# UbiBeam: An Interactive Projector-Camera System for Domestic Deployment

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## Abstract

Previous research on projector-camera systems has focused for a long time on interaction inside a lab environment. Currently they are no insight on how people would interact and use such a device in their everyday lives. We conducted an in-situ user study by visiting 22 households and exploring specific use cases and ideas of portable projector-camera systems in a domestic environment. Using a grounded theory approach, we identified several categories such as interaction techniques, presentation space, placement and use cases. Based on our observations, we designed and implement *UbiBeam*, a domestically deployable projector-camera system. The system comprises a projector, a depth camera and two servomotors to transform every ordinary surface into a touch-sensitive information display.

## Author Keywords

Steerable projection; projector-camera system; domestic deployment; ubiquitous computing

## ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation (e.g. HCI)]: User Interfaces

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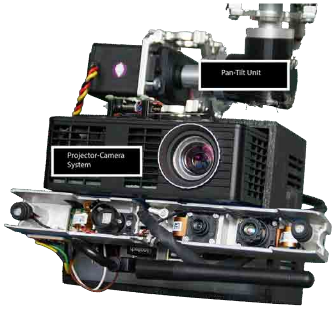

**Figure 1:** The UbiBeam System a Compact and Steerable Projector-Camera System

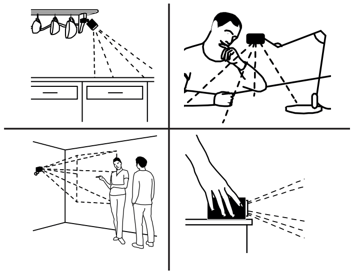

**Figure 2:** Possible scenarios for the usage of projector-camera systems in a domestic environment

## Introduction

Public displays, smartphones, and tablets are devices that aim for constantly providing information to users in ubiquitous usage contexts. They all can be regarded as initial steps towards ubiquitous and everywhere displays as envisioned by Weiser [2]. However, such physical devices still cannot fully achieve the ubiquity and omnipresence of Weiser's vision, as they do not fully blend into the environment.

Recent research aims to achieve this ubiquity by simulating omnipresent screens with a projector-camera system (e.g. [5, 3, 1, 6, 7]). The main focus of these projects was to research the interaction with projected user interfaces. While previous work provides valuable insights into either interaction techniques or technical implementations, most of these projects focused on instrumented laboratory environments. Very little of them researched the use and interaction of projector-camera systems outside of the laboratory. Therefore, the interaction space is limited to interaction with the content and not on deployment or domestic scenarios for the user.

In this work, we introduce UbiBeam (figure 1), a small and portable projector-camera system which is designed based on an in-situ study in the homes of 22 people. We envision a future where such devices will be sold in hardware stores. They could be available in different form factors, either as a replacement for light bulbs or a simple small box which can be placed in several ways inside the users' environments (figure 2). The design of these devices will not only focus on the interaction with the content but also on aspects such as deployment and portability. This work is a first step towards developing projector-camera systems for end users as it provides system and design requirements derived from an in-situ study.

## Design Process

We conducted an exploratory field study to investigate the requirements and to gain a deeper understanding of how projector-camera systems can be used in domestic environments. To collect data, we visited 22 households (10 female, 12 male) between 22 and 58 years of age (M= 29) and conducted semi-structured interviews. The participants were provided with a mock up which consisted of an APITEK Pocket Cinema V60 projector inside of a card box mounted on a Joby Gorillapod. This low-fidelity mock up was used to stimulate the creativity of the participants.

The interviews consisted of a questionnaire about the use of a projector-camera system and the creation a potential set-up using the mock up (figure 3). To analyze the data, we selected a grounded theory approach. The data gathering was conducted using semi-structured interviews, notes, pictures and video recordings of several sessions. Two of the authors coded the data using an open, axial and selective coding approach. The initial research question was: ”*How would people use a small and easy deployable projector-camera system in their daily lives? When and how would they interact with such a device, and how would they integrate it into their home?*”.

During the process we discovered that the four main categories the participants were focusing on when they handled the projector-camera system were: *Projector-Camera System placement:* Where was the projector-camera system mounted inside the room ? *Projection surface:* What projection surfaces did the participant choose ? *Interaction modalities:* What modalities were used for the input and why ? *Projected Content/Use Cases:* What content did the participant want to project for each specific room and ?

**Figure 3:** Users building and explaining their setups

*Content and Use Cases*
The exact use cases were dependent on which room the participants were referring to. However, two larger concepts could be derived from the set-ups the participants created: *information widgets* and *entertainment widgets*. We consider information widgets as use cases in which the participant almost only wants to aggregate data. The most use cases were used as an aid in finishing a specific task characteristic to the room. Entertainment use-cases were mostly created in the living room, bedroom and bathroom. Here the focus was on enhancing the free time one spends in these rooms and making the stay more enjoyable.

*Placement of the Projector-Camera System*
Similar to the use cases, the placement can be divided into two higher concepts: placing the devise *in reach* and *out of reach*. Participants placed the devices in the bedroom, bathroom and in the kitchen mostly within their reach. Each time the device was mounted on waist or shoulder height. In the living room, working room and corridor participants preferred a mounting above body height. These were also rooms where participants could imagine a permanent mounting. For this reason the device was placed in a way that it could project on most of the surfaces and was "*not in the way*" (P19).

*Orientation and Type of Surface*
For every interface participants preferred flat and planar surfaces. In the introduction to the study it was explained to each participants that it is technically possible to project onto non planar surfaces without distortion. Nevertheless, only one participant wanted to project onto a couch. All others created flat and planar interfaces: "*I prefer flat surfaces even if they are undistorted*" (P1). Therefore the only classification which could been made to the projection surfaces was if they were *horizontal*, like tables or *vertical*, like walls. Both types of surfaces were used almost evenly spread in the kitchen, bedroom, working room and living room. However in the corridor and the bathroom mostly vertical surfaces were used due to the lack of large horizontal spaces. The projection surface was mostly used to support the use-case and was influenced by the room.

*Interaction Modalities*
The main interaction modalities participants requested were *speech recognition*, *touch* or a *remote control*. Other techniques such as *gesture recognition*, *shadow interaction* or a *laser pointer* were mentioned rarely. The interaction modality was highly influenced by the room and the primary task in there. The location of the surface was a big influence on the interaction. If the surface was the table, touch was preferred. If the surface was a wall the remote control was used. One participant explained that his choices are mostly driven by convenience: "*You see, I am lazy and I don't want to leave my bed to interact with something*" (P22).

*Derived Requirements for Prototype*
After analyzing the data from the semi-structured interviews we combined the results with the questionnaires and derived several requirements for our prototype of a domestically deployed projector-camera system.

Analyzing the semi-structured interviews participants always wanted more than only one fix surface in every room. Considering the placement out of reach, we concluded that the projector-camera system must be *steerable*. Furthermore, due to the high amount of requests, the interaction with the device itself must be mediated trough a *remote control*. However the interaction with the projected interface should be

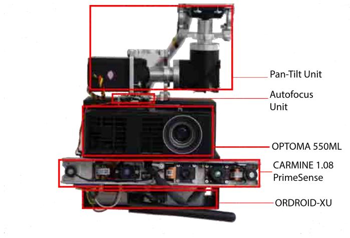

**Figure 4:** Implementation of the *UbiBeam*

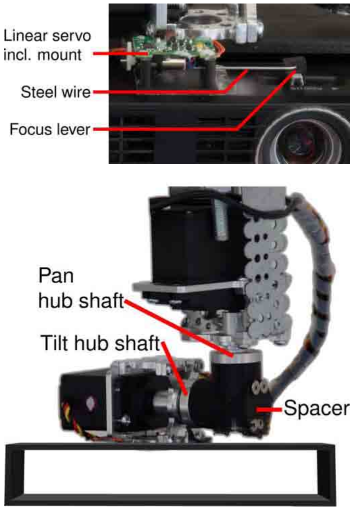

**Figure 5:** Hardware Construction for the Pan-Tilt Unit and the Auto Focus

implemented with *touch* to be able to create interactive tabletops. The form factor was mostly dictated by the projector used. We analyzed the set-ups of the participants and found out that the distance between the device and surface was between 40cm and 350cm (Mdn= 200cm). The projected surfaces sizes varied from the size of a cupboard door to a whole wall. Therefore, the projector used must be an *ultra-compact DLP* to have a high brightness at the required distance and still have a small form factor. Since participants wanted to carry the device into several rooms and have different use cases the mount must offer a *quick and easy deployment*. A last issue which came up several times was the focus of the projector. Participants did not want to adjust the focus every time they deploy the device in a new location. Therefore an *auto focus* must be realized.

## Implementation

*Hardware Architecture*

UbiBeam (figure 4) uses the ORDROID-XU as the processing unit which offers a powerful eight-core system basis chip (SBC). A WiFi-Dongle and a wireless keyboard are also connected to the SBC. The Carmine 1.08 from PrimeSence is used as a depth camera. It offers a wide range advantage in comparison to smaller Time-of-Flight cameras. Moreover, it is well supported by the OpenNI framework. As for the projector we opted for the ultra-compact LED projector ML550 by OPTOMA (a 550 lumen DLP projector combined with a LED light source). It measures only 105 $mm$ $x$ 106 $mm$ $x$ 39 $mm$ in size and weights 380 $g$. The projection distance is between 0.55 m and 3.23 m. For the pan and tilt of the system, two HS-785HB servo motors by HiTEC are used. These quarter scale servos offer a torque of 132 $Ncm$. To be able to provide an auto focus, we built similar to [6] a SPMSH2040L linear servo which is attached to the focusing unit of the projector. To control the actuators, an Arduino Pro Mini is used.

*Autofocus*. The focus of the Optoma 550ML is manually adjusted via a small lever. To realise automatic adjustment of the focus, the movement of the lever is controlled with a servo (SPMSH2040L). The servo is glued to the designed servo mount as shown in figure 5. To determine the required position of the servo for a given distance, a calibration task was conducted which determined a formula which calculates a PWM signal to a particular distance with a maximum error less than 40 $\mu s$.

The final hardware construction measures 10.5 $cm$ $x$ 12.2 $cm$ $x$ 22.5 $cm$ including the pan-tilt unit and weighs 996 $g$. To be able to easily mount the device to a variety of surfaces we adjusted it to a Manfrotto Magic Arm. The hardware components can be bought and assembled for less than 1000 USD

*Software Implementation*

Building a stand-alone projector-camera system requires a lightweight and resource saving software. Therefore, we used Ubuntu 12.04 on the ODROID. For reading RGB and depth images, OpenNI version 2.2 for ARM is used. Image processing is done with OpenCV in version 2.4.6. Visualisation of widgets is accomplished with Qt (version 4.8.2), a library for UI development using C++ and QML.

Based on the results of the qualitative study, we designed the interaction with UbiBeam following a simple concept: after running our software the projection becomes a touch sensitive interaction space. The user creates widgets on this space (e.g. calender, digital image frame etc) and interacts with them via touch (figure 6). The orientation of the device itself is done with an Android application sending pan and tilt commands. After moving the device

**Figure 6:** Deployment of UbiBeam inside a Kitchen

to a new space the auto focus and touch detection recalibrates automatically and creates a new interaction space.

*Touch Algorithm*. The touch detection was implemented based on an algorithm presented in [4]. A key feature is that touch is detected on any physical object without user driven calibration tasks. The developed touch detection can be separated into four parts. First the scenery is analyzed and a spatial image, the ground truth, is generated. This obtained image is filtered for noise and used to calculate a binary contact image while touch detection is running. The contact image is filtered and simple blob detection detects contact points. In a last step, contact points are tracked over time and transformed into interaction events which finally trigger events intended by the user. Detected contact points are tracked over time to classify them into different touch events (*touch down, long touch, move, touch release*). The spatial ground truth image is generated by temporal filtering of 30 single depth images.

*Picture Distortion*. To be able to project distortion free content onto surfaces not perpendicular to the device, a pre-warping of the projected content had to be done. First a plane detection on the depth map is executed following the concepts Yoo et al. [8]. This enabled us to find possible projection surfaces. Then four points situated on one of the detected planes, spanning a rectangle of the desired size are determined. Finally, the affine transformation which transforms the widget to the determined points is calculated and applied to render a corrected representation of the widget.

*Developing Widgets*. The developed framework allows a dynamic loading of widgets. All the complexity of the spatially aware projection, dynamic touch detection and movement of the projector-camera system are encapsulated and hidden from the view of the widget. This enables a straight forward widget development. Two different possibilities are supported to create a new widget. Developers are able to implement a provided interface to create a more desktop like looking widgets. Alternatively, developers can implement widgets using Qt User Interface Creation Kit (Qt Quick). It uses QML to describe modern looking, fluid UIs in a declarative manner.

## Discussion and Future Work

As mentioned in the introduction we envisioned small and deployable camera-projector systems which are designed for domestic use. In current set-ups, aspects like portability, deployment or domestic use cases and projection surfaces where not taken into account. Therefore, this work provides valuable insights into the domestic use of projector-camera systems. In a next step we would like to deploy the system and collect qualitative feedback over a longer time period. The design of the system is suitable to be able to conduct a long term study. This would provide insights not only into the use of the system but also into how often it is used.

## Conclusion

In this work we provided an insight into how people would use a projector-camera system inside their homes. We conducted a qualitative study using grounded theory that discovered and analyzed four important categories a domestically deployed projector-camera system must focus on (*Use Cases/Content, Placement of the Projector-Camera System, Projection Surface, Interaction Modalities*). Furthermore, the results from the qualitative study showed relationships between these categories. We showed that users differentiated between, basic information aggregation to support a specific in task in a room and entertainment to enhance free time. Based on these results, we derived requirements (*Steerable, Remote Control Interaction, Touch Input Interaction, Fast Deployment, Auto Focus*) for a first prototype, and explored different form factors. In a final step, we implemented *UbiBeam*, a steerable camera-projector system which is designed based on requirements we derived from the study.

## Acknowledgments

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