Automated Deviation Analysis for As-Built Status Assessment of Steel Assemblies and Pipe Spools

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ABSTRACT

Steel assemblies and pipe spools play an essential role in the industrial construction sector. Fabrication of steel assemblies has been a challenging task due to the limited fabrication precision of the tools used in the process and inadequate inspection during fabrication. Moreover, unfavorable deformations may occur during the transportation phase which makes the erection and installation phase more complicated. These deviations require further considerations for realignment and repair that are associated with rework on construction sites. Hence, a systematic and automatic framework is required to continuously monitor the fabrication and installation processes of steel assemblies. Current approaches lack a sufficient level of control and are prone to error. This paper presents an automated framework to detect defective parts in steel assemblies and pipe spools in particular. A laser-based point cloud, which represents the as-built status, is compared to the original state from the CAD drawings that exist in the Building Information Model (BIM). Therefore, the defective parts are detected in a timely manner. The comparison is distance based and the procedure is fully automated. The experiments conducted to validate the proposed approach show that the model has high precision and a high rate of recall and has the potential to be employed for automated damage detection in order to improve productivity on construction sites.

PROBLEM STATEMENT

Steel structural assemblies are one of the critical components in both residential and industrial construction. Pipe spools are also key components for most industrial construction projects such as refineries and power plants. Utilizing steel structural assemblies on construction sites requires accurate fabrication and incident free shipment to site. Due to the advantages that staged fabrication of modules provides such as a controlled environment for fabrication, improved safety and improved productivity (Song et al. 2005) with similar conditions prevailing around the world, production of industrial components is mostly performed through modularization. Hence, production procedure consists of three primary steps: (1) fabrication, (2) transportation and shipment, and (3) erection and installation. Due to the complicated shapes of industrial assemblies and the limited capacity of transportation vehicles, successful delivery of materials on construction sites becomes a very challenging task. The incurred inaccuracies and defects are sometimes unpreventable due the challenging fabrication and transportation phases (Hu and Mohamed 2012).

Limited accuracy of existing manufacturing machines and the complicated shapes of the assemblies are the challenges involved with the fabrication process. Moreover, complicated fabrication tasks such as drilling, cutting, and bending are never performed perfectly; thus, some imperfections and errors during fabrication are unpreventable. This is the fatal flaw that fabrication has not yet overcome.

Additionally, there are inevitable errors that occur during shipment. Although 10-20% of the material is used to brace and support the huge assemblies and pipe spools during shipment, inevitable distortions and deformations occur due to vibrations and other unfavorable movements. When assemblies are delivered on construction sites, defective components should be detected in a timely manner. Otherwise, further adjustment and alignments are required to overcome misfit and avoid out-of-tolerance erection. It has been stated that approximately 10% of the total required rework is due to late defect detection (Akinci et al. 2006). The required rework with incurred errors includes finding the appropriate actions, for example, such as repair and replacement of the defective assembly.

Thus, an effective inspection framework is required to continuously monitor the assemblies. Current approaches for inspection and quality control performance are conventionally performed using tape measurements and other traditional methods. Thus, the current approaches for inspection are time consuming and inaccurate due to repetition and manual processes. This research presents an automated approach to effectively and accurately detect for fabrication errors and inaccuracies. This framework provides the ability to detect defects in a timely manner before causing excessive costs to construction projects. Moreover, it prevents falling behind schedule and, therefore, has the potential to improve construction productivity.

BACKGROUND

Industrial assemblies are key sectors of heavy construction which includes various types of projects such as petrochemical and power plants. Due to its nature, industrial construction requires intensive piping to convey the flow of gas and fluids between different locations. A pipe spool is a set of pipes and fittings (e.g. elbows and flanges) that are connected together (Figure 1). The connections can either be welded or bolted. The process of a pipe spool fabrication includes cutting, fitting, welding, quality control checking, stress relief, hydro testing, and painting and other surface finishing. Thus, the fabrication process directly influences the pipe spool functionality and the site construction consequently. Therefore, a framework to monitor the process of pipe spool fabrication is essential (Wang et al. 2009).

Figure 1. Prefabricated pipe spools to be shipped to construction sites. (Photos are taken by the author at an Aecon fabrication shop, Cambridge, Canada)

As previously discussed, the fabrication process of pipe spools includes cutting and welding. These sub-processes cause residual strains during the fabrication process due to high temperature change during welding and stress concentrations resulting from cutting. Recently, innovative technologies and materials have been used to minimize the fabrication error and improve productivity. Weldless piping assemblies are examples of using new materials in order to minimize the error (Safa et al. 2011). Moreover, bent members and elbows used in piping assemblies (Figure 1) have always been challenging members to fabricate correctly because existing punching, drilling, straightening, and bending tools lack the desired accuracy. Thus, correct fabrication of these members, within the desired tolerances, is not achievable using existing cutting and fitting tools. Hence, continuous monitoring of piping and involved processes, which are critical parts of the industrial construction sector, is essentially required.

The current process for monitoring the fabrication process of pipe spool assemblies is briefly described here. The process includes non-destructive measurement and inspection, analysis, and required corrective actions (Safa et al. 2013). The measurement and inspection involved in this process are conventionally applied using traditional measurement tapes and then comparing with existing drawings manually. Such a process is time consuming, error prone, and inadequate for complicated assemblies.

Recently, research studies have been attempted to improve the quality of fabricated pipe spool assemblies using simulation (Hu and Mohamed 2012; Wang et al. 2009; Wang and Abourizk 2009). Having simulated the fabrication process, the users are able to identify the conflicting processes using different scenarios. The fabrication process is then expedited using simulation; however, the highlighted deviations still need to be addressed, as fabrication inaccuracies and transportation errors are unavoidable. Automating quality control processes of pipe spools will result in an accelerated supply chain and productivity improvement. Hence, an automated monitoring framework that is sufficiently accurate to detect incurred defects is still missing in the fabrication process for industrial construction.

Recently, deviation analysis has been employed in order to conduct a comparison between designed state and laser-scanned point clouds that represent as-built status (Anil et al. 2013). In this study, deviation analysis is used to investigate discrepancies in residential buildings and the approach is distance based. Although the procedure is customizable and faster compared to conventional methods, it has not reached a sufficient level of automation as it requires prior knowledge to run the employed commercial software packages. Additionally, feature-based registration may cause error in finding the best fit between the designed state and as-built status. From these limitations, greater automation is desired which would also lead to improved performance of the inspection process.

METHODOLOGY

In this section, the proposed method for automated deviation analysis is presented, and required metrics and algorithms are formed. Figure 2 shows an overview of the proposed method.

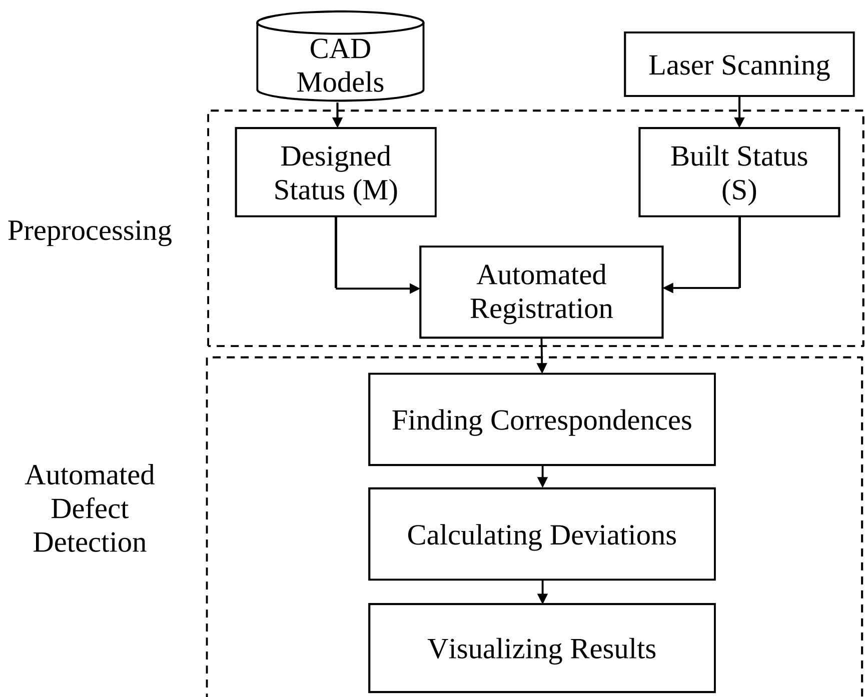

Figure 2.Proposed model for automated deviation analysis for defect detection

As shown in Figure 2, the proposed method is initiated with a preprocessing step in order to prepare the point clouds in the appropriate format to enhance the registration required to compare the designed state and built status. The involved challenges with the preprocessing step consist of noise filtering for the acquired built status point cloud and converting 3D CAD models into point cloud format. Registration is then performed in coarse and fine registration main steps (Kim et al. 2013). In this paper, the acquired laser scanned point cloud is called *Scene (S)* and the 3D CAD model in the point cloud format is called *Model (M)*.

Having found the best match between built and designed status, the incurred discrepancies and deviations can be captured. The main procedure for the automated defect detection framework is then applied. As illustrated in Figure 2, the proposed method is applied in three main steps: (1) finding correspondences, (2) calculating deviations, and (3) results visualization. Each step is described and the challenges involved are discussed in the following sections.

Finding Correspondences. Once coarse registration and then fine alignment provide the comparison between the built status and CAD models, a criterion should be defined to find corresponding features in both point clouds to characterize the incurred error. Since the built and designed statuses are being investigated in the point cloud format, point based features should be detected. The corresponding features proposed here are closest points that yield a distance-based deviation analysis. Thus, closest point searchers and algorithms are employed in order to find the correspondences. Brute-force is the algorithm used in this paper for finding closest points. This search method is the basic idea of calculating all distances followed by choosing the nearest neighbors which is also called exhaustive search or naïve approach (Kjer and Wilm 2010).

Calculating Deviations

Having found the corresponding points in *M* and *S*, incurred error which is the Euclidian distance between corresponding points is calculated for each point. For this purpose, one of the point clouds is considered as the reference state and the distance from the corresponding point in the other point cloud is calculated as follows:

$$d_i = \|\mathbb{M}_i - \mathbb{S}_i\| = [(M_{1i} - S_{1i})^2 + (M_{2i} - S_{2i})^2 + (M_{3i} - S_{3i})^2]^{\frac{1}{2}}$$

In which, $\mathbb{M}_i$ and $\mathbb{S}_i$ are 3×1 vectors that represent the i^{th} point coordination in *M* and *S* and i is the total number of points considered for closest point searchers in the reference point cloud. Calculating the corresponding distance for each point leads to a 4×1 vector that consists of geometry (coordination) and the incurred error at that point, including measurement error.

Results Visualization. For visualizing the incurred deficiencies and errors, which is a 4D vector as discussed previously, points in the acquired point clouds are illustrated in different colors based on the incurred inaccuracy in the fabrication process. This colorization process can be customizable to define number of colors used for illustration and threshold values to investigate the inaccuracies. The proposed algorithm along with the required preprocessing step is programmed in MATLAB. Examples of effective variants on the visualization map are shown in Figure 3.

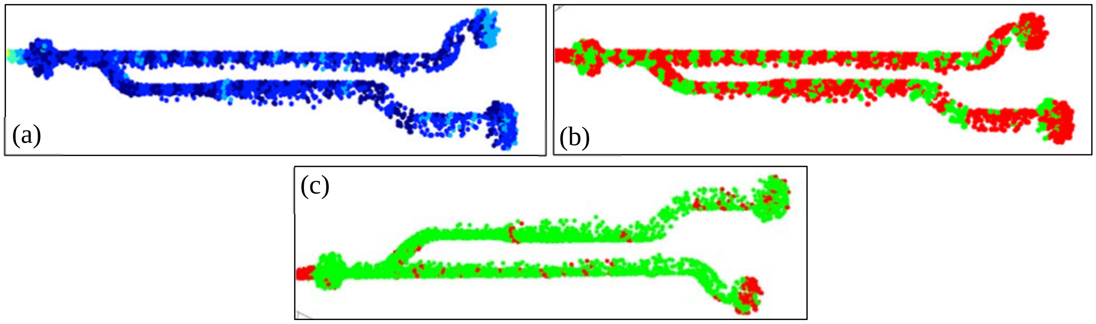

Figure 3. Customizability of the proposed method. Continuous vs. binary colors to capture the errors (a) and (b). Low vs. high thresholds to characterize the incurred deviations (b) and (c). (Red points are detected defects)

EXPERIMENTS

In order to measure the performance of the proposed method for automated defect detection and characterization, an experimental study is conducted in University of Waterloo's infrastructure analysis and sensing laboratory. The laboratory is facilitated with a set of reconfigurable pipe spools. The pipe spool connections are designed such that they provide recofigurability of the end flanges. The capability of this small scale pipe spool provides the investigation and measurement of the proposed model for defect detection. The pipe spool is tested at different deliberately incurred deviations to evaluate the recall rate of the method. The small scale pipe spool and a specific set of experiments are shown in Figure 4.

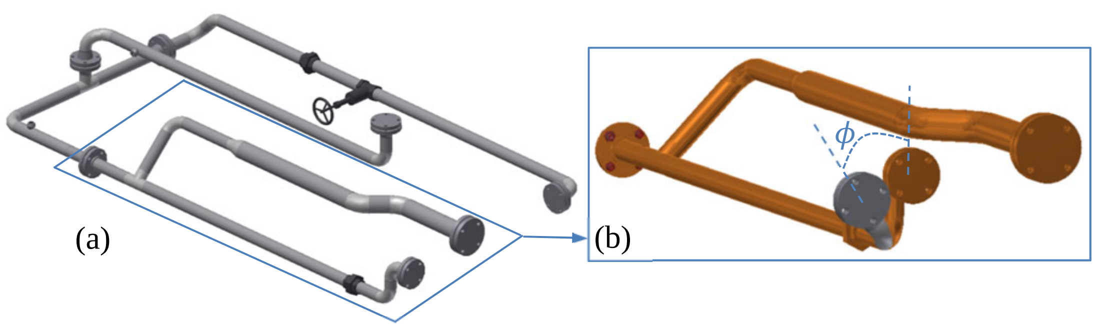

Figure 4. (a) Reconfigurable pipe spool in UW's Sensing Laboratory, and (b) applied alterations to conduct the tests for measuring the performance of the proposed method

RESULTS AND DISCUSSIONS

Conducting the described sets of experiments, shown in Figure 4-b, leads to the conclusion that the proposed method can capture inaccuracies and errors incurred in the fabrication process robustly and quickly. Different end flanges of the experimented pipe spool are investigated at multiple alterations. In summary, 11 alterations are performed on two different branches of the pipe spool. For each pipe spool two side flanges are investigated. One side is alternatively rotated to impose inaccuracy and measure the performance of the method, while the other side stays unchanged to evaluate the accuracy and recall rate of the method for negative cases. Experimental results are shown summarily in Table 1.

Table 1. Experimental results for the conducted tests. Different cases are categorized to investigate the accuracy and recall rate

Spool #	Number of tests	Investigated cases	True Positive (TP)	True Negative (TN)	False Positive (FP)	False Negative (FN)
1	7	14	7	7	0	0
2	4	8	4	3	0	1
Total	11	22	11	10	0	1

As shown in Table 1, all positive cases, which represent incurred errors in fabrication, were captured. For negative cases, which represent the other side of assembly that was fabricated correctly, 10 out of the 11 cases were truly classified using the proposed method. It is shown that only 1 case is wrongly detected as an inaccuracy in a correctly fabricated part. This wrong classification may be due to the registration results that are affected by geometry. Symmetry is a significant factor that plays role in the registration process. Thus, for symmetric assemblies and pipe spools, the imposed inaccuracy may not be seen because the correct registration is not the best registration. However, for the conducted experiments, the results show that the proposed algorithm has a promising accuracy (95%) as it correctly classifies 21 out of 22 total cases. Additionally, the recall rate for the method is 92% (11 out of 12). Recall rate is generally the proportion of the truly classified cases to total number of detected cases.

CONCLUSIONS

An approach is presented here to automatically perform the deviation analysis for defect and inaccuracy detection and characterization which is particularly validated for industrial facilities and pipe spools. The method is initiated with an automated registration step and is then followed by a distance-based deviation analysis. An experimental study is conducted to measure the performance of the method. The results show that the method can be employed to improve the quality control and inspection process by providing a sufficient level of automation and an acceptable rate of accuracy and recall comparing to the existing methods discussed in the background section. However, there are some factors that limit the application of the proposed method. The proposed inspection process may not work robustly for symmetric assemblies. Other effective variants such as the search method for finding the correspondences should also be investigated in order to improve the method. For example, the search method can be modified for large point clouds by using more efficient approaches such as KD-tree (Rusinkiewicz and Levoy 2001). Having detected and characterized the incurred misalignments and fabrication errors in industrial assemblies opens up a solution for autonomous quantification and local comparison of the inaccuracies that could be a potential for future studies.

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