Robotic Kinematics Analogy for Realignment of Defective Construction Assemblies

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ABSTRACT

Aligning and plumbing of construction assemblies is a fundamental problem because of reliance on manual solutions for geometric feedback control problem involved with practices such as pipefitting and steel structures erection. Where defective components and segments are not well controlled, the errors propagate in larger components and therefore cause more severe problems. In order to address such a challenging problem and tackle potential solutions, this paper presents a framework for automatic and systematic development of realignment actions required to achieve a target state by borrowing concepts from: (1) 3D imaging that enables the identification of the as-built status and then quantification of incurred discrepancies as a feedback by comparing the captured status with the designed state existing in the building information model (BIM); and (2) an inverse kinematics analogy that results in the calculation of required changes in the degrees of freedom defined where realignment and changes can be applied. Experimental results show that the framework can generate the required actions for achieving a desired state systematically and accurately.

Keywords: Realignment and refit; 3D imaging; Robotics; Inverse kinematics; As-built status assessment.

1 Problem Statement

Efficient assembly and erection of construction components requires continuous monitoring and understanding of design drawings. Defective assemblies must be appropriately detected in order to plan for required actions such as realignment, repair and replace. The current approach for detecting discrepancies of construction components in fabrication shops and on sites relies on manual approaches, which are inefficient and ineffective. An inefficient approach is also a source of rework in projects. Rework emerges in a project as a consequence of quality deviations necessitating the repetition of processes or activities and is comprised of direct and indirect costs. While direct rework impacts are said to attribute to 3-5% of contract cost, the indirect impacts have a more profound effect on achieving production efficiency, reducing costs, improving productivity and retaining market competitiveness [1]. The majority of rework occurs during fabrication and on-site assembly. Rework emerges during fabrication in the form of errors and omissions, inefficiencies, and design and process misinterpretation. Rework emerges during module assembly as inefficient alignment and the measures and schedule impacts associated with realignment and rehabilitation. To remain competitive and align with emerging industrial trends, a comprehensive strategy needs to be developed to automatically detect the discrepancies in order to effectively plan forward and minimize the unfavourable rework occurrence.

Fortunately, 3D imaging has been found as an effective tool to monitor processes automatically. Moreover, 3D imaging technologies, such as laser scanning, structure-from-motion and range imaging have been proven to be fast and accurate tools for detecting the state of industrial assemblies. These tools should be applied to improving the construction industry by minimizing rework. 3D sensing during fabrication, integrated with a data-fusion framework can be used for detecting, reporting, and providing the opportunity to immediately eliminate non-conformance as it occurs. This would also provide project personnel with an accurate source of information, allowing for the creation of better rework strategies.

This research aims to develop effective tools for detecting discrepancies where and when they occur and planning for the required corrective actions. By exploring and combining the underlying theories in 3D imaging and using an analogy of robotics, a process can be developed to detect and control discrepancies, check tolerances, and propose realignment strategies. Once assembly has been completed, a comprehensive module non-conformance check will identify accumulated tolerance issues and issues related to the critical external module interfaces. In order to realign assemblies efficiently, automated planning can feed into a combination of mechanical and thermal realignment methods. Beyond the fabrication process, sensing technologies can be utilized to monitor tolerances and the overall state of assemblies and modules throughout their lifecycle. Data from this monitoring can feed into an automated framework for designing, fabricating and constructing, that pre-emptively plans for plumb and fit, controls tolerances, and manages risk. The format of the three dimensional data makes it a natural candidate for augmented reality tools and could be used to aid in design interpretation, fabrication planning, constructability checking, and to provide effective process feedback.

2 Background

In the following sections, the related research background is investigated in order to comprehensively determine the need for this research. Sensing technologies used for automated as-built modelling along with the recent achievements are reviewed. The application of robotics in construction and the required concepts such as forward and inverse kinematics are then presented.

2.1 Sensing Technologies for Automated As-built Modelling

In practice, sensing technology devices have been used to provide 3D spatial information for construction applications such as semi-automated progress tracking [2-4]. Sensing technology devices have been introduced as reliable data acquisition tools in the early 2000's. Among sensing technology devices, laser and image-based techniques that provide a sufficient level of automation and accuracy are known as the most common and affordable methods.

As-built modelling is a potential solution for assessing the fabricated state of construction assemblies. Once reliable and accurate data is acquired, the as-built status can then be generated in order to assess the quality of component fabrication or installation, and automate the construction processes involved. However, converting the acquired 3D point clouds into meaningful information is not trivial and is yet to be fully automated. Several studies have attempted to show the impact of automated modelling of industrial assemblies in particular [5-8]. The approaches have significantly improved the processes involved by aiming to fully automate construction management systems such as quality control and automated fabrication [8,9], and progress tracking [6]. In the construction industry, a Building Information Model (BIM) that contains all drawings, schedule, and all other specifications, is considered as prior knowledge. Automated as-built modelling can generally be performed with and without prior knowledge. Based on Bosche's definition [10], *Scan-vs.-BIM* [11,12] and *Scan-to-BIM* [5,7] are equivalently used for automated as-built modelling with and without prior knowledge (BIM), respectively.

2.2 Robotics Application in Construction

Generally, performing tasks in harsh conditions and environments as well as performing repetitive tasks by robots has improved safety, schedule performance and productivity on construction sites [13]. Using algorithms and concepts originally developed in the robotics literature has improved the level of automation in construction activities [14]. For instance, using the "*path planning*" concept, which was originally developed for robotics, expedites construction processes (e.g. heavy lifts) and prevents interference of conflicting tasks and consequently increases the level of safety.

Construction robots that have been developed over the past few decades have significantly facilitated the process of construction by increasing the level of automation. The idea of using robots for automating repetitive construction tasks was developed in the early 1980's [15]. Health and safety were concerns that motivated the use of robotics in difficult construction tasks. Excavators, haul vehicles, fork-lifts, large scale manipulators, and welders are the common construction equipment that actually perform tasks as robots and are now commercially available technologies.

Various other examples of construction robots that are predominantly used in offsite fabrication and modularization can be found in [13]. The use of robots in offsite fabrication is due to the repetitive nature of the tasks that can be improved and expedited using robots. In later years but before the rise of modern and advanced laser scanners and 3D sensing technologies, Cho et al. (2002) revealed the usefulness of fusing fundamental robotics concepts and computer aided simulation for the purpose of geometric area modelling [16,17].

For establishing the discrepancy quantification and required corrective action generation, the approach proposed in this work employs robotic kinematics to develop the transformations assigned to local axes. In other words, for autonomously measuring the discrepancies with respect to the local axes, a transformation is required for measuring the discrepancies in local coordinates rather than calculating the discrepancies in a reference global coordinate system. This local discrepancy is then fed as an input for calculating the corrective actions using an inverse kinematics analogy. This approach is extensively described in the methodology section of this paper.

Forward kinematics generally refers to the calculation of the position and orientation of end effectors in robotics systems [18]. An example of using forward kinematics in the construction industry is the calculation of an excavator bucket's position and orientation knowing the geometry (i.e. length of members) and current joint angles in a large scale manipulator [19]. A common method for systematic modelling of local axes, in which the characteristics of joints and members are taken into account, is defined by Denavit and Hartenberg [20]. The incorporated parameters are called Denavit-Hartenberg (D-H) parameters. On the other hand, inverse kinematics can also be used if a target position is desired for assembly or erection purposes. These metrics and functions are formed and thoroughly explained in the methodology section.

In summary, the background analysis shows that developing a framework for automated quantification of the incurred discrepancies in fabricated assemblies still needs to be addressed to avoid rework on construction projects. Promising technologies such as 3D imaging techniques have already provided the required level of accuracy necessary to track the as-built status. This paper integrates an automated (semi) real-time comparison of the collected 3D data with design information that detects discrepancies early, facilitates quantification of those discrepancies in local coordinate frames, and generates realignment plans to simplify and guide restoration work. The detailed methodology is presented in the following section.

3 Proposed Methodology

The methodology for this paper will specifically build on the recent developments made by the authors [9,21,22]. The proposed methodology has two primary steps: (1) as-built status identification that enables the quantification of the discrepancies incurred, and (2) fitting and realignment that results in the calculation and efficient application of the required corrective actions. Such a framework will make it possible to detect, localize, and quantify the geometric discrepancies incurred. The flow between the components of the primary steps as well as the required inputs and the desired output is shown in Figure 1. Primary steps and the required metrics for implementation are detailed in the following sections.

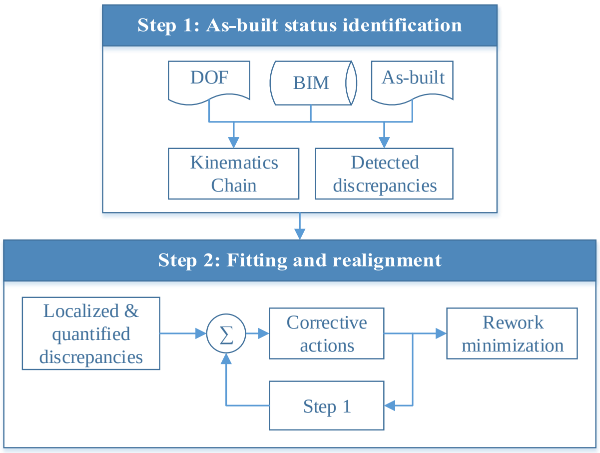

Figure 1: The proposed algorithm and the flow of information for automated discrepancy quantification and realignment

3.1 As-built Status Identification

Acquiring an accurate and reliable as-built status makes it possible to assess the fabricated status of construction assemblies, as they are being assembled. Extracting meaningful information from the massive amount of data acquired on construction sites is a fundamental challenge, because it is computationally intensive and therefore time consuming. In summary, the as-built status assessment is generally performed using two different approaches: (i) automated as-built modelling by finding the geometric relationship between parts of an object and reconstructing the detected object, and (ii) taking advantage of building information models (BIM's) and comparing the as-built dimensions with the originally designed dimensions. The latter approach which employs BIM as a-priori knowledge for as-built status identification is used in this research proposal. The identification system relies on the accuracy of the as-built status acquisition tool. Clearly, accurate data is required to reliably plan required work. The key challenge for as-built status acquisition is to employ an appropriate tool that can provide real-time data for capturing the built status accurately.

3.1.1 Inputs and preprocessing

The inputs to the proposed framework include the originally designed 3D drawings existing in building information models (BIM), and the as-built status acquired in an appropriate format with a reliable level of accuracy. The preprocessing step required for preparing the designed drawings is to convert the solid objects into an appropriate format that can be employed in further steps. The acquired point cloud representing the as-built status is also noise-filtered. Once the required preprocessing is performed, a point cloud registration is applied in order to enhance a comparison between the built and designed states. A modified iterative closest point (ICP)-based approach is employed to perform the registration. The modified ICP is capable of considering the local situations (i.e. connection to the adjacent regions), as well as the global situations. It results in a reliable and accurate feedback which is the key input of the realignment strategy.

3.1.2 Discrepancy Localization and Quantification

In order to locally calculate the incurred discrepancy, a robotic analogy is developed. Using robotics theory and developing a forward kinematics chain results in the transformation from global to local work coordinates. The discrepancy is initially calculated in the form of a rigid transformation (i.e. a rotation and translation) using a modified iterative closest point (ICP) algorithm in the global coordinate system [23]. Defining the degrees of freedom (DOF's) where realignment can occur (with skilled trades input) results in a chain of transformations (kinematics chain) that indicates the relationship between the global and local coordinates. The kinematics chain is developed using Denavit-Hartenberg (D-H) convention [18,20]. A typical industrial assembly is illustrated in Figure 2. The local coordinates and the geometric parameters are shown.

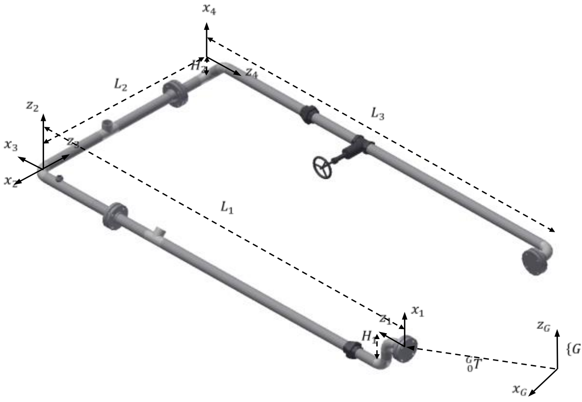

Figure 2: Defined DOF's for developing the kinematics chain

The relationship between the local $\{l\}$ and global $\{G\}$ coordinates can be defined as:

$$ {}^{G}_{l}\vec{f} = {}^{G}_{0}\vec{f} \times {}^{0}_{l}\vec{f} \qquad (1) $$

Where, ${}^{0}_{l}f$ is calculated by D-H notation based on the geometry. ${}^{G}_{l}f$ is the required link between global and local coordinates of a given assembly that is used in the next section for converting the required transformation calculated in the local coordinates. The local coordinates $\{l\}$ can be located at any arbitrary position where discrepancies are investigated. For the typical assembly shown in Figure 2, $\{l\}$ coordinates is located at joint 4. D-H parameters are then defined based on the assigned local axes and the kinematics chain is thus generated as shown in Equation (2).

$$ {}^{0}_{l}f = {}^{0}_{4}f = {}^{0}_{1}f\ {}^{1}_{2}f\ {}^{2}_{3}f\ {}^{3}_{4}f \qquad (2) $$

The geometry of the construction assemblies (member lengths and connection types) is inherent in the kinematics chain. Performance of the discrepancy localization and quantification toolbox is shown in Figure 3. As illustrated, the as-built status, acquired by an appropriate method, is imported to the toolbox and real-time step-by-step feedback is provided for guiding the fabrication/assembly. In the case that pipefitters read the drawings or choose pieces incorrectly (i.e. steps 2 and 3 in Figure 3), the real-time feedback avoids incurring or accumulating such errors and misinterpretations in a timely manner. The associated error, and the risk of it, is therefore minimized.

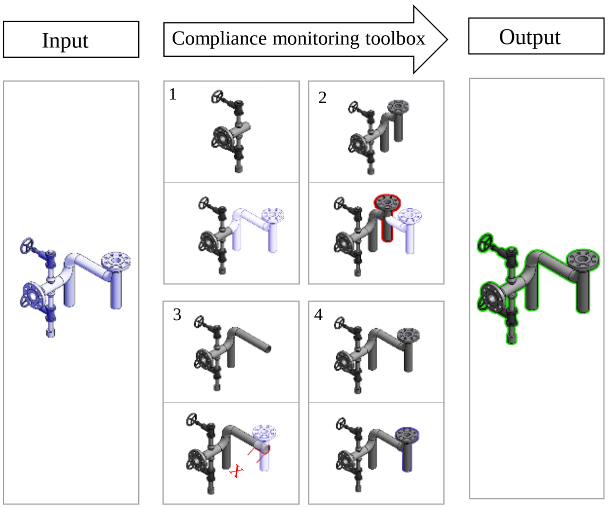

Figure 3: Compliance control using the proposed methodology. The processing step includes (1) the as-built status (top row), and (2) the toolbox feedback (bottom row).

3.2 Fitting and Realignment

3.2.1 Potential Realignment Calculation

The as-built identification system developed is not only capable of localizing and quantifying the discrepancies but can also plan for the required corrective actions using an inverse kinematics analogy. Using the analogy of robotics and developing the kinematics chain results in the calculation of required reconfigurations to achieve any state as the target. For calculating the required joint changes, a Taylor-based linearization (approximation) is used. A Moore-Penrose pseudoinverse [24] is then calculated for generalizing the inverse matrix required for calculating the joint changes to achieve a target position. This approach is associated with the inverse kinematics of robotics theory. The forward kinematics developed in the previous step is used to identify the end flange/member position as a function of the joint angles and lengths. In other words, end flange/member position (P) can be defined as a function of $P = f(\Phi)$, where Φ represents the degrees of freedom. On the other hand, inverse kinematics is used to calculate the joint angles and lengths that lead to a given end flange/member position (target point). In the functional form, inverse kinematics represents the degrees of freedom as a function of the end position [$\Phi = f^{-1}(\mathrm{P})$]. The Jacobian of the kinematics chain is the link between the coordinate space and joint space.

In order to solve the inverse kinematics problem resulting from the analogy with robotics, a Taylor-based linearization (approximation) is used as follows:

$$f(\Phi^{i+1}) \approx f(\Phi^{i}) + \frac{\partial f}{\partial \Phi}\,(\Phi^{i+1} - \Phi^{i}) \qquad (3)$$

where, $\partial f / \partial \Phi$ is the Jacobian matrix (J) of the kinematics chain f, and the superscript i represents the state in the i^{th} step. Therefore, Equation (3) can be rewritten as:

$$f(\Phi^{i+1}) - f(\Phi^{i}) = \Delta P = J \times (\Delta\Phi) \qquad (4)$$

Pre-multiplying both sides of Equation (4) by $J^{-1} = J^{+}$ results in:

$$(\Delta\Phi) = J^{+} \times \Delta P \qquad (5)$$

in which, J^{+} is the pseudoinverse of the Jacobian matrix (J). Pseudoinverse is the general form of the inverse matrix and is used for general cases, particularly when a matrix (e.g. matrix J) is non-invertible (non-square). The most general form of a pseudoinverse is the Moore-Penrose pseudoinverse [24] and is defined as follows:

$$J^{+} = (J^{T} J)^{-1} J^{T} \qquad (6)$$

where, J^{T} is the transpose of (J).

The proposed algorithm for the inverse kinematics analogy is summarized in Figure 4. *th* shown in Figure 4, is the allowable tolerance required for achieving the designed state that can be defined using existing codes or experts' experiences.

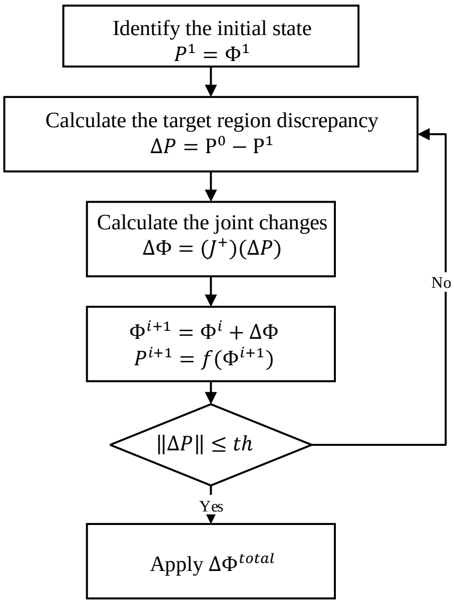

Figure 4: Summary of the proposed algorithm for the inverse

3.2.2 Corrective Actions Development, Application and Communication

Once the required corrective actions are automatically calculated using the inverse kinematics analogy, the changes should be applied in order to realign defective assemblies or guide the pipefitters during the assembly. For example, "*cold fit-up*" is currently the most common approach for fitting the assemblies. Given the required displacement and rotation at critical points (DOF's), measured in the previous step, it becomes possible to systematically apply the required adjustments. In other words, required corrective actions in the form of translation and rotation should be converted to feasible actions that can be applied on an assembly. A combination of mechanical and thermal realignment actions can be derived in order to continuously monitor the process and minimize the associated rework. This requires the incorporation of mechanical and structural properties in the framework based on previously defined DOF's.

4 Realignment Framework Performance Using Robotics Analogy

For validating the proposed framework for the automated discrepancy quantification and realignment strategy, a set of experiments were designed in the Civil and Infrastructure Sensing (CIS) Laboratory at the University of Waterloo. A small-scale pipe spool that has reconfigurable joints and connections makes it possible to measure the performance of the proposed methodology. The connections are altered at various configurations. The incurred discrepancy is detected and quantified using forward kinematics combined with 3D imaging frameworks. For the as-built status acquisition, a laser-based approach is employed because of the level of accuracy required. The detected, localized, and quantified discrepancy is then fed into the realignment strategy framework. Based on the calculated discrepancies at the previously defined DOF's, a realignment strategy is calculated using the inverse kinematics analogy. In other words, the target points that may be defined by the originally designed CAD drawings existing in BIM or continuously updated drawings, are defined by typical users of this toolbox. A potential realignment plan is then calculated and suggested based on the DOF's. Typical results of the proposed framework on the small-scale assemblies in the laboratory are shown in Figure 5.

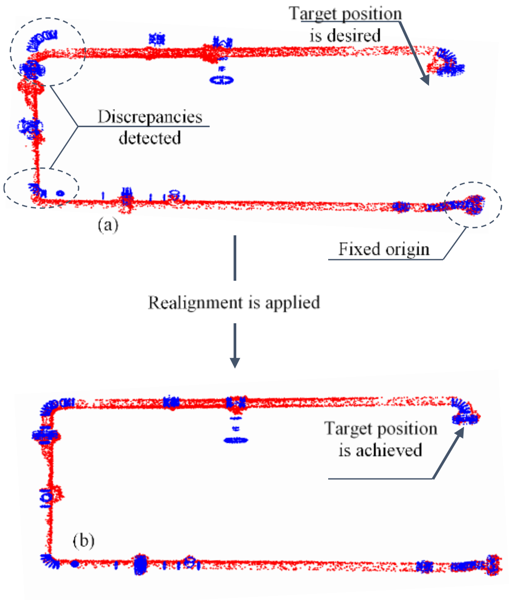

Figure 5: Typical results of the realignment strategy. (a): The as-built status (red) and the originally designed state (blue). (b) Realigned state (red) and the originally designed state with the desired target point (blue).

5 Discussions and Conclusions

A framework is presented in this paper that enables automated quantification of incurred discrepancies and therefore potential realignment strategy. The framework employs robotics analogy for calculating the discrepancies and realignment plans based on the built status acquired by an appropriate 3D imaging approach. While the framework can be applied to a broad range of applications and sectors in construction, this paper focuses on industrial assemblies such as pipe spools that are critical in the industrial construction. The framework was verified and validated by a set of laboratory experiments. Some remarks and insights follow:

- The automated discrepancy quantification was sufficiently time-effective and provided the required level of accuracy. Therefore, reliable data is fed to the realignment framework.
- The realignment framework requires only a few iterations which improves the usability of the proposed framework in real-time modelling applications.
- The desired state is achieved within a reasonable timeframe using the realignment strategy. The realignment strategy is considered in the form of rotation and translation which means physically applying torques, re-welding, and cutting.
- The framework has the potential to be integrated with real-time data acquisition tools in order to provide real-time feedback for pipefitters and welders. This results in rework avoidance and therefore huge time and cost savings.

One limitation of the proposed framework is that it is currently only capable of modelling serial assemblies such as pipe spools with one target position (end flange/member) and minor internal errors. Generalizing the framework requires the extension of the toolbox for parallel assemblies such as structural frame (pipe racks), and pipe spools with multiple target points. Detection of gross errors such as those illustrated in Figure 3 uses a related set of algorithms described in a subsequent paper and thus precludes the need for the approach described here for gross errors. Such frameworks are being extensively investigated and developed by the authors.

Acknowledgement

The authors would like to thank SNC-Lavalin, Aecon, and National Science and Engineering Research Council (NSERC) Canada for financially supporting this research.

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