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AIR-MODELLING: A tool for gesture-based solid modelling in context during early design stages in AR environments

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ABSTRACT

Augmented reality (AR) technologies are just being used as interface in CAD tools allowing the user to perceive 3D models over a real environment. The influence of the use of AR in the conceptualization of products whose configuration, shape and dimensions depend mainly on the context remains unexplored. We aimed to prove that modelling in AR environments allows to use the context in real-time as an information input for making the iterative design process more efficient. In order to prove that, we developed a tool called *AIR-MODELLING* in which the designer is able to create virtual conceptual products by hand gestures meanwhile he/she is interacting directly with the real scenario. We conducted a test for comparing designers' performance using *AIR-MODELLING* and a traditional CAD system. We obtained an average reduction of 44% on the modeling time in 76% of the cases. We found that modelling in AR environments using the hands as interface allows the designer to quickly and efficiently conceptualize potential solutions using the spatial restrictions of the context as an information input in real-time. Additionally, modelling in a natural scale, directly over the real scene, prevents the designer from drawing his/her attention on dimensional details and allows him/her to focus on the product itself and its relation with the environment.

1. Introduction

The product development process, specifically the conceptualization stage, is a creative and iterative process (see Fig. 1) in which after analyzing the problem, the designer in an inspirational mode tries to express his/her ideas in an efficient flexible way [1]. In the case of products whose shape depends mainly on the spatial conditions of the environment, such as furniture, structure frames and piping networks, the conceptualization begins in the real environment of the product with mapping and ends in the design office with the 3D modelling of the concepts, away from the real environment of the product (see "Current" situation in Fig. 1). Because of this, each iteration is done asynchronously between the context of the product and the office. Thus, the designer has to go side to side for reviewing, performing model modifications, taking new measurements or discussing the solution with the customer, until accomplishing both convergence criteria: spatial restrictions and customer satisfaction. As a result, the conceptualization stage, and consequently, the whole design process for the aforementioned kind of products, actually demands much time and resources.

Some proposals have been presented for taking the context into account during the design process, although in an indirect way, in order to interact with it. Arbeláez and Osorio [3] present different approaches related to this, such as context 3D modelling, camera mapping or projection, camera solving, context scanner or photogrammetry and photomontage. Though these approaches allow the designer to visualize the product over the context, they are mainly computer-centric tools where the designer is desk-bound [4] and he/she does not have a clear spatial perception since the interactions with the 3D models are usually based on 2D interfaces, such as a 2D mouse and a 2D screen. In this way, there is not direct spatial mapping of virtual and physical spaces ([5]), making the design and visualization tasks more difficult.

On the other hand, mixed reality (MR) technologies (see Fig. 2) are being used in CAD as an emergent alternative for human–computer interaction, allowing the user to perceive 3D models more clearly and, in most cases, to perform actions in a free and natural way, moving his/her hands in a 3D space (3D input). Despite this, not all MR technologies allow the user to have a direct interaction with the context, such as virtual reality, whereas

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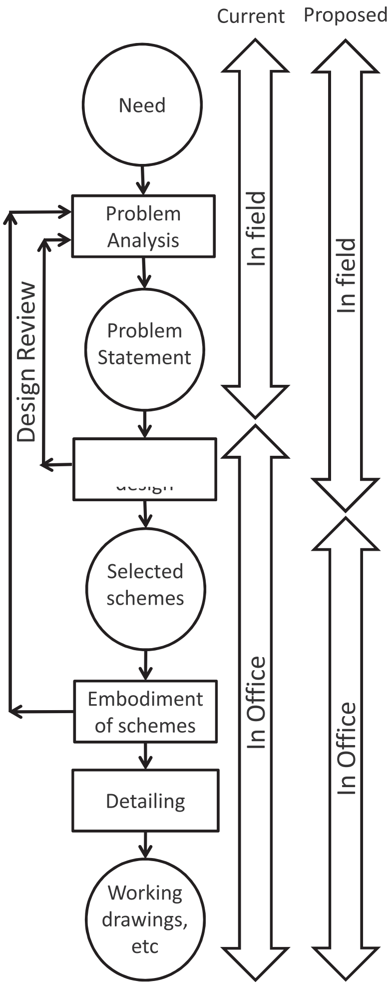


Fig. 1. Product design process.
Adapted from [2].

augmented reality (AR) technologies do. We aim to prove in this paper that modelling in AR environments allows to synchronize the conceptualization and the design review in the real scenario, using the context in real-time as an information input for making the iterative design process more efficient (see "Proposed" situation in Fig. 1), specially for products whose shape depends mainly on the spatial conditions of the environment. In this way, we developed a tool, hereafter so-called *AIR-MODELLING*, in which the designer is able to create virtual conceptual products in a quick and intuitive manner, taking advantage of hand gestures while he/she is interacting directly with the context. This allows the designer, to consider in real-time the spatial restrictions that the context imposes on the product configuration, shape and dimensions. Thus, the designer is able to create, review and update in real-time the virtual concept according to the requirements of the environment. Our case study is focused on office furniture design, which are products whose configuration and dimensions are, in most cases, strongly influenced by the context.

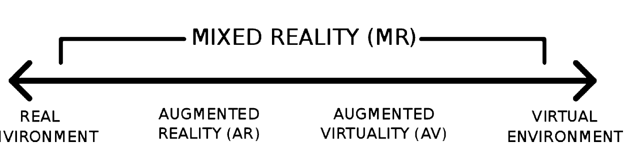


Fig. 2. Mixed reality continuum according to Milgram et al. [6].

This paper is organized as follows: the related work is presented in Section 2, the technical approach is described in Section 3, the test and results are presented in Section 4. Finally, the discussion and conclusions are summarized in Section 5.

2. Related work

An AR environment consists on merging a real scene with virtual information [7]. Applications go from medical fields ([8]) to video games [9], art design [10] and design in engineering, our field of interest. Particularly in CAD, the main advantage of this technology is that the user may interact with a real environment during the design process. Additionally, the substitution of the limited 2D WIMP (Windows-Icon-Menu-Pointer) interface with a natural 3D interface makes spatial manipulation and perception of 3D shapes easier due to the direct mapping between the physical space and the modelling space [11].

Most works merging AR with CAD have centered their attention on the latest stages of product design, such as assembly modelling [12–15] and visualization [16–18], staff training [19,20] and maintenance [21,22].

On the other hand, early stages of product design in AR-based systems are just being explored. Some researches have been directed towards 3D sketching, others towards geometric modelling and other towards solid modelling.

2.1. AR in 3D sketching

Haller et al. [23] presented a tabletop AR environment for collaborative 2D drawing, Xin et al. [24] presented a tool for creating 3D sketches on top of a physical napkin and Prieto et al. [25] presented a system for creating 3D frames for structural design. These proposals only allow wireframes creation, which could be difficult to understand for complex geometries. Bergig et al. [26] presented a tool for converting 2D sketches into 3D models and display them in AR environments, thus allowing 3D modelling, but from a limited and ambiguous 2D input.

2.2. AR in geometric modelling

Fiorentino et al. [27] and Santos et al. [28] reported the creation of tools for modelling of free-form curves and surfaces with tracked pens. Fuge et al. [29] presented a similar system which permits interaction with the virtual model through a tracked glove. These tools are very useful for designing products with organic shapes, such as car bodies, ski boots, motorbikes, packages, among others; but they could result difficult to use and inefficient for aesthetic design of simple-form products, such as furniture, structure frames and pipe networks.

2.3. AR in solid modelling

Tinmith-Metro, presented by Piekarski and Thomas [30], is a wearable system for exterior building design that allows creating 3D models over a real scene but only through a limited and traditional 2D interface where the pointer is controlled by the user's hand, making the manipulation of virtual objects complex. Similarly, Do and Lee [31] presented 3DARModeler, a tool for solid modelling from a traditional 2D desktop interface but with visualization in AR scenes. Novotny et al. [32] presented a prototype for visualizing and modifying 3D models that appear over independent markers, which implies that the modelling space is restricted only to the space over the working desktop. Ong et al. [33,4] created an application for creating and modifying 3D parts in collaborative AR environments. In this tool, the user can interact with the virtual model with only one hand though a virtual stylus rendered on a marker. This implies that the camera must always have both the marker related to the virtual part and the marker related to the stylus, in its range of vision. In this way, the modelling space is restricted only for small scale models. Pan and Choo [34] introduced interior design with AR technology with a system that lets the user to include and position pre-designed 3D models over a real scene for decorating interior spaces, but it does not allow editing these models in real-time. If any modification is needed, a traditional over-desktop work is required. Ng et al. [35] presented a AR-based system for solid modelling and part assembly using the hands; however, it is limited to table-top works and, consequently, it is restricted to small scale models lacking for real interaction with the environment, one of the main advantages of AR-based systems.

2.4. Contribution of this paper

After the literature review, it was concluded that there are not any tools for simple-form product conceptualization that allow both: (1) 3D-model creation and modification with a bimanual interaction using the context in real-time as an information input and (2) new, virtual-parts creation without the need of adding new physical associated markers in the scene. In this paper, we present a tool, so-called *AIR-MODELLING*, that addresses the aforementioned lacks.

3. Technical approach

AIR-MODELLING (AM) is a tool for solid modelling during early stages of product design in which the user can create with his/her hands in an easy and intuitive way, conceptual virtual models inside the real scene using AR technology. It allows the designer to use the context as an information input and to visually verify the dimensions, proportions and positions of the 3D models at the modelling time. This tool is more useful for aesthetic design of products whose shape depends mainly on the context, such as furniture, structure frames and pipe networks.

3.1. Interaction techniques

With the aim of taking advantage of the gestures that the designer does with his/her hands expressing potential solutions, after analyzing the problem, the interface of the presented system is based mainly on the user hands and their movement. Thus, the user may quickly give the dimensions and place boxes over the scene using his/her hands and a single-command remote control,

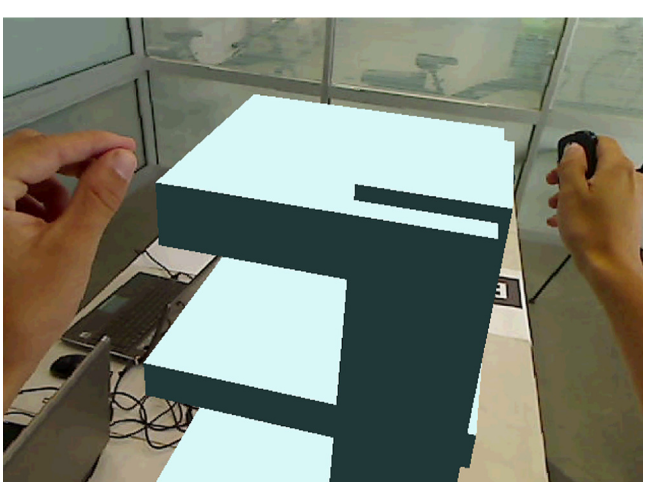


Fig. 3. Box creation using *AIR-MODELLING*. User view.

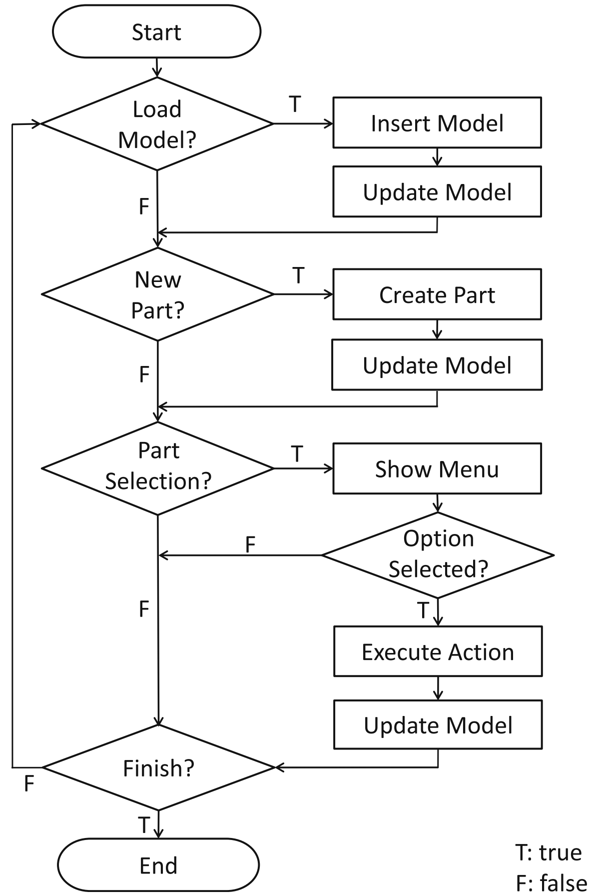


Fig. 4. Flowchart of the modelling procedure in *AIR-MODELLING*.

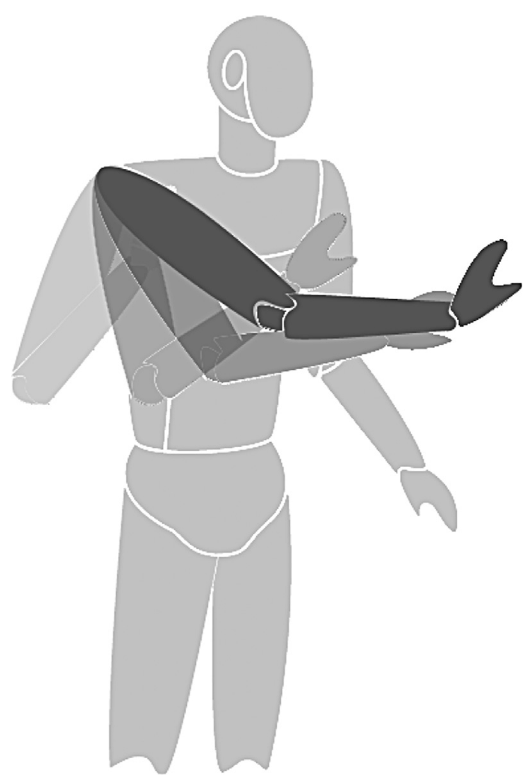


Fig. 5. Dynamic gesture for new part creation.

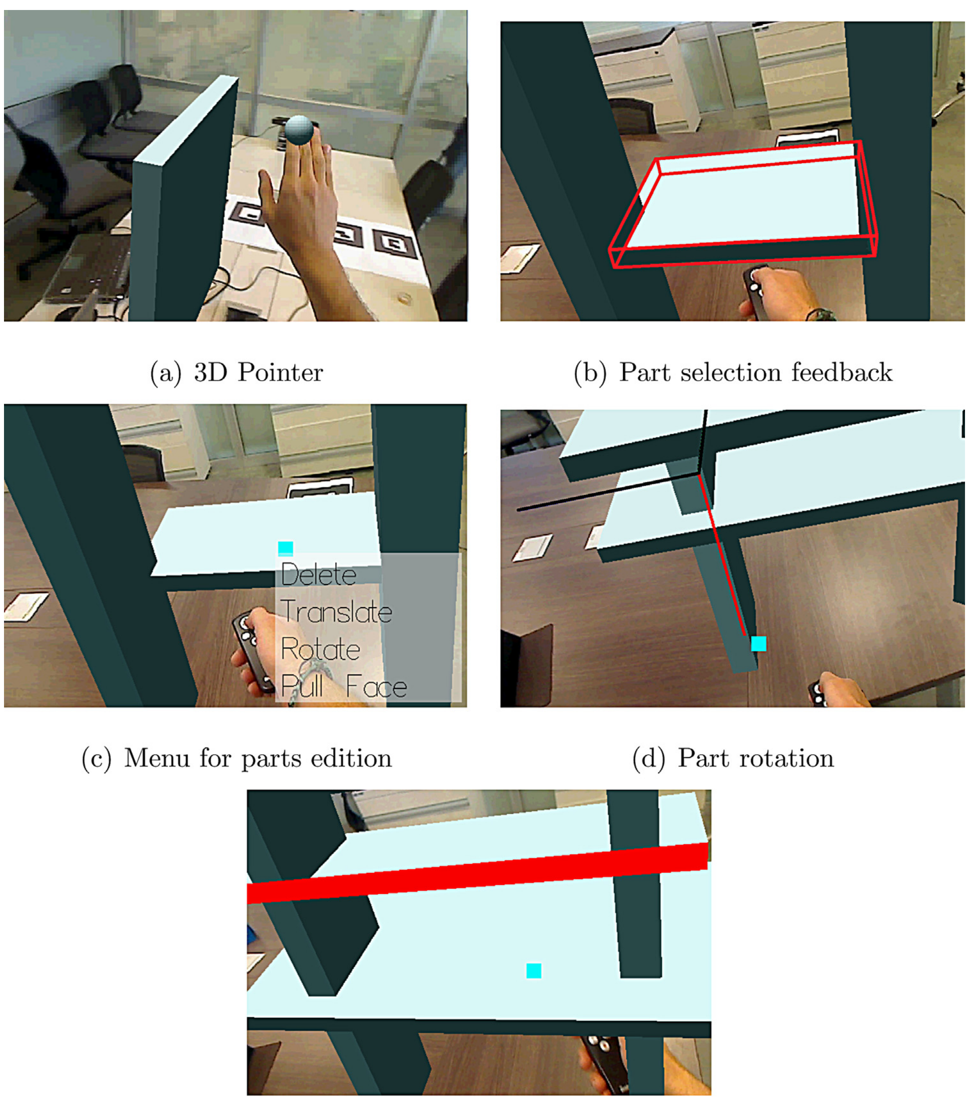
as it is presented in Fig. 3. Fig. 4 presents the flowchart of the modelling procedure in *AIR-MODELLING*, which is based on the top-down design approach. Initially, the user has the possibility of loading pre-designed models; afterwards, new parts can be created *in situ* by doing a gesture of push and pulling with his/her arm, as it is shown in Fig. 5, and then located and dimensioned with the hands in the desired place, confirming with the remote control. The gesture consists on holding the hand up, push it towards the sensor, and then immediately pulling it back. The user is always able to modify or delete parts of the assembly. For selecting any part, the user must touch it with the 3D pointer, which is a small sphere as it is presented in Fig. 6(a). Visual feedback is transmitted to the user highlighting the part with a wire frame as it is presented in Fig. 6(a), when the user touches any part of the model with his/her hands. For displaying the menu (Fig. 6(c)), the key of the remote control must be pressed when the part is highlighted. The menu allows deletion, translation, rotation and stretching of the selected part. In order to rotate a part, the user must first select the desired rotation axis as it is presented in Fig. 6(d). For the stretching, the user should select the face to stretch (Fig. 6(e)).

3.2. System architecture

As it is depicted in Fig. 7, *AIR-MODELLING* uses a depth camera (Microsoft Kinect®) to calculate the user's hands position vectors. The depth camera also detects a dynamic hand gesture (Fig. 5) which was implemented as the command for creating new parts. The other component of the interface is a single-command remote control that the user holds in his/her hand for event confirmation. Finally, a USB video camera captures the context which includes the fiducial marker that allows showing the virtual model over the context with the correct perspective projection in the head-mounted display (HMD). Fig. 8 presents the scene setup for *AIR-MODELLING* usage.

3.2.1. Software

The software of *AIR-MODELLING* was developed in C/C++ using Visual Studio 2010® and it is composed by multiple threads, as it is presented in Fig. 9 shows. The scene capture thread is in charge of capturing the scene, including both the user and the context. The reconstruction of the user's skeleton and particularly his/her



(a) 3D Pointer (b) Part selection feedback

(c) Menu for parts edition (d) Part rotation

(e) Part stretching

Fig. 6. Interaction with the 3D model.

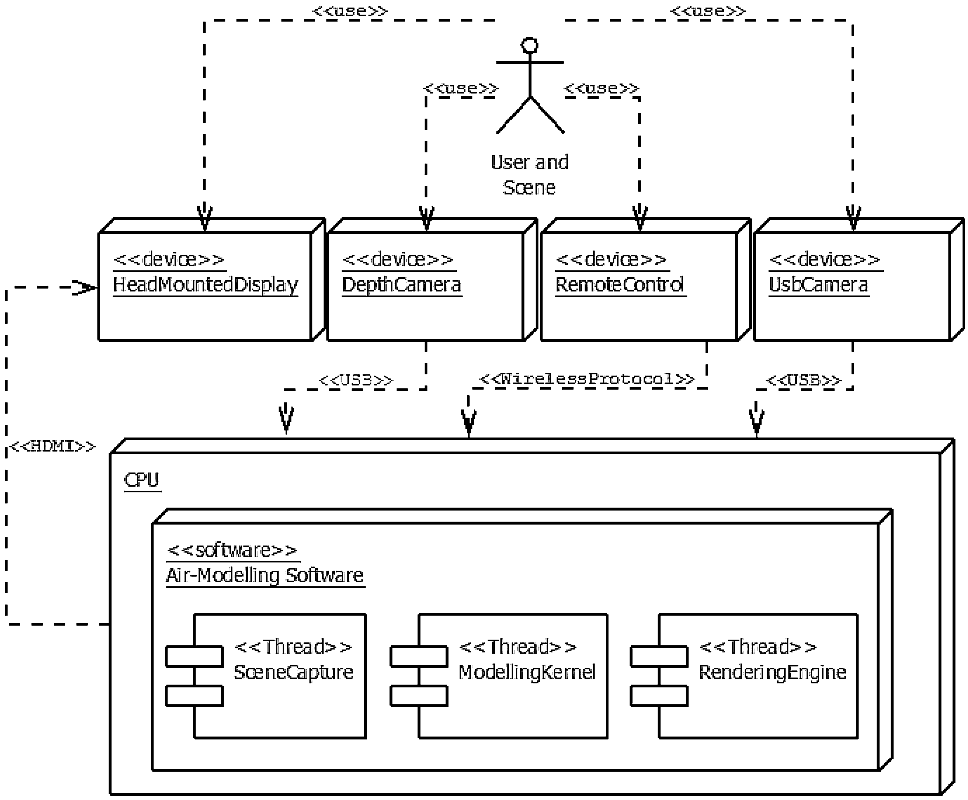


Fig. 7. System architecture.

hands' position is computed by the library for body tracking NITE™. In the modelling engine thread, a B-rep (boundary representation) of the virtual models is created, stored and updated according to the user's commands and hands position. The AR scene, merging the stream of the real environment captured from the HMD with both the user perspective and the virtual model, is provided by the rendering engine thread. The correct perspective projection is achieved by the ARToolkit [36] library. The virtual model is rendered using OpenGL.

For data interchange between threads, a limited buffer producer–consumer model was implemented (see Ref. [37] for details). The scene capture thread must provide the modelling kernel thread with the user's hands position vectors and the recognized gestures. The modelling kernel thread yields the geometry of the virtual models to the rendering engine. The saving and loading tasks of virtual models files are carried out by the modelling kernel.

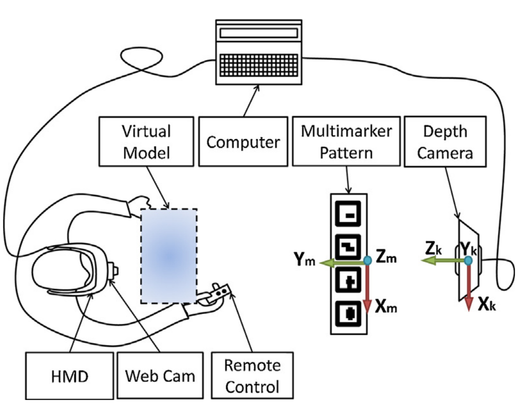


Fig. 8. Scene setup.

4. Test and results

In order to evaluate *AIR-MODELLING*, 21 users were invited to use it. As the presented tool was developed by the Product Design Engineering Research Group (GRID), most of the students were from the Product Design Engineering program at the EAFIT University. The users were selected with different characteristics

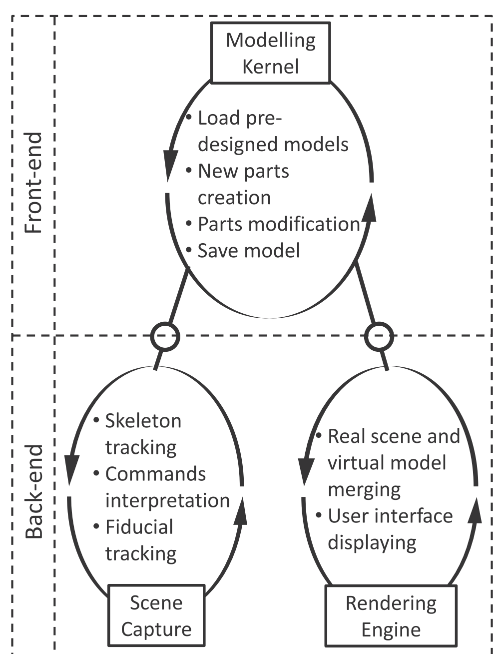


Fig. 9. Software architecture.

Table 1
Sample description.

Total users	21
Male users	15
Female users	6
Experience with CAD	19
Experience with SW	9
Experience with AR	6

and knowledge: 71% (of the total users) without any AR experience, 81% (of the total users) with CAD experience, from which only 53% with specific experience with SolidWorks® (SW), the software used in the test to compare the users' performance conceptualizing a 3D model. Table 1 presents the details of the sample.

In order to compare the traditional way to conceptualize products with the proposed tool, the test was carried out in two step: using *AIR-MODELLING* and using SolidWorks®, a standard modelling software for desktop PCs. In both cases, a brief introduction to the tool was first made, after that the users were asked to perform elementary tasks for creating and manipulating (translating, rotating, scaling) boxes. Finally, practical exercise was presented to each user in which they should propose a conceptual 3D model of a bookcase for certain context. The users should design a three-level bookcase over an existent desk and they were free to choose their own design but the same concept has to be modeled in both tools. The order of use of the tools for the exercise was altered to prevent that the usage of one of the tools conditioned the conceptualization, and consequently, the usage of the other tool. The whole session was videotaped to ensure that all actions of the user were recorded for analysis.

The evaluation includes quantitative as well as qualitative methods, such as questionnaires, user observation and interviews, for determining if the proposed tool really allowed a more efficient conceptualization and how the users experience was. The aspects evaluated during and after the test were:

- Time to complete individual tasks for creating and manipulating geometries.
- Time to complete a conceptual design of a proposed case study.
- Expressions of satisfaction, confusion, frustration or tiredness of the users using both tools.
- Tiredness on feet, arms and eyes after finishing the test.
- Preferred tool to create and modify boxes.
- Tool that allowed better perception of the modelling space.

Fig. 10 presents a comparison of the mean time to perform individual task such as creation, translation, rotation and stretching boxes using both tools. It is noticed that there is a significant difference in the time to create new geometries. However, in translation, rotation and stretching we obtained similar performance. On the other hand, we found a time reduction in 76% of the cases using *AIR-MODELLING* in comparison to the traditional way of creating 3D models for product concepts. It is, to a certain extent, due to the time associated to the use of measurement tools during the design process. No users employed measurement tools during the design sessions with *AIR-MODELLING* and in contrast 67% of the users used measurement tools modelling with SolidWorks®, once or twice (see Fig. 11). In Fig. 12 the histogram of the reduction percentages in the cases with positive results is presented. The histogram presents a peak at 40–50%, where the average reduction of 44% with a standard deviation of 20% is located. Some examples of the created concepts for the proposed exercise using both tools are presented in Fig. 13. It is noticed that the models created in the traditional CAD package are more accurate. However, the core in conceptual design is to conceive a physical configuration to meet the demand of the customer [38] and, in a later stage, the details of the model are refined.

After finalizing the test, all users were interviewed in order to evaluate their feelings and usage experience. Summarized results of the questionnaire are presented in Table 2. We found that almost half of the users showed tiredness gestures during the sessions with *AIR-MODELLING*, which was due to the weight of the HMD. Although only 33% of the users manifested tiredness in their arms or legs after using our tool, it is clear that prolonged use will generate ergonomics issues. Despite this, the majority of the users (76%) expressed to have a better perception of the modelling space using *AIR-MODELLING*. Results show a

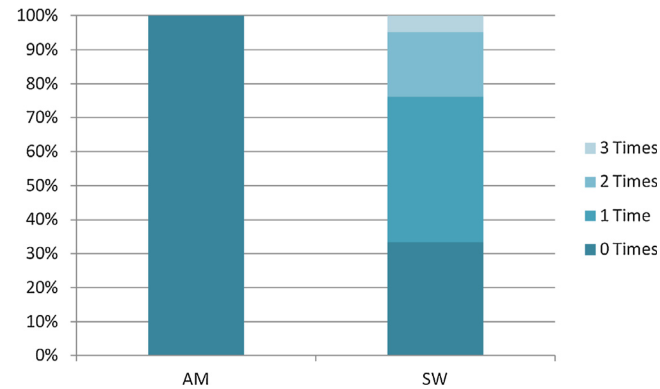


Fig. 11. Use of measurement tools during the tests using SolidWorks® (SW) and *AIR-MODELLING* (AM).

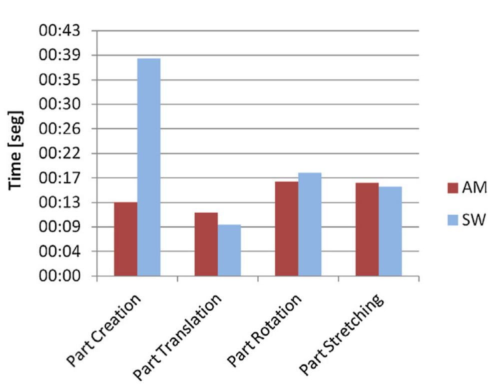


Fig. 10. Usability test results using SolidWorks® (SW) and *AIR-MODELLING* (AM).

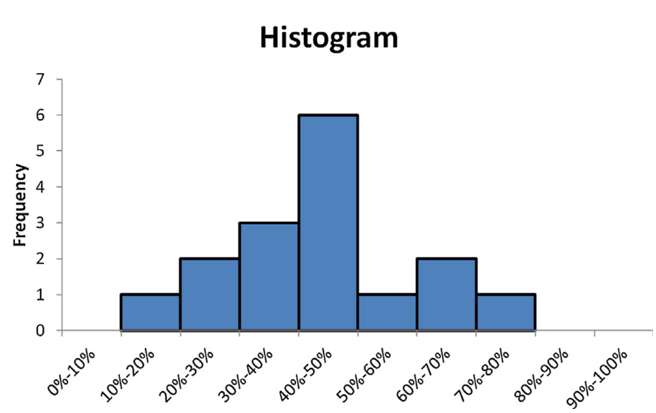


Fig. 12. Histogram of the modelling test results.

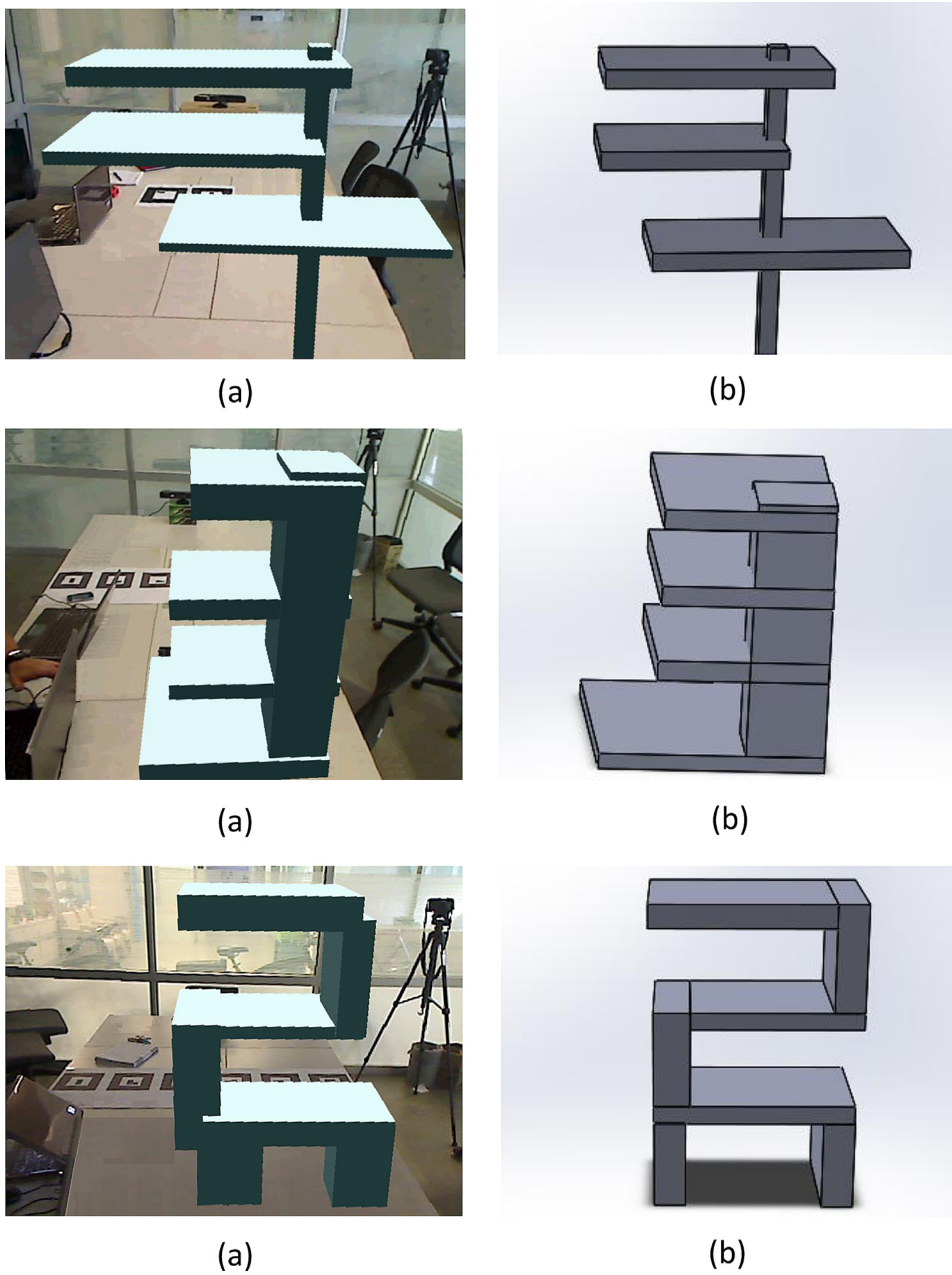


Fig. 13. Products developed in (a) *AIR-MODELLING* and (b) SolidWorks®.

preference of the users for boxes creation and translation using our tool but it seems that rotation and stretching do not generate a better experience than the traditional way using a WIMP-based interface (see Table 2).

Table 2
AIR-MODELLING (AM) usage results.

Tiredness gestures	48%
Despair gestures	19%
Satisfaction gestures	38%
Confusion gestures	10%
Tiredness on legs	10%
Tiredness on arms	33%
Tiredness on eyes	33%
Preference for AM for boxes creation	81%
Preference for AM for boxes rotation	48%
Preference for AM for boxes translation	71%
Preference for AM for boxes stretching	52%
Better space perception in AM	76%

5. Discussion and conclusions

In the present work, we found that modelling in AR environments using the hands as interface allows the designer to conceptualize quickly and efficiently, potential solutions, exploiting as much as possible, inspirational instants. Modelling in natural scale directly over the real scene, using the context as an information input prevents the designer from drawing his/her attention to dimensional details, and allows him/her to focus on the product itself and its relation with the environment, carrying out the design review during the conceptualization stage. This becomes even more relevant for products whose shape, configuration and dimensions depend mainly on the environment.

The obtained results (see Section 4) suggest that boxes creation is more efficient with a 3D input in comparison with the 2D interface of the traditional CAD packages, in which the user must perform many steps to create a simple geometry body: activate the feature, select the plane, draw a sketch and select the extrusion direction. These results, together with the fact that when the user expresses the dimensions and position of the model with his/her hands, he/she does not need to focus on the numeric value of the dimensions (see Fig. 10), generating a significant reduction in the time for products conceptualization.

We detected that marker-based AR software is very sensitive to scene luminosity, affecting the pattern recognition during the image processing and consequently producing some jitter in the virtual model visualization under certain conditions. Therefore, further research is required to improve the AR module of our proposed tool, in order to make the virtual models rendering more robust. On the other hand, it would be interesting to allow the modelling with more primitive geometries and features and prove the applicability of the tool in other products highly dependent on the context, such as piping networks and structure frames. Data interchange in standard CAD formats is required to use pre-designed models from commercial CAD packages and to pos-process models generated in *AIR-MODELLING*. In addition, it is clear that the scale of the products modeled in the presented tool is limited by the volume that the user can reach with his/her hands. In that way, future work is required for allowing to zoom in and zoom out the virtual model, in order to adjust it to the active modelling volume. This will allow a better performance developing both large-scale and small-scale products.

Finally, we believe that this kind of technologies would encourage both designers and customers, making the conceptualization of customized products more efficient with the reviewing during the product conception. In addition, it is possible to increase the customer satisfaction since he/she can visualize a virtual model of the product in natural scale over the real scene and take decisions before the product materialization.

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