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Survey of Interactive Displays through Mobile Projections

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ABSTRACT

Projectors shrink in size, are embedded in some mobile devices, and with the miniaturization of projection technology truly mobile projected displays became possible. In this paper, the authors present a survey of the current state of the art on such displays. They give a holistic overview of current literature and categorize mobile projected displays based on mobility and different possible interaction techniques. This paper tries to aid fellow researchers to identify areas for future work.

KEYWORDS

Interaction, Mobile, Projected Displays, Projection

INTRODUCTION

Over the last few decades, technology constantly shrank and became more efficient. Nowadays smart phones are ubiquitous devices that are equipped with advanced technology. Even pico projectors are integrated into phones and are commercially available e.g. the Galaxy Beam, and with the miniaturization of projection technology and the increasing capacity of batteries, truly mobile projected displays became possible. This development has spawned an ever increasing amount of research in the field of HCI that investigates multiple factors of such mobile projected displays. Besides needed interaction techniques also factors such as social implications, mobility and perception have been explored (Cowan et al., 2012; Kaufmann et al., 2012; Pouli and Subramanian, 2012). Such mobile projectors have the ability to create ad-hoc large-scale personal displays that allow for exploration of large-scale information. While Rukzio et al. (2012) presented a very comprehensive overview of the field of mobile projection, latest research and development has driven the field much further than initially expected.

We previously (Löchtefeld, 2015) presented a survey and categorization of mobile projection research. Here, we provide a more holistic overview of the current state and categorize the different works based on their mobility and provided interaction techniques. In terms of mobility, we categorize

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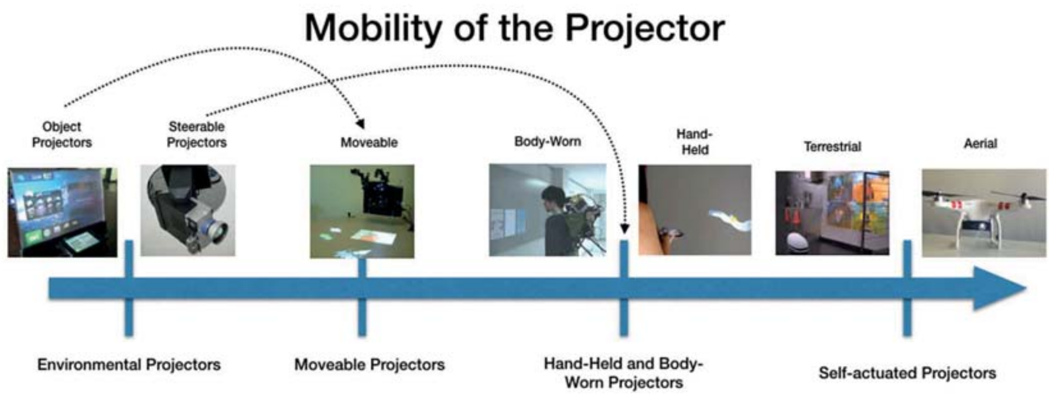
Figure 1. Mobility of projected displays - The four different categories aligned, where the x-axis represents the increasing mobility (from left to right). The subclasses of Object- and Steerable-Projectors are hybrid classes indicated by the arrows



mobile projected displays into four different classes that start with fixed display and afterwards increase in their mobility.

In this paper, we extend our previous survey of mobile projections. We use six different classes to categorize interaction techniques, including Bi-Manual manipulation of Surface and Projector as well as Around the device interaction.

By using this classification, we not only give an overview on existing works, we furthermore identify less investigated areas and present opportunities for future work. Therefore, this paper can yield as a holistic overview of current research in the field of mobile projected displays.

TYPES OF PROJECTED DISPLAYS

When it comes to different projected displays, we can distinguish between four types that differ in the amount of mobility they provide: Environmental Projectors, which as the name suggests are located in the environment, e.g. projectors installed in meeting rooms; Moveable Projectors which are not fixed in the environment but need to be set up before operation; Hand-Held and Body-Worn Projectors are fully mobile projectors that are either held in the hand, e.g. a projector phone, or worn on the body; Self-actuated Projectors presents the most mobile setting, in which the projector can move through the environment on its own. This categorization is visualized in Figure 1.

Environmental Projectors

Environmental Projectors are characterized by the projection unit being immobile and therefore fixed in the environment. The most common example for this class would be projectors that are installed in e.g. meeting rooms. In this case the output – the projected display – is usually fixed as well. Thereby Environmental Projectors provide the advantage of a large undistorted projected display.

Still two subcategories exist that are a hybrid between Environmental Projectors and more mobile classes. The first class is represented by Steerable Projectors where even though the projector is fixed in the environment, the projected display can be created at different positions in the environment. This subclass represents a hybrid between the Environmental Projectors and the Hand-Held and Body-Worn Projectors. The second subclass are Object Projectors, where the projector is mounted on a moveable object but the created projected display is limited to this specific object. This subclass is a hybrid between Environmental Projectors and the Moveable Projectors class.

Steerable Projectors

Steerable Projectors allow, even though the projection unit is mounted in a fixed position in the environment, to create projected displays at nearly arbitrary positions in the environment. This capability of Steerable Projectors makes them nearly as powerful as Hand-Held and Body-Worn Projectors in their dimensions of freedom to create displays. Therefore the sub-class of Steerable Projectors represents a hybrid between the Environmental Projectors and the Hand-Held and Body-Worn Projectors.

Two general solutions exist to create steerable projections. The first one would be to attach a steerable mirror on top of the projection lens. This has been done by Pinhanez (2001) with the Everywhere Displays. The steerable mirror allowed him to deflect the projection into the direction of the demanded display. The second possibility is to make the whole projection unit moveable as it is done e.g. for the beaMover projectors (2015). Similar to a Pan-Tilt-Zoom camera the projector is mounted on a controllable moving head that can rotate and tilt the projector to a certain direction.

But both approaches suffer from the same drawback. Since in most cases the projection is not orthogonally aligned with the projection surface, keystone effects occur. To circumvent these drawbacks Pinhanez created a method to remove perspective distortion based on a three dimensional model of the environment. But his approach has two major drawbacks, the first one would be the loss of resolution as the projection of the undistorted image does not take full advantage of the whole possible projection size. And the second drawback is the need for a three dimensional model of the environment. As this is often not available for all environments it makes this approach less suited for a mobile projector in an unknown environment. Still, Molyneaux et al. (2012) applied a similar approach for Hand-Held and Body-Worn Projectors based on an ad-hoc created three dimensional model constructed from Kinect depth data.

A variety of applications can be enabled through these techniques, apart from the projection of standard desktop user interfaces (Pinhanez, 2001), such projectors can also aid as help for finding objects in the environment (Butz et al., 2005). A good overview of possible applications for such steerable projections can be found in Pinhanez et al. (2003).

Object Projectors

The second subclass of the Environmental Projectors are Object Projectors. This category is characterized by the fact that the projector and the projected display are contained completely in one object. This object can be moveable but the projector and the projected display create an environment and reference system on their own. With these preconditions, it represents a hybrid class between the Environmental Projectors and the Moveable Projectors. In contrast to the Moveable Projectors this class does not require any kind of set up and the projection is not created in the surrounding environment. Such Object Projectors are only possible through the miniaturization process described in the introduction. Examples for such self-contained Object Projectors are presented by Benko et al. (2008), Löchtefeld et al. (2011), Löchtefeld et al. (2013), and Virolainen et al. (2012).

Especially interesting is the Pileus system by Matsumoto and Hashimoto (2009). The system integrates a projector into an umbrella. The projection surface of this system is located at the inside of the umbrella. With the PenBook, Winkler et al. (2013) presented a tablet with integrated projector and an Anoto based projection surface. Büttner and Röcker (2015) integrated a projector into an augmented reality (AR) assembly assistance system that supports users in the production process by projecting picking and assembly information into the physical workspace. Based on their insights gained with their stationary projector system, Büttner and Röcker propose the use of mobile projectors and describe the design ideas for applying mobile projection in the context of industrial manufacturing.

Moveable Projectors

The class of Moveable Projectors is, apart from being mobile, characterized by the requirement of a surface, on which the projector has to be positioned for usage. Furthermore, they require a surface in the environment to project on. They significantly differ from the Environmental Projectors as they can be set-up ad hoc in many different environments. One of the simplest projectors for this kind would be a peripheral projector for notebooks that can be set-up for meetings spontaneously.

Even more sophisticated examples for such kinds of projectors exist in research as well as in current commercial products. One of the earliest prototypes is the iLamps by Raskar et al. (2006). The camera-projector combination of Raskar et al. allowed for combining a cluster of projectors ad-hoc to one big display using a structured light approach.

With PlayAnywhere, Wilson (2005) presented a Moveable Projector approach to augment surfaces without instrumentation of the environment. Using a short-throw projector, which allows for creating large projected displays from a short distance through a specific lens-mirror-system, Wilson developed a prototype that allowed for creating large interactive surfaces that even was capable of augmenting documents placed in the projection area. This concept was recently picked up by the Taiwanese company UrRobot (2015) and they built a commercial product for kids that incorporates an interactive projection. Their Robii system is an educational system that allows kids to learn through a variety of different techniques such as interactive puzzles. The SurfacePhone by Winkler et al. (2014a) is highly related to this approach.

With MobiSpray, Scheible and Ojala (2009) presented a system consisting of a Moveable Projector and a mobile phone that can be set up spontaneously. After a short calibration phase, multiple users can then utilize their mobile phone to “spray” on the calibrated projection canvas.

Hand-Held and Body-Worn Projectors

Most of the currently developed and investigated prototypes fall in the class of the Hand-Held and Body-Worn Projectors. This class is characterized through the fact that the projector is fully mobile and creates projected displays on either user chosen surfaces or on the user itself (e.g. on the user’s arm). The high mobility of this class comes at the drawback of a perspectively distorted projection. This problem has been solved through a variety of approaches, ranging from the creation of three dimensional models following the Everywhere Displays approach (Molyneaux et al., 2012; Pinhanez, 2009) to sensor fusion based approaches (Dao et al., 2007). To ensure a more accurate overview, we divide our overview of this class into two sub-classes.

Hand-Held Projectors

The earliest hand-held prototype was presented by Rapp et al. with their SpotLight system (Rapp et al., 2006; Rapp, 2010). Albeit their prototype not being fully mobile, they presented a sophisticated system that based on dynamic peephole interaction allowed users to explore large-scale content. That such hand-held projectors are effective when exploring large-scale content was demonstrated by Hang et al. (2008). Beardsley et al. (2005) investigated early AR applications for hand-held projections with the RFIG lamps. With MotionBeam, Willis et al. (2011) presented a sophisticated mobile system for character interaction with handheld projectors. Their work is based on the tradition of pre-cinema handheld projectors that they had investigated (Willis, 2012).

Molyneaux et al. (2012) presented a system that created an ad-hoc model of the environment with either a hand-held Kinectprojector unit or several Kinects installed in the environment. This model allows for removing the problem of the distortion and creates a perspectively corrected projection. Through the decrease in price of mobile projection hardware it also became possible to investigate multi-user scenarios. Cao et al. (2997) tracked multiple hand-held projectors in the environment to allow for co-located multi-user interaction. Besides several new interaction techniques they introduced the concept of merging multiple projections in one information space. To circumvent the drawback of a tracking system, Willis et al. (2011) followed a different approach with their Side-by-Side system by projecting invisible fiducial markers through infrared light.

Body-Worn Projectors

Karitsuka and Sato (2003) presented to the best of our knowledge the earliest Body-Worn Projector prototype. With a projector mounted over the shoulder of the user the system allowed for spontaneously created projected displays. Even though at the time, the available projection technology was large in size, their system was able to project undistorted images with infrared reflected markers onto equipped surfaces. Based on an infrared emitting spotlight and a camera the system was even able to track user input using infrared reflective markers placed on the fingers of the user. A similar approach was taken up by Mistry et al. (2009). The Wear-Ur-World system tracked the fingers in front of a projector necklace using colored finger caps.

Other possibilities to sense the users input for Body-Worn Projectors have been investigated by Harrisson et al. (2010; 2011). The drawback of Skinput was that the users had to wear a sensor on the arm. Therefore, Harrisson et al. (2011) replaced this sensor through a depth camera that was shoulder worn as well in their OmniTouch system. This approach was later extended by Winkler et al. (2014b) with AMP-D. In contrast to OmniTouch, AMP-D is an ambient information display that constantly projects information onto the floor in front of the user.

Vechev et al. (2015) suggest that projected interfaces should support all kinds of projector positions, such as head-worn, chest-worn or being attached to a bicycle. Consequently, they propose to create a smooth transition between the different mediums and application contexts.

An extensive overview of suited positions for projectors worn on the body based on the visibility of the projected display has been presented by Ota et al. (2010). They conclude that the shoulder is one of the best suited spots for a Body-Worn Projector, this is in line with most of the aforementioned work.

Self-Actuated Projectors

The last class represents the most mobile kind of projectors, the Self-Actuated Projectors. Even though the class of Hand-Held and Body-Worn Projectors already represents fully mobile projectors that except of the projected displays are independent from the environment, Self-actuated Projectors are going one step further as they are not only fully mobile but actually can move through the environment on their own. Basically this can be done through robotic components that allow the projector to move on its own without human control either through the air, on land or on water. Such independent drones have – especially if they are terrestrial – the advantage that they can carry a larger projector and other bigger sensors that allow to project undistorted bright images. This is for Hand-Held and Body-Worn Projectors not always possible as they have size limitations to be still small enough to be hand-held. So far two different kinds have been explored, terrestrial Selfactuated Projectors and aerial Self-Actuated Projectors.

Terrestrial Self-Actuated Projectors

The vision of projectors being integrated into robots is quite old. R2D2 from the Star Wars movie trilogy was capable of projecting holographic images while at the same time being an autonomous terrestrial robot (Lucas). The R2D2 idea was recently picked up by Keecker (2014). Even though currently they only have a design vision, they want to commercialize an autonomous robot that can be controlled and called using a mobile device.

Aerial Self-Actuated Projectors

Besides these autonomous driving robots recently also flying drones with projectors have been explored. Scheible et al. (2013) presented the Displaydrone a mobile projector mounted on a multicopter. The content of the projection was transferred to a phone that was connected to the projector. Floating Avatar by Tobita et al. (2011) is a prototype that consisted of a flying blimp with an integrated projector in the blimp corpus. The projector created a projected display on one surface of the blimp's corpus. The system is meant to be used as a tele-presence system.

INTERACTION TECHNIQUES FOR PROJECTED DISPLAYS

At this point, we want to review existing interaction techniques for mobile projected displays. We focus only on projected displays that are created by Moveable Projectors or projectors of even higher mobility. When we refer to interaction with mobile projected displays, we consider the projection to be the output, not a way of triggering actions on other devices as it has been done by Schmidt et al. (2012). Very similar Hosoi et al. (2007) used a projection to control a robot by projecting the path in front of it.

For our classification we divide the existing interaction techniques into six categories, which are the following:

- **Direct Interaction on the Projection:** This class covers all cases where the user is able to reach the projection with one of his extremities and manipulate it directly.
- **Input on the Projection Device:** This class represents techniques where the user interacts with the projected display through input on the projecting device.
- **Movement of the Projector:** In this case the projected display is controlled through relative- or absolute movement of the projector.
- **Manipulation of the Projection Surface:** Here all techniques are included where the interaction is triggered through manipulation of the surface that contains the projected display.
- **Bi-Manual Manipulation of Surface and Projector:** This class incorporates techniques that rely on simultaneous manipulation of the surface where the projected display is created and the projector itself.
- **Around the Device Interaction:** The last class covers techniques where the interaction is triggered by movements of the user in the vicinity of the projector, without either touching it or the projected display.

In the following we will present several techniques for each the different categories.

Direct Interaction on the Projection

Interaction techniques covered by the class of Direct Interaction on the projection are characterized by the fact that the user can reach the projected display with one of his extremities. This fact allows him to directly manipulate and interact with the content in the projection. This comes at the drawback that the user has to stand rather close to the projection. This means in cases of Hand-Held and Body-Worn Projectors that the projection is limited in size, especially since for current projection units no short-throw lenses exist.

The most frequently used technique in this category is the interaction with the projected display by touching it. The earliest system was developed by Karitsuka and Sato (2003) as discussed earlier. The PlayAnywhere system employed infrared light as well, but Wilson's (2005) finger tracking algorithm is based on shadow tracking and did not require the user to wear anything on his fingers. Another system that allowed for interaction in this way was presented by Winkler et al. (2011) but their system even employed an optical tracking system.

Another technology allowing for such interactions are depth cameras. Especially the works by Harrison et al. (2011) and Molyneaux et al. (2012) provide sophisticated detection techniques. These techniques don't require the surface to be augmented as for example Skinput (Harrison et al., 2010) did which is a major advantage to facilitate mobility.

Furthermore, the usage of a pen has been investigated as well. Pens provide the advantage that they can incorporate markers to allow for easy tracking. Additionally, writing with a pen is one of the oldest interaction techniques known to man. Cao and Balakrishnan (2006) employed this technique using the Vicon system that also tracked their projectors. In Winkler et al.'s (2013) PenBook an Anoto pen was used that allow tracking its own position on the Anoto paper based projection surface. Furthermore, McFarlane et al. (2009) presented a body-worn system that allowed for input through a telescopic metal pointer. Funk et al. (2014) used everyday objects as tangible input for projected user interfaces, and thus they enabled user-defined tangibles. Wolf and Baeder (2014) used a stationary projector to project texture images on plane surfaces to generate materiality illusions. For example, the illusion of surface deformations could be generated after the user was pressing at the smooth and undeformable surface using on-surface projections.

Even though direct touch and pen input is one of the most compelling interaction techniques as it is quite well known from current devices such as smartphones or tablets, other direct interaction techniques have been investigated as well. Cauchard et al. (2012) presented a foot interaction technique that allows the user to step on the interface elements. Due to the size of the foot, this technique requires large sized user interface elements for precise input. But for ambient information displays or quick interactions with a body-worn projector such as the AMP-D system (Winkler et al., 2014b) this technique would be well suited.

Input on the Projection Device

The class of Input on the projection device represents all interaction and manipulation techniques in which the user interacts with the projection device itself. Even though most pico-projectors do not provide this feature, projector-phones such as the Samsung Galaxy Beam (2012) fall into this category as they only rely on input on the touch-screen. Input on the projection device has the advantage that the sensors, such as a touch-screen, a joystick or keys and buttons can be integrated into the device and that they do not rely on complicated sensing techniques. Furthermore, the user can be further away from the projection as they don't have to be able to reach it as opposed to the Direct Interaction on the projection class. This allows for larger projected displays.

Most Hand-Held and Body-Worn Projectors allow for this kind of interaction as well but normally in combination with another technique. The system developed by Cao and Balakrishnan (2006) featured button input on the projector as well as Movement of the projector. SideBySide (Willis et al., 2011) follows a similar approach. On the one side the user was able to move the projection but to trigger actions on the other side he had to press a button on the projector. Löchtefeld and Krüger (2013) investigated input on a projector-phone with a back-side touch screen during a phone-call inspired by the work of Winkler et al. (2011).

Movement of the Projector

Due to the increasing mobility of the projection technology, Movement of the projector as a mean of manipulating the content in the projected display became possible. In this category all techniques that rely on the movement of the projector are covered. Due to the spatial coupling of the projector and the projected display, the movement of the projection unit naturally comes with a movement of the projected display. This approach allows for larger projected displays as the user can stand further away from the projection surface compared to Direct Interaction on the projection. Still, if the content on the projection is manipulated through movement, the size of the projected display has to be significantly smaller than the projection surface, as the movement will need space as well.

The concept of moving a projector to create life like animations has already been employed with the laterna magica (Willis, 2012). But to the best of our knowledge Rapp et al. presented with Spotlight the earliest form of such a movement based interfaces for mobile digital projectors (Rapp et al., 2004; Rapp, 2010). Their early hand-held prototype allowed for exploring large scale content such as a calendar, by moving the projection unit. They employed the so called dynamic peephole interaction which has also been used by Cao et al. (2007) for multiple projectors that shared one large virtual workspace. Blasko et al. (2005) adopted the dynamic peephole technique in their studies of a wrist-worn mobile projector. Even though their prototype was only simulated by a short throw beamer, their investigation showed a lot of suitable interaction techniques for such a projection unit mounted in a smartwatch. Beside the peephole technique they also investigated scrolling and other navigation techniques for websites that are based on rotating and moving the wrist where the future projector might be mounted.

As the dynamic peephole technique is often seen as one of the most promising interfaces for mobile projectors Kaufman and Ahlström (2012) developed a model for target acquisition using a projector and a dynamic peephole. Their model was based on prior findings for mobile devices. In later studies (2013) they also showed that the technique can aid spatial memory.

Interfaces where the Movement of the projector is the mean of input have not only focused on the dynamic peephole so far. With Motionbeam, Willis et al. (2011) presented a technique where a character that is contained in the projection could be animated by movement. As already mentioned, their technique is based on pre-cinematic techniques of moved projectors (Willis, 2012). The SideBySide prototype is another example for such interactions (Willis et al., 2011). The same concept was also applied by Shilkrot et al. (2011). But instead of the invisible infrared markers of SideBySide, their prototype used visible markers in the projection to retrieve the relative positions of the projectors. A system that exploits the user’s spatial memory through movement has been presented by Cauchard et al. (2012). Instead of using one virtual workspace that is placed in the environment they allowed the user to distribute several workspaces relative to him that are always shown completely.

In most cases where mobile projection is used for augmented reality (AR) applications, the area that needs to be augmented is much larger than the projected display. Therefore, the display needs to be moved to reveal the whole augmentation. With this, the AR overlay is revealed similar to the dynamic peephole interaction discussed above. One of the earliest cases where a mobile projection unit was used to create an AR overlay are the RFIGlamps by Beardsley et al. (2005). A far more sophisticated prototype was shown by Ni et al. (2011) with AnatOnMe. Their system tried to ease doctor-patient communication by allowing to project detailed medical information directly onto the body of the patient. Yoshida et al. (2010) presented with Twinkle a mobile camera-projector unit that allowed for augmenting an arbitrary physical surface. Through a variety of computer vision algorithms, the system recognizes the features of the physical environment and displays images and sounds that are generated based on the user’s motion and collisions of projected images with objects. This concept is based on findings that have been presented by Löchtefeld et al. (2009). An in-depth analysis of requirements for mobile projection based AR applications, can be found in Löchtefeld et al. (2010).

Manipulation of the Projection Surface

The interaction class where the user is the closest to the projected display is represented through the Manipulation of the projection surface. As the user does not only need to carry the projection device but also the projection surface, this class effectively can be seen as an Object Projector with the user being the object. Here all techniques are included where the interaction is triggered through manipulation of the whole surface. But so far only one system exists that uses Manipulation of the projection surface as a mean of input. The Cobra system presented by Ye and Khalid (2010) consists of a shoulder worn projector that allows for input through deforming and moving the projection surface relative to it. Cobra sensed the position of the projection surface relative to the projector by infrared LEDs in the surface and a Wii Mote on the shoulder. Additionally, the system is able to sense deformations of the surface by flexsensors integrated into the surface. This allows for a very flexible input with a huge expressiveness.

Bi-Manual Manipulation of Surface and Projector

The class of Bi-Manual manipulation of Surface and Projector represents a combination of the classes Manipulation of the projection surface and Movement of the projector. It incorporates techniques that rely on simultaneous manipulation of the surface where the projected display is created as well as the projector itself. Even though this requires the user to be very close to the projected display in order to be able to touch the surface, this combination increases the expressiveness of the interaction drastically. Nevertheless, it has often been neglected in current investigations.

Willis et al. (2013) presented a system of this class, called Hide-Out. As one of their main use cases, they present the possibility of interactive story telling. To enable an expressive and intuitive way, they incorporate tangible interaction with real world objects into the system. The tracking of these objects is accomplished by infrared reflective markers that are invisibly painted onto the objects. The projector is equipped with a camera and an infrared spotlight. By moving the projector, or the objects, users can manipulate and develop their own story. The LittleProjectedPlanet system (Löchtefeld et al., 2009) allowed to project physical simulations on the real world. By manipulating the properties of the real world, the user can interact and change the simulation.

Around the Device Interaction

The last class, around the device interaction, is characterized by the user neither interacting on the projected display nor the projecting device. The user can stand at arbitrary distances for this interaction as there are no requirements in terms of reachability or needed surface size. The techniques in this class make use of the space around the projector through midair interactions. One of the earliest systems that represents this class would be the SixthSense system by Mistry et al. (2009). A body-worn projector could be controlled by conducting gestures between the projector and the projected display. A very similar technique was explored by Cowan and Li (2011), but their ShadowPuppets system relied on casting shadows onto the projected image.

The aforementioned system of Molyneaux et al. (2012) also allowed for the shadow casting technique of Cowan and Li, but they also incorporated mid-air pointing as one possible interaction. An in-depth analysis of such mid-air pointing techniques has been conducted by Winkler et al. (2012). By comparing different positions for such pointing, they found that interacting behind the phone yields the highest performance, albeit showing an error rate that was twice as high.

CONCLUSION

Reflecting on the works we presented in our survey, we realize that are still some unexplored areas. We especially can see that for self-actuated projectors only very little interaction techniques have been investigated. With the current developments in the field of robotics this is a very promising area for future investigation. Additionally, physical manipulation of the surface has been under-investigated. Given the advances in the field of shape changing and organic user interface this could be a natural fit for further research as well.

In this paper, we presented a categorization of different projected displays based on their level of mobility. Additionally, we classified existing interaction techniques for mobile projected displays. We hope that these categorizations can aid other researchers firstly as a way of distinguishing their own work from already existing approaches and secondly help them finding areas that are rather unexplored yet. Thereby we contribute with a novel way of characterizing interactions with mobile projected displays as well as the kind of projected display itself.

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