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Enhancing user experience for BIM visualization with VR and XR technologies

MASTER THESIS IN
COMPUTER SCIENCE AND ENGINEERING -
INGEGNERIA INFORMATICA

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Abstract

Building Information Modeling (BIM) is currently transforming Building industry environment, enhancing communication between interdisciplinary teams during the entire project lifecycle. Working with BIM greatly benefits from new technologies in user experience, for which there is still a lack of dedicated interfaces. This thesis aims at supplying to BIM workflow dedicated interfaces for communication with new technologies in Virtual and Mixed Reality, new features and tools are also to be designed and implemented for greater information retrieval from BIM. This application targets both students and professors from Architecture courses for supplying multimedia contents to enrich university lectures.

Keywords: BIM, Virtual Reality, Mixed Reality, Representation techniques

Abstract in lingua italiana

Building Information Modeling (BIM) sta attualmente rivoluzionando il campo dell'industria edilizia, migliorando la comunicazione tra team multi disciplinari durante l'intero ciclo vitale di un progetto. Lavorare con BIM trae grandi benefici dalle nuove tecnologie nell'ambito di esperienza dell'utente, per cui c'è attualmente una grave mancanza in termini di interfacce dedicate. Questa tesi ha come obbiettivo di aggiungere al workflow BIM delle interfacce dedicate per Realtà virtuale e Realtà aumentata, nuovi strumenti verranno inoltre progettati e implementati per aumentare le informazioni disponibili per l'utente da BIM. Questa applicazione è designata per sia studenti che professori di Architettura, per aggiungere esperienze multimediali ai tradizionali corsi universitari.

Parole chiave: BIM, Realtà virtuale, Realtà mista, Tecniche di rappresentazione

Contents

1 | Introduction

Building Information Modeling is revolutionizing building industry environment since its early development, the previous "silos" organization in project development severely crippled communication capabilities among interdisciplinary teams: each team needed to manually communicate between every other needed team about progresses and modifications to a common project, increasing development time and costs. BIM greatly solved this problem by transforming project development from "silos" to a centralized architecture, with a common view of the model automatically updated on each progress. Furthermore BIM incentivized a more machine-oriented approach relation-based: relations between and among objects are utilized by software to automatically update the model according to various view requests, improving cost efficiency and decreasing development time. Nowadays BIM is not fully exploited by new technologies, from which great enhancements can be obtained to shift from a 2D screen perspective, to a more immersive 3D user experience.

1.1. Our objective

This thesis aims at designing, implementing and testing an application to link BIM software to new technologies in Virtual and Mixed reality. The objective consists in creating a workflow from BIM software, such as Revit, to Euclideon Holographic Table, a Mixed reality device at LaborA, and to Virtual reality head mounted displays; the VR interface is independent from device choice, although the application has been tested on Oculus Rift S. Purpose of this application rely on enriching architectural courses at Polimi with a multimedia experience on BIM visualization, spacing from the usual 2D screen perspective, to a more immersive 3D experience.
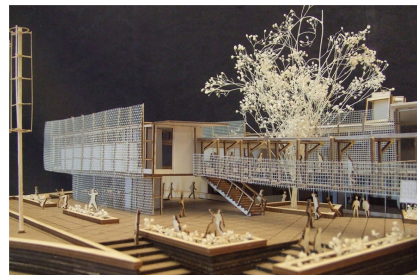
1.2.   Thesis outline

Thesis is organized as follows:

- **Chapter 2 - *How technology changed 3D modeling*** provides the reader an introduction to how architecture and building industry transformed with the latest technological progress. It also supply a brief history of CAD and BIM software with novelties and drawbacks.

- **Chapter 3 - *New user experience technologies*** provides a brief history and definition of Virtual reality, Augmented reality and Mixed reality.

- **Chapter 4 - *An application for new user experiences in BIM*** describes the requirements and the objective of this application, it also shows the design procedure followed for the new tools and a brief description of technologies utilized.

- **Chapter 5 - *Tools and interfaces implementation*** explains the technical details and the implementation procedure, it also shows the application behaviour with some screenshots.

- **Chapter 6 - *Testing*** illustrates the experimental results and evaluation of the testing process with Polimi students, both from Architecture and Computer Science courses.

- **Chapter 7 - *Conclusions and future developments*** draw some conclusions from this thesis and illustrate possible future research and development in this field.

2 | How technology changed 3D modeling

3D modeling can be defined as the process of creating three dimensional representations of a surface or an object; up until modern times this process took entirely place in the physical world, despite its intuitiveness lots of drawbacks related to physical handling of materials couldn't be avoided: in a complex model as in Fig 2.1, even the slightest modification require time to be applied, damage and error repair costs could escalate with the model complexity and scrape material during design would worsen cost ef-

Figure 2.1: An example of a complex physical mode

ficiency. A starting point about digital transformation in 3D modeling can be tracked down back in 1963 with "Robot draftsman" by Ivan Sutherland (Fig 2.2a), this computer program constituted the very first graphical interaction between humans and machines, allowing drawings to be made and modified digitally, digital drawings allowed better accuracy, faster speed of drawing and possibility to modify parts without the need to erase them [1].

2.1. Computer Aided Design CAD

The term CAD (Computer Aided Design) has been coined for the first time during 1950s by Douglas T. Ross, who was working in the MIT on radar technology and computer display systems, although his work was not properly CAD, it laid the foundations for further development of this concept [9]. "Robot draftsman" constituted the first CAD application and showed how machines could assist humans in creative work, soon followed ADAM in 1971 and the most known AutoCAD in 1982, AutoCAD was the very first CAD software meant to run on the IBM personal computer and constituted a major turning point, causing a widespread use of CAD applications not only in automotive and

aerospace industries, but opening to commercial engineering business one. Up until now, CAD software are mainly operational in two dimensions, things changed in 1987 with the release of PRO/Engineering (Fig 2.2b) as the very first parametric CAD software able to work on 3D, it allowed engineers to insert parameters, features and relationship between objects to fully capture intended behaviours, the heavy computational load excluded its usage on new IBM PCs and instead, required UNIX workstations to work on.
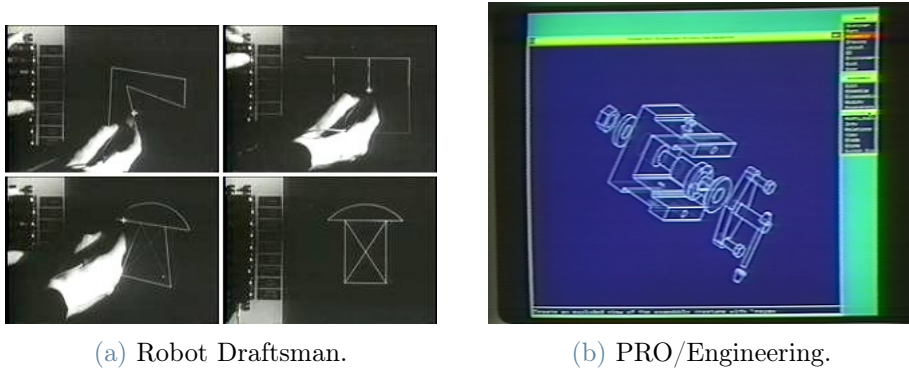

(a) Robot Draftsman.   (b) PRO/Engineering.

Figure 2.2: Software novelties, on the left the first GUI software in 1963, on the right the first 3D CAD software in 1987.

2.2.   Building Information Modeling revolution

Construction business greatly benefited by the transformation from analog modeling to computer aided one, now drawings could be reused with extreme ease and different views could be performed on the same project, modifications no more implied redoing the whole project and could be performed at computer level precision. Despite all the aforementioned advantages CAD brought to construction and modeling business, one major flaw persisted: lack communication between teams. There was no easy way to keep different teams automatically updated about project progresses and information, that were still organized in silos; this represented a pending problem in heavily multidisciplinary industries as the construction and modeling one [2]. The concept of Building Information Modeling (BIM) had been firstly introduced in 1975 by Charles M. Eastman, although with the different name Building Description System: Eastman described a centralized project ecosystem in which information was shared among all sectors, updates would be automatically be applied on the overall model and, in a machine readable form, any type of quantitative analysis could be coupled directly to the description. All data preparation for analysis or reports could be automated [3]. in 1986 the term "Building modeling" was coined by Robert Aish, Aish described in his article how CAD drawings could be effective

in multidisciplinary teams by projecting design information in appropriate representations as 3D views, orthographic drawings or even non-graphic representations [4]. Lastly, BIM made its appearance in 1992 with "Modelling multiple views on buildings" by G.A. van Nederveen and F. Tolman. In this paper an approach was presented with which different disciplinary teams could collaborate by working on different aspect models of the same reference model [11].

2.2.1. BIM and software

BIM can be described as process for creating and managing information on a construction project throughout its whole life cycle. Procedure involves communication enhancement among multidisciplinary teams by unifying model visualization and automatic updates: every changement updates a common 3D model visualization, disrupting the previous "silos" architecture in building construction projects. Modern parametric BIM work with 2D orthographic plans with a common 3D model in a object based and data rich environment, the parametric approach allows to introduce a set of rules during design phase than ensure consistency in the model, changes in scale, dimensions or geometry are able to automatically restructure the model to be still consis-

Figure 2.3: Lifecycle of buildings with BIM, covering each phase of building process

tent with the parameters specified by the designer. An example of a functional parameter can constrain the wall size, ensuring that it extends from a floor level until the bottom of a ceiling is found; this way the model can be rearranged by the designer without worrying of an off-scale wall. The very first BIM software available for personal computer can be traced back in 1984: "Radar CH" (Fig 2.4a), later known as ArchiCAD by Gábor Bojár; used for residential and small commercial projects, to date, Graphisoft claims that more than 1,000,000 projects worldwide have been designed using ArchiCAD. Released during April 2000, Revit (Fig 2.4b) is up to date the most known and used BIM software on the market, allowing for planning the whole lifecycle of a building, its functionalities have been subdivided in three different sections[1]: "Revit Architecture" aims at conceptual design and documentation of the building, "Revit Structure" allows for structural analysis and

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[1]https://blogs.rand.com/architectural/2010/11/what-s-the-difference-between-revit-architecture-structure-and-mep.html

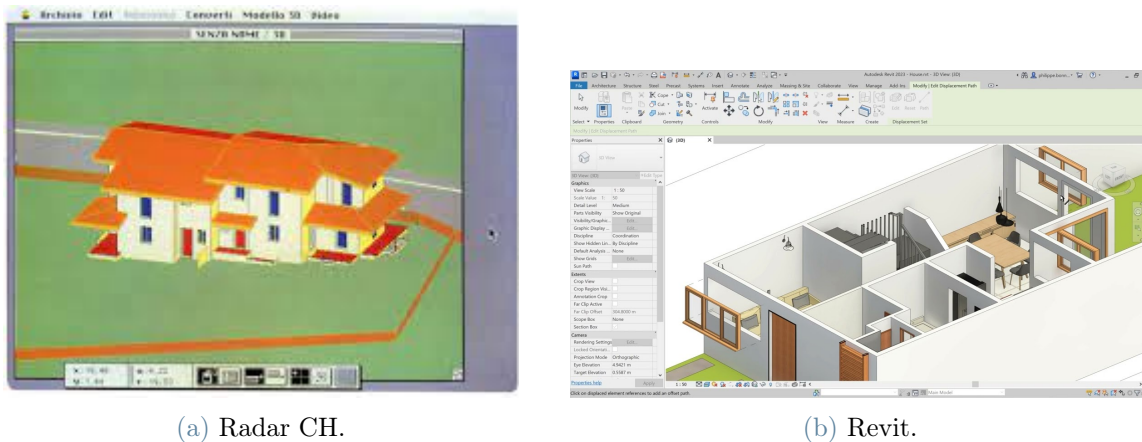"Revit MEP", designed for specific elements like idraulic and mechanical components.

(a) Radar CH.

(b) Revit.

Figure 2.4: A comparison between the very first BIM software, Radar CH in 1984, and the nowadays most used Revit

2.2.2. Limitations of BIM

BIM is currently metamorphosing the construction industry, its performance improvement during all phases of building construction is such known that in 2011 UK provided BIM as mandatory for government buildings construction since 2016. However, despite its popularity and ground breaking novelties, BIM still presents some drawbacks such as its cost and requirement for trained staff. First of all BIM disruptive nature still presents a challenging task in implementing it in construction companies technology [6]. One of the other major drawbacks concerns software activation: licenses for a BIM proprietary software represent an heavy investment both in monetary terms and computational power requirements, complex projects can be handled by today software, such as Revit, but needs powerful machines and a well performing computer system to truly exploit all BIM software capabilities [2]. Another cost for BIM utilization is constituted by the necessity of training staff members to fully exploit new software: recent innovations and a fast growing market imposed an investment of time, and resources, in training to correctly embrace BIM.

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[2]https://knowledge.autodesk.com/support/revit/learn-explore/caas/sfdcarticles/sfdcarticles/System-requirements-for-Autodesk-Revit-2021-products.html)

3 | New user experience technologies

Technological progress and discoveries made possible to design and implement new user experiences varying from the classical 2D screen experience, various advantages can be brought therefore in BIM applications to fully exploit its 3D and object relations nature, heavily limited by 2D screen visualization capabilities. This chapter aims at describing how Virtual Reality, Augmented Reality and Mixed Reality work and supplying it with a brief history of their development.

3.1. Virtual Reality

A Virtual Reality experience is often referred to as making the user effectively immersed in a responsive and interactable fully virtual world [5], this can be achieved through a computer-generated 3D environment, with the purpose of tricking the user into accepting the virtual environment by simulating stimulus (usually visual and auditory) for its senses.

3.1.1. Brief history of Virtual Reality

Although the term "Virtual Reality" (VR) has been coined in 1987, the research for the most immersive experience can be traced back long before it, starting from the 19th century: in 1787 Robert Barker patented the "Panorama", a new method for displaying landscapes images to make the user feel inside the scene. Panorama method consisted in an apparatus able to isolate and control what it was possible to see from the user perspective, this was accomplished by obliging the user into a platform situated at the

Figure 3.1: Immersive Panorama paintings (1787)

center of a 360° canvas, lighted from above with no windows and with a entrance from

below, user was also restricted from going too near to the picture.

The stereoscopic view

Modern Virtual Reality is based on the "Stereoscopic view" concept: giving the brain two slightly different 2D pictures, it will elaborate a 3D merged sense of sight, this principle has been discovered in 1832 by Charles Wheatstone and been extensively applied for 3D filming and Virtual Reality, difference among the two images is called "Parallax" and can lead to cybersickness if not adequately applied[1]. The Stereoscopic view concept led to various practical applications, first of all the "Stereoscopic" by its discoverer Charles Wheatstone in 1838, despite the novelty however, the bulky mirrors system made it not particularly pop-

Figure 3.2: View Master device and reels

ular, improvements on its portability will come in 1849 by David Brewster, making it a particular binoculars with two pictures attached to it, and eventually led to the most known View-Master stereoscope in 1938.

From Viewer to User

One of the advantages "Virtual Reality" brought was the possibility of visualizing and feeling immersed in a reality often too dangerous to live in, however this immersion sensation was limited by the impossibility of interaction with the simulated environment; with this perspective Ed Link, in 1929, created the first mechanical prototype of a series of interactable virtual reality devices: a Flight simulator called "Link Trainer". Link Trainer was a mechanical apparatus able to simulate flying instruments in response to pilot interactions, external disturbances and flying conditions, this allowed pilots to train their flying skills without the hazard of flying a real airplane; US military largely ex-

Figure 3.3: Morton Heilig's Sensorama

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[1]https://www.frontiersin.org/research-topics/12692/cybersickness-in-virtual-reality-versus-augmented-reality

ploited the new flight simulators (due to the Air Mail scandal too that, in 1933, caused the death of 13 airmen)[2]. In 1957, Morton Heilig patented the "Sensorama" (Fig.3.3), an arcade-like theatre cabinet for an immersive viewing experience, although its lack of user interaction, the Sensorama brought the novelty of multisensory experience (now called multimodal). sight was not the only sense stimulated but auditory, touch and smell too thanks to smell generators, fans, stereo speakers and a vibrating chair.

Head Mounted Displays

In 1960 Morton Heilig, maker of the Sensorama, patented the "Telesphere mask": the first Head Mounted Display (HMD), the device allowed the user to view not-interactive films and was equipped with stereo sound although with no head tracking system. One year later, two Philco Corporation engineers (Comeau & Bryan) patented what can be considered as the first headset of history: "Headsight", the greatest novelty brought was a fully working motion tracking system, implemented by a closed circuit camera linked to the magnetic system, head movements would move a remote camera, making the user able to navigate inside the simulated environment.
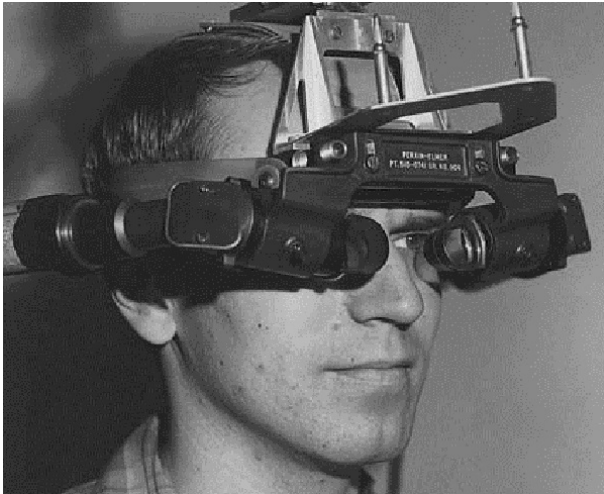

The same research for the most immersive user experience can be found in "The ultimate display" , a short paper in which Ivan E. Sutherland, in 1965, described the concept of a perfect simulated reality with no visible difference with the true one [7], three years later, with help of his students, a prototype of "The Sword of Damocles" was created (Fig 3.4), consisting in an enormous HMD connected to a computer that would generate wireframe rooms over what could be seen from the user perspective; The Sword of Damocles was the first HDM generating and visualizing images with a computer instead than visualizing

Figure 3.4: Ivan Sutherland "Sword of Damocles" (1968)

from a camera. Making the user able to interact with the simulated environment can largely enhance his perception over it, in order to make the interaction possible hand movement detection is mandatory and, in 1977, a first prototype, the "Sayre gloves", implements it through light based sensors situated all over a glove.

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[2]https://en.wikipedia.org/wiki/Air_Mail_scandal

VR for a public usage

Starting since 1990s, Virtual Reality will slowly shift from its private research nature into a public oriented one, Virtuality group will, in 1991, release the first VR device explicitly created for entertainment purposes: the "Virtuality 1000CS", despite its novelty, the project failed to approach the public usage due to its enormous cost (sixty thousands dollars per device).

3.1.2.   User devices

Headsets

Today VR devices comprise mostly headsets, or Head Mounted Displays, the illusion of 3D is accomplished through two stereoscopic lenses that distort the screen into two slightly different 2D images, these images are then elaborated by the user perception into a fake 3D image. In order to create the 360° environment in which the user shall feel immersed into, display is moved accordingly to the user head movement, tracked with sensors mounted on the headset; head movement tracking is also utilized for audio computing, then played on two different speakers, one per user ear, exploiting new spatial audio technologies. Today wireless headsets can be found on the market, in order to overcome the necessity of a wired connection with a computer, these usually can exploit a wireless connection, as HTC Vive and Vive PRO with the proper adapter, or rely on less computational power but directly installed into the headset, making it a standalone device, as Oculus Quest series. Despite overcoming physical discomfort as tripping into the cable or be limited in the movement you can perform, today wired headsets still provide the best performances of resolution, refresh rate and field of view[3].
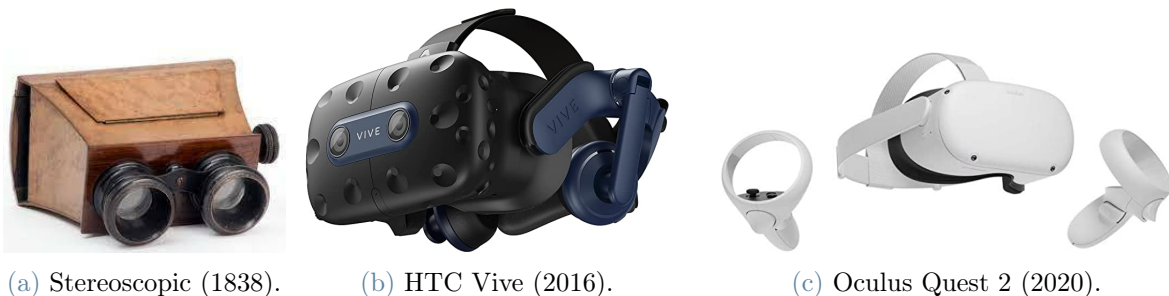

(a) Stereoscopic (1838).   (b) HTC Vive (2016).   (c) Oculus Quest 2 (2020).

Figure 3.5: Visual comparison between VR headsets during their development

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[3]https://www.cablematters.com/Blog/Virtual-Reality/wireless-vr-vs-wired-vr

Input devices

A complete VR experience involves an interaction with the user, while a sophisticated head mounted display provides an immersive output for sight, sound and, occasionally, other senses, other devices are required for allowing the user to fully interact with the virtual environment. The most common input devices for Virtual Reality are hand controllers, with the precise purpose of integrating hand movements inside the VR applications; starting from 1976 with "Sayre Gloves" covering the full hand, nowadays controllers are less bulky allowing for a better trade-off between user comfort and tracking precision, "Oculus touch" as an example, Meta signature input device, have been constantly developed for better user comfort since 2015 in three different iterations[4].

Hand controller state of the art is currently being developed as being controller-free, hand tracking currently works with built-in cameras in headsets, images are then processed by an artificial intelligence specialized in machine vision and then hand position, orientation and finger gestures are represented in the virtual environment, studies showed that multiple benefits in user comfort can arise with hand displacement in the virtual environment [8]. Less common devices, usually because of both monetary and space expensive cost, can comprehend navigation devices, such as Omnidiretional Treadmills, to allow the user to wander around the virtual environment, in Fig 3.6 the Omnidiretional Treadmill in LaborA.

Figure 3.6: Omnidiretional Treadmill at LaborA

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[4]https://en.wikipedia.org/wiki/Oculus_Touch

3.2.   Augmented Reality

Augmented Reality (AR) is a term utilized for referring to an experience between Virtual Reality and Real world, in an Augmented Reality experience, the real world environment is enhanced with a visible virtual layer stimulating user senses. During 1997, Azuma well defines Augmented Reality [10] as a variation of a Virtual Environment (VE) in which virtual reality is not a replacement but a supplement for the real world, an AR system also needs to fulfill three requirements:

1. Must combine both real and virtual reality.

2. Must be interactive real-time.

3. Must be registered in 3D.

3.2.1.   Brief history of AR

The very first prototype of AR can be tracked back in 1968 with "The sword of Damocles" by Ivan Sutherland, however up until this point AR and VR development coincide. The term "Augmented Reality" was coined in 1990 by Thomas Caudell to define his work in Boeing company: an HMD to superimpose on the worker eyes the cable positions on a physical multipurpose board.

Interacting with AR

Figure 3.7: Louis Rosenberg "Virtual Fixtures", allowing computer assisted movements, 1992

During 1990s 3D graphic generation was too slow to allow for a photorealistic and spatially registered augmented reality environment, Louis Rosenberg overcame this problem with "Virtual Fixtures", as we can see in Fig 3.7, the user was provided with a pair of physical exoskeletons to be used during physical tasks. The main concept behind Virtual Fixtures consisted in enhancing human activities with sensory overlays, a good metaphor to understand this concept can be drawing a straight line on a piece of paper hand-free, a difficult task for an human but a simple one for

computers; Virtual Fixtures was presented to U.S. Air Force in 1991 with the surgery use case: the physical scalpel was to be directed by a surgeon and computer assisted, to improve accuracy and reduce mental load by the surgeon. In 1994 the first approach to the entertainment industry is done by "Dancing in Cyberspace", founded by the Australia council for the arts: a group of dancers and acrobats performed a choreography interacting with body sized virtual objects on the scene.

AR to the everyday customer

A first example of an AR application that benefits everyday customer was "FoxTrax" (Fig 3.8): FoxTrax consisted in an Augmented Reality system by Fox Sports Telecast, created in 1996, that allowed to track the puck in a TV hockey game; implemented by a modified puck with sensors interpreted by the computer to generate a colored trail on the screen[5].

AR greatly benefits from user movement in the physical world, however this possibility has been crippled by bulky and not easily portable hardware; it goes without saying that technology innovations in portable devices greatly enhanced AR in the everyday customer up until today mobile devices, supplying to the technology enough computational power and portability to fully exploit AR possibilities.

Figure 3.8: FoxTrax (1996) allowing spectators to easily visualize puck position and trajectory during matches

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[5]https://en.wikipedia.org/wiki/FoxTrax

Virtual gaming in the real world

A first example can be found in 2000 with ARQuake in Fig 3.9, the AR version of the popular game implemented a shooting system with a virtual overlay over the real world environment: monsters would appear next or behind real buildings, however game would need proper portable hardware on a backpack

Figure 3.9: First prototype of AR gaming on open world

to correctly work, resulting in a project not available to everyday customers. In 2014 the first prototype of a virtual overlay on the physical environment was developed with "Google glasses": it featured an Android-based computer with speakers and a microphone for voice commands to be used hand-free. Due to severe privacy concerns the project got withdrawn from the market and released to a more restricted target. With the advent of mobile gaming and an improvement over its performances, AR gaming took a turn, the most famous example of which is Pokemon Go (Fig 3.10): a mobile game developed in 2016 with, as main concept, interaction between the physical environment and a virtual one; in order to progress through the game the player needs to travel in the real world. Pokemon Go registered more than 500 million downloads which more than half only the first year.
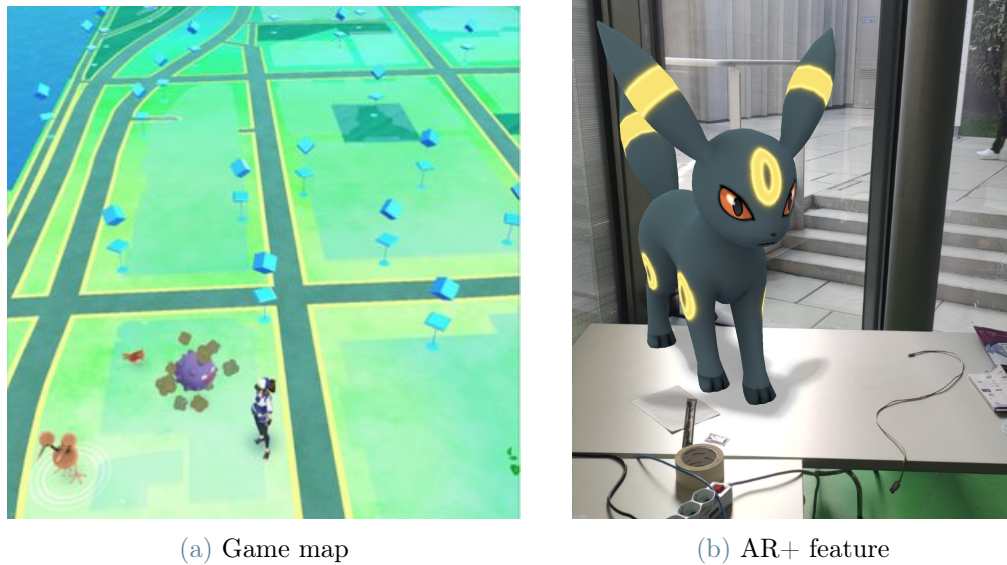
<table>
<tr><td>(a) Game map</td><td>(b) AR+ feature</td></tr>
</table>

Figure 3.10: Pokemon Go (2016) Game map and World map coincide (a) and pokemons appear as part of the environment (b)

3.3. Mixed reality

The term "Mixed Reality" (XR) has been coined by Paul Milgram and Fumio in 1994 [12] to define the Real-Virtual continuum in which Virtual and Augmented Reality lie.
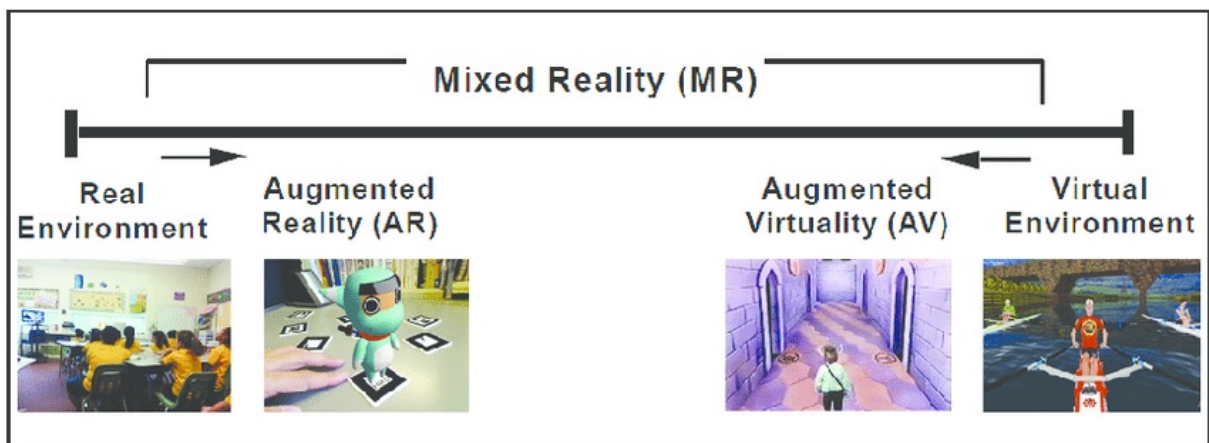

Figure 3.11: Mixed Reality (XR) continuum, spacing from real environment to a fully virtual one

As we can see in Fig 3.11, Mixed Reality consists in four main categories, but can space in any proportion between Real and Virtual environments. In between two extremes of Real and Virtual environments, in which one completely replace the other, cases vary based

on observer perspective: if the observer environment is mainly Virtual it's Augmented Virtuality case, in which the virtual environment is supplemented with real environment elements, such as the physical location of doors, walls and physical object in a game-like environment. Otherwise, if the observer environment is mainly real, it's the Augmented Reality case, AR applications consists in supplementing the real environment with virtual elements, such as with Google Glasses, a wireframe visualization of real world, or famous games like Pokemon Go. Main focus of nowadays Mixed Reality consists in including environmental inputs and their correct elaboration, aiming at making Real and Virtual realities with no visible difference from the user perspective.

4 | An application for new user experiences in BIM

With this thesis we wanted to enrich the user experience during 3D model visualization of BIM objects: this will be accomplished by designing and implementing new data exploration features and, subsequently, exploit new technologies to enhance user immersion during the experience via Virtual Reality and Mixed Reality.

4.1. Experience design at LaborA

LaborA is a Polimi structure, founded in march 2021, that aims at supporting architecture students both with physical and virtual tools and spaces for 3D modeling: students are provided with an open space for physical modeling, 3D printers, tools for laser cutting and a room for painting procedures. LaborA virtual department task consists in enhancing the process of 3D modeling with new experiences for the students, new technologies are then experimented and exploited to provide the best, immersive, and responsive experience possible. This thesis aims at establishing a workflow between BIM modeling software, such as Revit, and technologies at LaborA, such as the holographic table and Virtual Reality devices. New data exploration features have also to be designed and implemented to fully exploit this workflow. First step of this thesis consists in designing the workflow between BIM software and LaborA technologies: both Virtual Reality devices and Euclideon HoloTable are supported with a well suited Unity API; furthermore Unity provides a proprietary plugin, "Unity Reflect", that helps in converting BIM into a Unity format freely exploitable; Fig 4.1 illustrates its workflow from third party plugins, for architecture BIM, to Unity.
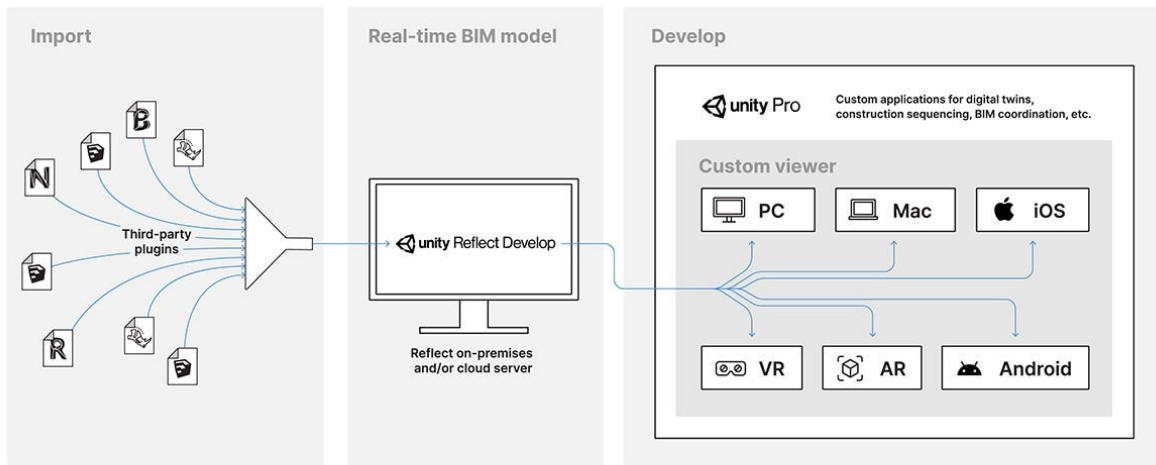
Figure 4.1: Workflow of Unity Reflect, between BIM software to Unity Pro

4.1.1.   New tools design

In order to fully exploit new technologies and enhance user experience, new tools need to be designed and implemented: Unity Reflect already provides external views features such as light management, filter tools and distance measurements, however internal views and details are not exploited enough, and hence will be target for the first tool to be designed:

Section tool objective therefore consists in providing internal views of the model with a freely maneuverable plane, usage of this tool will allow users to perform transversal views and filter the visible part of any given model. Another "Unity Reflect" feature not exploited enough are metadata assigned to objects: BIM rely its popularity on metadata organization and relations
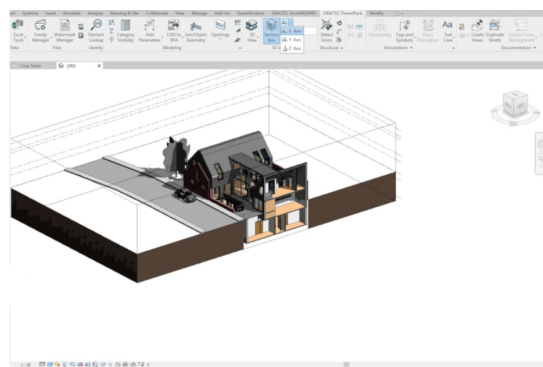

Figure 4.2: Section tool implemented in Revit, allowing for internal views of the model

among objects, therefore each component of a BIM is imported into Unity workspace with a metadata component that comprehend ID, structural and specific features. However these features are not exploited by any tools accessible by the user, objective of a

new tool: "Heatmap" will hence be to visualize metadata provided by BIM: given an user specified parameter, each object of the model will assume a custom texture with an RGB value directly dependent from its parameter value; parameter not found will result in a transparent object or, depending on its value, a shade interpolation between two colors, representing low and high values.
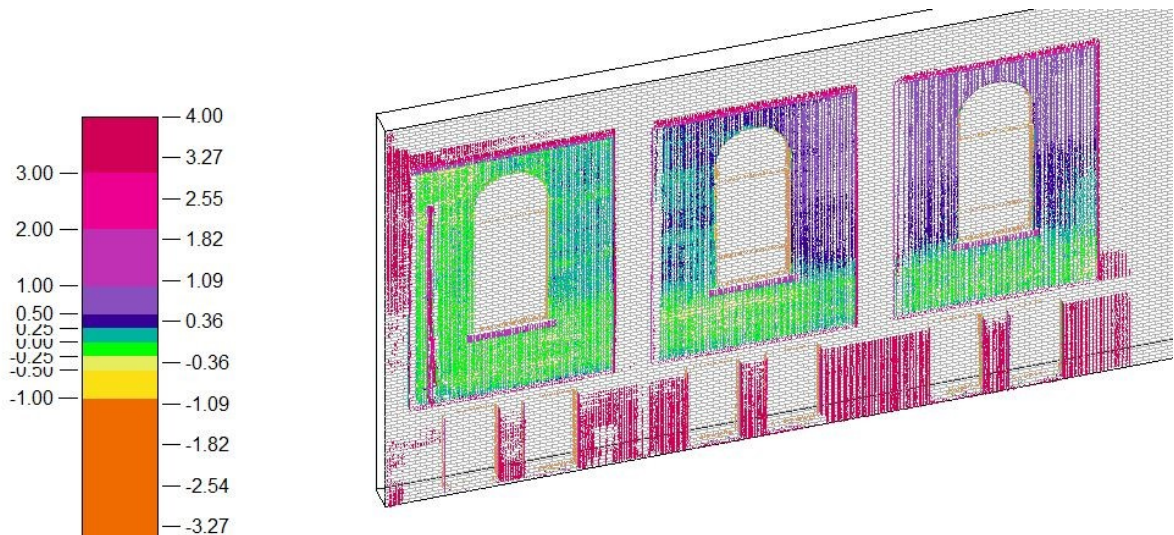

Figure 4.3: Heatmap sample, tint of the object texture is modified accordingly to its parameter value

4.2.   Technologies

LaborA virtual department is provided with both Virtual and Mixed Reality devices, aim of this thesis will also consists in designing and implementing interfaces for new BIM workflow to work on two devices: Oculus Rift S for virtual reality and Euclideon Holo Table for mixed reality.

4.2.1.   Euclideon Holo Table

Euclideon Holo Table is a large, flat surfaces with an embedded projection system. This device projects 2D objects that, thanks to a polarized pair of glasses, appear to the user as a 3D object in a space limited by display dimensions and a fictional height, going from 1m under and 0.7m over the display; Euclideon Holo Table differ from most holographic tables for Axiom Holographics' new Multi-User Hologram Technology, allowing two separate views and two users at the same time with a single hologram.

The table is 2.1m x 2.1m with 61.5 height and needs a complete dark room of at least 3m x 3m for adequate usages, it comes with proprietary software and two pairs of glasses and wands: the latter are utilized as input devices, embedded with input buttons and a ray sensor to allow the user to select a specific portion of the hologram. In Fig 4.4 a pair of input devices is shown, both devices are embed-

Figure 4.4: Table input devices, comprehending a pair of glasses and a wand for button input

ded with a tracking system to be detected by the four sensors on the table (bottom left) in order to correctly model the position and orientation, the wand tracking system is also utilized to enrich the button input with a point input on the visualized model. In Fig 4.5b its shown the bottom part of the table, the illusion of 3D models on a 2D screen is made possible with the usage of four different projectors, pointing to the same screen with slightly different images.
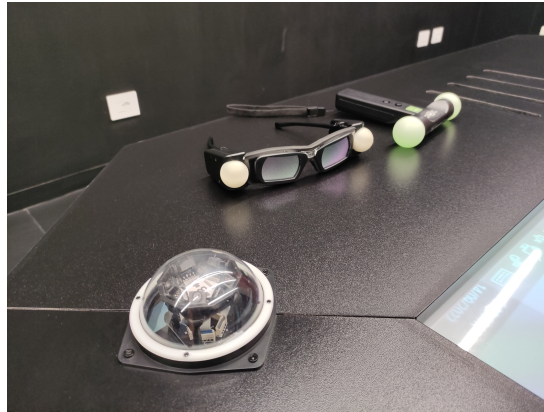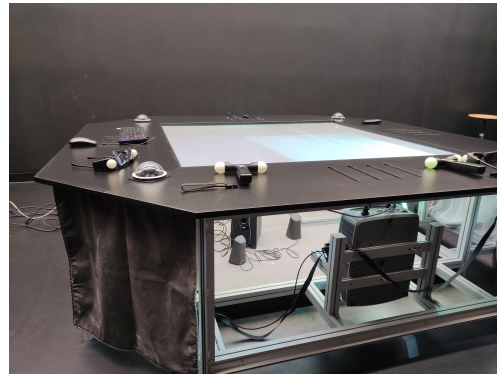

(a)

(b)

Figure 4.5: Two perspectives of Euclideon Holo Table at LaborA

4.2.2. Oculus Rift S

Oculus Rift S is a wired Head Mounted Display, by Meta and Lenovo for Virtual reality, announced and launched in 2019. It is equipped with a single fast-switch LCD panel with a resolution of 2560×1440, a 115° field view and an 80 Hz refresh rate with a single screen, the absence of dual displays makes inter pupillary distance (IPD) adjustment possible only

from software, differing from more modern HMD (such as Oculus Quest 2). Two "Oculus touch" controllers are also provided for input usage. Rift S utilizes "Oculus Insight" to recognize spatial movement of the headset: a prediction engine is provided with inputs from accelerometers, from both headset and controllers, and inputs from five cameras built into the headset, cameras are also utilized for controller position input thanks to track infrared diodes embedded in the controllers. Despite its light weight of 0.5kg, it needs a wired connection with a computer, not allowing free roaming of the user into the space.

Figure 4.6: Oculus Rift S at LaborA, used for testing the application

5 | Tools and interfaces implementation

This chapter aims at describing implementation details and procedures followed for this thesis, it also provides pictures from usage of Reflect on new devices and new tools.

5.1. Section tool

Section tool has to allow the user to freely maneuver a separating plane across the model to get various internal views: in order to do so, the program needs to compute every object position, with respect to the plane and assign the adequate texture; in case of intersection between the plane and an object, the program needs to assign a transparent texture only to the correct object portion at a pixel level precision for a correct display.

Efficiency and scalability during section usage are pivotal in order to guarantee a fluid experience to the user: updates must be both frequent and efficient, not frequent enough updates may lead to lag between plane transformations and texture updates, on the other hand, the tool needs to work fluidly regardless of model complexity. Unity Shader Graphs were used for texture computation, with a vector oriented approach to fully exploit GPU ca-

Figure 5.1: An example of an object transversal to the section plane, precise computation pixel-level needs to be performed

pabilities: computation for position assignment of each pixel is assigned to the scalar product between two vectors: normal of the section plane and a vector between center of section plane and position of the pixel, alpha value of pixel RGBA is then modified according to the result, ensuring all pixels on the same side of the section plane are transparent or not.

(a) Model before section
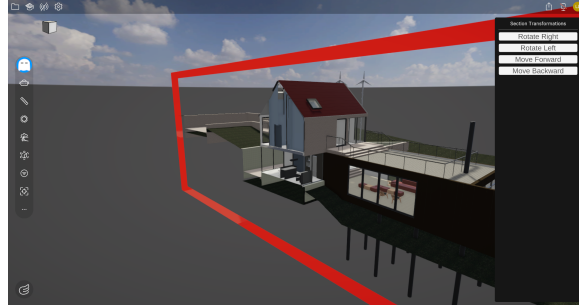

(b) Model after section

Figure 5.2: Before-after the section tool, the plane defines which portion of the model to make transparent and which no transformation needs to be applied
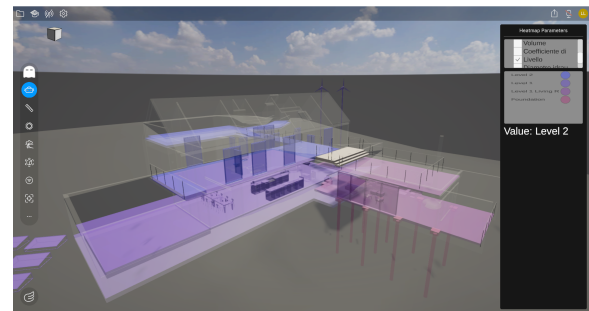
5.2.   Heatmap tool

Heatmap tool purpose consists in creating a visual representation of the model according to its parameters: user shall specify a parameter for the visualization, each object will then be assigned an RGBA value according to its value. Program computes, for each object, a coefficient based on its value position in a range in which minimum parameter value correspond to 0 and maximum to 1, two distinct colours are then assigned to minimum and maximum values and a tint shade to every value in between. Two special colours are also utilized for maximizing information gain: objects shall result transparent if the specified parameter is not found, or coloured with a different tint in case of out-of-range values; in case of categorical values, for which ranging between a minimum and a maximum values does not apply, different colours are assigned to each distinct value.

(a) Model before Heatmap
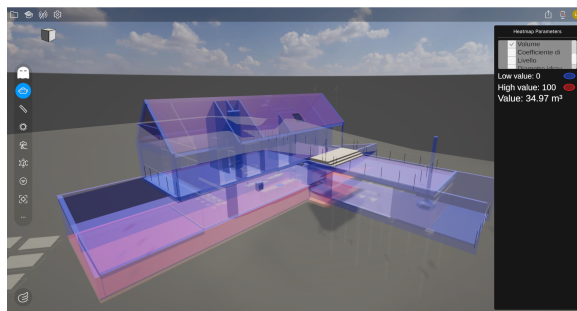
(b) Model after Heatmap, numerical

(c) Model after Heatmap, categorical

Figure 5.3: Before-after the Heatmap tool, the model is tinted accordingly to the specified parameter, for the numerical case, a min-max range is visible (b) and, for the categorical case, a list of values (c)

5.3.   User Interface with Holo Table

Euclideon Holo Table comes with proprietary software and plugins, it also supply the user with a unity package for import table structure and sensors as prefabs, custom application can hence be developed by managing these prefabs in the scene, main components comprehend an "event system", for table related events, and a prefab of the table itself, used to determine which portion of the scene to be visualized into the physical table. The main challenge of implementing an interface for the Holo Table consisted in UI placement and modification: the original Reflect UI is programmed to work on Screen Space, a canvas rendered to fit the selected screen, on the other hand Holo Table needs World Space, in which UI canvas and elements have a transform point specifying position, rotation and scale on the scene; however space management is pivotal for programming with Holo Table despite its dimensions, UI elements need to be big enough to be easily readable but little enough to make the user able to visualize the model underneath. Implementation of the new UI followed a control panel approach, reserving one fixed table edge for UI elements and leaving the other three for model visualization, this implementation allowed UI elements to be easy readable without hindering the possibility of visualizing the model

at the same time.

5.4. User Interface with Virtual Reality

Reflect already provides a Virtual Reality interface for its proprietary Viewer, this interface however is limited for navigation functionalities, no UI or inputs apart from moving the camera are allowed while in VR navigation, and strictly reserved to proprietary software, custom Reflect apps hence don't support VR navigation yet; Therefore a new interface needs to be designed and implemented by scratch. User navigation inside the model follows the classical point-and-click approach: when the trigger button is pressed, a raycast is performed from the controller to detect any collision with objects in the scene, if a collision occurs a green box appear to the user reporting the new location to teleport into, with the pressing of another trigger, user is then teleported to the new location; a debug movement system has also been implemented with the controller pads, linking pad and user movements into the scene, this system has been designed and implemented with the precise purpose of helping the user in moving inside the model and through objects that, otherwise, would block the teleportation process and forcing the user to physically step outside an object. We wanted the user to be free to modify the views of the model during VR navigation, possibility not contemplated on the original Reflect Viewer app; UI placement is hence pivotal for this application given the requirement for canvases and UI elements to be easily readable but far enough to allow the user to effectively interact with them: we opted for a world space placement on the arm of the user, UI is programmed to stick slightly behind the left user controller to create the illusion of placement on the user arm, its rotation is forced to match the user headset to make sure UI elements are always on an adequate position and rotation for user to interact with.

6 | Testing

This thesis's application aims explicitly at user experience enhancement, it goes without saying that the testing process is particularly relevant in this case. Given BIM strength relies on making communication among multidisciplinary teams possible and more feasible; we thought that the target for this test should not only focus on architecture students, who can provide a functional review for BIM visualization, but should instead comprehend at least Computer Science students, for a more technical review of interfaces and tools implementation, and a group of students not related to nor architecture nor Computer Science, to provide an objective evaluation of the usability for an external user. Students could test one or both applications, providing reviews for the tested interface by compiling the apposite survey section. The survey is subdivided in four sections:

- **Section 1 - *General information*** for questions unrelated to the interface implemented, general information about the tester background BIM knowledge and tools usefulness.

- **Section 2 - *Holographic Table interface*** for questions related to the Holographic Table usability and devices handling.

- **Section 3 - *Virtual Reality interface*** for questions related to the Virtual Reality usability and interface devices.

- **Section 4 - *Interface comparison*** overall comments and comparison of usability between interfaces.

Section 1 - Generic information

	Question	**Answer type**
Q1	Gender	Male/Female/Other
Q2	What do you study at Polimi?	One of • Architecture • Computer Science • Other • I'm not a Polimi student
Q3	Insert the date you tested the application	Date input
Q4	What interfaces have you tested?	One of • Only Holographic table • Only Virtual Reality • Both
Q5	Do you have any previous experience with BIM visualization?	Yes/No
Q6	How would you rate your previous experience with BIM visualization?	Range 1 -> 5
Q7	In your opinion, could this kind of experience enrich a traditional university or high-school lecture?	One of • Yes • No • Maybe but in specific cases
Q8	Would you appreciate lessons with this kind of support?	Range 1 -> 5
Q9	Would you use new "Section" and "Heatmap" tools during BIM visualization?	One of • Yes • No • Maybe but in specific cases
Q10	New "Section" and "Heatmap" tools are useful for BIM visualization	Range 1 -> 5
Q11	Do you have any general comment for the application? No comments on the interface (VR or Holo Table)	Open answer

Table 6.1: Test survey, section 1 for generic information

Section 2 - Holographic Table testing

	Question	Answer type
Q1	Activating commands in the holographic environment was easy	Range 1 -> 5
Q2	I felt comfortable in the holographic environment	Range 1 -> 5
Q3	I understood within a reasonable time what I could do in the holographic environment	Range 1 -> 5
Q4	How would you rate the usability of the hand-held device	Range 1 -> 5
Q5	How would you rate the usability of the holographic environment	Range 1 -> 5
Q6	An holographic visualization of BIM is useful for your studies	Range 1 -> 5
Q7	Being able to move the model view inside the table is useful	Range 1 -> 5
Q8	New "Section" and "Heatmap" tools are useful on the Holographic table	Range 1 -> 5
Q9	New "Section" and "Heatmap" tools are easy to use on the Holographic table	Range 1 -> 5
Q10	How would you rate the usability of this app on the Holographic table? (first approach)	Range 1 -> 5

Table 6.2: Test survey, section 2 for Holographic Table testing

Section 2 - Holographic Table testing

	Question	Answer type
Q11	How would you rate the usability of this app on the Holographic table? (after a few steps and explained)	Range 1 -> 5
Q12	Overall, do you find this application on the Holographic table useful for your studies?	Range 1 -> 5
Q13	If possible, would you use this application on the Holographic table?	One of • Yes • No • Maybe but in specific cases
Q14	Overall: Do you prefer using the Holographic table or the standard computer version?	One of • Holographic table version • Standard computer version • No preferences
Q15	Did you find something annoying/something you would want to be changed/added in the Holographic table version? Sincere answers will be appreciated	Open answer

Table 6.3: Test survey, section 2 for Holographic Table testing

Section 3 - Virtual reality testing

	Question	Answer type
Q1	Do you have any previous experience with VR?	Yes/No
Q2	How would you rate your previous experience with VR?	Range 1 -> 5
Q3	Moving in the virtual environment was easy	Range 1 -> 5
Q4	Activating commands in the virtual environment was easy	Range 1 -> 5
Q5	I felt comfortable in the virtual environment	Range 1 -> 5
Q6	I understood within a reasonable time what I could do in the virtual environment	Range 1 -> 5
Q7	How would you rate the usability of the hand-held device	Range 1 -> 5
Q8	How would you rate the usability of the 3D environment	Range 1 -> 5
Q9	Do you find useful to be able to access UI during VR mode?	One of • Yes • No • Maybe but in specific cases
Q10	Have you encountered difficulties using UI in VR mode?	Range 1 -> 5

Table 6.4: Test survey, section 3 for Virtual Reality testing

Section 3 - Virtual Reality testing

	Question	Answer type
Q11	Have you ever experienced VR motion-sickness before?	One of • Yes • No • Never tried VR before
Q12	Did you suffer from motion sickness while using the application?	Range 1 -> 5
Q13	Do you find new "Section" and "Heatmap" tools useful during VR mode?	Range 1 -> 5
Q14	Were "Section" and "Heatmap" tools easy to use during VR mode?	Range 1 -> 5
Q15	How would you rate the usability of this app on VR? (first approach)	Range 1 -> 5
Q16	How would you rate the usability of this app on VR? (after a few steps and explained)	Range 1 -> 5
Q17	Overall, do you find this application in VR mode useful for your studies?	Range 1 -> 5
Q18	If possible, would you use this application on VR mode?	One of • Yes • No • Maybe but in specific cases
Q19	Overall: do you prefer using the VR version or the standard computer?	One of • VR version • Standard computer version • No preferences
Q20	Did you find something annoying/something you would want to be changed/added on VR mode? Sincere answers will be appreciated	Open answer

Table 6.5: Test survey, section 3 for Virtual Reality testing

Section 4 - Interface comparison

	Question	Answer type
Q1	Which version was easier to you to use?	One of • VR version • Holographic table version • Standard computer
Q2	Which version you found more interesting to use?	One of • VR version • Holographic table version • Standard computer
Q3	If possible, which version would you like to use?	Multiple choice between: • VR version • Holographic table version • Standard computer
Q4	Do you have any final comment on the application and version comparison you deem useful?	open answer

Table 6.6: Test survey, section 4 for Interface comparison

7 | Conclusions and future developments

We designed, implemented and tested an application for enhancing user experience during BIM visualization, to be interfaced with the technological devices at LaborA. This application aims at developing new methods for teaching architecture at Polimi, exploiting the immersive Mixed Reality and Virtual Reality technologies to improve the immersive feeling during design and validation steps of the building process. During thesis development, first steps consisted in designing and implementing new features to better exploit alternative experiences other than classical 2D computer screen. Therefore, two devices at LaborA were chosen to provide the user immersive experience: the Euclideon Holo Table, for a Mixed Reality experience in between real and virtual environment, and Oculus Rift S for a completely virtual environment experience; both interfaces to these devices were designed and implemented from scrap exploiting Unity packages and APIs of proprietary software, for the Euclideon Holo Table, and open source Unity API for Virtual Reality on Oculus Rift S. This application was then tested with the help of Polimi students, mainly from Architecture, for a functional review of the features and experience capabilities, and from Computer Science, of a more technical review of the thesis implementation; other Polimi students and some non-Polimi were also invited for a more objective user experience review, not biased towards functionalities or implementation design. Students were provided with the interface to be tested on their owns, to gather data on how a new user would approach this application and how intuitive, or not, it can be; then a brief explanation of how commands works and features was provided and the user would be requested to gather some information on the model. Virtual, Mixed and Augmented realities are surely transforming most of software experiences today with an astonishingly speed rate, most of the students who tested the application didn't have experience in VR and were more biased towards it for the total immersion feeling that VR can provide, Mixed Reality turned out to be a very interesting approach to the problem, but still falls behind the Virtual Reality counterpart. Overall, both interfaces have been described as very interesting to be used. Future developments surely heads towards more user com-

fortability during the experience and new features to fully exploit the enormous quantity of data provided. Another possible future development can consists of the design and implementation for real-time modifications on the BIM, from appropriate software, taking place on the viewer. Lastly, new technological devices interfaces would greatly enhance this application, as a mobile version or a VR implementation with the Omnidiretional Treadmill.

Bibliography

[1] A man-machine graphical communication system. I. E. Sutherland. SketchPad, AFIPS Conference Proceedings 23, 1963.

[2] The BIM Revolution: A literature review on rethinking the business of construction. C. Allen and W. Shakantu, Nelson Mandela Metropolitan University, 2016.

[3] The Use of Computers Instead of Drawings in Building Design. AIA Journal, Eastman, C.M. 1975

[4] Building modelling the key to integrated construction CAD, Robert AIsh, July 1986

[5] What's Real About Virtual Reality? Frederick P. Brooks, Jr. University of North Carolina at Chapel Hill, 1999

[6] Advantages and Disadvantages of BIM Platforms on Construction Site, Rui Pedro Lopes Fernandes, Faculdade de engenharia da universidade do Porto, 2013

[7] The Ultimate Display, Ivan E. Sutherland, 1965

[8] Hand tracking for immersive virtual reality: opportunities and challenges Gavin Buckingham Department of Sport and Health Scineces University of Exeter Exeter, UK

[9] Ross, Douglas T. "Computer-Aided Design: A Statement of Objectives MIT USAF 8436-TM-4" (PDF). Massachusetts Institute of Technology.

[10] Ronald T. Azuma. A survey of augmented reality. Presence: Teleoperators and Virtual Environments.

[11] G.A. van Nederveen, F.P. Tolman, Modelling multiple views on buildings, 1992

[12] Paul Milgram and Fumio Kishino. A taxonomy of mixed reality visual displays.IEICE Trans. Information Systems, E77-D(12)

List of Figures

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