



Initiation to Reverse Engineering by Using Activities Based on Photogrammetry as New Teaching Method in University Technical Studies

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Abstract. Nowadays, reverse engineering is used in multiple professional fields that impel to develop different processes for obtaining virtual objects from real objects. Moreover, the importance of providing students with basic knowledge in this type of data collection processes increases, but sometimes the most sophisticated tools are not available because of their high cost and level of knowledge. Among the types of scans that can be found for three-dimensional reconstruction, there is an alternative based on the photogrammetry whose method is denominated Image-based 3D Modeling and Rendering (IB3DMR), which uses a set of photographs in 2D to generate a three-dimensional digital model. With the aim of students learning the basics of scanning and three-dimensional reconstruction of objects, point clouds or mesh of an object, reverse engineering, exportation to other CAD formats and preparation of models for 3D printing, a series of activities with tools of low cost related to photogrammetry are proposed in this communication. This study was performed among students from three different subjects taught at the Technical University of Cartagena during the first term of the 2017/18 course: ‘Industrial Design’ and ‘Graphic Expression’ (both from the Degree in Mechanical Engineering), and ‘Graphic Expression’ (Degree in Industrial Technologies Engineering). The obtained results demonstrate a high level of satisfaction and interest in this type of methodologies during the academic education of the students. Using this type of tools prepares students in new technologies and applications that are increasingly being implemented in all professional fields of society. Universities must be prepared for these new challenges and offer them as a complement to their academic education.

Keywords: Learning · Engineering education · Educational experience · Photogrammetry · Low-cost tools

1 Introduction

In modern industry, reverse engineering is increasingly becoming more relevant in the design and development process of any product. The use of technologies to obtain information about a product to know how it works, what it is made of or to have an overall view of its shape has become an obligation to be competitive in the market, assuming an advantage that can reduce costs and increase efficiency of any product. To obtain such information requires a device called a 3D scanner that is used to analyze an object or a scene and use the data obtained to build three-dimensional digital models that are used in a wide variety of applications.

In the market, several types of three-dimensional scanners that permit to get a great precision of the acquired data can be found: contact, contactless, active, passive, etc. [1–3]. Some of these technologies are not easy to be obtained due to their high cost and the requirement of qualified personnel for their use. For this reason, other alternatives based on more accessible and economic software are being used more and more. These new alternatives consist of scanning and three-dimensional reconstructing an object by using a set of successive photographs, also called Image-based 3D Modeling and Rendering (IB3DMR). More specifically, this type of methodology is based on the detection, clustering and extraction of characteristics (sides, vertices, etc.) that are present in an image to be later interpreted as common elements of a 3D model.

This method can be divided into two parts. On one hand, there is Image-based rendering (IBR) which uses images instead of polygons. The goal is to get a faster and more realistic rendering, simplifying the process of modelling. This technique consists of either knowing the precise positions of the cameras or carrying out automatic “stereomatching” which, in the absence of data, requires a large number of images close in proximity. On the other hand, there is Image-based modelling (IBM), which refers to the use of images to guide the reconstruction of three-dimensional geometric models.

Despite the fact that 3D scanning is a standard source of data entry, image-based modelling seems to be a complete, economical, practical and flexible alternative to expensive scanners. Rather than render objects or scenes using the traditional approach of polygons, IBMR uses large amounts of images (photographic or synthetic) to achieve a high level of realism. This type of technique has been used for several years and many studies have been conducted on it [4–6].

One of the main objectives of this work is the utilization of low cost tools for its use as a teaching tool. In this sense, several applications based on the described IB3DMR methodology can be found, as for instance Autodesk Recap (the new version of Autodesk Remake and 123D Catch), Microsoft PhotoSynth, Patch-Based Multi-View Stereo (PMVS), PixelStruct, VisualSize, Bundler, BigSFM or OpenPhotoVR, among others. Based on this type of technology, some previous studies have been analyzed to compare the suitability of this type of applications. Cavas et al. [7] studied the behavior of Microsoft PhotoSynth and PMVS for the reconstruction of different types of fruits, offering the PMVS software better results when applying textures. That same year, a later study by the same authors [8] analyzed the software Microsoft PhotoSynth, PMVS and 123D Catch for the reconstruction of mechanical metal parts, demonstrating the

high accuracy of the reconstructions using the 123D Catch software compared to the rest. On the contrary, PMVS does not offer good results when textures are applied and Microsoft PhotoSynth only provides a cloud of few points that does not complete the scanned part.

One of the first works that demonstrated the performance of 123D Catch was the study developed by Cervera et al. [9], who used several applications to perform an acoustics analysis by 3D modeling of closed spaces. That same year, Venkatesh et al. [10] studied the 3D models obtained by photogrammetry as a simple and inexpensive source of images for diagnosis and evaluation in the field of dentistry, serving as a complement to other diagnostic images in 2D as X-ray images. A similar study was carried out in the field of architecture by Santagati and Inzerillo [11], in which a study of the metric precision of 123D Catch was performed. In turn, Santamaría y Sanz [12] deepened the use of Autodesk 123D Catch for 3D modeling of terrain, as an alternative to other more complex and expensive topographical methods. Another study to highlight is the one carried out by Lerma et al. [13], where they compared the results of image-based modeling software (Autodesk 123D Catch, Fotoglife and VisualSFM) with the results of time-of-flight laser measurements in two different cave paintings. Even under the sea, this methodology has been used to obtain the reconstruction of aquatic organisms in an easy, fast and non-intrusive way [14].

Taking into account the characteristics and possibilities that 3D scanners provide, this work has looked for an affordable and accessible alternative to recreate a reconstruction process with a really useful purpose for engineering, its application as a didactic tool. After the analysis made to the different mentioned studies, the Autodesk ReCap tool has been selected for this work. The objective of using this type of low cost technologies as didactic tools is to bring students to some knowledge and work methodologies that can later be applied in the labor world through more sophisticated tools. On the other hand, a new process of obtaining photographs is offered to substantially improve the quality of three-dimensional reconstructions with respect to the conventional system recommended by the program. This study was performed among students from three different subjects taught at the Technical University of Cartagena during the first term of the 2017/18 course: 'Industrial Design' and 'Graphic Expression' (both from the Degree in Mechanical Engineering), and 'Graphic Expression' (Degree in Industrial Technologies Engineering). These students conducted a series of activities to acquire basic concepts of scanning and three-dimensional reconstruction of objects, point clouds or mesh of an object, reverse engineering, exportation to other CAD formats and preparation of models for rapid prototyping. At the end of the study, their evaluations and comments are analyzed, highlighting their satisfaction and the usefulness of this type of complementary activities for their education and their future work.

2 Application of ICT Tools in Teaching

There are several examples of how the application of information and communication technologies (ICT) in teaching has a great impact on the teaching-learning process of the student and how he increases his motivation if he becomes an active part of his learning [15, 16]. The universities demand, more and more, complementary formative

actions as support to the face-to-face teaching. Camacho et al. [17] showed a didactic resource in the study of mathematics in the Economics and Business degrees, demonstrating an increase in the assimilation of the concepts developed in the classroom and supposing a feedback to the teacher to improve his teaching methodology. In the Engineering field, computer-aided design (CAD) is key in different areas of study where the use of 3D virtual models permits students to acquire different knowledge and skills that complement their academic training [18–20].

More specifically, and relating teaching with 3D scanners, we find examples in the field of Health Sciences, where volumetric representations are increasingly applied in the educational process to allow the student to have a closer visual comprehension to the three-dimensional reality of the object of study. An example is a the teaching innovation project developed by Prados et al. [21] with the aim of obtaining a multimedia material from the most complex areas of the human anatomy that allows an active teaching methodology by the student, using a laser scanner and software for processing and conversion of scanned data. On the other hand, Mateos Quintanilla et al. [22] developed an optical 3D scanner prototype and present how the students learnt to handle the scanner and perform various practices to acquire data, reconstruct elements, compare them, etc.

In relation to reverse engineering, we can find an example where these new technologies of digitalization and reengineering was tried to be brought to students, such as the study by Sinha [23], where a preliminary presentation of different 3D scanning and reverse engineering tools was carried out.

Engineers have to face multiple projects in their working life and, increasingly, this type of scanning and three-dimensional reconstruction tools are used within a reverse engineering process. These technologies are booming and, for this reason, this work proposes a series of activities that permit the students to acquire basic knowledge to face them in the best possible way.

3 Materials and Methods

3.1 Reverse Engineering Process

The purpose of the use of these tools is to show students two ways to obtain virtually mechanical and daily objects, and their subsequent use for possible redesigns or prototypes in a reverse engineering process. The scheme that can be considered traditional for data acquisition of an existing object is the one that requires measurement tools to achieve them (hardware); another alternative is the use of 2D images. Both methods permit to obtain virtual models with which to work and generate 3D-printed prototypes (Fig. 1).

In order for students to know de basic concepts related to reverse engineering, different activities have been performed in every subject of the study. These activities are considered complementary to the subject, and they permit the students to develop all aspects related to the three-dimensional scanning and reconstruction of objects and their transformation for 3D printing of prototypes. Subsequently, the students have completed a series of tests to evaluate every phase and their satisfaction with this type of activities.

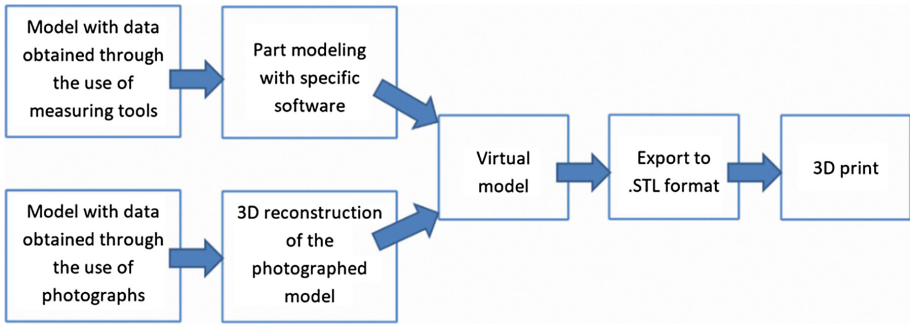


Fig. 1. Scheme for obtaining data from measuring tools and from photographs.

3.2 Objects Used in the Study

For this study, a great variety of pieces with different geometries and textures has been used, enabling the students to work the tasks of scanning and three-dimensional reconstruction. Some of the objects used by the students are shown in Fig. 2.



Fig. 2. Some of the objects used for the study.

3.3 Activities

Scanning Phase

The software used for the three-dimensional reconstruction is Autodesk ReCap, which offers a series of recommendations for obtaining images in this first scanning phase: the photographs must be taken in a dynamic environment, where the pieces remain fixed and the photographs are taken around it. However, in this study a new methodology is

proposed: the photographs have been obtained in a special way by rotating the piece instead of the camera, and taking the photographs from the same point. A white background has been used and essential reference elements for the connection between photographs have been placed on a rotating base (Fig. 3). The use of this new methodology permits to obtain results optimized for the reconstruction of the piece, since the lighting remains fixed and does not vary between photographs, and no shadows are produced. The number of photographs to be taken is between 40 and 70, and from two different heights (0° and 30° approximately).



Fig. 3. Scenario used during the scanning phase.

The camera used to take the photographs was a Nikon D80 Digital Reflex Camera, with 10 megapixels of resolution and a sensitivity calibrated from 100 to 1600 ISO. The computer used for all processes of reconstruction, import and export of data is equipped with an Intel® Core™ i7-4790k 4 GHz processor, Windows 7 Professional 64-bit operating system and 32 GB RAM.

The first practice consisted of preparing the scenario for obtaining the photographs of the objects of study, constituting the scanning phase. This process does not require a laboratory or special room, so it facilitates the student's work if a distance modality of teaching is contemplated. This practice, which a priori may seem simple, requires controlling several parameters such as lighting, contrast between the colors of the piece and the environment, reference elements, etc. so that the result is the most optimal in the reconstruction (Fig. 4).

Reconstruction Phase

The application used in this study is ReCap Pro 2018, for Windows 64-bit systems. Autodesk offers the possibility to download a free educational version of the program from its website. Once installed this version, another program called Autodesk ReCap Photo is also installed, which offers new tools for the management of the reconstructed models and that will be later used.



Fig. 4. Students performing the scanning phase.

The reconstruction process begins with acquiring the photographs taken in the previous scanning phase. To perform this, the user must select the “New project” option, which is used to choose the desired photographs for the reconstruction. It should be noticed that Autodesk ReCap Pro performs the reconstruction task on its own servers to later download and view it in the program. This way permits the virtual models to have a good quality at the same time that they are processed quickly and without consuming memory or CPU resources from the user’s computer.

Once the reconstruction is finished and visualized on the screen, it can be saved as OBJ or RCM file. For this study, the RCM extension is used. This RCM file is then opened with the Autodesk ReCap Photo application (Fig. 5a). After verifying that the reconstructed object is adequate, those parts of the environment that surround the object must be cleaned (Fig. 5b), and the model can be exported to any of the five formats offered by the application: OBJ, FBX, STL, PLY and PTS. For the present study, the generated models have been exported to STL format.

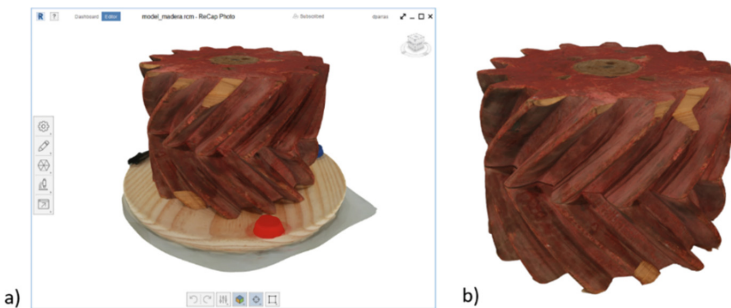


Fig. 5. Piece reconstructed: (a) with environment to be cleaned, (b) without environment.

One of the reasons for obtaining virtual models is their subsequent reproduction through 3D printing. This process consists of manufacturing a three-dimensional solid object from digital models in STL format. The STL format allows defining the geometry of 3D objects, excluding information such as color, textures or physical

properties that do include other CAD formats. This format uses a closed triangular mesh to define the shape of an object: the smaller the triangulation size used, the higher the final resolution. Figure 6 shows the meshed surface of the model within Autodesk ReCap with (Fig. 6a) and without texture (Fig. 6b), and the model in STL format in MeshLab (Fig. 6c). This MeshLab tool is used to optimize, if necessary, the mesh of the virtual model, also giving the possibility of exporting to other CAD formats. It is an open source application that offers a number of tools for the editing and processing of surfaces in the form of triangular 3D mesh models, and is based largely on the VCG library, developed by the Visual Computing Laboratory of ISTI-CNR.

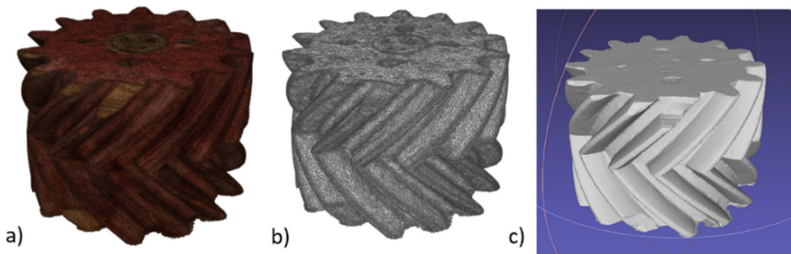


Fig. 6. Meshed surface of the model: (a) with texture (Autodesk ReCap), (b) without texture (Autodesk ReCap), (c) model in STL format (MeshLab).

In this second activity, the students obtain a three-dimensional reconstruction of the objects from the photographs taken in the previous activity (Fig. 7). They should evaluate the degree of similarity in terms of geometry, color and textures between the study piece and the generated three-dimensional model. This phase is very motivating for the students since they are the ones who get results with every given step. This phase has multiple applications in the real world, since the acquisition of virtual models is used in different fields, such as medicine for anatomical analysis and prostheses, archeology for the conservation and dissemination of historical objects, virtual museums, etc.



Fig. 7. Students performing the reconstruction phase.

Prototyping/Exportation Phase

Once the three-dimensional reconstructions of the objects have been obtained, different processes can be performed for their analysis, such as the comparison of pieces. If the objective is to use other software to process and edit the mesh of the virtual object or obtain a prototype by 3D printing, the model can be exported to other file formats from those offered by the program. In this way, students are able to assimilate concepts and processes of reverse engineering and processing of virtual models in a more didactic and motivating way. The activities carried out in this phase include observing the manufacturing process by 3D printing.

The 3D printing technology used during this study was Fused Deposition Modeling (FDM), which provides a great quality-cost relation, and ABS (Acrylonitrile Butadiene Styrene) material (Fig. 8).

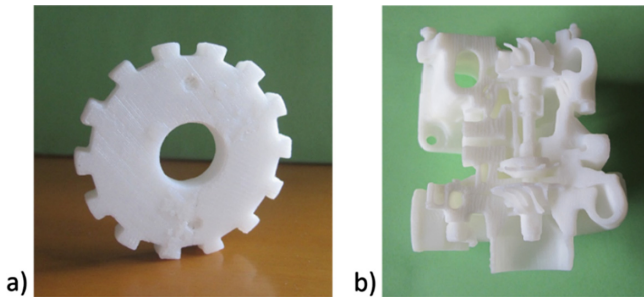


Fig. 8. Some prototypes obtained by 3D printing: (a) gear wheel, (b) engine.

Once the final 3D models have been obtained by using reverse engineering software, an STL file must be generated so that the additive manufacturing machine can interpret the geometric information (triangularization) modeled in CAD.

4 Results









4.1 3D Reconstructions

Among all the reconstructions performed by the students of the three subjects analysed during this study, only those that offered the best aspect were selected. Table 1 shows the images of these selected reconstructions and their respective real objects.

4.2 Students Tests

In order to analyze different characteristics of the proposed activities, the students completed a test for every activity: (i) scanning, (ii) reconstruction and (iii) prototyping/exportation. The students also performed a test to assess globally all activities, analyzing the level of knowledge of the most important concepts and their interest in learning more about this type of methodologies.

Table 1. Comparative table for the reconstructions that offered the best results.

<i>Model</i>	<i>Real object</i>	<i>3D Reconstruction</i>
Wooden gear		
Wooden mold		
Gear wheel		
Toy robot		

(continued)

Table 1. (continued)







Toy car		
Old coffee grinder		
Engine		

Table 2. Test questions about the scanning phase.

Evaluation questions from 1 to 5 (1 Disagree/5 Agree)	S1. The proposed methodology is easy to understand
	S2. It is necessary a prior knowledge about photography to perform this activity better
	S3. The time to elaborate the activity is sufficient
	S4. The activity carried out is interesting

Evaluation of Scanning Phase

Table 2 shows the questions presented to the students about the scan phase. The results (Fig. 9) obtained in all the study groups highlight the following conclusions: the proposed methodology is easy to assimilate, some type of previous knowledge about taking photographs is required, some more time should be required in order to perform this phase better, and everything learned through this activity has been very interesting for them.

Evaluation of Reconstruction Phase

Table 3 shows the questions presented to the students about the program operation and the reconstruction process. The results (Fig. 10) show that the software is quite easy to operate and highlights the importance of taking good photographs for obtaining an accurate reconstruction. In this phase, student satisfaction is more variable because the results obtained in the reconstructions are not always what they expected.

Table 3. Test questions about the reconstruction phase.

Evaluation questions from 1 to 5 (1 Disagree/5 Agree)	R1. The proposed software is intuitive and easy to use
	R2. Obtaining photographs according to the proposed methodology improves the results in the reconstruction
	R3. The time invested in this phase is adequate
	R4. The results of this phase are satisfactory

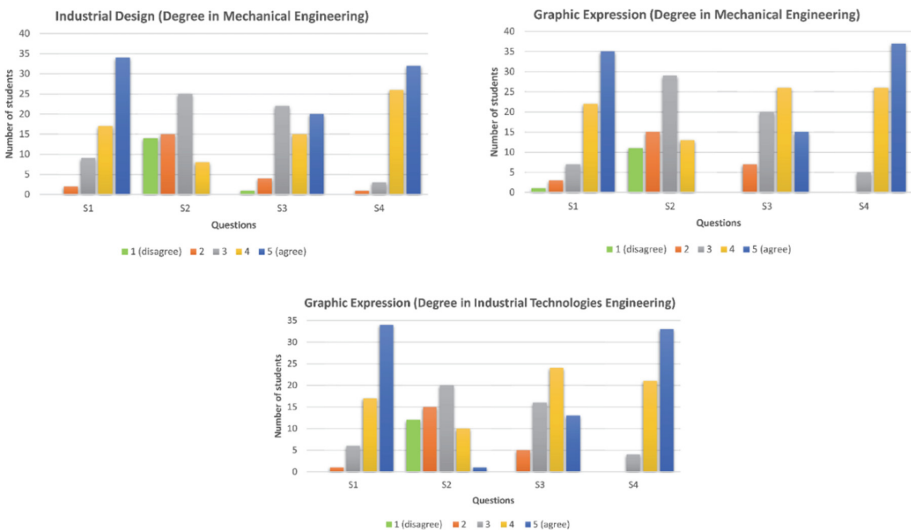


Fig. 9. Results of questions related to scan phase for the three groups of the study.

Evaluation of Prototyping/Exportation Phase

Table 4 shows the questions about the use of CAD formats and 3D printing techniques. The results (Fig. 11) reflect the importance that students give to a good management of the different types of CAD formats and the acquisition of a general knowledge of 3D printing processes and techniques for their professional future. On the other hand, they consider that a little more time should be dedicated to this phase and that the knowledge acquired in this stage could be very useful in other subjects.

Table 4. Test questions about the prototyping/exportation phase.

Evaluation questions from 1 to 5 (1 Disagree/5 Agree)	P1. Handling of different CAD formats is relevant to my academic education
	P2. The knowledge of 3D printing techniques is interesting for my professional future
	P3. The time dedicated to this activity is appropriate
	P4. The knowledge acquired in this phase is useful in other subjects

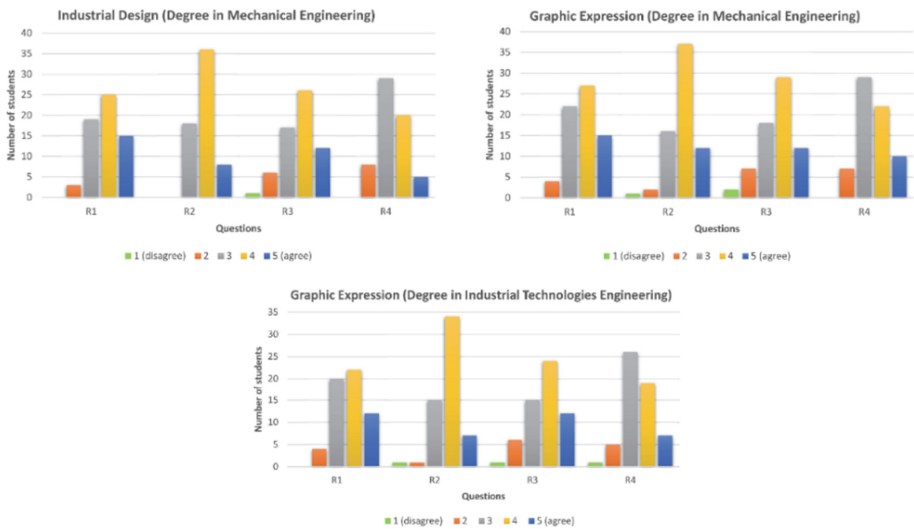


Fig. 10. Results of questions related to reconstruction phase for the three groups of the study.

Global Evaluation of Activities

To analyze different aspects of the activities in a general way, the students assessed the questions shown in Table 5. As can be seen in the different results (Fig. 12), there is no extended knowledge about the concepts of reverse engineering, photogrammetry or the proposed methodologies. On the other hand, there is great interest by most students in continuing to learn more about everything related to this type of methodologies. The general assessment is very satisfactory in all groups and reflects the support and interest that this type of activities has obtained in the considered subjects.

Table 5. Test questions about the global evaluation of the methodology.

Evaluation questions from 1 to 5 (1 Disagree/5 Agree)	G1. Degree of knowledge of the concept of reverse engineering prior to these activities
	G2. Degree of knowledge of the concept of photogrammetry prior to these activities
	G3. Degree of knowledge of the proposed methodologies prior to these activities
	G4. Degree of interest in learning more about this type of reverse engineering methodologies
	G5. The time devoted to the expositions of theoretical content has been sufficient to address these activities
	G6. The practical exercises carried out are sufficient to understand the proposed methodologies
	G7. This type of learning is important for my professional future
	G8. General assessment of activities

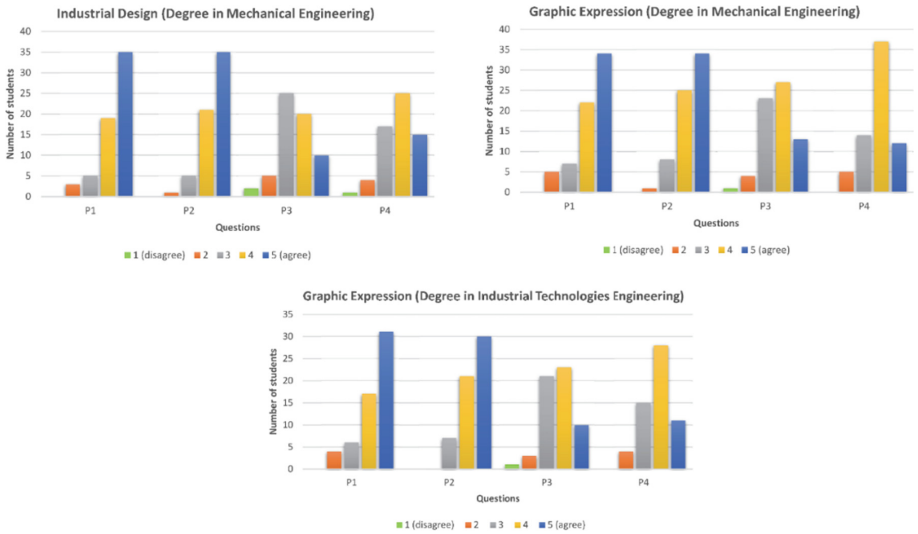


Fig. 11. Results of questions related to prototyping/exporting phase for the three groups of the study.

The students had the possibility of providing personal opinions or suggestions during the tests. Some of them are the following: “More practices of this type should be done”, “It has been a good experience, the results have been quite good”, “I think it is a necessary and very interesting activity. Hopefully more time would be devoted to its execution” and “It is a very good initiative; other subjects should do the same”. These comments reflect the interest that this type of activity arouses in students.

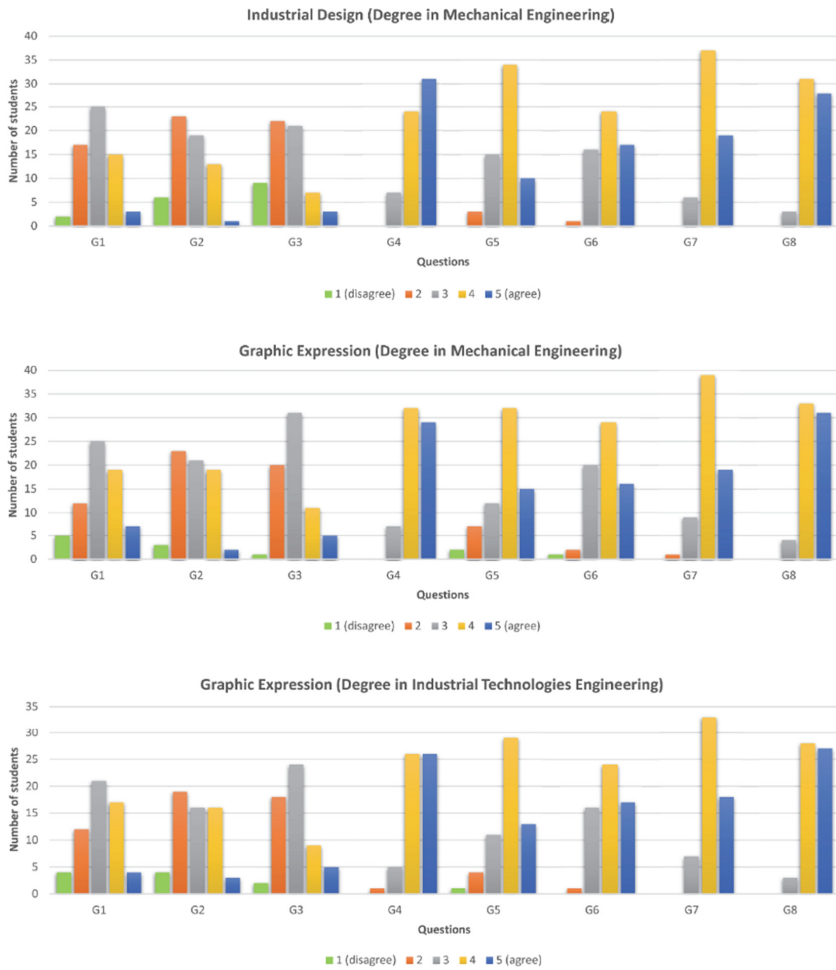


Fig. 12. Results of general questions related to the methodology used during the study.

5 Discussion

A comparative study of the results of reconstruction of the selected pieces that offered the best aspect can be shown in Table 6. In this analysis, different characteristics and shape aspects were taken into account.

If the reconstructions of the wooden gear and the wooden mold are analyzed, a very good quality in all the defined aspects can be observed. This is due to they are compact pieces without hollows or deep holes, so the definition of their shape is very good. The gear wheel also has a pretty good finish, but its definition in the edges and in the holes is deficient, since it is a thin piece. The reconstruction of the toy robot presents good quality in most of the features except in the holes that constitutes the wiring. The toy car also stands out for its good result in both shape and appearance. The old coffee

Table 6. Comparative table of the results of reconstruction of the pieces that offered the best aspect.

	Wooden gear	Wooden mold	Gear wheel	Toy robot	Toy car	Old coffee grinder	Engine
Colours	++	++	++	++	++	++	++
Textures	++	++	++	++	++	++	++
Model details	++	++	++	+	++	++	+
Holes definition	++	++	–	–	++	+	–
Borders	++	++	+	+	++	++	+

grinder highlights for having a great definition in most aspects despite having gaps and thin elements in some of its parts. This is a general problem of this type of technologies that needs to be improved, although it has been solved in this piece. Finally, the engine has a good result in terms of geometry, but finishing can be improved in its interior details.

It can be verified that the general results are quite good in most of the pieces. The surface characteristics of the type of piece can influence the reconstruction result, but with a good illumination of the models, in this case improved with the new process of taking photographs (scan phase), the reconstruction results are more than acceptable.

This study has been carried out as a pilot experience for students from three different subjects taught at the Technical University of Cartagena during the first term of the 2017/18 course: ‘Industrial Design’ and ‘Graphic Expression’ (both from the Degree in Mechanical Engineering), and ‘Graphic Expression’ (Degree in Industrial Technologies Engineering). These students did not have any previous knowledge about this type of methodologies and it has been possible to verify the great interest in every executed activity. In general, ratings have been very positive and the students have even asked for more activities of this type to be done.

6 Conclusions

Nowadays, reverse engineering is used in multiple professional fields that impel to develop different processes for obtaining virtual objects from real objects. This study is a sample of the use of open access applications as didactic tools within a reverse engineering process. This type of practice is only an initiation to this process. The ideal solution would be to use more sophisticated and professional tools, but not always they are reachable.

The present study has shown the process of scanning and 3D reconstruction by images of several pieces. This method, which is denominated Image-based 3D Modeling and Rendering (IB3DMR), uses a set of photographs in 2D to generate a three-dimensional digital model. The tool used during this study is Autodesk Recap, which has been proved to offer a good quality in most reconstructions. In case of

requiring a possible mesh editing process, the MeshLab software has been shown. This tool is used to optimize, if necessary, the mesh of the virtual model giving the possibility of exporting to other CAD formats.

Three-dimensional reconstructions obtained from scanning by images can have multiple applications in different fields such as engineering. Acceptable virtual objects can be obtained to perform the required simulations in a design process, analyse characteristics and surface properties of any type of piece, etc. In addition, this type of tools does not highlight by its equipment accuracy, but its ease of use, low cost and flexibility make them very appropriate for the teaching field as didactic tools, and especially for distance learning.

This work has presented a series of activities that allow students to begin in the reverse engineering process, work in the process of scanning and reconstructing objects by images, and exporting them to different formats according to the needs required by the piece. Using this type of tools prepares students in new technologies and applications that are increasingly being implemented in all professional fields of society. Universities must be prepared for these new challenges and offer them as a complement to their academic education.

The analysis of the tests completed by the students highlights that this type of methodologies are unknown and most of the students have a high level of interest in learning them because they consider that it may be important for their professional future.

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