INTEGRATING DATA FROM 3D CAD AND 3D CAMERAS FOR REAL-TIME MODELING

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ABSTRACT

In a reversal of historic trends, the capital facilities industry is expressing an increasing desire for automation of equipment and construction processes. Simultaneously, the industry has become conscious that higher levels of interoperability are a key towards higher productivity and safer projects. In complex, dynamic, and rapidly changing three-dimensional (3D) environments such as facilities sites, cutting-edge 3D sensing technologies and processing algorithms are one area of development that can dramatically impact those projects factors. New 3D technologies are now being developed, with among them 3D camera.

The main focus here is an investigation of the feasibility of rapidly combining and comparing – integrating – 3D sensed data (from a 3D camera) and 3D CAD data. Such a capability could improve construction quality assessment, facility aging assessment, as well as rapid environment reconstruction and construction automation. Some preliminary results are presented here. They deal with the challenge of fusing sensed and CAD data that are completely different in nature.

KEY WORDS

Capital facility management, 3D camera, 3D CAD, data fusion, construction automation

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INTRODUCTION

Over the last fifty years, the construction industry has been lagging behind other industries in terms of productivity improvement (US-Bureau-of-Labor-Statistics 2003). Additionally, it is generally admitted that higher productivity could be achieved, not only in construction but more broadly in the capital facilities industry, if more adequate interoperability existed. Specifically, the US National Institute of Standards and Technology (NIST) reported that in 2002 inadequate interoperability cost approximately $15.8 billion to the US capital facilities industry (Gallaher et al. 2004). The NIST report also emphasizes that this loss should prompt investment in integration and automation technologies in the construction industry.

Interoperability is defined as "*the ability to manage and communicate electronic product and project data between collaborating firms' and within individual companies' design, construction, maintenance, and business process systems*" (Gallaher et al. 2004). Product and project data are all data that must be shared among all stakeholders in order for each of them to perform their work in an efficient and project-consistent way.

Dimensions and positions – referred as "3D data" in the rest of this paper – constitute critical industry data. 3D data is both generated and used by almost all project stakeholders – architects & engineers, contractors, specialty fabricators & suppliers, and owners & operators, at any time in the facility life cycle, and in many different forms. For instance, 3D data is created by architects during design in very precise CAD formats, while 3D data is recorded, manually or using surveying technologies, during construction and operation phases for construction quality and as-built & aging assessment. Many efforts have been made in improving the speed and quality of the generation and exchange of 3D data, but the industry still suffers from inadequate or inefficient 3D data interoperability.

The research presented here focuses on the rapid combination and comparison - "integration" in the rest of this paper - of 3D sensed data acquired using a 3D camera and CAD data. In this paper, state-of-the-art construction 3D technologies are first reviewed. Section two presents the investigation of real-time 3D sensing and integration with CAD data. The research has been conducted in a joint effort by teams of the University of Texas at Austin (UT-Austin) in US and the University of Waterloo (UW) in Canada. Section three presents the experimental results, and the last section reviews the achieved results and lays down future work.

RESEARCH MOTIVATION

STATE-OF-THE-ART 3D MODELING IN CONSTRUCTION

Research efforts emerged from the industry's increasing awareness of inadequate 3D data interoperability. Some of the resulting advances are now intensively investigated or/and readily available to gather 3D data or improve 3D visualization, and are presented below.

For improving 3D visualization, a recent concept is Augmented Reality (AR). In AR, the user looks at the environment with a pair a special glasses, Head Mounted Displays (HMDs), and his view is augmented/overlaid with CAD data (a priori knowledge) positioned exactly (Wang and Dunston 2005). "*An AR system supplements the real world with virtual* *(computer-generated) objects that appear to coexist in the same space as the real world*" (Azuma et al. 2001). AR systems can be used to envision modified cityscapes, to assess the impact of proposed buildings (Novitski 1994; Webster et al. 1996), etc.

Global Positioning System (GPS) technology impressively benefits the capital facilities industry. GPS is an active beacon localization approach taking advantage of triangulation to precisely locate any signal receiver on the planet. Differential GPS can now reach centimetre accuracy. The industry uses this technology for precisely locating assets (Song et al. 2006; Song et al. 2004) as well as obtaining site elevation information for better planning and faster and even automated applications (Hampton 2005; Ward and Brown 2004).

LAser Detection And Ranging device (LADAR) (Cheok et al. 2000) is becoming a widely used 3D data acquisition technology. This technology resembles a digital camera except that instead of brightness, it stores range (depth) information, providing 2½D scans of scenes (although they are usually referred as 3D models). The LADAR technology shows great promise due to its high accuracy and large field of view. Applications of LADAR are numerous. For instance, they can be used for quality assessment by recording detailed 3D views of constructions that can then be compared with 3D CAD models (Gordon and Akinci 2005), or by providing 3D data of old facilities for which 3D models are required for renovation purposes (Alessandri et al. 2005).

Recent researches have also resulted in a new sensor, the 3D camera. 3D camera – also called "flash" LADAR - can be described as a digital camera providing arrays of range distances instead of brightness. Therefore, like LADARs, this technology provides dense range point clouds. Contrary to a regular LADAR, however, "pictures" can be acquired with a frequency of up to 30 Hz. An example of 3D camera is the Swiss Ranger 3000 (SR3000), developed in collaboration by the Swiss Center for Electronics and Micro-technology (CSEM) [http://www.csem.ch] and the Swiss Federal Institute of Technology (EPFL) (Gut 2004; Lange 2000). This 3D camera is used in this research. A picture of it is provided in Figure 1.

Figure 1: The time-of-flight Swiss Ranger sensor from CSEM (CSEM 2004)

NEED FOR INTEGRATION OF 3D SENSED AND 3D DATA

Progress is clearly accelerating in the development of new technologies that improve the acquisition and display of 3D data. While the potential impact of these technologies is acknowledged by industry professionals, their use is still limited. A major reason is the lack of interoperability between these technologies and existing ones, including especially 3D CAD engines. For instance, LADAR pictures definitely contain interesting 3D information. However, their integration with existing 3D CAD drawings is neither trivial nor yet fully automated. Tools are needed for improving and automating the integration of 3D data from the sources identified above.

3D DATA INTEGRATION INVESTIGATION

Integration requires development of common representation or of mediation methods among varying representations for which their knowledge composition is formalized. Integration also implies that operations will be performed on data to compare, fuse or transform the data. The following sections focus on developing a common representation.

3D SENSED DATA

Sensors used to acquire 3D data generally produce point clouds as output data. In the case of the SR-3000, a maximum of 176x144 data points can be acquired per image, while LADAR like the Leica HDS4500 (Leica-Geosystems 2004) can acquire up to 400,000,000 (20,000 x 20,000) points per image.

Previous research conducted at the Univeristy of Texas using the CSEM® SR-2 (earlier version of the SR-3000) included the development of algorithms capable of rapidly processing sensed point clouds to extract information such as object detection, velocity calculation, etc. Algorithms perform data cleaning, data transformation, data segmentation, and data classification (see (Teizer et al. 2005) for more details). Output data can be obtained in the following formats: (1) occupancy grid segmented point clouds and (2) convex-hulls.

The use occupancy grids was pioneered by H. Moravec and A. Elfes in 1985 (Moravec and Elfes 1985; Moravec 1996), and used in combination with a sonar range finder. This method helps wisely reduce the amount of data prior to attempting any further analysis. Data points can be gathered into each one of the voxels (volume pixel) of a predefined world model grid (see Figure 2). If enough data points are present in a voxel, this one is then considered full. Therefore, while reducing the amount of data prior to segmenting it, it also serves as a noise filter since each cell that doesn't include enough data points will not be considered full. This approach is interesting because, while it can be used to gather all sensed data in a single global model, it provides an efficient way for reducing and cleaning data.

Once occupancy grid segmented point clouds are obtained, they can be further processed to obtain convex hulls. The convex hull of a set of N points S in n dimensions is the intersection of all convex sets containing S. The saved result is therefore a series of N facets and N+1 vertices per convex-hull. Convex-hulls show great results for representing 3D volumes with far less information than point clouds and a very limited loss of information.

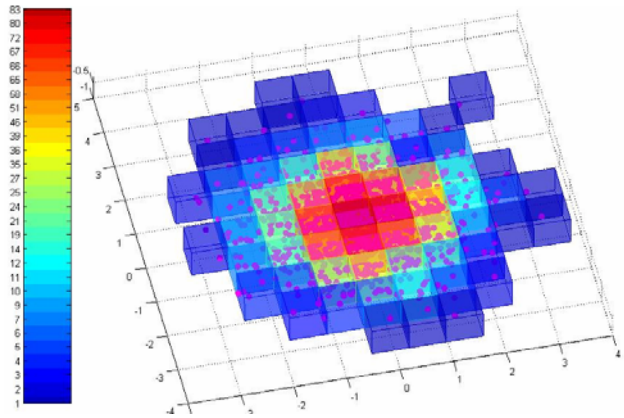


Figure 2: Principle of occupancy grids. The level of filling of each cell is represented by its color [image courtesy to R. Brégeon, Magnitude]

3D CAD DATA

For facility design, at least a couple of dozen packages software are used around the world. Although most software packages have different native formats, they all provide a wide range of possible exporting formats. While software companies are trying to agree on sharing their formats with one another in order to improve interoperability, it must be noted that the quality of exported files in non-native formats may not always be acceptable since some features may disappear or be wrongly translated.

Also, with more and more powerful CAD engines, data files get heavier and exchange of information can rapidly become very tedious. While the details included in CAD design serve some important purposes, this level of detail is not always necessary. For instance, an engineer evaluating the space available for operating a piece of equipment doesn't need to know where bolts on a beam are located, or any other similar level of detail. He may not even need the exact shape of the beam. Approximations of the CAD drawing may be sufficient. For such situations, some formats were developed. They are referred to as formats for performing Virtual Reality (VR). These formats present the advantage of simplifying 3D models while conserving sufficient quality for the supported applications. They include, among others, the VRML/XML and STL formats. It must be noticed that, interestingly, both formats are available as exporting formats in most CAD engines. The STL format is used in this research. More details about it can be found in (Burns 1993).

INTEGRATION FORMATS

From the previous data format analysis, it appears that combining and comparing sensed and CAD data is not straight forward because the need has not been anticipated by data formats developers or there is a commercial penalty involved. Additionally, it is acknowledged that each data format is generally developed for a specific application. The context of this research is the real-time comparison of 3D sensed and CAD data with potential applications such as:

- Rapid 3D localization for automation in construction (e.g. self-localization and automated path planning of robots or semi-automated equipment on project sites).
- Rapid 3D model updates from actual facility status (e.g. tracking CAD objects in sensed data and deduce design or schedule deviations, or new objects in remaining sensed data)

Such applications have the following important characteristics:

- While 3D CAD data is generally created once or changes with very low frequencies, sensed data from 3D cameras is acquired with high frequencies (up to 30Hz).
- While 3D CAD data is exact, sensed data has some error (noise, artifacts, technology limitations, etc.). Therefore, the best overall achievable accuracy is driven by the quality of the sensed data.

These characteristics imply that the format chosen to integrate both data shall be as close as possible to the sensed format – possibly the sensed data format itself. Indeed, the closest the integration data format to the sensed data format, the less transformation the latter one requires to be compared and consequently the less information is lost during that transformation and the higher the processing speed.

Since a research conducted at UT-Austin showed that transforming the sensed data into an occupancy grid undeniably benefits the data processing, the team at UW decided to investigate the feasibility for combining and comparing sensed and CAD data using the occupancy grid format as common data representation. Results of this investigation are presented and discussed in the following section.

EXPERIMENTAL RESULTS

As presented earlier, this research was conducted in two parts, one in UT-Austin, the other in UW. The research conducted at UT-Austin focused on the feasibility of the use of 3D camera on construction sites, and more generally by the capital facilities industry. Through many experiments, the authors showed that there is great potential for taking advantage of this technology. "*Condition assessment, maintenance, operations, and construction activities can exploit 3D models for improved visualization, communications, and process control*". While the focus of the current paper is on the second part of the research effort, more details on the first part can be read in (Teizer et al. 2005).

Some experiments have been conducted to investigate the possibility to integrate 3D sensed point clouds with 3D data. Those preliminary experimental results are presented below.

3D SENSED AND CAD DATA INTEGRATION EXPERIMENTS

In order to integrate both 3D sensed and CAD data into a common occupancy grid model, it is necessary to first transform the CAD data. It is important to understand, as presented earlier, that CAD data is updated with very low frequency. This implies that time is not a limiting factor in this data transformation. To perform the data transformation, a two-step approach is proposed (Figure 3):

- The 3D CAD drawing (Figure 3-1) is exported in STL format (Figure 3-2) – this format is available on the most common CAD engines and presents CAD data in a simple manner and with minimal loss of 3D information.
- The STL formatted drawing is then changed into a point cloud that is imported into a world occupancy grid (Figure 3-3).

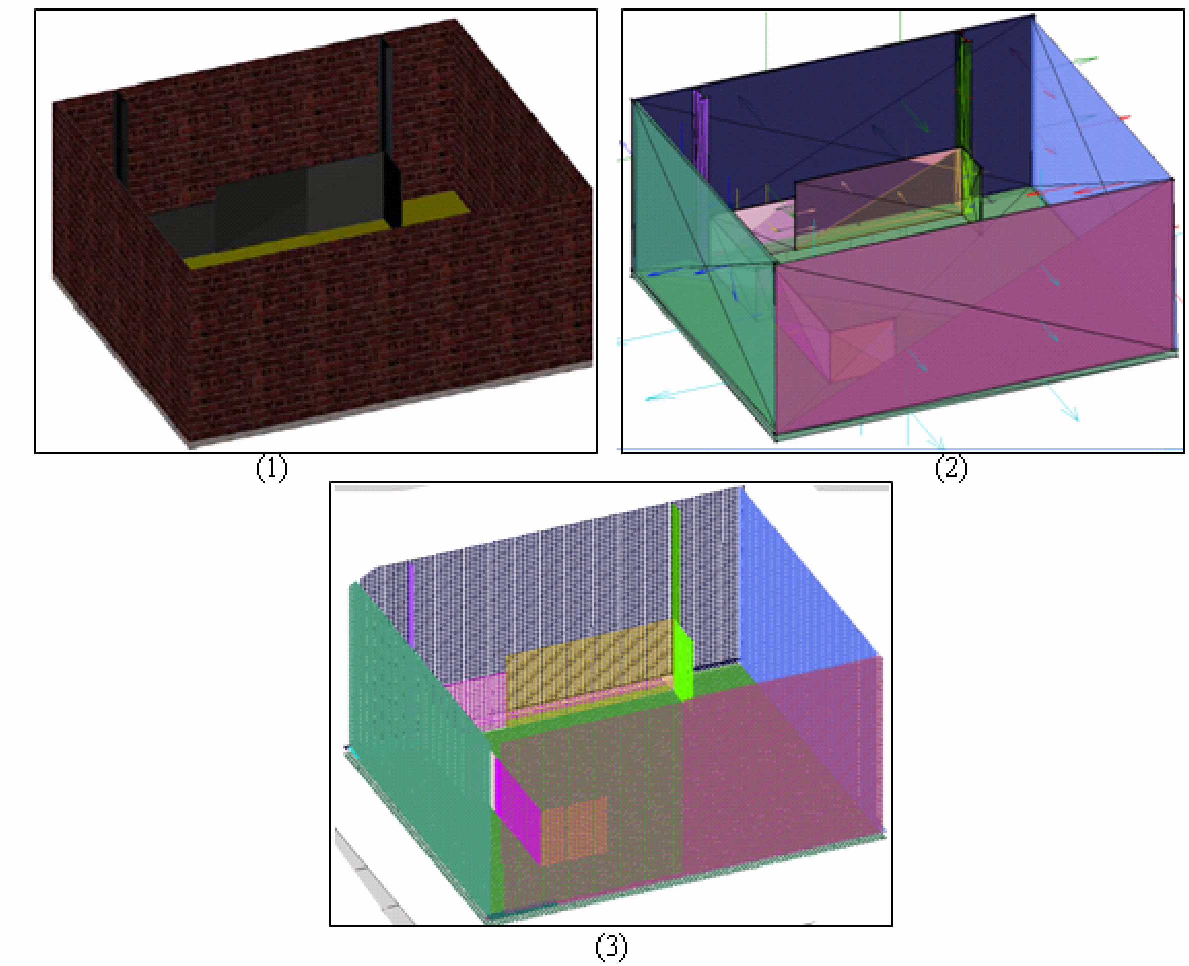
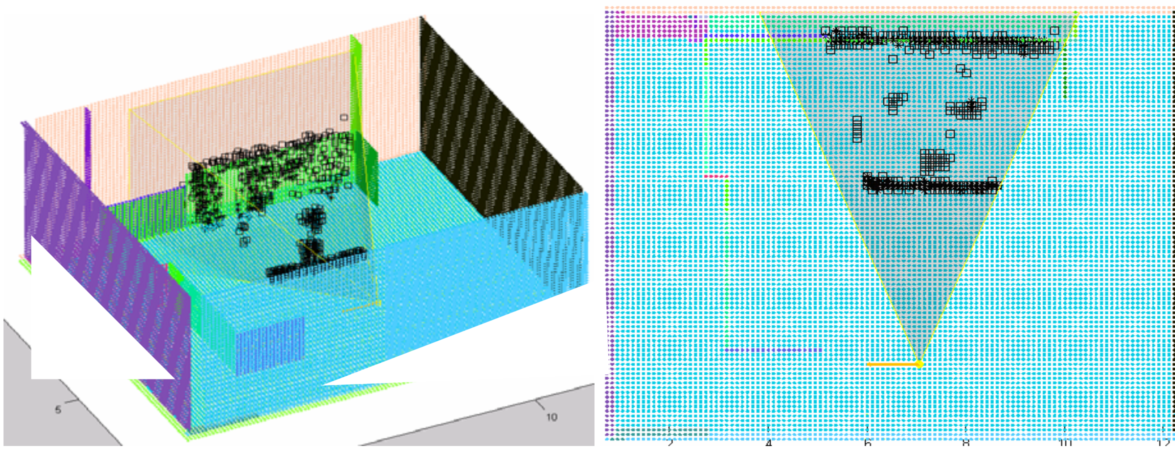


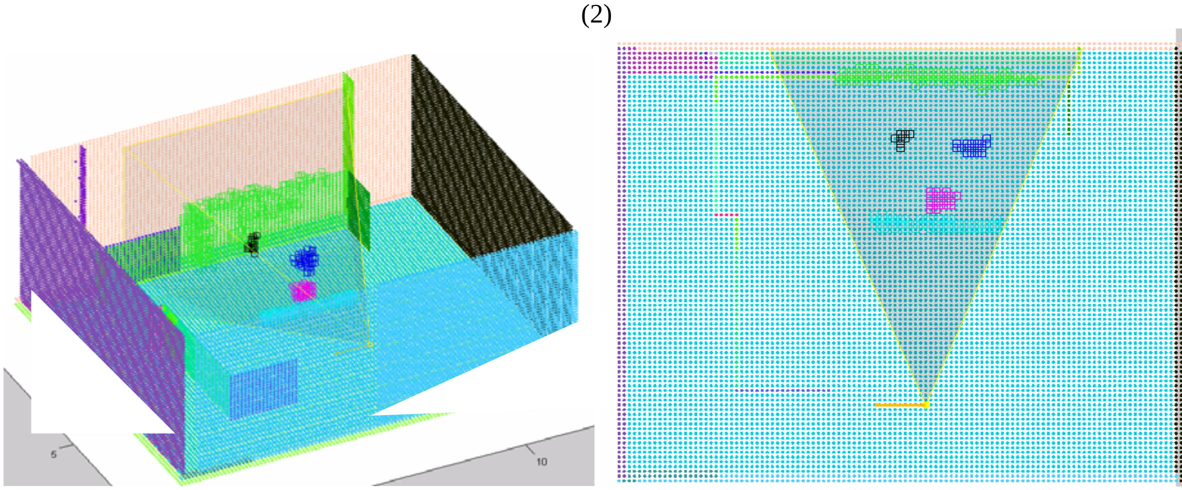
Figure 3: (1) CAD-formatted (.dgn) lab model (2) stl-formatted lab model
(3) point-cloud-formatted lab model

The second step of this transformation is being investigated in two different ways. Two different point clouds can be obtained. The first one is the list of occupancy grid voxels that approximate the volume of each STL form ("solid" point cloud). The second one is the list of voxels that approximate the surface of each STL form ("hollow" point cloud). The interesting characteristic of the second approach is that surface point clouds correspond to the data actually sensed by a 3D camera (they don't sense volumes but rather surfaces).

(1)



(2)



(3)

Figure 4: Example of integration of 3D sensed and 3D CAD data.

A series of experiments was conducted using data acquired in the Field Systems and Construction Automation Laboratory (FSCAL) at UT-Austin. The lab was modeled using Bentley® Microstation®. Sensed data was acquired using the Swiss-Ranger SR-2 3D camera

– a predecessor of the SR-3000 camera – developed by CSEM. Finally, sensed and CAD data processing algorithms were developed using the Matlab® environment. One frame of a stream of 90 frames obtained during one experiment is presented in Figure 4 below. In this specific experiment, the 3D camera was used inside the FSCAL lab. Additional non-CAD static and dynamic objects were set to cross the field of view of the 3D camera. Figure 4 -1 shows a picture of the scene and the 3D CAD model of the lab. Figure 4 -2 displays the CAD and sensed (black) data in the world occupancy grid model. Finally, Figure 4 -3 shows that some sensed data has been identified as similar to CAD object (sensed data representing the back wall is colored in the same color) while the rest of the sensed data is segmented. The result of this segmentation finds 4 unknown (non-CAD) objects in front of that wall.

CONCLUSIONS AND FUTURE WORK

The research presented here showed that the use of 3D camera could have a significant impact on the capital facilities industry. However, some research is first necessary to overcome the interoperability issue of integrating 3D sensed and 3D CAD data. Early results indicate that it is possible to perform such integration in a rapid and probably even a real-time manner. Future work will focus on ways to improve the quality and speed of such integration by assessing different data formats and conducting core data comparison operations.

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