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Skeleton-based discrepancy feedback for automated realignment of industrial assemblies

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ABSTRACT

Automated and timely detection, characterization, and quantification of fabrication discrepancies and errors are fundamental problems in construction engineering. Despite the fact that the precision of manufacturing machines is continually improving, there are inevitable discrepancies between the designed and built assemblies because of construction realities. Such non-compliant assemblies should be detected early, and the required corrective actions should be planned accordingly. This paper presents an algorithm for automated quantification of discrepancies for components of assemblies. Rather than using dense point clouds, the geometric skeleton (wireframe) of assemblies is extracted for further manipulation, once the as-built status is captured using the appropriate method. The extracted skeletons, which abstractly represent the designed and built states, are registered using a constrained iterative closest point (ICP) algorithm. In order to identify the points making up each straight segment, the skeletons are clustered, and a straight line is fit to each resulting cluster. The corresponding segments in both states are then compared and investigated for quantifying the incurred discrepancy in the form of a rigid transformation. Experimental results show that the accuracy and speed of the new framework are superior to a previously developed method (3D sliding cube).

1. Introduction

The industrial construction sector is a major part of the construction industry in any economically developed or industrially developing country. Industrial construction primarily includes petrochemical, oil and gas, power plants, and manufacturing facilities. According to the US Census Bureau [1], over $83 billion was spent in 2013 on industrial power generation plants, in total, for private and public construction sectors, which is approximately 10% of the total construction output in 2013. In the UK, the output of the industrial sector in the first quarter of 2014 was 10% of the total construction projects [2]. Piping, typically comprises about 50% of the cost of industrial construction projects.

Piping design, fabrication, installation, and inspection involve complex processes. Design drawings, which are integrated with building information models (BIM), may be used to fabricate and erect the components. While "shop drawings" are still in common use that typically render pipe spools as cut lengths in an isometrically projected linear 3D model, the use of solid model renderings in the shop and the field is emerging as a new norm. Despite these rich models, errors still occur during the fabrication and construction phases, so engineers and construction managers need a tool to keep track of the built status of construction components. Such a tool must provide a sufficient level of accuracy in a timely enough manner in order to be reliably integrated with the construction processes involved. Discrepancies would thus be detected before required corrective actions cascade into costly rework scenarios.

Detecting discrepancies with conventional measurement and surveying approaches, is difficult and time consuming; because of the complicated geometry of industrial assemblies. Promising approaches for acquiring 3D data of construction assemblies now exist affordably and quickly (Fig. 1). Using these accurate and robust data acquisition approaches such as laser scanning and structure from motion from digital photographs and videos, provides the required level of accuracy for as-built dimensional analysis (better than 1 mm accuracy, if well employed and applied). Although, such automated and accurate technologies have the potential to be digitally integrated with other construction processes, their output is relatively disconnected with the automated processes involved in the construction management systems. In other words, extraction of meaningful information (i.e. as-built dimensions for the components) from the acquired as-built status is still being performed manually. The manual processing for generating the as-built BIM is performed for further manufacturing designs and engineering considerations such as inspection, maintenance, and planning for corrective actions where a discrepancy is detected. Manually performing such analyses for full scale industrial facility, such as a power plant, is time consuming and costly, and thus is not yet in common use.

In order to address these needs, this paper presents an algorithm to assist in automated discrepancy detection of industrial assemblies. It operates on 3D scan data that has been selected manually

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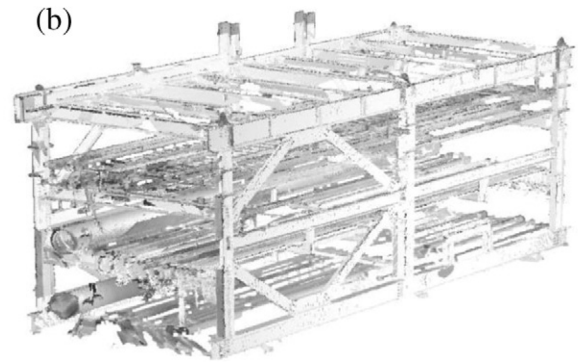

Fig. 1. A typical module including structural frame(s) and pipe spools (a). Laser scanned point cloud for as-built status assessment (b). Photo and scan are taken by the authors in December 2011.

or automatically from a reasonably complete 3D point cloud, ant it requires a priori design input. As-built and as-designed states are represented by abstract geometric skeletons (wireframes). The skeleton of the as-built state is automatically derived from the 3D point cloud subset selected, and the skeleton of the as-designed state is similarly derived from a point cloud representing the designed state. Direct use of a traditional isometric shop drawing line model would also be possible. When the skeletons are registered in one coordinate system, it becomes possible to detect, characterize, and quantify the discrepancies between the as-designed and as-built states. Skeletonization of the point clouds has been found to effectively represent pipe assemblies and structural frames or modules [3]. Once the discrepancies are quantified, it becomes possible to feed such information into a construction control process for generating the required corrective actions. The corrective actions may include potential realignment plans based on the existing situations, such as re-welding, cutting, and bending alignment where applicable. The output of the algorithm presented here can be integrated with the construction process, potentially the fabrication and erection steps, for providing the pipe-fitters or iron workers with real-time feedback about the discrepancies that have already occurred. The proposed algorithm is tested on a small-scale pipe spool, and the accuracy, as well as the performance, of the framework is evaluated by comparing to the previous methods.

2. Background

The related background is investigated from different points of view in order to determine the knowledge gap thoroughly. First, existing tools for industrial infrastructure surveying are reviewed and advantages and disadvantages of these methods are evaluated. The existing approaches for as-built modeling and assessing of civil infrastructure, in general, and the industrial sector, in particular, are then discussed to frame the emerging need for this research in the related industry.

2.1. Surveying tools for as-built status acquisition

Generally, surveying methods are grouped based on the level of automation they can provide for data collection. Conventional tape measuring is the most well-known method to collect data for quick inspection purposes, which is performed manually and therefore prone to error and is time consuming. Although, it might be sufficiently accurate and reliable in most cases, the required time for data collection makes the use of tape measurement limited in complex industrial plants. Moreover, manual measurement is not effectively and efficiently integrated with construction processes, as discussed previously.

On the other hand, automated data collection tools have provided the required level of accuracy and have the potential to be fully integrated with construction management systems. Using promising approaches and tools such as total stations, laser scanners, digital photos, and video recordings in various aspects of surveying have made substantial improvements in project schedule, planning for delivery of materials, and therefore significant cost savings [4–6]. Particularly, in the industrial sector, these promising approaches have been employed for automated as-built modeling [7], progress tracking [8], safety planning [9], health monitoring [10], quality control [11], and material tracking [12] on construction sites. Depending on the application of the automated measurement system, and the level of accuracy and resolution required for the processing phase, the appropriate method of data acquisition is utilized. According to [4,13,14], all of the above-mentioned technologies and tools (i.e. laser scanning, photogrammetry, videogrammetry) can be employed with a sufficient level of accuracy and automation; however, laser scanning has been found the most robust and therefore reliable tool.

2.2. Automated as-built modeling of industrial assemblies

Once reliable and accurate data is acquired, the as-built status can then be generated in order to assess the quality of the fabricated or installed components, and automating the construction process feedback involved. However, converting the acquired point clouds into meaningful information is not trivial and is yet to be fully automated. There are some commercial software packages such as ClearEdge [15], Kubit PointScene Buildings which is now integrated with FARO Scene [16], Autodesk ReCap Pro [17], and IMAGINit [18] that can extract some as-built status information; however, the process is not fully automated and requires expertise for performing the software commands. It is therefore time consuming and disconnected from shop floor or electronic and automatic construction management systems. Several studies are attempted to show the impact of automated modeling of industrial assemblies, in particular [3,19,20]. The developed approaches have significantly improved the processes involved aiming to fully automate construction management systems such as quality control of fabrication [3,21], and progress tracking [8]. In the construction industry, Building Information Models (BIM) integrated with 3D drawings, schedule information, and all other specifications, which is known as nD BIM [22], is considered as prior knowledge. Automated as-built modeling can generally be performed with and without prior knowledge. Based on Bosche's definition [19], *Scan-vs.-BIM* [23] and *Scan-to-BIM* [20] are equivalently used for automated as-built modeling with and without prior knowledge (i.e. required specifications integrated with BIM), respectively. This study is therefore considered as Scan vs. BIM based on this definition, because it requires integrated specifications with BIM for the processing steps.

Generating the as-built BIM, also known as automated as-built modeling, without prior knowledge requires geometric modeling of the components involved, which is complicated as previously discussed. Extraction of features representing industrial components is a potential way to subsequently avoid processing dense point clouds and therefore