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Generating virtual environments of real world facilities: Discussing four different approaches

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ABSTRACT

There is an increasing need to generate detailed real-time virtual environments that closely mimic real world facilities. Approaches for the generation of virtual environments can be manual, automatic, or hybrid. Manual approaches are time consuming, inaccurate, and coarse whereas automatically generated data sets are less than optimal for practical use within real-time virtual environments because of the huge unstructured amount of data. Therefore, common approaches are most likely to have a balance between human and computer effort. Based on different projects, we discuss possible distributions of manual and automatic methods for the generation of 3D virtual environments. We present different facets of the pipeline from initial data gathering up to the final deliverable. The approaches employed in these projects vary from fully hand made up to semi-automatic reconstruction of the environments. The paper concludes with recommendations regarding the reconstruction methods.

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1. Introduction

There is an increase in use of 3D virtual environments in architecture, engineering, and construction (AEC) industries. Applications like virtual training environments, virtual prototyping of designs, and joint virtual development of information systems require a valid representation of the real environment. Often, the real environments are industrial facilities such as oil rigs, container terminals, or manufacturing plants.

There is no single reason why 3D virtual environments are increasingly popular, but drivers stem from multiple backgrounds. Advantages of 3D virtual environments are found in improving communication [1], increasing insight [17,23], supporting collaboration [4], and supporting decision-making [13]. The divergence in applications requires different levels of fidelities of the 3D virtual environment. This can be illustrated by the different levels of fidelity required in the design process of a manufacturing plant. Designing the plant is mostly done in a 3D environment with high precision. The design drawings are complex, show different layers (e.g. mechanical, electrical, and plumbing), and therefore become hard to understand. On the contrary, for the presentation of the final result to stakeholders, a 3D visualization with a reduced level of complexity is preferred. The 3D visualization can be used as a platform for shared understanding to be used by every stakeholder involved in the design process. The different types of visualizations, both in 2D and 3D, achieve different types of fidelity for each specific goal.

1.1. Realism in 3D virtual environments

According to Webster's dictionary, “fidelity” means the accuracy in details. Fidelity is the general term for the way in which a model is a valid representation of a reference system; 3D modelers tend to use the term “realism,” as their reference system is the real world, i.e. the real industrial facility. Ferwerda [8] distinguishes three varieties of realism in computer graphics: physical realism, photorealism, and functional realism. For each type of realism, there is a criterion which needs to be met in order to achieve that type of realism.

Physical realism is achieved when computer graphics provide the same visual stimulation as reality. This type of realism means that “the image has to be an accurate point-by-point representation of the spectral irradiance values at a particular viewpoint in the scene.” It requires an accurate description of the scene, simulation of the spectral and intensive properties of light energy, and reproduction of those energies by the display device. Technically this type of realism is the hardest one to achieve. Although this aspect is often ignored for models that have to be visually appealing, it might become essential in 3D virtual environments for future uses. In this paper, physical realism is ignored.

Photorealism in a virtual scene provides the same visual response as the real scene. It aims at displaying an image indistinguishable from a photograph of the real scene. Although achieving photorealism has primarily been a task for off-line rendering algorithms (such as

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algorithms for global illumination), modern interactive 3D visualization software libraries tend to surpass the vague threshold towards photorealism.

Functional realism is about providing the same visual information as found in reality. The main concern of this type of realism is about transferring information about the real objects such as their shapes, sizes, motions, and materials. As this type of realism aims at providing the necessary information to perform visual tasks, functional realism can be found in photo-realistic images as well as in simplistic sketches. Measuring whether functional realism is achieved is therefore a challenging task as it requires an interpretation from human observers. The functional realism aimed for in this paper is what engineers would call 'accuracy.'

Although the three types of realism are compared against "reality" and "real environments," a realistic 3D environment is not necessarily one-to-one mapping of an environment found in the real world. A highly populated city could be displayed photo-realistically although the buildings and layout have been procedurally generated (e.g. reference [21]). In virtual environments for AEC, the common practice is to model existing facilities or facilities under design or construction. When under design or construction, a valid reconstruction of the future facility is required before it can be displayed. Several methods and techniques are available to perform these reconstructions. The key aspect in which they differ is the level of automation. Some methods require a completely manual reconstruction. Other methods however facilitate that data can be gathered automatically thus leaving everything up to algorithms which can be run on computers.

1.2. Human and computer effort in the reconstruction of virtual environments

Building a 3D virtual environment based on real world data is a tedious task. In reference [14], we discussed which technologies can be used and which skills are needed. The question remains to what extent automation is feasible and appropriate in building virtual environments of real world facilities. This question has come forward in multiple studies resulting in different approaches. These approaches are mainly situated in one of the following four groups: geometry based, image based, point cloud based and hybrid approaches [3,5,12,19,24].

In the gaming and animation industry, manual 3D modeling is the dominant approach. This approach, known as geometry based approach, is one of the most labor intensive ones. It therefore scales badly to large or detailed environments in which each new object has to be modeled separately. Some level of automation is possible in this approach, mainly making variations on objects and environments. The skills of the designer are essential for the quality of the result.

Image based modeling approaches aim at retrieving 3D models from a single or multiple 2D images of a physical object [6,10,16]. The typical workflow starts with the retrieval of (calibrated) pictures. Then geometry is extracted from these pictures. Once the geometry has been extracted, textures based on the initial pictures are applied. This approach has shown promising results but is still under research (some recent advances are described in references [2,9,18]).

The point cloud based approach uses capturing devices capable of recording 3D points in real environments. Capturing devices are known as active sensors (in contrast to passive sensors, e.g. camera, used in image based modeling) and laser scanners are a well-known example. Active sensors are split in two categories: ground laser scanners and airborne light detection and ranging (LiDAR) sensors [11,20]. Due to the advanced equipment and setup, this approach is relatively expensive and difficult to use. The results that can be achieved are highly detailed 3D models (e.g. reference [7]).

Hybrid approaches use a combination of the aforementioned approaches to surpass some of the disadvantages found in using a single approach. In most cases, these disadvantages are costs and capabilities of a particular approach.

Although image based and point cloud based approaches are near fully automated, they still require a lot of human effort. In image based approaches, taking images need to adhere to specific requirements, and postproduction is a necessity. Point cloud based approaches provide huge data sets which cannot be used directly in current virtual environments. The level of automation is case-specific and approaches are tailored towards requirements coming forward from that case. Besides the visual appearance, semantics have to be added to provide additional information: currently intelligent segmentation of the data is an active research topic [15].

2. Reconstruction of virtual environments in practice

2.1. Introduction

We present four projects wherein a real world facility has been modeled as a 3D virtual environment. The mix of manual and automated approaches varies between all four projects: we start with a project where no automatic generation took place and end with one that was almost generated automatically. For each project, we start with a general introduction and the requirements set in terms of what type and level of reality we aimed for. We continue by discussing the trade-offs we had to make in terms of effort, automation, and use of existing data. Finally, we discuss the choices made, present how the implementation took place, and what the challenges were.

2.2. Training environment for supervisors

The conventional way of training supervisors for the petrochemical industry combines hands-on training in training facilities and the use of videos, slides, and questionnaires. Experiential learning is assumed to improve the knowledge retention over conventional learning methods. A pilot project has been conducted at a large oil company to explore the benefits of 3D virtual training/serious gaming for training supervisors in the petrochemical industry. The objective is not to replace current training solutions but to position serious gaming as an additional teaching method. To do so, we developed an immersive 3D serious game that was based on an actual training location.

2.2.1. Requirements

The 3D environment is based on an existing location in use for real life training. Therefore, a key requirement of the virtual counterpart was achieving a high degree of photorealism with the existing location. Artificial defects were going to be integrated and had to behave correctly.

The following requirements were proposed for the 3D environment:

1. The 3D environment has to look photo-realistic; spatial correctness is less important than visual appearance.
2. Details that are of importance to the training scenario have to be homogeneous to the rest of the environment, so they will not be easily recognizable.
3. When possible, use the photographic information gathered during acquisition for the texturing process.
4. Weather conditions should be changeable.

2.2.2. Trade-offs

We chose a site with a compact size because of the high amount of details needed to be generated. The site was manually modeled based on photographs without rectifications or orientations. Therefore, the models were approximations of the actual objects with regards to dimensions. Nevertheless, they appeared photo-realistic because of the textures that were based on actual photographs.

Most of the detailing was focused on the objects and locations that were of importance to the scenario. Specific details take a lot of time to create whereas stock content can be used almost instantly. Therefore, the environment outside the compound (the drilling site) was neglected and the buildings that were of less importance were modeled generically.

Manual 3D modeling was used in favor of automatic acquiring techniques because the "pipeline" for creating the content for this particular industry and client was just getting started. With no awareness of the manual procedures, it is hard to correct mistakes in automatically generated content.

The final 3D model has lots of straight corners and planes although in reality there are none. This was a trade-off that had to be made based on the capabilities of the 3D visualization engine and the amount of work that is needed to create a more realistic 3D model. Most high frequency detail is captured and applied by using photographs as textures. Some tests have been carried out to assess displacement maps. However, the amount of work associated with the task did not balance well in the time frame associated with the complete creation process.

2.2.3. Implementation

The environment was implemented in Unreal Engine 3 using the development environment that comes with the engine. Most of the layout of the site was created with the included editor to provide a modeling framework. The details however, which are harder to model, were created with specialized 3D modeling tools. As the facility consisted mainly of piping, a component based approach was created which allowed us to reuse existing models to assemble the complete environment.

By making heavy use of photographic information, a rich set of textures was created but due to this large amount of photographic material, approaches had to be found to reduce memory issues. Procedural textures were therefore used to reapply them on multiple models. Furthermore, the photographic material was taken during different lighting conditions that required additional work from the texture artists to fix.

2.2.4. Results

The immersive 3D virtual training environment/serious game, shown in Fig. 1, demonstrated the power of serious gaming for training supervisors. Although a thorough evaluation has yet to be performed, the first informal evaluations show some promising results.

Approximately 40 people provided feedback with regards to the environment and were overall positive. People familiar with the site directly recognized it up to the details. Most people even assumed the environment was spatially accurate although it was only approximately correct.

Because manual modeling was the selected method, a lot of man hours were used to create the environment. It took two designers three full months to just model the environment. The amount of time needed to provide this much detail with manual methods raises the question if there is no speedier and more cost-effective way to achieve these kinds of results.

2.3. A design environment for automated container terminals

Novel modes of operations have to be developed to handle the increasing numbers of containers at modern container terminals. Automated handling equipment provides a solution and is becoming the default choice for the design of new container terminals around the globe.

Many actors are involved in the design process of container terminals. After the first design draft that is mainly developed by designers, the design has to be assessed by business developers and analysts. Once the design has been thoroughly studied using simulation models, it has to be presented to authorities and decision makers. The latter often lack technical knowledge to understand CAD drawings. Because of this, scale models, artists' impressions, and 3D movies are made to be used during presentations to non-technical actors. Constructing presentation material is a time and financially expensive task. It lacks the flexibility needed to present various designs during the design process. We have constructed a solution that enables designers to achieve insight, communicate their designs, and experiment with different layouts. We designed a support tool to easily construct and present 3D virtual environments of the new container terminals.

2.3.1. Requirements

The 3D environment has to support the design process of container terminal that do not yet exist. This means it is not possible to actually go on location to acquire data using acquiring technology such as laser scanners. The major source of data consists of CAD drawings made by designers and photographs of equipment that will be used in the future terminal.

The virtual environment has to be generated from the CAD drawings in an effort and time efficient manner. To do so, the conversion should preferably be as automated as possible. As the virtual environment will be used throughout the design process of the new terminal, the drawings will be changed and updated regularly,

Fig. 1. The training environment for supervisors: (A) the virtual environment based on (B) the real environment.

leading to updates in the 3D virtual environment. This prohibits custom modeling work for the 3D environment as it will be overwritten with each update. The 3D environment should also be as precise as the CAD drawing that is used as an input, as details are important during the design process.

The following requirements were identified:

1. Automatic generation of the virtual environment from the layout CAD drawings.
2. Spatial precision in respect to the CAD drawings.
3. Precise 3D models of the equipment.
4. Visual appearance was important for possible presentations.

2.3.2. Trade-offs

To automatically generate the virtual environment, a component based approach was used for the translation from CAD to VR. The downside of this approach was having the same models duplicated multiple times, resulting in a decrease of realism as real equipment often differs in details like rust and damage.

Customization based on key features of locations (e.g. environment outside of the terminal) is also not considered in this approach. As the design process of such terminals takes up to a year (or more), the possibility of developing custom partial models can be considered. This would give the designers an idea of the real world environment in which they are operating.

2.3.3. Implementation

The implementation consists of an Autodesk AutoCAD plug-in and a stand alone application developed using OGRE for the 3D visualization. The AutoCAD plug-in handles the translation from CAD to VR while the stand alone application visualizes the 3D environment.

Using a predefined convention based on blocks in AutoCAD, a translation to an intermediate XML format has been made. This approach, based on the library based approach as described in reference [22], was found to be appropriate as a large amount of objects are reused throughout different terminals. As the CAD drawings use millimeters as the main unit, the resulting virtual environment could benefit from this precision.

The stand alone application reads the intermediate XML file to construct the virtual environment. The 3D models in the virtual environment have been modeled based on CAD blueprints of the actual equipment which resulted in precise models. Photorealism was further aimed for by using photographs of existing equipment to texture the models. Photographs were also used for the different types of materials found on a virtual terminal: concrete, tarmac, metal, etc. The environment was further enriched using aerial pictures.

2.3.4. Results

The resulting virtual environment, shown in Fig. 2, serves as a support tool in the design process of automated container terminals. The virtual environment can easily be changed by modifying the CAD drawing. It serves as a knowledge sharing platform for this novel type of terminals.

Although photorealism is less important than functional realism, the level of photorealism present in the virtual environment ensures everybody has a clear understanding of the new container terminal. Moreover, using the virtual environment as a presentation tool helps in communicating future developments outside of the company (e.g. fairs and professional congresses).

2.4. Chemical installation

Europe is densely industrialized: the most appropriate locations for industry are taken which leaves little choice for new industrial sites. Therefore, brown-field engineering is more common than green-field. This implies that knowing the state of installations is of crucial importance when revamping a site or when maintenance has to take place.

A lot of installations have been designed and built decades ago: if engineering data are available, it is in most cases too old, incomplete, or wrong. Nowadays computer programs are being used to handle 3D engineering data to support the replacement and design processes. For a proper job, good reference data are essential.

There was a strong need for accurate and complete 3D reference data for a large revamping project. Due to the complexity of the task at hand, the model would have to be ready for interaction and collaboration. Multiple engineering companies were involved in the project. A chemical pipeline of eight inches needed to be routed from a storage vessel to a production plant for which it had to cross two pipe racks, a road, and another production facility. The 3D model should be used to create a planning and discover complexity and would be the main metric information source.

2.4.1. Requirements

The following requirements were identified:

1. A complete 3D representation of the areas the pipeline has to cross with a tolerance of 2 mm for connecting flanges and 5 mm for the rest of the model.
2. All crossing structural steel, piping, and other objects needed to be present for clash checking.
3. The individual objects needed to be aligned with the engineering grid.

2.4.2. Trade-offs

Laser scanning was chosen over traditional surveying because of the accuracy and completeness that laser scanning can provide. This

Fig. 2. The design environment for automated container terminals: (A) the virtual environment based on (B) the real environment.

means that there was some level of automation in the 3D acquisition process. Because the engineering software that was used in the project could not interact with point clouds, the entire point cloud had to be translated to solid geometry. The modeling process itself could not be automated at that moment in time.

There were problems in previous projects with cloud-fitted models. In reality most things are a little tilted, offset, or damaged which is reflected in the cloud-fitted models. However, most engineering packages handle their models as being perfect. By bringing in slightly imperfect models into the engineering software, things go wrong, e.g. incorrect centerlines, slopes, and elbows. Because of previous experiences, the decision was made to create the models within the engineering software with the scans as a reference instead of being depended on cloud fitting geometry algorithms.

By using detailed clash checks on key locations, the accuracy could still be maintained; however, lots of accuracy was lost by only referencing the scans. It is expected that design environments will be more adapted to real world facilities in due time.

2.4.3. Implementation

The Leica HDS 3000 has been used to acquire 79 scans which were geo-referenced for accuracy and control of the process. Because the scans were geo-referenced, they could be semi-automatically registered. Although it takes more time on location, it is for many survey companies the preferred way of working. Because an initial location is known, improving the registration process by iterative closest point (ICP) to get a tight fit between the clouds was automatic.

Furthermore, the scans were modeled by loading them in a piping specific engineering application. They were traced to acquire a solid model; an approach that is somewhat less accurate than cloud fitting, but the engineering environment was not able to cope with intelligent objects combined with deviating geometric forms.

The engineering of the model was done by experts: the decisions involving the differences between laser scans and CAD models could therefore be settled on the spot. Also, regular meetings with the involved engineers with present model/scans were used to facilitate decision-making.

2.4.4. Results

The model, shown in Fig. 3, was used to interactively create the routing of the piping. By using laser scans as a base for the design process, the time for the entire project has been reduced. Comparing the throughput time with the conventional planning schemes showed time reduction of approximately 25% and in some cases even up to 75%.

Less automated geometrical data acquisition would have been difficult because of the divergence and complexity found in the environment for the pipe routing process. The manual modeling process used in this case study resulted in a tedious task to create the 3D models.

Furthermore, maybe even as important were the collaboration possibilities early in the process because rich detailed 3D data were available for discussion. During meetings between the engineers, this proved very valuable. One could say that there are multiple stages in the process that might be facilitated by different models.

2.5. Off-shore platform

For this case, two methods were used to construct the 3D environment of an off-shore platform. The same part of the environment was modeled twice: one semi-automatically based on laser scanning and one using full automatic modeling based on the same laser scans. This was done to provide insight and compare results in order to quantify the results. Part of the results of the automatic modeling process is described by reference [15]. Because this example (laser scanning and automatic modeling) provides insight into an almost fully automated creation process, we discuss the results from this perspective.

For engineering purposes, an accurate 3D model of an off-shore platform had to be generated. Some of the piping needed to be replaced, preferably a one-on-one replacement. Because labor on an off-shore platform is more dangerous and expensive than on-shore, prefabrication of parts is desirable. Moreover, the 3D model needed to be used to find optimal decommissioning and reattachments of parts as the piping that needed replacement is interweaved with the rest of the piping. Furthermore, many off-shore facility drawings are out of date and when they are up to date, the majority is in 2D, altogether good reasons to laser-scan the facility.

2.5.1. Requirements

The model had to be generated for engineering purposes; therefore, accuracy is of major importance. The piping is one to three inches in diameter, which in this case means approximately five millimeter accuracy. All objects that could provide a clash with the decommissioning or reattachment needed to be represented in the 3D model.

An additional requirement was set by the tight schedule the project was on. Due to this, development speed was preferred over costs, which provided an additional challenge.

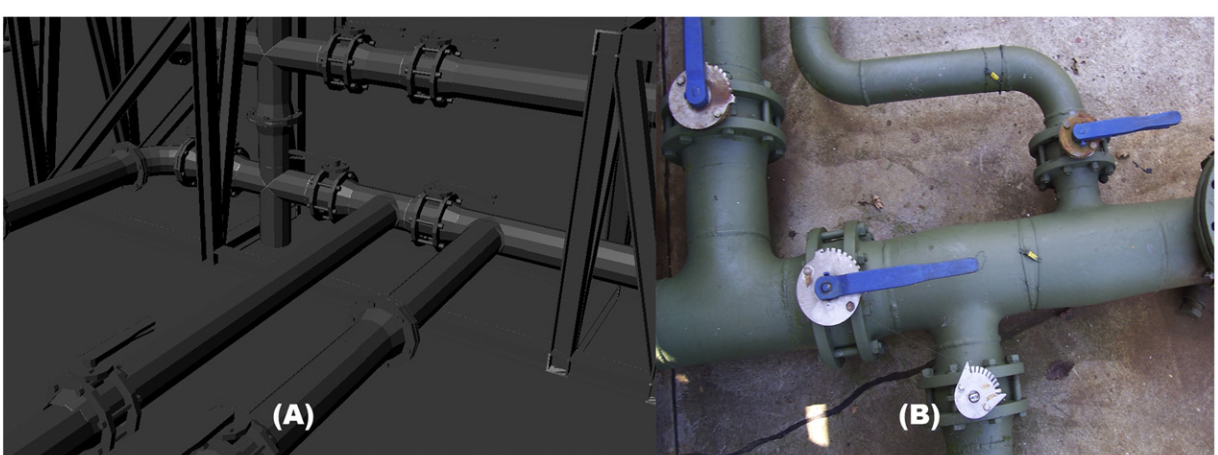

Fig. 3. The chemical installation: (A) the virtual environment based on (B) the real environment.

2.5.2. Trade-offs

Because of the high accuracy standards used in engineering and the tight schedule, laser scanning was the preferred choice of technology. Conventional surveying could however provide the same models although it would have been too slow.

Although laser scans can be registered automatically, it was decided to do a manual registration process to have control over the registration process because of the uncertainties of automatic methods. For the modeling process, the decision was made to semi-automatically create the 3D model. A fully automatic modeling process followed afterwards to compare the results.

2.5.3. Implementation

To get comparable results between semi-automatic and fully automatic modeling, a single room of the off-shore facility was modeled. The room's approximate length was 12 m wide, 6 m long, and 4 m high. There were 32 scans created to get 80%–90% coverage of the room whereas all critical components had 100% coverage. Control of the scanner and the total station required 2 people.

The semi-automatic modeling process was done using region growing algorithms [15] using specialized point cloud reconstruction software. Solid geometry was generated and exported so it could be used within an engineering CAD viewer. The viewer was used to interact with the 3D environment so decisions for spool sizes, decommissioning, and fitting could be made between the experts.

2.5.4. Results

The time needed to get the scans (shown in Fig. 4) done was approximately 4 h using a Leica HDS 3000. The registration process took approximately double that time. The registration parameters were all below 5 mm. The experts on location estimated that this would be at last a week to do manually.

The semi-automatic modeling process took 15 days to create 2602 objects (planes, cylinders), counting the complex geometry in planes. In comparison, 2338 objects were detected fully automatically although there were quite some subdivided objects, e.g. round columns could be detected multiple times because of missing information in the point cloud, slicing up the data set. The points that were part of the segmentation process were approximately 80% of the total amount of points whereas the points on the generated objects, 53%. This resulted in 946 planar patches and 1392 cylinders [15]. An estimated 40% of the semi-automated modeled objects were directly usable.

3. Reflections and conclusions

The approaches presented show an increase of the level of automation possible in the acquiring and modeling process for the reconstruction of virtual environments. Firstly, we started with the discussion of the training environment for supervisors that was modeled manually. Secondly, we continued with the virtual container terminal which consisted of building a component library and using this library to automatically construct virtual versions of multiple container terminals around the world. Thirdly, we discussed a project wherein a chemical installation was reconstructed using laser scanners but due to scene complexity, manual models were made based on the point clouds gathered from the laser scanners. Finally, we presented the case of the off-shore platform in which a high level of automation was achieved.

The choices for the different approaches were based on the properties of the real environment and on the goals of the virtual environment. The real environment can vary from being small to large and from being simple to complex. The goals of virtual environment can result in the need for photorealism, the need for functional realism, or both. Based on these properties and goals, we will propose recommendations that can be useful for future projects. A summary of these approaches with the properties and goals can be found in Table 1.

Whenever a virtual reconstruction of an environment has to be made, size and complexity of the environment play an important role. Although automatic techniques give the possibility to acquire spatial information rather quickly, modeling can be troublesome due to the large amount of data gathered. These data need to be modeled according to the possibilities of the visualization engine wherein it is going to be used. When using automatic techniques such as laser scanning, the resulting point clouds tend to be huge, making it impossible to use it in real-time environments. To reduce the amount of information, specific algorithms can be used. Nevertheless, these algorithms do not give optimal result for complex scenes as for the chemical installation case study where a huge amount of pipes and small details were present. In these cases, manual intervention is still required, reducing the level of automation possible in the modeling phase. In less complex scenes, algorithms for mesh simplification are better suited for the task.

As using methods for automatic acquiring and modeling is still labor intensive and requires specific skills, the choice for manual methods is still often considered. Automatic acquiring methods result in a high level of accuracy (up to a millimeter), thus functional realism, which is not always needed. In training environments, such as the one for training supervisors, photorealism is preferred whereas accuracy is not even required. In these cases, manual modeling gives the possibility to fully concentrate on details using a team of artists instead of skilled engineers.

Choosing between manual and automatic methods for the acquisition and modeling phase for the reconstruction of a virtual environment is not straightforward. Trade-offs have to be made based

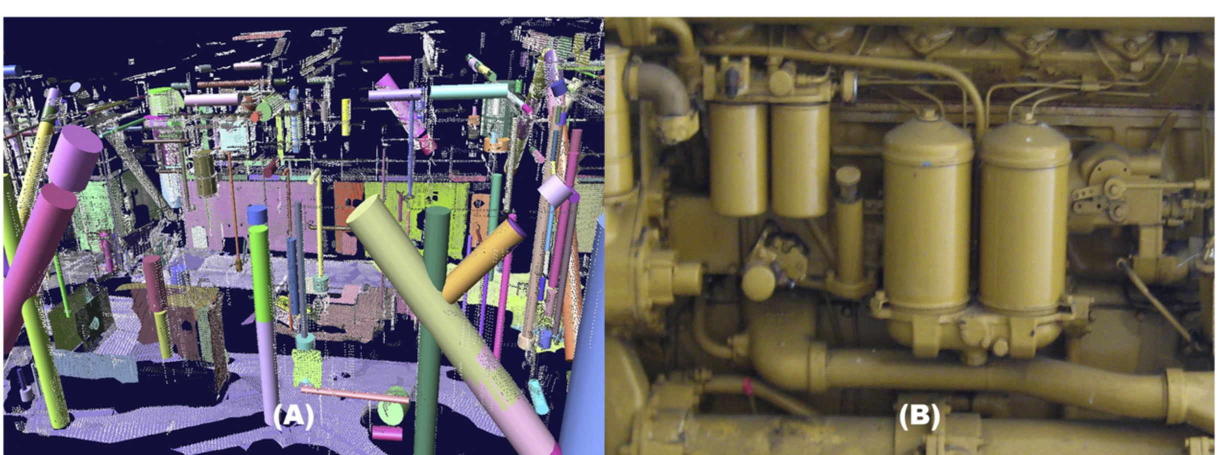

Fig. 4. Part of the off-shore platform: (A) the virtual environment based on (B) the real environment.

Table 1
Conclusions based on the properties of the real environments and the goals of the virtual environments.

Case	Size	Complexity	Functional realism	Photorealism	Acquiring	Modeling
Supervisor	Small	Low	Low	High	Manual	Manual
Automated container terminals	Large	Low	High	High	Manual	Automatic
Chemical installation	Small	High	High	Low	Automatic	Manual
Off-shore platform	Small	Low	High	Low	Automatic	Automatic

on the environment that is being reconstructed and the requirements set for the virtual environment. Although automatic methods are gaining popularity, thanks to their accuracy and speed, human intervention is still often needed. Complete automatic methods can only be used in ideal circumstances, which are less common than one would wish for.

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