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A Low Cost Optical See-Through HMD - Do-it-yourself

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ABSTRACT

HMD that provides Virtual Reality and Augmented Reality capabilities are emerging in the last years. Manufacturers are seeking to design hardware that maximizes the field of view (FoV) and depth of field (DoF). On the other hand, we did not found a device that allows the variation of these parameters. This paper presents a model to build HMD using mirrors reflection. Our model allows the adjustment of the DoF. Consequently, the FoV also changes. Our prototype shows that the proposed feature is a feasible alternative. Furthermore, we present a simple and low-cost alternative for HMD development.

1 INTRODUCTION

Virtual Reality and Augmented Reality implemented in wearable platforms sound like the new thing for the next years. Users have had the opportunity to enjoy this technology for entertainment, work tasks, body information, and other daily activities. For years, engineers and researchers are developing technologies to build the Head Mounted Displays (HMDs) for many different purposes.

HMD designers need to take into consideration at least two main parameters on the HMD building process. Field of View (FoV) represents the size of the projected image viewed by the user. Depth of Field (DoF) is the distance between the virtual image plane and the user's eyes. Most HMD manufacturers created their devices trying to maximize the FoV and DoF, providing a wide FoV on long distance.

Although, most of these projects are converging towards to provide these features, we raise a relevant question in this paper. A fixed DoF causes user fatigue since the user needs to change the eye focus many times while using an HMD. For example, if the virtual image is near to the user and the object is far away from him, he will need to change his focus frequently. The main HMD available on the market does not allow the changing of the depth of field. Probably, this occurs due to the way how the HMD are created. This paper presents a description of main HMD feature and properties and introduces a simple model to build HMDs with adjustable depth of field. Our model uses adjustable mirrors to change the DoF. The prototype presented in this paper as proof of concept is a helmet and has a low cost of creation.

We use a 3D printer to create a prototype as the proof of concept of the presented model. We use three and five mirrors to project the image on our experiments. In order to compare the depth of field of the projected images, we have captured two images, and all of them presented different sizes of the projected image. These pictures evidence the successful changing of the depth of field.

The main contributions of this paper are:

- To describe a review about the HMD classification
- To introduce an HMD system able to adapt the depth of field
- To show an HMD prototype as proof of concept of our model
- To introduce a low cost HMD

This work is organized as follows: The first section presents an overview of the general HMDs features and overview. Second section introduces the model to build HMD with mirrors and depth of field adjustment. Third section shows some features of the main HMDs available on the market on our model. Next section presents the proof of concept of our model. Finally, conclusions and future works are described.

2 HMD OVERVIEW

Since the late 1960s, when the first Head Mounted Display (HMD) was released, there have been many attempts by researchers and manufacturers to develop a variety of HMDs aimed for Virtual Reality (VR), Augmented Reality (AR) and Wearable Computing applications. HMDs have a wide range of applications in AR, including military, industrial, medical, educational, training, navigation and entertainment applications. The development of an ideal HMD to all situations is extremely hard. Therefore, the identification of the target application requirements and restrictions is crucial to define which technologies will be employed in the development of a specific HMD for this target application. Some of the main characteristics and aspects that need to be observed when developing an HMD for a given target application are: type of see-through display and ocularity demanded by the application; optical design to be employed; resolution which the application requires; field of view amplitude; occlusion capability and depth of field requested by the application; latency, parallax effect, distortions and aberrations introduced by the chosen architecture; and matters related to user's experience and acceptance.

2.1 HMD Classification

Augmented Reality Head-Mounted Displays can be classified according to various parameters. Therefore, we choose to classify HMDs according to three main parameters which are suggested by [4] and [6]: the type of see-through display, the type of ocularity and the optical design employed in the HMD development.

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2.1.1 See-through Displays

In general, there are two main types of see-through displays in AR: optical see-through and video see-through displays.

Optical See-through Displays: Through an optical system, the real and virtual images are combined using an optical device that is partially transmissive and reflective. The real world image is fully seen through this optical combiner while the virtual image overlays the real one. The advantages of the optical system see-through include: natural and instantaneous view of the real world, and its structures are usually light and simple [4]. Most of HMDs use an optical see-through display to provide an augmented view for users. Some examples of optical see-through HMDs are Google Glass, Optinvent Ora, Epson Moverio and Microsoft HoloLens [4, 6, 10, 3].

Video See-Through Display: When using a video see-through display, the real world image is first captured by a video camera, then, the captured image and the virtual one are digitally combined. Finally, the combination of the images is displayed to the user through a video display, as an LCD or LED screen. The advantages of the video system in relation to the optical system include a pictorial consistency (precise overlay of the virtual image on the real one) and the availability of countless image processing techniques [4]. [2] and [1] show HMDs that use video see-through system to display an augmented view for users. Steve Manns EyeTap HMD [8] can also be considered as a video see-through HMD.

2.1.2 Ocularity

Another criterion used for categorizing HMDs is the ocularity, a measure of the number of eyes needed to see something. There are three types of ocularity: monocular, bi-ocular and binocular. A monocular HMD, as the name suggests, has a single viewing device and is recommended for applications in which stereoscopic view is not required, such as general purpose and daily usage HMDs. Google Glass, Optinvent Ora and EyeTap are examples of monocular HMDs [9, 6, 10, 8]. A biocular HMD provides a single image to both eyes while a binocular HMD has two separate displays with two input channels, one for each eye [4]. A binocular HMD can function as a stereoscopic HMD only when two different image sources are properly provided. For AR, binocular video see-through HMDs are highly recommendable due to their capability of generating stereoscopic images [4]. Epson Moverio and Microsoft HoloLens are examples of binocular HMDs [6, 3].

2.1.3 Optical Design

Regarding the optical designs, HMDs can be divided into two categories: pupil-forming and non-pupil-forming. The architecture that represents the pupil formation has frequently been used since the first HMDs to allow a wide field of view, despite presenting greater size and weight. This architecture generates, at least, one intermediate image and the exit pupil is collimated by the eyepiece. In relation to the size of the device that creates the images, the existence of an intermediate image offers a flexible optical design [4, 5].

With the emerging of high resolution displays and small imaging devices, the architectures without pupil formation have become more common [4]. Besides, high resolution and small imaging devices allowed a moderate field of view in a light and compact structure [4, 5]. On the other hand, they have a less flexible optical design and do not generate any intermediate image [4]. Free-form prisms, holographic optical elements and optical waveguide are some of the technologies used in architectures without pupil formation. Some recent HMDs like Google Glass, Optinvent Ora, Epson Moverio and Microsoft HoloLens use optical designs based on waveguides [4, 6, 10, 3].

2.2 HMD Characteristics and Limitations

The main characteristics of HMDs (such as image resolution, field of view amplitude, occlusion capability, depth of field and optical design) are intrinsically related to the current limitations of the technology (such as pictorial consistency, vergence-accommodation conflict, latency, parallax effect, distortions, and aberrations). After analyzing the constructive aspects of the HMDs, it is important to define the characteristics which are demanded by the target application and try to minimize the technology limitations related to it.

2.2.1 Resolution

The resolution of a see-through determines the integrity of the virtual image in relation to the real image. The resolution of the whole system is limited by the optical system, by the image generator device, and possibly, by the camera resolution (in the case of video see-through HMD). Regarding the resolution of the virtual image, an ideal HMD will need to have up to 12,000 x 7,200 pixels to compete with human view, which has an angular resolution of 60 pixels per degree (PPD), considering the human total field of view of 200° (horizontal) per 120° (vertical) [4]. As it is not possible to achieve this value of PPD with the current technologies, it is necessary to make a trade-off between the angular resolution and the amplitude of the field of view to achieve a viable solution. However, as the resolution of the screen tend to increase each year, this trade-off between angular resolution and amplitude of the field of view must disappear in the future [4]. It is important to note that only the augmented view suffers from limit resolution issues in optical see-through HMDs system while in video see-through HMDs both, the real and augmented view, suffer from resolution limit [5].

2.2.2 Field of View, Depth of Field, Vergence-Accommodation Conflict and Occlusion Capability

In Augmented Reality Head Mounted Displays, the Field of View (FOV) is an important parameter, which is typically measured in degrees and gives us an idea of how wide is the augmented view that the user see. Generally, HMDs for AR applications, such as Microsoft HoloLens, require wide and stereoscopic FOV, while smart glasses applications, such as Google Glass, can have narrower and monocular FOV [4, 6].

Meanwhile, the depth of field refers to the set of distances in relation to the eye (or to the camera) in which a given object remains focalized into the FOV. In real life, the accommodation of the eye is automatically adjusted to focus on an object according to the distance, and objects outside this depth of field seem to be distorted. On the other hand, the virtual image is usually observed from a fixed distance. This focal distance of virtual image represents a problem because the accommodation and the convergence of the human view system are intrinsically linked. This way, adjusting only one of these aspects and keeping the other fixed might cause ocular fatigue [4, 5, 6]. This problem is also known as vergence-accommodation conflict [5].

Another desirable characteristic for AR HMDs is the occlusion capability. An HMD with occlusion capability can introduce a virtual object between real objects providing important depth information about the augmented view [4, 11]. The occlusion occurs in such way that the real object in front occludes part of the virtual object, and the virtual object occludes part of the real object behind it. Occlusion capability is easily achievable with video-see HMDs than with optical see-through HMDs [4, 11, 7].

2.2.3 HMD Limitations

Some of the main limitations in Augmented Reality Head-Mounted Displays are latency, parallax effect, distortions, and aberrations. These restrictions are related to the chosen optical design, as well as to other hardware issues, and must be minimized. Some of these problems are harder to deal with in an optical see-through design than in a video see-through design, and vice-versa.

2.3 User Experience in AR HMDs System

Opposed to smartphones or smartwatches, HMD can be a discomfort when the users need to wear it and take it off frequently. A future perspective for HMDs is that they will become light, small and comfortable, in a way that users will be able to use them continuously for an long period during the day for diverse purposes. Nevertheless, the HMD might be useless, or even harmful if the content it shows is irrelevant to the current context of the user. This issue is least noticeable in HMDs for AR, once it is expected to have a wide field of augmented view covering the central field of view of the user. In such situations, a system of AR must be aware of the users environment contexts, so it must change its content and presentation style correctly and dynamically according to the context [4, 8].

The HMDs used inappropriately might induce undesirable symptoms like headache, shoulder stiffness, nausea, or even more severe harm to the users health. From an ergonomic point of view, HMD must be as light, small and comfortable as possible during usage. Besides, the look and appearance of HMDs must satisfy the applications requirements. The center of mass in the HMD must be placed as close as possible to the users head. A heavy and well balanced HMD might seem lighter to the user than a light and unbalanced HMD [4, 7].

The matters of safety have equal importance. Because of their nature, AR applications tend to distract the users attention from what happens around him/her due to virtual images overlaying the real environment. AR applications must present minimum information to avoid catastrophic results and at the same time, help during the realization of the target task satisfactorily. When the matter of security is considered a top priority, HMDs with see-through optical systems are recommended over HMDs with see-through video systems. This happens because video see-through HMDs restrict the user's peripheral view. Moreover, in case of failure, the central view of the user would be lost [4, 11, 7].

3 A MODEL FOR BUILDING HMD

The current state of the art of HMD design was presented in the previous section. The way how these tools are built make them expensive once is necessary to acquire particular materials that usually are expensive. This fact makes the prototyping cost and the end user's product price/cost unfeasible in some cases. The model presented does not use a particular lens in its construction. Our system includes mirrors and an image source. A set of mirrors has been used to increase the depth of field from the user and provide the most comfortable user experience on the HMD use. The current proposal allow to adapt the depth of field distance from the user.

3.1 Mirrors Reflection

This section describes the mirror reflection module created. A set of mirrors were designed in order to set the distance of virtual image shown to the user, avoiding users change their eye's focus frequently. The proposed model and its equations are described below. Images 1 and 2 are used to explain the model. Table 1 describes the variables used on the system.

Figure 1 represents the system model from side view. We use two modules to describe the system. First one called of *Mirrors Module* composed of a set of mirrors and an *Image Source*. The second module is named *User View Module* whose role is to show the projected image to user. Figure 2 represents the *Mirrors Module* from top view. Image source is the device which projects the image. It can be a small display, projector, smartphone or other device able to project digital images.

We use the Figure 2 as reference to explain the mirrors projection. M(i) is the mirror, where *i* corresponds to a mirrors index. Each mirror is placed near to *Image Source* and indexed in ascending order considering the reflection order in the mirror. For example, the first mirror to reflect the image receives index *1*, the second mirror receives index *2* and so forth. VI(i) corresponds to the virtual image formed behind of M(i), where *i* corresponds to the index. For each mirror, we demonstrate the distance of image behind of mirrors. We use the D_{VIi}, where *i* corresponds to the index of mirror where VI(i) is formed. The mirrors are rotated in an α angle in order to reflect the image to next mirror(M(i+1)). The arrows from *Image Source* and mirrors illustrate this angle of reflection. M(n) is the last index mirror and its virtual image is projected to the user on HMD visor.

Table 1: Variables used on model

Variable	Description
M(i)	M(x) is the mirror, where i corresponds to a mirror index.
V(i)	Virtual Image formed on M(i)
DVI(i)	Distance of V(i) formed on M(i)
l	Distance among mirrors
k	Distance between M(n) and HMD Visor
w	Distance from user eye to HMD Visor
DF	Distance of Virtual Image formed on HMD visor
h	Diagonal Size of image source
n	Number of mirrors
θ	FOV Angle

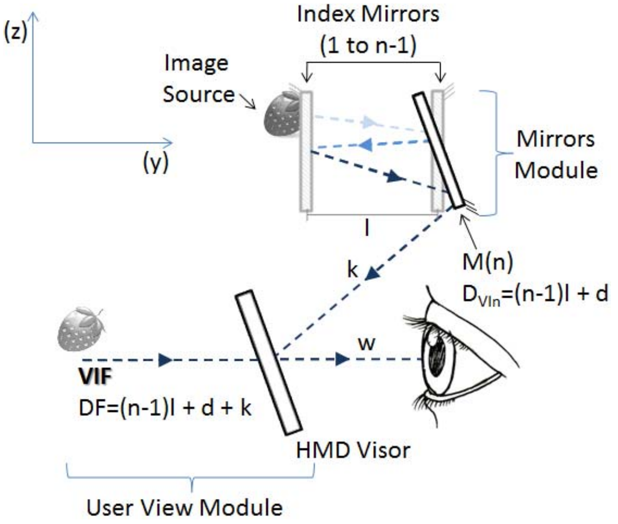

Figure 1: Side View of Proposed Solution

Let consider that *d* is the distance from M(1) to *Image Source*. The distance of virtual image (D_{VI1}) formed behind the M(1) is *d* how demonstrated on Equation 1.

$$D_{VI1} = d \tag{1}$$

Each mirror is placed in parallel position at the distance *l* and the same α angle. The mirror M(n) is the exception because it is set at a different angle to reflect the image to HMD visor. This procedure is explained on Figure 1. The distance of virtual image on M(2) is the distance of virtual image on M(1), i.e. D_{VI1}, plus *l*, the distance from M(1) to M(2). Equation 2 demonstrates the distance:

$$D_{VI2} = l + d \tag{2}$$

The distance 'l' is applied on each time that the image is reflected in a mirror. This way the distance of virtual image on M(n) is represented by the Equation 3, where *n* is the number of mirrors:

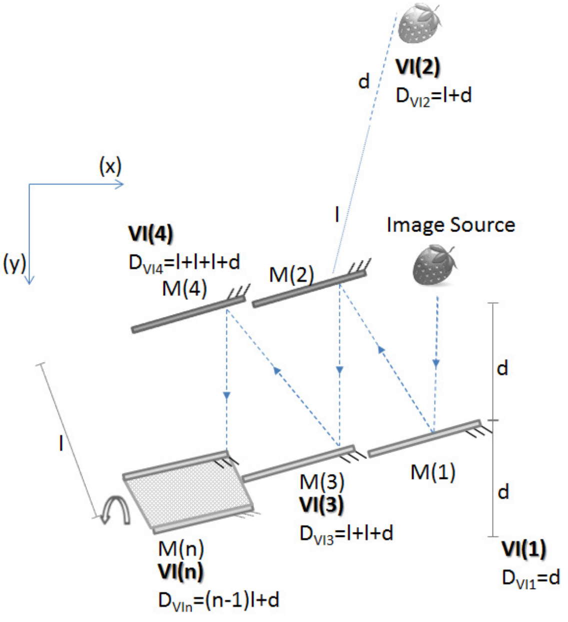

Figure 2: Top View Proposed Solution

$$D_{VIn} = (n-1)l + d \tag{3}$$

Figure 1 represents the same model on side perspective. The dashed mirrors represent the index mirror M(1) to M(n-1). Dashed arrows represent the image on z-axis formed on each one mirror. Note that the mirror M(n) has a rotation on the x-axis. This rotation is necessary to reflect the M(n) image on HMD visor. There is a distance k between M(n) and the visor. This distance is added to the final distance of the projection on user visor (DF). The DF equation is represented by:

$$DF = (n-1)l + d + k \tag{4}$$

3.2 Relationship Between the Size of Image and FOV

Another feature described in this paper is the relation between the size of *Image Source* and the field of view (FOV) of the model described. We decide to explain this feature to make our model more flexible, to describe a model and to make it comparable with other HMD available on the market such as Google Glass, Reconjet, and others.

Furthermore, we are concerned to provide a feature which is not found on most of available HMD. Usually, these devices have a static FOV and a fixed depth of field. Depending on the HMD usage, the user need to change the eye focus to see the projected image. In some critical situation, this behavior can cause risk live to the user. For instance, let consider the use of an HMD device for snowboarding. Usually, the user is at a high speed and is necessary keep attention on lane and objects all the time while he is down the mountain. Therefore, changing vision focus can distract the user attention and put him/her on risk. There are other scenarios that the distance of image need to be changed while the user is running their application. This is the case of industrial plant. Each moment users can be in a different industrial environment that demands to change the distance of the projected image.

The distance of the projected image on our model can be adjusted trough the variation of the variable 'l' in the equation 3. Another choice is to handle the number of mirrors, represented by 'n' in the same equation.

Figure 3 shows the user perspective of the projected image. 'h' is the diagonal size of the image. θ is the angle of FOV. Equation 5 describes the FOV.

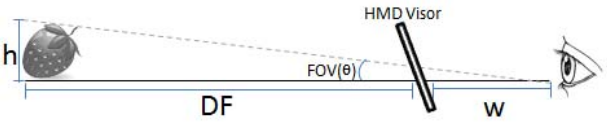

Figure 3: FOV Demonstration

$$\tan(FOV(\theta)) = h/(DF + w) \tag{5}$$

Hence, the equation to define θ is:

$$FOV(\theta) = \arctan(h/(DF + w)) \tag{6}$$

4 IMPLEMENTING OUR MODEL TO OTHER HMD

This section summarizes the other HMD parameters and shows how some of them can be built using our model. Is not our intention to compare our model with other models. The current state of technology does not give conditions for the reproduction of our proposal on glass. This model is appropriated to build a helmet for specific applications. In our case, we plan to reproduce then for industrial appliances. Furthermore, the main benefit of our proposal is the low cost of the platform and the possibility to adjust the depth of field. Table 2 summarizes the main HMD available on the market. Note that each HMD described has different FoV and different depth of view. Normally, manufacturers has the focus on maximize the FoV and depth of view.

Let take as an example the Google Glass. This device presents an FOV of 24° and a depth of field of 2.4 meters. To reproduce these configurations with our model is necessary to use an *Image Source* with ≈25" of diagonal size. Is perceptible that our solution can not substitute all devices, due the size of objects and wearable requirements. Optinvent Ora is the device which has the great FoV and major Depth of Field. It can show a projected image on 4 meters with 24 of FoV. To reproduce it on our model is necessary to use an *Image Source* bigger than Google Glass.

Depth of Field of Epson Moverio and Reconjet was not found on their specifications. Due this fact, we cannot show their construction using our model.

Our model cannot provide the same FoV and same depth of field provided by other HMD's. On the one hand, it seems a problem of the model because, to provide a satisfactory FOV for a long distance is necessary a large *Image Source*. Usually, image sources are screens and need to be placed on the user's head. On the other hand, there is no a consensus of the ideal FoV and Depth of View. Each application may demand different FoV on a different field of view. For instance, let consider the it use in an industrial environment, where workers may use this different depth of view for each task. Usually, jobs that demand the operator equipment manipulation need of less than one meter of the depth of view. To develops these works, normally the workers are near to the equipment for manipulation. This is the case of tasks like maintenance of a device. Tasks that does not demand worker operation, such as a checklist, the user can be performed with more the one meter of the depth of view.

Vergence accommodation is a condition considered by the current HMD's. This is a issue raised by researchers and HMD users [5]. The current HMD model construction does not allow the change the depth of field distance. This can cause discomfort and fatigue to the user, because he/she need to change the focus of the eyes several times.

Table 2: Features of Main HMDs

Product	Form Factor	See-through	Ar Capable	Diagonal FoV	Depth of Field (Meters)	Application
Google Glass	Monocular		No	14	2.4	General Purpose
Epson Moverio	Binocular	Yes	Yes	23		General Purpose
Optinvent Ora	Monocular	Yes	Yes	24	4	General Purpose
ReconJet	Monocular	No	No	16		Sports
Hololens	Binocular	Yes	Yes	$\approx$32	0.6	General Purpose

5 PROOF OF CONCEPT

This section describes the prototype created as the proof of concept. We designed the prototype in the software Auto CAD123 and the model was printed in the 3D Printer MakerBot Replicator 2X. The main objective is to show the mirrors reflection and the depth of field of the image projected. Figure 4a shows the 3D model of the project. Figure 4b shows the prototype already printed. After printing the prototype, we have installed the prototype's visor (a semi-transparent mirror) below the printed structure and then we have tested the prototype, using the smartphone as image source. Figure 4c shows the prototype testing.

To validate our proposal, we have changed the number of used mirrors by changing the image source position. We have tested the prototype using two configurations: first, we tested the three mirrors configuration and, then, we tested the five mirrors configuration. During these tests, we have evaluated the prototype depth of field for each configuration. In the three mirrors configuration, we have achieved a 30 cm depth of field. In the five mirrors configuration, we have achieved a 40 cm depth of field.

Figure 5 shows the test results. Figure 5a shows the virtual image which we are trying to overlay into the real world. Figures 5b and Figure 5c show the user's point of view of the virtual image being overlaid into the real world. Figure 5b shows the virtual image overlay in the three mirrors configuration and Figure 5c shows the virtual image overlay in the five mirrors configuration. It is worth noting that the field of view decreases as the depth of field increases and this is an issue which we want to address in future work.

6 CONCLUSION AND FUTURE WORK

This paper has introduced a single model to build HMDs. A review of the features and properties of several available HMDs was presented. Our model is different from the others, because we use the mirrors reflection to project the image. We have used a single prototype with three mirrors and five mirrors configurations to experiment this feature. Pictures were taken of these configurations. We could perceive the different size of the projected images that demonstrate the successful of the experiment. The depth of field adjustment changes the Field of View (FoV). While the depth of field increases, the FoV decreases. In order to improve the FoV we plan to use a set of lens as a future work of this project. This paper, reports the first step of a new way to create HMDs.

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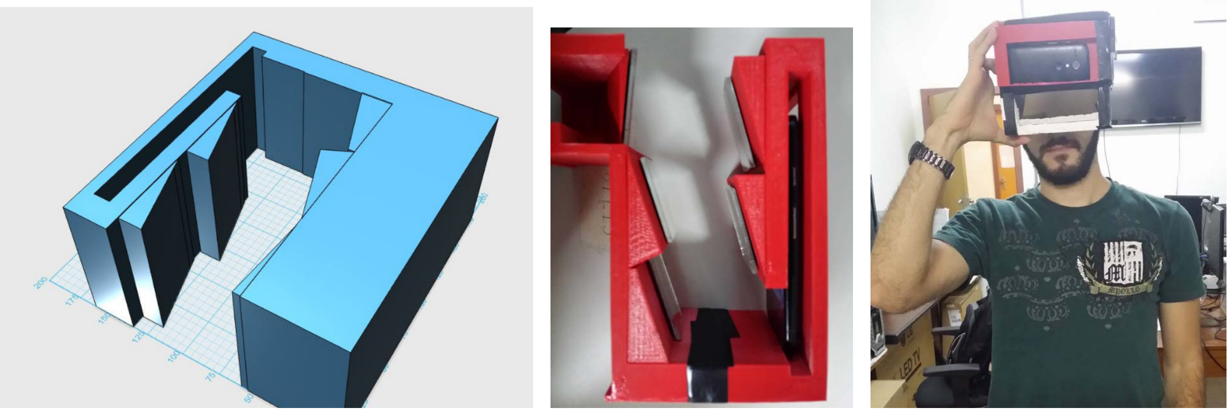

(a) 3D Model (b) Top View of 3D Printed Prototype (c) Prototype Test

Figure 4: Prototype Development and Test

(a) Image Source (b) Projected Image using Three Mirrors (c) Projected Image using Five Mirrors

Figure 5: Source Image and Projected Images Size - User View