Pers Ubiquit Comput (2015) 19:509–521
DOI 10.1007/s00779-015-0847-y

ORIGINAL ARTICLE

# Head-mounted mixed reality projection display for games production and entertainment

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Received: 20 November 2014 / Accepted: 3 April 2015 / Published online: 19 May 2015


**Abstract** This research presents a mixed reality (MR) application that is designed to be usable during a motion capture shoot and supports actors with their task to perform. Through our application, we allow seeing and exploring a digital environment without occluding an actor's field of vision. A prototype was built by combining a retroreflective screen covering surrounding walls and a headband consisting of a laser scanning projector with a smartphone. Built-in sensors of a smartphone provide navigation capabilities in the digital world. The presented system was demonstrated in an initially published paper. Here, we extend these research results with our advances and discuss the potential use of our prototype in gaming and entertainment applications. To explore this potential use case, we built a gaming application using our MR prototype and tested it with 45 participants. In these tests, we use head movements as rather unconventional game controls. According to the performed user tests and their feedback, our prototype shows a potential to be used for gaming applications as well. Therefore, our MR prototype could become of special interest because the prototype is lightweight, allows for freedom of movement and is a low-cost, stand-alone mobile system. Moreover, the prototype also allows for 3D vision by mounting additional hardware.

**Keywords** Head-mounted projection display · Mixed reality · Motion capture · Laser projector · Immersive environments · Games production

## 1 Introduction

Entertainment industry products such as video games and films are deeply depending on computer-generated imagery (CGI). There are many cases where CGI characters' movements need to meet real-world physics. One of the widely used ways is to capture motions of human actors in a dedicated vision-based motion capture [24] studio as shown in Fig. 1. Alternative motion capture techniques beside vision-based techniques have also been investigated for daily activities and professional motion capture [26, 35]. A typical setup of a motion capture studio is as shown in Fig. 1; a large space shoot area, motion capture cameras aiming at the shoot area, conventional cameras and sometimes projection displays, film cameras and pre-visualization (previs) cameras.

Motion capture actors are generally using a quite minimal scenery as acting environment. Usually simple metal or wooden props are used to create the acting environment. Previous research has shown that actors can experience challenges to perform in such an environment and that these quite diversely skilled "actors" would benefit from improvements in a motion capture shoot procedure [17, 18]. This is why this research addresses this issue

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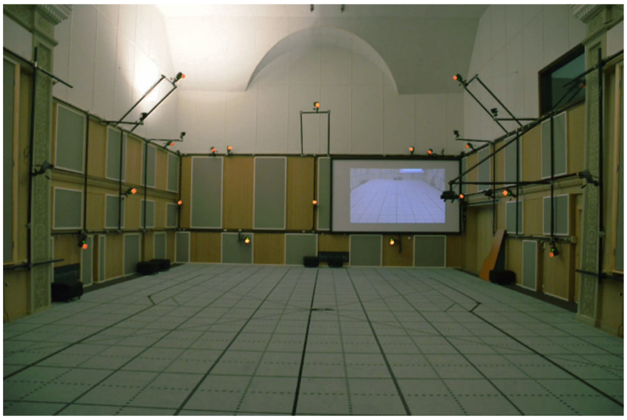

**Fig. 1** Motion capture studio of Imagination Studios located in Uppsala, Sweden. The studio is equipped with near-infrared light source-equipped motion capture cameras, and a projection display

and aims at providing a new interface for motion capture actors that is closer to an actual movie set and especially allows to give visual aid that can be used to act off.

Providing a mixed reality application to motion capture actors would bring the benefit to see and explore a digital environment without having to build real-world props. Scenery and animation could be shown through CGI. The mixed reality is meant to support actors to perform. Such a system could help to guide and immerse the actors through their performance and to understand the scenario of the play faster. Furthermore, it could allow actors to find their positions and paths to walk, act and interact.

To provide an application for a motion capture environment, the application needs to comply with the specific needs of the environment. It is important for some motion capture shoots that the face and vision of an actor are not occluded by virtual reality glasses or other equipment. This is especially the case for facial motion capture shoots, stunts and when interactions with real-world objects or other persons would interfere with the worn hardware.

For some motion capture shoots, as depicted in Fig. 1, a projection display showing the virtual environment from a single perspective is mounted and usable for motion capture shoots. During a motion capture performance, it is in most cases not possible for actors to see the computer-generated virtual world around them without performing unnatural movements like turning the head to look at the screen. This especially becomes an issue if this is an unwanted movement. Therefore, it would be better for an actor to see the virtual environment in a more natural and usable way while acting.

This paper is an extended version of an already published conference paper [1]. Here, we describe our prototype that we developed for a motion capture scenario and discuss how we think that this prototype could be used in other gaming, entertainment and training applications as well. Furthermore, we conducted user tests on a gaming application using our head-mounted projection display to support this discussion. Improvements and further development of our prototype are also documented in this article.

## 2 State of the art

The interest in head-worn display systems [4, 28, 29] is rising with the increasing number of products on the market, where they are being used excessively in entertainment industry. Most of the see-through products offer a near-eye solution with a limited field of view, a constant focus, single eye usage (no stereoscopy), and limited depth of field. Many near-eye solutions come with a great deal of optical complexity in design, e.g., Google Glass [25], or research [10], in which an additional specially made contact lens has to be used to see the content. Thus, the users are having the problem of interacting naturally with the physical world due to these optical limitations. By simply disconnecting the user from the real world, the mentioned problem is avoided via opaque wearable stereoscopic head-worn displays on the market, e.g., Oculus Rift [6] as virtual reality glasses. Nonetheless, the challenge remained the same for real-life use cases. Our focus is to address these challenges by enhancing the optical quantities such as bigger field of view, or focusing at any depth that are vital in a real-life scenario.

Although there are great advancements within the past years, head-worn display prototypes from different institutions are not yet in an affordable price range and real-life applications do not meet the promised usability on a everyday basis, even though there is research that proposed a projection display for daily use [21]. Usability is especially of importance as we intend to provide real-time video content shown from a game engine to motion capture actors while acting, or even gamers while playing a video game.

HMPD’s and their image qualities as well as the use and evaluation of reflective materials, used as a screen, have been discussed and introduced already [13]. This technology was also already used in other research where digital content is projected to reflective surfaces [3] as well as non-reflective surfaces [22, 23] to allow interactions between users and the system. Even though research [3] used a head-mounted projector setup that projects 2D video content onto a reflective surface and allows for interaction with the system already, it differs to the approach we describe in this paper.

According to our point of view, a laser scanning pico projection display was an exciting development and has some interesting aspects to explore in research as it does not require any optical components to focus on any surface and the pixel size stays nearly constant with the increasing distance between the projector and the screen. Additionally, it comes with a coin size light engine [7], where it is very obvious that it reserves room for miniaturization in head-worn display systems. One of the valuable contributions of this paper was embedding such a pico projector into a head-worn display, so that it can provide infinite depth of focus, enhanced color gamut through laser technology and serves as a light-weight mobile system without requiring fixed cabling to a stationary system. The system we provide is independent from any additional system, e.g., a tracking system or an image-processing server, and carries all equipment on a headband.

Laser projectors, as we use it in our research, have been used in research projects before [12]. There, a shoulder-mounted projector was combined with a depth camera to project images to non-reflective surfaces and to allow gestural interactions. It is obvious that the use of their described system is completely different, even though the laser projector is the same. For our purpose, it was necessary to have a head-mounted system that allows having the projector close to the eyes without blocking the users' vision. Furthermore, our system needs to record head movements and should not limit an actor in his movement capabilities. This also means that a rigid setup that cannot move easily was needed in our setup, as for motion capture acting, stunts and athletic movements have to be considered in the requirements toward a HMPD. Furthermore, a more optimized projector setup was needed for our purposes. So we reduced the size of the projector and connected it to an external battery pack which allowed to extend the uptime of the projector and allowed to have a more minimal setup.

Unlike other systems like, e.g., from CastAR [14] or other research projects [33], our system does not require multiple projectors. Thus, problems originated from using multiple projectors such as the keystone or image registration effect are not an issue in our system. Even though the CastAR glasses or even similar AR glasses are about the size of normal sport sunglasses, parts of the face such as the eyelids and eyebrows are still covered when acting for facial motion capture. In our system, only a minor part of the forehead is covered.

Another more practical issue and difference to our system lays within the fact that, e.g., the CastAR system uses tracking markers with infrared LED's on their reflective display material. A reason to try to avoid this within motion capture is that the cameras would pick up the light and could get affected by it. Masking the regions of those markers within the motion capture software so that these regions are simply ignored while acquiring motion capture data could be a solution for stationary reflective surfaces or objects, but for dynamic setups, it is rather unlikely to mask and recalibrate a motion capture system after every setup change; it is simply ineffective.

With our head-worn display, connected to a game engine which is running on a mobile phone, we approach creating a wearable mixed reality projection in a slightly different way than as the literature has shown. Other researchers have created an augmented reality application that provides additional information about certain real-world locations and provide navigational help using RFID technology. This information is then shown on wearable data glasses [19]. Such applications differ from our application scenario, especially in the sense that the purpose for our use case is to immerse users into the digital environment and allow them to explore it instead of providing information or navigational guidance. This includes that the digital environment should be superimposed onto the normal vision in a higher resolution showing digital content from a game engine.

Conventional off-the-shelf laser scanning pico projectors can provide an illumination of 10–20 lm. On the other hand, conventional off-the-shelf projectors can provide up to 1000 lm. Thus, it is required to use the light in the most efficient way in a system equipped with such a pico projector. Availability of different retroreflective materials is another excitement for our purpose, since they provide high light gain when used as screen. In the past, retroreflective surfaces were used as a part of head-worn displays as in the case of [3, 15, 31] as well. Combining a recently licensed stereoscopy method [2, 8] based on polarized glasses is as well an easily realizable method for providing 3D imagery.

## 3 Head-worn projection display

Head-worn display systems are investigated extensively among the optics design community and are believed to be the expected hardware upgrade for future virtual reality applications. In this section, we introduce the architecture of our head-worn projection display. The section also provides information on our mixed reality application implementation, which can be seen in Fig. 2.

### 3.1 Hardware description

Our head-worn projection display system, as shown in Fig. 3, consists of several off-the-shelf hardware: (1) a stripped-down laser pico projector, SHOWWX+ from Microvision, Inc., (2) a Sony Xperia S smartphone, (3) retroreflective material from Reflexite (not in the figure), and (4) in-house 3D printed housing for the equipment.

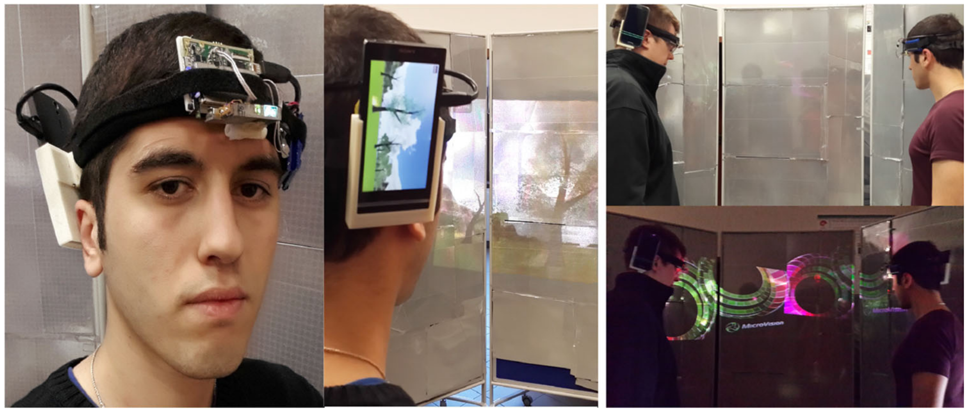

**Fig. 2** The *left picture* shows two different photographs of a user with our wearable mixed reality display, the system is composed of a smartphone, an external battery, and a pico projector with 3D printed housings. The two photographs to the *right* are showing a scenario where multiple users independently taking benefit of a passive retroreflective screen without crosstalk


**Fig. 3** A photograph of the hardware device, equipped with a smartphone, a battery and a pico projector. The housing for both items is in-house 3D printed

#### *3.1.1 Pico projector*

The white laser light from the pico projector is a combination of three different laser light sources (RGB: 643, 530, and 446 nm, respectively). The laser spot scanned from the projector is a Gaussian beam [9]. The Gaussian laser spot beam waist and the best resolution appear at about 80 cm distance from the projector. However, using first-order optical approximations, we can assert that the image is always in focus beyond that distance since the image size and the spot size both increase linearly with distance, i.e., a number of resolvable spots do not change with distance. The laser light source does not require beam-shaping optics as in conventional projectors. The content shown with the pico projector remains in focus and brightness even in case of distance variations. In Fig. 3, the pico projector acts as the light engine in our head-mounted display prototype, thus, a user wearing the prototype does not suffer from any key distortion effect, even when the surface used as a screen is totally distorted, as can be observed within Fig. 4.

#### *3.1.2 Smartphone*

A conventional smartphone is equipped with different types of sensors (gyroscope, accelerometer, magnetometer, GPS sensor, etc) and can be connected to the pico projector through an HDMI port or a MHL adapter. The maximum native resolution of the projector is 848 px $\times$ 480 px @60 Hz *vsync* in size. Thus, a smartphone provides content at the same resolution and refresh rate. For our application, we address the sensors of the smartphone as means of controlling the digital environment.

#### *3.1.3 Battery*

An off-the-shelf pico projector comes with a lithium-ion battery with 3.7 V, and 1800 mAh, which corresponds to 6.7 Wh of energy. The mentioned battery allows a pico projector to operate constantly around approximately 1.5 h. In our prototype, we replaced the parts of the projector's housing and the battery with two lithium polymer batteries $(2 \times 3.7\,\mathrm{V} \times 2000\,\mathrm{mAh} = 14.8\,\mathrm{Wh})$. This modification reduced the size of the overall system and increased the usage time of the pico projector. Furthermore, the modification also allows us to upgrade the battery by adding more battery cells to the prototype. It should be mentioned that the smartphone runs on its built-in battery. As an overall system, the expected uptime is 3–4 h.

#### *3.1.4 Retroreflective screen*

The final part of our head-worn projection display is a high-gain screen, which has the property to retroreflect the light to the source. Thus, a user standing close to the light source, in our case the projector, has high light gain; he or she basically sees the screen very bright. Through trials, it was observed that the screen brightness is good enough for outdoor applications, e.g., sunny weather situations. Nonetheless, for our application, we only aimed at indoor use.

**Fig. 4** *Left* A photograph of the visible key distortion problem when the separation between the camera and the projector is high. *Right* This photograph shows that there is no visible key distortion effect when the camera is placed close to the pico projector, although the surface is curved

Retroreflective material used as a screen can be in different forms: cloth/paint type [5], corner-cube (prismatic) type [30], and cat's eye type [32]. The one used for our prototype was a corner-cube type retroreflective material. The corner-cube retroreflective material can have the highest efficiency among the others, when they are placed in a hexagonal arrangement to have a high fill factor. Typical corner-cube type retroreflective materials, found on the market, have a pitch size in between 0.1–0.3 mm. The distance between the pico projector and the screen is in the range of 1–10 m.

### *3.1.5 Use of reflective materials in optical motion capture*

During our research, we encountered an obvious issue: When using a projector-based solution that includes a retroreflective material, an optical motion capture system will be affected by the light reflections of such a material. We tested different retroreflective materials within a motion capture studio and found that all reflective foils were recognized by the motion capture system. In some situations, the cameras were not functional for a short time anymore as the retroreflective foil returned too much light to handle for the camera.

As a test environment, we used a motion capture studio with 32 Eagle 4 cameras and the Cortex software from Motion Analysis. The foils that we tested were the Reflexite VC310 and the 3M 4090.

The motion capture cameras picked up A4-sized samples of each foil in an equal manner. Moving an A4-sized piece of the foils toward one camera led to a shutdown in about 2 m distance to the camera. A larger piece that was available from the Reflexite VC310 foil was then placed, as intended, behind the cameras on a wall of the shoot floor. The sample sheet was 9 m × 0.775 m in size. Cameras on the other side of the shoot floor in about 8 m distance from the foil started to shut down immediately when running the motion capture software. Other cameras that faced the foil at an angle but were located at the very end of the shoot floor were still affected by the returned light and sporadically shut down as well.

We found two solutions to the above explained problem:

1. Masking the foil in the motion capture software, so that it will not be considered.
2. Applying a notch filter to the retroreflective foil.

The first solution is only possible when the reflective materials are not covering a large enough area to affect the cameras and when the reflective materials will not be moved. Otherwise re-masking would be necessary.

The second solution worked in our quick tests surprisingly well. To avoid the problem of reflecting infrared light that the motion capture cameras could pick up, a screen has to have a band-pass filter (notch filter), which absorbs infrared wavelength light, but allows visible light to pass. Initially, we tested a see-through plastic coating on top of the retroreflective material. We observed that the see-through plastic coating seems to act as a notch filter for infrared light. Nonetheless, this finding needs extended empirical testing and development.

### *3.1.6 Stereoscopy*

The hardware described so far can provide stereoscopic vision [34] through conventional stereoscopic methods using additional passive 3D glasses, such as the long known Anaglyph method [36], or a common method used in movie theaters: the polarized glasses method [27]. The active methods such as shutter glasses [11] cause noticeable flicker with our prototype, due to the low vertical refresh rate of the pico projector. Previously, a new method [2] which solves the flicker problem and combines the benefits of a shutter glasses system with a polarized passive glasses type system has been invented. Although the method has an active component (a liquid crystal polarization rotator) mounted on the projector, it works without any noticeable flicker in pico projectors that have low refresh rates. The method requires the screen to be polarization maintaining. To make our prototype stereoscopic using the mentioned technique, a polarization rotator has to be mounted on the photonics module of the pico projector. Additionally, the user has to wear polarized passive glasses or contact lenses. Currently, our system does not provide 3D imagery, but with the modifications mentioned, it is possible to provide 3D imagery.

### 3.2 Software description

As software development environment, the Unity 4 engine, which is widely used in industry and research, was chosen for our prototype. One requirement for the software was to be able to create and change digital environments that will be shown to actors in a quick way and by allowing to use file formats that are common in computer games creation and entertainment applications. Another requirement to be considered was that the built-in sensors of our prototype such as gyroscope and accelerometer were meant to be used to control the digital environment. These decisions limited our choice to a few game engines that support mobile phone game development. As the Unity 4 game engine is a cross-platform and state-of-the-art game engine, our decision was to use it to develop our software. To develop the software and create the digital environment, we used Unity 4.3.1f1 by compiling the software to an Android phone (tested phones: Samsung Galaxy S4+, S4, S4 mini, S3, and Sony Xperia S).

Furthermore, we implemented controls to make the environment exploreable through using the gyroscope reacting to the movements of the phone, which can be mounted in different positions on the head of a user (back-head, top-head, and side-head). The accelerometer was used to determine the steps and the direction of movement of a user. In places where there is limited space to walk, a solution based on walk-in-place [20] was also implemented as an option. Note that multiple users using multiple prototypes can run the same software independently, but our software does not provide any synchronization between the users at this moment. Head rotations, independent from the phone's mounting position, and walk-in-place movements look accurate so that exploring a digital environment is possible.

For testing purposes and also to allow switching scenarios and scenes quickly without reconfiguring or loading new digital environments, we added the feature of switching to different locations or scenes within the environment so that, e.g., for motion capture shoots, scenes can be switched in an instance and in real-time.

In Fig. 5, the four locations that were implemented for testing and exploring our digital environment are depicted. To create the digital environment, a height map of an island was taken and modified to get the basic layout of the digital environment. Used content and textures to create the environment are freely accessible on the Internet or through the Unity Asset Store.

The created scenarios depicted in Fig. 5 were created to serve as a basis to test our prototype. To provide a slightly better perception of a more realistic environment, trees are animated through shadows and reactions to wind; water is animated through reoccurring wave cycles.

## 4 Application of the prototype in motion capture

Using our prototype in a motion capture studio revealed a few challenges and questions to be solved. We already mentioned the issue of a reflective material in a motion capture studio above, but we also have to mention that motion capture cameras can detect the light source of the pico projector as well. Even though this is true, we found that it is a fairly weak signal and mostly detected as noise in the motion capture system. As many motion capture shoots use skeletons and animation rigs to connect and mask the markers mounted on an actor, the detected light from the projector could even be neglected. Nonetheless, a better solution is to slightly decrease the sensitivity of the marker detection so that the motion capture system already filters the light from the projector.

Emitting light from the projector into the motion capture cameras could lead to a temporary malfunction of a camera. In our brief tests, this only happened when the projector is facing the camera directly and from a short distance (<2 m). The capture of motions is not affected directly in such a situation because the motion capture system calculates the marker positions from multiple cameras and angles.

Acting for motion capture could mean that one or multiple actors need to act and interact at the same time. When using our HMPD, light is constantly emitted. As the projector only has 15 lm, other actors or persons on the shoot floor are not blinded when further away than 3 m. Nonetheless, there is an issue when two actors face each other directly, e.g., when having a dialog. Then the projectors would blind the actors and possibly interfere with facial motion capture recordings. This is a very specific but certainly occurring scenario and needs to be considered and further explored. One solution could be to simply stop projecting when actors face each other. An additionally head-mounted camera, detecting the presence of another user's face could be used for this which then only projects black pixels in regions of another user's face. In our

**Fig. 5** Screenshots from the different locations in the digital environment

prototype, this functionality or a more advanced solution to the problem was not yet implemented.

A clear vision of real objects and persons is essential in motion capture acting, especially for stunt, martial art and bodily demanding scenes. Even interacting with objects such as aiming a rifle needs to be performed as professional and believable as possible. Therefore, virtual reality or augmented reality glasses covering parts of an actor face and vision are usually impractical. Our prototype complies with these challenges and allows for this freedom of movement. The components mounted on the headband are stable and do not shake even during fast movements. Nonetheless, there are no housings that would make the prototype more rigid and shock proof so that an application for stunts or martial arts is safer.

For the above-mentioned hardware and software prototype, we decided to collect feedback from users that were not familiar with our prototype and the environment to get an initial understanding which parts needed to be improved.

## 5 Functionality tests

For our informal functionality tests and to get a first impression from users about our prototype, we conducted a test with 10 users, three female and seven male testers. The testers were in the range of 20–35 years, and nine out of 10 testers have not experienced a wearable projector or display before. Three out of ten testers had an acting background. Nonetheless, for our initial tests, we neglected to test the environment as a motion capture acting aid because it was more important at this stage to proof the functionality and to see how users react to the application we built.

In Fig. 2, the test setup can be seen. The tester is wearing a headband that holds the projector on the forehead and holds the phone on the back side of the head. Walls with a retroreflective foil that reflect the image of the projector into the eyes of the users were placed in front of the testers.

When conducting the tests, each user was given an introduction to the prototype and its functionality. Then, the users were asked to explore the environment and to test the prototype on their own pace. Functionality possibilities and hints were mentioned during the tests, and a dialog using the think aloud method was performed to understand what the user experiences while testing the prototype. The user tests were also videotaped as reference material and as another source of data collection to evaluate the user reactions and comfort or discomfort while using the prototype. In addition, a questionnaire was filled out by the users to help evaluating their experiences with the prototype.

Evaluating the questionnaires and video recordings revealed that there was a mixed opinion among the testers in terms of how comfortable the prototype was to wear. Half of the testers mentioned that they realized that they were wearing the prototype while performing the tests; the other half did not or rarely notice the worn hardware. When we asked whether testers experienced any symptoms of nausea or discomfort while testing, none of the testers experienced any of the mentioned symptoms.

Qualitative feedback toward the question how immersed the testers felt into the environment while testing was also positive. On a Likert-scale, five testers answered with "fully immersed" and five with "immersed." When we asked how realistic the environment felt, we need to report that the testers gave a fairly mediocre feedback. The reason for this lies within the fact that (1) the reflection area and exploreable space need to be enlarged and (2) the walking algorithm and the perception of movements in the digital environment need to be improved as well.

The general feedback from the tests we performed was positive and the testers showed interest in the application. When we asked the testers whether they could imagine using this application for private entertainment or training purposes, four testers answered on a Likert-scale with "strongly agree," three testers answered with "agree," and three with "undecided."

Testing the prototype has also shown that the phone's sensors do provide enough accuracy for simple navigation and movements. The gyroscope accuracy used for head movements was sufficient enough to provide smooth reactions when looking around in the digital world. On the other hand, the accuracy of the phone's built-in accelerometer was quite limiting. Movements within the digital world have been rather unreliable. Natural movements were therefore not usable to create an immersive or natural feel for navigation in the digital world. Simple walk-in-place movements were possible to implement with the accelerometer sensor. Using more accurate sensors or even multiple sensors for navigation might be a way to improve this for future applications. Furthermore, our tests showed which parts of the application need to be improved to create an even better experience, especially for future work and entertainment applications.

## 6 Prototype improvements

After the functionality tests of the first prototype shown in Fig. 3, some changes have been made to provide a more stable and ergonomic prototype. It was furthermore our goal to improve the comfort when wearing the prototype.

Therefore, the 3D printed parts have been redesigned and cables have been placed around and closer to the headband. The improved prototype can be seen in Fig. 6. Here, the redesigned 3D printed parts of the projector allow for more stability to mount and handle the projector. The housing also prevents the projector to be damaged by minor impacts.

The complete prototype now weighs 400 g, thereof are 175 g from the prototype and 225 g from the smartphone (Samsung S4). Replacing the smartphone with a smaller and more lightweight processing unit could be a way to further improve the prototype, as well as to make it more lightweight. We did some initial experiments with an android mini PC to replace the smartphone. Some testing led to the conclusion that the mini PC we used was simply not powerful enough to show the digital environment in an acceptable quality. Furthermore, we experienced that some functions like debug menus and buttons of our Unity generated Android app were not supported on the mini PC.

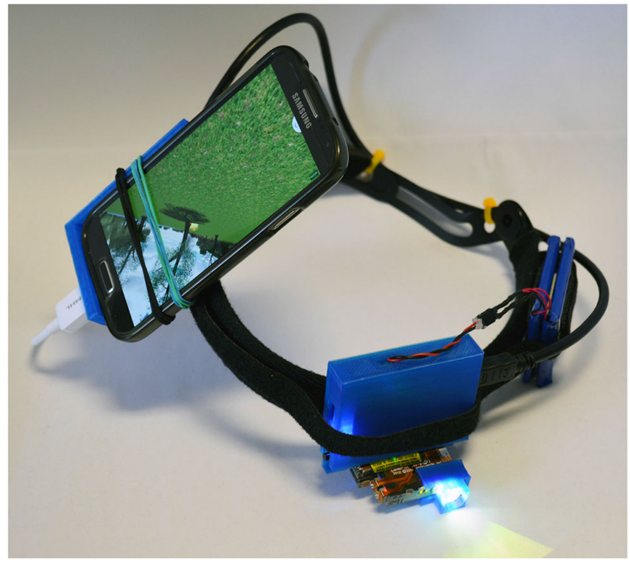

**Fig. 6** Improved prototype with mounted lens and a more ergonomic and stable design

Moreover we looked into a more flexible way of using the retroreflective foil to reduce the setup time for dynamic objects and scenery. A solution was to look into retroreflective cloths. We tested the cloth no. 6101 from RB Reflektör and realized that the optical properties of the cloth are of a higher quality than the retroreflective foil that we used before. A cloth might be preferable in situations where the projection surface needs to be moved, transported or reused, as the foil is meant to be glued to the surface where digital content needs to be reflected.

We have some further ideas on how to improve the current prototype, as described in Sect. 10. Moreover, we see a possibility to use our setup for gaming and entertainment applications and explain our take on this as well as our conducted tests in the following chapters.

## 7 Using the prototype in gaming and entertainment

The development of our prototype was focused on providing a useable prototype that complies with a motion capture environment. Nevertheless, we see the potential to use the prototype for other applications, such as gaming and entertainment, as well.

Our prototype is designed to allow for freedom of movement and to be able to see the real world as well as the virtual world. Therefore, we see the application area in games where movements and body interactions are of importance or games and entertainment applications that allow exploring digital environments. These kinds of applications seem to be suitable as the projected image follows the head movements of the users and creates a natural demand to use and experience the environment around the users.

Game and entertainment experiences could be made fairly immersive, especially when real-world objects like, e.g., racquets, balls or similar, can be used to steer and control the play.

Even multiple users could play with or against each other, as the retroreflective screen allows using the same projection surface for multiple users, even with different content. This works without crosstalk. In a gaming context, it could be a great opportunity to allow for co-op, strategy or sports games. One player cannot see the content of the other player, only when this is digitally projected. The laser pico projector that we used has 15 lm, and digital content could be seen by other players or observers when the environment is fairly dark, under normal light conditions this is not an issue. Crosstalk of projected content could occur when two players stand behind each other looking at the same screen with approximately the same body height. As soon as tracking of players would be implemented to the prototype, this problem might be solvable.

An issue that occurs currently and might even be an issue in the before-mentioned multiplayer scenario is when two players face and look at each other. The projectors could in this case blind the opposing person. These challenges stay for future iterations and developments of our prototype.

Currently, we are also exploring the use of transparent, thin-layered see-through projection screens, as shown in Fig. 7. These screens allow to be placed at convenient locations or can even be mounted in front of the users head or garments can be placed wherever a screen might be needed. This could especially be interesting for applications with the need of flexible setups and in cases where multiple layers of information need to be shown. This could be achieved through a combination of screens (see-through screen in front of a traditional screen or real-world objects).

As our current prototype is lightweight, it allows for mixed reality application and freedom of movement, we think that the presented prototype has potential to be used in entertainment, gaming, and other applications. To test this statement, we created a game using our prototype and conducted user tests with our set up. This is explained in the following section.

## 8 Conducted user tests within a gaming application

To explore the idea of using our prototype for gaming applications, we created a video game and conducted user tests. The video game was created in the Unity game engine and was installed on the smartphone, which uses the players head movements as game control. Through the head movements, the players were able to explore the game world and were able to steer a crosshair to shoot at asteroids approaching the player. Shooting targets was automatic, as soon as the crosshair was aligned in direction with the approaching objects. Figure 8 shows the game world in a first person view, as well as the setup that was used to test the environment.

### 8.1 User test method

The user tests were conducted over the course of 3 days with 45 participants, whereof 11 were female and 34 male. The age of the testers ranged from 20 to 25 years (5 pers.) and 26–35 years (27 pers.) to older than 35 years (11 pers.). The testers had no particular background in gaming or game development and were no regular users of head-mounted displays. For many participants, it was the first time to use a head-mounted display.

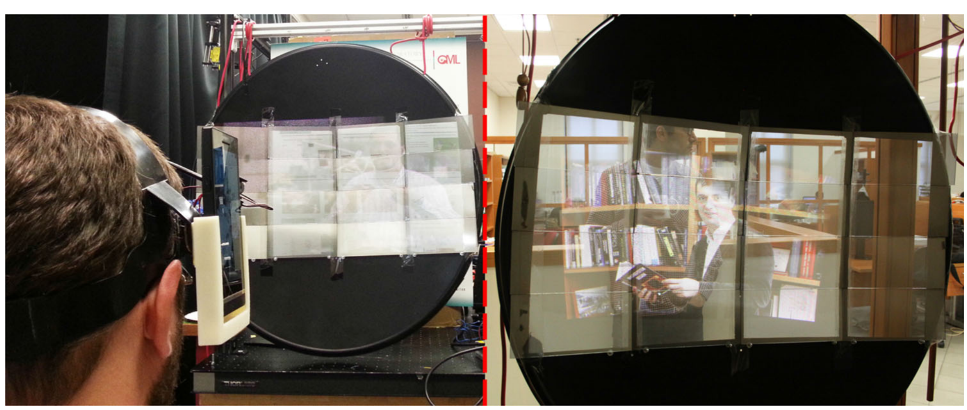

**Fig. 7** The figure shows a test setup for the see-through screen in combination with the alpha version of our prototype. The *left image* shows a user using the HMPD; the *right image* shows the see-through capabilities of the screen with a person standing behind the screen

**Fig. 8** The setup of our test environment and users wearing the prototype are shown on the *left part* of the image and screenshots of the game are shown on the *right side* of the image

At the beginning, participants got introduced to the system, its functionality, and the tasks to perform. The participants were given two rounds to play the game, where one round lasted 1.5 min. The first round was meant to get used to the system and understand the game controls; the second round was set to be competitive with the goal to shoot as many asteroids as possible. To set a competitive gaming atmosphere, it was explained to the participants that the person with the highest score wins a cinema gift card. During the tests, observations of the participants were conducted and videos of the performance from two different angles were recorded. After the gaming tasks, the participants were asked to answer an online questionnaire.

This questionnaire aimed at understanding whether our prototype could be used for gaming applications. The questions were also meant to rate the comfort to wear and use the prototype, as well as to evaluate the game controls. Therefore, we asked questions which were inspired by the Immersion and Experience Questionnaire (IEQ) [16]. Yet, our goal was not to evaluate the level of immersion or the game quality. Therefore, we only considered parts of the IEQ questionnaire and modified the question according to our needs (evaluating comfort and game controls). The questions of our online questionnaire were aiming mostly at three categories: comfort, game controls, and gaming and immersion. The results of our findings are listed below.

### 8.2 Results

*Comfort* To get an understanding of the comfort when using our setup, we asked the participants whether they realized the prototype while playing the game. Eleven percentage of the participants answered that they did not realize the worn hardware while playing the game at all and 51 % answered that they rarely realized it. Other testers mentioned that they felt the weight of the smartphone or generally that they are wearing a device on their head.

Furthermore, we asked whether the testers experienced any nausea or discomfort. Seventy-one percentage answered that they did not experience any nausea or discomfort while using our HMPD. Other testers reported a light dizziness, an uncomfortable seating position.

*Game controls* To understand the status of the games control, we asked the participants the question: On a scale from 1 (Very Difficult) to 5 (Very Easy), how was your perception of the game control? The results showed that the majority of testers found the controls as easy to control, as can be seen in Fig. 9.

To understand the difficulties that users might experience with the controls, we integrated an open question into the questionnaire and furthermore interviewed some of the users that had difficulties with the game controls. The major issue mentioned was the slight drift of the gyroscope, which sometimes gave the impressions of a slight lag or moving the crosshair a bit too far as intended. One tester

**Fig. 9** Questionnaire results on game controls

| 5 – Very Easy | 4 – Easy | 3 – Mediocre | 2 – Difficult | 1 – Very Difficult |
|---|---|---|---|---|
| 4.44% (2) | 60.00% (27) | 22.22% (10) | 13.33% (6) | 0.00% (0) |
| *100.00% (45)* | | | | |

**Fig. 10** Results of the users' engagement while playing the game

| 5 – Strongly Engaged | 4 – Engaged | 3 – indifferent | 2 – Disengaged | 1 - Strongly Disengaged |
|---|---|---|---|---|
| 33.33% (15) | 60.00% (27) | 4.44% (2) | 2.22% (1) | 0.00% (0) |
| *100.00% (45)* | | | | |

**Fig. 11** Results of the willingness to use the prototype for personal gaming uses

| 5 - Strongly Agree | 4 – Agree | 3 – Undecided | 2 – Disagree | 1 - Strongly Disagree |
|---|---|---|---|---|
| 20.00% (9) | 51.11% (23) | 24.44% (11) | 2.22% (1) | 2.22% (1) |
| *100.00% (45)* | | | | |

also mentioned that looking around in the game world seemed to not correctly match natural head movement distances. We think that these issues could be addressed by using a more responsive gyroscope sensor as the built-in smartphone sensor and even by adjusting the game mechanics.

*Gaming and immersion* As we use a rather unconventional way to steer the game play with your head movements, we asked an open question whether the participants experience any difference to Exergames, games using head-worn displays or body-controlled games such as Kinect games or computer games in general. Some participants mentioned that they could see the complete environment around them; that playing felt immersive; that they had the feeling of being in the environment. Other participants mentioned that it is new to them to control the game with their head movements instead of body movements or using game controllers.

We also wanted to know whether the testers felt engaged with the game and about the level of engagement while they were playing the competition round. Here, 33 % answered that they were strongly engaged and 60 % mentioned that they were engaged, as shown in Fig. 10.

Through observations and video recordings, we noted that the participants were eager to perform well and got into a competitive mood. This was especially seen when they showed emotions and actions like surprise, enjoyment, self-motivation, anger about missed objects or not beating the high score. Some testers even asked whether it would be possible to play again or whether other games would be available to play.

Moreover, we asked the question: On a scale from 1 (Strongly Disagree) to 5 (Strongly Agree), would you use the application for private entertainment or gaming purposes? The results were rather positive, as can be seen in Fig. 11 below.

The participants also suggested some improvements, such as having a larger screen, maybe even a 360° screen to play the game. It was also suggested to improve the ergonomics of the prototype, as well as to improve the game controls, as mentioned above.

The results and evaluations of our user tests with the gaming application have shown that there is a potential to use our prototype setup for gaming applications. Our success criteria are based on the questionnaire results and on the observed behavior of the participants, as mentioned above. The high levels of engagement and the general willingness to use the device for private entertainment and gaming, supports our initial idea that the prototype could be used for gaming purposes as well. Still there are some improvements to be made, as mentioned before, to allow for an even better gaming experience. These improvements would largely benefit, not only applications for computer games but also applications for motion capture acting support.

## 9 Conclusion

In this paper, we have demonstrated a lightweight, low-cost, mobile and ergonomic head-worn projection display using off-the-shelf equipment. The used equipment was modified to create a compact and longer lasting prototype (3–4 h). Our prototype uses a single 15 lm pico projector and does not require a cable connection to a stationary unit. Perceived images by the users are focus free, bright, and distortion free. A perceived field of view is 50° in diagonal. Since the projector moves together with the user's eyes, the projected image covers a fixed field of view in the visual field and does not suffer from any optical distortion even when projected at the corners of the room. The vision of the users is not occluded and no hardware is placed in the users field of vision. We have shown that exploring a virtual environment is possible with our prototype and allows to create a fairly immersive experience. Multiple users can independently use the screen without experiencing crosstalk. Moreover, we discussed and tested the usage of our prototype for gaming applications. Our prototype is an inexpensive, lightweight, and stand-alone MR HMPD that shows the potential to be used in motion capture studios as well as in other gaming and entertainment applications. This is especially the case because the system is mobile and not dependent on external tracking, computing, or displaying systems.

## 10 Future improvements

As our goal is to use the prototype for motion capture acting aid and possibly other entertainment applications, a few improvements and changes need to be done to allow the use of the prototype for such environments. Improving the controls and walking algorithms of the prototype through better sensor data needs to be performed to get a more precise and natural feel. Using different and possibly multiple inertial sensors is a current idea to solve this issue. Therefore we are developing wireless, battery-driven inertial sensors hosting an accelerometer and gyroscope.

Another improvement that we are planning to address is to replace the smartphone with a smaller and more lightweight processing unity. Many functions of the smartphone are not used and can therefore be neglected.

Testing and improving the prototype's physical rigidness need to be done to allow wearing the prototype for stunt motion capture shoots as well as to make the prototype even more ergonomic and rigid.

The next version of the software is expected to provide interaction in between multiple users sharing the same digital content. Alternatively, there can be multiple screens used and shared by multiple users in remote locations.

**Acknowledgments** On behalf of Mälardalen University, we would like to thank KKS Stiftelsen for their support of the Industrial Research School, ITS-EASY. On behalf of Koç University, we would like to thank the Scientific and Technological Research Council of Turkey (TÜBITAK) with their support in Project No. 111E183.

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