight metaphor (Blaskó et al., 2005; Cao and Balakrishnan, 2006; Cao et al., 2007, 2008; Rapp et al., 2004), where the projector reveals a section of a larger virtual environment that is tied to a physical space. The spotlight metaphor is primarily concerned with navigating a virtual background space. In contrast, this work is focused on interaction with characters in the foreground. I believe the two approaches are complimentary and represent the primary metaphors for gestural interaction with mobile projectors.

### 3.1.4 Character Interaction

There has been a significant amount of work on controlling and navigating on-screen characters with input modalities such as body movement (Maes et al., 1997), voice (Igarashi and Hughes, 2001), sketching (Thorne et al., 2004), and tangible interfaces (Johnson et al., 1999). However the use of mobile projectors to project into arbitrary physical environments represents a largely different interaction scenario from previous fixed-screen systems.

## 3.2 MotionBeam

*MotionBeam* is an interaction metaphor for controlling projected characters with user movement and gesture. The essence of the *MotionBeam* metaphor involves the control of an object on the end of a metaphorical beam (Figure 24). The user has control over one end of the beam, while the object is linked to the opposite end. Moving the object up, down, left, and right is as simple as pointing the beam in the desired direction. The direct control of the projection device creates an immediate link between the device and the projected object. Physical movement and angling of the device draws upon our understanding of 'naive physics' and our 'body awareness and skills' (Jacob et al., 2008).

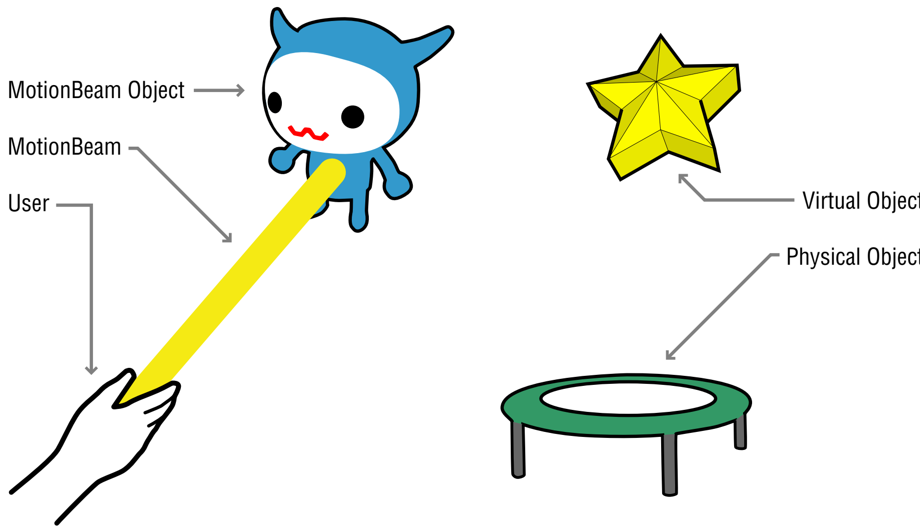



**Figure 24:** The *MotionBeam* interaction metaphor is used to control characters as if they were attached to the end of a metaphorical beam, allowing interaction with virtual and physical objects in the environment.

Characteristics of the object can be changed dynamically based on how the user moves, gestures, and interacts with the *MotionBeam*. This can include the direction the object faces, animation of the object, size of the object, distance from the end of the *MotionBeam*, or viewing angle. These characteristics may also change when encountering other digital objects in the environment.

### 3.2.1 MotionBeam Components

The *MotionBeam* metaphor can be abstracted to a set of five core components:

- ***User***: Moves, rotates, and points the *MotionBeam*.
- ***MotionBeam***: A metaphorical beam that guides and controls the *MotionBeam* object.
- ***MotionBeam Object***: A virtual object linked to one end of the *MotionBeam* and controlled by user interaction on the other end.
- ***Virtual Object***: Objects that are displayed in the physical environment. Virtual objects can interact with the *MotionBeam* object.
- ***Physical Objects***. Objects within the physical environment. Physical objects can interact with the *MotionBeam* object.

## 3.2.2 Interaction Principles

The interaction principles outlined here show how the *MotionBeam* metaphor can be applied using mobile projector-based systems. To guide the design of these principles I have drawn from frameworks in related fields pertaining to animation (Lasseter, 1987) and sequential art (McCloud, 1993). This work deals directly with the use of imagery to illustrate the characteristics of animated characters and their interaction with other objects. I take a similar approach by defining principles that are not hard binding rules, but rather a toolkit for designing a wide variety of interactions with the *MotionBeam* metaphor. The interaction principles are not mutually exclusive and may be combined appropriately for each design scenario.

### Local & Global Space

The *local space* is contained within the projected image and the *global space* encompasses the overall projection environment. Physical gesturing of the projection device translates the entire local space across the global space (Figure 25). The existence of two spaces contrasts dramatically with the static display frame used throughout the history of moving image. The *MotionBeam* metaphor is designed explicitly to work with a moving screen. The *MotionBeam* object is tied to the middle of the local space, with the primary motion caused by the user moving the entire local space across the global space.

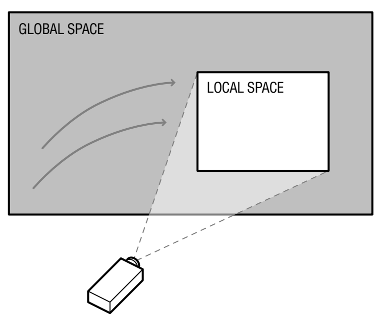



**Figure 25:** *Local & Global Space* Interaction Principle.

### Movement

*Movement* is the change in location of the local space within the global space. Movement can be accentuated by displaying a motion trail left behind from past locations (Figure 26). Sequential art utilizes numerous techniques to stylize movement including: zip ribbons showing a path traveled, multiple images depicting past object locations, and blurring akin to long exposure photography

(McCloud, 1993). Afterglow effects have also been used to illustrate changes in the state of interface widgets (Baudisch et al., 2006). When using these techniques with the *MotionBeam* metaphor, the motion trails emerge from the *MotionBeam* object then flow out in the opposite direction from user movement. A path of motion is 'left behind' that maps out the most recent series of locations.

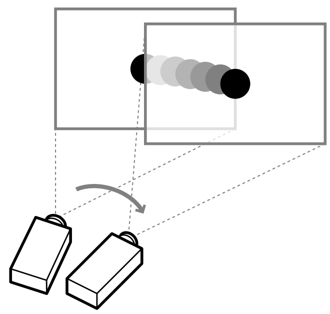


**Figure 26:** *Movement* Interaction Principle.

## Physics

*Physics* is the simulation of physical properties to illustrate interaction between the *MotionBeam* object, virtual objects, and user gestures. Each interaction pair can utilize different physical properties to illustrate and emphasize the interaction taking place. *Physics* can often be depicted using simple translations from the center of the local space. For example, a feeling of friction can be created if the object resists user movement and moves in the opposite direction (Figure 27). The texture of a virtual or physical surface can also be illustrated by translating the object to depict a bumpy or smooth ride. The object can also be influenced by gravity; an upward flick motion can throw an object out of the screen, only for the object to return back again with gravity.

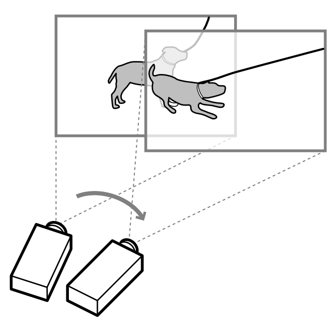


**Figure 27:** *Physics* Interaction Principle.

## Animation

*Animation* is the depiction of changes in the state of the *MotionBeam* object over time. It can be depicted in a number of ways including rotation, deformation, transformation, or color change. *Animation* can be derived from movement within the global space, interaction with virtual and physical objects, character behavior, or user gestures. A fundamental form of animation is based on the heading and speed of the handheld projector. For example, the individual frames from Eadweard Muybridge's *The Horse in Motion* can be animated with a left to right motion. This leaves the impression of the horse galloping across the physical background (Figure 28). Objects can also be animated to face the direction of movement. These approaches reflect to the user that the object is aware of the overall environment and responsive to user interaction.

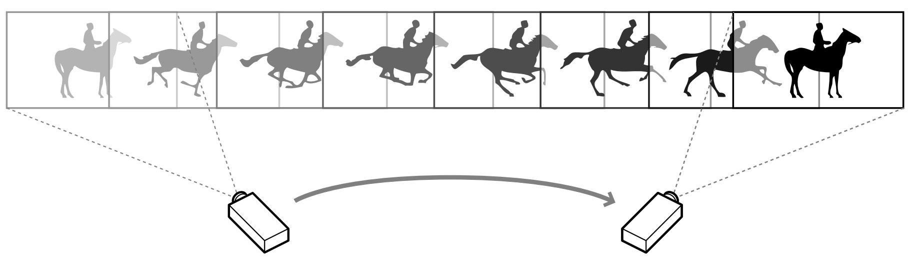


**Figure 28:** *Animation* Interaction Principle.

## Augmentation

*Augmentation* is the interaction between the *MotionBeam* object and physical objects. This relationship can flow in two directions; a physical object can affect the *MotionBeam* object or the *MotionBeam* object can 'push back' and affect the physical object. For example, a car driving along the top of a picture frame falls off when it reaches the end (Figure 29). Conversely, the car could cause the picture frame to come ajar by landing on top of it with force.

## Perspective

*Perspective* is the viewpoint of the *MotionBeam* object in relation to the projection device. The viewing angle of the *MotionBeam* object can be mapped to the angle at which the user is pointing with the projection device. For example when projecting a 3D cube, pointing the projector towards the ground displays the top of the cube; pointing the projector toward the ceiling displays the bottom (Figure 30). *Perspective* mappings can create an intuitive correlation between the physical pose of the projector and the viewpoint of the projected object.

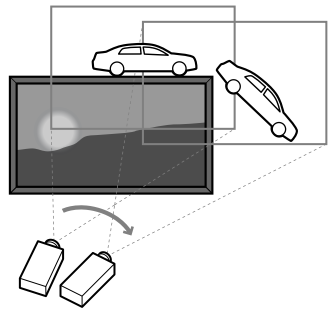


**Figure 29:** *Augmentation* Interaction Principle.

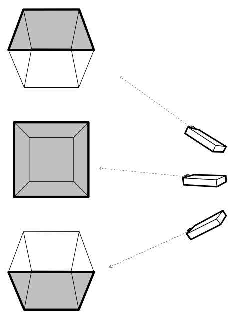


**Figure 30:** *Perspective* Interaction Principle.

## Staging

*Staging* is how the *MotionBeam* object is situated within the physical environment. In traditional animation *staging* aims to focus the attention of the audience by minimizing distractions in the frame (Lasseter, 1987). An important aspect of *staging* is the use of silhouette to highlight the main point of focus. This is particularly important for mobile projectors that have limited image brightness and contrast; a strong silhouette will still be visible in conditions of high ambient light. The foreground object can be rendered on a black background to avoid displaying the rectangular projection frame. This strengthens the illusion of the object existing unframed within the physical environment (Figure 31).

## Closure

*Closure* is the relationship between actions performed in separate projection frames. The concept of *closure* is used in sequential art to infer meaning from a sequence of image panels (McCloud, 1993). By viewing one panel followed by another a single meaning emerges. For example, a panel of a shooting

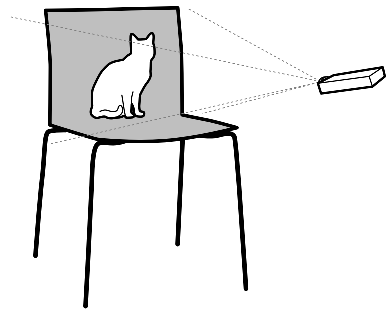


**Figure 31:** *Staging* Interaction Principle.

gun beside another of a speeding ambulance infers that someone has been shot. This same principle can be applied to interaction with multiple projection frames where only parts of a larger scene are revealed. Actions are shown sequentially in each frame to infer an overall meaning. For example, depicting a pitcher throwing a baseball from one frame, followed by a baseball entering a separate frame, infers that the ball has passed from one frame to the other Figure 32). The baseball may not have followed a perfect path or transitioned with perfect timing, but *closure* leads us to perceive it as the same object.

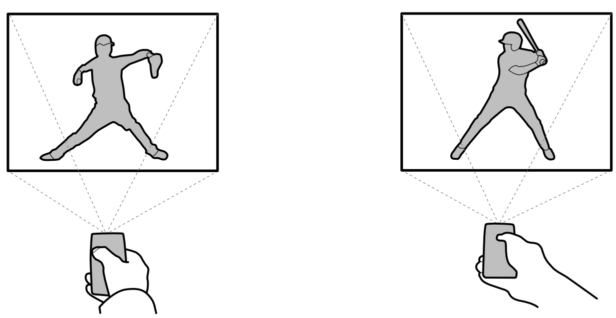


**Figure 32:** *Closure* Interaction Principle.

## 3.3 Implementation

I now describe the creation and implementation of a handheld prototype and several example applications. The prototype system is used to determine the feasibility of the approach – issues such as sensing accuracy, projection quality, and system latency, to explore the possible application space, and to demonstrate the *MotionBeam* interaction principles.

I developed two example game applications that provide an ideal platform to explore a range of character interaction scenarios. These applications demonstrate each of the *MotionBeam* interaction principles with the exception of *Closure* and *Augmentation*, which are explored in-depth in the *Mobile Projector-based Multi-user Interaction* and *Mobile Projector-based Interaction with the Environment* chapters respectively.

### 3.3.1 Prototype

The *MotionBeam* prototype is implemented using an iPod Touch 2G, a Microvision ShowWX laser projector, and a microcontroller-sensor unit (Figure 33). The attached sensors include a 9DOF accelerometer/gyroscope/magnetometer board and an ultrasonic distance sensor (MaxSonar). Applications run in real-time on the device and are written in a combination of C++, OpenGL, and Objective-C.

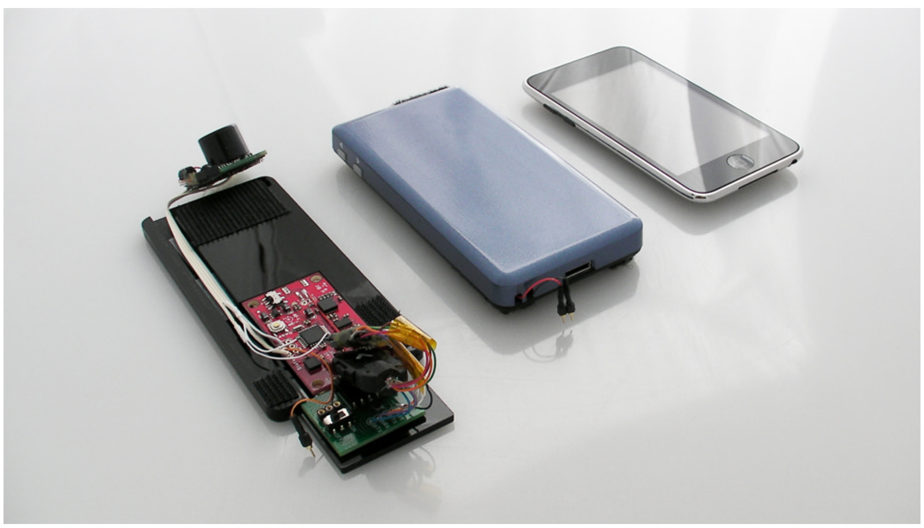


**Figure 33:** The *MotionBeam* prototype. From left to right, a sensor unit, a mobile projector, and an *iPod Touch*.

After a simple calibration sequence, the 9DOF sensor provides absolute orientation values. The distance sensor is used to determine if there is a projection surface within range. The iPod dock connector is used to communicate via serial with the sensor unit and send an S-Video signal to the projector. The touch screen can be used for input simultaneously with the projector. However due to the gestural nature of the interaction metaphor I chose to limit touch screen interaction to a single

‘Start’ button. The size of the device is 164 x 62 x 32mm and it can be grasped by an average sized hand. System latency is almost unperceivable from a user standpoint. The response time between gestural motion and change in projected imagery is no longer than a single frame update (~40ms) running at ~25fps.

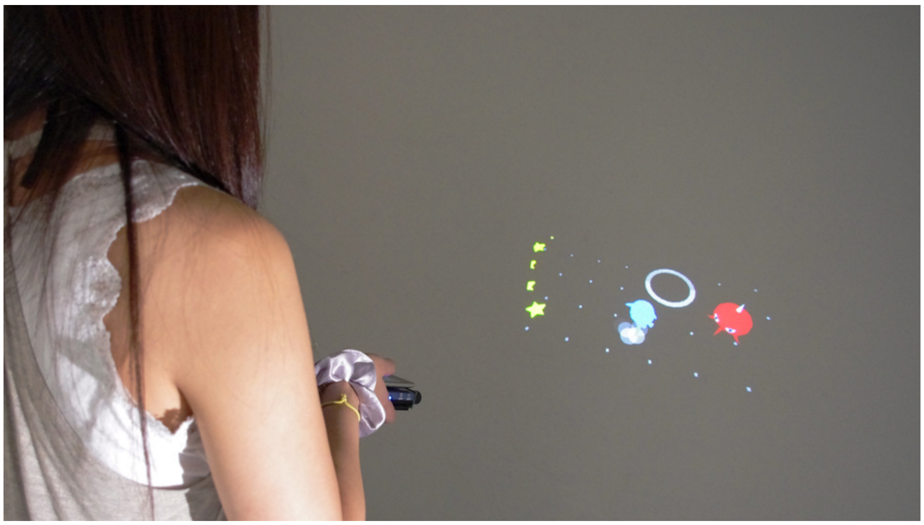


**Figure 34:** Interaction with the *MotionBeam* character game.

### 3.3.2 Character Game

In the character game the user guides a character through the game space by pointing with the projection device (Figure 34). Movement of the character is relative to other objects in the game space, allowing the user to lead the character towards or away from other game objects. Game play involves guiding the character along a trail of stars to collect points and increase the user’s score. The user must try to avoid the ‘bad-guy’ character that chases them in an attempt to throw the character in the air and decrease their score. Once the user reaches the end of the trail they discover the goal – the character’s missing car. The faster the user reaches this goal, the higher their score.

The mechanics of the character game are based on interpreting user movement of the device and mapping it to the projected image in real-time. Specific mappings are guided by the *MotionBeam* interaction principles. In keeping with the overall *MotionBeam* metaphor, the position of the character stays fixed to the middle of the projection frame. The *Local & Global Space* principle governs how transformations of the character are applied within the local space (the projection frame), while overall

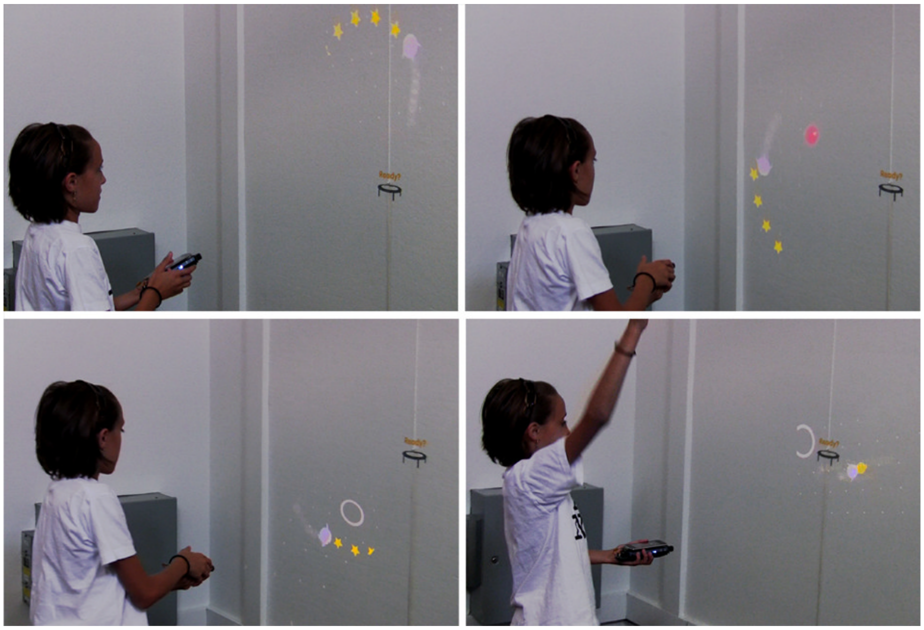


**Figure 35:** In the character game, the user guides the character through the game environment by physically moving and gesturing with the projection device.

movement of the character across the physical environment is perceived in the global space.

The *Movement* principle is used to emphasize the motion of the character across the physical environment. A motion trail is added behind the character to indicate the speed and direction travelled. A simple implementation can be visually effective using only a short window of relative acceleration.

The *Animation* principle is applied by rotating the character to point in the direction of movement. This gives the impression that the character is attentive and aware of user input. Other simple animations include the character transitioning to riding its car when the two objects intersect.

The *Physics* principle is used when the character interacts with other objects in the game space. For example when the 'bad-guy' intercepts the character and sends it flying into the air (Figure 36, top), or when the character strays into an out-of-bounds area and falls from the game area. In both of these examples the character is displaced from the center of the local space to depict the physics based interaction.

The *Perspective* principle is used to change the viewing angle so display of the character is changed in relation to the environment. When projecting at a right angle to the wall, the character is viewed from a top-down perspective so it can easily be guided around in relation to other game objects. Tilting the device downward incrementally shifts the viewing angle so the character is viewable from the front. This adds depth to the game by allowing the character to be viewed in 3D form and also allows the user to view the game space from multiple perspectives.

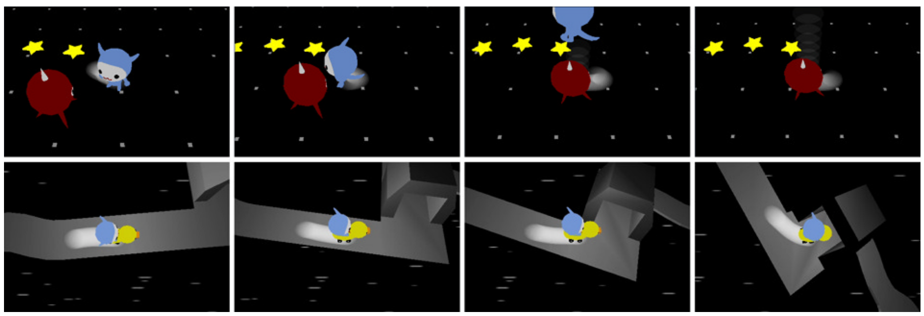


**Figure 36:** The *Physics* (top) and *Perspective* (bottom) interaction principles applied in the *MotionBeam* prototype games.

## 3.3.3 Racing Game

In the racing game the user steers the character's vehicle to reach the end of a racetrack without falling off (Figure 23, 37). By tilting the projector from side to side, the user controls the direction of the vehicle as it moves along the track. The speed of the vehicle is controlled automatically and gradually increases as the game progresses. The track also becomes more difficult as the game goes on, the user must navigate sharp turns, dead ends, and tunnels. If the vehicle does fall from the track it is repositioned after a short delay. As with the character game, the faster the user reaches the goal, the higher their score.

The racing game demonstrates a similar selection of interaction principles as the character game. These are implemented using variations of the algorithms from the character game. *Animation* is used to control the rotation of the vehicle so it faces in the direction of user input. *Movement* is used to emphasis the speed of the vehicle by displaying a motion trail. *Physics* interaction displaces the vehicle from the center of the projection frame when it collides with an obstacle or falls from the track. *Perspective* is used to change the viewing angle of the game scene. When projecting at a right angle to the wall, a top view is displayed; by tilting the device downward the view gradually shifts to a front-on position. This enables the user to navigate through areas of the track, such as tunnels, that are not

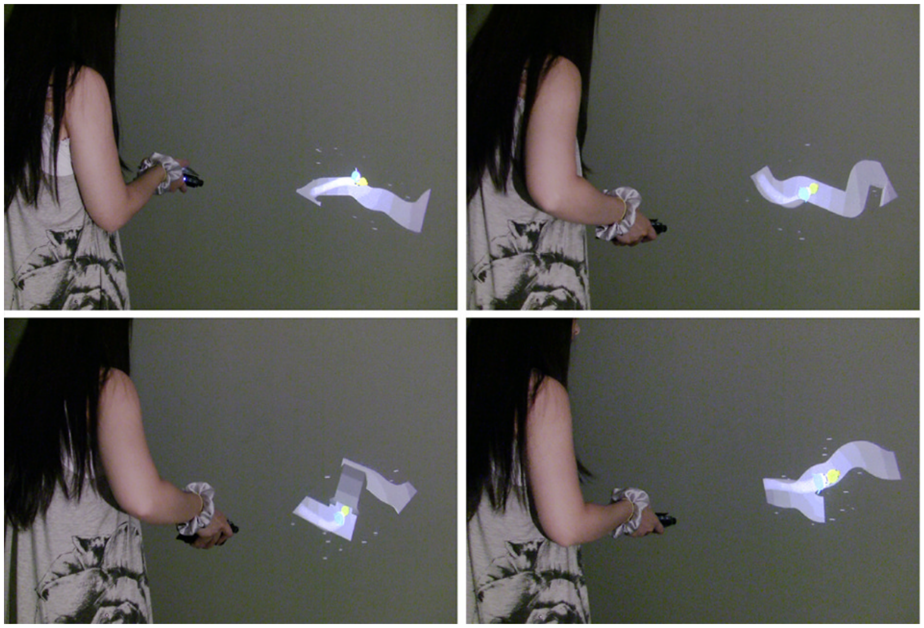


**Figure 37:** In the racing game, the user leads the characters vehicle along a track by physically tilting the projection device.

visible from the top view (Figure 36, bottom).

## 3.4 User Study

I now present details of a preliminary study conducted to observe user interaction with the *MotionBeam* system and answer the following questions:

1. Does the amount of projector movement and distortion required by the *MotionBeam* metaphor make the screen difficult to watch?
2. How do users gesture with the device? How can we improve the interface for this interaction style?
3. At what range do users interact? For what reason?
4. What are the participant's impressions of the system?
5. What future studies are needed to better understand interaction with mobile projectors?

### 3.4.1 Participants & Procedure

Eight participants (five female and three male) were recruited from the local area. Five were adults aged between 21-41 (mean 27.83) and three were children between 8-12 (mean 10). Participants played the game in pairs with the exception of two people who played individually due to cancellations. None of the participants had used the system before. Participants were first given a simple demonstration of the game and then invited to play it themselves. No time limit was set for interaction, rather participants were invited to replay the game at will. During the game play we observed interaction and filmed each participant for later analysis. Data was recorded including sensor readings, start/finish times, and game events. Participants then filled out a questionnaire to gauge their impressions of the interaction and the system as a whole. The questionnaire contained both open-ended questions and questions based on a 5 point Likert scale. This process was repeated once for each game and was followed by an interview where users commented on their experiences. The whole process took between 30-45 minutes.

### 3.4.2 Screen Movement & Distortion

One of the major concerns when dealing with a new type of interactive system is how easy it is for new users to adapt to its use. Systems using the *MotionBeam* metaphor differ significantly from fixed screen systems due to the heavy use of motion to guide characters. Projector movement and acute projection angles were a concern because they could potentially make viewing of projected imagery difficult. This was the motivating factor behind question one.

To gain an idea of how often the projected image was moved into a distorted position we analyzed data recorded from the ultrasonic distance sensor on the device. This sensor uses time-of-flight readings to determine distance and is typically orientated in a perpendicular position to a surface. When the sensor is moved more than 40 degrees from perpendicular, readings time-out and a large value is returned. In our case this indicates that the projector has been orientated at an acute angle and the image is likely to be distorted considerably. These large time-out values occurred with seven of the eight participants and represented 4% of the total readings recorded (Figure 38, values over 150cm). The character game requires more physical motion so had a greater number of time-out values compared to the racing game, with 5% vs. 2% of total readings respectively. This data suggests that users do orientate the device so that the projected image becomes distorted. The image is typically moved into a distorted position for only a short period of time, before quickly returning to a less acute viewing angle. Distortion of the projected image is typically coupled with quick movements of the device.

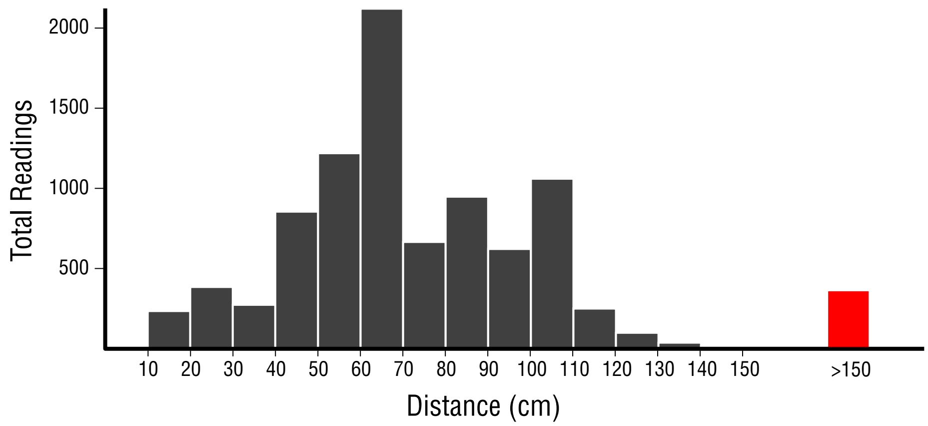



**Figure 38:** Distribution of distance readings measured between the projection device and the projection surface.

To understand how the distortion and movement of the projected image affected the user experience, participants were interviewed and asked them how difficult it was to watch the screen. Participant responds of note include participant 8 describing interaction with the projection device as 'natural' and stating that she was unaware of the screen because her focus was on controlling the character in the game. Participant 8 also stated that she only became aware of the projector when moving closer to the screen caused the image to shrink and vice versa. Participants 6 and 7 stated that they were unaware of the motion of the screen except for the rare instances when their screens would overlap. We noted that participants 5, 6, and 7 also projected onto the surrounding walls, but each responded that this did not cause problems. Participants were finally asked in the questionnaire 'Was it difficult to watch the screen?' and scored on a 5 point Likert scale between *Really Difficult* (1) and *Really Easy* (5). The results for both games were the same with a median of 4.5 and a mode of 5. These results illustrate that watching the screen was not difficult; the overall consensus was that motion and distortion of the projected image was barely noticed.

### 3.4.3 Movement Styles

Two prominent styles of movement were observed by participants interacting with our system: wrist movement and arm movement. The character game required the participant to lead the character in all directions, so was suited to full arm movement. Conversely, the racing game required the participant to orient a vehicle, so was better suited to finer wrist movement.

Participants who used arm movement with the character game, generally picked up the interaction quickly. Those who used wrist movement struggled initially as they tended to roll the device towards a given direction rather than point. However, when it was clear that the character was not responding as desired, these participants quickly adapted to arm movement. Although the device size was not overly large, creating a more compact and graspable form-factor would afford more liberal movement of the device.

### 3.4.4 Projection Range

The handheld form-factor of the projection device allowed participants to project at any distance from the projection surface. Figure 38 illustrates the distribution of distance values measured during the study. Figure 39 shows the median and mode value calculated for each game. This data reflects the range at which participants felt comfortable interacting during the study. However, the brightness of the projector, the amount of ambient light, and the size of the projection surface are all factors that contribute to the user's chosen projection range. The differences in projection range we observed were relatively large. A change in distance from 50cm to 100cm results in the projected image doubling in size and losing considerable brightness. Several participants commented on their preferences: participant 6 preferred a larger image and therefore stood further back, while participant 7 preferred to stand closer for a brighter image.

| | Median | Mode |
|---|---|---|
| Character Game | 72.39 | 62.23 |
| Racing Game | 66.68 | 62.23 |
| Both Games | 67.31 | 62.23 |

**Figure 39:** Median and mode distance readings (cm) from the projection device to the projection surface.

### 3.4.5 Participant Impressions

Participants were asked to comment freely on the overall experience and their reactions to the session were very positive. Participants consistently described interaction with the character as 'natural' and 'easy'. Participants were allowed to replay the game as many times as they wanted, and we were surprised by their enthusiasm to play again and again. The character game, which was the shorter of the two, was played on average 8.75 times per participant, and the racing game on average 4.5 times per participant. When asked: "Where would you play projection games like this one" the preferred venue was *Home* (10 responses), followed by *Outside* (8 responses), then *Car* (6 responses). Participant 1 commented it would be possible to project onto people's backs on the bus and participant 4 suggested the game would be a fun social activity with a large screen and multiple players.

### 3.4.6 Future Studies

A number of directions for future studies were identified. The motion and distortion of the screen was not a noticeable issue for participants in this study. A contributing factor may be the willing suspension of disbelief, as the user ignores imperfections in the presentation to follow the interaction. Although many mobile projector-based systems utilize image stabilization and distortion correction, a future study may seek to determine if the user perceives a difference when these techniques are implemented and not. It is possible that the distortion of the image appears more 'natural' because it conforms to our naïve understanding of optics.

Contrary to the experiences of system users, there were rare cases of spectators having trouble watching the screen. Informal comments suggested that viewing the screen was at times difficult and could even cause a very mild feeling of motion sickness. This can be likened to the motion sickness experienced by vehicle passengers, but not by drivers, when riding in a vehicle (Rolnick and Lubow, 1991). A formal study is required to identify the specific circumstances when viewing a moving screen is problematic.

### 3.4.7 User Study Summary

By observing user interaction with the *MoitonBeam* system it is clear that participants did not find the high level of screen motion and distortion to be an issue. How participants gestured with the device and at what range was also observed. These observations have real practical use for the design of projection devices or the environments in which they are used. This study also identified several directions for future studies that can enhance our understanding of mobile projector-based interaction.

## 3.5 Summary

I have presented the *MotionBeam* metaphor for character interaction with mobile projectors. This work draws from the tradition of historic mobile projectors that use direct physical manipulation to control projected imagery. Unlike the dominant direction of research that uses the spotlight metaphor to navigate a virtual *background* space, this work focuses on establishing a complimentary interaction metaphor to control characters in the *foreground*. I believe these two approaches represent the primary metaphors for direct gestural interaction with mobile projectors.

Although the *MotionBeam* metaphor is applicable across a range of interaction scenarios, there are some limitations:

- The metaphor is designed for the control of a single virtual object. It is unclear how the metaphor can be extended to control multiple objects simultaneously.
- The metaphor relies heavily on physical movement. It may not be appropriate for use in confined spaces or for users with limited mobility. Fatigue may be a factor when interacting for extended periods, but it is comparable to the use of video game motion controllers such as the *Nintendo Wii* remote.
- The metaphor works at human scale. Using gesture and movement to control a miniature or oversized object may not be appropriate.
- Our current prototype is limited to the use of appropriate projection surfaces and ambient lighting conditions. However we have found that suitable environments are readily available and expect that advances in technology will continue to overcome this limitation.

I have detailed interaction principles that will aid other researchers to design systems using the *MotionBeam* metaphor. The prototype applications developed provide a clear example of how the *MotionBeam* metaphor can be implemented using current technology. Further miniaturization of the prototype would allow a compact form-factor akin to modern mobile phones. Such a device has the potential to establish a new 'game projector' platform for mobile gaming. Unlike existing portable game devices, a 'game projector' can use the real world as a playground and encourage direct interaction between multiple users.

# 4 Mobile Projector-based Multi-user Interaction

Interaction with handheld computing devices remains a largely solitary, single user experience. Today's devices do not typically provide interfaces and supporting technologies for co-located multi-user work, learning, and play – crucial elements of human interactions in the real world.

This research is motivated by the vision of handheld computing devices that allow users to dynamically interact with each other in shared interactive spaces. Mobile projectors are an enabling technology that could realize this vision. They are sufficiently small to be grasped in a single hand, and light enough to be moved from place to place. Multiple users can project digital content directly into the physical environment. The relatively large size of projected images allows them to be easily seen by multiple users, making them a particularly natural fit for co-located multi-user interaction (e.g. Figure 40).

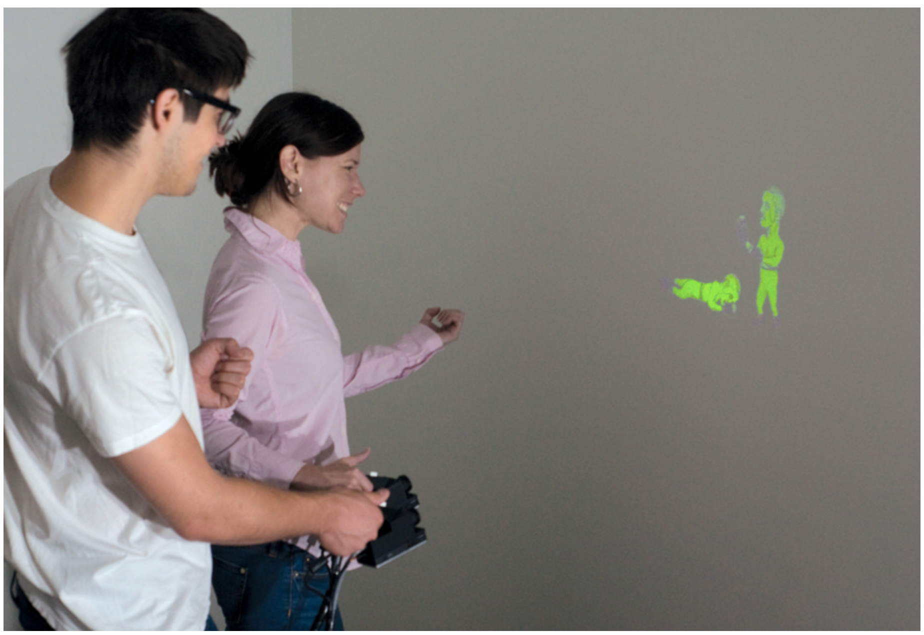


**Figure 40:** Interaction with the *SideBySide* system.

There has been rapidly growing interest in mobile projectors from both the industry and research communities (Rukzio et al., 2010, 2012), however, the majority of work has focused on single user applications (e.g. Beardsley et al., 2005). Existing work exploring the potential of mobile projectors for multi-user interaction typically requires instrumentation of the surrounding environment with complex sensing infrastructure (Cao et al., 2007; Hosoi et al., 2007). This significantly reduces the usefulness of multi-user mobile projection systems in any real world scenario where user mobility is required.

In this chapter I present *SideBySide*, a system designed for ad-hoc multi-user interaction with mobile projectors. *SideBySide* does not require instrumentation of the environment and can be used almost anywhere. It uses a device-mounted infrared (IR) camera and a novel hybrid visible/IR light mobile projector. The *SideBySide* software platform tracks multiple independent projected images in relation to one another using invisible fiducial markers projected in the near-IR spectrum.

The resulting system allows a broad range of new interaction scenarios where users are not tied to a fixed location. Exchanging digital content, such as personal contact information or media files, can be initiated without any infrastructure. Multiple users can play projected games together by creating ad-hoc gaming spaces. Interaction scenarios for education allow teachers and students to study together using a shared information space. Most importantly, these interaction scenarios can happen anywhere – in an elevator up to a business meeting, in a child's bedroom after lights out, or in the hallway outside a classroom. I present the following contributions:

- I outline the design and implementation of the *SideBySide* hardware system, including a hybrid mobile projector unit that projects both visible and IR light.
- I introduce the *SideBySide* software system for tracking multiple projected images in relation to one another with invisible fiducial markers. In particular, I present techniques for tracking overlapping fiducial markers and optical communication between devices.
- I present a range of applications that demonstrate the exciting and engaging multi-user interaction scenarios possible with the *SideBySide* system.

## 4.1 Related Work

Research related to the *SideBySide* system can be divided primarily into three categories: projector-based augmented spaces, multi-user mobile projector systems, and invisible marker tracking.

### 4.1.1 Projector-Based Augmented Spaces

An important aspect of multi-user interaction is extending interaction beyond a single user's screen and into the environment. Rekimoto (1997)'s *Pick-and-Drop* system defined interaction techniques to support data transfer between multiple computers and handheld devices. The *Augmented Surfaces* project later established a direct spatial relationship between laptop screen content and content projected onto nearby surfaces (Rekimoto and Saitoh, 1999).

The use of arbitrary surfaces for content projection was explored with the *Everywhere Displays Projector* (Pinhanez, 2001) to augment indoor spaces with projected content at any location using a steerable projector. The *Play Anywhere* system used a portable short-throw projector to create interactive tabletop experiences with handheld devices and tangible objects (Wilson, 2005). The *Bonfire* system also offered a portable form-factor to extend the desktop computing experience onto the tabletop using several mobile projectors mounted on the back of a notebook computer (Kane et al., 2009).

These projects highlight the potential for projected content to enhance the user experience by operating beyond the bounds of a single display. They are however, designed for use in a stationary position and are not suitable for use when moving between different locations. The recent emergence of mobile projectors offers a lightweight solution for unbounded mobile interaction.

### 4.1.2 Multi-user Mobile Projector Systems

In the 1800s mobile projectors were commonly used with multiple performers in the Japanese *utsushi-e* performance (Kobayashi, 1987). Each performer would coordinate their movement to change the size and location of projected images, creating relatively complex real-time animation in the pre-cinema era. This important history of mobile projector-based interaction underlines the potential for multiple small projectors to interact together in a seamless way.

The relatively large public displays created by modern mobile projectors make them ideal for multi-user interaction scenarios. Sugimoto et al. (2005) created a mockup system where two overlapping projection screens were used with a PDA touch screen to initialize file transfer between devices. An exhaustive range of multi-user interaction techniques were developed by Cao et al. (2007) using a motion capture system for location tracking. These interactions focus on operations within a virtual workspace, such as content ownership, transfer, viewing, and docking.

Multi-user games have also been developed that allow users to work together to reach a goal. Hosoi et al. (2007) developed a multi-user handheld projector game for guiding a small robot along a projected path. Users line up pieces of track for the robot to follow and reach its goal. Cao et al. (2008) developed a multi-user jigsaw game where users would pick up and place pieces of a puzzle together.

To enable interaction between multiple mobile projectors, these systems rely on infrastructure being added to the environment. This ranges from a fixed camera above the interaction area (Hosoi et al., 2007), to a professional motion capture system (Cao et al., 2007). Relying on fixed infrastructure within the environment severely limits where mobile projectors can be used, substantially limiting their mobility. The vision for this project is to enable multiple users to interact side-by-side, anywhere, in any space. This is one of the main design considerations for this research, and one that strongly differentiates the *SideBySide* technical solution from past work.

Since the development of the *SideBySide* system, several projects have attempted to overcome the limitations of fixed infrastructure by using on-device sensing. *PicoTales* uses an on-board IMU to convert device acceleration and velocity into linear movement (Robinson et al., 2012). Although this approach is very lightweight, it requires an initial calibration step, limits user movement, and is susceptible to sensor noise and drift over time. *PoCoMo* uses projected markers and camera-based tracking to allow interaction between multiple projection devices (Shilkrot et al., 2011). Large colored dots are superimposed over the projected image for tracking purposes. Although a highly mobile system, the visible markers used by *PoCoMo* are obtrusive and impact upon the user experience. The ability to hide projected marker patterns from the user clearly differentiates the *SideBySide* approach.

### 4.1.3 Invisible Marker Tracking

Fiducial markers have been used widely for location tracking due to their lightweight, robust performance. A well-known issue with structured, 2D barcode-style fiducial markers is their unnatural appearance that users cannot read or understand. Barcode style markers are difficult to integrate into the design of interactive systems due to their fixed aesthetic and form-factor that is intolerant to changes in color, shape, or material.

To address these concerns numerous systems have been developed to disguise or hide fiducial markers from the user. Custom marker patterns have been developed that are disguised to look like wallpaper (Saito et al., 2007), markers have been created with invisible inks for use with IR cameras (Park and Park, 2005), retro-reflective markers have been used together with IR cameras and lights (Nakazato et al., 2008), temporal sequencing of markers has been used with projectors and high speed cameras (Grundhöfer et al., 2007), structured pattern style markers have been projected with IR lasers (Köhler et al., 2007; Wienss et al., 2006), and several systems have been developed using IR projection from a fixed projector in either pure IR (Chan et al., 2010; Shirai et al., 2003; Weng et al., 2009) or with hybrid IR/visible light (Lee et al., 2007).

Natural marker detection techniques have also been developed to detect imagery and objects based on their natural features without any structured marker pattern (Ozuysal et al., 2010). However, natural marker detection typically requires time consuming training for each object and is computationally expensive when compared to structured marker detection.

To track the movement of mobile projectors, a prototype that can project invisible fiducial markers in the near-IR spectrum as well as content in the visible spectrum was developed. As noted above, this has previously been accomplished using a fixed projector, but I am unaware of any system implementing IR projection in a handheld form-factor. The smaller form-factor and portability of mobile projectors introduces a number of new considerations for IR marker tracking with multiple users, where markers constantly move and can frequently overlap.

## 4.2 SideBySide Approach

The *SideBySide* approach is guided by the vision of multiple users playing and interacting with each other using mobile projection devices (Figure 41). Key to this vision is interaction that can happen anywhere, at any time, in a fluid, spur-of-the-moment fashion. Users should be able to establish and break off interaction in a natural and transparent manner. Standing side-by-side and projecting images into the same space should be sufficient to establish immediate communication between devices and initiate interaction. Figure 42 shows the fundamental system design and technology solution proposed to realize this vision. Two requirements guide the development of the system: on-device sensing and lightweight communication.

### 4.2.1 On-device Sensing

All sensing is embedded on the projection device itself. Prior instrumentation of the environment, either with passive or active sensing infrastructure, should not be necessary. Each of the projection devices is equipped with a camera, an inertial measurement unit (IMU), a ranging sensor, and a push button (Figure 43).

A key requirement of any projector based multi-user interaction scenario is accurate registration of

**Figure 41:** The *SideBySide* concept – a self-contained, full color, handheld projection device allowing multi-user interaction in almost any space.

moving images projected from different devices. Each device must understand what other devices are projecting and where they are projecting it. On-board cameras are used to accurately track the position and orientation of moving projected images relative to each other.

Because tracking visible projected images restricts the type of content that can be projected, track invisible fiducial markers projected from the mobile projection device (Figure 42, 44). To achieve this the light sources of a mobile projector are modified to add an IR projection channel. This allows independent visible and invisible content to be combined in a single projected light stream. An on-board IR sensitive camera constantly identifies and tracks the position and orientation of all fiducial

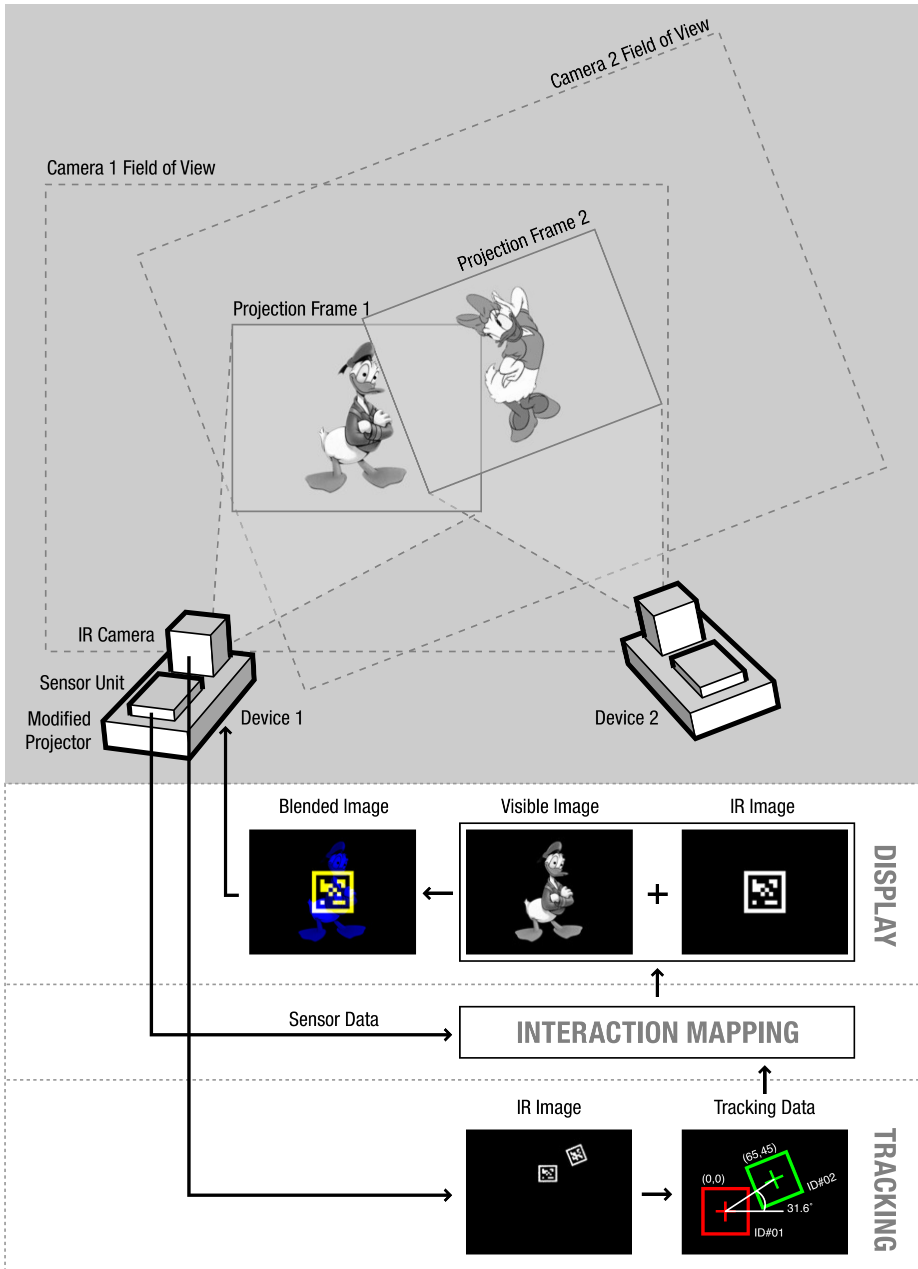



**Figure 42:** The *SideBySide* system overview.

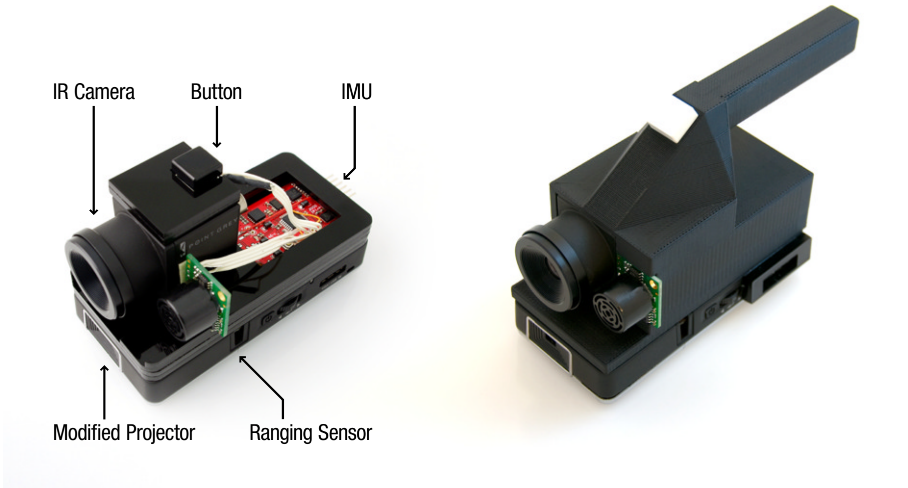



**Figure 43:** Two iterations of the *SideBySide* prototype device. An ABS plastic 3D printed enclosure was added to the original prototype (left) to allow easy gripping using a handle (right).

markers projected. This data is then used to drive interactive applications. No tracking data is visible to the user, creating a fluid interaction experience.

### 4.2.2 Lightweight Communication

Lightweight, instant communication is enabled between devices. Communication protocols, such as Wi-Fi or Bluetooth, typically require numerous steps to establish an explicit network connection. *SideBySide* uses optical communication by projecting symbolic fiducial markers in the invisible IR spectrum. This can be used to communicate events such as button presses, or changes in the state of applications. Optical communication can also be used to initiate other forms of network communication as required.

## 4.3 Hardware Platform

The *SideBySide* hardware platform consists of two core components: a hybrid IR/visible light projector and an on-board sensor assembly. Two prototype devices were developed that are currently tethered to the same computer. This greatly simplified the development and evaluation of *SideBySide*. It is

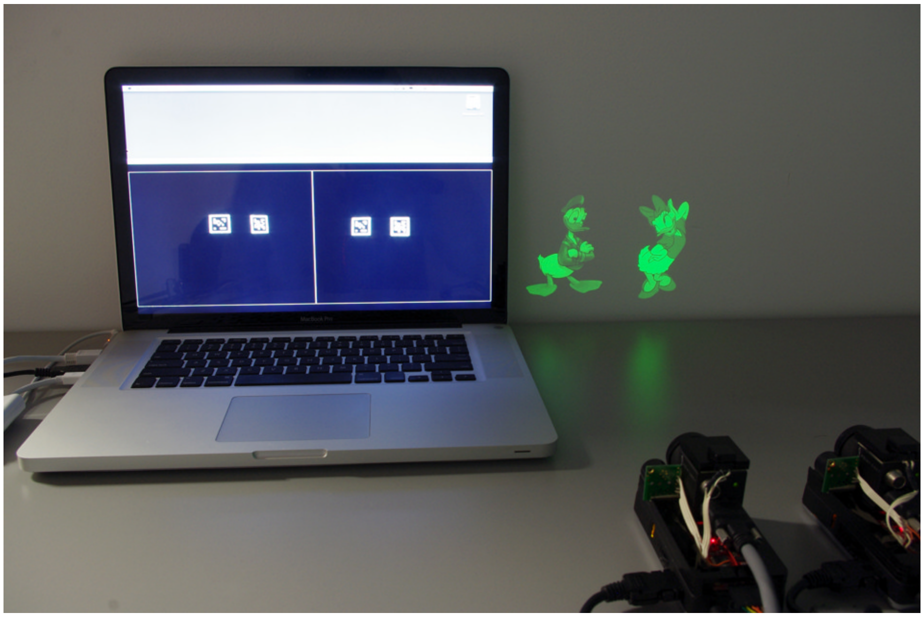


**Figure 44:** Projecting visible and IR images in a single stream. The characters are visible to the user, and the markers are visible to the IR camera.

important to stress, however, that there is no communication and no data shared between devices – all interaction is based on locally sensed data. The techniques and applications presented can therefore be implemented as a standalone handheld device in the future.

### 4.3.1 Hybrid IR/Visible Light Projector

An off-the-shelf Optoma PK102 mobile projector was modified that uses the Texas Instruments DLP pico chipset[6], a commonly used projection engine found in many commercial devices. Its optical assembly consists of three high power LED light sources emitting red, green and blue light. The red and green LEDs were replaced with equivalent IR LEDs (Osram SFH4232), allowing projection of an IR image without modifying the projector optics (Figure 45). Two IR LEDs create a sufficiently bright image to be used for marker tracking with the on-board IR camera.

The remaining green LED was replaced with an equivalent white LED (Osram LUWW5AM) to produce

[6] DLP Pico Projectors: http://dlp.com/pico-projector/

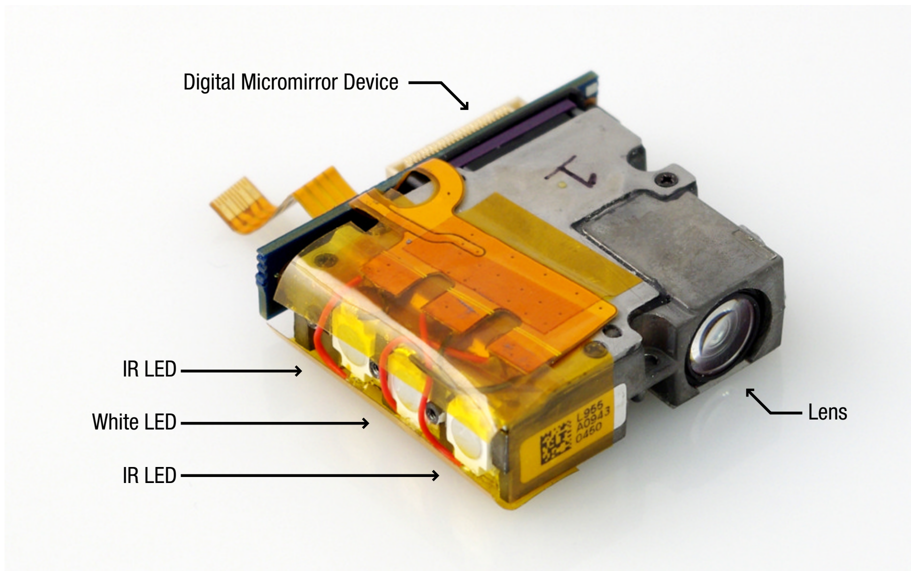



**Figure 45:** A DLP pico projector engine was modified to project both IR and visible light.

a brighter visible projected image. Due to the properties of the projector's optical assembly, undisclosed by the manufacturer, the projected visible image changes to a light green color. To provide the white LED with sufficient voltage (3.2V), it is connected to the blue LED power source that has the highest source voltage (~2.92V). The red and green power sources (~1.6V & ~2.5V respectively) are used with the IR LEDs that have lower voltage requirements (1.5V).

Although this prototype restricts the working color palette to monotone, the aim was not to engineer an entirely new projection device but to evaluate the feasibility of projected IR markers for tracking and registration. Designing a full RGBIR (Red, Green, Blue, Infrared) pico-projector can be achieved by numerous manufacturers, and is therefore beyond the scope of this current work.

### 4.3.2 On-board Sensor Assembly

The *SideBySide* prototype is equipped with a PointGrey Flea3[7] IR-sensitive black and white camera mounted above the projector (Figure 43). An IR pass filter is used to cut visible light from the camera

[7] Flea3 Camera: http://www.ptgrey.com/products/flea3/

image and avoid interference with fiducial marker tracking in the IR spectrum. The camera is fitted with a fixed focal length 3mm wide-angle lens that is mounted directly above the projector lens for optimal optical alignment.

Gestural interaction is enabled using an IMU with a three-axis accelerometer, gyroscope, and magnetometer. The IMU enables measurement of absolute device orientation, as well as relative acceleration and angular velocity. An ultrasonic ranging sensor is used to determine the distance to the projection surface. Because the projected image is much brighter when the device is closer to the projection surface, the ranging sensor allows the image threshold level to be dynamically adjusted for more robust marker recognition.

The size of the original prototype allows users to hold and manipulate the device with a single hand (Figure 43, left). To make the prototype more manageable for children, a second iteration was developed using 3D printed ABS plastic with an easy to grip handle on top (Figure 43, right). Because the system does not require any additional instrumentation of the environment, the device can be self-contained and reduced in size significantly. Many of the individual components used in the *SideBySide* prototype can be found in current generation mobile devices. A compact and relatively inexpensive commercial implementation of *SideBySide* is very much possible.

## 4.4 Software Platform

The *SideBySide* software platform provides functionality to combine visible and IR imagery, track and register projected images using fiducial markers, resolve overlapping fiducial markers, and optically communicate arbitrary information between devices. I now discuss implementation details of the software platform.

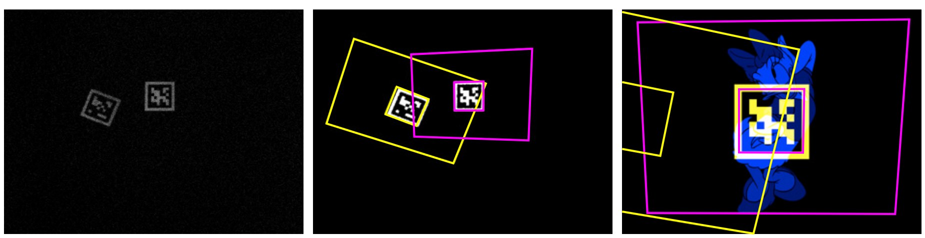
### 4.4.1 Combining Visible and Infrared Imagery

To project an invisible image in the near-IR spectrum a monotone image is loaded into the red and green channels of an OpenGL frame buffer. The visible image is loaded from a separate monotone image into the blue channel using OpenGL's additive blending mode (Figure 42). This combines the channels in real time using the graphics processing unit. Ghosting between channels, i.e. leaking from the IR channel into the visible channel (or vice versa), can be resolved by setting the system display color profile to 'generic RGB'. This allows the projection of clean, separate images in the visible and IR spectrums. This approach can scale to work with a full RGBIR image, where the IR channel is handled in a similar way to how alpha channels are used to specify transparency.

### 4.4.2 Tracking and Registration of Projected Images

To enable multi-user interaction with mobile projectors, each device must know the spatial relationship between its projected image and others nearby. These spatial relationships are determined with tracking and registration techniques using invisible projected fiducial markers.

Each device projects a unique, static, 'reference' marker in the center of its projection frame. The on-board camera has a larger field of view than the projection frame, so it can observe markers from multiple devices (Figure 42). Each device firstly observes its own reference marker, then observes markers projected by other devices, next it determines the location and orientation of each marker in relation to its own marker, and finally estimates the size and orientation of the projection frames.



a) IR Camera Image     b) Marker Identification     c) Map to Projection Space

**Figure 46:** Invisible projected markers are captured by an IR camera (a), located and identified (b) and then mapped from the camera coordinate space to the projection coordinate space (c).

The current implementation uses the *ARToolkitPlus* library for marker tracking (Wagner and Schmalstieg, 2007). A one-time calculation of the intrinsic camera parameters and homography matrix is performed to correct for lens distortion (Figure 46a). Once the markers are registered in camera coordinates (Figure 46b), they are remapped to the projector coordinate system. Remapping is based on the location of the projected marker in the scene and the scale ratio between the original pixel size of the projected marker and the size of the same marker captured by the camera. This process provides spatial information in the coordinate system used to design interactions and display graphics (Figure 46c).

### 4.4.3 Overlapping Markers

In multi-user interaction scenarios with mobile projectors, two projection frames often overlap. This can be accidental or an essential element of the interaction. For example, Cao et al. (2007) used overlapping images for file transfer and magic-lens style navigation of large images. Robust tracking of overlapping projected markers is therefore a key requirement for the *SideBySide* system.

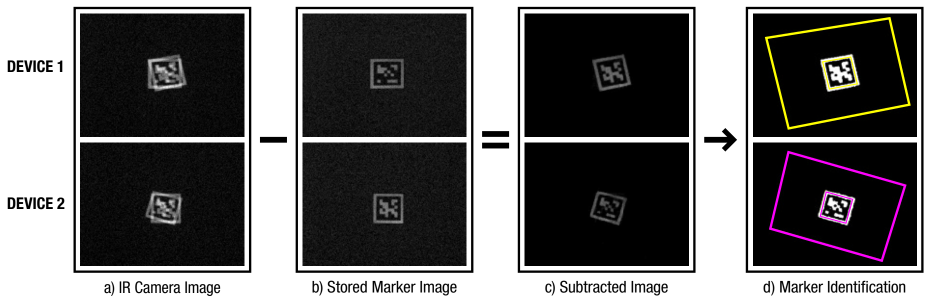



**Figure 47:** Recovery and tracking of overlapping projected markers.

Unlike printed markers that are typically opaque, projected markers can overlap and still leave adequate information to identify each marker individually. The overlapping region increases in brightness due to the additive nature of projected light (Figure 47a). A reference marker projected in the middle of the projector frame is known, unique, and relatively static (Figure 47b). By subtracting it from the scene, the markers projected on top of it by other devices can be recovered (Figure 47c), identified, and tracked (Figure 47d).

A naïve approach to marker subtraction would be to store a static binary representation of the reference marker in memory. However, environmental conditions such as lighting and properties of the projection surface constantly change as users move throughout the environment. The *SideBySide* marker recovery procedure continuously adapts to the changing environmental conditions by refreshing the stored image of the reference marker when there is no overlap, resulting in more robust performance.

Due to the close optical alignment of the camera and projector axes, projected images captured by the camera are relatively invariant to positional changes of the camera in relation to the projection surface. Even when the user points the device towards the projection surface at an acute angle, the projected markers appear relatively static and rectangular to the camera (Figure 48). The adaptive marker subtraction technique is robust in situations when the angle of projection is constantly changing.

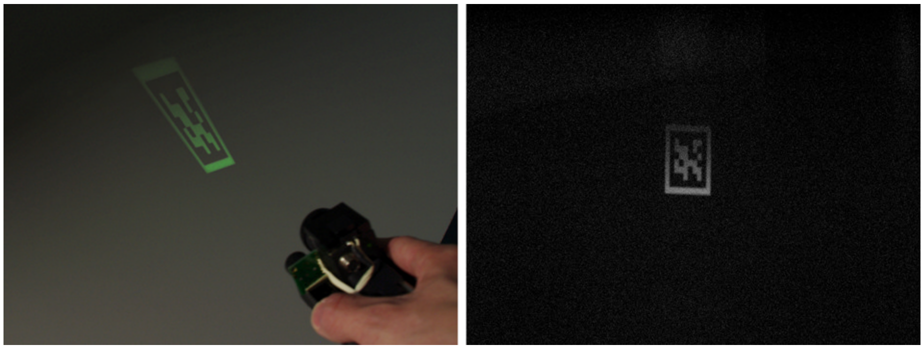


**Figure 48:** Projected markers that look distorted to the user (left) will appear relatively square when viewed from the device camera (right).

### 4.4.4 Optical Communication

To communicate events such as button presses, or changes in the state of the application *SideBySide* utilizes optical communication by projecting invisible event markers. Event markers are standard fiducial markers used exclusively for symbolic data communication rather than location tracking (Figure 49). To project dynamic event markers, the sender device firstly identifies an empty region in the projection frame. It then projects a marker into this region for a given duration, in the current implementation 1000 ms. The event marker is projected towards the viewing area of the other device's camera, minimizing the possibility that it will fall outside the camera field of view. The camera on the receiving device observes the marker, recovers its ID, and executes the appropriate application-specific response. A total of 4096 marker IDs can be used with the *ARToolKitPlus* library to communicate between devices.

To measure the time taken for an event marker to be sent from one device and received by another device a simple latency test was performed. The transmission time of 100 event markers was recorded while both projectors were in a static position. All markers were successfully transmitted with a mean latency of 121.45 ms and standard deviation of 8.49 ms. This latency is roughly half the typical minimum human response time of 240 ms (Card et al., 1986) and suitable for general-purpose interaction.

Communication bandwidth between handheld projection devices can easily be increased with the use of more sophisticated spatial encoding techniques, such as QR codes, or temporal encoding techniques, such as modulated IR light. These techniques allow larger amounts of information to be transmitted between mobile projection devices, such as URLs, geolocations, address data, status

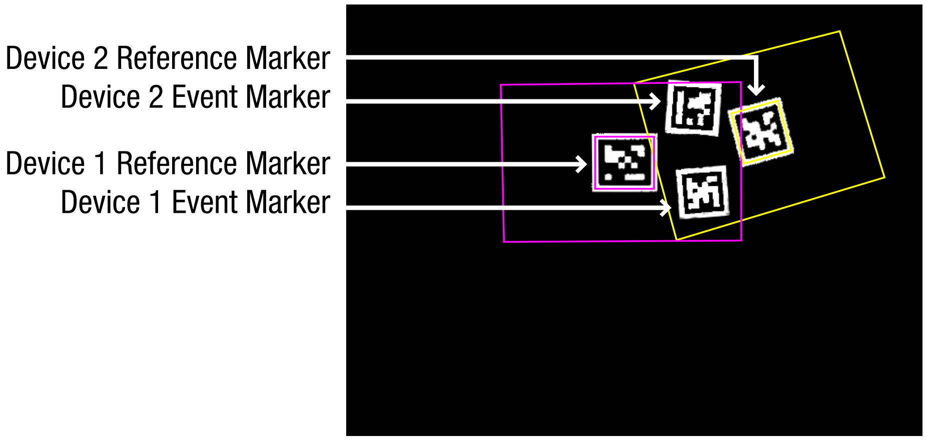



**Figure 49:** Event markers communicate event and state change information between devices.

updates, calendar events, and email addresses. Optical communication can also be used to facilitate a 'heavyweight' network connection, such as WiFi or Bluetooth, for even larger files or secure communication between devices.

## 4.5 Applications

The *SideBySide* system supports a range of co-located multi-user interaction scenarios. By tracking the spatial relationship between multiple projected images, the system is ideally suited to interaction techniques utilizing the distance and angle between projections. Angle and distance can be used for continuous control, e.g. to zoom in/out, or as a binary control to trigger events, e.g. when the two projections overlap. Properties such as the alignment of the projections, the highest/lowest projection, or the relative size of the projections can be used to support further interaction techniques. With these basic building blocks *SideBySide* can support a diverse range of applications. Example applications have been developed that focus on three areas: Mobile Content Exchange, Games, and Education.

### 4.5.1 Mobile Content Exchange

Mobile projectors can be used to support content exchange between devices in ad-hoc interaction scenarios.

## Contact Exchange

The *Contact Exchange* application shows how common procedures such as exchanging contact information can be performed with the *SideBySide* system. One user scrolls through their list of contacts by tilting the device up and down. When she finds the contact she wants to exchange she presses a button and drags the contact on to the recipients projected address book (Figure 50). At that stage an invisible QR Code with embedded contact information is projected, and the recipient's device scans the code to complete the transfer. This technique can also be adapted for use with multiple devices by projecting the contact information code into open space and having multiple recipients scan the code at the same time.

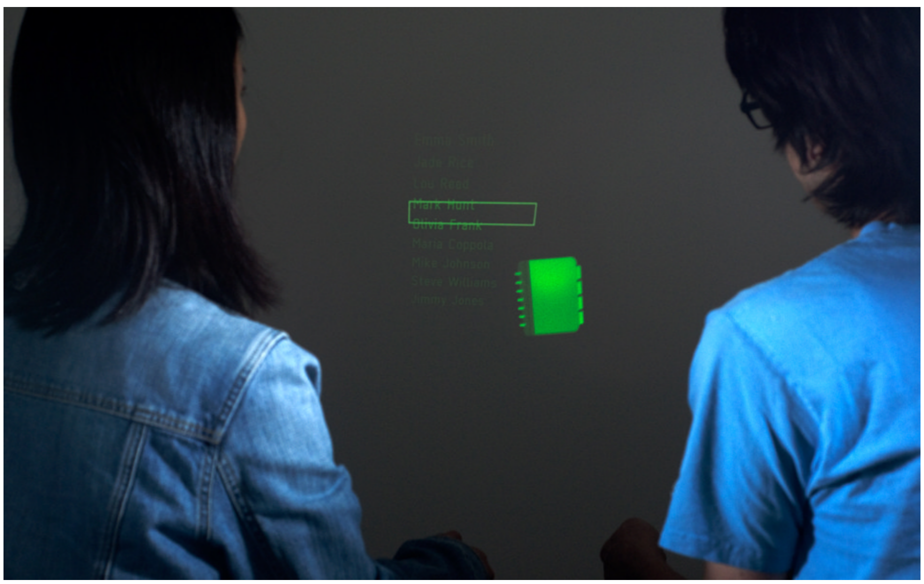


**Figure 50:** The *Contact Exchange* application allows contact information to be exchanged by dragging and dropping a contact onto another users projection.

## File Transfer

The *File Transfer* application illustrates how users can transfer files from one device to another. The sender begins by scrolling through the files on her device with simple flick gestures. When she locates the file she wishes to transfer she drags it on to the receivers projected folder (Figure 51). As with the *Contact Exchange* example, a QR Code is then projected that contains a location where the file can be retrieved. Depending on the implementation this may be a URL or a Bluetooth address.

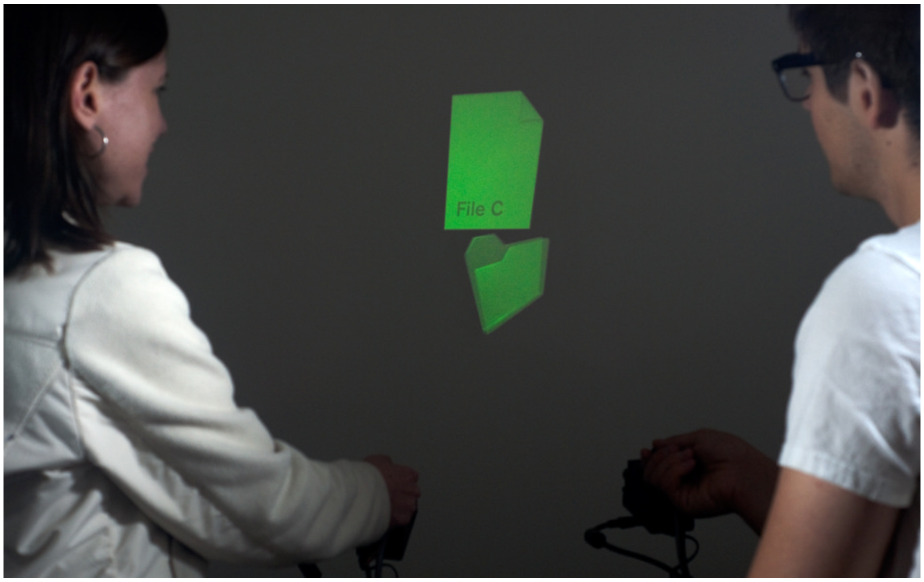



**Figure 51:** The *File Transfer* application allows digital files to be exchanged by dragging and dropping a file onto another users projection.

The *Contact Exchange* and *File Transfer* applications are two specific instances of content exchange. They greatly simplify the often-cumbersome task of locating a specific device to connect to, by providing a direct 'project-and-drop' style interaction. Any digital content, such as photos, videos, music, URLs, applications, and messages, can be transferred using variations of these techniques.

### 4.5.2 Education

Mobile projectors offer a novel, lightweight platform for learning applications.

#### Question & Answer

The *Question & Answer* application is designed to teach basic vocabulary to young children as either a first or second language (Figure 52). The teacher begins by projecting a question and several written answers from her device. At the same time the student's device depicts a pictorial version of the answer. The student answers the question by pointing to the correct written answer and pressing the button. This activity works both in a one-to-one context as well as with small groups of children taking turns to answer the questions. This allows for a more participatory style of interaction when compared to standard computers, but is more intimate than using a large overhead projector.

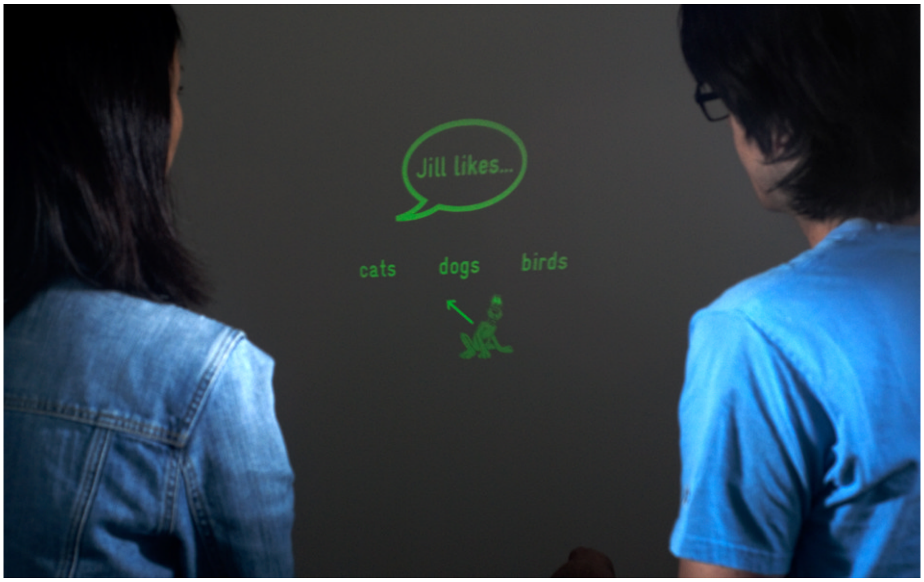



**Figure 52:** The *Question & Answer* application is designed for answering projected questions by pointing the correct answer with a mobile projector.

### 3D Viewer

The 3D Viewer application lets two people control and view a 3D model together (Figure 53). One user projects an image of the 3D model and the other user projects a tool that controls the view. For example, the orbit tool maps the x,y difference between the two projection frames to the 3D rotation of the model. The zoom tool maps the distance between the two projection frames to the amount of zoom applied to the 3D model. These tools allow both users to actively control the vantage point or zoom level of the model. We envision the 3D Viewer as a useful way to demonstrate 3D content in situations where a display or projector is not available. Models could range from mechanical objects, to architectural CAD renderings, to 3D molecular structures.

## 4.5.3 Games

Devices with embedded projectors offer an exciting new modality to play ad-hoc co-located games.

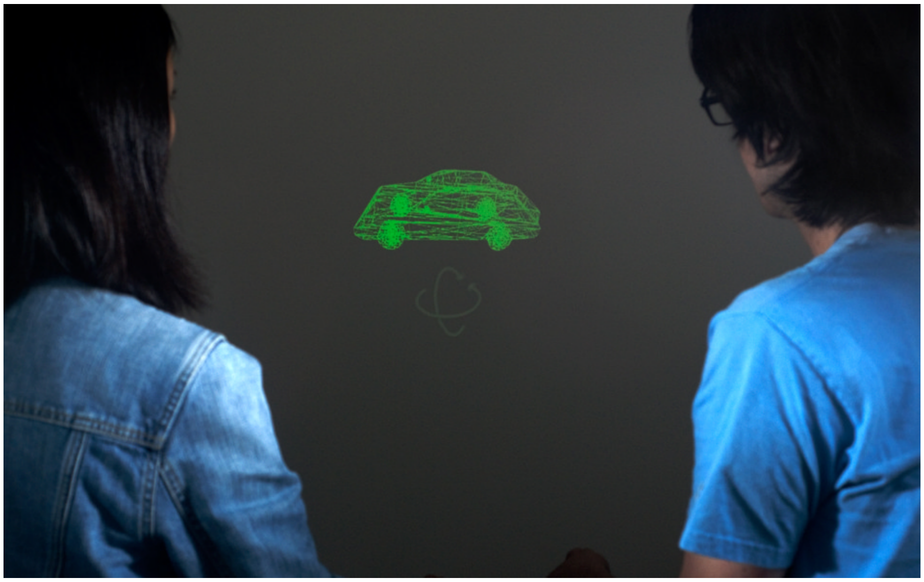


**Figure 53:** The *3D Viewer* lets two people control and view a 3D model together.

## Boxing

The *Boxing* game is a playful rendition of a boxing match. Each player controls a boxer character by moving the projector (Figure 40). A single button on the projector is used to throw punches, but these land only if the player's character is within striking distance of the opponent. The game is played without a boxing ring, meaning the players are free to roam around and make full use of any available space. To communicate a punch being thrown event markers are projected for the other device to read. If the distance between the two characters is within striking range, the other device responds to the punch.

## Falling

In the *Falling* game two players work together to safely guide falling chicks into their nest. One player controls the nest location and direction of the falling chicks, and the other player controls the 'mama bird' to push the chicks into the nest (Figure 54). When one chick falls into the nest, the location of the nest shifts, and both players must re-adjust their positions to guide the next chick into the new nest location. A simple physics simulation is used to animate the falling chicks as well as IMU sensor data to make sure they are always falling downwards when the projector is rotated. An invisible physics object is created and mapped to the location and orientation of the mama bird, so the chicks projected from one device appear to collide and interact with the mama bird projected from the other device.

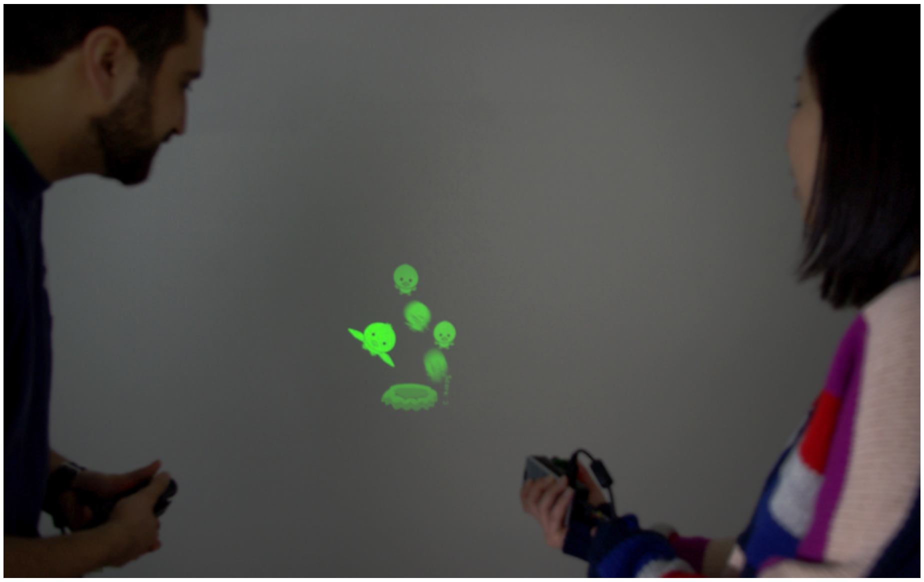


**Figure 54:** In the *Falling* game two players position and rotate their projectors to guide falling chicks into a nest.

## Cannon

In the *Cannon* game two players work together to knock a stack of bricks off a platform by firing a projected cannon ball from one screen to another (Figure 55). One user controls the location of the bricks by moving their projector, and the other user controls the location of the cannon in a similar manner. Pressing a button on the device fires the cannon ball from one projection frame to the next. Based on the relative location of the two projection frames the ball may miss the bricks or collide to knock them off the platform. To determine the location of the ball an event marker is projected when the ball is fired. The device receiving the ball reads this marker and creates another ball with the same location and trajectory in its own projection space. When the ball is about to switch between projection frames, it is removed from one frame and made visible in the other. Even when there is some distance between the two projections, the *Closure* interaction principle leads us to fill in the gaps and perceive that a single ball has traveled across the two frames.

**Figure 55:** In the *Cannon* game two players work together to knock a stack of bricks from a platform by firing cannon balls that cross from one projection into the next.

### Gorilla

In the *Gorilla* game one player controls a gorilla character and the other controls a rescue plane (Figure 56). The rescue plane must try to capture the gorilla by moving in close and launching its net. The gorilla can resist being captured by punching at the rescue plane to destroy it. The button on each device triggers either the gorilla attacks or the rescue plane net. When the net is launched at the right angle and distance, the gorilla is captured and transfers from one projection screen to the other – temporarily hanging from the bottom of the rescue plane in the net.

## 4.6 User Study

I now present details of a preliminary study conducted to observe user interaction with the *SideBySide* system. Children are a natural audience for a technology that has historically been used to entertain and tell stories (Figure 14). Despite this fact, limited research has focused on children's interaction with mobile projectors. It is therefore important to develop a better understanding of children's interaction with this novel interaction modality. The current study aims to answer the following questions:

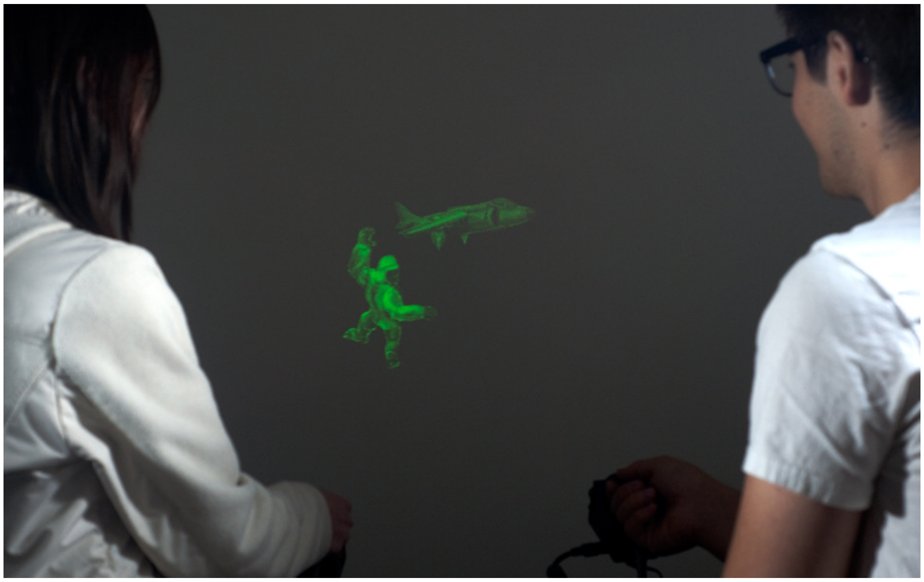


**Figure 56:** In the *Gorilla* game two players compete to capture (or avoid being captured) by moving and chasing one another with the projected characters.

1. What gestures do children commonly perform with the *SideBySide* system and how can future mobile projector systems be designed that better support these gestures?
2. How well does the *SideBySide* tracking system perform and what are the technical challenges for future mobile projector systems?

### 4.6.1 Procedure

Twenty-nine children participated in a study involving several different activities. Interaction with *SideBySide* was the first activity. Due to procedural errors 5 participants were eliminated from the data analysis to leave a total of 24 participants (11 female, 13 male), aged between 4-10 (mean 6.04). Participants played together with one partner, for a total of 12 sessions. Participants were paired with other participants they knew where possible. Each session lasted approximately 15 minutes, equally divided between the *Boxing*, *Gorilla*, and *Falling* games. These three games were chosen as they are simple to learn and provide different types of characters and interactions styles. None of the participants had used the system before.

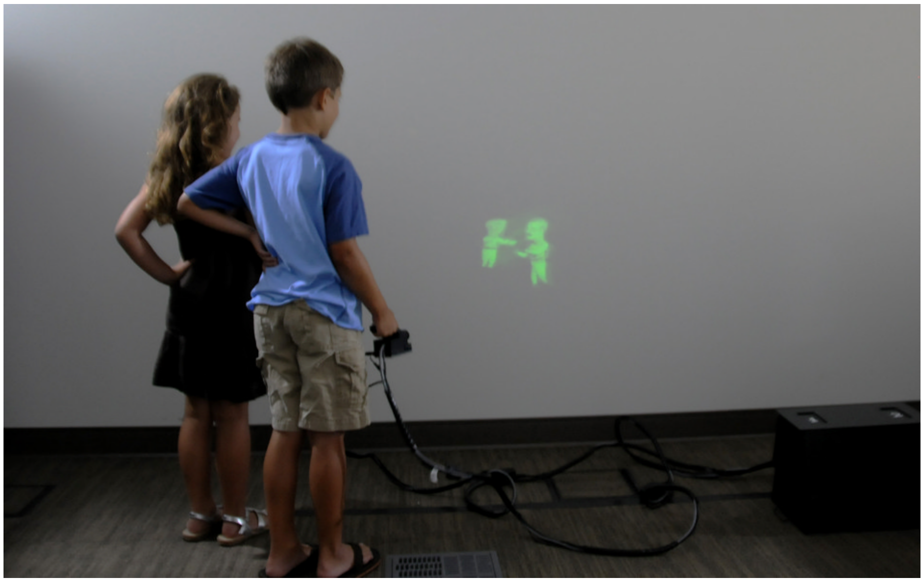


**Figure 57:** Children interacting with *SideBySide* during the user study.

### 4.6.2 Children's Gestures

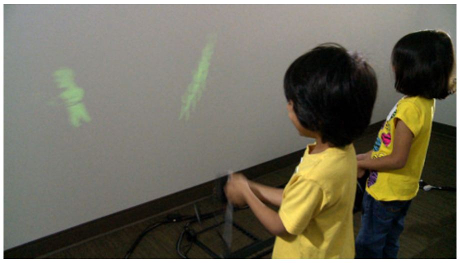
Gestures are an increasingly important part of interaction with computing systems. The mobility of mobile projectors makes them an ideal platform for gestural interaction. Listed below are gestures observed during the study.

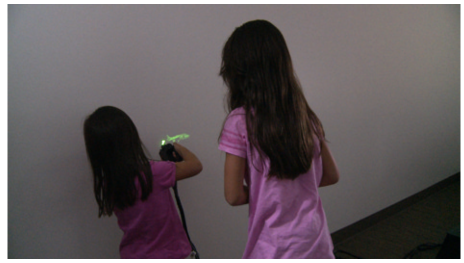
#### Circling

Many participants moved the projector in a circular swinging motion (Figure 58a). This was particularly noticeable in the competitive *Boxing* and *Gorilla* games where avoiding the opponent's character was a key part of game play. One frustrated participant appealed to their opponent: "*Stop moving it that fast!*" and another asked "*How can I get her? She's moving too much!*"

#### Scaling

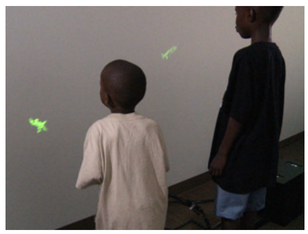
Many of the participants actively changed the size of the projected character by moving closer or further from the projection surface: "*I'm giant! I'm tiny!*", "*I can't get you when you're that tiny!*" (Figure 58b). It was clear that participants expected characters to take on abilities that correlate to the projection size, *e.g.* a large character is more powerful.





**(a)** Circling

**(b)** Scaling



**(c)** Hiding

**(d)** Animating

**(e)** Exploring

**Figure 58:** Children's gestures observed during the study.

## Hiding

Participants employed a range of tactics to avoid their opponents. One common technique was to point the projector in the air or behind them so it could not be seen (Figure 58c). Another effective method was to cover the lens of the projector with a hand during game play. One participant used this technique to hide her character, gloating to her opponent: *"You can't see me!"*

## Animating

Despite the relatively bulky size of the prototype, participants gestured with the device to animate projected imagery (Figure 58d). One participant 'flew' a plane around the room: *"Im going really fast now!"* Another participant responded to a knock-out of her boxing character by rotating the projector and gestured with the device so the unconscious character 'stood up' and began 'sleep-walking'.

## Exploring

Participants commonly explored different surfaces to project on (Figure 58e). These included interior surfaces such as the floor, ceiling, and walls: *"You're making it harder for me. I don't know where the birdies are!"*, *"The birdies are on the ceiling... they're on the carpet now!"* Participants also experimented with projecting on their opponent and other people nearby.

The *Hiding*, *Scaling*, *Animating* and *Exploring* gestures have been observed with adult users of mobile projectors (Cowan et al., 2012). Other adult gestures such as *Juxtaposing* and *Superimposing* projected imagery with physical objects (Cowan et al., 2012), were not performed by children in the current study. Likewise, the *Circling* gesture that was performed by children, was not observed with adults. One difference between these gestures is the scale and precision of movement required. The *Circling* gesture is a very physical gesture with large arm movements, while the *Juxtaposing* and *Superimposing* gestures require precise control to align projected content with physical objects. In general, children were very physical with the handheld device, but lacked the precise control of adults.

It is worthwhile noting that even when the game was paused the majority of children performed these gestures using the static projected characters. This supports the claim that even the most basic mobile projector system can afford novel interaction modalities (Cowan et al., 2012). Regardless of the interactive capabilities of a given system, children naturally expect they can make projected characters interact together. This underlines the importance of developing systems that support multi-user interaction with mobile projectors.

### 4.6.3 Designing for Gestures

Many of the gestures observed can be utilized in the design of future systems for children. Gestural motions such as *Circling* can be interpreted using motion sensors and mapped to system behaviors, e.g. a boxer character becoming dizzy or graphical icons spinning. The more complex movement observed when *Animating*, can be interpreted by pattern recognition algorithms to enhance interaction. For example, users can train their projected characters to recognize specific gestures and playback appropriate animations.

Gestures like *Scaling* require specific sensing hardware that can calculate the distance to the projection surface. Although other systems like *Twinkle* (Yoshida et al., 2010) compensate for user movement to keep a constant image size, an alternate approach is to use the change in image size for interaction. For example, a character that becomes extra strong when the projected image is larger or gains extra mobility when it becomes smaller.

Computer vision algorithms can be used to sense activities such as *Hiding* or *Exploring*. For example, a user may be hiding when the system can not detect the image it is projecting or detects a hand covering the camera lens. Depending on the interaction scenario it may be appropriate for a character to hide, or for an 'out of bounds' warning to be displayed. For users exploring, computer vision techniques can be used to detect the type of projection surface based on color and texture. For example, a projected character that can run faster on smooth surfaces and struggles on rough surfaces. Systems that support tangible interaction can also use computer vision techniques to recognize specific objects and playback appropriate animations.

### 4.6.4 Tracking Gestures

To evaluate the tracking performance of the *SideBySide* system, data recorded from the onboard camera of each device was analyzed. Data was recorded for 24 different games over the 12 sessions, 8 times each for the *Boxing*, *Gorilla*, and *Falling* games. As each game was played by two participants, a total of 48 recordings were analyzed. To understand how reliably projected IR markers can be tracked, camera data was analyzed to detect the marker projected from the same device. As the device's own IR marker is constantly projected, it should always be present in the camera image provided there is a suitable projection surface available, i.e. not projecting into the air or onto a distant surface. The *SideBySide* algorithm was compared to a brute force algorithm that iterated over every possible camera threshold value and logged the number of markers found. The brute-force algorithm cannot be performed in real-time and is used to represent the best-case tracking performance.

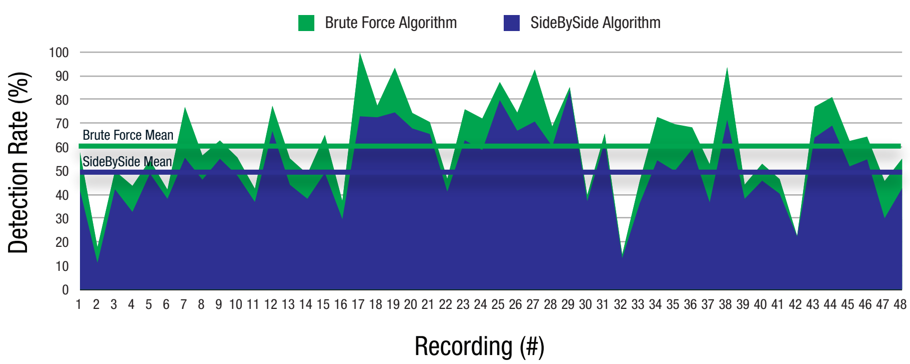



**Figure 59:** Detection rate of IR markers projected from each device using the *SideBySide* tracking algorithm and an offline brute force algorithm.

Figure 59 shows the results for the two algorithms as a percentage of markers detected in all image frames for each recording. Even the brute force algorithm struggled to find the marker projected from the same device at all times, with a mean detection rate of 60.99% (SD=19.44%). This indicates that approximately 40% of the time, a suitable projection surface was not available. Participants were likely projecting in the air, projecting on a dark surface (*e.g.* carpet), projecting at an acute angle, or projecting from too far away. The *SideBySide* algorithm had a mean detection rate of 50.64% (SD=16.73%). In other words, when a suitable projection surface was available and a marker present, the *SideBySide* algorithm could detect the marker 83% of the time. In practical terms, a real-time application running at 30fps can expect tracking updates at 15fps (50.64% of the time) when using the *SideBySide* algorithm.

### 4.6.5 User Study Summary

This preliminary user study shows us that children are adventurous when interacting and clearly engaged by the use of mobile projectors. They employ a range of gestures to explore the technology and some differ from adult gestures in terms of physicality and precision. Surprisingly, the low fidelity of projected imagery did not deter participants, nor were they concerned with image distortion, brightness, or quality. None of the participants questioned why the projected image was monotone, or why the projector was dim. Far more important to the user experience was robust tracking that could deal with physical movement and deliver reliable game play. Children actively moved the projection devices with little constraint and this can be demanding for camera-based tracking approaches. Despite these challenging conditions, the *SideBySide* system performed well and engaged the children with projected characters that actively responded to user interaction.

## 4.7 Limitations and Tradeoffs

The current *SideBySide* prototype has several limitations and tradeoffs.

### 4.7.1 Accuracy

To determine how precisely two shapes projected from different projectors could be aligned with the *SideBySide* tracking system an experiment was conducted (Figure 60). The distance was measured from each corner of a square shape (Device 1) to each tip of an identically sized 'x' shape (Device 2). Measurements were taken in ten different locations distributed randomly across the projection area, for a total of 40 measurements. The mean misalignment between the two shapes was 5.28mm, with a standard deviation of 3.34mm. Although this level of accuracy is not ideal for perfect alignment of images, it works well for general-purpose interaction where alignment is not the most critical requirement. It is worth noting that even professional level motion capture systems struggle to perform with a perfect level of precision (Cao et al., 2007). Optimization of the underlying *ARToolKitPlus* tracking library can further improve the accuracy of the *SideBySide* system.

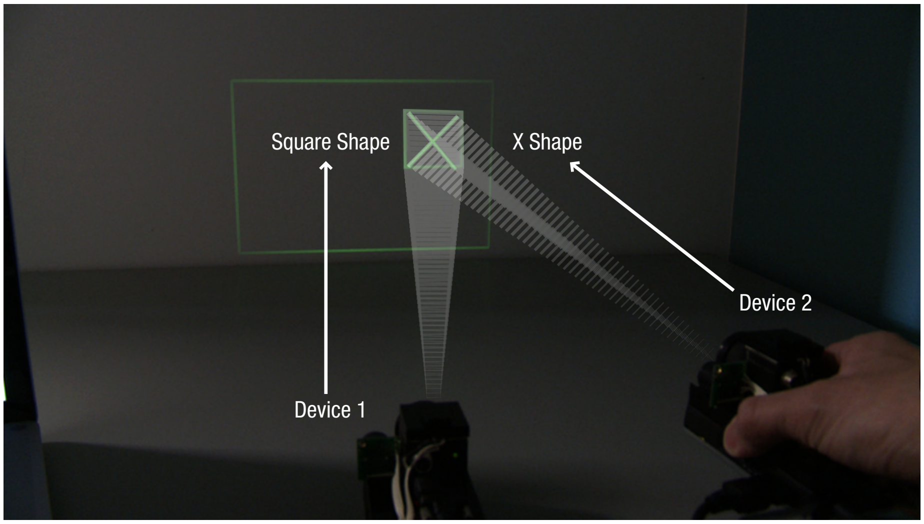



**Figure 60:** Testing tracking accuracy by aligning two identically sized shapes from different projectors.

### 4.7.2 Natural Light

A well-known problem for interactive systems using IR cameras and computer vision techniques is sunlight and other sources of IR light in the environment. This restricts usage of *SideBySide* to places without an abundance of natural light, such as indoor spaces with controlled lighting or outside spaces at night.

### 4.7.3 Camera Configuration

A number of general camera decisions need to be made based on the application scenario. Motion blur was an issue during the user study when the device was used for quick gestural interaction. Reducing the camera exposure time can help minimize motion blur; however, this comes at the cost of a dimmer image, decreasing tracking performance. The choice is therefore application dependent. When quick gestural movements are required, shorter exposure times should be used. When quick gestures are not required, longer exposure times will allow for better tracking performance.

Camera lens selection introduces another trade off. Wide-angle lenses capture a larger area well beyond the bounds of the projected image. This is useful to detect markers even when they are located at relatively large distances apart. However wide-angle lenses cause each marker to occupy fewer pixels of the camera image and result in coarser tracking and reduced accuracy.

### 4.7.4 Multi-user Interaction

Relative tracking limits the type of interactions that can currently be implemented with the *SideBySide* system. Camera-based systems for absolute localization, however, are a well researched area (Nakazato et al., 2008; Saito et al., 2007) and could easily be combined with the relative tracking approach used by *SideBySide*.

Tracking overlapping markers is currently limited to either two overlapping markers at one time, or multiple markers overlapping different areas of the reference marker. It will fail when two markers overlap on top of the reference marker. This limitation can be overcome by using temporal sequencing of projected markers, so that each device projects a marker in sequence one after the other. Temporal sequencing can be also used to increase the number of projected event markers used at one time. With the current implementation, as the number of event markers increases it becomes increasingly difficult to locate free space for them to be projected. By projecting them one after the other this issue can also be resolved. I elected to leave the investigation of these techniques for future work.

### 4.7.5 Projection Brightness

Images projected from mobile projectors have limited brightness, making it important for the projector to remain in close proximity to the projection surface. During the user study, the distance from the device to the projection surface constantly changed as participants moved and projected at different angles. In the current implementation, increasing this distance beyond 100 cm causes both the visual and IR projected images to dim. This makes it difficult for users to view projected content and decreases the reliability of marker tracking. From the previous user study we know that mobile projectors are typically used at a range of 60-70cm from the projection surface, where projected imagery is clear and easily seen – *SideBySide* functions reliably within this range.

### 4.7.6 Performance

The current implementation of *SideBySide* runs two separate handheld devices on a single Apple MacBook Pro (2.89 GHz Intel Core 2 Duo) at a frame rate of ~45fps. Camera imagery is processed at 640x480 pixels and graphics are outputted at 800x600 pixels before being downscaled to the 480x320 resolution supported by the DLP projection engine. The underlying *ARToolKitPlus* tracking library is designed for use with mobile devices and has numerous optimizations that are applicable to the *SideBySide* system (Wagner and Schmalstieg, 2007). I believe an embedded version of *SideBySide* will run sufficiently on a current generation mobile device and within 2-4 years will match the performance of the current implementation.

## 4.8 Summary

*SideBySide* is a novel hardware and software platform for ad-hoc multi-user interaction with mobile projectors. Through use of a device-mounted camera and a hybrid visible/IR light handheld projector I have shown the viability of tracking projected content with invisible fiducial markers. Unlike previous systems that dramatically limit mobility by relying on infrastructure embedded in the environment, *SideBySide* is completely self-contained and can be deployed as a handheld device.

Through the development of a range of example applications I have shown the wide and varied interaction scenarios where *SideBySide* can be put to use. A preliminary user study has demonstrated the applicability of the system for use with children and evaluated the tracking approach in real world conditions.

Enabling separate mobile projection devices to interact together is an important step towards truly seamless interaction across the greater ubiquitous computing landscape. I envision a day when digital content can traverse the boundaries of individual screens for fluid interaction between devices, people, and the physical environment.

# 5 Mobile Projector-based Interaction with the Environment

Mobile projectors enable interactions that are situated in the immediate environment around us, rather than confined to a mobile device. Interaction in the physical environment builds upon our 'pre-existing knowledge of the everyday, non-digital world' (Jacob et al., 2008) and opens up a rich space for mobile devices that support tangible interaction. This research is motivated by the vision of mobile projectors that are responsive to tangible objects and surfaces in the immediate environment — identifying each object, tracking its position, and projecting appropriate content back into the environment. Objects and surfaces such as books, posters, tabletops, walls, and board games can all be brought to life with projected imagery.

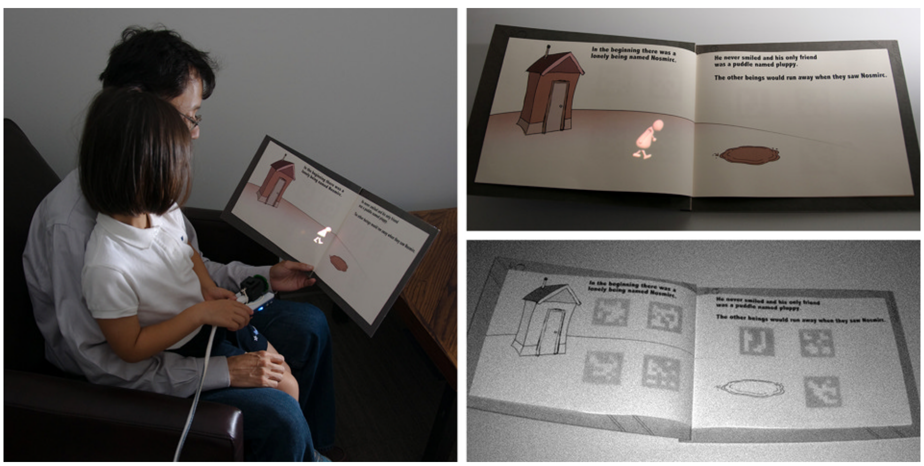



**Figure 61:** Interaction with the *HideOut* system.

In this chapter I present *HideOut*, a prototype system that can map projected imagery onto tangible objects and surfaces in the environment to empower new applications and interaction techniques (Figure 61). The system consists of a custom mobile projector device with an onboard camera to track hidden markers applied with infrared (IR) absorbing ink, as first described by Park and Park (2004). The obtrusive appearance of fiducial markers is avoided and the hidden marker surface doubles as a functional projection surface. The resulting system serves as a platform to explore new mobile and tangible interaction techniques that map interactive imagery onto tangible objects and surfaces. Digital media files can be browsed with a large projected image using available table or wall space. Immersive games can be developed that allow interaction with physical objects and surfaces within the environment. Story books can be brought to life with interactive content in a lightweight and exploratory way. The system does not require active sensing infrastructure, meaning interaction can take place with minimal preparation of the environment. Interactive objects and surfaces can quickly be prototyped for reliable tracking and identification. I present the following contributions:

- A detailed exploration of the application space for mobile projector interaction with objects and surfaces in the immediate environment, including example applications that demonstrate the range of interaction scenarios possible.
- A functional prototype system consisting of custom hardware and software, and discussion of the design and rationale behind the system.
- Documentation of the performance, practicalities, and implementation details for creating hidden marker projection surfaces using IR-absorbing ink.

## 5.1 Related Work

Research related to the *HideOut* system spans across the areas of spatial augmented reality, mobile projector interaction, and hidden marker tracking.

### Spatial Augmented Reality

Augmentation of the environment with projected imagery has been the long-term goal of 'spatial augmented reality' (Bimber and Raskar, 2005). Notable approaches to image tracking and registration include commercial motion-capture systems (Bandyopadhyay et al., 2001), photo-sensors with structured light patterns (Lee et al., 2005), steerable camera-projector pairs (Pinhanez, 2001), fiducial marker tracking (Rekimoto and Saitoh, 1999), and depth-camera-based systems (Wilson and Benko, 2010). These projects highlight the potential to enhance the user experience by augmenting environments with projected imagery. A number of portable systems have also been developed that do not require instrumentation of the environment (Kane et al., 2009; Wilson et al., 2010). These systems, however, are designed for use in a stationary position — this research aims to enable mobile interaction that can augment objects and surfaces in any space.

## Mobile Projector Interaction

Prototype systems exploring the use of mobile projector-based interaction with the environment have used active sensing to identify and interact with tagged objects (Raskar et al., 2004) and navigate virtual workspaces (Cao and Balakrishnan, 2006; Cao et al., 2007). Camera-based systems allow mobile interaction with surfaces in the environment (Mistry et al., 2009; Yoshida et al., 2010) and with other users (Cowan and Li, 2011; Ni et al., 2011). Depth-camera-based systems (Harrison et al., 2011; Huber et al., 2012; Izadi et al., 2011; Molyneaux et al., 2012) can sense detailed information about the geometry of the surrounding environment. The *HideOut* approach using hidden markers can compliment the use of depth-cameras when lightweight object identification is required, or when there is a lack of visible/depth features in the scene, e.g. with a large flat white wall.

## Hidden Marker Tracking

The obtrusive nature of fiducial markers has motivated a number of approaches for concealing markers from the human eye. These can be divided roughly into four categories. *Retroreflective materials* have been reliably used with several systems (Izadi et al., 2008; Lee et al., 2008; Nakazato et al., 2008; Spindler et al., 2010), but are difficult to conceal entirely and can reflect visible light back to the user when used with handheld projection. *Scaling* the marker pattern down, so it is nearly imperceptible to the user, is another approach used by the *Anoto Digital Pen* system (www.anoto.com). Although the Anoto marker pattern performs well as a projection surface (Song et al., 2010), tracking is limited to within close proximity to the marker pattern. Transparent *polarizing films* are another approach for concealing marker patterns when a polarized back-light is readily available, such as an LCD screen (Hyakutake et al., 2010; Koike et al., 2009). However, without polarized back-lighting, a gray-colored polarizing filter must be applied — degrading the transparent effect.

Finally, *IR-absorbing ink* has long been used in the security industry for document authentication. IR-absorbing inks have been utilized for interaction to embed hidden information in knitted artifacts (Rosner and Ryokai, 2008), to hide fiducial markers for use with augmented reality video see-through displays (Park and Park, 2004), and to support tracking and registration of imagery from fixed projector systems (Nam, 2005). IR-absorbing ink is particularly useful because it can be applied to a range of materials without changing the surface texture or finish. Commonly available papers function as projection surfaces and can easily be embedded with hidden patterns. Based on these properties, *HideOut* builds upon the use of hidden fiducial markers (Park and Park, 2004; Nam, 2005) to explore novel interaction techniques and applications enabled by the new affordances of mobile projectors.

## 5.2 HideOut

I now describe the key components of the *HideOut* system: hidden marker projection surfaces, the custom hardware device, and the software system.

### 5.2.1 Hidden Marker Projection Surfaces

Hidden marker projection surfaces utilize a single surface for both tracking *input* and projector *output* (Figure 62). These two information streams are kept separate by embedding marker patterns that are hidden to the human eye but can be viewed with a camera in an invisible spectrum, such as IR. The output image is projected onto the same surface and is visible to the human eye but invisible to the camera. Both information streams operate independently without crosstalk. This approach provides both a plain projection surface for unimpeded viewing of the projected imagery and a textured surface for simplified tracking. Arbitrary information can also be encoded into the surface markings such as location data, object identification codes, or website information.

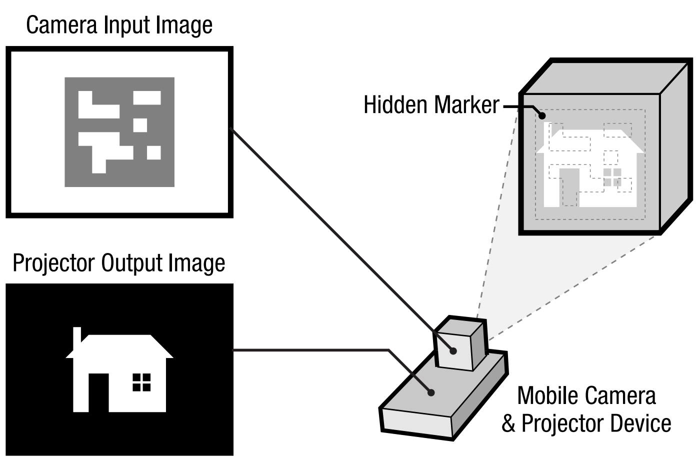



**Figure 62:** Camera input and projector output are focused on the same hidden marker projection surface.

IR-absorbing inks are used to create marker patterns that are hidden to the human eye (Figure 63a), but visible to an IR-sensitive camera (Figure 63b). This approach avoids the obtrusive appearance of visible fiducial markers and frees up valuable space to function as a projection surface. IR-absorbing inks that are suitable for use with projection are carefully selected; these inks do not fluoresce when exposed to projected light as with previous work (Park and Park, 2004, 2005). A novel technique for overprinting visible graphics on top of hidden marker patterns has been developed for use with the

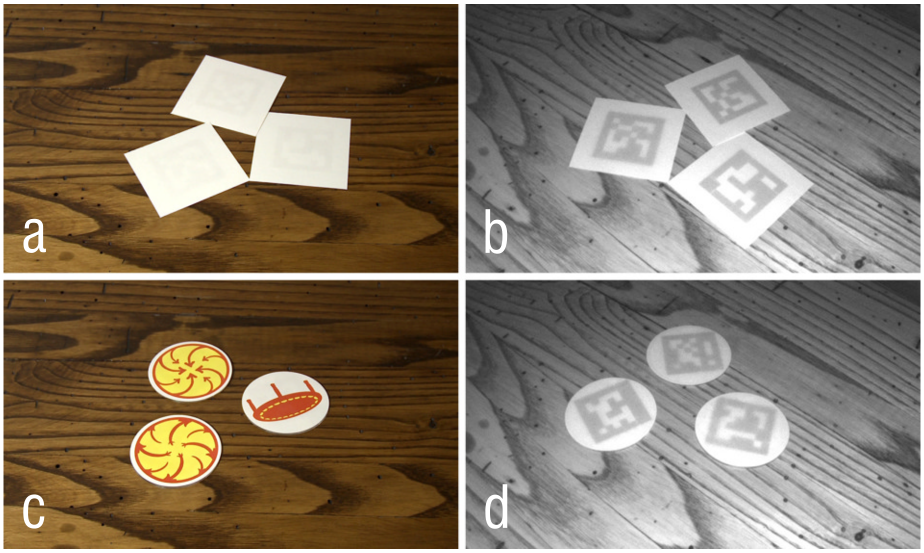



**Figure 63:** IR ink markers shown in the visible (a,c) and IR spectrum (b,d), with (c,d) and without (a,b) printed overlays.

*HideOut* system. Arbitrary graphics can be used to decorate tangible objects (Figure 63c) without obscuring the underlying marker pattern (Figure 63d). In the prototyping section I describe the techniques used to create hidden markers.

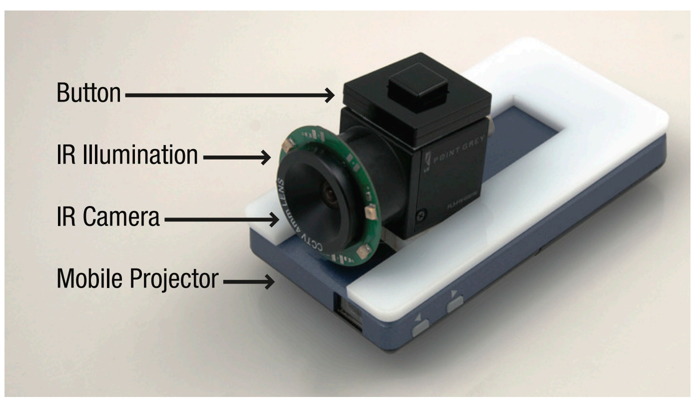



**Figure 64:** The *HideOut* prototype mobile device.

### 5.2.2 Hardware

The *HideOut* hardware platform consists of a prototype mobile device with onboard projector, camera, IR illumination source, and button (Figure 64). A Microvision ShowWX laser projector is used for focus-free projection with a comparatively wide field of view. The onboard camera is a Point Grey Flea3 IR-sensitive black-and-white camera with an IR filter (89B Wratten) to avoid interference caused by projected imagery. The camera is fitted with a fixed focal length, 4.3 mm lens mounted directly above the projector for optimal optical alignment. As the ink used with the system absorbs IR light, an IR illumination source is attached directly to the camera to ensure robust tracking in different lighting environments. Four 830 nm IR LEDs are attached directly to the camera on a custom PCB. In the current implementation, the mobile device is tethered to a standard computer to simplify the development process, enable rapid evaluation, and facilitate exploration of the application space. Computer vision applications are increasingly being deployed on current generation smartphones and a compact and relatively inexpensive smartphone implementation of this platform is possible.

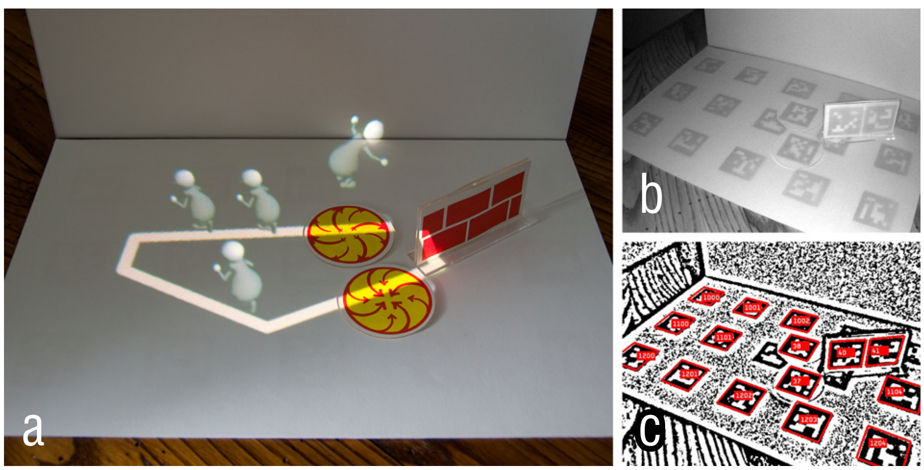



**Figure 65:** Marker tracking is applied to a scene (a) in the IR spectrum (b) using adaptive thresholding (c).

### 5.2.3 Software

The *HideOut* software system provides support for object identification and tracking, as well as multiple projection techniques. The *ARToolKitPlus* library is used to detect markers embedded in objects and surfaces. Adaptive thresholding is applied to the camera image using the *OpenCV* library for robust marker detection (Figure 65). Once the markers are identified, a standard homography technique is used to estimate the poses of the projector and objects in the scene (Hartley and

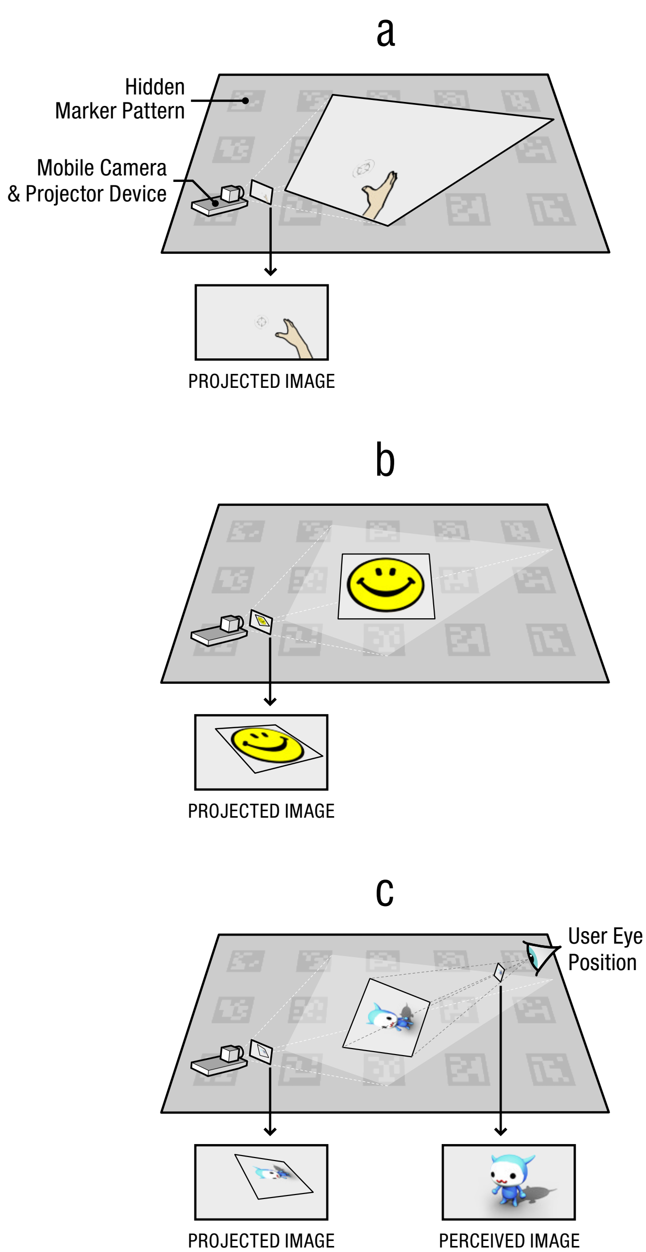



**Figure 66:** Projection techniques: *Standard Projection* (a), *Surface Projection* (b), *Anamorphic Projection* (c).

Zisserman, 2004). The extrinsic parameters of the projector, with respect to the camera, are calibrated in advance (Audet and Okutomi, 2009).

The *HideOut* software system supports several different projection techniques from the literature. Using *standard projection* an image is projected 'as is' without any geometric correction (Figure 66a). This can be used for first-person style interactions where a *MotionBeam* style pointer, hand, or projectile appears to extend from the projector outwards into the environment. *Surface projection* can be thought of as adding a projected 'skin' to a physical object (Figure 66b). Projected imagery is geometrically aligned to the projection surface, for example, projecting text aligned to a piece of paper or projecting a texture mapped onto a physical model (Raskar et al., 2001). *Anamorphic projection* is used when projecting 3D geometry that does not exist in the physical scene (Figure 66c). A pre-distorted image is projected that appears three-dimensional when viewed from the user's vantage point (Lee et al., 2009) (Figure 67). For example, projecting a life-like character that appears to stand on the floor beside you.

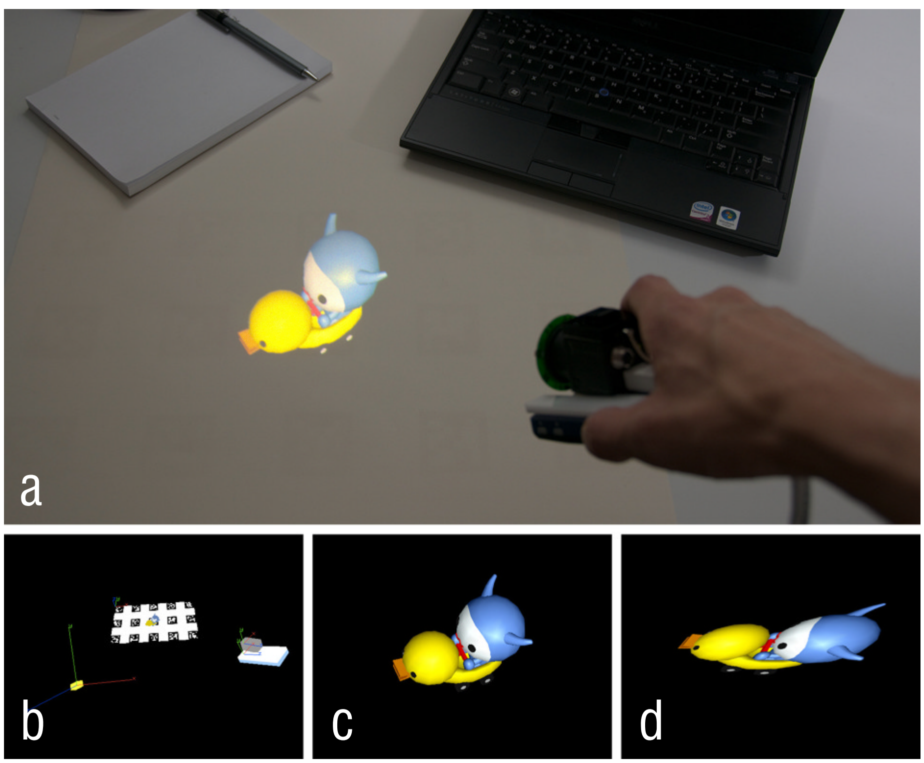



**Figure 67:** Anamorphic projection of a 3D character (a), the 3D scene view (b), the image rendered from the user's view point (c), and the pre-warped image for projection (d).

The projection techniques supported by the system are not mutually exclusive and can be used together to add depth and realism to projected imagery. In the next section I introduce example applications that demonstrate how these projection techniques can be used.

## 5.3 Applications

I now describe the application space enabled by the *HideOut* system and introduce example applications that focus on *information & media navigation* and *storytelling & games*.

### 5.3.1 Application Space

*HideOut* supports a range of mobile and tangible interaction scenarios. Tangible interaction is supported by embedding hidden marker patterns on the surface of tangible objects for lightweight tracking and object recognition. Context-sensitive imagery can then be projected on or around the object. Unlike video see-through or head-mounted displays, imagery is projected directly onto the environment without an intermediary display. User attention can be solely focused on the physical environment while multiple people can view the same scene together. Tangible objects can be moved and manipulated to dynamically control and interact with projected imagery. Multiple tangible objects enable two-handed interactions that track and respond to the spatial relationships between each object. Non-flat tangibles, such as boxes, walls, or other 3D shapes can have their geometry stored by the system and retrieved for interaction when the appropriate marker is identified. Tangible objects can be decorated with graphics that are invisible to the device camera, but communicate functionality to the user.

*HideOut* is well suited for mobile interaction as no active sensing needs to be installed in the environment, enabling interactions that move from space to space. Camera *input* and projector *output* are entirely embedded within the mobile device, meaning it can be used from a handheld or static position based on the interaction scenario. Imagery is updated and aligned with the projection surface dynamically, allowing users to move the device freely, without the need for recalibration.

Using the *HideOut* system, future smartphones with embedded projectors can be used to browse digital media files with a large projected image on available wall space. Specially designed game controllers can project interactive imagery that responds to set locations and surfaces throughout a physical environment. Theme park rides can be fitted with projectors to enable immersive interaction with characters and objects throughout the ride environment. Board games can become interactive displays that respond to tangible objects without complex sensing and projection infrastructure. These are a few of the many applications I envision in the future. Next I introduce example applications that demonstrate some of these scenarios using the current prototype system.

## 5.3.2 Information & Media Navigation

As mobile devices become more powerful, the ability to navigate information and media content becomes increasingly important. *HideOut* can be used to display information and navigate media directly in the physical environment.

### Scan Viewer

The *Scan Viewer* application illustrates how projected imagery can be dynamically mapped to tangible objects (Figure 68). The user manipulates a small freestanding vertical surface to control the display of a 3D MRI scan of a patient's head. The mobile device is placed on a tabletop and the user moves the standalone surface directly with her hands. The position of the surface is used to control the section of the scan displayed, and the orientation of the surface controls the angle of the scan, either top, front, or side view. The surface projection technique is used to map the scan imagery onto the standalone surface. This approach is particularly useful for viewing 3D models, and can be adapted to intuitively view cross-sections of architectural models or industrial design prototypes.

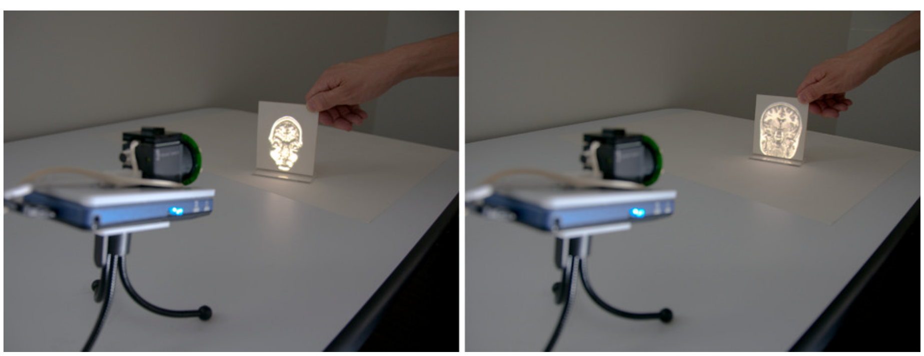


**Figure 68:** In the *Scan Viewer* application, imagery from an MRI scan is dynamically mapped onto a tangible object based on its location.

### Photo Viewer

The *Photo Viewer* application shows how digital media files can be projected and aligned onto surfaces in the physical environment (Figure 69). As the user points the mobile device at a tabletop the photos on their device are projected and aligned to the tabletop surface. Scrolling the center of the projection area over a photo causes the photo to 'pop up' from the surface, indicating it has been selected. The surface projection technique is combined with anamorphic projection to show the selected photo from a 3D viewpoint. Other digital media files such as album covers, e-books, or videos can also be viewed in a similar manner.

**Figure 69:** When browsing photos with the *Photo Viewer* application, photos 'pop-up' from the surface to indicate selection.

### Schedule Viewer

The *Schedule Viewer* application demonstrates how highly localized information can be projected from a mobile device to create digital signage (Figure 70). A sign with embedded markers is mounted outside a conference room and users project onto this surface to reveal the conference room schedule. Pointing with the device scrolls through the reservations for the day and can be viewed by multiple people. The surface projection technique is used to align the schedule information with the conference room signage. This approach can situate dynamic information in the physical environment without installing dedicated displays.

## 5.3.3 Storytelling & Games

*HideOut* can be used to enhance and extend storytelling and game experiences that are not tied to a fixed location.


**Figure 70:** The *Schedule Viewer* application enables a static sign to be augmented with projected information from a conference room schedule.

## Interactive Book

The *Interactive Book* application enhances the storytelling experience by projecting animated characters onto a children's story book (Figure 61). As the parent reads the book, the child holds the mobile device and guides the character around the page. When the character encounters objects in the story it responds accordingly. For example, when the character walks through a puddle printed in the book, it leaves behind footprints that are dynamically projected. Control of the character is based on the *MotionBeam* interaction principles for character interaction. The interactive book demonstrates how *HideOut* can be used in an intimate setting to subtly enhance the storytelling experience.

## Shooting Game

The *Shooting Game* application engages the user with interaction that takes place throughout the environment (Figure 71). Using the mobile device as a 'projector gun', the user must search for hidden 'bugs' in the environment that are marked out by hidden markers. When the user finds a bug, she presses the button on the device to launch a 'bug bomb' that fires towards the target. The bug bomb creates an explosion when it hits the surface, killing the bugs within range. The standard projection technique is used to display the crosshair target and the launching of bug bombs, giving the impression that the bug bomb is ejected directly from the projector. Surface projection is used to display the explosion in a fixed location. The shooting game illustrates how *HideOut* can be used to interact across large spaces without complex sensing infrastructure.

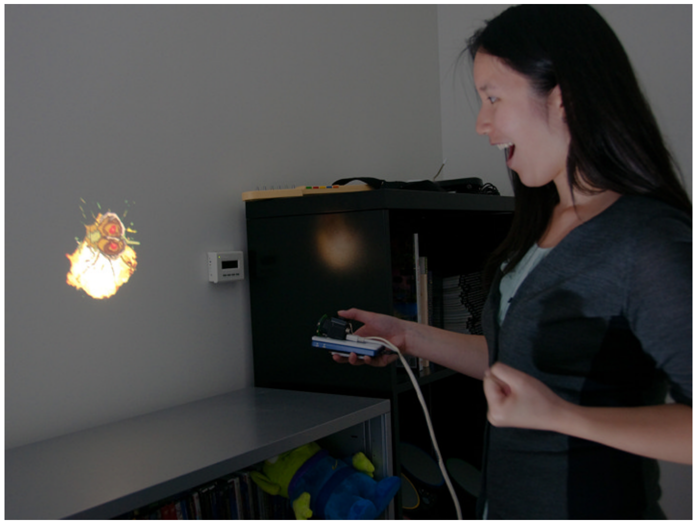


**Figure 71:** In the *Shooting Game* application, users search for hidden 'bugs' in the environment marked out with hidden markers.

### Board Game

The *Board Game* application transforms a traditional board game into an interactive display surface with projection (Figure 72). The user begins by opening up the board game, pointing the projector, and clicking the button to drop characters into the game. The characters walk slowly around the board, and tangible objects are used for interaction – a trampoline object bounces them into the air, an open box object captures them and lets the user eject them in another location, a wall object changes their direction, and a portal object teleports them to a different location (Figure 73). The mobile device can be held in the user's hand for exploration, or placed on a small tripod beside the board. Anamorphic projection is used to render the 3D characters as though they are standing on top of the physical board. The board game application demonstrates how tangible board game objects can be transformed with digital content.

## 5.4 Prototyping

I now provide a detailed account of the performance, practicalities, and implementation details for prototyping hidden markers using IR-absorbing ink.

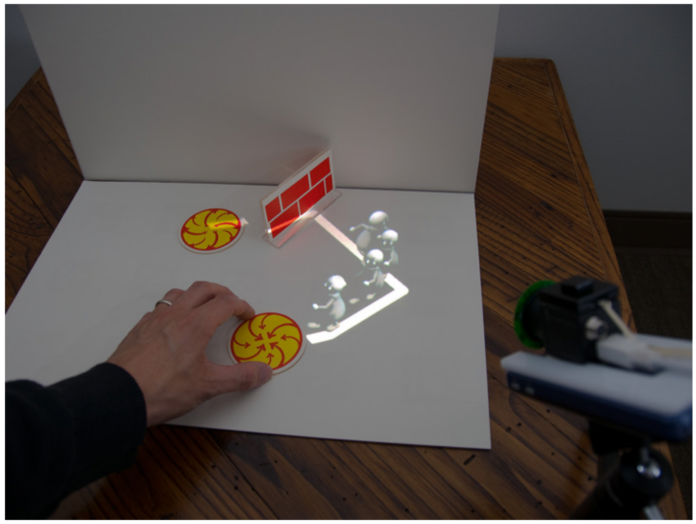


**Figure 72:** In the *Board Game* application, projected characters react to tangible board game pieces such as a wall and 'portal'.

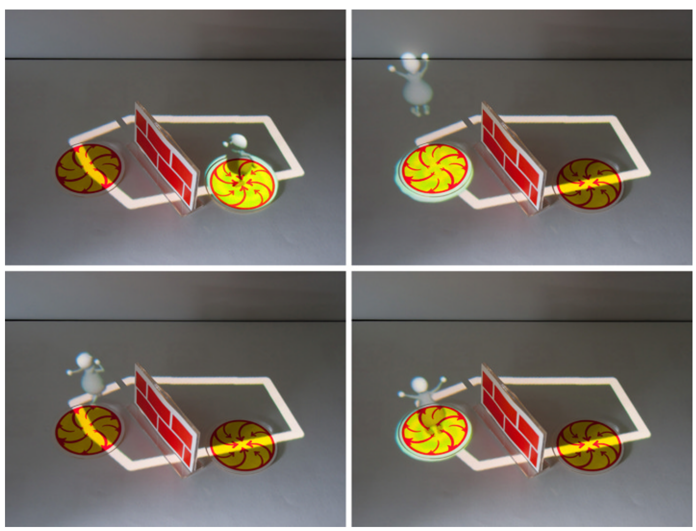


**Figure 73:** A projected character responds to tangible objects to teleport over a wall in the *Board Game* application.

### 5.4.1 Invisible Inks

A variety of 'invisible inks' are available that absorb and/or fluoresce in the ultra-violet (UV) or IR spectrums. This work focuses on the IR spectrum as commercial CCD/CMOS cameras are typically less sensitive to the UV spectrum. IR-absorbing inks are particularly suitable for use as projection surfaces because they do not fluoresce when exposed to RGB light from the projector. For this reason, the inks used in previous work (Park and Park, 2004, 2010) were not applicable. In the remainder of this section IR-absorbing inks are evaluated for contrast, invisibility to the human eye, and resistance to fading.

| Ink Name | Manufacturer | Absorbance Peak | Visible Color |
|---|---|---|---|
| IR1310 | AG & C | 990 nm | Green |
| IR2066 | AG & C | 977 nm | Green |
| IR9807 | AG & C | 807 nm | Green-Grey |
| Spectre 300 | Epolin | 778 nm | Green |
| Spectre 340 | Epolin | 859 nm | Brown |

**Table 1:** IR-absorbing inks evaluated.

### 5.4.2 Infrared Ink Contrast

Five different IR-absorbing inks (Table 1), provided in a concentrated form, were evaluated. To evaluate both the level of contrast in the IR spectrum and visibility to the human eye, each ink was tested at different strengths. Starting with 10 ml of solvent (acetone) and adding 0.1 ml increments of concentrated ink with an eye dropper. At each step, one drop of the diluted ink was deposited on regular white office paper and the process was repeated nine times. To measure the level of contrast in the IR spectrum, images of each ink sample were captured using an 8-bit grayscale Point Grey Flea3 camera with an 89B Wratten IR filter (50% pass at 720 nm).

Images of each ink sample were captured from a fixed position with constant camera settings. Lighting was aimed at emulating normal usage and consisted of standard office lighting from fixed fluorescent tubes. From the captured images the difference between an averaged sample of the inked area and the plain paper area was calculated to get a measurement of contrast in the IR spectrum. Figure 74 shows the results for each ink; higher values indicate greater contrast. The Spectre 300 ink clearly produces the highest contrast, with approximately twice as much contrast as the other inks. As distributed by the manufacturer, Spectre 300 is a highly concentrated ink, and its absorbance peak (778 nm) makes it well suited to CCD/CMOS cameras that are most sensitive to shorter IR wavelengths. Of the other

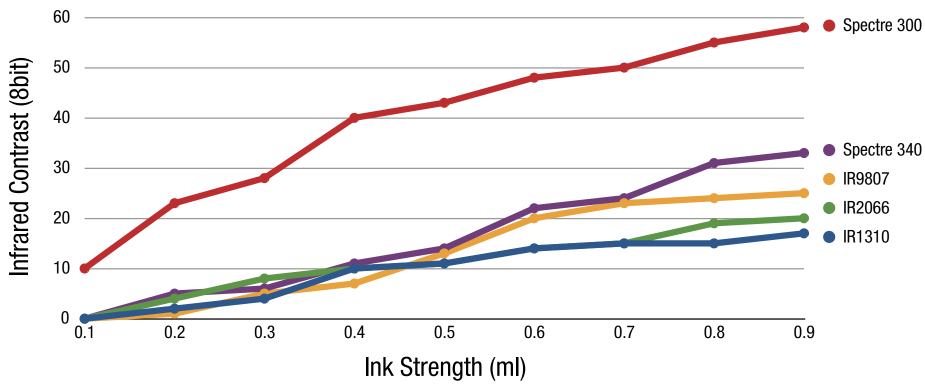



**Figure 74:** Contrast of IR-absorbing inks to an IR-sensitive CCD camera.

inks, Spectre 340 had the next highest contrast, followed by IR9807. The remaining inks, IR2066 and IR1310 performed similarly to each other, with low contrast.

### 5.4.3 Infrared Ink Invisibility

To quantitatively evaluate the perceived 'invisibility' of each ink, would require an in-depth perceptual study that is beyond the scope of the current work. Based on ink samples from the IR contrast test, the IR9807 was subjectively judged as the most invisible. This ink has a very neutral color with a slight green tinge. When applied to white paper it appears similar to a slight oil/grease residue, without a strong hue. Spectre 340 was arguably the next most invisible ink, with a visibly brown hue. The Spectre 300, IR1310, and IR2066 are visibly green in color and quite apparent to the eye.

### 5.4.4 Infrared Ink Fading

Fading is a known issue when dealing with IR ink. Exposure to UV light from the sun or other sources can cause significant degradation of the ink in a matter of days. To determine which of the inks is most resistant to fading over time, a fade test was performed with each of the five inks. The contrast of one new uncoated sample and two 12-day-old samples with protective spray coatings (Krylon UV Resistant 1309, Krylon Crystal Clear 1303) was measured and compared. The two coated samples were exposed to fluorescent light in standard office conditions for the 12-day period. Figure 75 shows the reduction in contrast as a normalized percentage of the new ink sample; lower values indicate greater fading. All inks experienced some degree of fading. The Krylon UV Resistant 1309 made a statistically significant difference in reducing the amount of fading relative to the uncoated ink sample ($t_4 = 3.980$,

$p = 0.016$). Although fading is an issue that requires consideration, in practice IR-ink markers that are not exposed continuously to UV light function for months and possibly years after they are first created.

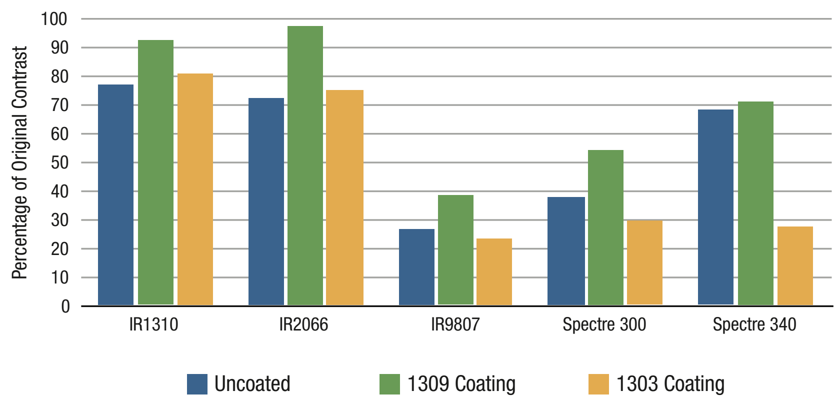



**Figure 75:** Fading of IR inks with and without coatings after a 12-day period.

## 5.4.5 Visible Overprinting

Although the main motivation for the current investigation is to provide marker patterns that are hidden to the human eye, there are situations where overprinting visible imagery on top of marker patterns will be appropriate. Some standard CMYK printer inks appear invisible in the IR spectrum and can be used to print graphical overlays on top of IR ink. In particular, overprinting magenta and yellow on top of IR ink (Figure 63c) does not effect marker detection in the IR spectrum (Figure 63d). Although this is a limited color palette, almost all printers can produce these colors without additional hardware or software. Other special inks, such as carbon-free black, are also invisible in the IR spectrum and can be investigated in future work.

## 5.4.6 Infrared Ink Application

Each ink evaluated had different strengths in the key areas of IR contrast, invisibility, and fade resistance. Although IR9807 was preferable for invisibility and Spectre 300 for IR contrast, Spectre 340 offered the best all-around performance in each of the key areas. Markers used with the *HideOut* system consist of Spectre 340, diluted at a ratio of 0.5 ml ink to 10 ml solvent, and applied to a cream-colored paper to match the ink hue. A laser-cut mask and spray gun is used to evenly coat the paper surface with ink.

## 5.5 Discussion

The current system has several limitations and tradeoffs that can be addressed in future research.

### 5.5.1 Invisibility vs IR Contrast

The concentration of an IR ink affects both the visibility to the human eye and the amount of contrast in the IR spectrum. Stronger concentrations allow for more robust tracking, but are more visible to the human eye. In general I have opted for stronger concentrations to enhance tracking and compensate for fading. Future work may look to explore ways to further disguise ink patterns using custom marker designs.

### 5.5.2 Ink Selection

A small selection of inks were evaluated in this chapter to act as an introduction to prototyping hidden marker projection surfaces. Unlike the aqueous inks commonly used in ink-jet printers, the IR inks tested have a solvent base, such as acetone, cyclohexanone, or methanol. Due to the active chemicals in the inks, care should be taken when handling them. However once the ink has been applied and the solvent has evaporated, only a minimal amount of trace chemicals remain in the paper itself. Solvent-based inks are also difficult to work with due to rapid evaporation and interaction with certain plastics. Future research may look to evaluate water-based IR inks that can be applied accurately and efficiently using a regular inkjet printer.

### 5.5.3 Multi-viewer Anamorphic Projection

Currently, eye tracking is not performed when creating an anamorphic projection. Instead, some simple assumptions are made about the pose of the user's eye. A basic assumption for orientation, is that the user's eye is always looking at the middle of the projection area. For position of the eye, the assumption is based on the type of interaction. For applications such as an interactive book or board game, the user's eye is assumed to be above and to the front of the projection surface. For handheld applications where the user actively explores with the mobile device, the user's eye is assumed to be directly above the mobile device. This approach works well in practice because the user generally shares a similar viewpoint with the direction of projection. However, anamorphic projection does break down when multiple people view the projected image from very different angles, *e.g.*, two people viewing a board game from different sides of a table.

### 5.5.4 Latency

When aligning projected imagery precisely with a physical object or surface there is some observable latency in the system. This is due to the camera exposure time, image transmission time from the camera to the GPU to the projector, and projector display time. By analyzing recordings of the system in use, the projected image was found to lag 167 ms (5 frames at 30 Hz) behind the current scene. Although this amount of latency acceptable for general purpose interaction, future work may seek to reduce the lag time with a custom hardware pipeline.

### 5.5.5 Field of View

In some applications, the close proximity between the mobile device and projection surface means the device field of view may not cover the entire scene (*e.g.* Figure 69). However, limited field of view can be used for 'spotlight' interaction where the projector reveals part of a larger scene (Rapp et al., 2004). Laser projector field of view will continue to increase with the emergence of brighter, more efficient lasers and camera field of view can be increased using wide angle lenses. Features such as dynamically settable field of view will allow projector resolution to be increased and decreased based on the type of user interaction.

### 5.5.6 Occlusion

Occlusion is a well-known issue with projector-camera systems and at times affects interaction with the *HideOut* system. Tangible objects and the user's hands can occlude the scene from the device camera and projector. Future work may look to explore how multiple users can track and project onto the same scene to reduce these occlusion issues.

## 5.6 Summary

The *HideOut* system supports mobile and tangible interaction with objects and surfaces in the physical environment. Using custom hardware and software, projected imagery from a mobile projector can be mapped onto surfaces embedded with IR ink-based hidden markers. *HideOut* does not rely on active sensing, meaning interactive objects and surfaces can be quickly prototyped for reliably tracking and identification. A range of example applications have shown the wide and varied interaction scenarios where *HideOut* can be put to real world use, including media navigation tools, interactive storytelling applications, and games. Enabling projected content to be mapped onto everyday surfaces from mobile devices is an important step towards seamless interaction between the digital and physical worlds.

# 6 Interaction with Embedded Mobile Projectors

The ongoing miniaturization of mobile projector chipsets opens up new possibilities for *Embedded Projection*. Compact, lightweight projectors can be entirely embedded in tangible objects to project imagery from the inside out onto their external surfaces. As the projector is fixed within the object, this approach greatly simplifies the registration of projected imagery, but requires the design of custom optics to guide the projected light and match the geometry of the object. Creating custom optical elements has traditionally been expensive and impractical due to the manufacturing precision and finishing required. Recent developments in 3D printing technology have enabled the fabrication of high resolution transparent plastics that are ideally suited for use with mobile projection. One-off 3D printed optical elements can be designed and fabricated literally within minutes for significantly less cost than conventional manufacturing.

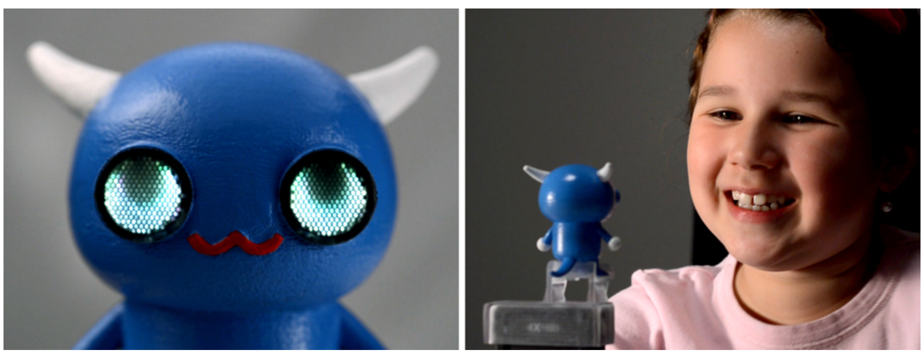


**Figure 76:** A 3D printed character with animated eyes created using embedded light pipes and a mobile projector.

In this chapter I present two novel techniques for prototyping with *Embedded Projection* using 3D printed optical elements. *Light Pipes* are cylindrical 3D printed structures, similar to optical fiber, that can be used to guide light from point to point. Unlike conventional optical fiber, light pipes allow arbitrary geometries to be created in software and then fabricated in a single 3D print. Light pipes are used to guide light from an embedded mobile projector onto the surfaces of an interactive object (e.g. Figure 76). *Internal Illumination* consists of inner forms within a 3D printed model that can be viewed from the outside when illuminated. These internal forms are created with reflective pockets of air within a solid transparent object. When mapped to areas of an image from a mobile projector, the internal forms become an active display and illumination area. I present the following contributions:

- A technique for displaying information on the surface of arbitrary shaped objects using embedded projectors and 3D printed light pipes.
- A technique for displaying information within arbitrary shaped objects using 3D printed internal geometry illuminated with embedded projectors.
- Example applications that demonstrate how these techniques can be implemented and used in interactive devices.

## 6.1 Related Work

I now introduce research related to embedded projection with light pipes and internal illumination.

### 6.1.1 Light Pipes

3D printed light pipes are related to optical fiber, that is widely manufactured and used in the industry due to its flexibility, low light loss, and fine resolution. Specialized printed variations of optical fiber have been fabricated on substrates to form both planar (Hayes and Cox, 1998) and non-planar (Lorang et al., 2011) waveguides. Printed waveguides have had limited commercial application due to the non-standard equipment required and the limited range of geometry possible. Conventional optical fiber has been deployed in commercial display applications to create translucent concrete walls with embedded arrays of optical fibers[8]. Optical fiber has also been a tool of choice for many systems researchers to guide and shape light traveling through stacked tangible blocks for tabletop interaction (Baudisch et al., 2010), to create non-planar display areas inside tangible tabletop objects (Hoover et al., 2010; Fukuchi et al., 2011), to provide compact multi-touch sensing (Jackson et al., 2009), to avoid issues of camera occlusion (Weiss et al., 2010), to create grasp-sensitive objects (Wimmer, 2010; Go et al., 2012), and to guide structured light patterns for projector calibration (Lee et al., 2004).

One of the inherent problems with optical fiber is maintaining alignment with large numbers or long lengths of fiber. This can be overcome to some extent by developing a calibration system that remaps misaligned fibers in software (Jackson et al., 2009). 3D printing optical fibers avoids the issue of alignment as fibers can be accurately fabricated and enclosed inside a rigid support structure. Optimal packing patterns can be produced in software to maximize light transmission with large arrays of

[8] Litracon: http://litracon.hu

optical fiber. Routing fibers from point to point becomes a matter of software to create a fiber design, rather than a manual hardware assembly process.

### 6.1.2 Internal Illumination

The increasing availability of digital fabrication tools, such as computer numeric control (CNC) mills, laser cutters, and 3D printers, has led to new areas of research that explore digital fabrication for the creation of novel displays. A number of projects in the computer graphics and vision literature involve milling or 3D printing the *outer* geometry of a physical model in such a way that light interacts with the model to form an image. Approaches include using self-occluding drill patterns (Alexa and Matusik, 2011), caustic effects from refracted light (Papas et al., 2011), surfaces reliefs (Alexa and Matusik, 2010), and surface reflectance (Weyrich et al., 2009). Optically clear material allows for the design and fabrication of *inner* forms within a 3D printed model. Internal forms can be viewed from the outside and highlighted with illumination. Internal illumination can be used with interactive devices to display information ranging from simple indicators to complex volumetric displays.

Volumetric displays have a long history of research and development that is related to illumination and display systems using internal structures (Blundell and Schwarz, 2002; Favalora, 2005). Most relevant to the current work are volumetric displays that use a static volume to render a 3D scene. This can be achieved in a number of ways including crossed-beam laser excitation of a gas/material to cause fluorescence (Ebert et al., 1999) and fiber optic arrays distributed inside a physical volume (MacFarlane, 1994). The current work uses optical reflectors with a mobile projector, in a similar manner as Nayar and Anand (2007), but fabricated using 3D printing rather than laser induced damage. By utilizing the unique properties of 3D printing, custom shaped optical reflectors can be embedded in optically clear material to form internal illumination elements, while the outer model can have arbitrary outer geometry.

### 6.1.3 Interactive Fabrication

Embedded projectors can be used to situate interfaces side-by-side with fabrication machinery. Unlike conventional graphical user interfaces on a separate display, projected interface elements exist within the same field-of-view as the fabrication area. Bringing physical input and output closer together can aid in recapturing the creative process seen in earlier forms of direct making. This has the benefit of establishing a closer relationship with materials and allows designers to better understand their properties and nuances.

Computer numerical controlled (CNC) milling machines enhanced with projection have been used to enhance the visibility of occluded tools and visualize real-time data with a custom display case (Olwal et al., 2008). *CopyCAD* enhances the cutting surface of a CNC mill with projected imagery that guides the user through a computer aided design process (Follmer et al., 2010). A top mounted camera is used to capture the shape of physical objects that can then be altered and milled directly on the cutting surface.

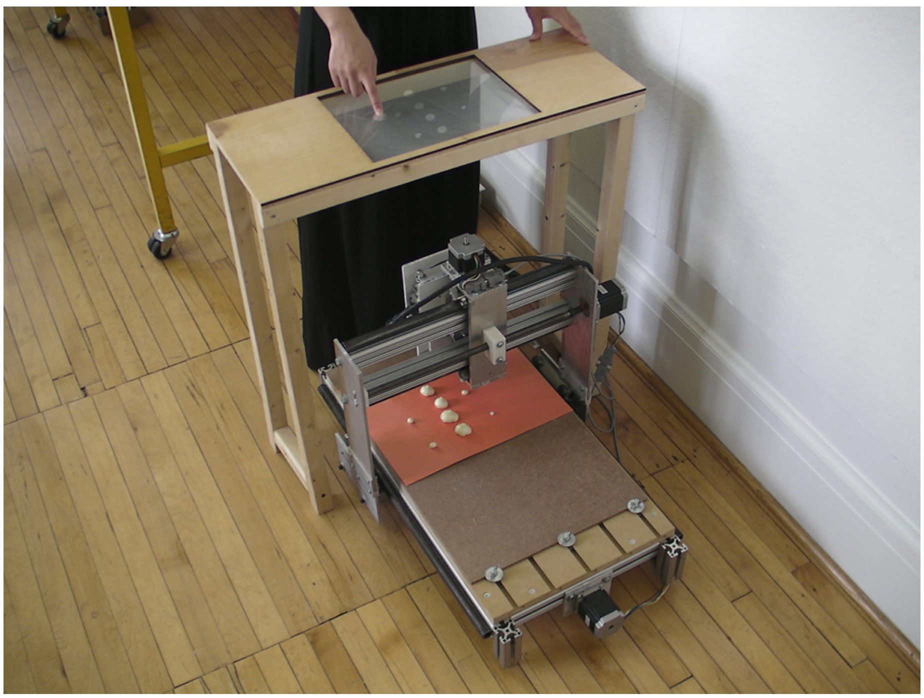


**Figure 77:** *Shaper* is a prototype CNC machine with an embedded mobile projector to interactively dispense expanding polyurethane foam material.

My explorations in this area take the form of *Shaper* (Willis et al., 2011c), a prototype CNC machine with an embedded mobile projector to interactively dispense expanding polyurethane foam material (Figure 77). The user controls the device via a rear-projected translucent touch screen to create physical artifacts with sketch-like gestures. *Shaper* challenges the conventional process of digital fabrication by allowing direct interactive control. The translucent touch surface is situated above the fabrication area, so that users can directly see the physical output. The gesture interface is projected onto the rear of the touch surface and a depth map is stored to allow multiple layers to be built up into three-dimensional form. The software detects when sketch lines intersect and raises the dispenser head to the appropriate height; material can then be built up layer by layer. The polyurethane foam dries into a lightweight and smooth material.

### 6.1.4 Commercial Toys

Finally, a number of commercial toys use simple techniques to guide and project light from an internal source to an external display area. The Tron Legacy action figures[9] animate the face of the character with a series of projected images (Figure 78). This is achieved by illuminating five LEDs in sequence and projecting through a small slide to a diffuse surface on the characters head. This approach is limited to a single image sequence but uses very simple and inexpensive parts for mass production.

**Figure 78:** A commercial figurine with a simple LED projection mechanism to create an animated face.

[9]Tron Legacy action figures: http://www.disney.co.uk/tron/figures.jsp

The AppMATEs series of toy cars[10] are designed for use on top of a tablet computer (Figure 79). Using capacitive sensing through three conductive 'touch' points on the bottom of the car, the location of the car can be recovered. The tablet computer then displays areas of light under the car that enter into several light guides. Two of the light guides lead to the headlights of the car, and another to the top of the car. The end of each light guide glows slightly and the headlight effect is enhanced by lighting effects displayed on the tablet computer, as if it was projecting light onto the road.

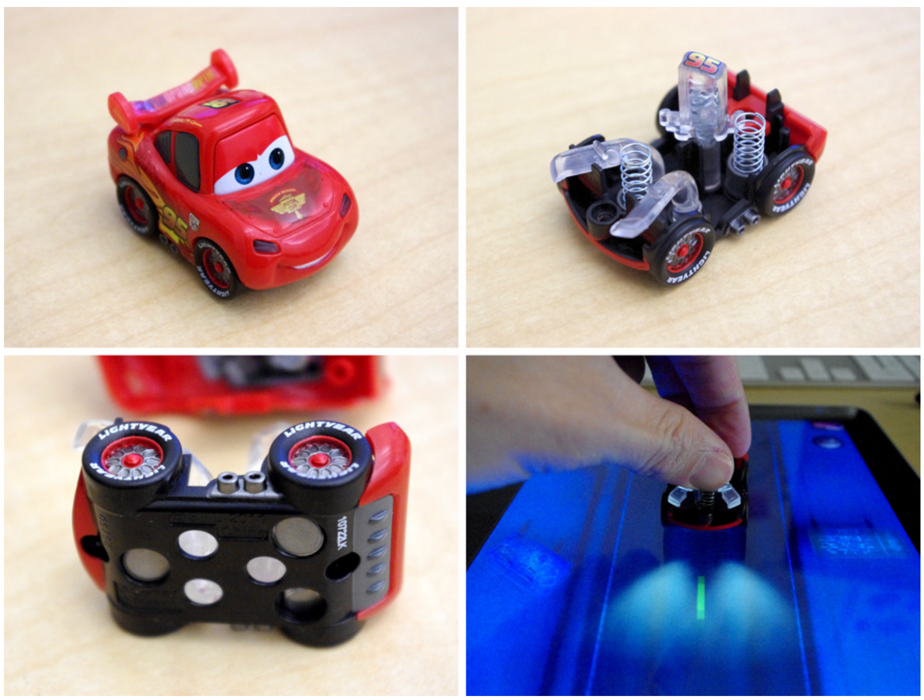


**Figure 79:** A commercial car toy with embedded light guides that direct light from a tablet computer into the headlights.

3D printing is currently a convenient tool for fabricating highly customized objects and the techniques presented in this chapter are aimed primarily at prototyping using 3D printed optical elements with mobile projectors. However, active research within the additive manufacturing community is exploring how 3D printing techniques can be scaled up for mass production (Heere and Polle, 2012) and at the same time embedded with active electronic components (Church, 2012). I envision it will be possible

[10] AppMATEs: http://www.appmatestoys.com

in the future to have much closer integration between 3D printed form and mobile projectors, while at the same time making mass production a very real possibility.

## 6.2 3D Printed Optical Elements

3D printing allows digital geometry to be rapidly fabricated into physical form with micron accuracy. Usable optical elements can be designed, simulated in software, and then 3D printed from transparent material with surprising ease and affordability.

The fabrication process begins with a digital geometric model that is converted into a series of slices to be physically fabricated layer-by-layer. 3D printing of optical quality materials typically requires a photopolymer-based process. Each layer is fabricated in sequence by selectively exposing a liquid photopolymer material to an ultra-violet (UV) light source, causing the material to cure into a solid state. Traditionally this has been achieved using 'stereolithography', where a precise laser is traced through a vat of liquid photopolymer. Other approaches include controlled exposure to UV light using a projector, or physical deposition of liquid photopolymer in the presence of a UV light source. The fundamental process of layer-by-layer fabrication with photopolymer materials is common throughout each approach.

In this work an Objet Eden260V 3D printer and Objet VeroClear transparent material is used to fabricate optical elements. VeroClear has similar optical properties to Poly(methyl methacrylate) (PMMA), commonly known as plexiglas, with a refractive index of 1.47 (650nm light source). Several other manufacturers also provide similar transparent materials, including DSM Somos' Watershed XC 11122 and 3D Systems' Accura ClearVue.

The Objet Eden260V has a print resolution of 600 dpi (42 microns) that is significantly higher than fused deposition modeling (FDM) 3D printers (e.g. Stratasys Dimension, MakerBot, or RepRap) that are typically around 100 dpi (254 microns). High resolution printing allows the creation of visibly smooth models without internal gaps. Model surfaces can be further enhanced with a manual finishing process to achieve optical clarity. This process consists of removing support material, sanding the surfaces with incrementally finer sandpaper, and then buffing[11].

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[11] Creating Clear or Translucent 3D Models:
http://www.objet.com/Misc/_Pages/Application_Notes_Left_Pane/Creating_Clear_or_Translucent_Models/

3D printed optical elements currently have some limitations. These include issues of light transmission, surface finishing, clarity, and hollow area fabrication. I describe each of these limitations in the Discussion section of this chapter.

## 6.3 Light Pipes

*Light pipes* function much like optical fiber by guiding light from point to point. 3D printing enables arbitrary geometries to be created in software and then fabricated in a single 3D print. Simply by changing software parameters, light pipes can be created with variable widths, rounded caps, and joints with other light pipes. In contrast conventional manufacturing requires considerable effort for individual fiber optic strands to be mechanically assembled, fused/deformed with heat, or chemically bonded.

Internal light pipe geometry can be embedded inside a larger model that has its own independent form-factor (e.g. Figure 76). As each light pipe can be precisely fabricated at a given location, the process of light pipe routing to avoid intersections becomes a well defined software problem. One current limitation of 3D printed light pipes fabricated on the machine used with this project suffer from imperfect light transmission with longer pipes or pipes that curve significantly. The characteristics of this light loss are outlined in the Discussion section of this chapter. I have designed around this limitation to produce functional prototypes, but envision these techniques can be expanded using future 3D printers that are optimized for optical performance.

### 6.3.1 Example Applications

I now outline several example applications that demonstrate how 3D printed light pipes can be used with mobile projectors.

#### Animated Characters

The small form-factor of mobile projectors makes them well suited to mapping projected imagery onto arbitrary surfaces using light pipes. Figure 80 shows a character with 3D printed light pipes embedded to guide projected light through the inside of the model and onto its outer surfaces. The character is 3D printed with a grid of $\varnothing$0.5 mm light pipes leading from its feet to its eyes (Figure 80a). The entire model is printed in a single pass, painted, and the ends of the light pipes sanded and polished.

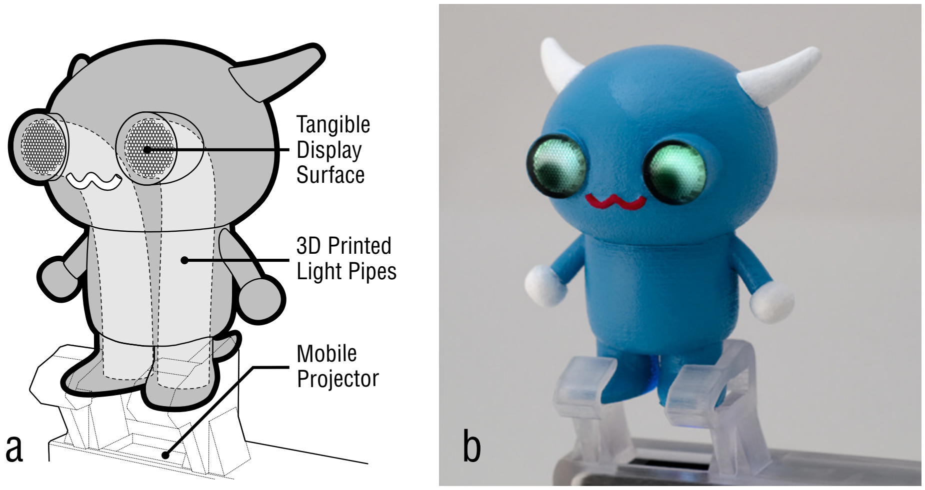


**Figure 80:** A 3D printed character with mobile projector and embedded light pipes (a) to map a projected image onto the characters eyes (b).

A laser-based mobile projector is used to focus an image at very close range. When the feet are attached to the projector, the character's eyes become a display surface that responds to user interaction such as sound or physical movement (Figure 80b). The eyes are animated to look around, blink, and portray various emotions. Although the eyes are only a small area of the entire character, they can convey a wide range of expressions.

## Projection Car

Compact projection engines found in mobile projectors can be entirely embedded inside small objects. Figure 81 shows the internal structure of a prototype 'projection car' with an embedded projector. 3D printed light pipes housed in the front of the car are used to guide light from the projector mounted internally in the rear. Light travels from the projector into a 27 x 15 array of 1mm light pipes that guide an image onto the non-planar front surface of the car. This surface becomes an active display area with computer-controlled realtime graphics. The current prototype is tethered to an external computer that outputs a composite video signal for the embedded projector.

To generate interactive graphical content, an optical mouse sensor is mounted on the bottom of the car. The mouse sensor communicates the relative movement of the car to the external computer via serial. As the car is held in the user's hand and pushed forward, the image on the surface of the car changes dynamically in response. Interactions range from abstract graphical lines that represent the speed of

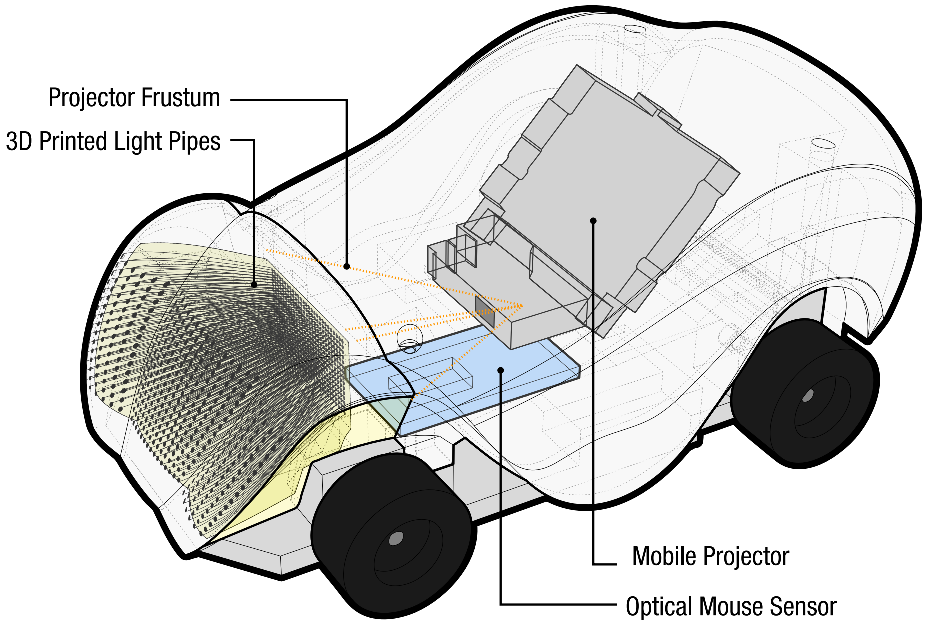


**Figure 81:** A toy 'projection car' uses an embedded projector and 3D printed light pipes to form a non-planar display.

the car's movement, to representational designs such as animating the car's headlights or projecting character-like eyes. The projection car measures 168 x 118 x 64 mm and demonstrates how compact projectors can be entirely embedded inside small objects to create new display form-factors.

## 6.3.2 Fabrication Technique

3D printed light pipes function in a similar manner to optical fiber with light reflecting internally as it travels along the length of the pipe. Internal reflection is caused by a difference in the refractive index of the internal *core* (through which light travels) and the external *cladding* (which surrounds the core) (Figure 83). Light pipes are fabricated using model material (Objet VeroClear) for the core and support material (Objet Support Resin) for the cladding. The model material cures into a rigid transparent material and the support material into a soft material designed to be easily broken apart for quick removal. To create a mechanically sound model, the brittle support material is surrounded with an outer casing of rigid material. Light pipes can be fabricated down to a thicknesses of ∅0.25mm core with a cladding layer thickness of 0.084mm. The solid outer layer that surrounds the light pipes has a 1mm wall thickness where the pipes end to allow for final surface finishing. To create accurate digital

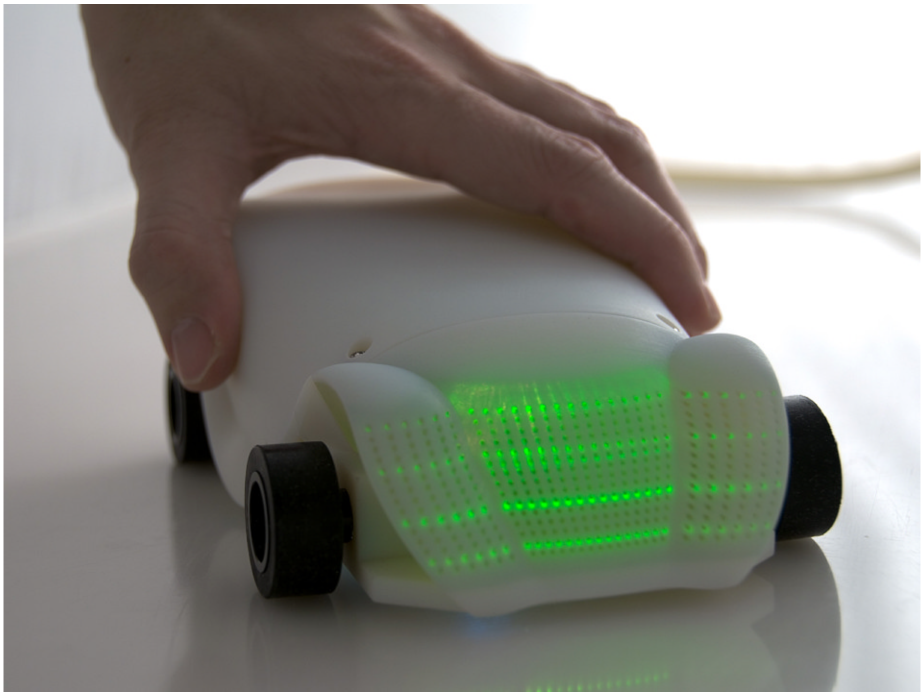

**Figure 82:** The front display surface of the projection car responds to user movement.

geometry, the light pipe grids are programmatically generated using Python scripting inside the Rhinoceros 3D application[12]. This geometry can then be exported into a mesh-based format suitable for 3D printing.

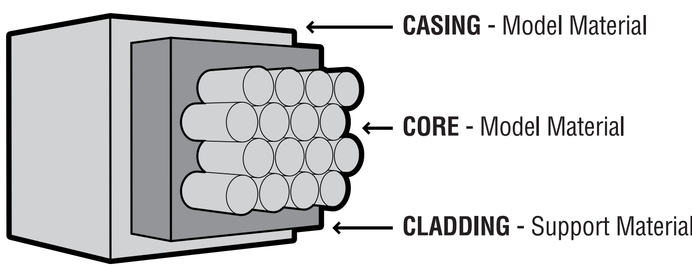


**Figure 83:** Light pipes consist of a rigid transparent core, a soft cladding, and a rigid outer casing.

[12] Rhinoceros 3D: www.rhino3d.com

## 6.4 Internal Illumination

Although 3D printing is known for its ability to precisely fabricate the *outer* form of physical objects, optically clear material allows the user to see *inner* forms within a 3D printed object as well. When highlighted with illumination from a mobile projector, these internal forms create a new area for displaying information within the object itself. Internal illumination is the process of shining light into an optical element to illuminate internal forms for display purposes. In this section I introduce techniques for internal illumination by creating reflective pockets of air within a solid transparent model.

### 6.4.1 Example Applications

I now outline several example applications that demonstrate uses for internal illumination.

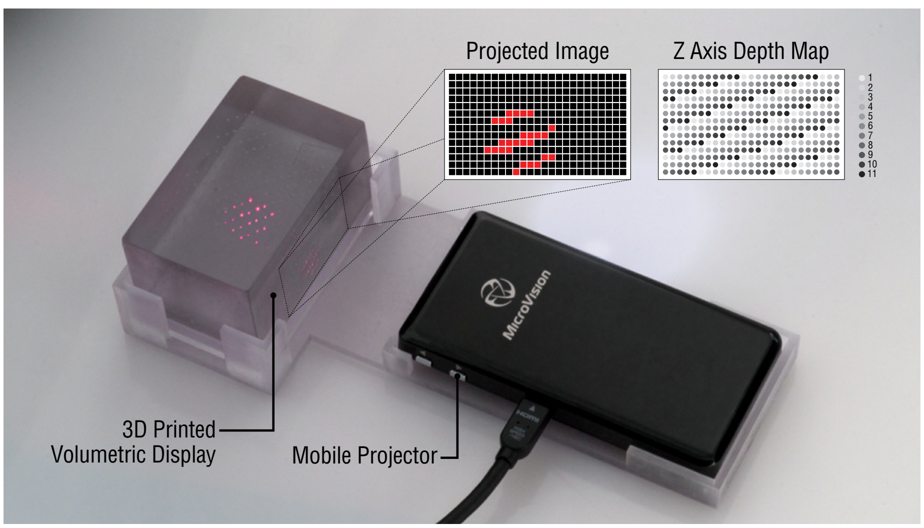


**Figure 84:** A mobile volumetric display created with embedded *dots* of air inside a 3D printed volume. A sphere is displayed inside the volume by remapping 2D pixels using a Z axis depth map.

#### Volumetric Displays

3D printed internal structures are an enabling technology for static-volume volumetric displays, allowing precise alignment of 3D pixels within a volume. Using the versatility of 3D printing, a volumetric display based on *Passive Optical Scatterers* (Nayar and Anand, 2007) has been implemented.

This display has a mobile form-factor with an 4 x 8 x 11 array of ∅1.2 mm *dot*-shaped air pockets embedded inside a 40 x 80 x 50 mm volume of transparent 3D printed material (Figure 84). The display is mounted to a laser-based mobile projector (Microvision ShowWX+). 32 x 32 pixel blocks are used to address each of the dots inside the volume. 2D pixel blocks are mapped to 3D dots using a Z axis depth map. An automated camera calibration routine is used to compensate for any slight mechanical misalignments.

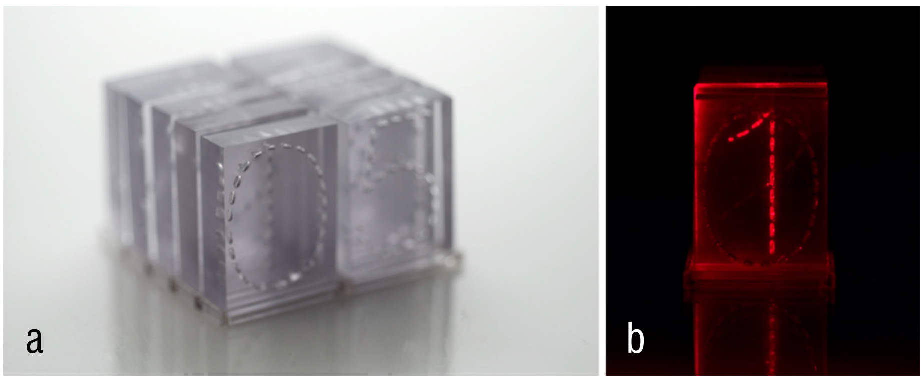


**Figure 85:** A numeric display (a) created with hollow *sheets* of air that reflect light when illuminated (b).

### Internal Text

Text within a 3D printed structure can be fabricated to create robust signage that is resistant to impact and everyday wear. The optical clarity of the material makes it possible to view internal text under normal daylight lighting conditions or with illumination at night. Using flat 3D printed 'sheet' shapes to fabricate internal text, a nixie tube style numeric display has been created (Figure 85a). Individual 3D printed layers with embedded numbers are mounted together and side-illuminated using a mobile projector (Figure 85b).

## 6.4.2 Fabrication Technique

By creating enclosed pockets of air within a solid transparent model, light intersects with the air pockets and is transmitted or reflected depending on the angle of incidence. By carefully designing the geometry of the air pockets light can be guided internally within the model or externally out towards the users eye.

Air pockets can be created using 3D printers that deposit small beads of material layer-by-layer to build

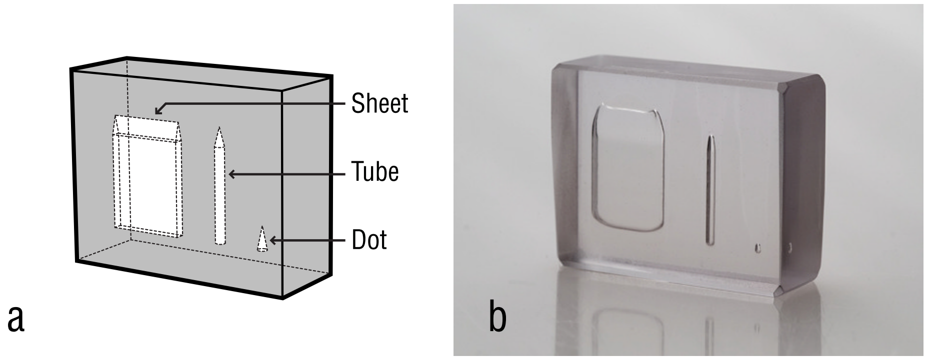


**Figure 86:** *Sheets*, *tubes*, and *dots* are primitive elements for fabricating reflective pockets of air inside a 3D print that can be illuminated with mobile projectors to form a display area. Due to material settling, digital geometry (a) differs slightly from the actual printed form (b).

up a model. As individual beads of material are deposited, they must have a supporting surface beneath them or they fall down with gravity. However, a small amount of step-over (overhang) from layer to layer allows for hollow areas to be slowly closed. In practice a step-over angle equivalent to 14 degrees (from vertical) allows air pockets to be reliably closed with minimum shape distortion. Greater step-over angles cause the material to fall into the air pocket and slowly raise the air pocket location vertically or fill it entirely. Figure 86 shows a series of primitive elements that can be fabricated from air pockets. The digital geometry sent to the printer (left) differs from the actual air pocket shape fabricated (right). This difference is due to beads of material settling without direct support structure during the fabrication process. To programmatically generate patterns from the *dot*, *tube*, and *sheet* primitives, the Grasshopper programming environment[13] inside the Rhinoceros 3D application is used. This allows primitive elements to be mapped to lines, enclosed within solids, or aligned with illumination sources.

## 6.5 Discussion

3D printed optical elements have unique limitations that should be considered during the design and fabrication process.

[13] Grasshopper: www.grasshopper3d.com

### 6.5.1 Light Pipe Transmission

3D printed light pipes fabricated with the current setup suffer from limited light transmission. To more accurately characterize the conditions under which light loss occurs, two light measurement tests were performed with light pipes over varying distances and curvature. To simulate a typical application scenario off-the-shelf components were used: a red 5mm LED emitter and a photodiode-based receiver (Taos TSL12S). For each reading, light was directed into the light pipe with the emitter and a voltage value measured from the receiver at the other end.

For the distance test the light transmittance of a ∅2mm 3D printed light pipe was compared to a commercially produced ∅2mm optical fiber made of PMMA. The 3D printed light pipes consisted of a core, cladding, and casing configuration with distances ranging from 10-100mm in 10mm increments. The commercial optical fiber was cut to the same lengths and mounted in a rigid casing. For the curvature test a series of light pipes following a 90°arc were created, each with an incrementally larger radius. The length of the light pipes was extended on each end to be precisely 50mm in total length.

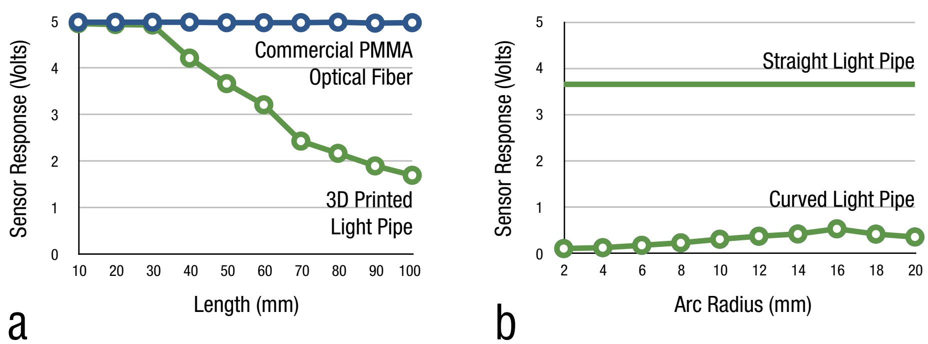


**Figure 87:** Light transmittance of 3D printed light pipes compared to commercial optical fiber (a) and transmittance of 50mm 3D printed light pipes in 90°arcs with increasing curvature radius (b).

Figure 87a shows that 3D printed light pipes currently suffer from increasing light loss with distance. Adding curvature to a light pipe further increases light loss when compared to a straight light pipe of equal length (Figure 87b). I believe this limited performance is due to two factors. Firstly, the contours where two different materials intersect are currently not perfectly smooth (Figure 88). Microscopic inconsistencies on internal surfaces result in light being lost or redirected in unpredictable ways. This makes it difficult to accurately model the behavior of light passing through the interior of a 3D printed light pipe. Secondly, although the refractive index of the core material is known, no information is available for the refractive index of the cladding material. Because support material is not intended as an optical material, its performance as cladding is understandably low. The refractive index of each material is likely close enough to restrict the angle of incidence to a relatively small value and thereby limit internal reflection.

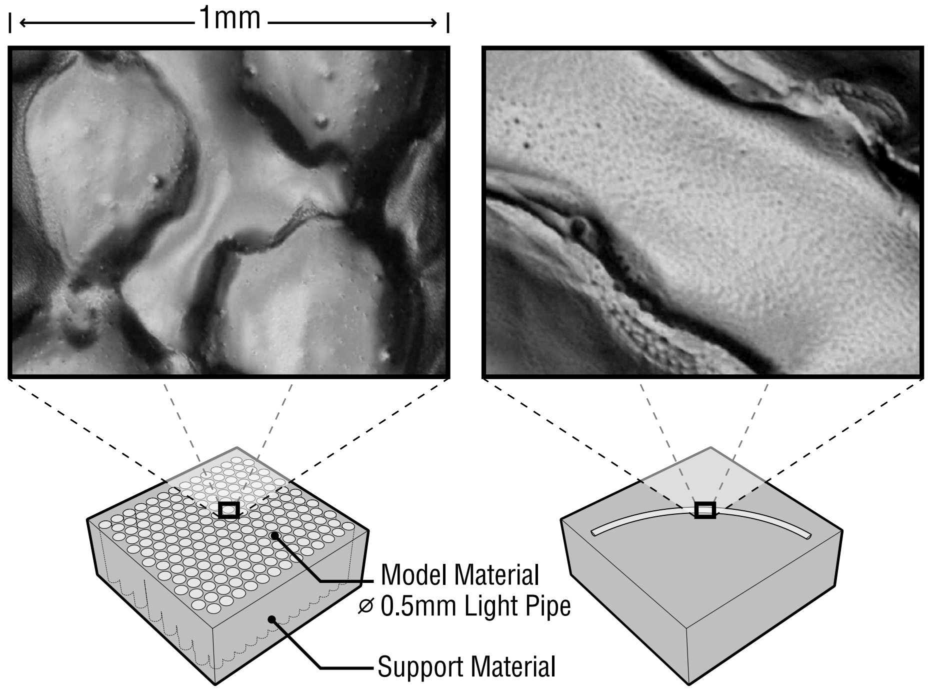


**Figure 88:** Magnified view of the material intersections in 3D printed light pipes.

Although the current materials and printing process used is not optimized for optical performance, promising materials science research has demonstrated that photopolymer waveguides can be fabricated with minimal light loss (Lorang et al., 2011). I am therefore optimistic about the possibilities for fabricating light pipes in the next generation of optically optimized 3D printers. It is worth noting that many commercial display technologies routinely encounter significant light loss, e.g., resistive touch screens reduce display light transmission by up to 20% (Ge and Wu, 2010).

## 6.5.2 Surface Finishing

In current generation 3D printers, unfinished surfaces appear smooth and transparent to the naked eye, but not optically clear. Unfinished surfaces can be used when some amount of light scattering is acceptable, however to maximize light passing to/from the interior of a 3D printed optical element, surface finishing should be performed (i.e. sanding and buffing). Flat surface finishing can be performed using power tools such as a belt sander and buffing wheel. Curved surfaces require hand sanding and are more time intensive. Textured surfaces or surfaces with small micro-facets are difficult to perform finishing on without specialized equipment.

a b

**Figure 89:** Surface smoothing is applied by depositing additional uniform layers of material (b) to improve the raw finish (a) of a lens.

A smoothing technique discovered during the process of this research can be used to improve the surface quality of models. Additional uniform layers of material are deposited from a height above the surface of the model, coating it with an even layer of liquid resin. When the resin is cured by UV exposure, the surface finish can greatly improve. Figure 89 shows the difference in surface finish when ten additional layers of material are deposited. This process is performed entirely inside the Objet 3D printer without any software or hardware modifications.

### 6.5.3 Clarity

The clarity of 3D printed optical elements currently depends on several factors. *Model Thickness*: thicker models tend to lose optical clarity and appear increasingly cloudy. *Print Direction*: the greatest clarity is seen when looking perpendicular to the printed layers, looking parallel to the printed layers appears blurrier. *UV Exposure*: Overexposure to UV light during the curing process can cause a loss in optical clarity, making the model appear yellow in color. *Surface Quality*: greater clarity can be achieved with extra sanding steps during the finishing process.

### 6.5.4 Hollow Areas

As 3D printed objects are built up layer by layer, hollow areas typically require support material inside the hollow. Printing completely enclosed hollow areas can seal the support material inside with no means for it to be extracted. Completely enclosed hollow areas of air can be fabricated using 3D printers that deposit small beads of material layer by layer; support material must be disabled and internal geometry must have minimal step-over in the vertical axis. This requirement for self-supporting geometry limits the design space when creating hollow areas. In theory, internal geometry can be combined with arbitrary external geometry complete with overhangs and support material. In practice, the 3D printer used for this research did not allow selective use of support material; it must be either enabled or disabled for each print. This restriction, however, can be resolved with an improved software interface to the 3D printer.

## 6.6 Summary

Mobile projectors embedded in physical objects open up a range of new possibilities for interaction. With the development of optical quality 3D printed materials, display areas no longer need to be confined to rectangular, flat, two-dimensional surfaces. Using the techniques introduced in this chapter, light can be guided from the projector to arbitrary surfaces using light pipes, or internal areas of an object can be illuminated to form an active display area.

This research represents an initial exploration of how mobile projectors can be combined with custom 3D printed optical elements. With the continuing emergence and accessibility of 3D printing technology, combined with the decreasing size and price tag of mobile projectors, numerous other form-factors and interaction scenarios will undoubtably be explored. I foresee future 3D printers with a diverse range of optical printing functionality. The ability to dynamically control optical properties such as the refractive index, reflectivity, transmittance, absorption, and diffusion will enable an even richer design space for interaction with embedded mobile projectors.

# 7 Conclusion

The vision of *ubiquitous projection* involves the proliferation of tiny, bright, power-efficient projectors embedded into devices throughout the environment. In this concluding chapter I reflect on how this research has contributed to realizing this vision, what the specific outcomes have been, what challenges still remain, and how future work can advance us along the path towards *ubiquitous projection*.

## 7.1 Contributions

The research community continues to push the boundaries of how, where, and why mobile projectors are used. This research adds significantly to this body of work with a number of contributions.

*A comprehensive survey of mobile projector-based interaction* was presented that documents the use of historic projection devices. For the first time, contemporary research dealing with mobile projectors has been contextualized within the greater landscape of historic mobile projection devices such as the handheld magic lantern and the Japanese *furo*. This survey not only adds great depth to an emerging research field, but also informs the development of new mobile projector-based systems by providing insight into the use of these devices.

*Novel interaction techniques, metaphors, and principles* were developed that can be applied to the design of mobile projector-based systems. Together they form a toolkit that can aid researchers and designers to quickly understand the many nuances of mobile projector-based interaction. The *MotionBeam* metaphor, for example, enables simple yet intuitive character control, while the supporting interaction principles provide a concrete means for implementation. The overall toolkit spans across single-user and multi-user cases, as well as encompassing techniques for interaction with the environment and embedded mobile projectors.

*Functional prototypes and in-depth implementation details* were presented. A core part of this research has involved designing and developing mobile projector-based interactive systems. Working prototypes have enabled a rapid exploration of the design space for these new interfaces. Implementation details throughout this document guide the reader in replicating and building upon this work. Many of the low-level implementation details are generalizable to other areas of research and can be applied in numerous ways.

*Technical contributions* that can be generalized for use in other systems were documented. Many of the interaction scenarios proposed by this research required technical problems to be solved. For example, the *SideBySide* system required mobile projector-based multi-user interaction without instrumentation of the environment. This requirement led to the development of a specialized projector and custom marker tracking algorithms. These technical innovations and others, such as the use of 3D printed optical elements for displays, can be applied to future systems using mobile projectors as well as a broad range of other applications.

*Preliminary user testing* was conducted with the prototype systems when appropriate. This user testing was aimed at understanding elements of the user experience, technical system performance, and to demonstrate the viability of mobile projector-based interaction with first time users. Due to the novel nature of the interaction and the immaturity of the systems, I judged it premature, and possibly inappropriate, to perform conventional comparative studies with other systems.

## 7.2 Outcomes

The publications resulting from this research are listed in the appendix. Within the short period of time since publication, over 50 papers related to mobile interaction, augmented reality, and tangible user interfaces have referenced this work. Elements of this work has also been used in an educational context. Students at the University of Cambridge used the *MotionBeam* metaphor and interaction principles as a basis to develop a series of mobile phone-based games (Figure 90). During a six week course led by Prof. Kenny Mitchell they developed android applications using the built-in sensors and projector on the Samsung i8520 Galaxy Beam – one of the very first commercial devices to incorporate similar capabilities to the original *MotionBeam* prototype.

Within the media, this research has been widely covered in articles by Wired, New Scientist, Discovery, BBC, and numerous others. This research was also featured in a recent article discussing key issues and research dealing with mobile projectors in *ACM Interactions Magazine* (Dachselt et al., 2012). Perhaps the crowning achievement so far has been the awards of *Best Paper*, *Best Paper Nominee*, and *Best Demo* (twice) at the *ACM UIST* conference. *UIST* has been a notable venue for mobile projector-based systems and is highly regarded within the HCI community. A number of opportunities are being explored for the commercialization of this research with Disney Research. Numerous enquires have been fielded from companies involved in the consumer electronics, mobile communications, and game development industries.

The short-term future for research related to mobile projectors looks promising due to continuing

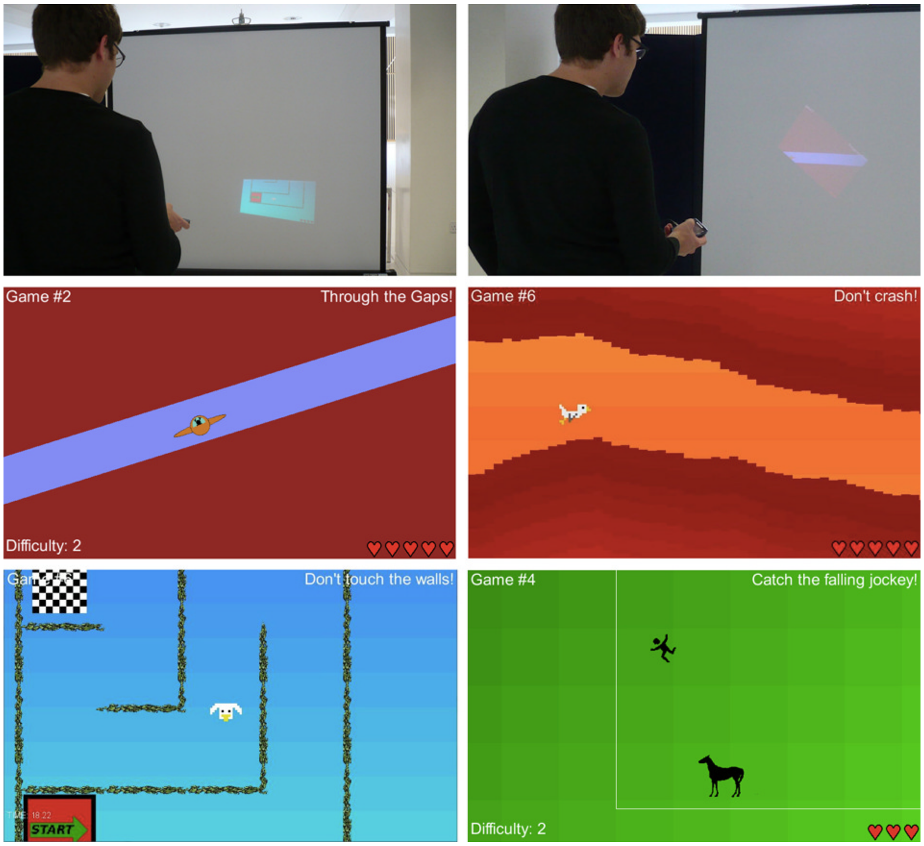


**Figure 90:** Mobile projector-based games developed as part of a class at the University of Cambridge based on the *MotionBeam* metaphor and interaction principles

interest from industry, academia, and the general public. It is difficult to say how long the current level of activity can be maintained. Although the cyclic nature of technology-based research suggests the next new technology is just around the corner, it is difficult to see a technology as fundamental and historic as projection fade away without a realistic substitute.

## 7.3 Challenges

Despite the promising outcomes achieved, a number of general challenges still need to be overcome. The brightness of mobile projectors is one of the key issues limiting greater adoption. Commercially available mobile projectors currently range in brightness from 10-50 lumens. By comparison, a 60 watt incandescent bulb emits approximately 850 lumens, and a 5 watt incandescent 'night light' emits approximately 25 lumens. However, lumens represent the total visible light *emitted* by a source and do not take into account how much light is *received* in a certain area. With a 60 watt incandescent bulb, the equivalent of only 100 lumens may be reaching an evenly lit one square meter area of a room. In full daylight however, the equivalent of 10,000 lumens may be reaching a one square meter area. This suggests that with increases in LED brightness, mobile projectors will become more viable in lit indoor spaces, but will not compete with the sun outdoors. The key challenge is not related to brightness, but to power efficiency and battery life. Current commercial models aim to provide approximately 100 minutes of battery life for movie viewing on a single charge. Consuming 1 Watt of power, equates to a 10 lumen projector with 350mA LEDs for each color. Higher capacity batteries or more efficient LEDs are the two paths to brighter projectors.

Mobile projectors pose a number of questions related to social interaction in public spaces. Personal projection stand in stark contrast to conventional mobile devices that have small personal displays. Relatively little is known about how users will adapt to projecting imagery from their devices that is clearly visible to others nearby. Although applications such as viewing photos and movies have precedents for communal viewing, other applications, such as viewing email, contacts, or calendar entries, are typically solitary activities. Initial research has begun to explore the social issues surrounding projection into public space on both a theoretical level (Ko et al., 2010) and with concrete studies of users interacting in 'the wild' (Wilson et al., 2010; Cowan et al., 2012). However these small scale studies can only begin to address the larger implications of *ubiquitous projection*.

Perhaps the most pressing issue that can be addressed by researchers and designers is developing compelling applications that resonate with the public. In the early stages of this research it remained a challenge to develop applications without a suitable hardware platform. This led to the development of a number of custom hardware systems through which a range of applications could be prototyped. However, the 'chicken and egg' problem of developing applications without suitable hardware is being overcome by commercially available smartphones with embedded projectors. This development is important because it vastly decreases development time, creates standardization, and removes the barrier of hardware development. We can expect to see a growing amount of work using off-the-shelf devices to develop novel applications in the very near future.

## 7.4 The Future

This research has begun to explore the future of *ubiquitous projection* using todays technologies. However, as projection technologies continue to evolve, what can we expect in the long term?

Mobile projectors excel because they can project imagery into spaces that were previously impractical. An obvious long term extension is developing technologies that can extend the range of spaces that projection can work in. Brightly lit spaces pose a significant problem for projection that can not be fully addressed by simply increasing the power of the light source *signal* so it rises above the *noise* caused by ambient light. A theoretically possible but immensely challenging approach might involve light cancelation by sensing the wavelength of incoming ambient light and emitting an inverted signal. Although a similar general approach is used with noise canceling headphones, the speed, wavelength, and wide distribution of light will likely make this impractical. Another approach would involve developing intelligent projection screen materials that are capable of reflecting light from a projection source and absorbing light from other sources. Metamaterials, artificial materials that have properties not found in nature, are one candidate for the development of such a screen.

Overcoming projection's reliance on a reflective surface is another challenging problem that will be the focus of research well into the future. The ability to project into free space has been popularized by holographic displays in science fiction films, but is already an active area of research. One approach worthy of mention is the use of focused laser light and the plasma emission phenomenon to ionize air and produce glowing spots of light in free space (Kimura et al., 2006). Although this work is currently far from commercial development, it does demonstrate how projection will likely be a core component in free space 3D displays of the future. Compact, mobile implementations of these projection devices would further empower many of the interactive techniques, metaphors, and principles presented in this research.

This research has put forward the vision of *ubiquitous projection*, enabled by tiny, bright, power-efficient projectors embedded into devices throughout the environment. Unlike the projectors we encounter today, mobile projectors will be distributed in our houses, embedded in our vehicles, and carried with us in mobile devices. They will facilitate shared interactive spaces, transform physical objects with dynamic imagery, and dramatically change how we think about lighting and illumination. The mobile projector will continue to build upon and advance the centuries old technology of projection well into the future.

# A Publications

The following is a list of publications resulting from this research.

## A.1 Full Papers

- Karl D.D. Willis, Takaaki Shiratori, and Moshe Mahler. HideOut: Mobile projector interaction with tangible objects and surfaces. In *Proc. TEI '13*. ACM, 2013
- Karl D.D. Willis, Eric Brockmeyer, Scott E. Hudson, and Ivan Poupyrev. Printed Optics: 3D printing of embedded optical elements for interactive devices. In *Proc. UIST '12*, pages 589–598. ACM, 2012a
- Karl D.D. Willis. A pre-history of handheld projector based interaction. *Personal and Ubiquitous Computing*, 16(1):5–15, 2012
- Karl D.D. Willis, Ivan Poupyrev, Scott E. Hudson, and Moshe Mahler. SideBySide: Ad-hoc multi-user interaction with handheld projectors. In *Proc. UIST '11*, pages 431–440. ACM, 2011a
- Karl D.D. Willis, Ivan Poupyrev, and Takaaki Shiratori. MotionBeam: A metaphor for character interaction with handheld projectors. In *Proc. CHI '11*, pages 1031–1040. ACM, 2011b

## A.2 Short Papers

- Karl D.D. Willis, Ivan Poupyrev, Scott E. Hudson, and Moshe Mahler. SideBySide: Multi-user gestural interaction with handheld projectors. In *Proc. Mobile HCI '12*, pages 203–206. ACM, 2012b
- Karl D.D. Willis. Character interaction with handheld projectors. In *Proc. TEI '11*, pages 445–446. ACM, 2011
- Karl D.D. Willis, Cheng Xu, Kuan-Ju Wu, Golan Levin, and Mark D Gross. Interactive fabrication: New interfaces for digital fabrication. In *Proc. TEI '11*, pages 69–72. ACM, 2011c
- Karl D.D. Willis and Ivan Poupyrev. MotionBeam: Designing for movement with handheld projectors. In *Ext. Abstracts CHI '10*, pages 3253–3258. ACM, 2010a
- Karl D.D. Willis and Ivan Poupyrev. Animation & sequential art principles for handheld projector interaction. In *Proc. Ubiprojection Workshop, Pervasive '10*, 2010b

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