

Towards an Augmented Reality Head Mounted Display System Providing Stereoscopic Wide Field of View for Indoor and Outdoor Environments with Interaction through the Gaze Direction

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Abstract: An Augmented Reality prototype is presented. Its hardware architecture is composed of a Head Mounted Display, a wide Field of View (FOV) stereo-vision passive system, a gaze tracker and a laptop. An associated software architecture is proposed to immerse the user in augmented environments where he/she can move freely. The system maps the unknown real-world (indoor or outdoor) environment and is localized into this map by means of binocular state-of-the-art Simultaneous Localization and Mapping techniques. It overcomes the FOV limitations of conventional augmented reality devices by using wide-angle cameras and associated algorithms. It also solves the parallax issue induced by the distinct locations of the two cameras and of the user's eyes by using Depth Image Based Rendering. An embedded gaze tracker, together with environment modeling techniques, enable gaze controlled interaction. A simple application is presented, in which a virtual object is inserted into the user's FOV and follows his/her gaze. While the targeted real time performance has not yet been achieved, the paper discusses ways to improve both frame rate and latency. Other future works are also overviewed.

1 INTRODUCTION

Nowadays, Virtual Reality (VR) is commonly used to generate realistic images of virtual environments. These images can be displayed on VR headsets in order to create an immersive experience. Besides, Augmented Reality (AR) consists in enhancing the user's current perception of reality by attaching some virtual elements to the real-world environment. AR thus requires a fine mixing of real and synthetic elements.

AR and VR can be used in several applications, such as teleconferencing, gaming, entertainment, education, medical assistance, or to help a worker to carry out his/her tasks. A review of AR applications is available in (Carmigniani et al., 2011).

AR devices mounted on headsets can be categorized as Optical See-Through Head Mounted Displays (OSTHMDs) and Video See-Through Head Mounted Displays (VSTHMDs). Their respective advantages and drawbacks can be summarized as follows:

- An OSTHMD is close to traditional spectacles, as the user sees the real environment through the transparent lenses used as a screen. A projector is

usually located within the arms, and the virtual content is displayed through a semi-transparent mirror in front of each user's eye.

- A VSTHMD consists in the assembly of an opaque screen with lenses placed in front of the user's eyes. It is equipped with cameras in charge of grabbing images of the environment. These images are augmented with virtual content, then displayed.

Current AR systems have some limitations, which prevent a comfortable experience. For instance:

- The field of view (FOV) of traditional perspective cameras is usually about 120 degrees. This is too small to map the wide human FOV (about 180 degrees in azimuth).
- The cameras and the user's eyes are not located at the same positions, resulting in different perceptions of the scene. When the cameras are aligned with the eyes and have the same inter-ocular distance (Steptoe et al., 2014), (Pankratz and Klinker, 2015), this difference can be neglected. In other

cases, it has to be taken into account so as to avoid discomfort, nausea or headaches for the user.

- The real environment has to be analyzed in order to incorporate virtual content: recognizing objects or persons, detecting scene structures as ground or walls, etc. Three-dimensional mapping can easily be achieved with active vision devices (such as Kinect) that project light onto the environment. These systems work well in indoor scenes but are subject to failure outside, due to the lighting of the sun which hinders the detection of the projected light.
- The user's head position and orientation has to be determined with respect to the scene in order to display a virtual content at the correct pose. To achieve this, additional sensors can be used (Inertial Measurement Unit (IMU) and/or motion capture systems), resulting in added complexity and cost for the system. Another possible approach is to use the images provided by the embedded cameras to estimate the user's pose, by observing specific recognizable objects (2D tags, markers or known patterns) added in the scene at known positions. Nevertheless, it is desirable to avoid the use of such dedicated targets by using detection and mapping of existing objects so as to extend the possibilities of use in unknown environments.
- The system has to satisfy strong real time constraints in order to account for the head motion. In case of AR through OSTHMD, lags are clearly perceived due to the wrong location of the virtual elements displayed over the real scene. For the VSTHMD, the whole image (real environment and virtual content) is delayed, resulting in discomfort because of the mismatch between the user's visual and inner ear systems. This discomfort is called "motion sickness" or "cybersickness". For example, the VR headset Oculus Rift has shown this side effect (Munafo et al., 2017).

Our purpose is to develop a system that addresses all these problems and is suited to both indoor and outdoor environments. Our research targets the same goal as (Keller et al., 2005), whose orthoscopic VSTHMD device addresses the parallax induced by the gap between the mounted cameras and the user's eyes. However, we propose to overcome this problem through computer image synthesis. Such methods have been used by (Saito, 2011) and (De Sorbier et al., 2010), by means of active time-of-flight sensors, while our approach relies on passive stereovision. A passive system is suggested by (Lai et al., 2016a), which emulates an HMD with different num-

ber of cameras in a synthetic scene. Our prototype can be compared with the commercially available stereoscopic Wrap 1200DXAR of Vuzix (Vuzix, 2017). However, it provides a wider field of view, a higher resolution, and works in unknown environments thanks to its integrated SLAM. It should not be compared with a VR HMD like the HTC Vive (Vive, 2017), which provides a single facing forward camera. It is closer to the future Acer Windows mixed reality headset, which is endowed with two cameras on the front side (Acer, 2017). However, the way how this commercial device handles the parallax problem (which needs to be solved as the stereo rig baseline is wider than the interocular space) is not made explicit in the product documentation. In addition, according to the product technical data, the headset seems to have a SLAM and a 3D reconstruction algorithm, but it does not include a gaze tracker. Our system also integrates some interaction abilities through the user's gaze, a problem that is addressed by devices from TobiiPro (TobiiPro, 2017).

This paper describes the current state of our project, as well as the main hardware and software components developed. It is organized as follows. In Section 2, a general description of the proposed system is presented. We argue the use of wide angle cameras and present our stereoscopic model in Section 3. The main modules of the system, *i.e.*, binocular Simultaneous Localization And Mapping (SLAM), Image Generation (IG) and Gaze Tracking (GT), are respectively described in Sections 4, 5 and 6. Finally, Section 7 presents the currently reached real time performance, and future work is introduced in Section 8.

2 OVERVIEW OF THE PROJECT AND PROTOTYPE

2.1 Proposed Hardware Architecture

The desired properties of the targeted system are depicted below.

- The system must be usable in unknown indoor/outdoor environments without requiring the deployment of additional external parts (for instance, fixed cameras or 2D tags).
- The system must be carried by the user, for instance in a backpack.
- The system must be able to display AR content in order to fill the user's FOV.
- The system must be comfortable and provide immersive visual effects.



Figure 1: Front view of the AR prototype.

- The system must enable interaction with the virtual environment through the tracking of the user's line of sight.

An OSTHMD would fit these requirements better. But due to the lack of wide FOV devices on the market, we decided to use an available VSTHMD with a 110 degrees FOV (Oculus DK2 by (Oculus, 2017)) in order to develop the proposed hardware and software modules. Importantly, the proposed solutions can be transposed to any future OSTHMD. For the same reason, as the human monocular FOV covers about 180 degrees horizontally and 130 degrees vertically, we decided to use wide FOV cameras to perceive the scene even though the used VSTHMD has a smaller FOV. A stereo-vision system composed of two synchronized 1.3 Megapixels global shutter cameras with fish-eye lenses has then been designed, providing stereoscopic 180 degrees FOV. These two cameras have been positioned on the prototype so as to be localizable on an OSTHMD, *i.e.*, at the extremities of the spectacle arms instead of beyond the user's eyes as this last option would obstruct the FOV. So, a synthetic rendering of the scene captured by these cameras must be generated and suitably displayed to the user. The synthesis of these images is performed through a process named Depth Image Based Rendering (DIBR), presented in the sequel.

Figure 1 shows a front view of the designed prototype. The VSTHMD lies in the center of the image, while two fish-eye cameras are on the sides.

To measure the user's line of sight, a custom micro camera coupled with an infrared lighting system have been designed and inserted into the HMD (Figure 2). This device measures the user's right eye position as well as its gaze direction, so that he/she can interact with the system just by gazing.

2D tags or other camera(s) fixed in the environment can be used to localize the HMD with good performance (accuracy and latency). However, for the system to work in unknown environments, we inte-

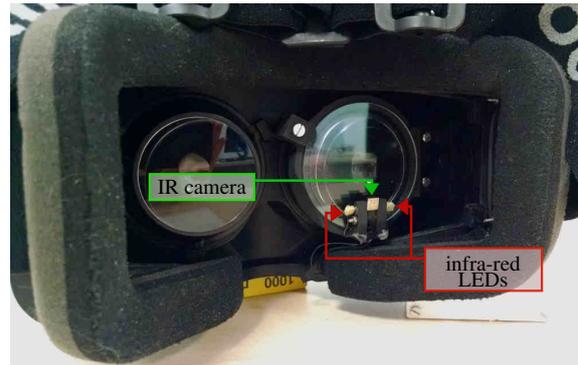


Figure 2: Back view of the AR prototype, showing the custom gaze tracker.

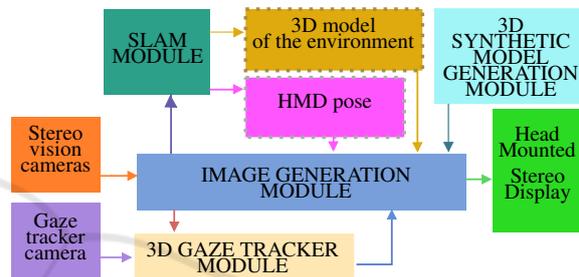


Figure 3: Block diagram of the general architecture.

grated a binocular SLAM that processes the data provided by the embedded stereoscopic sensor.

2.2 Software Architecture

Figure 3 summarizes the main components of the system together with their data flow. The Image Generation (IG) module generates the required color images and depth maps. In addition, it generates images to be used for SLAM on the basis of the simple pinhole camera projection model. It also converts images grabbed by the stereo-vision system into synthetic images suited to the viewpoint of the user's eyes. To compute synthetic data to be displayed on the HMD, this module needs the two captured stereoscopic images, the HMD pose, the model of the environment estimated by SLAM, the 3D model of the virtual object which must be superimposed on the real scene, and the 3D point of interest pointed by the user's gaze. This last 3D point is deduced from the 3D gaze computed by the Gaze Tracker (GT) module and from the depth map computed by the IG module, by means of standard stereo-correlation techniques.

The IG module is composed of two stages. First, a Depth Image Based Rendering (DIBR) algorithm converts the stereoscopic input images into images corresponding to a different viewpoint. This algorithm includes a stereo matching stage which com-

putes depth maps for both input camera images. A second stage of the IG module augments the synthesized image with the 3D synthetic model. More details are given in Section 5.

Some algorithms are available off-the-shelf under open-source licences:

- The selected SLAM implementation is ORB-SLAM2, an open-source C++ software developed by Mur-Artal et al. (Mur-Artal et al., 2015) using Oriented FAST and Rotated BRIEF (ORB) features. A great advantage of this implementation is the robustness provided by its ability to re-localize the camera.
- The stereo matching software is an open source C++ code from external contribution distributed with OpenCV 3.1.

Other algorithms have been specifically developed for our project:

- An existing monocular open-source toolbox for omni-directional camera calibration has been extended to a binocular setup (see Section 3). This allows to calibrate the wide FOV camera stereo-vision system in order to perform 3D measurements from the images.
- The Depth Image Based Rendering has been coded to generate synthetic images from various viewpoints.
- The Gaze Tracker provides the gaze direction and corresponding 3D points in the scene.

In order to easily develop and parallelize modular software, we have used the ROS (Robot Operating System) middleware.

2.3 Combined Use of DIBR and Stereo Matching

Active vision systems based on time-of-flight or structured light projection are preferred in many applications over passive stereo-vision systems because they provide depth images in poorly textured environments at a high frame rate. However, these sensors tend not to be efficient in outdoor environments. Moreover, we are not aware of any available active device that provides the requested FOV for our application. For these reasons, we chose passive stereo-vision.

We argue that the combination of DIBR and passive stereo-vision is a right choice. Stereo-vision would generate imprecise depth maps in untextured areas because the values of close pixels in the images would be similar to each other. For a near viewpoint, DIBR can use these erroneous (but close) values to generate the pixels of the synthetic images. The same

holds for repetitive textures which are likely to break down stereo-vision, as the DIBR can use patches of images that were not taken at the right locations but have the same appearance. So even when stereo-vision fails, the DIBR can generate visually acceptable images for the user.

3 STEREOSCOPIC LARGE FIELD OF VIEW FOR VSTHMD

We use a pair of fish-eye cameras to obtain stereoscopic images of the scene and to allow interaction over the full human FOV. Even if the Oculus FOV is limited to about 110 degrees, we anticipated for future HMDs which will provide wider FOV.

As a side benefit, the wide FOV cameras provide more distinguishable features for SLAM. Indeed, when dealing with locally repetitive textures or textureless areas in the environment, a SLAM using traditional small FOV cameras is likely to fail. Contrarily, wide angle cameras allow to keep track of the camera pose by exploiting features located on the borders of the FOV.

During our development, a stereo calibration software for fish-eye cameras was supposed to be available in the OpenCV open-source computer vision library but its geometric model is just an extension of the standard pinhole camera model with additional degrees of freedom to account for radial distortions. This model has proven not to be efficient for real wide angle cameras (FOV over 120 degrees). We decided to use a better fitted model proposed by (Scaramuzza et al., 2006) who open sourced OcamCalib, a Matlab toolbox for omni-directional (dioptric and catadioptric) camera calibration using this model. We have extended this toolbox to allow the calibration of stereo-vision systems.

The used model assumes that the cameras are central systems, *i.e.*, all the perceived rays intersect at a single point. The model is rotationally symmetrical with respect to the z axis. It maps a 2D point (u, v) in a virtual normalized image plane to a 3D vector P (direction of ray) through a polynomial function f as shown in Equations (1) and (2). The degree of the polynomial can be freely chosen, and a quartic equation model proved to be a good compromise as stated by Scaramuzza and measured in our own experiments.

$$P = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} u \\ v \\ f(\rho) = f(\sqrt{u^2 + v^2}) \end{bmatrix} \quad (1)$$

$$f(\rho) = a_1 + a_2\rho + a_3\rho^2 + a_4\rho^3 + a_5\rho^4 + \dots \quad (2)$$

Small misalignment between sensor, lens or mirrors are modeled using an affine 2D transformation as shown in equation (3), where (u', v') stands for the real distorted coordinates in the sensor image plane and (u, v) are ideal undistorted ones in a virtual normalized image plane.

$$\begin{bmatrix} u' \\ v' \end{bmatrix} = \begin{bmatrix} c & d \\ e & 1 \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} xc' \\ yc' \end{bmatrix} \quad (3)$$

The monocular model for the camera i is hence parameterized by the set of intrinsic parameters: $P_i = (c, d, e, xc', yc', a_1, a_2, a_3, a_4, a_5)$.

We propose to extend this model to a stereoscopic version consisting of two independent monocular models parameterized by P_i and P_j and related by a 6 dof rigid transformation modeling the translation (t vector) and rotation (r vector using Rodrigues parametrization) between the two camera frames. It allows the automatic estimation of the stereo model parameters using pairs of (synchronized) images of a standard checkerboard pattern. It first performs two individual monocular calibrations using the corresponding images. It then estimates r and t using the previously computed intrinsic parameters P_i and P_j . It finally refines the complete set of parameters using nonlinear optimization. Once these parameters are estimated, two 2D maps are pre-computed to generate pairs of epipolar rectified images. 3D points are observed to the same horizontal 2D lines in these two rectified images. This permits dense depth maps to be obtained using fast stereo-matching techniques. Figure 4 shows the different images involved in the 3D dense modeling process from the left camera point of view.

4 BINOCULAR SLAM

The Oculus DK2 comes with its own localization system. This system is composed of an IMU and a camera that has to be fixed in the environment. This camera perceives the pattern of infra-red LEDs covering the HMD and deduces the HMD relative pose, assuming the HMD stays inside its FOV. This prevents the user from moving freely in the environment. To circumvent this, we use Simultaneous Localization And Mapping (SLAM) to localize the HMD in unknown and virtually unbounded environments.

Vision based SLAM continuously enriches a 3D map of the scene and localizes a camera in this map from the images it delivers. While monocular SLAM provides the camera's poses up to an unknown scale and requires the scene to be observed from different locations to infer the 3D map, binocular SLAM is able

to estimate the scale and can integrate 3D points in the map as soon as they appear in the stereoscopic FOV of the system. Thus, we integrated the binocular ORB-SLAM2 in our system. For the moment, the camera's wide FOV is not fully exploited as ORB-SLAM2 only integrates the pinhole camera model. Hence, the generated epipolar rectified images (Figure 4 (b)) are used, covering about a 120 degrees FOV.

5 IMAGE GENERATION

5.1 Pipeline

The Image Generation (IG) module is composed of a sequence of sub-modules as shown in Figure 5. In a first stage, the epipolar rectification is performed so as to provide images to the SLAM and DIBR modules. The latter is in charge of rendering the images (and disparity maps) at the user's eyes position. The IG modules also performs simple scene analysis from the generated SLAM point cloud and augments the images with the 3D virtual content.

5.2 DIBR

The internal structure of the Depth Image Based Rendering (DIBR) module is shown in Figure 6.

- The first stage performs the stereo matching on the epipolar rectified images. We use the open-source C++ implementation of Semi Global Block Matching from OpenCV 3.1. The resulting disparity maps being noisy, a filtering is introduced, as proposed by (Kauff et al., 2007).
- The second stage is in charge of 3D warping, *i.e.*, the projection of images and depth maps on synthetic cameras at distinct poses. To this aim, a 3D point cloud is generated from the depth maps pixels. These points are then rotated, translated and projected to the synthetic cameras so as to render corresponding synthetic images and depth maps. Small holes are generated in the rendered images for multiple reasons: there is no one-to-one pixel correspondence between the input and generated images; the change of viewpoint requires to render parts of the scene that were not observed in the input image. We partially solve this problem by using the image content from the two cameras in order to render each synthetic images, *i.e.*, the two 3D point clouds are virtually projected to each of the two synthetic cameras using **stereo** 3D warping. The remaining holes are removed in the two next stages of the pipeline.

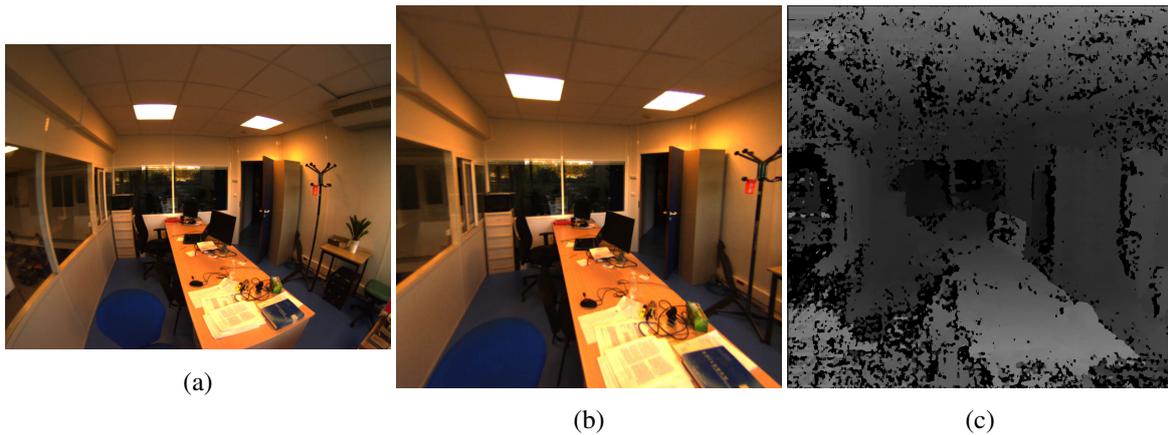


Figure 4: (a) an image captured from one camera, (b) the corresponding epipolar rectified image and (c) the computed disparity map (the closer areas appear brighter, and completely black regions correspond to undetermined disparity, for instance because of lack of texture).

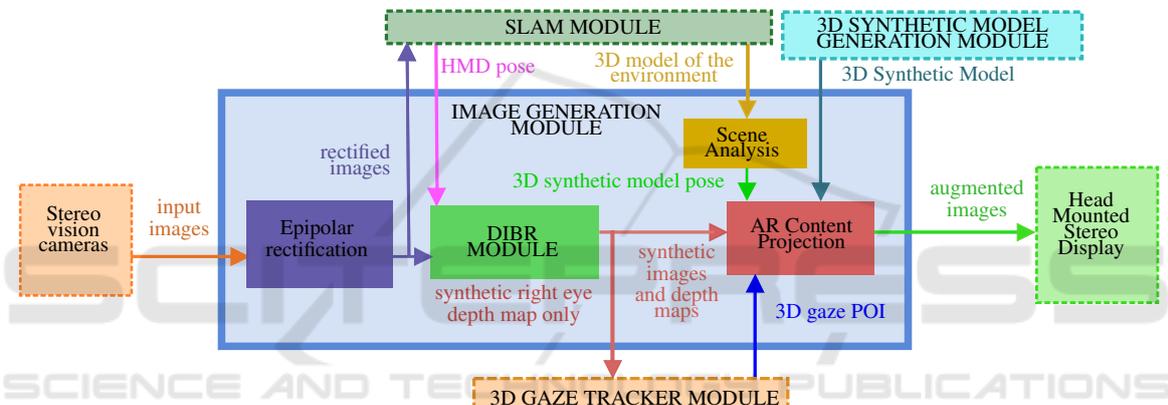


Figure 5: Image Generation block diagram.

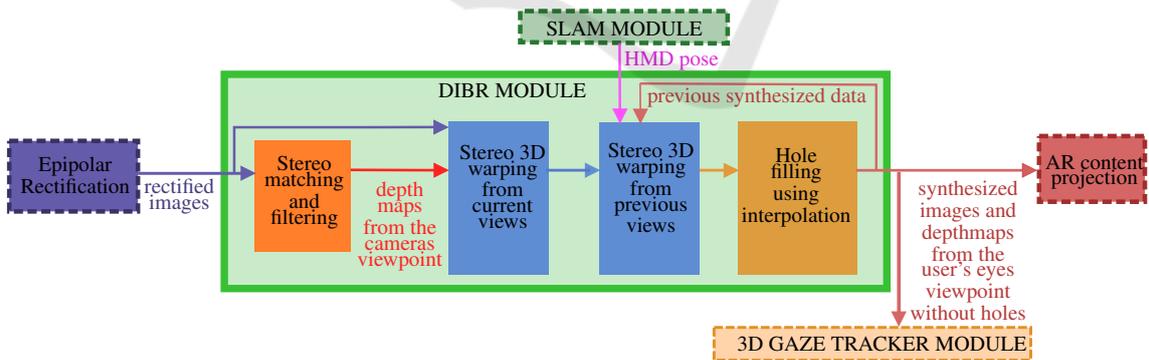


Figure 6: DIBR block diagram.

- The third stage carries out another 3D warping to enrich the view, considering the 3D point cloud built at the previous iteration and the motion between the two point clouds obtained from the SLAM module. This allows to use some image content that may not be visible anymore in the input stereoscopic images and to increase the temporal consistency of the generated images.
- The final stage fills the remaining holes by interpolation for depth maps and images. Bilinear interpolation is used to fill holes of the depth maps, even if this tends to soften the object contours.

An example of DIBR rendered image using our pipeline is shown in Figure 7.

5.3 Scene Analysis

The surrounding environment is incrementally modeled by a 3D point cloud using SLAM while the user is moving. This 3D model is analyzed in order to detect geometric structures and to determine suitable areas where to add the virtual content. For the moment, we have implemented a simple robust plane estimation from the 3D point cloud in order to position moving 3D models onto it, as shown in Figure 8. More complex processing could be considered, *e.g.*, the detection and skeleton fitting of an human to augment him/her with virtual clothes.

5.4 AR Content Projection

Conventional OpenGL projection of textured 3D meshed models is performed to get augmented stereoscopic images. The rendering is done using the Oculus DK2 Software Development Kit which generates suitable camera projections for the two eyes. The SDK also provides a shader program to process the rendered images in order to take into account the chromatic aberrations caused by the low-cost optical system of the device. The synthetic images generated by the DIBR module are used as background while the synthetic depth maps serve to initialize the Z-buffer. As the OpenGL rendering cameras rely on the same geometric models as those of the DIBR, the 3D objects are easily rendered and integrated inside the real environment. The Z-buffer test determines for each rendered pixel whether it is occluded or not by the real scene.

Figure 8 shows an augmented stereoscopic image generated by our system, as displayed in the HMD. The rendering stage is able to take into account the user's gaze direction computed by the 3D GT module in order to interact with the augmented elements, as shown in the following section.

6 GAZE TRACKER AND INTERACTION

Our custom gaze tracker fits inside the HMD restricted space. Its hardware elements are a micro camera endowed with an infra-red (IR) bandpass filter and two IR LEDs. A two-eye gaze tracker could provide the 3D location in the scene of the Point Of Interest (POI) observed by the user, by intersecting the left and right gaze directions. However, we have chosen a single-eye gaze tracker to minimize the number of hardware elements to integrate, and because we use the information provided by the stereo-vision system

to assess the POI as explained later. Our solution is visible in Figure 2. The eye is illuminated by the IR LEDs and observed by the camera. Thanks to the IR filter, the camera is not disturbed by the light emitted by the display. The resulting hardware requires just a few millimeters and does not obstruct the FOV of the user, hence this architecture could also be used inside an OSTHMD.

The GT software module is composed of two main parts that process the images from the gaze tracker camera: the first fits an ellipse on the pupil contour and the second deduces the gaze direction from the pupil center (u_{pc}, v_{pc}) . For the gaze direction estimation, we use a polynomial model to compute the pixel (u_s, v_s) on the scene camera where the eye is directed to (see equations 4 and 5). Our method for the pupil detection and gaze estimation is similar to that of (Kassner et al., 2014).

$$\begin{bmatrix} u_s \\ v_s \end{bmatrix} = \begin{bmatrix} f_1(u_{pc}, v_{pc}) \\ f_2(u_{pc}, v_{pc}) \end{bmatrix} \quad (4)$$

$$\begin{aligned} f_i(u_{pc}, v_{pc}) &= a_{i1} + a_{i2}u_{pc} + a_{i3}v_{pc} \\ &+ a_{i4}u_{pc}^2 + a_{i5}v_{pc}^2 + a_{i6}u_{pc}v_{pc} \end{aligned} \quad (5)$$

A calibration must be conducted in order to estimate the parameters (a_{11}, \dots, a_{16}) and (a_{21}, \dots, a_{26}) . In this preliminary stage, the user must successively look towards nine points homogeneously distributed on the screen. This calibration has to be done each time the user wears again the HMD.

Once this calibration is achieved, our system is able to compute in real time the gazed 3D POI. As shown in Figure 5, the DIBR module provides the GT module with a synthetic disparity map corresponding to the user's right eye location. The POI is computed by intersecting the 3D gaze direction and this disparity map. Using this POI, the user is able to interact with the system. For instance, we have implemented a simple application where the user's gaze defines the position of an inlaid 3D model of a penguin. This penguin, rendered in Figure 8, moves according to the user's gaze along the top surface of a desk, whose geometry is estimated from the depth maps and the sparse 3D model computed by SLAM.

7 RESULTS AND REAL TIME CONCERNS

7.1 Real Time Concerns

Strong real time constraints are imposed on the system so as to avoid the user's discomfort when his/her

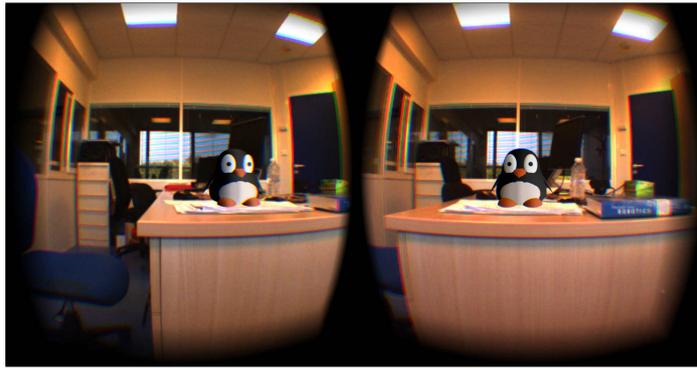


Figure 8: Augmented stereoscopic images displayed in the HMD.

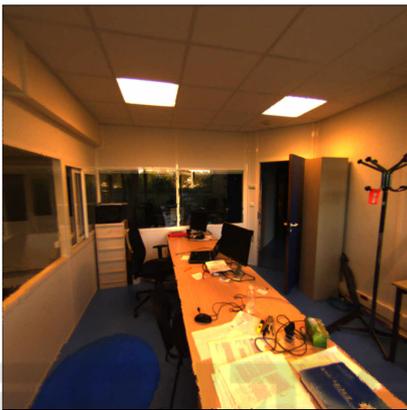


Figure 7: Image synthesized from Figure 4 (b) by DIBR.

visual and inner ear systems provide inconsistent pose estimations due to lag in the displayed images. Frame rate and latency are common constraints for gaming applications using HMD. The (Oculus, 2017) company suggests at least 70 FPS for the Oculus DK2. The required frame rate depends on the application. For virtual environments in HMD, (Chen and Thropp, 2007) advises a minimum threshold of 17.5 Hz. For applications involving fast motions, a high frame rate is mandatory. Claypool et al. (Claypool et al., 2006) describe the frame rate impact on user perception and gamer performance. The latency between the HMD's motion and the display of the images must also be limited so as not to be perceptible. Ref. (Adelstein et al., 2003) claims that it should not be higher than 17 ms.

Early encouraging results of the complete prototype have been demonstrated through the simple augmentation example presented above. Though the generated images are acceptable in static scenarios, the achieved FPS is far too low for now to enable a real interaction. The achieved FPS for the demonstrated penguin complete application is slightly below 1 FPS for the current version of the system. The corresponding latency is over 1 second, clearly above

acceptable values. The used laptop computer embeds an Intel Core i7-4800MQ octocore CPU running at 2.70GHz and a Quadro K1100M/PCIe/SSE2 graphic chipset.

The profiling of individual modules has led to the following conclusions:

- The duration of epipolar rectification can be neglected, as this process only involves bilinear interpolation for pixels locations stored in precomputed tables.
- Binocular SLAM is used on half resolution images (540x540 pixels) with a maximum limit of 1000 detected and tracked features. The maximum attainable frequency for SLAM alone is about 13 FPS when 3 CPU cores are involved. As the display is done at 60 FPS, a pose computed by SLAM must thus be used several times by the IG module.
- The IG stage is relatively time consuming. The entailed OpenCV Semi Global Block Matching CPU implementation itself requires nearly one second for one CPU core to correlate the images. The stereo 3D warping, hole filling and implemented scene analysis (consisting in simple robust plane fitting) stages require negligible time in comparison. The projection of AR content being done by the GPU and the projected model being composed of just a few hundred of textured triangles, its is achieved at high FPS. However, the required time to transfer the background images and depth maps appears to be a bottleneck.
- The GT module involves quite simple computations. So, it can be run at more than 50 FPS on a single CPU core. However, it is limited by the embedded camera rate of 30 FPS.

7.2 Results

In addition to the penguin interaction, we conduct a simple application to evaluate the impact of the

VSTHMD on the 3D environment perception. The idea is to check if the user sees the 3D synthetic objects at the location where they should be. If the user does not wear an HMD, he/she is able to point out a target point in the scene after closing his/her eyes. We first conduct an experiment without HMD: the user seated at a desk looks at a tag on the desk, closes his/her eyes and puts another tag on the remembered first tag location. This step is repeated for different tag locations. Both tags are localized by a camera with the AprilTags library (Olson, 2011) to compute the distance between them. This distance indicates the perception error. As a result, the target point can be found with a RMSE (Root Mean Square Error) of 1.84 cm. Then, to evaluate the 3D perception, this principle is tested when the user sees the environment through the HMD.

The procedure is the following. A checkerboard is displayed through the Oculus on a plane detected in the scene (a desk in our experiment). Successively different checkerboard squares light up to interact with the user seated at the desk. He/She has to look carefully at the scene seen through the Oculus and must remember where the lit up square is. Then he/she closes his/her eyes and puts a tag at the remembered square location. The stereo bench on the Oculus detects tags. This experiment is done twice: without DIBR, therefore the images from the stereo bench are directly displayed in the HMD; and with DIBR, therefore the displayed images are synthesized at the eye position.

It is important for the user to close his/her eyes while he/she moves his/her hand to put the tag on the square. If the user sees his/her hand, he/she will automatically correct his/her movement even if the perception through the VSTHMD is wrong.

As a result, when the user wears the HMD, he/she is able to find the square location with a RMSE of 4.42 cm without DIBR and 3.13 cm with DIBR. Both experiments have been repeated 55 times for different squares locations. The figure 9 details the results.

A rather similar experiment has been developed independently, and published in a recent paper (Lai et al., 2016b). In this paper, the user has to position a cube on three distinct locations. To manage this task, he/she has to remember the target position and close his/her eyes during his/her hand movement, as we did.

8 FUTURE WORK

Our future works will primarily focus on reaching real-time performance, but other aspects will also be investigated:

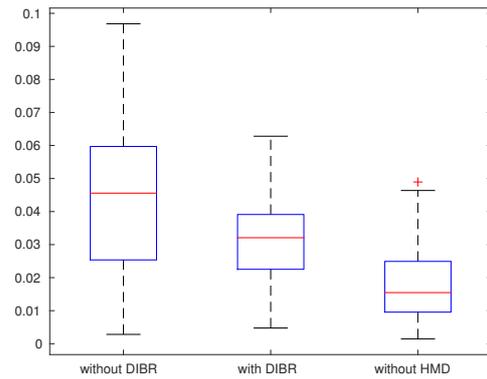


Figure 9: Perception error in meter for 3 experiments: from left to right, results without DIBR, results with DIBR and results without HMD.

- The algorithms have not been fully parallelized in order to efficiently use the multi-core architecture of the computer. Real time stereo matching algorithms such as the one proposed by (Atzpadin et al., 2004) could be used to drastically reduce the computation time. Some of the algorithms could also be ported to the GPU side to better use this computing resource, in the vein of the DIBR (Lai et al., 2016b). Even dedicated hardware (like FPGA) could be envisaged to run the most demanding tasks. The whole IG module, which mainly runs on the CPU, would benefit from a GPU implementation, as it only involves computations on geometry and images. As speedup factors greater than 30x are often observed for such problems, therefore our goal appears within reach.
- In order to reduce the latency of the system, a predictive algorithm could be introduced. For instance, the integration of a motion model for the HMD allows to predict its next pose and hence the two user's eyes location as shown in Figure 3. While the current implementation assumes a static model, an enriched HMD motion model could be supplied with high frequency measurements from an attached IMU so as to assess the pose at higher rate than with SLAM alone. Our DIBR system could easily make use of this information to generate the displayed images from the predicted viewpoints instead of the lagged ones, taking into account that the HMD moves between the capture of the images by the stereo-vision system and the display of the generated images.
- The quality of the DIBR can be improved through the use of a richer model for the scene (instead of the 3D point cloud).
- For now, ORB-SLAM2 is fed with synthetic images generated with the pinhole camera model. In

the future, we plan to integrate the camera model (Scaramuzza et al., 2006) into the binocular implementation of ORB-SLAM2. This way, we will be able to use the full FOV of the cameras instead of the currently limited 120 degrees FOV involved by the pinhole camera model. Thus more features will be visible, and the SLAM robustness to locally poorly textured environments will be increased.

- The stereo-vision cameras of our prototype are held together with a carbon fiber tube and 3D printed supports. Because of the unavoidable mechanical detuning of the stereo rig that happens even when the bench is held statically, *e.g.* due to ambient temperature changes, the system has to be re-calibrated regularly. This time consuming operation could be avoided if an on-line calibration was available. This requires to improve the Real Wide FOV binocular SLAM module through the integration of the stereo-vision wide FOV model intrinsic and extrinsic parameters in the estimation process.
- Our final objective is the integration of an OSTHMD. So, our work will be tested on such a device as soon as the hardware is available.

9 CONCLUSIONS

This paper has presented our original VSTHMD integrated system, which consists of multiple hardware and software modules. It provides a wide FOV (hemispheric for the sensing part and 110 degrees for the display part). It enables indoor and outdoor operation, as well as interaction through the user's gaze direction. The contributions are listed below:

- The FOV limitations on existing systems have been addressed. The two wide FOV cameras mounted on our HMD overcome the human FOV. This enables scene analysis, user interaction, and image augmentation at any location inside the FOV. A general stereoscopic calibration tool has been developed for this stereoscopic wide FOV system. One of the widest FOV VRHMD currently available on the market has been used, but the proposed solution can be adapted to future OSTHMD providing wider FOV.
- A binocular state-of-the-art implementation of SLAM has been successfully integrated to our system so as to enable 6-dof localization and AR content display in unknown environments.
- A complete original Image Generation pipeline using passive stereo-vision has been proposed. It

allows to generate stereoscopic augmented images from different viewpoints on the basis of images grabbed by the wide FOV stereo-vision system, thanks to our custom multiple-step DIBR. As passive stereo-vision is used, the proposed approach is applicable to outdoor environments, where conventional depth sensors tend to fail.

- A compact gaze tracker design has been proposed and its integration inside the HMD has been proved to enable simple user interaction.

The system has been demonstrated on a simple example application. However, it has not yet reached real time constraints required by this kind of human interaction. Possible future improvements that should reduce the computation time and increase the usable FOV have been discussed, and will be investigated. Recent independent achievements in the literature will be taken into account, such as the VSTHMD built in (Lai et al., 2016b) which includes a stereo bench and a depth sensor, and features a GPU implementation of a DIBR algorithm at 60 fps on a Nvidia GTX980. As the FOV and performances of OSTHMD increase, some elements of the software architecture will be later ported to these new devices, *e.g.*, the Meta 2 (Meta, 2017).

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