Dimensional variability analysis of construction assemblies using kinematics chains and building information models

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Abstract

Design optimization frameworks used in manufacturing can be adopted into construction to solve complex and relatively unsolved challenges, as recent construction methods progressively incorporate more manufacturing aspects. For example, the specification and dimensional control for compliance checking of construction components can be solved using tools existing in manufacturing. Even though building information models (BIM) assist with clash detection for identifying potential dimensional problems, dimensional variability remains a complex challenge to address in construction. This paper explores the use of a dimensional variation analysis (DVA), which is originally developed in the manufacturing industry as a design optimization tool. This paper presents a DVA approach which is based on kinematics theory in robotics to define the assembly equation (how various parts of a component are related to each other mathematically). A design-model based DVA is validated using a case study. Results show that the method is capable of determining variability between the designed and fabricated states with a reasonable level of accuracy.

Keywords:

Local feature descriptors, hashing, hash table, RANSAC, 3D object recognition, clutter, laser scanning

1 Introduction

The inevitable variability associated with the geometry of as-built construction assemblies can create problems if not properly controlled and managed. This type of variability has a direct relationship with how well components can be built and assembled together. Constructability is one method that can be employed to ensure problems associated with the construction and assembly of components are minimized. Constructability employs strategic knowledge during planning, design and execution to achieve project objectives. It therefore requires an investment in front-end planning in order to anticipate and solve potential problems [1,2]. Some of the most common problems that constructability addresses are related to rework, design errors, change orders, low product quality, project delays, tolerance problems, physical interface problems, and not meeting client expectations [3]. The common aspect of all of these problems is that they originate from the dimensional or geometric properties of components or construction assemblies. The ability to model construction components in a virtual three-dimensional space has enabled the use of building information modelling (BIM) and computer-aided design (CAD) tools to be used to aid in constructability [4,5]. Use of these virtual design and construction (VDC) tools places an emphasis on ensuring coordination between trades and detection of physical component clashes. The focus on both constructability and use of BIM in the construction industry shows that the proper management of component and system geometry is a key factor in overall project success.

The importance of controlling and managing variability of geometry is generally well accepted in the construction industry. While proper control of geometry is often not extensively considered up front in the design process, its impact is unavoidable during fit-up and assembly and can result in expensive rework. Dimensions and configurations of components always have some degree of variation from nominal specifications [6]. This is why the construction industry has adopted the use of standardized tolerances to ensure that acceptable limits are placed on dimensional variability [7,8]. Tolerances by themselves are not enough to solve geometric problems since tolerances can accumulate throughout assemblies, resulting in fit-up problems, delays, rework and increased costs [9]. Furthermore, the trend towards increasing industrialization in construction introduces an even greater demand on geometric compatibility between components and assemblies since the bulk of the fabrication and construction work occurs offsite and requires assemblies to fit properly once on site [10].

This paper presents a framework for dimensional variation analysis which uses kinematics theory as a method for modelling the geometric relationships between components. The related background is first investigated, then the proposed framework is then presented. A case study is provided to demonstrate how dimensional variability can be modelled through the use of kinematics chains.

2 Background

This section presents background related to: (1) existing methods for dimensional control in construction, and (2) theory behind kinematics chains for geometric modelling purposes.

2.1 Existing approaches for dimensional control in construction

While existing methods for analysis, detection and control of dimensional variability in the construction industry can utilize proactive 3D analysis techniques such as spatial change analysis [11] or automated compliance checking [12], the majority of variation control techniques during construction are still performed reactively (i.e., problems related to dimensional variability are only solved once they have occurred). This often creates a grey area during a project when variations in the field create installation challenges for specific contractors because the assumption of risk for out-of-tolerance occurrences is not well defined.

Proactive methods for controlling variability are generally restricted to the use of BIM-based clash detection. Proactive solutions for dimensional conflicts are superior to reactive methods, evidenced by the fact that 90% of commercial contractors are currently using clash detection on projects which utilize a building information model [13]. In a study by Leite et al. [14], it was shown that on-site clash fixes are costlier than creating a more detailed BIM upfront and using clash-detection. For this reason, spending more time during the design to detect and avoid clashes can offset the cost associated with field rework due to dimensional variations.

2.2 Kinematics chains for geometry modelling

Robotics theory has opened up a wide and efficient range of solutions in engineering problems. For example, robotics concepts combined with machine vision have been used for state modelling and sensing of construction equipment such as pipe manipulators and excavators [15]. A specific pose of the end effector (i.e., the end of a kinematics chain, which is the critical feature of interest) can then be modelled using the related inverse and forward kinematics. Robotics concepts can also be used for automating tasks associated with a high level of repetition or harsh tasks that are performed by workers in hazardous areas. For instance, a machine-vision-assisted system in introduced by [16] for automating the bricklaying assembly. Kinematics theory was also used for geometric modelling of construction assemblies as a mathematical function [17]. Discrepancies of the as-built state of construction assemblies are therefore quantified (via forward kinematics) and required corrective actions are then calculated (via inverse kinematics) [18,19]. Moreover, modelling the geometry using kinematics chains has been found to be very effective for integrating parametric models for systematic and algorithmic monitoring of civil infrastructure.

3 Research Methodology

In this paper, the geometric relationships between components in an assembly are derived using the analogy of robotics and kinematics chain (KC) modelling. It is assumed that construction assemblies are similar to robot arms with mutual degrees of freedom. As such, dimensional variability is modelled mathematically, and the critical component-features and their dimensional variations are then controlled systematically. The analogy of construction assemblies with robot arms was first used by Nahangi et al. (2015) [17], for quantifying incurred discrepancies in construction assemblies. It was then used to calculate the required changes for realigning defective assemblies [18] by solving the inverse kinematics problem. This paper is directed toward dimensional variation analysis, in order to investigate how deviations propagate an accumulate in an assembly.

3.1 Overview of the kinematics chain-based modelling

An overview of the proposed methodology is shown in Figure 1. Some critical information integrated in the BIM is required to develop the kinematics chain for DVA. As shown in Figure 1, critical interfaces and an assembly diagram are required for identifying the critical chains for variation analysis. The kinematics chain is then developed for the construction assembly.

This section describes: (1) how kinematics chains are developed for construction assemblies (Section 3.2), and (2) how the developed chain can be applied for critical interface and connection design (Section 3.3).

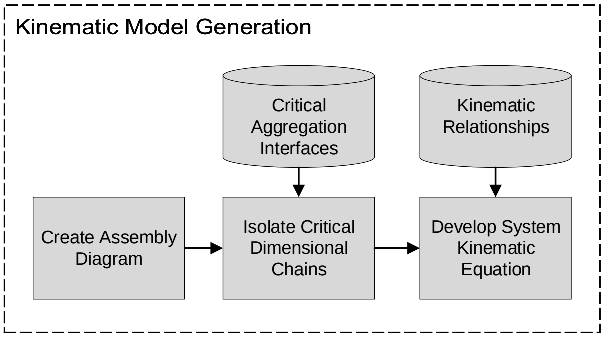

Figure 1: overview of the proposed framework for kinematics chain based DVA

3.2 Kinematics chain formulation

For developing the kinematics chain, a similar approach to [17] is employed. Transformations are then derived using the Denavit-Hartenberg (D-H) convention [20]. D-H convention is a systematic method that can be programmed and integrated with other components of the proposed framework. D-H parameters represent any homogeneous transformation as a combination of four transformations, as illustrated in Figure 2.

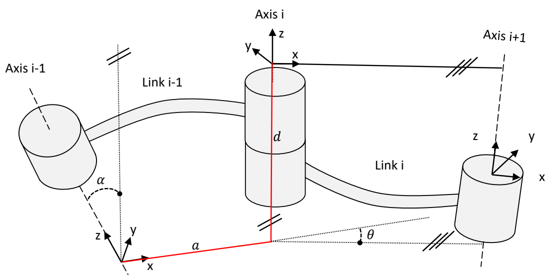

Figure 2: D-H parameters for a typical connection.

Of these four transformations (illustrated in Figure 2), two are rotational and two are translational transformations. These are represented by the following equation:

$$T_i = (Rot_{z,\theta_i})(Trans_{z,d_i})(Trans_{x,a_i})(Rot_{x,\alpha_i}) \qquad \text{Eq.1}$$

$$= \begin{bmatrix} c\theta_i & -s\theta_i & 0 & 0 \\ s\theta_i & c\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdots$$

$$\cdots \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c\alpha_i & -s\alpha_i & 0 \\ 0 & s\alpha_i & c\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

in which, θ_i, d_i, a_i, and α_i are parameters associated with link *i* and joint *i* (Figure 3). $c\beta$ and $s\beta$ denote $cos\ \beta$ and $sin\ \beta$, respectively. The four parameters θ_i, d_i, a_i, and α_i are also known as *"link length"*, *"link twist"*, *"link offset"*, and *"joint angle"*, respectively.

Generally speaking, two types of joints can define the characteristics of any construction assembly connection (Figure 3):

1. Rotational joints: are considered where dimensional variations can occur in the form of a rotational affect. Rotational joints are also known as revolute joints in robotics theory.
2. Translational joints: are considered where dimensional variation can occur in the form of translational or an extension effect. Such joints are also known as prismatic joints in robotics theory.

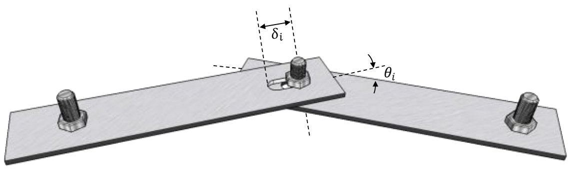

Figure 3: Schematic of a hypothetical joint. The joint is comprised of one translational joint and and one rotational joint (δ_i is variable for translational joints, and θ_i is variable for rotational joints).

In order to model variation of connections and joints, θ_i is the design variable used for rotational joints, and d_i is the design variable used for translational joints. For modelling the geometric relationship between different segments of an assembly and considering the dimensional variations that may occur, the appropriate joint type is considered and incorporated in the kinematics chain. In some cases, a combined joint comprised of many 'typical' joints (which are all coinciding at one point) may be modelled linearly. For example, the connection illustrated in Figure 3 is combined of one translational and one rotational joint in parallel, meaning that the order of their transformation can be reversed. However, in rare cases where a connection is complex (e.g., exterior cladding connection systems), it may have to be modelled as a series of joints. Also, placement of the origin for structural assemblies must follow a standard convention (typically at one corner or along an outer edge at the centre of the assembly). The position of the critical interface or node is modelled as a mathematical function with the potential dimensional variations as design variables.

3.3 KC-based DVA

Once the assembly and potential dimensional variations are modelled mathematically (by developing the kinematics chain), variation analysis of a critical feature becomes systematic and algorithmic. The assembly diagram which is extracted from the building information model identifies how various components are constructed and assembled. Variations can be predicted using the model in order to develop suitable tolerances and or to determine if the design tolerances are respected. As previously mentioned, the kinematics chain identifies the position of a critical feature or connection as a mathematical function of the possible dimensional variations. The variation of the critical feature can then be modelled and analysed for tolerance design and further considerations.

Since the dimensional variation is modelled mathematically, unprecedented analyses become possible for systematic monitoring and design of construction components. For example, the rate of variation propagation in the critical region of an assembly can be calculated by differentiating the kinematics chain with respect to the design variables. Furthermore, inverse kinematics can be used for tolerance allocation at each component for desired tolerance requirements of the critical feature.

4 Case Study

The case study investigated in this paper relates to the fabrication of the structural system of a single story modular building. In this project, the contractor experienced numerous dimensional fit-up issues during erection, resulting in misalignments between module connection points). To address these issues, a dimensional variation analysis using the proposed methodology was developed. This DVA model analysed the key fabrication processes for the steel frame structure.

Using the assembly diagram, kinematics chains were developed for analysing the dimensional variation of critical features (i.e., tie-in plates). The transformation required for analysing the tie-in plates is represented as a chain of transformations between several local coordinate systems. These local coordinate systems are found where either a critical deviation might occur or where a strict tolerance has been specified. Figure 4 shows the tie-in plates on a typical module, which are taken as the critical assembly features. A kinematics chain was derived from the structural system, with the critical features (tie-in plates) acting as end-effectors in each chain.

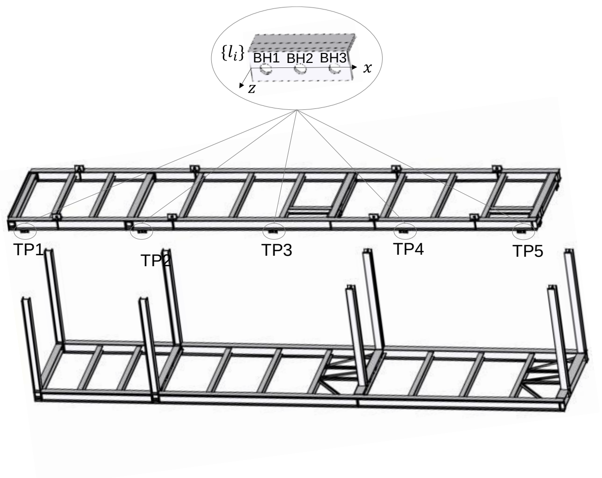

Figure 4: Kinematics chain and assembly diagram for representing critical features in the local $\{l_i\}$ and global $\{G\}$ coordinate systems.

In practice, there are two DVA approaches for use of kinematics chains for modelling dimensional variability in the proposed methodology: a design-model based approach and an as-built approach.

A design-model analysis, is used when design tolerances analysed using information provided in the building information model. This analysis identifies how design tolerances propagate through fabrication processes in order to determine an overall tolerance accumulation. Typical analyses on the case study used in this paper are shown and discussed in this section.

For investigating the case study, two stages of tolerance propagation can predict tolerance accumulation of the tie-in plates:

1. How the tie-in plate is installed and assembled with respect to the roof frame, and
2. How the roof frame is installed with respect to the floor frame (global coordinate system)

The spatial position of the tie-in plates and the impact of tolerance propagation can then be modelled by developing the kinematics chain relating the global to the local coordinate system. The allowable tolerance impact can then be measured in the global coordinate system in order to investigate the propagation of the tolerances.

An as-built analysis is used when the built status of a construction assembly is under investigation. Acquisition of the built status information (which can be done via 3D point cloud data from a laser scanner) provides accurate information that can be used for as-built modelling, updating the BIM and for understanding contributions of out-of-tolerances. In this type of DVA, the physical construction dimensions are extracted from point cloud data (or other accurate data sources) of the construction components, and the kinematics chain is then populated. Using the kinematics chains that were developed for the design-model DVA, input of the actual as-built dimensions can be used to visualize 2D deviation surfaces for the two design variables used (Figure 5). This information can also be used to visualize the propagation of dimensional variations for all tie-in plates along the length of the module (Figure 6). θ_1 and θ_2 are the design variables to be analyzed for dimensional variability of the tie-in plates. The ranges are chosen from the allowable tolerances identified in the design specifications. However, a typical range is chosen here for demonstrating the results.

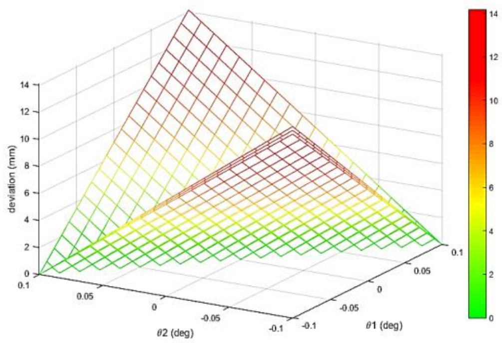

Figure 5: Results for the as-built DVA of the case study. Deviation surfaces and contour lines for the bolt holes (BH) are illustrated. The results are shown for the tie-in plate 2 (TP2).

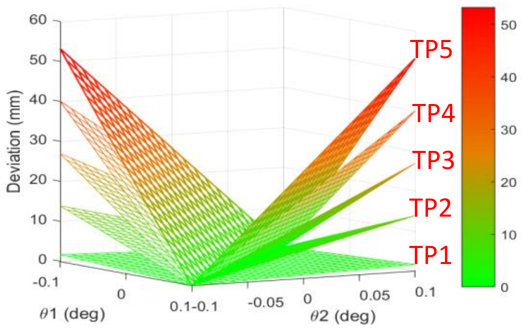

Figure 6: Propagation of dimensional variation along the roof frame of the case study in different tie-in plates. As seen, tie-in plates further from the datum have higher impacts.

These figures show two important conclusions. First of all, Figure 5 shows that the largest variation experienced in any given tie-in plate occurs when the design variables are at either their positive extreme (+0.1 deg and +0.1 deg), or at their negative extreme (-0.1 deg and -0.1 deg). This is not surprising since we would expect that the net effect of rotations in either the positive or negative direction will cause the tie-in plate to deviate the most from its nominal position. By modelling this variation however, we are able to calculate the value of the expected deviation, which can be used for inspection or remedial actions. Secondly, Figure 6 shows which tie-in plate will have the largest deviation with respect to the datum (note: in this case study the datum was located near the first tie-in plate). Again, it's not surprising that the furthest tie-in plate from the datum would have the largest relative deviation due to the rotations of θ_1 andθ_2. However, by modelling this kinematic chain, we are able to calculate the value of the expected deviation.

5 Conclusions

Dimensional variation analysis (DVA) is a powerful tool for modelling the relationship between parts in an assembly. The authors in this paper demonstrate how kinematics chains can be used to derive these relationships by assuming rigid body transformation (rotational and translational degrees of freedom). While DVA has an extensive use in manufacturing, the authors demonstrate that it can be used in construction for similar benefits.

The case study in this paper investigates how to spatially model the connection points of prefabricated modules in a building. This can be a very challenging process in the fit-up and assembly process due to the significant accumulation of dimensional variability. For this purpose, use of kinematics chains in DVA is used in two different ways: for design-models and for as-built conditions. These approaches employ the use of laser scanning (for the as-built state), and BIM (for the design-model state).

The results from both of these analyses represent the expected dimensional variability of the tie-in points for the modules. In practice, this information is very important for predicting potential fit-up conflicts before they occur. Furthermore, the expected dimensional variability can be considered in the design process for connection systems.

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