

A Virtual and Augmented Reality Course Based on Inexpensive Interaction Devices and Displays

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Abstract

In the last years a plethora of affordable displays, sensors, and interaction devices has reached the market, fostering the application of Virtual and Augmented Reality to many new situations. Yet, creating such applications requires a good understanding of the field and specific technical skills typically not provided by current Computer Science and Engineering education. This paper presents a graduate level course offered to MSc. Programs in Computer and Electrical Engineering which introduces the main concepts, techniques and tools in Virtual and Augmented Reality. The aim is to provide students with enough background to understand, design, implement and test such applications. The course organization, the main issues addressed and bibliography, the sensors, interaction devices and displays used, and a sample of the practical projects are briefly described. Major issues are discussed and conclusions are drawn.

Categories and Subject Descriptors (according to ACM CCS): K.3.2 [Computers and Education]: Computer and Information Science Education—Computer Science Education; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual and Augmented Reality

1. Introduction

Virtual Reality (VR) and Augmented Reality (AR) have currently a broad range of applications in entertainment, industry, medicine or marketing, among others, and never before has the technology been so affordable. As a consequence, a rapid growth of VR and AR use in those and other application areas is to be expected. Yet, developing such applications requires an understanding of the field and specific technical skills typically not provided by current Computer Science and Engineering education, even if VR as well as AR courses are considered natural complements to Computer Graphics education [Zar06].

This paper describes the main features of an elective, one-semester, graduate level course on Virtual and Augmented Reality offered twice at the University of Aveiro, simultaneously to MSc. Computer and Electrical Engineering students: in the first semester of 2013/14 to 17 students and in 2014/15 to 16 students. While presenting the topics addressed and the main bibliography, the emphasis is on the computer lab equipment and the practical projects.

The rest of the paper is organized as follows: section 2 addresses related work concerning VR in education and education in VR; section 3 briefly presents the course organization, topics addressed, and main bibliography; section 4 describes the hardware and software used for demos as well as practical projects; section 5 describes examples of successful student projects; issues, conclusions and ideas to improve future editions of the course are presented in section 6.

2. Related work

Virtual Reality has been shown to have the potential to enhance education [Ded09, DB09], and inexpensive sensors, displays and interaction devices have been used in education and training in various ways. Several authors describe how they have been taking advantage of current affordable VR technology to improve the education of Computer Science and Engineering students at their own institutions [Ci08, CRC*09, AAW11, SCPI3, HA14], in what circumstances VR should be used in education and training in general [Pan09], and how to use VR to create knowledge and solve complex problems in a group framework

[MUH10]. On the other hand, Augmented Reality is also considered as offering promising perspectives for Science education [DB09]. A study involving Computer Science, Information Systems, and Design students [SCP13] suggests that the participants were motivated and interested in developing AR systems, mainly for entertainment, using desktop and Android platforms; nevertheless, the complexity of programming languages and system architectures were viewed as challenging.

While Virtual and Augmented Reality being considered as promising tools in education is an interesting motivation to use them with students, we focus on how to include these technologies in the curriculum of the Computer and Electrical Engineering programs we offer; yet, we found not as many papers on this subject. Actually, this may reflect a relative scarcity of specific courses, and possible reasons might be the little room available for additional topics in current curricula, as well as a lack of faculty expertise and adequate equipment [Cli08].

G. Burdea, the coauthor of one of the first textbooks meant to support a VR course, made an informal world-wide survey (updated in 2008, <http://vrtechnology.org/resources/public/survey.html>) and concluded that as of 2004 the vast majority of universities offered no such courses and suggested that the cost of adequate laboratories might be an important reason [Bur04]. Yet, according to this author, even then that should no longer have been the case, since VR technology had evolved dramatically in the previous years entailing an increase in performance and a decrease in prices. A fortiori, at present this should not preclude offering courses in the field as a variety of low cost sensors, interaction devices and displays has reached the market, and a computer lab to adequately support VR/AR courses may have a cost affordable to most universities.

Meanwhile, several authors have described the VR/AR courses they lecture and offer advice on how to organize such courses, albeit having different approaches. We briefly mention the ones that have been more useful to design our own course.

Stansfield [Sta05] presents an elective course offered to Computer Science students having already some Computer Graphics background. The course is aimed at providing an introduction to Virtual Reality, as well as an opportunity to incorporate capstone elements that allow undergraduate students to apply many computing skills they have acquired in other courses. The course includes a lecture-based component and a hands-on experimental component. The latter component is an on-going, semester-long team project, based on an open software platform developed at Sandia National Laboratories, as well as on a software platform developed in-house. According to the author, demos of some of the more traditional display devices (such as a CAVE) are valuable. During their project teams build a complete

VR system having access to specific Virtual Reality H/W, as head-mounted displays and trackers.

Zara [Zar06] describes a course mainly based on VRML for students having already a background in Computer Graphics (CG). He contends that VR education fosters a better understanding of real-time 3D graphics and the trade-offs between image quality and rendering speed. Students' projects evolve from simple 3D scenes to complex, interactive virtual environments. Most students attending this course rated its usefulness high and its difficulty as medium; however, a strong negative correlation between the perceived difficulty and the students' CG background was observed, suggesting that a VR course may be viewed as a natural extension to CG education, as the author claims.

Cliburn [Cli06] integrates Virtual Reality concepts at the end of the introductory Computer Graphics course, and his students develop simple VR applications as a final practical project based on an in-house toolkit for multi-monitor graphics programming. According to the author, these projects were "immersive, interactive, and certainly imaginative, satisfying Burdea and Coiffet's three I's of virtual reality" and "contained a virtual world, immersion, sensory feedback, and interactivity, fulfilling Sherman and Craig's definition as well".

Häfner et al. [HHO13] describe how they teach a practical course in Virtual Reality for graduate and undergraduate students in diverse engineering fields (namely, mechanics, mechatronics and electrical engineering, computer sciences, physics and engineering management) combining lectures, demos, and practical classes. The course is based on state-of-the-art hardware and software, yet it also gives students the possibility to work with low-cost equipment. The authors started by using 3DVIA Virtools (<http://www.3dvia.com/products/3dvia-virtools>) as software platform, having as main advantages the documentation and a visual programming paradigm; however, there was no large users community, manual configuration of VR hardware was complex, and the costs for licenses were high. Eventually, they developed their own VR engine. The course is focused on fostering learning about VR by simulating interdisciplinary industrial projects and students' projects are developed by multidisciplinary teams. According to the authors, the most important factors for the course success are a careful design of the students' projects; a group configuration and task assignment according to the students' background; using an open source, well documented, and actively used software platform; and (last but not least) updating lectures and labs to keep the students motivated.

Our course was designed to be adapted to the context of our department educational offer and taking into account the experience presented by these authors. It was designed to be attended by last year Computer Engineering and Electrical Engineering graduation students, which implies starting by an introduction to Computer Graphics to ensure a min-

imum understanding by the latter. Students were given the possibility to propose their own projects (e.g., related to their MSc. dissertation). The course was also planned to make use of recent and affordable VR equipment, as well as open-source simple software (no complex and difficult to setup frameworks), the goal being not just modeling but actually understanding the whole process necessary to create a virtual environment.

3. Course organization, topics, and bibliography

The course is organized in 14 three-hour weekly sessions, each session typically comprising a lecture, a demo, a paper presentation by a student, and a lab class. In this section we briefly describe the topics addressed in the lectures and lab classes, as well as the main bibliography.

Slides and further material concerning the practical projects may be found at the course web page: <http://sweet.ua.pt/bss/disciplinas/RVA/RVA-home.htm>

3.1. Topics addressed

As the course is offered to last year students of the Computer Engineering MSc. (CE) and the Electrical Engineering MSc. (EE), who have different backgrounds and programming skills, some homogenization is needed, namely concerning Computer Graphics fundamentals and graphics programming libraries, which are new to EE students and may work as a recapitulation for EC students providing an opportunity to better understand basic concepts.

The main topics addressed in the lectures are:

- Introduction to VR and AR, historical perspective, overview of the main issues, applications and challenges;
- Rendering the virtual world;
- Physical modeling of the virtual world;
- Frameworks;
- Input and output devices;
- Camera models and calibration;
- User-centered design; interaction in VR/AR;
- Human factors; guidelines for VR/AR applications.

The computer lab classes are divided in two main blocks. The sessions in the first half-semester focus on 3D creation, visualization and interaction with virtual worlds using VTK as the main graphics engine. The remaining lab sessions deal with Augmented Reality: first an introduction to camera calibration, a central problem in AR, is done using OpenCV and teaching students the basics of camera calibration using a chessboard pattern. Then the ARToolKit (<http://www.hitl.washington.edu/artoolkit/>) is introduced to provide contact with an AR application. In the last session, the ARToolKit is adapted to run with VTK: with such an update students can develop AR applications without the need to learn an additional graphics engine.

VTK was chosen as the main graphics engine, despite

some limitations when compared with other engines such as OGRE, OpenSceneGraph or the more recent Unity, due to its flexibility and large range of application in visualization. However, VTK does present some limitations, namely regarding multiple texturing, creating difficulties when students try to generate more complex 3D worlds.

3.2. Main bibliography

One of the difficulties in offering a VR/AR course is the bibliography. While there are some books which are very useful to help define a course structure and support the history, principles and guidelines that should be addressed, VR/AR science and technology is rapidly evolving and every year new trends and devices appear, thus a constant update is needed. To stay current, we have been relying on conference and journal papers, as well as vendor sites for the technical features of new hardware.

The following books were used as main bibliography:

- Grigore Burdea and Philippe Coiffet, *Virtual Reality Technology*, 2nd ed., Wiley-Interscience, 2003.
- Doug Bowman, Ernst Kruijff, Joseph LaViola Jr. and Ivan Poupyrev, *3D User Interfaces, Theory and Practice*, Addison Wesley, 2005.
- Alan Craig, William Sherman and Jeffrey Will, *Developing Virtual Reality Applications, Foundations of Effective Design*, Morgan Kaufmann, 2009.
- Alan Craig, *Understanding Augmented Reality, Concepts and Applications*, Morgan Kaufmann, 2013.
- Mario Gutiérrez, Frederic Vexo and Daniel Thalmann, *Stepping into Virtual Reality*, Springer, 2008.
- John Vince, *Introduction to Virtual Reality*, Springer, 2004.
- Borko Furht (ed.), *Handbook of Augmented Reality*, Springer, 2011.
- William Schroeder et al., *The VTK User's Guide*, 11th ed., Kitware inc., 2010.
- Gary Bradsky and Adrian Kaehler, *Learning OpenCV*, O'Reilly, 2008.

The books by Burdea and Coiffet, and Bowman et al. have been used to structure the course and are recommended as the main bibliographic references for the topics addressed in the lectures. The book by Craig et al. approaches Virtual Reality mainly from the point of view of the design and implementation of applications and includes interesting in-depth application case studies. The book by Craig presents fundamental concepts in the design of applications, mainly addressing AR as a medium and is recommended as an introduction to Augmented Reality. The books by Gutiérrez et al., and Vince are suggested as introductory references to Virtual Reality, since they provide an easy to read motivating overview of the field. The books by Schroeder et al. and by Bradsky and Kaehler have been used as references for specific topics and examples used in lab classes. The hand-

book edited by Furht addresses technologies and applications and its chapter 1 is recommended as a brief outline of Augmented Reality issues, applications, and challenges.

The proceedings of the IEEE Virtual Reality (IEEE VR) conference, the IEEE Symposium on 3D User Interfaces (IEEE 3DUI) and the International Symposium on Mixed and Augmented Reality (IEEE ISMAR) have been providing most of the papers for student presentations. These presentations ensure that students have access to cutting edge research work, since they have to select and propose the papers they are interested in reading and presenting to the class.

4. Hardware and software

The course has a hands-on approach and thus it must be supported by a suitable computer lab.

The lab classes, demos and projects were based on a set of (mostly inexpensive) sensors, displays and interaction devices we have been acquiring over the past years; they are presented according to their pricing (more expensive to less expensive):

- VR2000 HMD (<http://www.vrealities.com>)
- Intersense Inertia 3 and Inertia Cube BT orientation sensor (<http://www.intersense.com>)
- Oculus Rift, version 1 and 2 (<http://www.oculus.com>)
- Microsoft Kinect version 1 and 2 (<http://www.microsoft.com/en-us/kinectforwindows/>)
- Razer Hydra (<http://sixsense.com/razerhydra>)
- Leap Motion (<http://www.leapmotion.com>)
- Nintendo Wiimote
- Google Cardboard (<http://cardboard.withgoogle.com>)

The lab set-up cost, including the latest version of each device, is about EUR 3 500. However, it is interesting to note that most of the budget was used to buy the less recent equipment (VR2000, Intersense). The latest devices — Microsoft Kinect, Google Cardboard, Oculus Rift, Razer Hydra, and Leap Motion — all together cost less than EUR 1 000, a cost we deem very reasonable to set up a lab allowing the development of a wide range of motivating and instructive applications.

Given the limited number of some devices — for instance, three Microsoft Kinect and two Oculus Rift devices were available, and given that some devices have similar features, namely two 3 DOF inertial trackers (Intersense and Intersense BT), and two 6 DOF magnetic trackers (Razer and Wintracker), the project proposals took in consideration the available equipment to maximize use and minimize superposition. The few cases of multiple groups sharing the same device were solved by assigning the devices to the students and let them organize their use.

Usually, in academic contexts, paying for the software licenses to develop VR and AR applications is problematic

and thus the course lab classes and programming projects are based on free, open-source software, namely VTK, OpenCV, and the ARToolKit, available freely for non-commercial use, the main disadvantage of this approach being the relatively reduced documentation available and the lack of support for more complex or recent devices [Bur04], which make the final projects more challenging.

5. Examples of successful projects

A set of projects were developed to help students acquire the understanding and the specific technical skills needed to create VR/AR applications. In the following, the reasoning behind the projects is briefly explained.

Along the course, students (organized in groups of two) have to carry out two projects. The first project is related to Computer Graphics and virtual world creation and modeling. The goal of the second project is to motivate the use of the available input/output devices in order to create engaging VR/AR applications, with a focus on the user interaction with the virtual environment. Whenever possible, students are encouraged to regard the second project as an extension of the work done in the scope of the first one. A different list of possible projects is provided each semester; however, students may propose their own work, for instance related to their MSc. dissertation.

In the first projects students are supposed to consolidate the issues addressed in the first lab sessions. Given their diverse background, students may have different knowledge and skills; for instance, Computer Engineering students have already attended a Visual Computing course based on OpenGL and OpenCV. The use of VTK allows introducing a different library and revisiting the main CG topics necessary to handle a virtual world. Thus, the first project reintroduces the main CG concepts while guiding the use of VTK. After attending those computer lab sessions and submitting the first project, students should be familiar with: 3D transformations, camera and lighting control, object and illumination properties, rendering options, and textures. Some time is also dedicated to interaction in 3D, through the use of callbacks and widgets. Manipulation of polygonal meshes and cutting/clipping operations are also addressed. Students are also introduced to other kinds of 3D data representations (e.g., unstructured grids, 3D volumetric grids).

The second project is less guided and implies selecting the interaction techniques to be used, as well as the most adequate devices, and then analysing and integrating the devices to enhance the interaction with the virtual environment.

Some examples of project proposals are the configuration of a virtual environment (3D immersive scenarios/games or visits), the visualization of several datasets (3D Skulls, atmospheric data, boreholes and seismic data, sound reflections in a room). Some projects were more interaction oriented, for example, the interaction with objects in virtual environments

or the use of natural markers to create an AR demo to publicize our department.

Some of the more successful projects developed in the past two years are presented next.

Quick 3D modeling of simple rooms from 2D floor plans

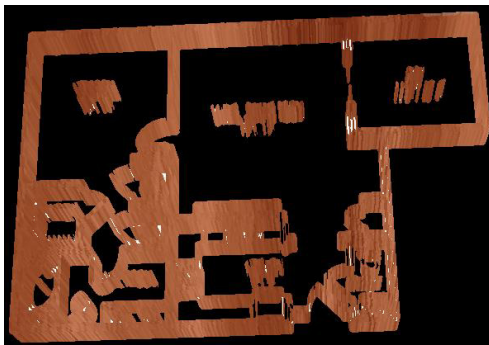
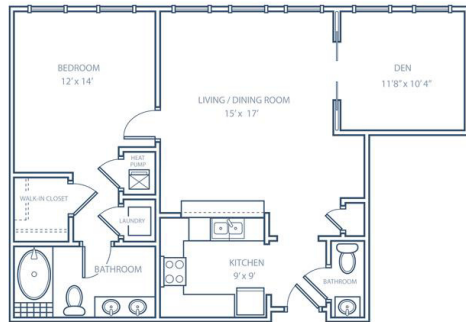


Figure 1: Original 2D floor plan and extruded 3D model.

The goal of this project was to produce an application for quick 3D modeling from 2D floor plans. The work involved some simple image processing, namely an edge detector that was implemented in VTK. The results of the edge detection were extruded in order to create a 3D representation with a given height. The application also allowed refining the edge detection results by changing the edge detector thresholds in real time. Finally, a texture was applied to the final 3D extruded model, as seen in Figure 1 with a 2D house plan as input.

Interactive 3D environment for music creation and playing

This project involved the development of a 3D world with several 3D widgets that can be used for music creation/modulation. The created environment allowed the activation of several instruments and corresponding soundtracks while interacting with 3D widgets. Some 3D models of music instruments freely available on the Web in different formats were integrated. Also, several frames with



Figure 2: Guitar and radio in the virtual environment. Clicking on a frame triggers the flying CD animation.

posters from music artists were placed on the walls (see Figure 2). Users could freely select instruments to reproduce some sounds. Alternatively, the selection of a frame would trigger the animation of a flying CD towards a radio and the following streaming of a music from the selected artist. The 3D world and interaction were based on VTK, and FMOD (<http://www.fmod.org>) was used for sound streaming.

3D visualization software for the robot soccer team CAMBADA

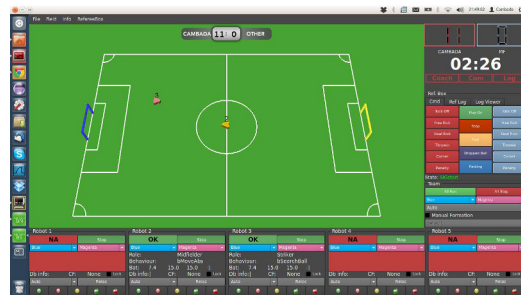


Figure 3: 3D robotic soccer console with a 3D visualization of the field.

One of the students of the 2013/2014 edition was a member of the robotic soccer team of the University of Aveiro – CAMBADA (Cooperative Autonomous Mobile robots with Advanced Distributed Architecture). He wished to create 3D visualization software that might be integrated within the current team console to replace the 2D view being used. The first project focused on the visualization (Figure 3). Besides displaying the field and robots, it might be used later during games to display additional information for debugging (such as heat maps with the results of algorithms running on the agents).

The work was further developed in the second project to allow an Augmented Reality module based on the ARToolKit and VTK. With this module the user can interact with the world by pointing a camera to a marker (see Figure 4) and test interactively the algorithms running on the robotic agents. The optical center of the camera can be used



Figure 4: AR interaction with the CAMBADA console interface.

as a pointer for data input (e.g., the 2D location of another robot).

Virtual interaction with a real environment

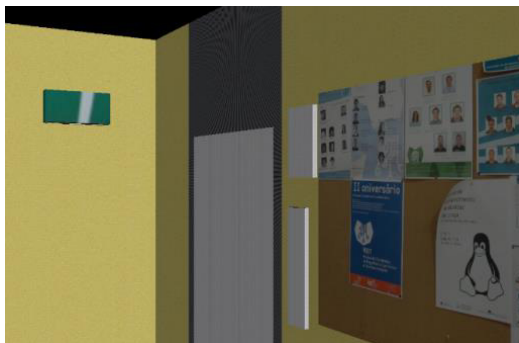


Figure 5: 3D model of a section of our department.

This project was aimed at evaluating the possibility of using a Kinect, an HMD (VR2000), and an orientation sensor to detect the position of a user in a real environment and allow him/her to move in a 3D enhanced replica of the environment. As an example, a section of a corridor of our department was modeled using SketchUp (<http://www.sketchup.com>) and texture mapped with real photographs (see Figure 5).

In addition to modeling, students developed a communications module with the Kinect. In the final demo, a user can move freely in the modeled section of the corridor, while seeing the 3D replica of the corridor in the HMD. The camera orientation was mapped using the InertiaCube BT orientation sensor, and user head position was given by the

skeleton tracking algorithm of the Kinect. A future evolution of this work, with several Kinects (to enlarge the tracking space) might be used to allow moving in a real environment while exploring an enhanced version of the room (for instance, a virtual enhanced museum, mapping the geometry of a real room).

Augmented promotional material of our department



Figure 6: IEETA building on a natural marker.

This project adapted AR examples based on the AR-ToolKit to allow an AR visualization of buildings using a natural marker (see Figure 6). In a first stage, the students modified the ARToolKit to allow the mapping of VTK models (instead of OpenGL) using several models developed in the first projects. The second part of the work involved image processing to replace the AR marker by a natural marker (the image of a department flyer). Some experiments were done using OpenCV for camera calibration and marker detection; however the achieved refresh rates were slow for real use.

AR tools for mobile platforms and examples

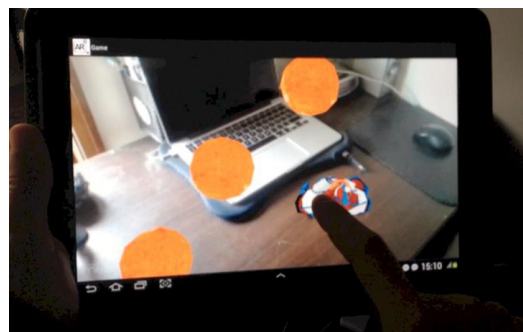


Figure 7: Meteorite avoiding game on an Android tablet using Metaio.

A student proposed to evaluate and test AR tools available for mobile platforms. In addition to a general analysis of available tools, some examples were developed using AndAR (<http://code.google.com/p/andar/>) and Metaio (<http://www.metaio.com>). Figure 7 presents a

game developed using Metaio. The user selected a surface where the physics of the game would take place, and could then control a character with his/her finger to avoid meteorites that roll on the surface at different speeds.

Exploring Google Cardboard

In this project, students were challenged to explore the possibilities offered by Google Cardboard and its SDK, creating an application using a mobile phone and Google Cardboard.

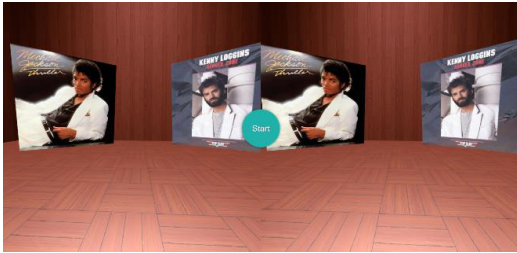


Figure 8: Google Cardboard demo environment.

Students started by exploring the SDK: however, using it would involve low-level OpenGL programming that was outside the scope of the course. They came up with an alternative: using three.js (<http://threejs.org/>). This option made easier the use of WebGL (since three.js is a high level library built over WebGL), and solved many compatibility and installation issues, since three.js runs on a browser. As final demo, students developed a simple 3D environment with texture and illumination. In the environment textured cubes with music album covers are displayed (see Figure 8). The gyroscope is used to detect head orientation and play music according to the album the user is looking at.

Oculus Rift lens distortion

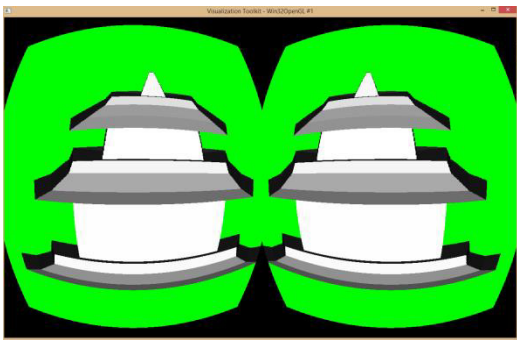


Figure 9: Rendering of a simple model using VTK and considering Oculus Rift distortion.

In this project students were asked to analyze the Oculus Rift lens distortion and image generation rules in order to

create a “plug-in” for Oculus Rift rendering of VTK-based projects. The idea was to make possible the use of Oculus Rift with any other project developed within the course. Students had to analyze the Oculus Rift SDK. Their work allowed to define two virtual cameras in VTK providing off-line rendering. The distance between the cameras is set accordingly to the Oculus Rift parameters that are read through the SDK. The two images are then distorted using the appropriate lens distortion equation. Finally, both images are merged into a single image that can be visualized in the Oculus Rift (Figure 9). The main limitation of the work was the low refresh rate (around 4 Hz), since all the computation and image lens distortion are computed in the CPU.

6. Discussion and conclusions

The Virtual and Augmented Reality elective course was offered twice, in a competitive course offering scenario, and it worked at maximum student capacity. At the end of both course editions students answered a questionnaire that allowed us to gather their feedback. The general impression was positive; most students enjoyed the course and found the topics and projects interesting and relevant. The main complaints were related to the heavy workload associated with each one of the courses they attended during the semester, resulting in a few students devoting significantly less time to the projects than expected. This was clearly visible in some projects, as students did not commit the time that was planned. Grades were coherent between both projects, with a few groups clearly below average.

In the first edition of the course, a lecture was allocated to present demos of all the available hardware. Some students suggested spreading those presentations/demos along the entire semester. In the second edition such presentations were spread among several sessions, with a short presentation of a different device between the lecture and the computer lab session; however, we still have mixed feelings about the best way to present the equipment so that all students have enough contact with it, both to understand the potential and limitations of each device, and to be able to select the one they should use in their projects.

One of the major problems we felt was the difficulty to find a VR platform flexible enough to easily integrate all the VR devices available, and thus most projects used vendor drivers. A system based on VRJuggler and OpenSceneGraph was developed [SDSSS14] as a possible platform for the course; nonetheless, its installation complexity and the lack of support for recent hardware prevented us from using it in the course. We are considering the use of more recent tools, such as Unity 3D [JGW*14] for future editions, yet further analysis is necessary since this solution also presents several drawbacks given that Unity 3D is a commercial platform and might reduce flexibility for use in some projects (e.g., involving data visualization), which has been a clear benefit of VTK. On the other hand, such a tool might ease

virtual world creation, resulting in more realistic and complete projects that might also be more rewarding for the students.

While deciding what software platform to use and the creation of challenging, motivating, and feasible projects are currently major issues in the design of a Virtual and Augmented Reality course implying trade-offs, we believe that the real challenges are directly related to the nature of this course: the careful balance between design principles and technological information, as well as the need of a constant update.

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