

# AN OCCLUSION-AWARE AR AUTHORIZING TOOL FOR ASSEMBLY AND REPAIR TASKS

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**Abstract:** The use of authoring tools has become a valuable trend for the fast development of Augmented Reality (AR) applications in industrial organizations. However, most of current AR authoring tools are actually programming interfaces that are exclusively suitable for programmers. Moreover, they do not provide advanced visual effects, such as occlusion or object collision detection, to the resulting AR applications. In this paper, we propose an easy-to-use AR authoring tool oriented to the development of AR applications for the execution of industrial sequential procedures. Unlike other recent easy-to-use AR authoring tools, this software framework allows non-programming users to develop low-cost AR applications, including occlusion capabilities, by means of the use of a Kinect sensor. These applications could be used in on-site assembly and maintenance/repair tasks where a certain level of depth perception is needed. In order to validate our AR authoring tool, we have developed four AR applications belonging to different industrial areas. The evaluation results show that overlaying 3D instructions on the actual work pieces reduces the error rate for an assembly task by more than a 75%, particularly diminishing cumulative errors common in sequential procedures. Also, the results show that the time required by non-programming users to develop the AR prototypes using our tool was more than 90% lower than the time required for developing the same prototypes with computer graphics programmers. These results show the potential of our approach and validate the tool as a general-purpose AR authoring tool for industrial AR applications.

## 1 INTRODUCTION

Augmented Reality (AR) systems have been widely used in numerous applications such as medical procedures, scientific visualization, manufacturing automation, cultural heritage and military applications (Ca-wood and Fiala, 2008). The term Augmented Reality (AR) defines computer graphic procedures or applications where the real-world view is superimposed by computer-generated objects in real-time (Azuma, 1997).

One of the main problems that prevents AR applications to become popular is the lack of AR authoring platforms that allow unqualified users in computer graphics to easily generate AR applications. There are popular software libraries like ARToolKit (Kato and Billinghurst, 1999) and ARToolKitPlus (Wagner and Schmalstieg, 2007) that use OpenGL, VRML or OpenSceneGraph (Burns and Osfield, 2004) to represent the 3D models on the real images in real time. OpenSceneGraph is a freely available graphics frame-

work for the development of high-performance graphics applications based on the concept of a scene, providing an object-oriented toolkit on top of OpenGL. However, the use of these and others computer graphics libraries requires programming skills to generate AR applications, and every AR development should be constructed from the scratch.

In order to avoid these problems, AR authoring tools were proposed a decade ago (Poupyrev et al., 2001; Haringer and Regenbrecht, 2002). The main advantage of AR authoring tools is that they do not rely on time and cost consuming recompilation steps, and therefore the changes and enhancements in the development of AR systems are fast and efficiently completed. In this sense, a software plug-in built on top of Macromedia Adobe Director allows to author AR content for this widely used multimedia development environment (MacIntyre et al., 2005). Also, an extensible and general-purpose AR authoring platform based on XML descriptions was proposed (Ledermann and Schmalstieg, 2005). However, interac-

tions are implemented in non-interpreted languages addressed through the XML parser. The STUDIERTUBE Framework was another proposal for the prototyping of AR applications (Schmalstieg, 2005), and even a well-known visual programming environment (ECT graphical programming tool) was modified to add support for AR input (Hampshire et al., 2006). Later, an extensible authoring tool that supports both scripting and a drag and drop interface and real time interpreted input was developed (Seichter et al., 2008). A recent work even classifies the existing AR tools depending on the use of external libraries, and the programming knowledge required for using them (Wang et al., 2010).

Assembly, maintenance and even repair tasks are some of the direct application fields of AR tools, and a lot of proposals have been made in these industrial areas (Neumann and Majoros, 1998; Baird and Barfield, 1999; Friedrich, 2002). However, most of the proposed AR systems have been specifically developed for enhancing certain procedures in the domain of the problem. The development of augmented reality systems usually involves two key design issues: the decision of implementing a mobile or a non-mobile system (Friedrich, 2002; Schwald et al., 2003), and the choice of selecting a helmet-mounted or a hand-held display systems as AR visualization device (Baird and Barfield, 1999). In this sense, a recent work (Wang et al., 2010) classifies AR development tools into two categories: AR-related software framework (Kato and Billinghurst, 1999; Wagner and Schmalstieg, 2007) and GUI-based AR authoring tools (Poupyrev et al., 2001). Nevertheless, although industrial environments could require mobile as well as non-mobile AR systems (Schwald et al., 2003), once a mechanic begins to physically manipulating objects in a task, he does not always need the visual information provided by the display (Henderson and Feiner, 2009) to complete certain steps of a given industrial procedure. On the other hand, although several AR systems have been proposed for industrial purposes, most of them superimpose the computer-generated objects on the real view of qualified workers. This forced superposition cause the occlusion problem, which occurs in AR systems when a computer-generated object closer to the viewer obscures the view of real elements farther away along the line-of-sight (Breen et al., 1996). If the occlusion problem is not properly addressed in the development of an AR system for industrial purposes, then the developed tool does not significantly facilitate workers their actual on-the-job tasks. This fact is especially evident in the development of AR systems for assembly or repair/maintenance purposes because of the cluttered backgrounds and the frequent

occlusions in these types of industrial environments (Sang-Cheol et al., 2005).

Figure 1 shows an example of the occlusion problem when a custom AR system has been used in the on-site repair process of a six-cylinder diesel engine. Concretely, the pictures included in this figure show the step when the first of six fuel injectors (modeled using eye-catching green colors) is fitted into the proper engine cylinder head. The top picture of this figure shows how a non-occluded 3D computer-generated fuel injector is visualized over the engine indicating the mechanic a misleading final location of the cylinder head. In this sense, the AR tool seems to indicate that the current fuel injector should be located into one of the cylinder heads located in the front side of the engine as observed from the user's point of view. Otherwise, the bottom picture of the same figure shows how this augmented fuel injector has been correctly occluded by the foreground real objects in the scene, indicating the proper location of the cylinder head within the back side of the engine.

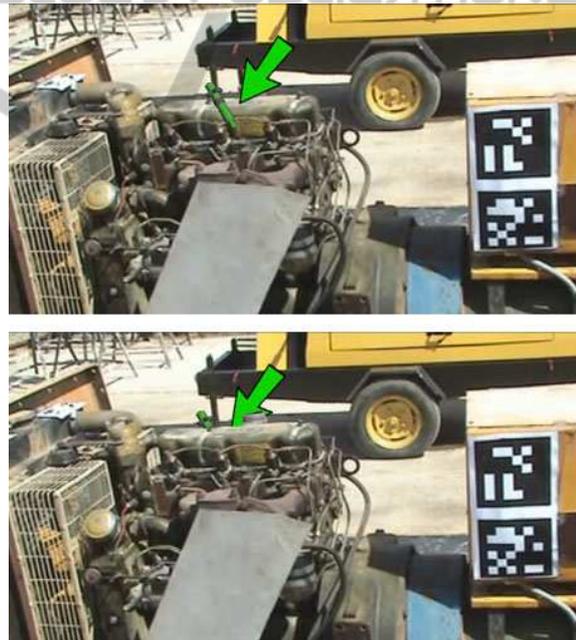


Figure 1: An example of the occlusion problem in an AR system for industrial purposes.

In this paper, we propose an easy-to-use AR authoring tool including occlusion capabilities. This AR tool, called SUGAR, has been intentionally designed to enable a rapid prototyping of low-cost AR systems. SUGAR allows describing industrial task, such as assembly, repairing and maintenance procedures as a set of sequential steps including different digital contents: video, images, text, manufac-

ture's manuals, and augmented reality information. Since our AR authoring tool does not use a proprietary format, any kind of device (PDA/smartphones, TabletPC, See-Through goggles, etc.) could be used for the AR applications generated by the proposed tool. Moreover, the iterative development process of an AR application and the corresponding maintenance phase can be completed with our tool by developers with non-programming skills. Unlike other authoring tools include some types of occlusion capabilities (Haringer and Regenbrecht, 2002), they deal with the occlusion problem using a model-based approach (Breen et al., 1996). This approach registers 3D geometric models of the real objects in the environment, denoted as phantom models, to their real-world counterparts. Since the 3D modeling of objects involved in the on-site industrial tasks would be an impossible or a very expensive procedure, our approach uses Kinect (Santos et al., 2011) for computing a depth map of the scene to produce occlusion effects. The application examples show, unlike other recent easy-to-use AR authoring tools (Wang et al., 2010), that the proposed tool can be used as a general-purpose and low-cost framework for generating different maintenance and repair AR applications. Also, this paper describes some experiments that test the relative effectiveness of AR instructions in assembly, maintenance and repair tasks. In this sense, three instructional media were compared to evaluate the performance of the developed AR applications: a printed manual, computer assisted instruction (CAI) using a TabletPC display, and CAI utilizing a head-mounted display. The evaluation results show that overlaying 3D instructions on the actual work pieces reduced the error rate for an assembly task by 79%, particularly diminishing cumulative errors (errors due to previous assembly mistakes). Moreover, the time required by non-programming users using SUGAR to develop the AR prototypes was much lower (approximately a 95%) than the time required for developing the same prototypes with expert programmers. These results validates the proposed tool as a general-purpose AR authoring tool for industrial AR applications.

The rest of the paper is organized as follows: Section 2 shows some related work about AR authoring tools for maintenance and repair tasks. Section 3 describes in detail the proposed AR authoring tool. Next, Section 4 shows different application examples of the proposed tool, and Section 5 shows the performance evaluation of AR instructions in an assembly task using the proposed tool. Finally, section 6 shows some concluding remarks and the future work to be done.

## 2 RELATED WORK

Augmented Reality has been tested in manufacturing environments since more than one decade ago (Neumann and Majoros, 1998; Baird and Barfield, 1999). The potential of AR systems led to national research projects like ARVIKA (Friedrich, 2002). ARVIKA was a coordinated project, funded by the German Government, focused on the use of AR technologies for supporting working procedures in the development, production, and servicing of complex technical products and systems. Although ARVIKA included mature concepts for integrating physical and digital workspaces in a common scenario, the final AR procedures resulted very poor in terms of intuitive interaction mechanisms, functionality and usability. At the same time, another work proposed a prototype hardware and a software framework for supporting a wide range of maintenance categories with AR (Schwald et al., 2003).

More recently, the most remarkable developments in the field of AR technologies for manufacturing purposes were collected in a remarkable survey (Ong et al., 2008). Also, another work proved that an AR application was more efficient than an enhanced baseline system in reducing time and head movement during the localization portion of maintenance tasks (Henderson and Feiner, 2009). The authors were especially encouraged to achieve these results with a population of professionally-trained mechanics working in a field setting, who expressed support for this approach.

Finally, another recent work includes a question examination mechanism in the AR authoring tool (Wang et al., 2010). From a pedagogical point of view, examination is an important method in understanding the efficacy of a system of learning, and this feature can be a valuable tool also in manufacturing environments. However, the target users of the proposed authoring tool are high school students, and the examination mechanism is limited in that study to this population. In this work, we propose an examination mechanism suitable for different target populations as well as a performance evaluation carried out using qualified participants into the experiments. Also, an important feature in this proposal is the fact that this AR authoring tool does not use a proprietary format, and any kind of device (with an adequate interface) can use the information generated by the authoring tool. The authoring tool models AR procedures as a set of sequential steps, which can be attached with different digital content including AR information with occlusion capabilities. Once the AR procedure has been modeled, the editor generates a very simple ex-

change file containing all the digital content as well as XML data. This exchange file can be loaded into different AR hardware platforms such as TabletPC, PDA/smartphones or even another type of devices, including low-power general purpose processors, to execute the AR procedures in on-site industrial environments.

### 3 AN OVERVIEW OF SUGAR

SUGAR (which stands for **S**ystem for the development of **U**nexpensive and **G**raphical **A**ugmented **R**eality application) is an open-source software platform designed to enable a rapid prototyping of low-cost AR systems. Our framework is oriented to develop complex AR software applications based on procedural simulations, which are modeled following an easy-to-use AR authoring editor. This AR editor generates an exchange file, describing the AR procedure, which can be loaded into different AR devices not requiring high computational power.

Figure 2 shows the workflow for the development of AR applications using SUGAR. The SUGAR editor allows users with non-programming skills the creation of augmented reality procedures based on steps. The main challenge when creating an Augmented Reality application is to achieve a correct overlap (registration) between the real world and the virtual information that is added on the real world. SUGAR allows the creation of virtual contents through an easy edition mechanism based on real world photos. The user takes photos of the real scenarios to be augmented, and is on these photos where the virtual content is edited. The ARToolKitPlus-based markers are automatically generated with a simple calibration step, in such a way that the user should only paste the AR markers on the real object in order to visualize the augmented scene. Therefore, SUGAR bridges the gap between virtual information and the real world, offering the user an easy way of creating virtual contents according to reality.

The SUGAR modules can be classified in two groups: description of the real world, and virtual content edition. The first group includes those modules necessary for creating the scenarios where the virtual contents will be displayed. Each scenario is composed of an image of the real environment, some AR markers that are generated automatically, and a depth map (the latter one only is presented if a Kinect is available when the photo is taken). In order to create this scenario, two wizards guide the user through some easy stages. The first stage, called the *PhotoKinect Wizard module*, displays the real-time im-

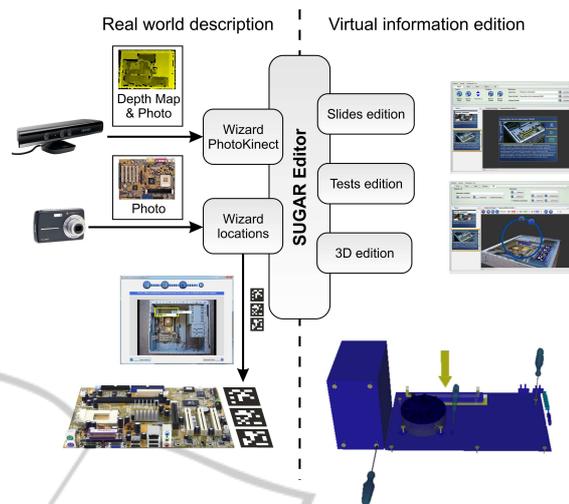


Figure 2: Proposed workflow for the development of AR applications using SUGAR.

age of the markers camera and allows taking photos storing at the same time the depth image. This depth information will be used later in order to produce correct occlusions. The other wizard, called *Locations wizard*, allows the user the creation of a scenario from either a conventional photo or a photo captured with AR markers. This wizard is also split into four easy substages: first, the desired images are loaded. Then, the wizard allows to draw a rectangle indicating a flat area where the markers can be located. The two final substages consists of the introduction of the flat area defined within the real image and the number of AR markers to be used. After these steps, the scenario is ready for editing the virtual contents. The virtual models will be adjusted to the size of the real object to be augmented by using the size information introduced by the user. At any moment, the user can select a scenario and print the associated markers in order to paste these markers on a real object. This simple wizard allows a user with neither programming, nor ARToolKit/ARToolKitPlus knowledge, the creation of an AR marker with the proper size and the corresponding associated configuration file. The absence to this editor would require that the user selects the images of the markers to be used (he also locates the markers in the correct position) and he finally creates a configuration file with the description of the size, location and rotation matrix of each of the markers within the image.

After the creation of the scenarios, the other group of modules includes the procedures for defining the virtual information. The editor of SUGAR uses a structure based on steps (denoted also as slides), where each of them is associated to one of the scenarios previously created. The edition of the virtual con-

tent can be split into three different stages: definition of the current step of the procedure, creation of the virtual content associated to each slide, and the definition of the corresponding evaluation tests for this step, if necessary. The definition of the slides includes some basic office functions: creation, ordering, text edition, aspect, associated video, associated pdf files, etc. All these functions can be easily performed, in a similar way to the creation of a conventional graphic presentation.

The creation of virtual content consists of adding some virtual elements that help to explain each step to the scenario displayed in the slide. The virtual elements can be created either from basic 3D objects organized in an internal 3D library, or loading 3D models previously created using Autodesk 3DS Max. The included 3D library consists of cubes, spheres, planes, cones, etc., which can be grouped to generate more complex models, and allows changing their textures, colors, or other properties. Also, we have developed an animation module based on keyframes that allows to animate the virtual objects. In order to allow the creation of 3D models that are appropriate for the scenario to be augmented, the 3D scene includes a template with the photo that is used as the model, and even (depending on the type of scenery) a mesh created from the picture taken with Kinect. Using this reference, the user only has to locate the virtual models on the template. This way of creating a scene, starting from a reference image, allows the location of the virtual elements and their size adjustment. The absence of this template would force the user not only to accurately measure the location of each virtual element and its orientation on the real object according to the ARToolKitPlus marker, but also requiring from the user a certain level of knowledge in 3D design, computational trigonometry and the use of the ARToolKitPlus library.

Figure 2 also shows how we have created a *Test Wizard* for the test edition process. This module can easily generate three kinds of questions: true/false questions, multiple answer questions, and selection on the image. The latter one consists of asking the user to mark a concrete area on the image (for example, a car battery). When creating the test, the user enters the photo and he marks each vertex of the correct area with the mouse.

### 3.1 Software Architecture

The software architecture of SUGAR is based on a modular approach oriented to develop procedural AR systems. Basically, the SUGAR framework consists of two applications: an easy-to-use editor for AR

procedures and an AR light viewer. Both applications share some software modules permitting them to reuse 3D-tracking data structure models, and visualization code.

Figure 3 shows the software architecture of the SUGAR framework for the development of AR environments. Both applications (“SUGAR Editor” and “SUGAR Viewer”) share the kernel of the AR framework denoted as “Data Core”. This kernel provides basic services for augmented reality facilities as camera tracking, marker handling and virtual object interaction.

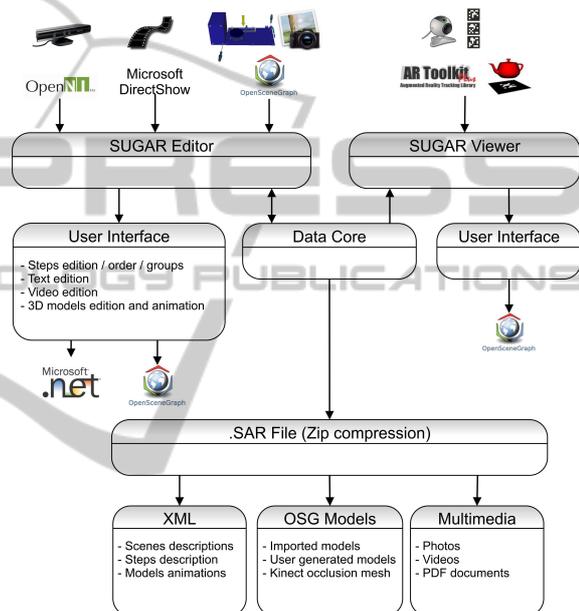


Figure 3: A modular view of the software architecture in SUGAR.

Although AR editor and AR viewer share this software module, each application includes a different user’s interface. Thus, the graphical user interface of the AR editor has been developed on Windows Forms and includes some components, developed on OpenSceneGraph, in order to offer high-performance 3D graphical capabilities when users create and edit the AR procedures. In this sense, the OpenNI software library allows accessing the depth map of the real scene using the Kinect device. Moreover, the Microsoft DirectShow API enables high-quality playback of streaming video and audio to be attached to the steps of the industrial (maintenance, repair or even assembly) procedures. In contraposition to this multiview 3D application, the AR viewer corresponds to a light Windows application, developed on Qt/C++ (Blanchette and Summerfield, 2008), embedding a reduced version of the OpenSceneGraph

framework and including a reduced set of primitives for this 3D high-level library tool. Since Qt/C++ is a cross-platform development framework, the same source code for a Qt application can be compiled on different operating systems without changes. In this sense, the “SUGAR Viewer” has been ported to Symbian and Android operative systems with minimum changes within the initial source code. The reduced computation workload of this multiplatform application allows the viewer to be executed on low-power general purpose processors to execute the AR procedures in on-site industrial environments.

The “Data Core” module also includes the definition and the basic properties of the exchange file format for the SUGAR framework, denoted as SAR files. These files are generated by the AR editor to be imported by the SUGAR multiplatform viewers. Basically, the SAR files are zip-compressed archives containing a structured representation of AR applications, and the corresponding multimedia content, that can be attached to the steps of the modeled AR procedures for industrial task. The organization of the digital content, including the depth maps obtained from the Kinect device, has been defined using XML files, providing a flexible configuration mechanism.

## 4 APPLICATION EXAMPLES

In order to validate our AR editor as an efficient tool for the rapid prototyping of AR applications for assembly, maintenance and repair purposes, we have tested our tool in four different application examples belonging to various industrial areas. Concretely, these application examples are the following procedures: the replacement of the cut heading within a lathe machine (metal machining area), the assembly of a computer starting from its basic components (computer and electronics manufacturing area), the repair of the admission system in a mobile lighting tower (maintenance of heavy machinery area), and the review of the spark plugs and the ignition coils on a BMW M3 E92 (420CV) engine (automobile maintenance area). We have denoted these procedures as *PROC 1* to *PROC 4*, respectively. Table 1 shows the amount of steps, gathered into groups, needed to complete each one of the tasks. Since not all the steps recommended by the manufacturer need visual indications to be completed, this table also shows, for each procedure, the number of steps that actually include AR contents.

In order to help in the completion of these tasks, SUGAR authoring tool was used to prototype two different AR systems (for each of the four procedures

Table 1: Decomposition of the procedures in steps.

Procedure	Groups	Steps	AR Steps
PROC 1	6	51	26
PROC 2	5	25	20
PROC 3	7	58	32
PROC 4	4	15	10

considered): a computer assisted instruction system using a TabletPC system (we will denote this AR system as S2) and a computer assisted instruction system using a head-mounted display (we will denote this AR system as S3). Concretely, the S2 system was developed on a Dell Latitude XT1 TabletPC (Intel Core 2 Duo at 1.2GHz, 2GB RAM, ATI Radeon Xpress 1250, Windows 7 Professional) including a LCD-CCFL 12.1-inch screen for outdoor environments, reaching up to 400cd/m<sup>2</sup> of brightness. The S3 system consists of the same Dell Latitude XT1 but connected to an “AR Vision 3D HMD”, which is a full stereoscopic video see-through AR device including a binocular SVGA (1024x768) displays and two separate 752x480 (60 FPS) color cameras. In order to illustrate the considered application examples, Figure 4 shows a snapshot of the proposed AR editor (SUGAR Editor) when implementing Procedure 1, while Figure 5 shows a snapshot of the SUGAR tool when used for Procedure 3.



Figure 4: SUGAR Snapshot for Procedure 1.

Figure 4 and Figure 5 show the interface of the proposed AR editor for sequential procedures included in SUGAR. The easy-to-use interface of the editor is very similar to the most common graphic presentation programs (such as Microsoft PowerPoint, Apple KeyNote, Open Office Impress, etc.), and it consists of a large view of the current step of the modeled procedure along with a view of the rest of steps (as a slide sorter) on the left side of the screen. The editor allows non-programming users to create AR applications consisting of a set of sequential steps handled by AR markers. In this sense, the toolbars on the top of the window allow to include multimedia

contents such as video, images, text, manuals and AR information into the steps of the AR procedure.

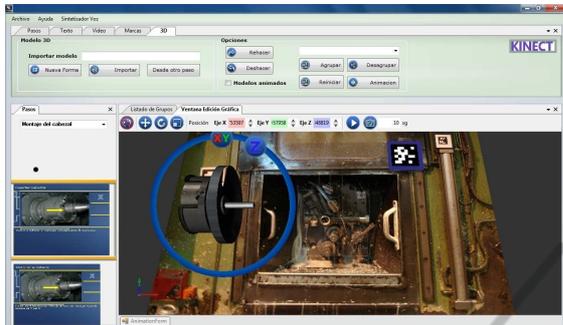


Figure 5: SUGAR Snapshot for Procedure 3.

Figure 5 shows the "Affine Transformation Tool-bar" that appears when 3D models (modeled using Autodesk 3DS Max or selected from a library included within the applications) are included into the current step of the procedure. This toolbar allows rotating, scaling, translating and defining animation for the 3D models that will be visualized by the user when the system recognize the AR markers located as a part of the environment. Also, the button located at the right upper corner of the screen allows to load a depth map of the real scene using the Kinect device. This feature is needed when the 3D model for the current step of the AR procedure needs occlusion capabilities. Figure 6 shows an example of an original image from a real environment and the corresponding color mapped depth image obtained by the Kinect device. Finally, Figure 7 illustrates the use of the S2 system when Procedure 1 was tested in a real industrial environment.

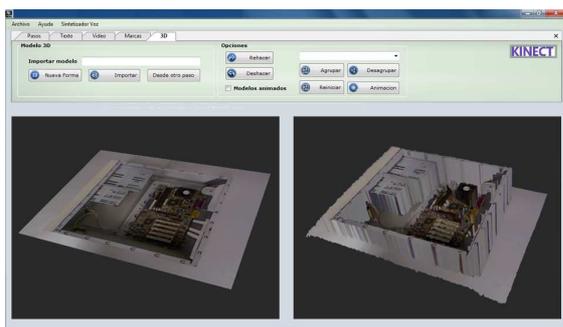


Figure 6: Results of the image from the original environment and the textured depth map using Kinect in SUGAR.



Figure 7: Real use of S2 system in Procedure 1.

## 5 PERFORMANCE EVALUATION

The performance evaluation of augmented reality authoring tools results in a complex task, since it is very difficult to quantitatively show the utility or effectiveness of the proposed methodology and tools. The measurement of costs reduction in software development and maintenance neither results an easy task. The main reasons are the lack of objective metrics in not only Augmented Reality, but also Virtual Reality, and the qualitative and even fuzzy nature of most software engineering studies (Seo and OhM, 2007).

A possible way of evaluating the performance of Augmented Reality tools is a qualitative, user-centered approach (Traskback et al., 2003). According to recent studies (Nilsson et al., 2010), the observations and questionnaire are the basis for a qualitative analysis. The questionnaire consists of several questions where the participants in the evaluation of the AR tool can freely answer on their experience of the AR system. The questions are usually related to overall impression of the AR system, experienced difficulties, experienced positive aspects, what they would change in the system and whether it is possible to compare receiving AR instructions to receiving instructions from an instructor. However, a qualitative approach does not allow neither to compare different AR tools on a fair basis, nor to evaluate their performance in comparison with traditional training or guidance tools. On the contrary, a quantitative analysis can allow a fair comparison of different tools. Some metrics like cost efficiency, development time and maintainability have been proposed for a quantitative analysis (Abawi et al., 2004). However, that work does not define concrete criteria for assigning values to the three metrics, and only the development time is accurately measured.

We propose a quantitative approach for the performance evaluation of the AR tool in some industrial environments. In order to measure the complexity of

the assembly, repair and maintenance tasks, we have followed the criteria proposed in (Campbell, 1988). Therefore, we have classified the application examples described in Section 4 as shown in Table 2.

Table 2: Classification of the task complexity.

Procedure	PROC 1	PROC 2	PROC 3	PROC 4
Complexity	Very High	Normal	High	High

In order to measure the performance provided by the AR systems prototyped with SUGAR, we have first measured the average completion time required by fifteen different users in order to completely execute each of the considered procedures. All the users were experts technicians in their area, but a training session was performed prior to the performance evaluation in order to allow the users to get in contact with the AR technology. The same users were used for performing the four procedures, in order to avoid any skew in the results due to the different skill of different populations. However, the fifteen users were divided into four groups, and the sequence of procedures executed by each group was different, in order to avoid skews in the experimental results due to the potential training with the technology. Moreover, not only it was the first time that the users executed the considered procedures, but also any of the groups repeated the same procedure using different systems, in order to avoid the benefit with the knowledge and experience that they acquire before.

For comparison purposes, the users also performed the considered procedures exclusively using a printed manual provided by the manufacturer. We have denoted this "system" as S1. Table 3 shows the average completion times required when using each system for all the procedures considered. As it could be expected, the average completion times for systems S2 and S3 are much lower than the ones achieved with S1 system. Also, this table shows that the times achieved with S3 (computer assisted instructions (CAI) using a head-mounted display) are lower than the ones achieved with S2 (CAI using a TabletPC display), reaching even less than half the time required for the same procedure with system S1 (in Procedures 1, 3 and 4). These results show the significant benefits that AR systems can provide to assembly, repair and maintenance tasks.

In order to get a more in-depth analysis of the results shown in Table 3, we have measured the mistakes made when executing the AR procedures for all the considered experiments. Table 4 shows the average number of steps in the experiments that were repeated by the qualified participants because of hu-

Table 3: Completion times with different systems.

Procedure	S1	S2	S3
PROC 1	4h 30min	2h 30min	1h 45min
PROC 2	50min	35min	30min
PROC 3	6 h	3h 30min	2h 45 min
PROC 4	2h	1h 15min	50min

man errors. As it could be expected, the direct visual guidance provided by the augmented reality devices in systems S2 and S3 resulted in a significant decrease in the number of repeated stages, compared to the use of manufacture's manuals in S1. The system S2 provides the lowest number of repeated stages. Since the execution of assembly and maintenance/repair tasks are often incremental processes, where the results of previous steps are the input of next steps, undetected mistakes in preceding stages (denoted as cumulative errors) result in repeating all the previous affected tasks, starting where the mistake was committed. For this reason, the number of the repeated tasks grows exponentially as the errors made by the participants increase. Nevertheless, the differences between S2 and S3 systems become significant even if taking into account this fact, showing that immersive augmented reality does not provide the best performance in industrial environments.

Table 4: Number of repeated stages when completing the AR procedures.

Procedure	S1	S2	S3
PROC 1	12.25	2.65	3.30
PROC 2	7.51	1.26	4.65
PROC 3	14.13	2.40	3.60
PROC 4	4.33	1.23	1.57

Nevertheless, Tables 3 and 4 do not actually measure the performance of SUGAR, but the prototypes developed with this AR authoring tool. In order to measure the performance achieved with SUGAR, we have asked two different teams to develop the prototypes whose results are shown in Table 3. One of the teams (we will denote this one as Team 1) was composed of AR programmers, and the other one (we will denote this one as Team 2) was exclusively composed of expert technicians. As a reference, we asked Team 1 to develop the prototype following the classic AR development approach, by writing, compiling and debugging source code. In this sense, Team 1 developed the AR prototypes using Microsoft Visual Studio 2010 as C++ development framework, OpenSceneGraph 2.9.7 as 3D graphics visualization toolkit and ARToolkitPlus 2.2 as software library for AR purposes. In order to measure the performance of

SUGAR, we asked Team 2 to develop the same prototypes with SUGAR.

Table 5 shows the development times (in working days) required by each team. The column labeled as “Team” shows the team, the column labeled as “Param.” shows the specific parameter of the development time measured by each row, and the other four columns shows the results for each procedure. The parameters measured are the following ones: SLOC measures the final number of source lines of code included within the final AR prototype, while FPS indicates the frame-rate (in frames per second) achieved using the test hardware. The parameter CT measures the number of working days required by the team for completing the coding stage of the prototype. The parameter DT measures the number of working days required by the team for completing the debugging/adjusting stage, and the parameter TT measures the total time required for the development of the prototype (the sum of CT and DT parameters).

Table 5: Source-code sizes and development times.

Team	Param.	PROC 1	PROC 2	PROC 3	PROC 4
1	SLOC	71853	64710	76254	53695
	FPS	28	44	32	50
	CT	95	76	108	59
	DT	15	10	17	6
	TT	110	86	125	65
2	SLOC	79215	71523	37749	60101
	FPS	31	40	35	50
	CT	3	3	2	2
	DT	1	1	2	1
	TT	4	4	4	3

Table 5 shows that the size of the source code generated by SUGAR is roughly a 10% higher than the source code created by traditional AR programming. However, this slight increase of the source code does not have an effect on the graphic performance of the AR application. Moreover, Table 5 also shows that the time required by non-programming users with SUGAR to develop the AR prototypes are less than 5% of the ones required for developing the same prototypes with programmers. These differences of orders of magnitude show the potential that an intuitive AR authoring tool like SUGAR can provide to industrial environments. Moreover, the ease of use of SUGAR allows to avoid the need for programming skills, exclusively requiring the expertise of technicians in that field for developing AR prototypes. Also, any potential change required by the prototype can also be made by technicians, without the need of programming skills.

## 6 CONCLUSIONS AND FUTURE WORK

In this paper, we have proposed an easy-to-use AR authoring tool, which allows the easy creation of interactive augmented reality applications without any programming knowledge. This authoring tool includes an easy-to-use editor for AR procedures and an AR light viewer, which share non-proprietary exchange files describing the AR procedures. The proposed tool allows the development of AR applications with occlusion capabilities to be used in on-site industrial procedures, where a certain level of depth-perception is necessary. Unlike other recent proposals, our tool does not rely on expensive or unavailable 3D models, and it uses Kinect for computing a depth map of the scene.

The performance evaluation of the proposed AR authoring tool includes both a qualitative and a quantitative assessment. Concretely, we have tested four AR applications, belonging to different industrial areas, using different instructional media. The performance evaluation results show that the registration of geometric models to the real-world counterparts in industrial procedures significantly facilitate workers their actual on-the-job tasks. The direct visual guidance provided by the AR devices significantly decrease the number of repeated stages when compared to commonly used manufacture’s manuals.

Also, the time required by users with non-programming skills to develop the AR prototypes using our tool was much lower than the time required for developing the same prototypes with expert programmers when following a classical development of AR systems. These results shows the potential of our approach and validates it as a general-purpose AR authoring tool for industrial AR applications.

As a future work to be done, we are working on new versions of the light viewer for iOS and Windows Phone devices. Moreover, SUGAR pretends to integrate a new tracking module, based on natural features, to improve the current augmented reality experience provided by the tool when executing on-site industrial tasks.

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