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Virtual and Augmented Reality in Architectural Design and Education

An Immersive Multimodal Platform to Support Architectural Pedagogy

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Abstract. Virtual Reality and Augmented Reality research in the architecture field show a variety of possible uses of systems to accompany designers, laymen and decision makers in their architectural design process. This article provides a survey of VR and AR devices among a corpus of papers selected from conferences and journals on CAAD (Computer Aided Architectural Design). A closer look at some specific research projects highlights their potentials and limits, which formalize milestones for future challenges to address. Identifying advantages and drawbacks of those devices gave us insights to propose an alternative type of system, CORAULIS, including both VR and SAR technologies, in order to support collaborative design to be implemented in a pedagogical environment.

Keywords. Augmented Reality, Virtual Reality, Design Education, Architectural Design

1 Introduction

In 1994, Milgram and Kishino [1] coined the mixed reality concept, illustrating a scale of realities, ranging from the real environment to the virtual environment, including both Augmented Reality (AR) and Augmented Virtuality (AV). Our focus will be on VR and AR, specifically their use in architecture. Both offer alternative types of design representations and have a high potential to enhance architectural ideation and design. Development of VR and AR didn't go as fast as expected, mainly due to technical issues and the cost of devices supporting those types of reality. VR can be experienced either with a HMD (Head Mounted Display) or within an immersive room. The commercialization of affordable HMD to support VR like the Oculus Rift, the HTC Vive, the Samsung Gear VR or the low-tech Google CardBoard, to name a few, makes it more accessible for institutions, universities or architecture studios to access and benefit from VR technology. Immersive spaces like CAVE's [2] or Panoscope[1] inspired platform still represent high investments for institutions or firms but had shown its worthiness. On the other hand, AR applications are available on a range of display devices, including easily accessible ones, like smartphones and tablets. The portability of those devices makes it suitable to develop on site applications to assist designers, workers and decision-makers to deal with design and construction issues.

In the first part of the article, a survey on research papers proposing VR and AR applications in architecture will give us an overview of the multiplicity of possible uses, for example to support immersive design, to visualize on-site simulations or to enhance collaboration. Existing survey articles on VR or AR research in the AEC (Architecture Engineering and Construction) field already gave a good overview of this research domain. Freitas and Ruschel's study [3] draw statistics about the evolution of VR&A research between 2000 and 2011. Portman, Natapov and Fisher-Gewirtzman's work [4] focused on the use of VR in architecture, landscape architecture and urban planning, synthetizing opportunities and challenges depending on each discipline. Wang's survey [5] of AR applications in architecture underlined the variety of user's interactions, display devices and tracking technologies, summarizing issues and challenges for future developments. Schnabel, Wang, Seichter and Kvan [6] proposed a theoretical framework to classify 7 types of realities, including VR and AR, that they exemplified with existing applications, showing how those can enhance urban and architectural design. Our quantitative study of more than 130 papers completes these previous ones. In the second part, platforms or projects' prototypes, that are analogue to our own, will be described, to point out their potentials and limits. Those references' analysis enabled us to define a framework for our application. In the last section of this article, we will introduce CORAULIS, an immersive multimodal platform designed by our laboratory research team that will be built in our university by the end of 2017. We intend to use this system as a design representational environment to support design review sessions during studio courses in the architectural design program. Finally, we will explain our motivations to develop such a tool, and underline the potentials, the challenges and limits raised by an equipment like CORAULIS.

2 General overview

The two cornerstones of VR are immersion and interaction [7]. Both are rarely completely achieved but remain VR's applications objectives and goals. VR gives the possibility to experience sensations and movement in an artificial environment that is a simulation of some aspects of the real world [7]. Concerning the field of architecture, VR applications' utilizations are wide, from design itself, construction and project's communication as well as collaborative decision-making. For Schnabel, Kvan, Kruijff and Donath [8], the manipulation of virtual environments during the design process pushes designers to better perceive space, for example its fluidity and functionality, without using 2D representations.

[1] http://panoscope360.com/ consulted 01/09/2016

On the other hand, AR systems combine the real and the virtual, and support a real time interaction and 3D registration [9]. AR applications in the architecture domain can be developed through a large type of systems, implementing HMD AR, Tangible AR, SDAR (Smart Device AR) or SAR which all include the merging of the real environment and virtual information using different techniques. The democratization of the use of smartphones and tablets opens a window for on-site AR to support interior design, building refurbishment or construction management. SAR and Tangible AR offer other types of use during the design process. SAR gives a chance to experiment on site, scale 1:1 design by displaying virtual data on the physical space, including walls, floors, desks or real objects [10]. For example, Raskar et al. office of the future [11] depicts how the use of common physical surfaces can serve as display screens to immerse users in a VE, supporting a remote collaboration. Tangible AR ameliorates collaborative design and the efficiency of decision making thanks to the accessibility of the design data represented in a more intelligible manner. The advantage of SAR compared to AR is that there is no added display interface like a tablet or a HMD.

The review of a corpus of articles from the Cumincad (Cumulative Index of Computer Aided Architectural Design) database outlined research conducted in VR and AR in architecture. The final papers were selected from the following conferences: ACADIA (Association for Computer Aided Design In Architecture), ASCAAD (Arab Society for Computer Aided Architectural Design), CAADFutures (Computer-Aided Architectural Design Futures), CAADRIA (Conference on Computer-Aided Architecture Design Research in Asia), eCAADe (Education and research in Computer Aided Architectural Design in Europe), SIGRADI (Sociedad Iberoamericana de Gráfica Digital). Two additional journals were covered, namely IJAC (International Journal of Architectural Computing) and Design Studies. 'Virtual Reality' and 'Augmented Reality' were used as key words in the Cumincad database, and on all the articles found (620 hits for VR, and 142 for AR, 01/09/2016), 122 were selected depending on their content (78 for VR and 55 for AR). Articles proposing studies on CVE (Collaborative Virtual Environment), VDS (Virtual Design Studio) or desktop virtual reality were put aside. In fact, articles on CVE and VDS show how the use of shared virtual environment can support remote synchronous collaboration. In most cases, the virtual environment is displayed on a desktop, which we consider as non-immersive representations, explaining why we didn't include it in our quantitative survey on VR.

All papers were semantically classified into six different categories. They were defined before surveying the articles and correspond to the features that we considered in the development of our platform's proposition. We intend to describe the current VR/AR research context where our proposition integrates, in order to point out its particularities. Some of the categories like collaboration, or education were reviewed previously by Freitas and Ruschel's in their study [3]. Our proposed themes are the followings:

- Communication and collaboration illustrates articles proposing the use of an application to enhance collaborative design and communication between decision makers (designers, contractors, laymen).

- Education represents papers where pedagogical issues are dealt with, for example a proposition to include VR or AR applications in a course curriculum.

- Representation focuses on the appraisal given by the types of visualizations offered by VR and AR applications.
- Sense and cognition regroups articles where the effects of VR and AR devices on the cognitive load or the multiplicity of senses stimulated simultaneously are highlighted.
- Design category rallies papers where systems were developed to accompany designers' creative process.
- System (hardware or software) corresponds to research articles precisely describing the device or application, like the software architecture.

Most of the articles are belonging to several categories (Fig.1).

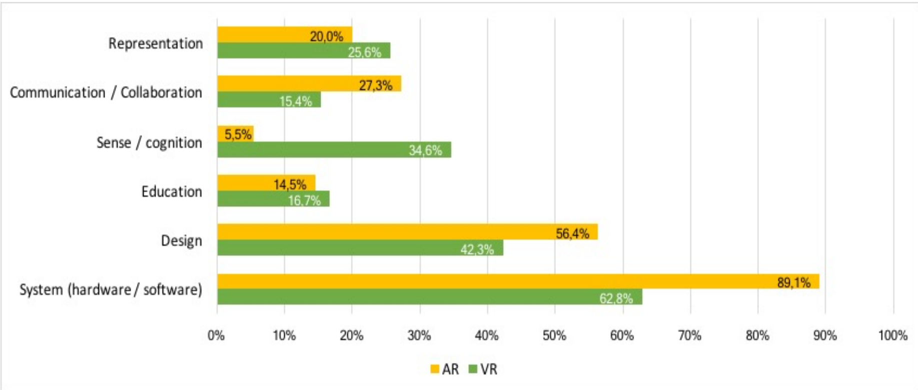

Fig. 1. Prevalence of the focus topics of the reviewed articles

The system's concept, either the hardware or software, is the most recurrent topic for both AR (89.1% of the AR papers) and VR (about 62.8% of the VR papers). In fact, most articles described the design process of the device as well as its potential or user tests results. Only 1/5 of the corpus focuses exclusively on the system. Design is the second prevailing topic as it was the focus for 56.4% of the AR papers and 42.3% of the VR ones. We noticed that research on applications' impacts on sense and cognition is more popular for VR applications that for AR ones, which seems relevant considering the immersive characteristic offered by VR visualization. The few papers on AR that are part of that category are putting forward cognitive load reduction thanks to the use of tangible interfaces to interact with the virtual world. Considering that VR technology is more developed than AR, this can explain the differences for that category. Communication and collaboration is the less prevalent focus for VR papers, while it is the third most addressed in AR ones. Indeed, tabletop tangible AR and on-site AR are brought forward for their easy-to-use characteristics and sharable quality favoring co-design between the users. On the other hand, the use of HMD for VR can be considered as a limit for collaboration since it affects users' communicational behaviors, particularly because it prevents primary natural non-verbal communication like eye contact. Fewer papers deal with pedagogical implementations. A lot of systems were tested by design students (architecture or interior design), but only the outcomes of its uses concerning the design activity are considered, and barely the effect on education. 40% of the total corpus described user experiences results, which was enriching to understand the limits and benefits of each study.

From this sample of articles, we can distinguish different display systems: using a HMD, a CAVE or an immersive screen for VR applications and implementing a HMD, a smart device / screen or any surface (SAR) for AR applications. Depending on the type of system used, the purpose and goals of the applications vary as shown in Table 1.

Table 1. Purposes and uses of VR and AR applications in architectural design, depending on the display system

	Display	Prevalent topics	Uses	Examples
VIRTUAL REALITY	HMD	> Design > Sens / Cognition > Education > Representation	> Immersive sketching and design > Sensitive experience > Remote collaboration > Spatial evaluation	[14] CAP VR [29]
	CAVE	> System > Design > Representation	> Scale 1:1 design > Spatial evaluation > Visualize simulations	[12, 26]
	Immersive screen	> Design > Sens / Cognition > Education > Representation	> Immersive sketching and design > Local and remote collaboration > Spatial evaluation	HYVE-3D [17, 18, 19] VizLab [27]
AUGMENTED REALITY	HMD	> Design > Communication	> Visualize simulations > Game oriented collaboration between designers > Remote collaboration > Merging digital and tangible	ARTHUR [32,33] BenchWork [35, 36] MxR [13]
	SDAR or screen based	> Design > Representation	> Visualize simulations > Reduction of design cognitive load > Including project management > On-site design > On-site technical data visualization	[34] [40] video-datAR [42] [43]
	SAR	> Design > Representation	> Scale 1:1 design > On site design > Seamless assessment of several design possibilities > Merging digital and tangible	SARDE [46,47,48]

In the next section, our focus will be on some of the applications referenced above, that were developed to assist designers alongside their design process, to support either ideation, simulation or evaluation.

3 VR and AR tools for architectural design

VR in design can be employed for VRAD (Virtual Reality Aided Design). This implies the interoperability between digital models (CAD – Computer Aided Design) and virtual models (models built in/for a VE – Virtual Environment) which points out one of the technical complications of VRAD environment's usability in this context. Designing in an Immersive Virtual Environment (IVE) is not a common practice in architecture, although it is quite developed in industrial design, in the automobile and aeronautic sector, to reduce cost production of scale 1:1 prototypes. Fuchs, Moreau and Guitton [7] explain that designers working with VRAD tools have to add more information to the model than when they design with CAD tools. Indeed, the behavior of each element has to be defined in the VE. The advantages of VRAD, according to these authors, are: creativity enrichment, contextualization of design outcomes or product, change of virtual models scale and explicitness of virtual representations, which favors the integration of the end users in the design process.

Several studies on the implementation of VRAD environment were conducted to assess its potential for early design stage activity [14], or to evaluate the impact of immersive full-scale design [15, 16]. Dorta's research team has worked for years on developing an immersive design platform, the Hybrid Ideation Space (HIS) and lately the HYVE-3D (Hybrid Virtual Environment – 3D) to promote immersive ideation and synchronous collocated or remote design collaboration [17, 18] (Fig.2).

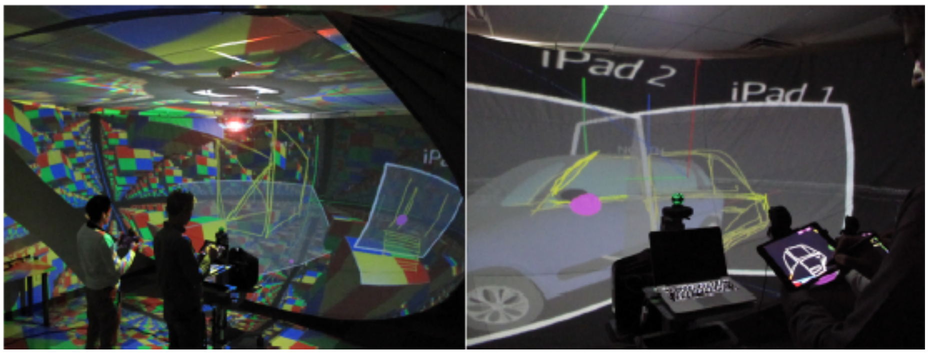

Fig. 2. Hyve-3D in use (source [18])

The Hyve-3D offers the possibility to draw directly in the VE displayed on the 360° screen, using an Ipad which also serves as an interface for navigation like walkthroughs and diverse interactions with the VE. It acts as an immersive working space for designers who can sketch with a natural designer's tool to design in a digital environment. The fluidity between sketching and digital visualization enhances the user's design flow, and consequently the quality of the design outcome [19]. For Schnabel, Kvan, Kruijff and Donath [8], remote design collaboration was also their intention in implementing the Virtual Design Studio between students from the University of Bauhaus of Weimar and the University of Hong Kong. In that case, only one student at a time was in the VE, wearing a HMD to experience VRAD design activity. He/she was always in audio contact with the other members of the team, who were seeing the scene on a display monitor. The experiment showed that the collaboration between students was effective and that immersive designing upraised their experience.

As far as using VR during the architectural design process is concerned, to date, there are no relevant studies of its use in a real practice situation. Nonetheless, some professionals integrate immersive VR in their daily design activities as illustrated in Demangel's interview in Dezeen magazine[2]. However, experiments where VR integration for design activities was tested with professionals or students in architecture are well documented. Those studies focused either on the benefit of VR for students to understand structure and construction [20], on the comparison of different VR systems [21], on the implementation of a new working environment or framework for designers [22,23,24], on the evaluation of remote design collaboration [25], or on the integration of VR in the curriculum for design courses at architecture schools [26,27]. On that last topic, it seems relevant to illustrate two of those studies. Kalisperis et al. [28] made an experiment at Penn State University with the aim to enrich the design process with the use of an immersive space (V-shaped screen). Students from 2nd and 3rd year of architecture took advantage of the platform for a semester for a specific course, as well as some of the 5th year, to work on and present their final project. The study showed how students adapted the platform setting depending on their needs, either for design or communication. The second research experiment took place at the College of Architecture and Planning of Ball State University. For three years in a row, the CAP VR environment, composed of a HMD, served as a design environment for 2nd year students [29] (Fig.3).

Fig. 3. CAP VR environment (source: https://capvrenvironment.wordpress.com/)

Results showed that students using this immersive environment to visualize their projects, enriched their spatial experiences, and enhanced their design outcomes. Students judged the CAP VR environment as beneficial for their design process. Although a few authors published on the advances of the use of VR in architecture to

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2 http://www.dezeen.com/2015/04/27/virtual-reality-architecture-more-powerful-cocaine-oculus-rift-ty-hedfan-olivier-demangel-ivr-nation/ consulted 09/05/2016

propose a framework for VR in architectural design or education [30, 31], that lack of research illustrates a potential gap to fill in the future.

As shown in the quantitative approach, collaboration and communication are one of the main qualities brought out from using AR applications for design activities. Only a few studies were made in situ, in real practice cases, but many systems were tested by professionals within research laboratories that are worth detailing. Experimentations using ARTHUR highlighted different behavior's patterns in design collaboration with or without the AR system [32,33]. The sharable quality of the information displayed was brought forward to support design efficiency. In that case, users wearing a see-through HMD, were able to generate new shapes and display agent behavior like pedestrians by using a PHO (placeholder object), a pointer or with gestures. Those features helped them in their design decision-making, thanks to the visualization of alternatives solution and dynamic simulations. Another study, from Gül and Halici [34], depicts different behavior's patterns in collaborative design depending on the workspace used, in that case an analogue model environment or a SDAR environment. They argue that using their SDAR application, the efficiency of idea generation and design development raised thanks to a reduction of designers' cognitive load. To offer a collaborative design environment was also the challenge of the BenchWork system using TUI's as well as a HMD [35]. Users can visualize their design, create new shapes and scribble notes inside the virtual environment. This device was tested to evaluate its interface's usability. The results showed that handling several cubes with markers instead of a 3D pen for interactions, enhanced collaboration within the designer's team [36].

The CDP (Collaborative Design Platform) offers a relevant visualization setting combining a tangible tabletop system and a SDAR application in the last version of that prototype [37]. In this scenario, users can place foam mock-ups on the augmented table and in the meantime, visualize the 3D models of the whole urban area as well as 3D simulations like wind or shadows through a tablet (Fig.4).

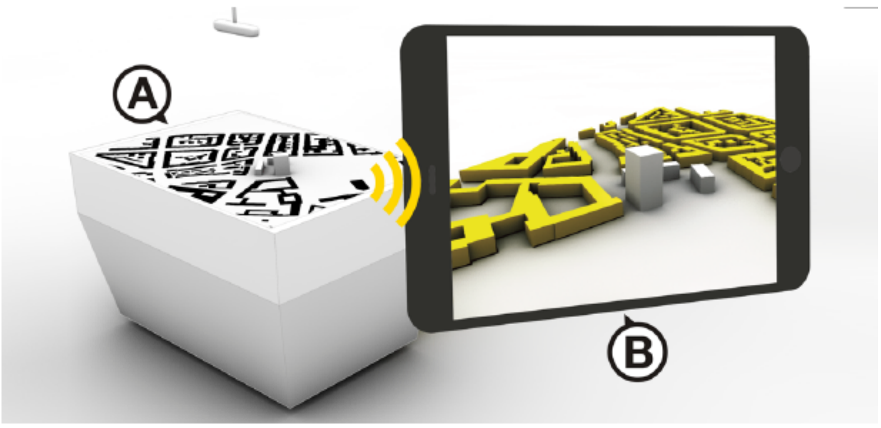

Fig. 4. Collaborative design platform with augmented tabletop and SDAR (source [37])

The aim of that interface is to facilitate design collaboration and active participation thanks to the tangible interface provided by the foam mock-ups, and to ease the design's decisions making process by augmenting the proposals with simulations. SDAR applications' potentials have been multiplied by the large commercialization of smartphones and tablets. Their uses vary from interior design as proposed by Hsu [38] who identified three models of SDAR, namely, filtered reality to arrange furniture into the room, parallel reality to visualize an entire portion of the room with augmented data and projective reality which consists of projecting a texture on the wall to see installations and wiring. SDAR systems are suitable for on-site AR, and have potential for integrating information technology for building refurbishment [39, 40], building management and construction [41] or future project's visualization [42, 43]. Linking BIM (Building Information Modeling) and AR is also a way for the actors of a design project to take advantage of an alternative way to represent technical data on a smart device, facilitating discussions between professionals and laymen [44, 45].

On-site design is the goal of several SDAR applications described before. Tonn, Petzold, and Donath [46] shared the same intentions by proposing a SAR application for 1:1 scale design for interiors. The system provides an environment for both color design and image based design (Fig.5).

Fig. 5. SAR application for on-site design and visualization (source [44])

A pointer and GUI projected on the wall assist the user to change colors and textures, to draw lines and to place images, for example a window or a door. A user study, comparing four methods to make propositions for a color design, that were traditional 2D plans on paper, 2D Photoshop visualization, 3D digital model and SAR, showed that the use of 3D models and the SAR application for that task were perceived as more positive tool than the two others [47]. A complementary user study highlighted that the visualization of design alternatives and 3D spatial perception was increased while designing with the SAR system, instead of traditional pen and papers [48].

In design education, tangible AR is brought out as a system to enrich design in the studios because of the interactivity that it offers [49]. Indeed, TUI's and AR provide a link between tactile action and visualization. In that way, students can learn by active experimentation. Moreover, the interface is shareable, which means that it can support collaborative learning. Designs' propositions are augmented by information on buildings, for instance, distances between buildings. The Luminous Planning Table concept supported the same idea, with environmental data visualization: traffic, wind, shadows and glass reflection [50]. Other types of exploitations of AR applications range from teaching of building physics, to the enhancement of student design in the studios through an AR representation of their design proposals or the improvement of 2D panels presentations with the use of SDAR to complement 2D representations of a project with dynamic and interactive ones [51]. An implementation of SAR for students in interior design, with the SARDE system (Spatial Augmented Reality Design Environment), showed that it supported their design decisions, and gave them more confidence to present their project [52]. The aim was to narrow the gap between what students think and tell about their design and what they actually show through their design representations. That last issue was not completely reduced with the SAR system, even though students felt that they better understood the connection between their 2D representations and the full scale one. Nevertheless, thanks to the SARDE device, students were able to design on site, and remodel their proposition.

As well as for VR and education research, only a few papers dealt with a framework to implement AR in the design education curriculum. Chen and Wang [49] made a proposition for an implementation of Tangible AR to increase and facilitate knowledge transfer and skill development. More recently, Morton [53], suggested that implementing AR systems in design studios could improve students design learning process since multiple solutions can be assessed faster and in a seamless way. Moreover, the author explained that linking BIM and AR provides alternative possibilities of data representation that students could benefit from during their learning process.

As we have seen, relevant research was conducted in order to provide suitable devices and applications to support the architectural design process. The intentions are either: to augment collaboration between the actors of a design project (remote and collocated); to increase designer's representation of his design by enhancing his embodiment in the EV; to provide a more natural interaction with the design object to enrich ideation; or to facilitate design activities by reducing the cognitive load required to evaluate design solutions. Depending on the end user and the objectives of the application, the physical and technical features are adjusted (display mode, user interface, number of users). The representation type differs in accordance with the display. SDAR applications mostly offer top down views on the scene, whereas HMD VR provide first person immersion in the VE.

Only a few papers focused on the appraisal of VR and AR use in terms of design education which offers an opportunity to develop a framework for the use of applications to support design learning. Many propositions focus on enriching design activities, which can be a part of design education process. However, for a pedagogic implementation, the application's features should be adapted. For architecture students, the design studio is the cornerstone of their curriculum. The CAP VR and the BenchWork systems were oriented to support design studio sessions, as well as the Luminous Planning Table. Except for that last example, the communication between students and teachers is hindered because users are wearing a HMD. Only one type of design representation is used for each of those device: immersed first person view for the CAP VR, and top down view for BenchWork and the Luminous Planning Table. Nonetheless, architects always work with multiple design representations. In the following section, we will underline the importance of the use of a variety of external representations' modalities during studio sessions.

Considering the significance of communication and representation, we will argue why exploiting the potentials of VR and AR can support architectural design learning. Merging enhanced top-down and first-person views of the same scene within the same immersive platform can provide a suitable representational environment for the critique sessions.

4 Towards an immersive VR and SAR platform to support design learning

Designing moments during the critique sessions help students to learn how to design, either by seeing their instructor designing or by experiencing collaborative design with their tutor [54, 55]. During design studio critique, students and instructor discuss design issues which drive the evolution of the students' designs [56]. Designing can be performed during the session, by either the student, the instructor or both. This moment is pedagogically important, which is why, collaboration and communication should be a primary concern. Conversations on design issues and potential solutions revolve around design representations. Miscommunication between students and instructor can penalize the learning potential of the discussion. The lack of constructive communication is driven by misunderstandings, that can be a consequence of the gap between the design expertise of both student and instructor, as well as a difficulty to synchronize the student's and the teacher's mental model of the design object.

Designing implies the manipulation of multiple types of representations. Indeed, architects work simultaneously in a synthetic and analytic way, which explains why they need to use a variety of design representations. The variety of points of view on their design enables them to deal with specific details in parallel to global concepts. Goel [57] established a connection between design phases and the types of representation used for a specific design activity. He considered two kinds of transformation of the design representation: a change in a concept or a detailing of an existing concept. External design representations perceived by the designer impact the design process evolution [58]. Design knowledge is embedded into external design representations, and their manipulation influences the direction taken during the design process. Therefore, handling representations during the critique session affects the overall student design process and its outcome.

Experienced architects have spatial representation skills allowing them to switch naturally from a planar representation of space to a 3D representation of the same space. It implies that while designing a project in a 2D plan, with a pencil and a sheet of paper, they mentally and seamlessly construct the spatial representation of that space. Nevertheless, students in architecture are still novice in manipulating their design representations. They are used to produce several representations (for example a section, a mock up and a plan) of the same object, that sometimes do not correspond to each other. The issue with traditional representations (plans, sections, 3D models, mock-ups, renderings) is that they are disconnected. It means that no link or synchronization is kept between the diverse representations of the same object.

We underlined several issues that could lead to a diminished pedagogic experience during the critique sessions: the difference of expertise between instructor and students in handling design representations and accurately representing the design object; misunderstanding and miscommunication due to a lack of synchronization of the student's and tutor's mental model of the design object. We believe that by modifying the representational environment used during critique sessions, enhancing it with VR and AR technology, it could benefit each session learning outcome for the student.

Systems using both VR and AR on the same device are not that common. However, Schubert, Anthes, Kranzlmuller, and Petzold [59] and Wang [60] already made that proposition to use both technologies to provide designers the possibility to switch from exocentric to egocentric view within the same physical space. The first example is an alternative configuration of the Collaborative Design Platform presented earlier. In that case, the table top is connected to a CAVE environment (Fig.6). On the other hand, the ARUDesigner concept is to use the same HMD to switch from a view of a table top in AR and the first person view in VR (Fig.6).

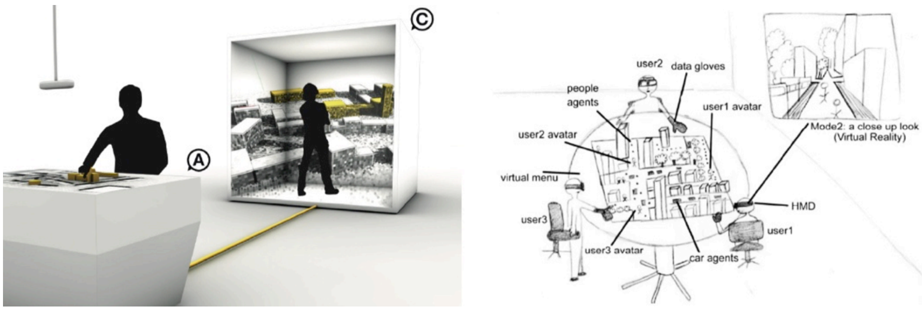

Fig. 6. (Left) A possible CDP configuration with the augmented tabletop (A) and a CAVE (C) (source [59]) (Right) Concept of the ARUDesigner project (source [60])

Both projects included simulations (wind flow, shadow cast, agent-based simulations) to help users assess their design propositions. With the ARUDesigner project and the Collaborative Design Platform, designers can experience both representations within the same space, and the connection between those representations is held since the same virtual model is used to create the visualization layers that are displayed.

As we mentioned before, designers need to handle design representations at multiple scales and from diverse points of view to perform analytic and synthetic cognitive activities that are inherent to the design process. Moreover, for a pedagogical use, we have to consider the synchronization of those representations to enhance their comprehension and ease the communication between the participants of the critique session. Using traditional media, no simultaneous link between distinct representation's prop like a 2D section and a 3D digital model are kept. Our proposal is to offer, for design studios, an immersive design representational environment providing synchronized top-down view and first-person view on the student's design, mixing VR and SAR techniques that will support user interactions in both spaces. By providing a dynamic interaction between a top down enhanced view on the project (analogous mock-ups enriched by an SAR application) and an immersed first person view (immersive VR), we intend to smooth the transition from one representation to the other one. Featuring this asset, we expect the design process during the session to be improved. Indeed, each user will access both egocentric and exocentric views within the same immersive space that will favor the collaboration within instructor and students. Moreover, it will facilitate individual spatial comprehension of the design, and this could reduce the gap between the critique participants' perceptions of the design object.

CORAULIS platform will support immersive VR thanks to its 360° screen, providing visual and aural immersion as well as SAR (4 of the 10 beamers will be use to project textures in the center of the platform). In our case, SAR will be used to map printed 2D plans or sections and mock-ups display on the tabletop. The same virtual model will provide input data for both SAR projection and the immersive first person view projected on the circular screen. We consider the representational environment offered by our platform as an illustration of the WIM (Worlds in Miniature) metaphor, coined by Stoakley, Conway and Pausch [61]. In the WIM paradigm, both exocentric and egocentric views on the building are displayed in the virtual world. The concept is to facilitate 3D objects manipulation in the virtual environment by representing a miniature replica of the life sized scene visualized in a HMD. Users can seamlessly interact with objects in both representations. The WIM metaphor supports a better visualization of space. It can help for navigation and orientation, and offers diverse objects' selection possibilities. Within CORAULIS platform, the miniature replica will be the augmented tangible objects, either mock-ups or 2D plans (Fig.7).

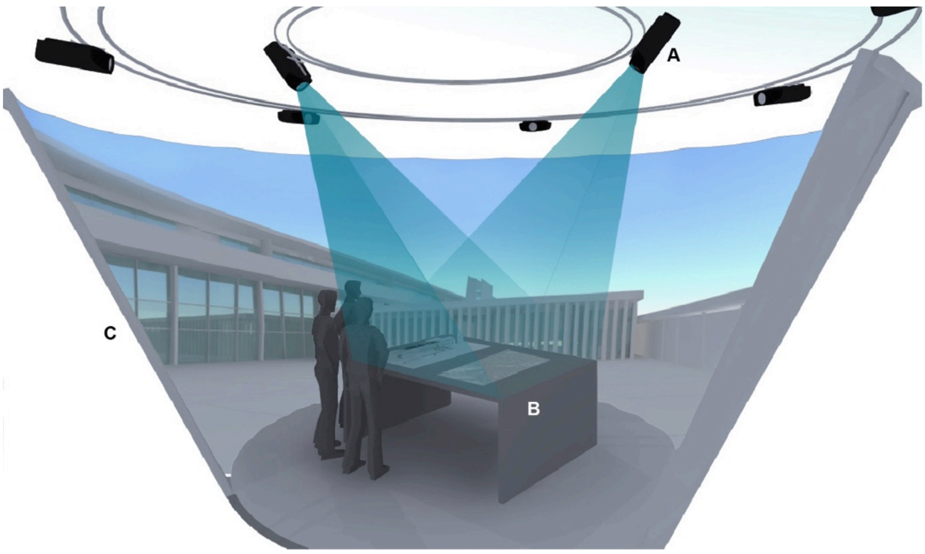

Fig. 7. Possible configuration for CORAULIS (A: beamers for SAR, only two are represented in the image, B: tabletop with augmented plans and mock-up, C: immersive screen)

To maintain the WIM paradigm concept, both visualization environments will act as navigation and interaction interface. Our challenge will also be to keep a synchronization between the SAR tabletop and the full-scale egocentric view of the same scene, projected on the 360° screen. Our application framework to be used in CORAULIS is composed of three modules: the virtual model module, the visualization module and the interaction module, as outlined in Fig.8. The virtual model will be based on a 3D model importation (a BIM model for instance). Simple simulations will then be generated and regrouped with the texture layer, in a conceptual simulation layer. The same virtual model is exploited within the visualization module that includes the SAR layer and the VR layer. The interaction module offers navigation within the virtual model either by walking or flying, as well as a GUI interface to activate simulations' layers.

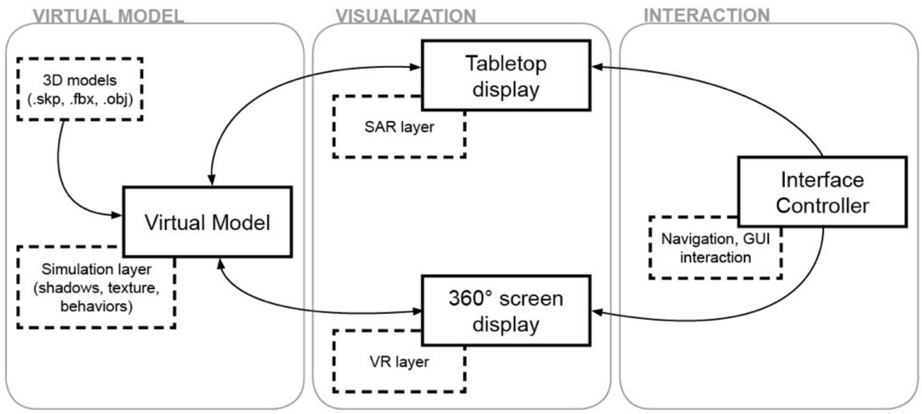

Fig. 8 Application framework for CORAULIS

During the critique session, the first part consists of the student presentation. He could navigate in the scene to support his idea. Within the navigation mode, participants will see an avatar moving on the tabletop projection while the first person view is changing according to the position of the avatar in the 3D virtual model. If needed, the simulation layer could be handled through a GUI displayed either on the screen or the table top. The efficiency of the proposed design solution can be discussed based on the shadow cast. If the time setting is changed, the shadow simulation will adjust accordingly in both views. The framework we proposed is a preliminary version of what can be implemented. For example, TUI's interactions could be developed by moving mock-up elements to try alternative possibilities, displaying modifications in the egocentric view in real-time. Primitives, like cubes representing building outline, could be generated and arranged within the virtual model with the GUI, and appear in the VR space and be represented by their shadow cast in the SAR space.

The proposed framework is specific to address local collaborative design activities in a pedagogic setting. The challenge raised by such a system and platform is to take advantage of both VR and SAR technologies: the feeling of embodiment for VR and the sharable quality of the augmented tabletop for SAR, to support design and co-design. Design is a collaborative activity, which includes individual moments of ideation. We aim to provide a platform for both individuation and collaboration by creating an environment that corresponds to the particularity of designing activities during studio critique sessions. Our system will work without a HMD which seems more relevant to offer a suitable environment to support collaboration and communication. The first-person view and full scale immersion will improve users' understanding of the student's design object. The consideration of the human scale perception of space is essential in architectural design and will help instructor and students to evaluate their design propositions. Moreover, the enrichment of tangible object (mock-ups) with SAR, offers an alternative and accessible way to visualize technical data that designers rely on. Compared to other devices that removed physical representation of the object being designed, our aim is to favor merging digital and physical representations. Architects usually work from a top down view or a bird-view that is why conserving that type of representation seems essential. Both egocentric and exocentric representations will be viewed in the same space. Complex design actions, to be processed and achieved, rely on representations switch including a change of format, scale or level of detailing. The switch will be addressed within that dynamic and interactive way to smooth the transition from one media to the other. The platform is not yet constructed, so the limits of the framework are not clear. The interaction/controller interface to handle those multiple representations is a challenge to undertake. Indeed, the cognitive load needed to interact and apprehend the whole system could affect the performance of the users. Users experiments will be conducted in order to assess the usability of our framework in such a pedagogic context.

5 Summary and discussion

This article provided an overview of applications of VR and AR in the field of architectural design. A high diversity of devices and systems have been developed in laboratories, however, in real practice, there are still few studios or firms benefiting from those technologies. Nevertheless, user studies showed the potentials of VR and AR applications in term of ideation, collaborative design, building management and design education. Only a few of those systems were designed to support design critique sessions in term of pedagogic outcomes. We can distinguish six families of systems that were used for either design studio sessions:

- HMD VR, for example the CAP VR system
- Immersive screen based VR, like the HYVE-3D
- Tangible AR, as illustrated by the Luminous Planning Table
- HMD AR as proposed by the BenchWork system
- SDAR (no example of SDAR use for design critiques were find in our survey)
- SAR, as exemplified by the SARDE system.

The CAP VR environment proved to be efficient to enhance the quality of students' design. Student's immersion in the virtual model of their design augmented their spatial comprehension and enriched their design's evaluation. However, the communication with the tutors wasn't seamless because students were wearing a HMD. The Hyve-3D offers a perfect environment for co-ideation, either collocated or remote, during the critique. Both 2D and 3D representations are exploited, although no physical representation can yet be integrated in the platform. On the other hand, the Luminous Planning main feature was the augmentation of tangible mock-ups. The intention of that device is centered on representations to enrich the critique and discussion more than to promote designing during the session. The drawbacks mentioned by students were that simulations' display (wind, shadows, traffic) oriented the design process. The BenchWork system was used by students only in the studios. Its objective is to offer a better collaboration space for co-designing. As well as for the CAP VR, communication can be obstructed by the wearable device. The SARDE system suits onsite, scale 1:1 interior refurbishment design but cannot be applied for architecture (building scale). Its use was also centered on improving students designing process, without considering student/instructor communication. Our proposition is an alternative to those devices. Our system, blending both VR and SAR technologies, aims to benefit from the assets of each of them. For a pedagogic use during the critique sessions, it seemed relevant to use an immersive screen for VR instead of a HMD, in order to conserve natural communication behavior. Students have to manipulate all kinds of representations types, physical and digital, which is why augmented mock-ups and plans appeared to have a high potential. CORAULIS will propose a design environment providing multiple enhanced viewpoints of the design object and seamless navigations and interactions in all of the representation spaces, that are merged in a single physical environment. Our future work will be to assess the effects of the use of our application in CORAULIS during a design review in an architectural studio at our university. This experiment will be run in the following year, and will serve as a test-bed to investigate the potential of VR and SAR for design critique, the limits of its usage and suggest guidelines to enhance design pedagogy in the architectural studio.

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