Optimization of prefabricated component installation using a real-time evaluator (RTE) connection locating system

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Abstract -

Prefabrication promises to industrialize the construction industry. By constructing elements within a manufacturing environment, producers can better control quality and maximize production efficiency. Since the major adoption of prefabrication, a wide variety of prefabricated components have been produced for varying applications such as new construction and exterior wall retrofits. While the production processes of these prefabricated components have seen much innovation, the installation process has remained relatively unchanged for decades. To innovate the installation process with modern technologies, a real-time evaluator (RTE) has been developed to reduce the installation cost of prefabricated components by reducing installation time, decreasing rework, and improving accuracy. The RTE uses developed software solutions with off-the-shelf hardware to assist erectors in completing an installation by measuring the real-time positions of connections and prefabricated components, providing installation guidance through a graphical user interface, and monitoring the accumulated installation errors. An overview of the RTE and proposed workflow is presented. A connection locating system that guides users in expediting the installation of connections is introduced. Laboratory experiments were conducted to determine the accuracy improvement and time savings of the RTE in installing connections for prefabricated components. RTE enabled a time saving of up to 37% compared to traditional connection installation methods using handheld measurement tools.

Keywords -

prefabrication, installation, real-time, automation, accuracy, time

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1 Introduction

Prefabrication promises to industrialize the construction industry [1]. Prefabrication is the process of manufacturing and preassembling several building components, modules, and elements before their shipment and installation on a construction site [2]. By constructing elements within a manufacturing environment, producers can better control quality and maximize production efficiency [3].

Modern surveying technologies include robotic total stations that expedite and improve the accuracy of building and land surveying. Additionally, 3D laser scanners can produce point cloud data for the development of 3D models using reality capture. However, these tools are most commonly used to assess the as-built conditions of the construction after prefabricated component installation. For example, many works have focused on the automated generation of as-built 3D models using laser scanning [4, 5, 6]. However, these methods are often utilized immediately after placement of components is completed. A better use of the technology is the active monitoring of the quality of construction and using this information to assist installers while the building is being constructed such that errors can be compensated in real-time. By compensating errors in real-time, total installation time can be reduced.

The construction industry would benefit from an installation tool that utilizes modern surveying technologies to provide corrective guidance in real-time to reduce installation time, decrease rework, and reduce cost. In other industries, laser trackers are commonly used to precisely inform and assess the manufacturing process. For example, in the aviation industry, three laser trackers measuring targets attached to a wing have been used to generate real-time guidance during attachment of the wing to the aircraft body [7]. Similar techniques using machine vision are often used for robotic assembly of cars [8]. A similar technique, used in construction applications, could enable real-time evaluation of components during placement, providing guidance for users such that errors are addressed.

To innovate the installation process with modern technologies in the construction industry, a real-time evaluator (RTE) was developed to reduce the installation cost of prefabricated components by reducing installation time, decreasing rework, and improving accuracy. The function of the RTE is illustrated in Figure 1. The RTE uses developed software solutions with off-the-shelf hardware to assist erectors in completing a prefabrication component installation by measuring the real-time positions of connections and prefabricated components, providing installation guidance through a graphical user interface, and monitoring the accumulated installation errors. An overview of the RTE and proposed workflow to expedite prefab installation on-site is presented. This paper will introduce a connection locating system to guide and expedite the installation of connections. Potential time-savings and accuracy improvements are detailed through laboratory experiments.

2 Methodology

The RTE has been developed, first and foremost, as a tool to expedite the installation of overclad panel retrofits. An overclad panel retrofit consists of adding an additional layer of insulation to the exterior surfaces of an existing building [9]. These overclad panels commonly include finish, insulation, a mechanical frame, and connections to the supporting structure. The panels are prefabricated to the exact dimensions of the existing building and require tight installation tolerances because the panels serve as the new air and water barriers for the building. As a result, the figures, descriptions, and experiments will focus on illustrating and validating the RTE in a retrofit application. However, even though the RTE has been designed specifically for retrofits, the tool can be equally applied to any form of prefabrication to enable faster installation.

2.1 Overview

The real-time evaluator consists of four components. These components are illustrated in Figure 2. Each component is described in detail.

First, a digital twin is necessary for the operation of the RTE. A digital twin is a digital model of the actual building as it will be constructed [10]. Many research efforts have focused on the automated development of digital twins for construction applications [5]. As part of the digital twin, the locations and connections for each component must be modeled in space. The RTE imports the digital twin to determine the geometry of the building and installation including the goal locations of components and connections. While a necessary part of the RTE, the automated generation of the digital twin is not the focus of this paper. For the RTE, an automated method of generating the digital twin for existing buildings has been developed and detailed in a previous paper by the authors [11]. This automated digital twin generation enables the rapid measurement and digitization of an existing building so that a panel retrofit can be quickly designed. For new construction, 3D models of the construction are often generated as part of the design process. For building retrofits, an as-built digital twin must be generated as an initial step. After procurement of the digital twin, the designer selects panel sizes and connection locations relative to the existing building. Whether the digital twin is automatically generated or developed as part of the construction design process, the goal install locations of each connection and component must be described within the model. The goal locations of connections and components are later used to generate installation commands.

An autonomous tracking system locates and tracks panels as they are being installed. The tracking system utilizes a robotic multi-station, operating as a laser tracker, to cycle through and locate multiple retroreflector targets (prisms) attached to the prefabricated component. Communication and control software modules direct the robotic multi-station to perform automated procedures and actively monitor the position of the component. Details on the automated tracking system and algorithms to track multiple prisms in sequence were detailed in a previous paper by the authors [12]. For the panel retrofit application, the autonomous tracking system collects the real-time position and orientations of the panel during installation.

A positioning assistant system generates installation commands for the user through a graphical interface. The system uses the data stored in the digital twin and collected by the autonomous tracking system to compare sets of goal locations to actual locations. From this comparison, required translational movements and reorientation angles can be derived to inform the user of the required installation procedures. The algorithms to reconstruct the pose of the prefabrication components during installation from the actual location to the goal location are detailed in a separate paper [13]. For the panel retrofit application, the pose reconstruction algorithms extract the translation and angles required to reposition the panel from the actual position to the goal position.

The connection locating system, which is the main focus of this paper, assists users in installing connections to the supporting structure to hold the prefabricated components. For panel retrofits, each panel must be attached to the existing building structure to support the weight of the panel. These connectors are specifically designed as part of the retrofit and are often preinstalled on the existing building before panel installation. The details of the connection locating system are further described.

2.2 Connection locating system

The connection locating system uses off-the-shelf hardware and novel algorithms to expedite the installation

Figure 1. A real-time evaluator to expedite prefabricated component installation. It provides real-time guidance on installing prefabricated components.

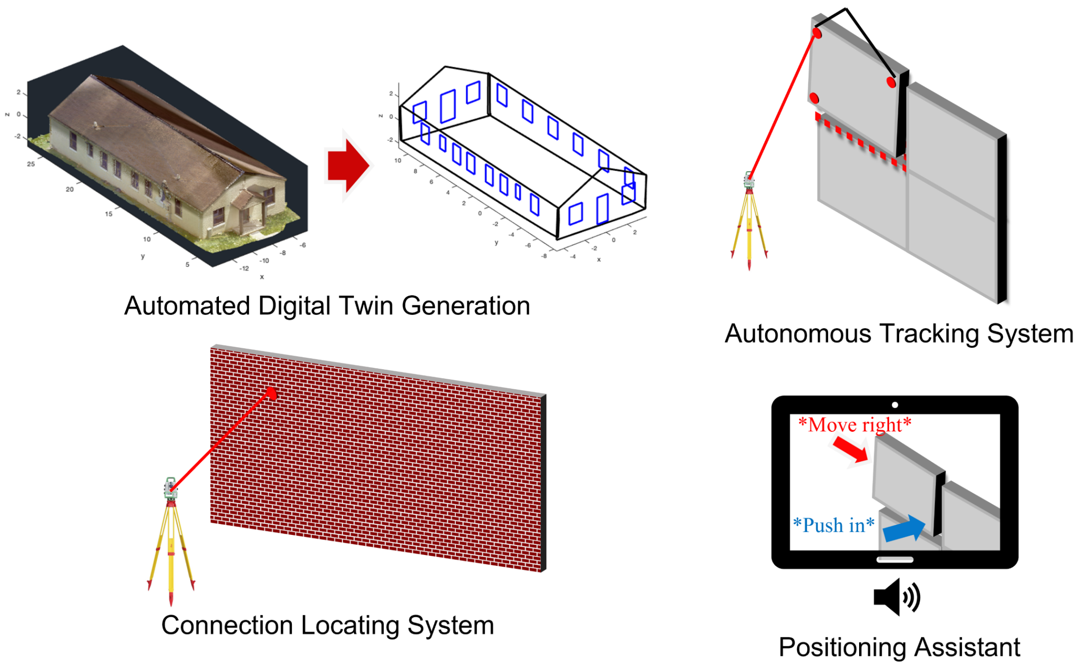

Figure 2. Components of the real-time evaluator.

of connections for prefabricated components. A robotic multi-station is controlled using communication protocols to measure the locations of reflectors attached to the physical connection hardware. The user installs connections to the supporting structure, either manually or with guiding assistance from the system. The physical location of

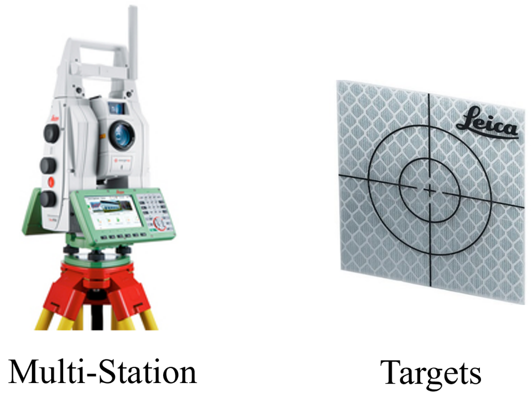

Figure 3. Hardware of the RTE connection locating system.

each connection is measured and stored during installation in the digital twin and compared to the design (goal) location of the connection. Real-time installation errors are calculated and reported to the user. The system will automatically raise flags when connections have an installation error beyond the user-specified tolerance. The user can access the reported errors to determine the corrective action required to correctly relocate the connection. The hardware, software, and processes to achieve these system features are further discussed.

2.3 Hardware and software

The hardware required by the RTE to perform connection locating functions is off-the-shelf and readily available. Additional hardware is required to perform the other functions of the RTE; however, because the focus of this paper is the connection locating system, only the hardware necessary for that system is detailed. Figure 3 shows the required hardware. A robotic multi-station is needed to track and measure the position of reflector targets. In this research, a Leica MS60 was used as the multi-station. Tape reflector targets are attached to the physical connection hardware. For each connection, the algorithms send commands to the MS60 to aim at the expected location of connection, search for the tape reflector, and measure the actual location of the reflector target attached to the connection hardware. In this research, a Leica reflector tape, GZM29, was used.

The software for the RTE was written in Python. Several modules are needed to handle the functions of the system. The communication methods of multi-stations vary by manufacturer. Leica multi-stations utilize an external communication protocol called GeoCom. GeoCom consists of sending and receiving string commands and feedback between the software and hardware. A communication module within the software handles the writing and receiving of string commands to the hardware. For example, the command `%R1Q,9027:Hz,V` requests the multi-station to turn to a position indicated by the horizontal angle, `Hz`, and vertical angle, `V`. Upon successful completion, the multi-station will respond with `%R1P,0,0:RC` indicating that the requested command was completed with no issues. All basic functions are performed as single request/response queries. A controller module handles the high-level functions of the instructions to the multi-station. For example, the task of measuring a tape reflector consists of a series of low-level functions including a turn to the reflector, a search for the reflector, a locking-in on the reflector, a measure of the reflector, and an output of the measured location to save for future reference. The controller module allows the user to access a single high-level function to perform a series of low-level functions for specific purposes. A calculator module performs geometry calculations such as determining horizontal and vertical angles of a specified point in 3D space, x, y, z, from the origin (location of multi-station). A digital twin module stores all of the design and actual locations of the building, control points, connections, and prefabricated components.

2.4 Implementation

To reduce installation time, the connection locating system removes the need for manual measurement of connection locations using hand tools. Two modes of operation have been developed for the connection locating system. The first mode of operation is guided installation. Guided installation utilizes the visible red laser of the multi-station along with the software implementation to point to the locations where connections should be installed based on the digital twin. The user then places each physical connector with a tape reflector aligned with the red laser as shown in Figure 4. After each connection is fastened, the user instructs the RTE to measure the actual position of the connection. The actual position is compared to the design location and an installation error is calculated. Upon comparison to a user-specified tolerance, the RTE will instruct the user in real-time if the connection has been incorrectly installed and, if so, how to correct the installation.

A second mode of operation assumes that connections have already been installed. The second mode of operation is evaluation. In this mode, the RTE will turn to the design location of each connection stored in the digital twin, radially search for the nearest reflector, measure the position of the reflector, and output the installation errors. The user will be notified of any errors beyond the spec-

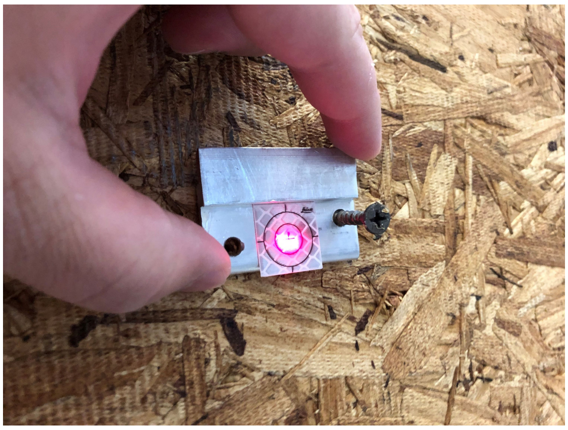

Figure 4. Guided installation of connection.

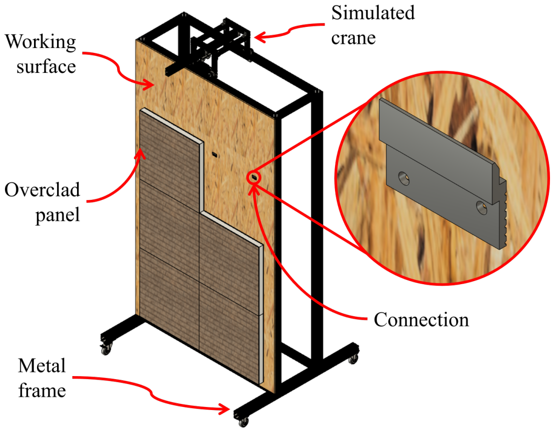

Figure 5. Digital twin of the lab demonstration.

ified tolerance and given corrective actions to rectify the problems.

The first mode of operation proposes to significantly reduce installation time by removing the need to use hand tools to measure the installation positions of connectors. Instead of using traditional hand tools such as tape measures, bubble levels, or laser levels, the RTE simply points a laser to the location where each connector should be installed. Removing the need for hand tools will also improve safety since these tools will no longer need to be carried up and down ladders. To verify that the connection locating system of the RTE reduces installation time, a lab-scale demonstration experiment was conducted.

3 Lab-scale demonstration

3.1 Lab-scale mockup installation

A lab-scale demonstration experiment was conducted within the Maximum Building Energy Efficiency Research Laboratory at Oak Ridge National Laboratory. A 1/3rd scale mockup of a three-story overclad panel retrofit was constructed. A digital twin of the mockup is illustrated in Figure 5. A metal frame (1.829 m wide by 3.124 m high) was constructed to simulate a three-story building at approximately 1/3rd scale. A working surface of an oriented strand board was attached to the metal frame to simulate the building facade upon which connections would be attached. Six simulated overclad panels and a simulated crane were manufactured; however, only the connections used to secure the panels to the working surface were used in this study. For each overclad panel, two connections near the top corners allow the panels to be erected onto the working surface. Each connector is a pair of metal brackets. One bracket is attached to the building facade working surface at the indicated position. The mating bracket is attached to the back side of the panel such that two sets allow the panel to hang. While these connections are not the same as traditional connection methods for overclad panels, the basic function is similar and the installation method is largely the same. The digital twin was exported to the RTE software so that the digital design location of each connection was stored. A total of 12 connections existed in the mockup.

3.2 Experiment

Two sets of experiments were conducted to quantify the possible installation time savings of the RTE connection locating system. The 1/3rd mockup building was set up approximately 8 meters away from the Leica MS60 as shown in Figure 6. The wheels of the mockup frame were locked to ensure that the frame was stationary during all tests. The MS60 was connected via Bluetooth connection to a personal laptop computer running the RTE software. Two experiments were conducted to determine the amount of time required to install the connections for the mockup overclad panel retrofit. A tape reflector was placed on each physical connector to be attached to the simulated building surface. Each connector was numbered according to the installation position to eliminate the variability of tape placement between experiments. For each experiment, the installation process was recorded to determine the time required for each step.

In the first experiment, the user installed the connections using manual methods. A drawing was generated from the digital twin indicating the exact design locations of all connections. Dimensions were generated for each connection on the working surface plane. Handheld tools, including a tape measure and bubble level, were used to mark connection installation points on the working surface. First, the elevation of two connection points was marked by measuring with a tape measure from the bottom of the working surface. From each of these marks, a level line of the elevation was marked using a bubble level. The exact po-

Figure 6. Setup of the connection locating system experiment.

sitions of connections were then marked along the level elevation line by measuring from the sides of the worked surface. The connections were installed at each marked location using a screwdriver to install the fasteners. Each connection required the installation of two fasteners. This process was repeated for each set of two connections. The highest set of four connections was only accessible using a ladder. The installation of connections was performed at a normal pace. After installing all connections, the MS60 was used to measure the exact positions of all connectors. Installation errors were calculated by comparing the actual position of connections to the design locations in the digital twin.

In the second experiment, the user installed the connections using the guided installation from the connection locating system of the RTE. The MS60 was instructed to activate the red visible laser and point to the design location for each connection, iteratively. The user installed the physical connector by aligning the red laser with the tape reflector and driving fasteners using a screwdriver. The user did not use any hand tools to measure the actual locations of connections. After installation of each connection, the user indicated completed installation from the laptop computer, and the RTE measured the actual installed location of the connector. The installation of connections was performed at a normal pace. Installation errors were calculated by comparing the actual position of connections to the design locations in the digital twin after each installation.

In both experiments, the same single user completed the installation processes. The manual process was completed first, and the guided installation process was completed second. Both experiments were completed in immediate succession. The second experiment, being entirely guided by the RTE, is unaffected by user affinity with the installation process. As a result, as the user gained knowledge and experience of the installation process, the time required to complete manual installation could be reduced while the guided installation would remain relatively unchanged.

Table 1. Installation times for 12 connections.

Method	Total Time (MM:SS)
Manual	13:51
Guided (RTE)	8:43

The total installation times for each method are shown in Table1. The manual method refers to the installation of connections using handheld tools. The guided method refers to the installation of connections using the connection locating system of the RTE. It is important to note that the time reported for the manual method includes only the installation process of the connections. The reported installation time for the manual method does not include the time required to manually measure the real positions of connection for the purpose of error calculations. However, for the reported time of the guided installation method, the time required to automatically measure the real position of each connection is included. The guided installation of the RTE connection locating system reduced installation time by nearly 37%. By removing the need for hand tools, the installation time savings are significant.

Installation errors for each connection according to the installation method are shown in Figure 2. For each method, installation error in each dimension is reported. For reference, the x-axis is left (-) and right (+) across the face of the working surface. The y-axis is towards (+) and away (-) from the face of the working surface. The z-axis is elevation. The installation error corresponds to the Euclidean distance calculated as $\|\text{error}\|_2$.

In general, the installation errors between manual methods and guided methods are very similar. The guided method did consistently reduce error slightly. In both cases, errors in the x-axis (left/right) and z-axis (up/down) were small in comparison to the y-axis (away/towards). Additionally, connections 9 through 12 were located at elevations that required the use of a ladder to install. For both installation methods, the largest errors were present in these connections at the highest elevation. For installation requiring a ladder, the quality of installation was lower.

Minimum, maximum, and mean installation errors for each method are shown in Table 3. Guided installation using the RTE connection locating system reduced errors although the degree of reduction in this case was negligible by most standards. For most cases, a peak accuracy of installation of 3 mm is needed due to the installation tolerances of components. However, for panel retrofits, a lower installation tolerance may be required since the panels serve as the new air and water barrier.

The maximum error is reduced by a significant pro-

Table 2. Installation error for each of the 12 connections.

Connection	Errors (mm)							
	Manual				Guided (RTE)			
	x	y	z	$\|\|error\|\|_2$	x	y	z	$\|\|error\|\|_2$
1	-0.21	0.93	-0.05	0.96	-0.10	0.43	-0.14	0.46
2	-0.07	0.50	0.05	0.50	0.04	0.61	0.22	0.65
3	0.06	1.13	-0.18	1.15	-0.15	0.85	-0.01	0.87
4	0.05	1.00	-0.12	1.01	0.16	0.80	0.00	0.82
5	-0.11	1.15	-0.01	1.16	-0.15	0.65	-0.11	0.68
6	0.07	1.22	-0.06	1.22	0.07	0.81	0.23	0.84
7	0.11	0.78	0.27	0.83	0.32	0.88	-0.03	0.94
8	0.13	1.07	0.24	1.11	0.13	0.88	-0.05	0.89
9	0.16	0.59	-0.17	0.63	0.32	0.27	0.01	0.42
10	-0.27	1.67	-0.92	1.92	-0.23	1.65	-0.80	1.85
11	-0.21	2.48	-0.12	2.50	0.39	1.42	0.05	1.48
12	0.17	1.32	-0.01	1.33	-0.04	1.12	0.07	1.13

Table 3. Installation errors of the 12 connections.

Method	Error (mm)			
	Min	Max	Mean	Std
Manual	0.50	2.50	1.19	0.0005
Guided (RTE)	0.42	1.85	0.92	0.0004

portion by the guided installation compared to manual methods. This reduction in maximum installation error could make the difference in an actual installation such that cumulative errors do not propagate into issues. Because installation errors are cumulative, individual errors as small as 1 mm can aggregate into several centimeters during the entire installation process of a large area multistory building. Therefore, it is still important to minimize installation errors to mitigate the risk of error propagation.

3.3 Limitations

Time savings of the guided installation of the RTE have been demonstrated in lab-scale experiments. However, time savings will vary widely between users, building types, and applications. To further investigate the time savings potential of the guided installation, multiple installers will be tested as part of the experiment to determine an average expected potential amongst all types of users. Additionally, as the size of the working surface increases, the difficulty and expertise required to perform manual installation also increases because handheld measurement tools become more complex and unwieldy. For this reason, it is expected that potential time savings will be larger for full-scale implementation.

The guided installation process requires that the multistation have a line of sight to the reflector targets. Users must be aware of blocking the line of sight between multistation and targets during the installation process. Avoiding this issue may be more difficult for multi-story buildings that require specialized equipment such as cherry pickers or manlifts.

4 Conclusions and next steps

A connection locating system for a Real-Time Evaluator (RTE) was developed to expedite and optimize the installation of connections for prefabricated components. The connection locating system uses off-the-shelf hardware and novel software to guide the installation of connections for prefabricated components. The connection locating system was tested in laboratory-scale experiments to determine the installation time-saving potential and accuracy improvements compared to manual installation using common hand tools. Results of the experiments conclude that the connection locating system can reduce connection installation time by 37% while maintaining better installation accuracy compared to manual installation.

In future work, the RTE will be tested to determine time-saving potential and accuracy improvements of overclad panel retrofit installation. Panel installation using the RTE will be tested at laboratory-scale and full-scale in a real overclad panel retrofit.

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