HideOut: Mobile Projector Interaction with Tangible Objects and Surfaces

Karl D.D. Willis [1,3]
[1] Disney Research Pittsburgh
Pittsburgh, PA, USA
{karl, moshe.mahler}@disneyresearch.com

Takaaki Shiratori [2]
[2] Microsoft Research Asia
Beijing, China
takaakis@microsoft.com

Moshe Mahler [1]
[3] Computational Design Lab
Carnegie Mellon University
Pittsburgh, PA, USA

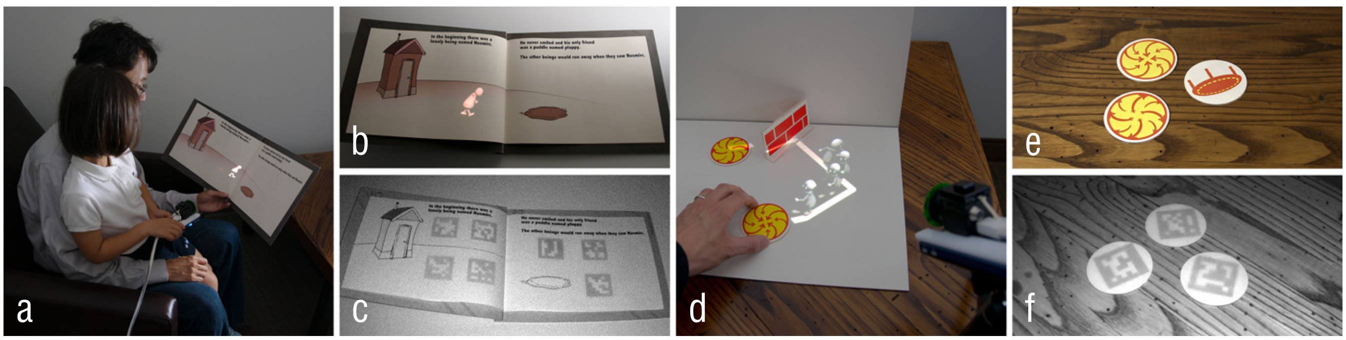

Figure 1. ***HideOut*** **is a mobile projector-based system that uses hidden markers (c,f) to map projected imagery onto tangible objects and surfaces (b,e) such as storybooks (a) and board games (d).**

ABSTRACT
HideOut is a mobile projector-based system that enables new applications and interaction techniques with tangible objects and surfaces. *HideOut* uses a device mounted camera to detect hidden markers applied with infrared-absorbing ink. The obtrusive appearance of fiducial markers is avoided and the hidden marker surface doubles as a functional projection surface. We present example applications that demonstrate a wide range of interaction scenarios, including media navigation tools, interactive storytelling applications, and mobile games. We explore the design space enabled by the *HideOut* system and describe the hidden marker prototyping process. *HideOut* brings tangible objects to life for interaction with the physical world around us.

Author Keywords
Mobile, projector, interaction, tangible, infrared, ink, hidden, marker

ACM Classification Keywords
H5.2[Information interfaces and presentation]: Miscellaneous

INTRODUCTION
Mobile devices have become an important part of our day-to-day interaction with computing systems. They allow us to communicate information at any time, view digital content on the go, and play games anywhere. Mobile projectors are a recent technology that enables these interactions, and many others, to be situated in the immediate environment rather than confined to a mobile device. Interaction in the physical environment builds upon our 'pre-existing knowledge of the everyday, non-digital world' [13] and opens up a rich space for mobile devices that support tangible interaction. We are 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. With as many as 39 million embedded projectors predicted to be on the market by 2014 [19], we believe now is an ideal time to explore this rich new space.

To realize our vision we have developed *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 1). 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 [25]. 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

TEI 2013, February 10–13, 2013, Barcelona, Spain.

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. We present the following contributions:

1. 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.
2. A functional prototype system consisting of custom hardware and software, and discussion of the design and rationale behind the system.
3. Documentation of the performance, practicalities, and implementation details for creating hidden marker projection surfaces using IR-absorbing ink.

RELATED WORK

Research related to the *HideOut* system spans the areas of projector-based augmented environments, mobile projector interaction, and hidden marker tracking.

Augmentation of the environment with projected imagery has been the long-term goal of 'spatial augmented reality' [3]. Notable approaches to image tracking and registration include commercial motion-capture systems [2], photo-sensors with structured light patterns [16], steerable camera-projector pairs [28], fiducial marker tracking [32], and depth-camera-based systems [39]. 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 [14, 38]. These systems, however, are designed for use in a stationary position — we aim to enable mobile interaction that can augment objects and surfaces in any space.

Prototype systems exploring the use of mobile projectors have used active sensing installed in the environment to identify and interact with tagged objects [30] and navigate virtual workspaces [4, 5]. Camera-based systems allow mobile interaction with surfaces in the environment [20, 40] and with other users [6, 24, 36]. Depth-camera-based systems [7, 9, 12, 21] can sense detailed information about the geometry of the surrounding environment. Our 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.

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 [11, 17, 22, 35], 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 [34], 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 [10, 15]. 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 [33], to hide fiducial markers for use with augmented reality video see-through displays [25], and to support tracking and registration of imagery from fixed projector systems [23]. 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, we build upon the use of hidden fiducial markers [25, 23] to explore novel interaction techniques and applications enabled by the new affordances of mobile projectors.

HIDEOUT

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

Hidden Marker Projection Surfaces

Hidden marker projection surfaces utilize a single surface for both tracking *input* and projector *output* (Figure 2). 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.

We use IR-absorbing inks to create marker patterns that are hidden to the human eye (Figure 3a), but visible to an IR-sensitive camera (Figure 3b). This approach avoids the obtrusive appearance of visible fiducial markers and frees up valuable space to function as a projection surface. We carefully select IR-absorbing inks that are suitable for use with

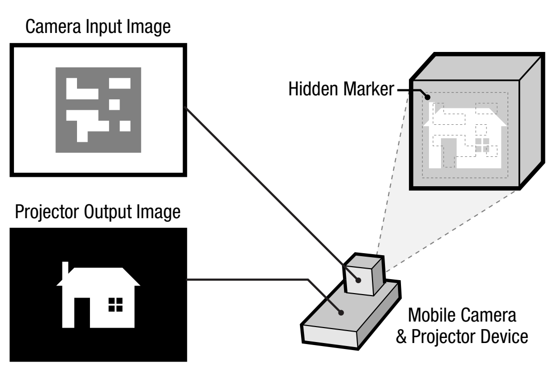

Figure 2. Camera input and projector output are focused on the same hidden marker projection surface.

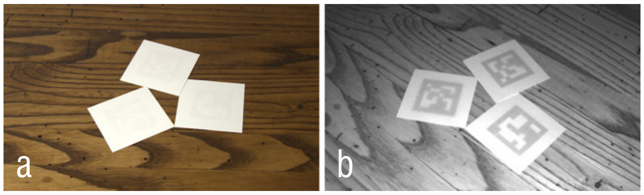

Figure 3. Hidden markers created with IR absorbing ink, shown in the visible (a) and IR spectrums (b).

projection, i.e. they do not fluoresce when exposed to projected light as with previous work [25, 26]. We have developed a novel technique for overprinting visible graphics on top of hidden marker patterns. Arbitrary graphics can be used to decorate tangible objects (Figure 1e) without obscuring the underlying marker pattern (Figure 1f). In the prototyping section we describe the techniques we use to create hidden markers.

Hardware

Our hardware platform consists of a prototype mobile device with onboard projector, camera, IR illumination source, and button (Figure 4). We use a Microvision ShowWX focus-free laser projector 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 our system absorbs IR light, we attach an IR illumination source directly to the camera to ensure robust tracking in different lighting environments. We use four 830 nm IR LEDs attached directly to the camera on a custom PCB. In our current implementation, the mobile device is tethered to a standard computer to simplify the development process, enable rapid evaluation of our approach, 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 our platform is possible.

Software

Our software system provides support for object identification and tracking, as well as multiple projection techniques. We use the *ARToolKitPlus* library to detect markers embedded in objects and surfaces. We apply adaptive thresholding to the camera image using the *OpenCV* library for robust

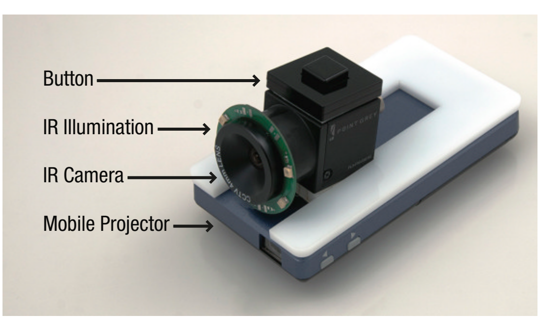

Figure 4. The *HideOut* prototype mobile device.

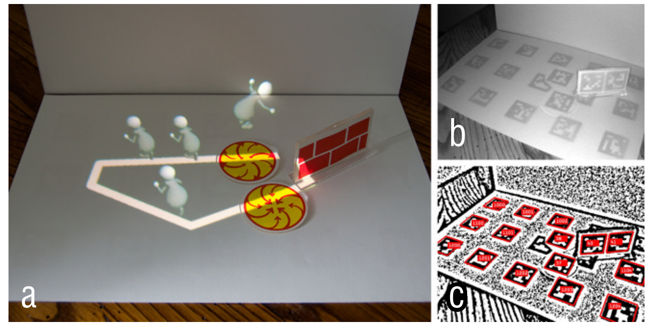

Figure 5. Marking tracking is applied to a scene (a) in the IR spectrum (b) using adaptive thresholding (c).

marker detection (Figure 5). Once the markers are identified, we use a standard homography technique to estimate the poses of the projector and objects in the scene [8]. The extrinsic parameters of the projector with respect to the camera are calibrated in advance [1].

Our software system supports several different projection techniques from the literature. Using *standard projection* an image is projected 'as is' without any geometric correction (Figure 6a). This can be used for first-person style interactions where a 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 6b). 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 [31]. *Anamorphic projection* is used when projecting 3D geometry that does not exist in the physical scene (Figure 6c). A pre-distorted image is projected that appears three-dimensional when viewed from the user's vantage point [18] (Figure 7). For example, projecting a life-like character that appears to stand on the floor beside you.

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

EXAMPLE APPLICATIONS

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

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

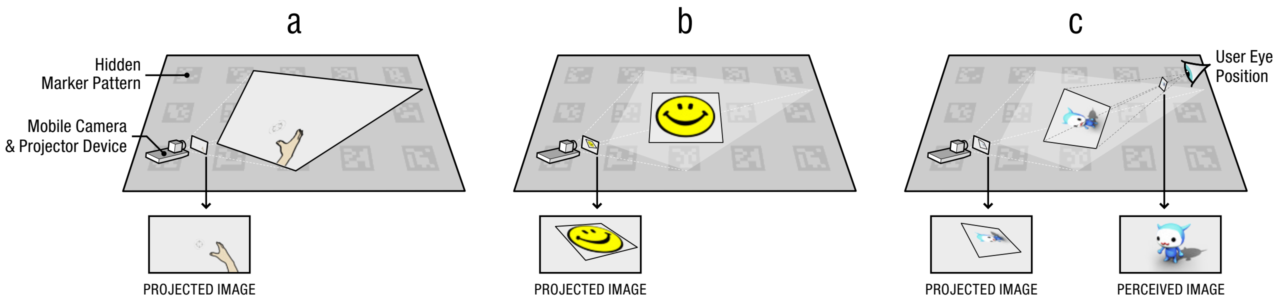

Figure 6. Projection techniques: *Standard Projection* (a), *Surface Projection* (b), *Anamorphic Projection* (c).

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

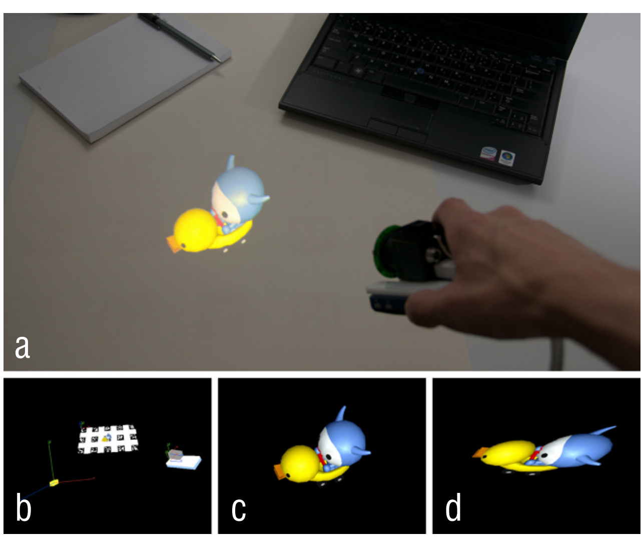

Figure 7. Anamorphic projection of a 3D character (a), 3D scene view (b), image rendered from the user's view point (c), and pre-warped image for projection (d).

can become interactive displays that respond to tangible objects without complex sensing and projection infrastructure. These are a few of the many applications we envision in the future. Next we introduce example applications that demonstrate some of these scenarios using our current prototype system.

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 8). 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.

Photo Viewer

The *Photo Viewer* application shows how digital media files can be projected and aligned onto surfaces in the physical environment (Figure 9). 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

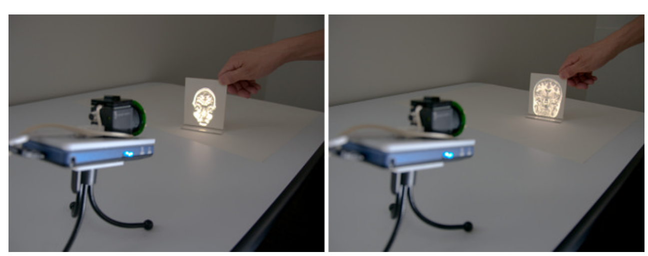

Figure 8. In the *Scan Viewer* application, imagery from an MRI scan is dynamically mapped onto a tangible object based on its location.

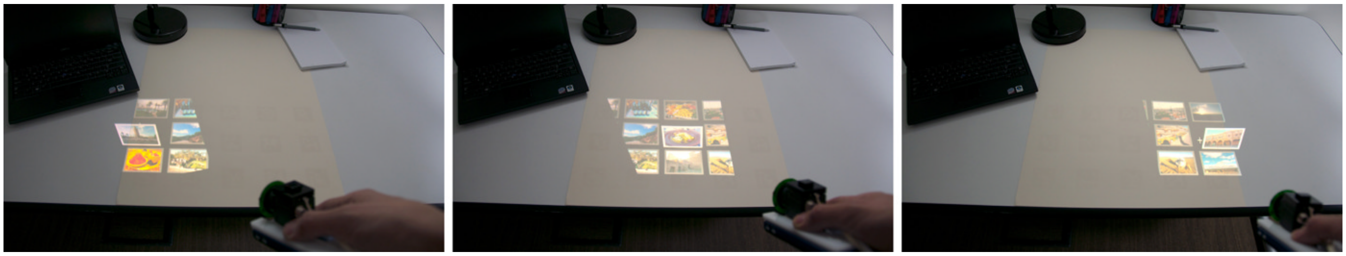

Figure 9. Browsing photos with the *Photo Viewer* application – photos 'pop-up' from the surface to indicate selection.

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.

Schedule Viewer

The *Schedule Viewer* application demonstrates how highly localized information can be projected from a mobile device to create digital signage (Figure 10). 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.

Storytelling & Games

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

Interactive Book

The *Interactive Book* application enhances the storytelling experience by projecting animated characters onto a children's story book (Figure 1a). 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 [37]. 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 11). 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.

Board Game

The *Board Game* application transforms a traditional board game into an interactive display surface with projection (Figure 1d). 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

Figure 10. The *Schedule Viewer* application enables a static sign to be augmented with projected information from a conference room schedule.

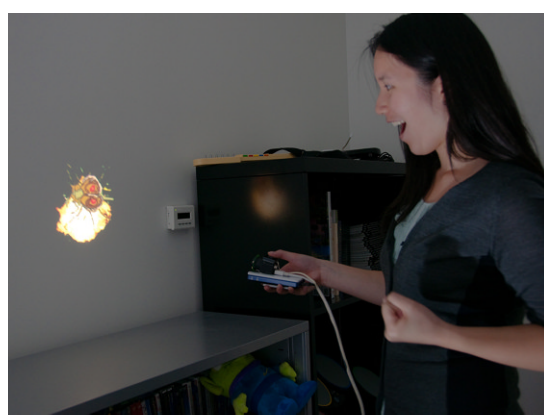

Figure 11. In the *Shooting Game* application, users search for hidden 'bugs' in the environment marked out with hidden markers.

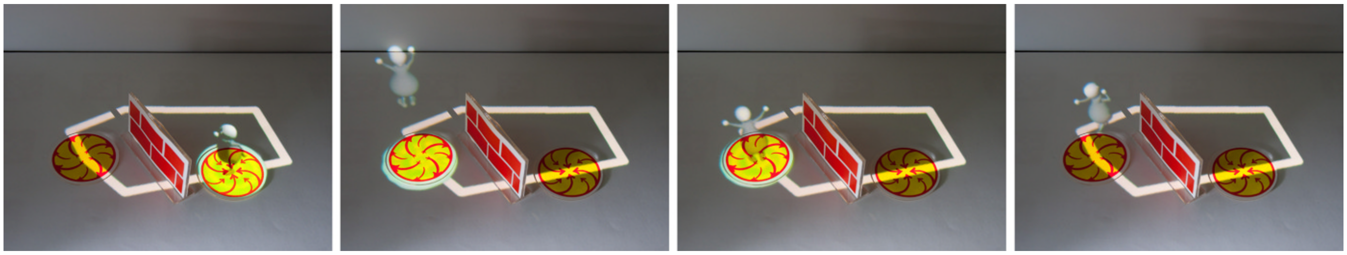

Figure 12. A projected character responds to tangible objects to teleport over a wall in the *Board Game* application.

object teleports them to a different location (Figure 12). 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.

PROTOTYPING

To aid the reader in producing hidden marker projection surfaces, we now provide a detailed account of the performance, practicalities, and implementation details for prototyping hidden markers using IR-absorbing ink.

Invisible Inks

A variety of 'invisible inks' are available that absorb and/or fluoresce in the ultra-violet (UV) or IR spectrums. We focus on IR as commercial CCD/CMOS cameras are typically less sensitive to UV. 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 [25, 27] were not applicable for our purposes. In the remainder of this section we evaluate IR-absorbing inks for contrast, invisibility to the human eye, and resistance to fading.

Infrared Ink Contrast

We evaluated five different IR-absorbing inks (Table 1) that are provided in a concentrated form. To evaluate both the level of contrast in the IR spectrum and visibility to the human eye, we tested each ink at different strengths. We started with 10 ml of solvent (acetone) and added 0.1 ml increments of concentrated ink with an eye dropper. At each step, we deposited one drop of the diluted ink on regular white office paper and repeated this process nine times. To measure the level of contrast in the IR spectrum, we captured images of each ink sample using an 8-bit grayscale Point Grey Flea3 camera with an 89B Wratten IR filter (50% pass at 720 nm). From the captured images we calculated the difference between an averaged sample of the inked area and the plain paper area to get a measurement of contrast in the IR spectrum. Figure 13 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.

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 inks evaluated.

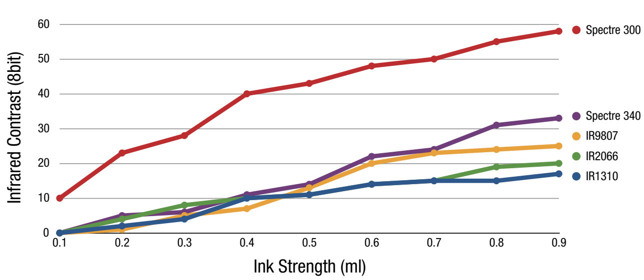

Figure 13. Contrast of IR inks in the IR spectrum.

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, we subjectively judged IR9807 as by far the most invisible. This ink has a very neutral color with a slight green tinge. Spectre 340 was arguably the next most invisible ink, with a visibly brown hue. We found Spectre 300, IR1310, and IR2066 visibly green in color and quite apparent to the eye.

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, we performed a fade test with each of the five inks. We measured 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). The two coated samples were exposed to fluorescent light in standard office conditions for the 12-day period. Figure 14 shows the reduction in contrast as a normalized percentage of the new ink sample; lower values indicate greater fading. We found that 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.

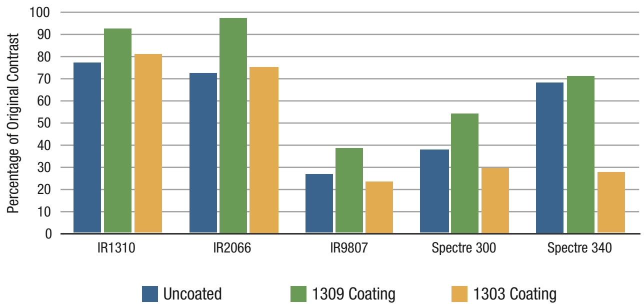

Figure 14. Fading of IR inks with and without coatings.

Visible Overprinting
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 does not effect marker detection in the IR spectrum (Figure 1f). 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 will be investigated in future work.

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. We use Spectre 340, diluted at a ratio of 0.5 ml ink to 10 ml solvent, and apply it to a cream-colored paper to match the ink hue. We use a laser-cut mask and spray gun to evenly coat the paper surface.

DISCUSSION & FUTURE WORK
Our current system has several limitations and tradeoffs that can be addressed in future research.

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 we have opted for stronger concentrations to enhance tracking and compensate for fading. Future work can explore ways to further disguise ink patterns using custom marker designs.

Ink Selection
We evaluated a small selection of inks in this paper to act as an introduction to prototyping hidden marker projection surfaces. Unlike the aqueous inks commonly used in ink-jet printers, the IR inks we tested have a solvent base, such as acetone, cyclohexanone, or methanol. We are currently researching water-based IR inks that can be applied accurately and efficiently using a regular inkjet printer.

Multi-viewer Anamorphic Projection
When using anamorphic projection we make simple assumptions about the pose of the user's eye based on the location of the mobile device. This 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.

Latency
When aligning projected imagery precisely with a physical object or surface there is some observable latency in our 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, we determined that the projected image lags 167 ms (5 frames at 30 Hz) behind the current scene. Although we found this amount of latency acceptable for general purpose interaction, future work may seek to reduce the lag time with a custom hardware pipeline.

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 9). However, limited field of view can be used for 'spotlight' interaction where the projector reveals part of a larger scene [29]. 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.

Occlusion
Occlusion is a well-known issue with projector-camera systems and at times affects interaction with our system. Tangible objects and the user's hands can occlude the scene from the device camera and projector. In future work we are interested in exploring how multiple users can track and project onto the same scene to reduce these occlusion issues.

CONCLUSION
We presented the *HideOut* system that supports mobile and tangible interaction with objects and surfaces in the physical environment. Using custom hardware and software, we have demonstrated how projected imagery from a mobile projector can be mapped onto surfaces embedded with IR ink-based hidden markers. Our system 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.

REFERENCES

1. Audet, S., and Okutomi, M. A user-friendly method to geometrically calibrate projector-camera systems. In *Proc. IEEE Procams* (2009), 47–54.
2. Bandyopadhyay, D., Raskar, R., and Fuchs, H. Dynamic shader lamps: Painting on movable objects. In *Proc. IEEE ISAR* (2001), 207–216.
3. Bimber, O., and Raskar, R. *Spatial Augmented Reality: Merging Real and Virtual Worlds*. A K Peters, 2005.
4. Cao, X., and Balakrishnan, R. Interacting with dynamically defined information spaces using a handheld projector and a pen. In *Proc. ACM UIST* (2006), 225–234.

5. Cao, X., Forlines, C., and Balakrishnan, R. Multi-user interaction using handheld projectors. In *Proc. ACM UIST* (2007), 43–52.
6. Cowan, L. G., and Li, K. A. Shadowpuppets: Supporting collocated interaction with mobile projector phones using hand shadows. In *CHI '11*, ACM (2011), 2707–2716.
7. Harrison, C., Benko, H., and Wilson, A. D. OmniTouch: Wearable multitouch interaction everywhere. In *Proc. ACM UIST* (2011), 441–450.
8. Hartley, R. I., and Zisserman, A. *Multiple View Geometry in Computer Vision*. Cambridge University Press, 2004.
9. Huber, J., Steiml, J., Liao, C., Li, Q., and Mühlhäuser, M. Lightbeam: Nomadic pico projector interaction with real world objects. In *Proc. ACM CHI '12* (2012).
10. Hyakutake, A., Ozaki, K., Kitani, K. M., and Koike, H. 3-D interaction with a large wall display using transparent markers. In *Proc. ACM AVI* (2010), 97–100.
11. Izadi, S., Hodges, S., Taylor, S., Rosenfeld, D., Villar, N., Butler, A., and Westhues, J. Going beyond the display: A surface technology with an electronically switchable diffuser. In *Proc. ACM UIST* (2008), 269–278.
12. Izadi, S., Kim, D., Hilliges, O., Molyneaux, D., Newcombe, R., Kohli, P., Shotton, J., Hodges, S., Freeman, D., Davison, A., and Fitzgibbon, A. KinectFusion: Real-time 3D reconstruction and interaction using a moving depth camera. In *Proc. ACM UIST* (2011), 559–568.
13. Jacob, R. J., Girouard, A., Hirshfield, L. M., Horn, M. S., Shaer, O., Solovey, E. T., and Zigelbaum, J. Reality-based interaction: A framework for post-WIMP interfaces. In *Proc. ACM CHI* (2008), 201–210.
14. Kane, S. K., Avrahami, D., Wobbrock, J. O., Harrison, B., Rea, A. D., Philipose, M., and LaMarca, A. Bonfire: A nomadic system for hybrid laptop-tabletop interaction. In *Proc. ACM UIST* (2009), 129–138.
15. Koike, H., Nishikawa, W., and Fukuchi, K. Transparent 2-D markers on an LCD tabletop system. In *Proc. ACM CHI* (2009), 163–172.
16. Lee, J. C., Hudson, S. E., Summet, J. W., and Dietz, P. H. Moveable interactive projected displays using projector based tracking. In *Proc. ACM UIST* (2005), 63–72.
17. Lee, J. C., Hudson, S. E., and Tse, E. Foldable interactive displays. In *Proc. ACM UIST*, UIST '08 (2008), 287–290.
18. Lee, J.-E., Miyashita, S., Azuma, K., Lee, J.-H., and Park, G.-T. Anamorphosis projection by ubiquitous display in intelligent space. In *Proc. UAHCI* (2009), 209–217.
19. Markets and Markets. Pico projector by application, technology & products market, 2010. http://www.marketsandmarkets.com/Market-Reports/pico-projector-market-196.html.
20. Mistry, P., Maes, P., and Chang, L. Wuw - wear ur world - a wearable gestural interface. In *Ext. Abstracts ACM CHI '09* (2009), 4111–4116.
21. Molyneaux, D., Izadi, S., Kim, D., Hilliges, O., Hodges, S., Cao, X., Butler, A., and Gellersen, H. Interactive environment-aware handheld projectors for pervasive computing spaces. In *Proc. Pervasive* (2012).
22. Nakazato, Y., Kanbara, M., and Yokoya, N. Localization system for large indoor environments using invisible markers. In *Proc. ACM VRST* (2008), 295–296.
23. Nam, T. Sketch-based rapid prototyping platform for hardware-software integrated interactive products. In *Proc. ACM CHI Ext. Abstracts* (2005), 1689–1692.
24. Ni, T., Karlson, A. K., and Wigdor, D. AnatOnMe: facilitating doctor-patient communication using a projection-based handheld device. In *Proc. ACM CHI* (2011), 3333–3342.
25. Park, H., and Park, J.-I. Invisible marker tracking for AR. In *Proc. IEEE/ACM ISMAR* (2004), 272–273.
26. Park, H., and Park, J.-I. Invisible marker based augmented reality system. In *Proc. SPIE VCIP*, vol. 5960 (2005), 501–508.
27. Park, H., and Park, J.-I. Invisible marker-based augmented reality. *International Journal of Human-Computer Interaction 26*, 9 (2010), 829–848.
28. Pinhanez, C. S. The everywhere displays projector: A device to create ubiquitous graphical interfaces. In *Proc. ACM UbiComp* (2001), 315–331.
29. Rapp, S., Michelitsch, G., Osen, M., Williams, J., Barbisch, M., Bohan, R., Valsan, Z., and Emele, M. Spotlight navigation: Interaction with a handheld projection device. In *Proc. Pervasive*, video paper (2004).
30. Raskar, R., Beardsley, P., van Baar, J., Wang, Y., Dietz, P., Lee, J., Leigh, D., and Willwacher, T. RFIG lamps: Interacting with a self-describing world via photosensing wireless tags and projectors. *ACM Trans. on Graphics 23*, 3 (2004), 406–415.
31. Raskar, R., Welch, G., Low, K.-L., and Bandyopadhyay, D. Shader lamps: Animating real objects with image-based illumination. In *Proc. Eurographics Workshop on Rendering Techniques* (2001), 89–102.
32. Rekimoto, J., and Saitoh, M. Augmented surfaces: A spatially continuous work space for hybrid computing environments. In *Proc. ACM CHI* (1999), 378–385.
33. Rosner, D. K., and Ryokai, K. Spyn: Augmenting knitting to support storytelling and reflection. In *Proc. ACM UbiComp* (2008), 340–349.
34. Song, H., Guimbretiere, F., Grossman, T., and Fitzmaurice, G. MouseLight: Bimanual interactions on digital paper using a pen and a spatially-aware mobile projector. In *Proc. ACM CHI* (2010), 2451–2460.
35. Spindler, M., Tominski, C., Schumann, H., and Dachselt, R. Tangible views for information visualization. In *Proc. ACM ITS* (2010), 157–166.
36. Willis, K. D., Poupyrev, I., Hudson, S. E., and Mahler, M. SideBySide: Ad-hoc multi-user interaction with handheld projectors. In *Proc. ACM UIST* (2011), 431–440.
37. Willis, K. D., Poupyrev, I., and Shiratori, T. MotionBeam: A metaphor for character interaction with handheld projectors. In *Proc. ACM CHI* (2011), 1031–1040.
38. Wilson, A. D. PlayAnywhere: A compact interactive tabletop projection-vision system. In *Proc. ACM UIST* (2005), 83–92.
39. Wilson, A. D., and Benko, H. Combining multiple depth cameras and projectors for interactions on, above and between surfaces. In *Proc. ACM UIST* (2010), 273–282.
40. Yoshida, T., Hirobe, Y., Nii, H., Kawakami, N., and Tachi, S. Twinkle: Interacting with physical surfaces using handheld projector. In *Proc. IEEE VR* (2010), 87–90.