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DiedricAR: a mobile augmented reality system designed for the ubiquitous descriptive geometry learning

E. Gutiérrez de Ravé [1] · F. J. Jiménez-Hornero [1] · A. B. Ariza-Villaverde [1] · J. Taguas-Ruiz [1]

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Abstract This article presents a mobile Augmented Reality system, called DiedricAR, aimed at the learning of Descriptive Geometry. Thanks to its ability to recreate virtual models in real space, Augmented Reality is a technology suitable for making Descriptive Geometry comprehension and interpretation easier. The DiedricAR application allows students to learn in autonomously way by using their own mobile devices (smartphones and tablets), that work as Augmented Reality displays over training material (DiedricAR exercise workbook) specially designed for the new learning model defined by the European Higher Education System. Compared to some of the existing Augmented Reality systems used to learn Descriptive Geometry, DiedricAR offers the advantage of being specifically developed for mobile devices giving the students the possibility of using ubiquitous learning to its ultimate extent by interacting with the didactical content (i.e. showing the desired intermediate step when solving dihedral exercises). The presentation of DiedricAR is completed by exploring some key items such as the potential benefits for students' spatial ability, the relationship between application design and user experience, and software performance on several mobile devices.

Keywords Mobile augmented reality · Descriptive geometry · Interactive learning environments

1 Introduction

Spatial perception is a very relevant skill [20, 38, 48] in engineering projects development, as it provides the necessary knowledge for performing the first phases of design in which the ability to expressing spatial thinking plays a very important role.

✉ E. Gutiérrez de Ravé
eduardo@uco.es

[1] Department of Graphic Engineering, University of Córdoba, Gregor Mendel Building, Campus Rabanales, 14071 Córdoba, Spain

The implementation of the European Higher Education System (EHES) attaches importance to the student's autonomous work and poses new challenges in subjects related to the graphic language of engineering [38]. In this situation, ubiquitous didactic resources, such as mobile Augmented Reality (MAR) systems become a very useful tool for teachers and students [11, 20, 58]. As a result, these Augmented Reality (AR) systems are the subjects of active research in education [10, 57].

The term Augmented Reality refers to the superposition of data and virtual information over the real world, that is added to what the user perceives naturally, creating an improved version of reality [59]. AR combines three-dimensional (3D) computer-generated objects and text superimposed onto real images and video, all in real time [35]. An interesting definition of AR has been described by Azuma 1997 [4], as a variation of virtual reality (VR). VR technology completely immerses a user inside a synthetic environment. While immersed, the user cannot see the surrounding real world. In contrast, AR allows the user to see the real world, with virtual objects superimposed on or composited with the real world. Therefore, AR supplements reality, rather than completely replacing it. According to Martin-Gutierrez et al. (2010) [35], with AR applications it is possible to show the user a common space where virtual and real objects coexist in a seamless way. From a technological point of view AR applications must fulfill the following three requirements [4]: combination of real and virtual worlds, real time interaction, and accurate 3D registration of virtual and real objects.

AR is an emergent technology [9, 27] with a huge impact on education [21]. One of the most promising features of AR is that it allows highly interactive visual ways of learning [32, 58]. Thus, it has been successfully used in classroom [12], E-learning applications [19] and remote laboratories [53]. The use of AR facilitates the understanding of abstract concepts which cannot be represented in 2D [1, 59] and an improvement in spatial vision [35, 37, 38].

The transition from computer aided learning (e-learning) to that assisted by mobile platforms such as smartphones and tablets, mobile learning, [49] responds to the fact that this technology is highly accepted by students [42] and offers advantages related to ubiquity and contextual learning [23]. An initial main pitfall was to find a robust and efficient technology to allow an AR application to run on mobile devices [55]. Nowadays, smartphones and tablets of a medium range have overcome this drawback.

At this moment, there are many educational AR applications focused on different fields [51, 58]. Among them are the initiatives promoted by researching groups such as CREATE [33], ARiSE [8] and MARIE [31], which are AR systems designed for learning subjects in different fields through interactive virtual models. *MagicBook* [7] is especially relevant as it has become the paradigm of AR interaction with books, known as augmented book, which is nowadays very popular. As Billinghurst et al. (2001) [7] stated, the *MagicBook* experience uses normal books as the main interface object. People can turn the pages of these books, look at the pictures, and read the text without any additional technology. However, if they look at the book through an AR display they see 3D virtual models appearing out of the pages. The models appear attached to the real page so users can see the AR scene from any perspective simply by moving themselves or the book. Following Billinghurst et al. (2001) [7], the models can be of any size and are also animated and users can change them by turning the book pages. When they see a scene they particularly like, users can fly into the page and experience it as an immersive virtual environment. Dias (2009) [13] identified several effects when using augmented book approaches, such as enhanced perceived values of learning material, educational illustration and better understanding of text material.

There are also mobile learning games based in AR such as those developed by the MIT and the *Education Arcade* [24, 25]. The most remarkable commercial project is *Science Center to Go* [29], that emulates small virtual laboratories in which primary and secondary students can simulate experiments. These systems allow the students to acquire knowledge from their own experiences [11].

The concept of Mobile Augmented Reality (MAR) was developed around the mid-1990s [2], applying Augmented Reality (AR) in truly mobile settings, away from conditioned environments, confined spaces, and the desktop [17]. Mobile Augmented Reality is one of the fastest growing research areas in Augmented Reality, partially due to the emergence of smartphones that provide powerful and ubiquitous platforms for supporting mobile Augmented Reality [5, 26, 40]. According to [28], MAR combines wireless communication, location-based computing and services and augmented reality to create an integrated interactive environment. MAR introduces a novel interaction method between the user and the system [43]. Users point their devices in the direction of an item of interest and the camera output augments the display with additional information about the environment [32]. In terms of architectural properties, the main components of MAR are [28]: A computational platform for the coordination of the tracking and the 3D record of the real scene; displays to incorporate the virtual data into the physical world; wearable or portable input and interaction technologies to interact with the augmented world; wireless networking to communicate with the system's infrastructure; and data storage and access technology for the data to be stored and retrieved as necessary. Following [28], MAR applications are highly decentralized, they focus on multiple objects in the environment and, as such, they need to devise means to individualize each object of interest, search for information that may be semantically attached to it, and present this information in a user- friendly manner.

MAR is one the growing technologies that have a great pedagogical potential and have been increasing recognized by educational researchers. With capabilities of merging virtual and real worlds together have given birth to new possibilities in improving the quality of teaching and learning activity [39]. Mobile AR systems, MARS, (e.g. [17]) offer some advantages in education such as: i) learning process is enhanced [58], ii) students motivation and attention are increased [3, 11], iii) mobile learning, m-learning, [23], (iv) lower costs in equipment, software and books.

According to the classification proposed by Specht et al. (2011) [47] about the educational patterns for mobile AR based on educational objectives and context information, Augmented books are the simplest form of relating real world objects and digital augmentations. In principle, these can be done by manual identification of objects via number codes, with camera based phones using visual codes. A mobile device is used for displaying the augmentation to the user. Mostly, these augmentations use the identity context to link augmentation and printed material. Via the integration of markers in books, different augmentations can be achieved and applications for more immersive book experiences or illustration of 2D static media with dynamic 3D media can be implemented [47].

As a result, it seemed fitting to test a MARS, based on the augmented book approach, specifically designed for learning Descriptive Geometry. With this in mind, an application called DiedricAR developed and used by the authors to teach the Dihedral System is presented in this work. Thus, some themes such as the potential benefits to students' spatial ability, the relationship between application design and user experience, software execution and stability on several devices and the advantages over some existing AR systems for learning Descriptive Geometry are explored here.

2 Related work

In the field of Graphic Expression in Engineering, some systems based on AR require advanced technology [22], such as HMD (head mounted devices), which despite offering a totally immersive and collaborative interaction, are very expensive and only available to reduced groups of students. There are more accessible platforms [1, 30, 37] which only require desktop computers or laptops equipped with a webcam, but the ubiquity problem stills remains.

There are a few studies about the application of AR to train spatial ability. All of them are desktop augmented reality (DAR) systems being the most relevant those known as Construct3D [22] and AR-Dehaes [35, 36]. Construct3D is a 3D geometric construction tool specifically designed for mathematics and geometry education. It is based on the mobile collaborative augmented reality system “Studierstube” [44]. AR-Dehaes is a didactic toolkit that provides the students a set of different kinds of exercises to train spatial abilities by means of an augmented book. Table 1 shows a brief comparison between both DAR systems and DiedricAR. MARS introduced in this work offers the Descriptive Geometry students an ubiquitous and autonomous use. According to [28], DAR applications are highly localized and usually superimpose information on one object in focus. In addition, DAR systems frequently require on-demand information provision regarding the object of interest. By contrast, MAR applications require real-time and continuous supplies of information regarding different objects of interest, typically in a context-aware manner. The freedom degree of the user increases in MAR systems compared to DAR applications.

3 Design of DiedricAR system

DiedricAR system introduced in this work has two main components as it is shown in Fig. 1: DiedricAR application and DiedricAR contents (workbook and models and markers). The proposal has to comply with the following requirements: i) Finding the ideal framework to develop AR applications that work in a robust and fluid processing on mobile devices; ii) Designing training material that assists MARS operation and complements the interactive content aimed at ubiquitous and autonomous learning (*m-learning*) of students; iii) Developing an application whose performance can be tested on different devices with the aim of improving the understanding of Dihedral System by using m-learning.

DiedricAR has been designed as a simple and robust system that gives clear information to the users through easy handling. Their interaction with the application can be classified as a “tangible interface with bookmarks” [18]. The user can handle the marker and the changes in distance and position are displayed through the virtual model rendered by the device.

DiedricAR application, whose menus arrangement is shown in Fig. 2, is able to identify and report to the user which exercise is associated with the marker recognized at every moment because all the markers and models are in the same dataset. Although the DiedricAR system has been described here by considering one dataset of exercises, the application has been designed to manage a large amount. By dividing the exercises into different datasets, it is possible to reduce the application load optimizing memory usage. In this situation, the user has to specify what dataset s/he wants to load by selecting it in the menu.

Table 1 Existing DAR systems to train spatial ability (Construct3D [22] and AR-Dehaes [35, 36]) and MAR system (DiedricAR) comparison, partly based on the information reported by [35]

DAR systems		MAR System
Construct3D	AR-Dehaes	DiedricAR
Domain		
• Construct3D is a 3D geometric construction tool specifically designed for mathematics and geometry education.	• AR-Dehaes is a 3D visualization tool designed for spatial abilities development based on simple technical drawing concepts.	• DiedricAR is a 3D visualization tool designed for spatial abilities development based on Descriptive geometry / Dihedral system learning.
Previous knowledge		
• Prior knowledge of geometry and mathematics are necessary to carry out the operations in Construct3D.	• Prior knowledge in technical drawing is not necessary.	• Prior knowledge in technical drawing is not necessary. • Some basic knowledge on Descriptive geometry / Dihedral system is required.
Content and learning mode		
• Open content: the teacher can propose new exercises to be solved with the system. • Teacher is the guide in the learning process. Face-to-face interaction between teacher and student	• Closed content: *MagicBook* approach, exercises are hard-coded. • Autonomous learning approach after initial presentation of the *MagicBook* operation. Teacher assistance is required only for the initial presentation.	• Closed content: *MagicBook* approach, exercises are hard-coded. • Autonomous learning approach: step by step exercises. Teacher assistance is not required because brief overview and application tutorial are included in the workbook.
Learning outcome		
• Primary outcome: learning of mathematics and geometry. • Secondary outcome: development of spatial abilities.	• Primary outcome: development of spatial abilities. • Secondary outcome: learning of some basic concepts of technical drawing.	• Primary outcome: development of spatial abilities. • Secondary outcome: understanding of some basic and complex concepts of Dihedral system and Perspective pictorial.
Equipment cost and availability		
• Sophisticated and expensive equipment (Server, HMDs, immersive cave). • Only can be used at a computer lab with special equipment.	• Simple and low cost equipment (a computer and web camera). • It can be used at home. A regular computer laboratory can be used, adding webcams to the typical PC configuration.	• Smartphones and tablets. • It can be used everywhere. It is ubiquitous.
Interaction		
• HMD, panel and instruments with sensors	• Mouse, keyboard and markers	• Touch interface and markers
Operating system		
• Windows server	• Windows	• Android / iOS

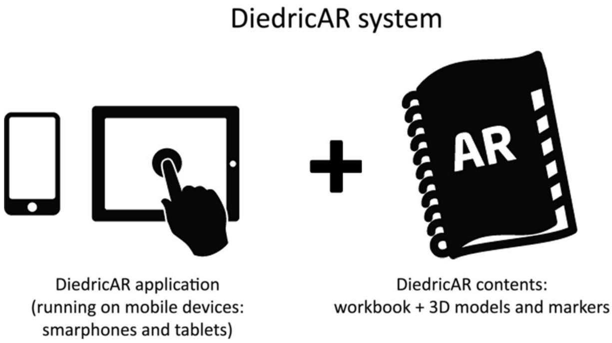

Fig. 1 DiedricAR system components

3.1 DiedricAR application

3.1.1 AR library and development framework

Although the hardware of mobile devices is constantly improving, the choice of the actual library and development framework plays a decisive role in performance [55]. The following requirements have to be taken into account for finding a suitable library and framework for DiedricAR application: i) optimal performance adapted to the processing constraints of mobile devices because the main difference between computers and mobile devices lies in the amount of their memory and transfer capacity [56]; ii) it had to be compatible with two of the most extended operating mobile systems, Android and iOS; iii) it had to have advanced interaction with 3D models such as pushing virtual buttons [45], not only markers for tracking recognition as well as the ability to associate models composed of several parts with a single marker [14]; iv) it had to be tested with good documentation and support.

According to these requirements, the library selected has been Vuforia SDK 1.5.9 [54]. The latter was designed by Qualcomm Developer Network to run AR apps on Android and iOS mobile devices. It is based in C++, so it allows the implementation of efficient applications by

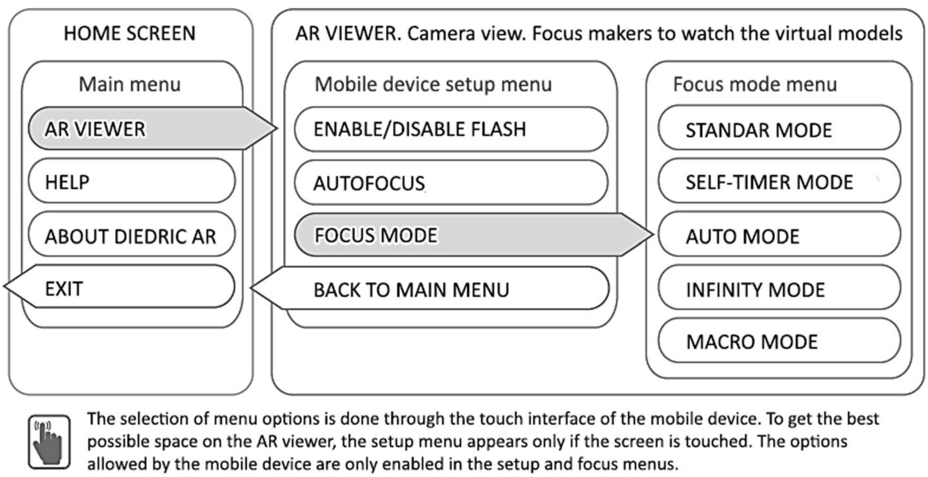

Fig. 2 DiedricAR application menus organization

direct control of the hardware resources of the device. Its main advantages are: i) marker recognition and tracking based on real images; ii) interaction through virtual elements (virtual buttons); iii) multiple markers tracking and recognition; iv) high level access to the hardware of the device, such as camera or flash; v) partially occluded markers reliable tracking and recognition.

Regarding the development framework, Unity3D [50] has been chosen. This is an object oriented framework with graphic interface which can build apps for many different platforms including iOS and Android. Unlike other frameworks, Unity3D allows an easy handling of virtual models.

3.1.2 Developing the application by considering user experiences

DiedricAR was designed by taken into account the principles proposed by Kourouthanassis et al. (2015) [28] in order to implement a high quality MARS from the point of view of user-centered approach. These design principles are the following five: 1) Using the context for providing content by employing sensor and marker technologies to collect contextual information in order to augment real-world objects with contextual information; 2) Delivering relevant-to-the-task content by filtering interactive content based on multiple contextual criteria, 3) Informing about content privacy by designing the functionality around different privacy spheres (i.e. public versus private content). This principle has no place in the context of DiedricAR usage, 4) Providing feedback about the infrastructure's behavior. The application should inform users regarding its current state or regarding changes in its state; and 5) Supporting procedural and semantic memory by using familiar icons and/or interaction metaphors to communicate the application intended functionality and ensure smooth user interactions.

Thus, DiedricAR was set up with the following features inspired by the design principles previously mentioned:

Principle 1 Use of tangible and reference markers to identify object properties. Use of finger tracking for gesture-based interactions. Interactive focus and context visualization. According to [28], finger-based gestures and tracking may interpret a personal association between the user and an object and adapt the application behavior accordingly. In addition, MARS raise the importance of user orientation, which may be used as an additional filter of information provision.

Principle 2 Development of adaptive interfaces based on camera and motion-based interactions. Following [28], MARS occupy a considerable amount of the user's perceptive and visual abilities, presenting unique interaction characteristics. The intrinsic mobility factor, as well as the required simultaneous attention to the task and the environment, suggests that a MAR system should enable users to focus easily on the desired information, thus reducing the cognitive overhead needed to interact with the application. The content of the system should include only relevant information to users eliminating the needless information.

Principle 3 Not applicable for DiedricAR due to its learning context.

Principle 4 Provision in real-time of some feedback information and guide user actions. Based on this, DiedricAR should always report user about the system's performance increasing the feeling of confidence on the presented information [28].

Principle 5 Use of self-explanatory icons to communicate system functionality. A MARS should prevent the development of extra non-automatic cognitive effort [28]. A solution to this challenge is to use common and widely-used interface metaphors. As Kourouthanassis et al. (2015) [28] stated, a MAR application needs to show the information in a widely-used manner. Symbols that may be easily perceived and related to the object in focus must be used to communicate a meaning and to preserve the learnability and usability of the interface.

3.2 Contents

3.2.1 Workbook

Following augmented book paradigm, a workbook with AR markers has been designed allowing the visualization and interaction with 3D models through virtual controls using a mobile device as viewer. This workbook contains exercises corresponding to spatial relationships and visualization. The first kind of exercises consists of drawing orthographic projections of 3D models on at least two principal planes with the aim of improving mental rotation and spatial perception abilities. To overcome the problems derived from the untrained 3D vision usually shown by the students, the exercises are solved step by step and each stage can be selected through virtual buttons attached to the markers controlling the visibility of the virtual model elements. The second type of exercises is related to spatial visualization skills. In this case, the perspective pictorial of 3D models is drawn from their orthographic projections.

The workbook sheets are ISO A4 (210×297 mm) so that they can easily be managed by teachers and students. It has been designed with the following structure:

– Introduction. A brief overview of the DiedricAR system.
– Exercises notebook:

  Dihedral system exercises (4 issues). These exercises contain the corresponding statements on separate sheets, as the example shown in Fig. 3. Intermediate and solution steps, like the ones displayed in Fig. 4 for the statement presented in Fig. 3, are also contained in single pages. The explanation of intermediate steps is introduced by means of AR markers that allow interaction virtually.

  Perspective pictorial exercises (2 issues): This kind of exercise has a statement sheet showing the orthographic projections (Fig. 5). In addition, another sheet is provided with orthographic projections and the AR marker, which permits one to view the 3D model.

  In all the cases, the markers have been properly scaled in the ISO A4 sheet with the aim of obtaining a correct display of the virtual model. Figure 6 shows an example of marker sheet for a dihedral system exercise which includes some explanations on the virtual buttons controlling the visibility of the virtual model for intermediate and solution steps. An illustration of a perspective pictorial exercise marker sheet is presented in Fig. 7. As it can be checked, the marker is aligned with the orthographic projections.

– DiedricAR Application Tutorial. A brief manual describing the operation of the application and its markers has been included.

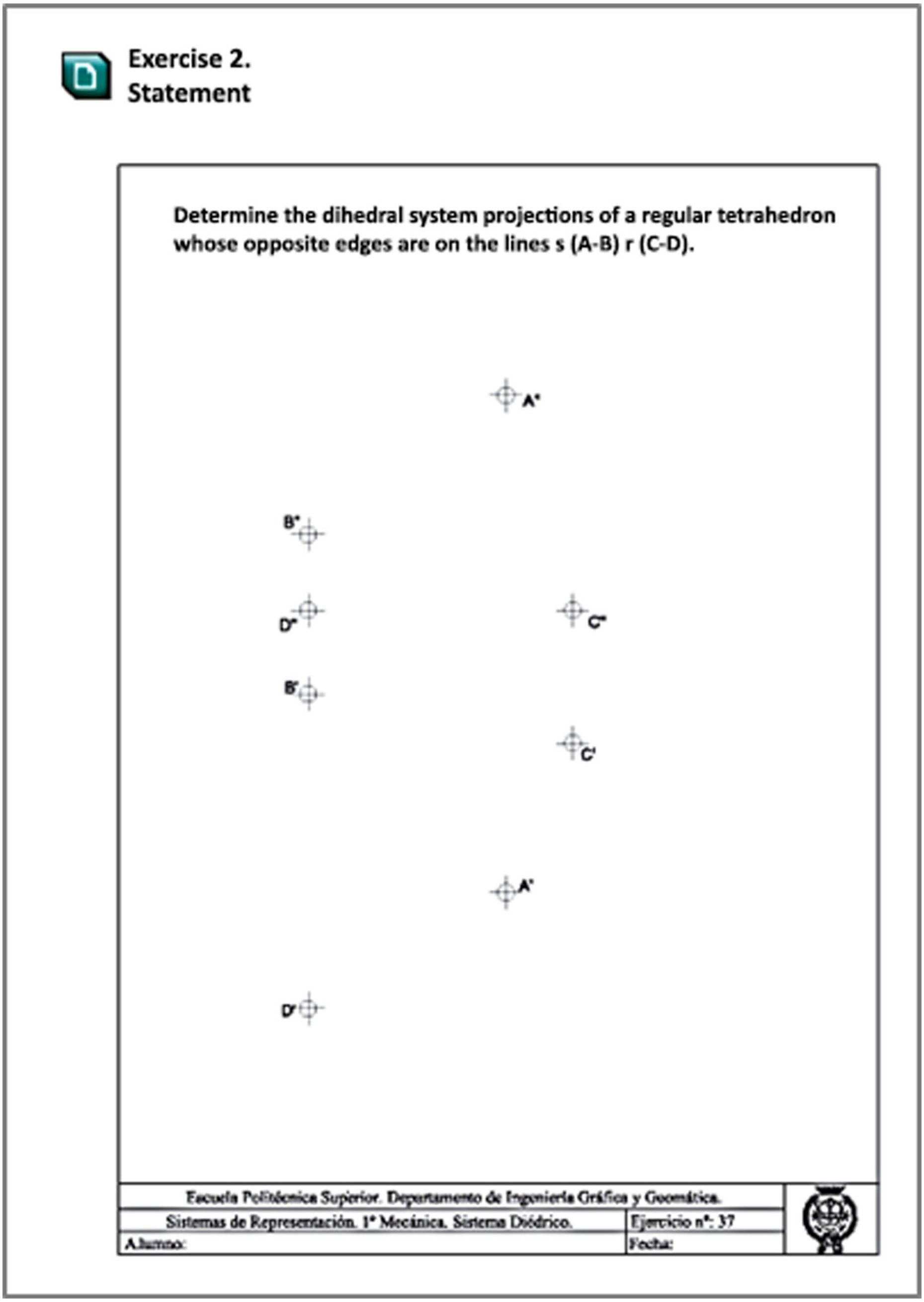

Fig. 3 Example of statement sheet for a dihedral system exercise

3.2.2 3D models and markers

The 3D models contained in the DiedricAR Workbook have been designed according to conventional graphic exercises from the course "Descriptive Geometry" taught by the authors.

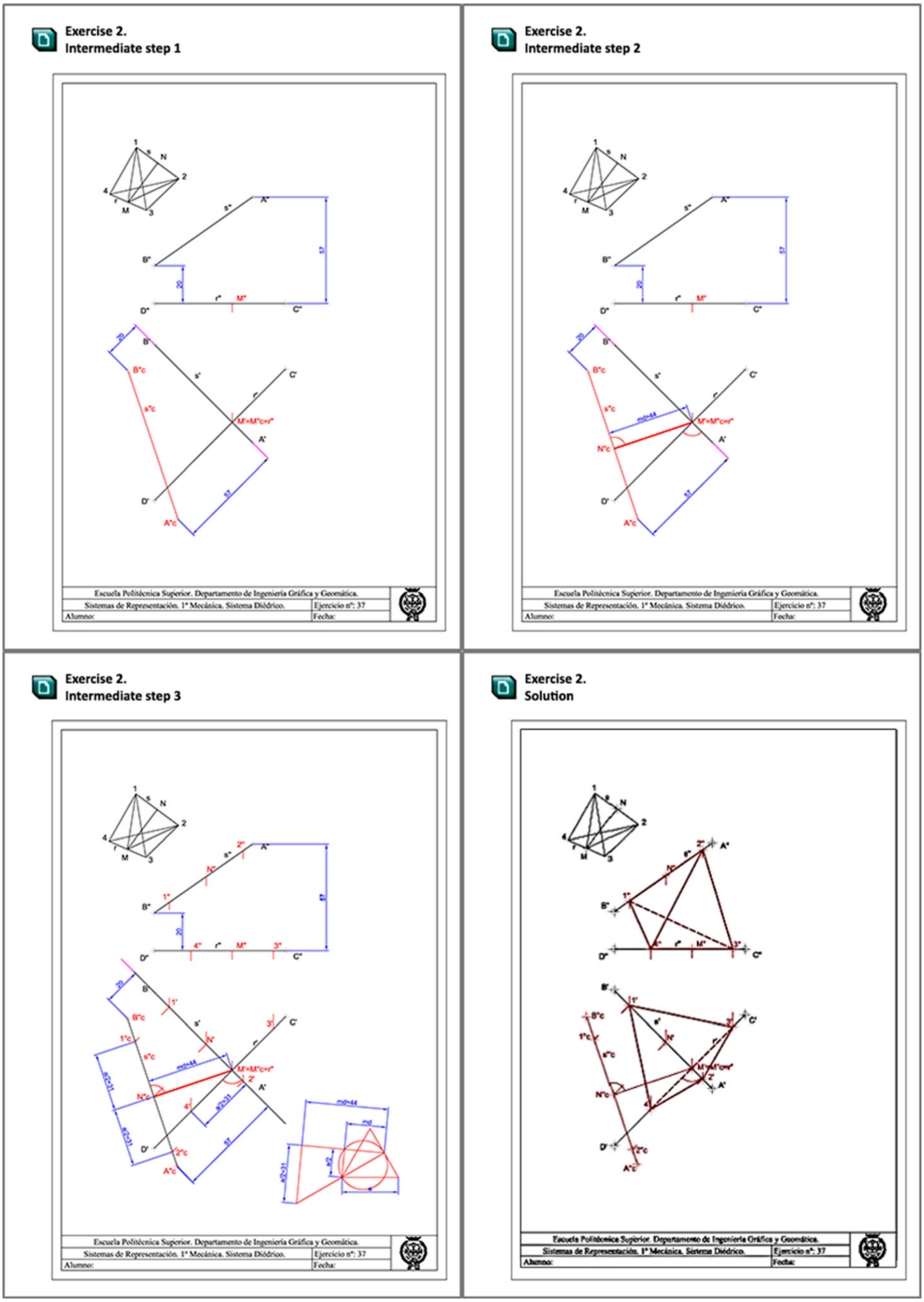

Fig. 4 Intermediate steps and solution sheets for the dihedral system exercise whose statement is shown in Fig. 3

These 3D models were prepared for the use in MAR environment with the aim of facilitating the students' perception during the individual studies.

The design process steps are as follows:

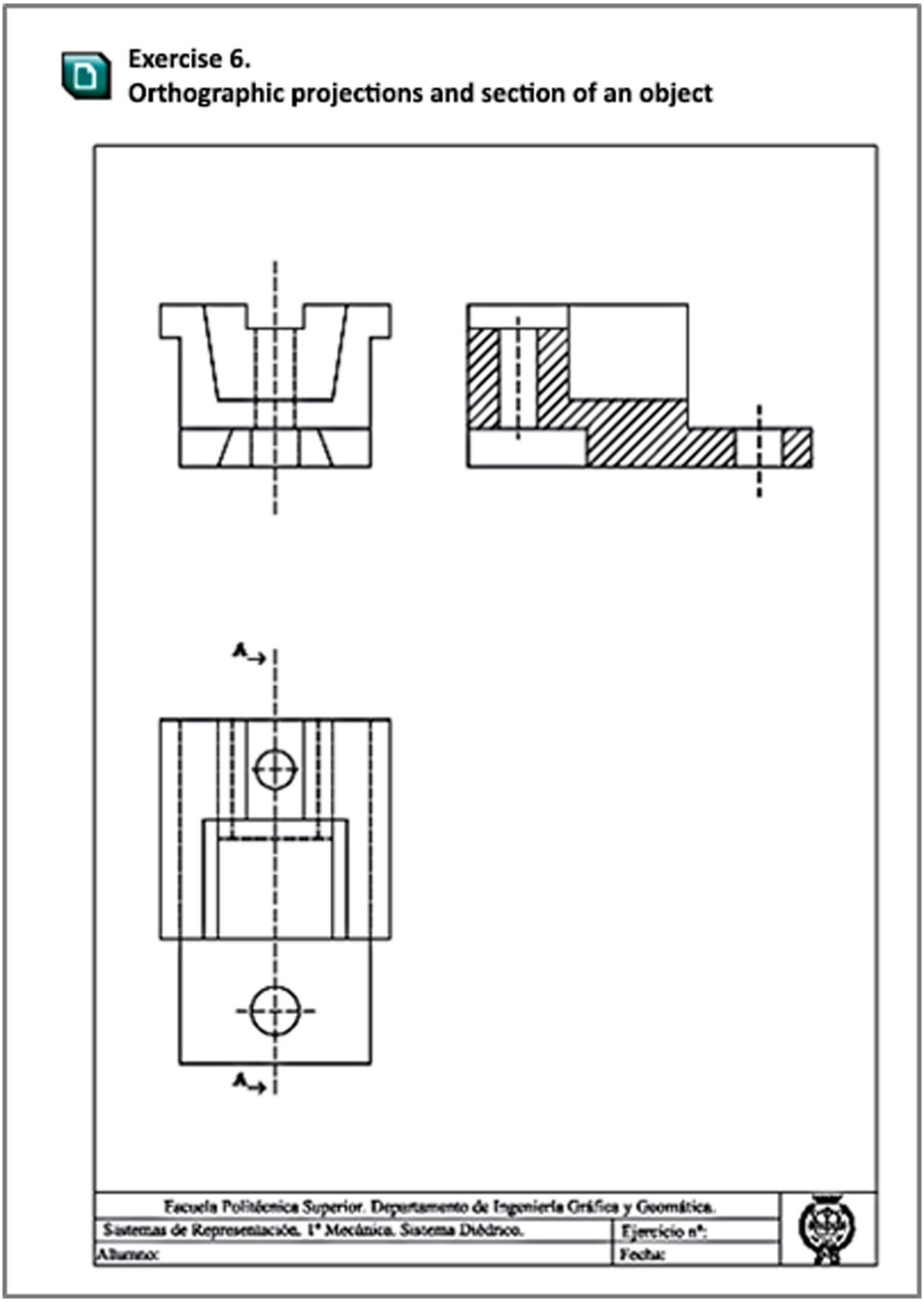

Fig. 5 Example of statement sheet with orthographic projections for a perspective pictorial exercise

1. Drawing of 3D models with Autodesk AutoCAD in DWG format and, later, exporting to Autodesk 3D StudioMax to define material textures and edges thickness.
2. Importing 3D models to Unity3D as objects that can be called from the code. It is necessary to mention that although 3DStudio and AutoCAD can be exported to Autodesk

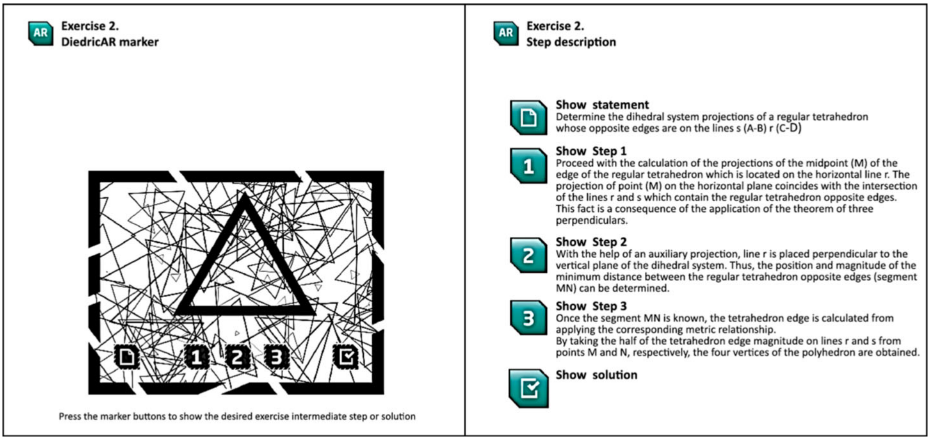

Fig. 6 Dihedral system exercise: AR marker sheet including some explanations on the virtual buttons controlling the visibility of the virtual model for intermediate and solution steps

DAE (*Digital Asset Exchange*) format, Unity3D does not render the models well. For this reason 3D models have been previously exported using OpenCollada.

The two AR operations that consume most resources are markers tracking and model rendering [42]. Vuforia gives an exceptional performance doing both tasks. In order to ease the render jobs, the models have been optimized by reducing the number of polygons as much as possible. Vuforia library has functions that allow markers

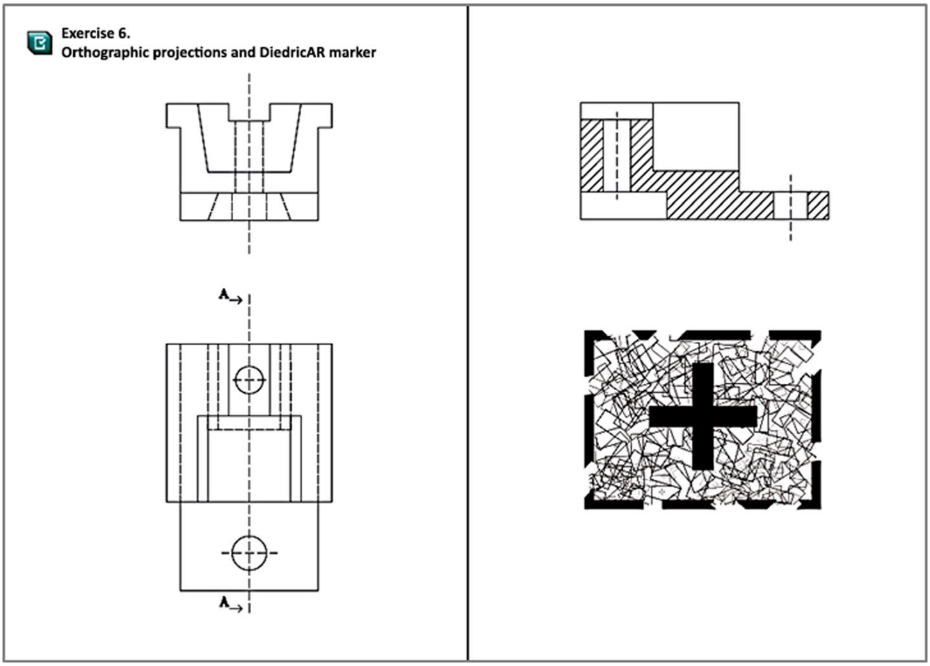

Fig. 7 Perspective pictorial exercise: sheet with AR marker aligned with the orthographic projections

recognition, the accurate calculation of their position and the rendering of the model view according to the marker position. A marker for each exercise has been created with a vector design program. Markers have to be codified by a web application developed by Vuforia. After that, markers can be downloaded for both OpenGL and Unity3D. The design of the markers significantly affects the robustness of rendering the current view, so it is very important to satisfy the requirements imposed by the library: (1) a high contrast between lines and backgrounds, (2) the avoidance of symmetries and repetitive patterns, (3) a high density of traceable points with a uniform distribution.

The virtual buttons have been added to the markers with an XML file that contains their description, position and dimensions of each one. Finally, the 3D models and the corresponding markers are saved in a dataset loaded into the application. Vuforia only allows one dataset loading at runtime.

Figure 8 shows two of the six 3D models created for (a) dihedral system and (b) perspective pictorial exercises. AR markers have been designed according to the requisites demanded by the Vuforia library previously described. The ones corresponding to dihedral exercises include virtual buttons. Figure 9 shows the result yielded when using Vuforia for extracting information from this kind of markers as points (called features) and it is encoded to generate a dataset. This library, in addition to giving an excellent performance, supports partial occlusion for markers and admits interaction through virtual buttons. Markers for displaying and interacting with the models described above are related to each kind of exercise:

a) Markers for dihedral system exercises. Each one consists of i) statement ii) intermediate steps (around 2 or 3 steps) and iii) solution. Technical drawing sheets and explanations describing each phase of the exercise resolution can be found in the workbook and they are useful for comparison with the virtual model. Each marker incorporates virtual buttons with which students can interact by occlusion to control the problem step that is being displayed by the application. A scheme for this interaction procedure is shown in Fig. 10.

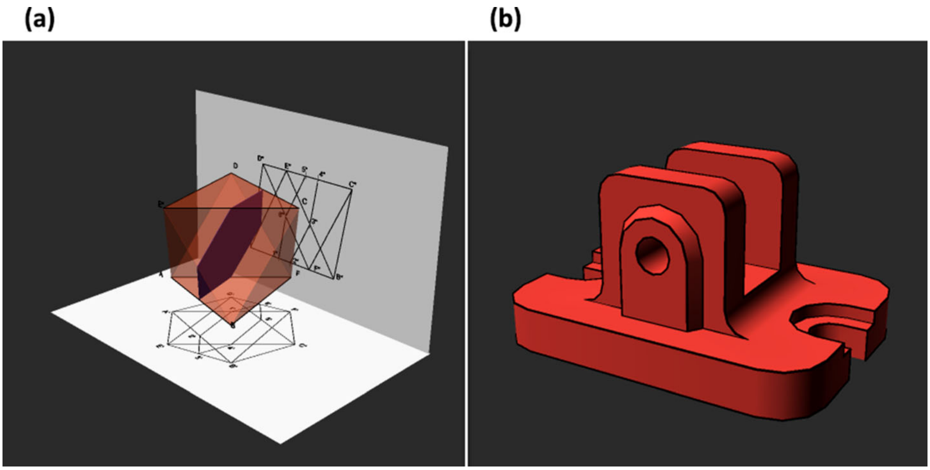

Fig. 8 Examples of modeled solutions provided by DiedricAR for **a** dihedral and **b** pictorial exercises

b) Markers for perspective pictorial exercises. DiedricAR application shows the whole 3D model and the students can compare different views to its orthographic projections included in the workbook. There are no virtual buttons in this kind of exercises.

Some results obtained by running the DiedricAR application, are shown in Figs. 11, 12 and 13 as several screenshots recorded from *Samsung Galaxy Tab 10,* the mobile device in which the best performance of DiedricAR is obtained as will be shown later. Thus, Fig. 11 displays the statement and intermediate steps of a dihedral system problem whose solution is shown in Fig. 12. By other hand, Fig. 13 exhibits the 3D model for a perspective pictorial exercise.

4 Validation of DiedricAR system

This section provides some information on three main aspects of the MARS presented here: i) application performance, ii) user experiences and iii) impact on the students' spatial ability.

4.1 Application execution and stability

With the aim of testing the application performance and check the most critical features, several mobile devices (Samsung Galaxy Tab 10.1; Samsung Galaxy SII; Samsung GT P-1000; Samsung Galaxy Ace; LG Optimus L3; Samsung Galaxy 3 GT i-5800) have been tested. The following items have been considered:

– Average loading time. This is the average time that the application requires to be launched, that is, the time taken since the application icon is touched until the main menu is shown. This time has been measured 5 times on each device to estimate the average time.
– Performance. This tests the application response in different routines: AR markers detection and tracking, model rendering and interaction through touchable screen and virtual buttons.
– Visualization. The representation of virtual models related to exercises has been analyzed.

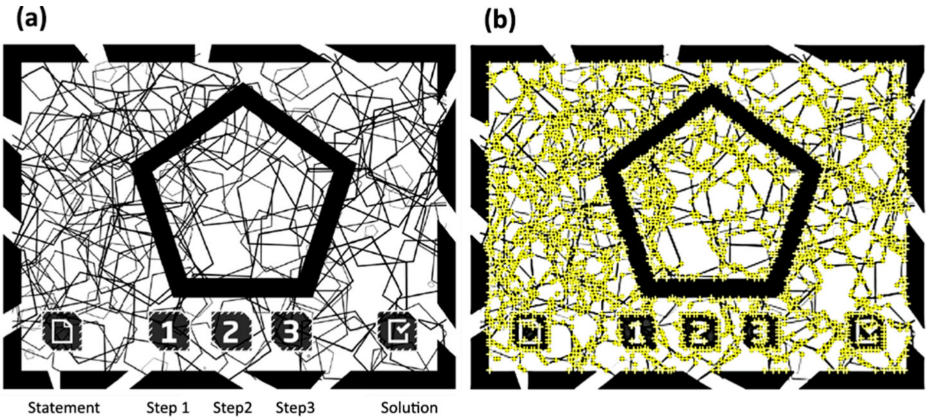

Fig. 9 **a** Dihedral exercise AR marker with virtual buttons. **b** The same marker with the features detected by Vuforia

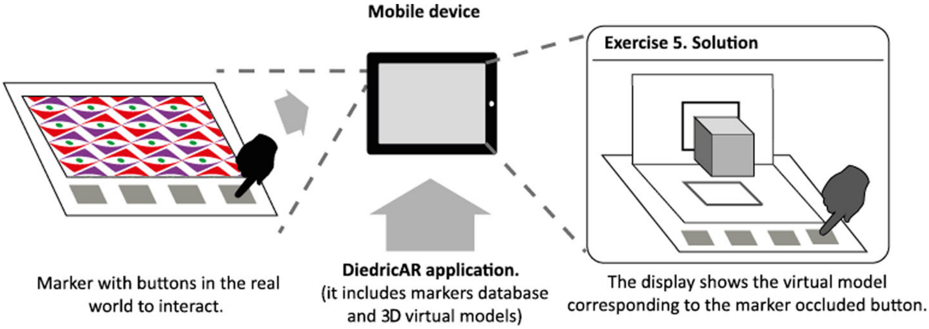

Fig. 10 Interaction through virtual buttons incorporated into the AR markers for dihedral exercises included in DiedricAR

– User Experience. It is the sum of the factors discussed above, which directly affect the user's experience.

DiedricAR gives the chance of interacting with geometric elements displayed in a mobile device which is a very effective way of acquiring spatial perception skills. Adaptation to tablets and smartphones has benefits that go beyond the ubiquity such as (i) its flexible access for students and teachers, (ii) low cost and (iii) the ease of use. Table 2 shows the results of running tests performed on different mobile devices. User experience was obtained according to the feelings of the same group of twenty students considered in the previous section. They took into account some key items such as loading time, performance and visualization to evaluate DiedricAR.

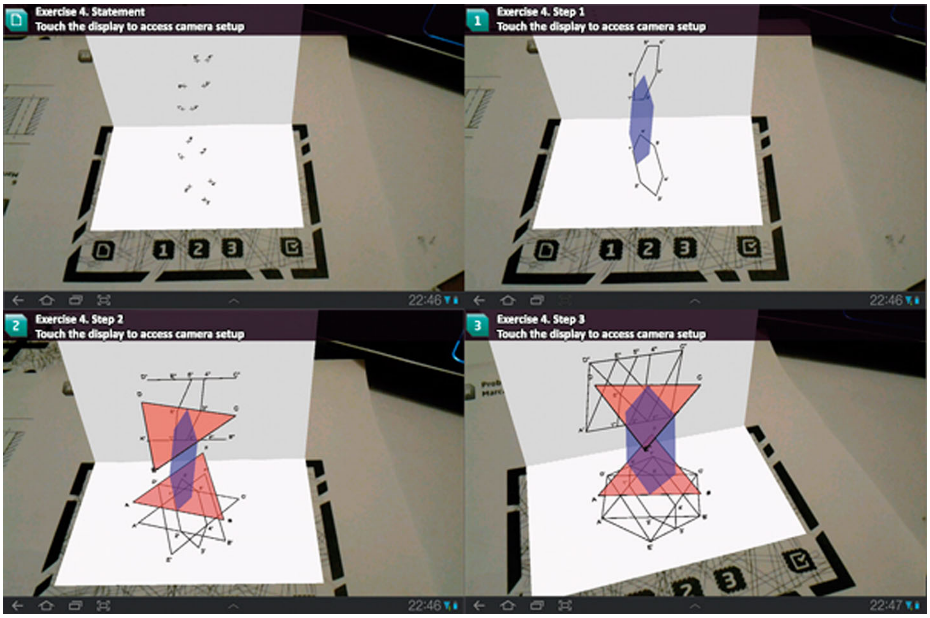

Fig. 11 Screenshots for a dihedral exercise provided by DiedricAR application: statement and intermediate steps 1, 2 and 3

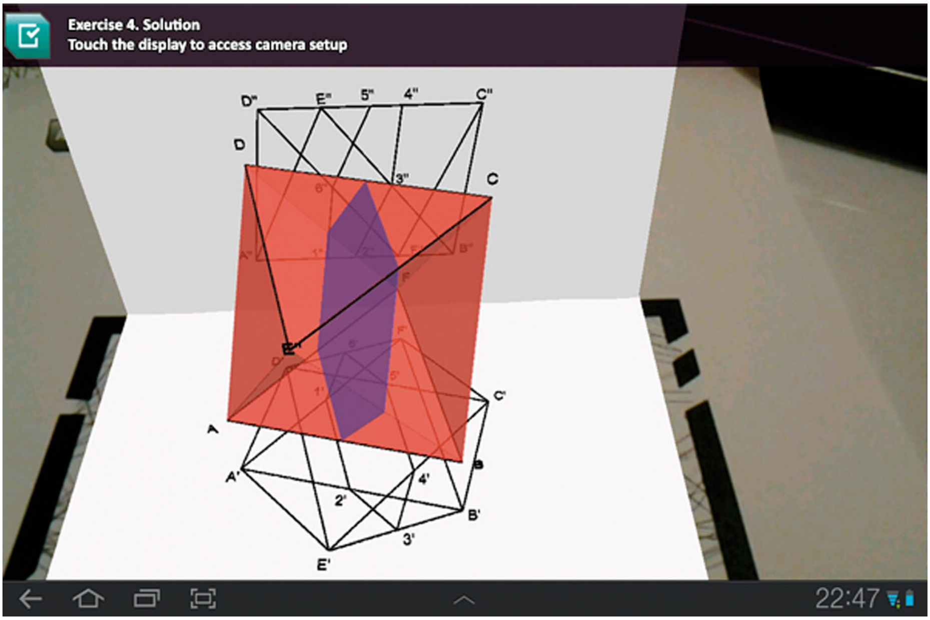

Fig. 12 Screenshot solution yielded from DiedricAR application for the dihedral exercise displayed in Fig. 11

According to the results given, DiedricAR running is affected by three main aspects: (i) mobile device processor which determines the response time of the application, (ii) screen resolution influences on the model representation, and (iii) design of the AR markers with significant impact on the robustness of detection and tracking routines. From the point of view

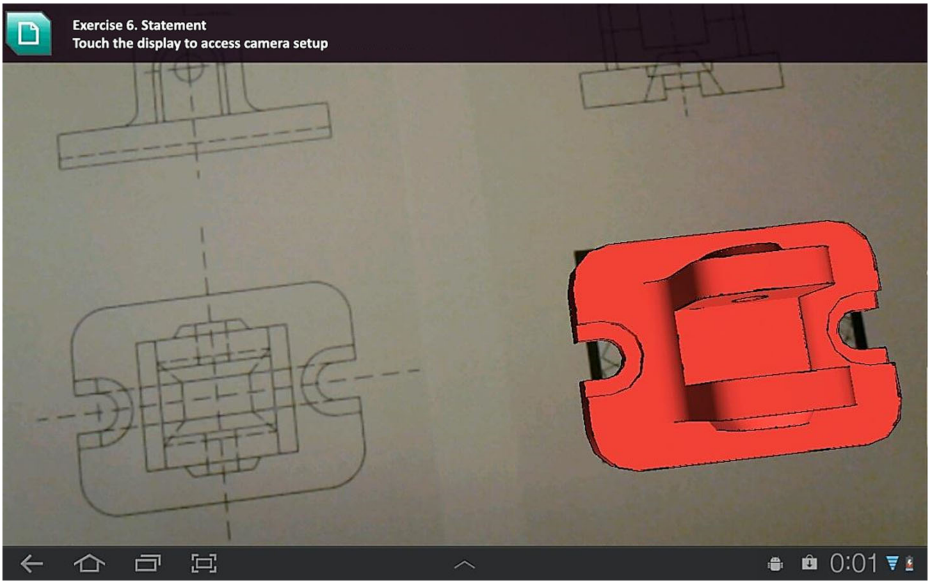

Fig. 13 Screenshot for the 3D model of a perspective pictorial exercise produced by DiedricAR application. The virtual model has the same scale as the orthographic projection

Table 2 Comparative of DiedricAR application running on different mobile devices

Mobile device	Loading time	Performance	Visualization	User experience
Samsung Galaxy Tab 10.1	5,8 s.	Short times of loading and response.	Very clear and precise.	The system works reliably and robustly.
Samsung Galaxy SII	5,9 s.	Short times of loading and response.	Very clear and precise.	The system works reliably and robustly.
Samsung GT P-1000	11,2 s.	Short times of loading and response.	Very clear and precise.	The device offers a high quality experience due to its high resolution screen.
Samsung Galaxy Ace	16,4 s.	Short times of response and recognition. Longer load times. Remarkable use of GPU.	Its low resolution screen hiders the visualization of some details (i.e. pixeled letters).	Although the time of response is short and it runs robustly, the visualization is poor.
LG Optimus L3	19 s.	Short times of response and recognition.	Its low resolution screen shows pixeled and sharpened models.	Although the time of response is short and it runs robustly, the visualization is poor.
Samsung Galaxy 3 (GT i-5800)	84 s.	Although the load time is excessive. Time of response and time of tracking is poor.	Its low resolution screen hiders the visualization of some details (i.e. pixeled letters).	Once the application is loaded, the markers are well tracked and the models are well rendered. The low resolution screen affects the user experience negatively.

of user experience, the screen resolution is considered more critical than the device's performance itself or its processing capabilities, which respond well even with devices with limited hardware (i.e. Galaxy model GT i-5800). However, the continued improvement in mobile devices suggests that these two limitations will soon be overcome.

4.2 User experiences and application design

Twenty students were randomly selected among those that had previously used the application (control group B) and their feelings about the above mentioned features were consulted by filling in a questionnaire. The overall impression of the application was positive. Focusing on the features considered to fulfill each of the principles proposed by Kourouthanassis et al. (2015) [28], the most widespread qualitative opinions are listed below:

Principle 1 High degrees of usability and overall performance. The interaction with DiedricAR was intuitive and user friendly by minimizing cognitive and information overload.

Principle 2 Improved user experience in terms of application usability. Overall usability is enhanced due to one-handed operation of the application and difficulties to interact with small-sized icons.

Principle 3 Not evaluated.

Principle 4. Prevents user uncertainty. The learning curve of using the system is improved. User frustration from system slow or unexpected responses during performance is minimized.

Principle 5. The interaction with the application was clear and understandable. As a consequence, the familiarity with the system is increased. The emergence of negative user emotions, such as confusion and frustration, is diminished.

4.3 Improvement of students' spatial ability

Two common types of spatial tests [46] such as Purdue Spatial Visualization Test Rotations (PSVT: R) [15]: mental rotation [52] combined with visualization; and Differential Aptitude Test (DAT-5: SR level 2): spatial visualization [6]. Among various mental rotation tests, the PSVT:R was chosen because of its prevalent use in educational research [34]. The original PSVT, which consists of three subtests entitled Developments, Rotations, and Views, respectively, was developed by Guay (1977) [15]. The test is comprised of 36 items, 12 from each subtest. The PSVT:R is an extended version of the subtest, Rotations, used to measure 3D mental rotation ability in 20 min [16]. The PSVT:R has 30 items consisting of 13 symmetrical and 17 nonsymmetrical figures of 3D objects, which are drawn in a 2D isometric format. All figures contain cubes or cylinders with varied truncated slots. In each item, the respondents' task is to mentally rotate a figure in the same direction visually indicated in the instructions and identify the most appropriate choice among the five options. By other hand, the DAT-5: SR level 2 has 50 items and it measures the ability to visualize a 3D object from a 2D pattern, and how this object would look if rotated in space. According to authors such as Pellegrino et al. (1984) [41], this spatial visualization stems on the mental manipulation and integration of stimuli consisting of more than one parts or movable parts, where usually there is movement among the internal parts of a complex configuration and/or the folding and unfolding of flat patterns.

In order to check the progress arising from the use of DiedricAR system on Descriptive Geometry learning, two groups of 50 full-time mechanical engineering students (aged 18–20 years) were considered. The first one, control group (A), only received teaching without the support of the MAR system. Therefore, these students learned the concepts of Descriptive Geometry through the traditional method based on lectures backed up by the blackboard and practical exercises. The second group, experimental (B), used DiedricAR to supplement its learning. Once the teaching period was over, the resolution of various exercises was proposed to students from both groups. Their spatial skills were evaluated by taking into account the quality and time spent on obtaining the solutions to these exercises. Thus, it was found that the results of group B improved those obtained by group A, as the average score of students who used DiedricAR was 17.5 % higher. Regarding the time needed to resolve the exercises, an average reduction of 8.1 % was detected for the students from group B. These results were completed with the spatial tests PSVT: R and DAT-5: SR level 2. According to the results obtained, the additional use of DiedricAR in experimental group (B) had a measurable and positive impact on the spatial skills of students, measured by these spatial aptitude tests. The increase in the mean score was 6.23 % for PSVT: R and 10.84 % for DAT-5: SR level 2 with respect to control group (A).

5 Conclusions

Some of the design principles proposed by Kourouthanassis et al. [28] have been applied in the development of DiedricAR. As a result, this application can be regarded as being a user-centered MARS which increases the students' positive feelings. In this sense, this work can be understood to be a response to the proposal made by Kourouthanassis et al. [28] to check their prescriptions on different application environments in order to obtain a suitable MARS. Thus, some features that enhance the user experience of DiedricAR have been incorporated during the design process. As a result, a positive impact on students' spatial ability has been reached as the results reported for the resolution of Descriptive Geometry exercises and spatial tests have demonstrated. In addition, DiedricAR has performed acceptably on several mobile devices. This fact provides benefits teachers and students in concepts such as flexible access, low cost and ease of use apart from the required ubiquity outside the classroom.

To the best of our knowledge, DiedricAR represents the first effort in designing a MARS specifically devoted to the learning of Descriptive Geometry. Not surprisingly, some improvement actions may be incorporated into the application such as (i) expanding the content by increasing the amount and types of exercises, including self-evaluation tests and (ii) storing the 3D virtual models in the Cloud and downloading them on demand. However, DiedricAR is an initial framework for researchers engaged in Descriptive Geometry learning that may be considered as a guide to developing future MARS to satisfy the needs of students and teachers in a suitable way.

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E. Gutiérrez de Ravé obtained his agronomic engineering PhD (1987) from the University of Córdoba (Spain). He is currently full professor in the Department of Graphic Engineering and Geomatics at the University of Córdoba. His research is focused in computer aided design, curves and surfaces and computer graphics.

F. J. Jiménez-Hornero obtained his agronomic engineering PhD (2003) from the University of Córdoba (Spain). He is currently full professor in the Department of Graphic Engineering and Geomatics at the University of Córdoba. His research is focused in computational fluids mechanics, multifractals and computer graphics.

A. B. Ariza-Villaverde obtained her agronomic engineering PhD (2013) from the University of Córdoba (Spain). She is currently developing her research activity as grant holder in the Department of Graphic Engineering and Geomatics at the University of Córdoba. Her research lines are GIS, axial maps, multifractals and computer graphics.

J. Taguas-Ruiz obtained his Computer Science degree (2004) from the University of Córdoba (Spain). Later, he completed the M.Sc. on Intelligent Systems (2012) at the same University becoming an expert on Augmented Reality. He is working know on Multimedia application to education and frequently collaborates with members of the Department of Graphics Engineering and Geomatics of the University of Córdoba.