Automated tracking of prefabricated components for a real-time evaluator to optimize and automate installation

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Abstract -

Trade associations for prefabricated construction estimate that about 50% of prefabricated wall projects have alignment problems that lead to defects and rework. Additionally, component installation times average between 30 and 60 minutes per component. To address these issues, a real-time evaluator (RTE) system was introduced to decrease cost and automate prefabricated component installation by reducing the installation time, decreasing rework, and enhancing energy performance through higher installation quality. The RTE uses commonly available hardware and software to perform autonomous tracking to measure the real-time location and orientation of components as they are crane-lifted and installed. The hardware, software, and algorithms that allow the autonomous tracking of components are detailed. An algorithm to automate the initial search for a component with three attached retroreflectors is proposed. Algorithms to automate the measurement of component position and orientation are also proposed. Simple lab-scale proof-of-concept experiments were conducted to assess the algorithms for automation of component searching, measurement of real-time movement, and measurement of component orientation. With additional development, the system can be used as a tool to generate the commands for autonomous crane operation or single-task construction robots.

Keywords -

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

1 Introduction

Trade associations for prefabricated construction, such as the Precast/Prestressed Concrete Institute (PCI), estimate that about 50% of prefabricated wall projects for new construction have alignment problems that lead to defects and rework [1]. Additionally, for the precast concrete industry, typical component installation times average between 30 and 60 minutes per component with a significant amount of time spent performing small adjustments, plumbing, and leveling near the final installation point [1]. Misalignment issues are common when the final connections are made from the prefabricated components to the substructure, resulting in delays of hours or more to rectify the issue onsite. Additionally, for multi-story buildings, wall panel installers are working from the interior of the building and are often unable to see the exterior surface of the panel to easily manipulate components to align architectural features, when present. In some cases, the as-built substructure dimensional variations are beyond the construction tolerances of the design documents leading to fitment issues of wall panels as they are attached to the substructure. Other industries in prefabricated construction have similar issues which lead to cost overrun and delays. Despite these issues, installation techniques for prefabricated components at the job site have experienced minimal innovation.

Recent advances in surveying technology include laser-based technologies such as robotic total stations that expedite and improve the accuracy of building and land surveying, as well as 3D scanners that produce point cloud data for the development of 3D models. Unfortunately, as shown in Figure 1, these tools are primarily used in prefab construction for as-built surveys after prefabricated component installation. That is, they merely point out errors after installation that can require expensive corrections to maintain the continuity of the air and water barriers in the building envelope and to meet the expected aesthetics of the facade. A better alternative is to actively check the quality of construction during the installation of prefabricated components so that errors can be compensated in real-time.

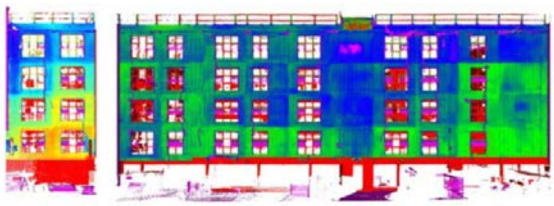

Figure 1. Measured normal point-plane distance of installed volumetric modules [2]. Maximum variation is approximately 3 cm.

The industrial construction industry needs a tool that uses as-built measurements from these laser-based devices to provide corrective guidance in real time to improve installation speed and quality, increase productivity, and decrease rework. Additionally, for automated crane applications or single-task construction robots to be applicable to a wide variety of construction sites, a feedback-in-the-loop position monitoring system is necessary to correctly position the crane payload or robot [3, 4, 5, 6, 7]. To address these issues, a real-time evaluator (RTE) system was developed to decrease cost and automate prefabricated component installation by reducing the installation time, decreasing rework and enhancing energy performance through higher installation quality. To assess the plausibility of the real-time evaluator system, initial research efforts focused on the development of an automated tracking system which could identify, monitor, and measure the position and orientation of components in real-time during installation. The selection of hardware and development of algorithms to automate the tracking system of the real-time evaluator is described in this work.

2 Methods and materials

For a real-time evaluator to be feasible, an autonomous tracking system needed to be designed and validated. An autonomous tracking system that measures the real-time locations of prefabricated components as they are being installed was designed using off-the-shelf hardware. An automated laser tracker and custom software monitor the location and orientation of each component during installation. The primary work of this paper will describe in further detail the algorithms, processes, and hardware of the autonomous tracking system.

The real-time evaluator is intended to be applicable to a wide variety of types of construction. The initial design focus was on prefabricated overclad panel retrofits which involve attaching insulated panels over the existing facade of residential or commercial buildings to improve the thermal performance. However, the system is agnostic to construction type and can be extended to monitor, optimize, and automate the installation of a variety of prefabricated components including prefabricated wall panels, prefabricated roof structures, prefabricated floor assemblies, volumetric modular units, and more. Additionally, the RTE workflows could allow the monitoring, optimization, and automation of installing individual structural members to create frames and load-resisting systems such as structural steel frames and prefabricated concrete frames.

2.1 Specifications and current installation methods

By engaging with stakeholders in the prefabricated construction industry, the research team was able to develop a list of minimum requirements or specifications that would enable the autonomous tracking system of the real-time evaluator to achieve impact in the industry. Partners in precast concrete construction and residential prefabrication were consulted to gauge the potential impact of the real-time evaluator and gather input that could improve the system. A list of basic specifications was drafted as minimum requirements of the RTE (Table 1).

Table 1. Specifications for the real-time evaluator

Requirement	Measure	Value
Position Measurement	Frequency	1 Hz
Position Measurement	Accuracy	3.175 mm
Orientation Measurement	Frequency	0.03 Hz
Orientation Measurement	Accuracy	30 "

The basic requirements requested from industry partners were specified measurement accuracy and speed. Because of the weight and size of most prefabricated components, the crane lifting and movement of these components are slow, especially when in close proximity to other components or the existing structure to which it will be attached. For these reasons, the required frequencies of positional and orientation measurements are not the primary concern, although any time savings in this process results in overall time savings during installation. In most cases, stakeholders were more concerned with measurement accuracy as compounding errors lead to issues that can create the most significant loss of time such as required on-site reworks or re-manufacturing of components.

For position measurements, industry partners recommended a measurement frequency of 1 Hz with positional accuracy of approximately 3 mm or less. Positional accuracy is important because joints between components are commonly 13 mm or smaller; therefore, a high degree of accuracy is necessary for positioning these components next to existing components or to meet installation tolerances of connections. If positional errors of more than 3 mm commonly exist for each installed component, this error can compound to create significant issues for adjoining components.

Stakeholders in the industry also recommended that the measurement of component orientation should be accurate to 30" (seconds of angle) of rotation and take at most 30 seconds in order to significantly impact the speed at which components could be installed. Stakeholders expressed that it is common for a component to remain in place very near to the final design location for 15 minutes or longer while it is precisely plumbed and leveled [1]. Erectors often measure plumbness and levelness by hand using plumb lines and levels which can take longer than a few minutes for each iteration. Components that are not plumb or level must be shimmed at joints or connections to correct orientation; then, the measurement process must be repeated until the installation tolerances are achieved.

Therefore, a high degree of orientation measurement accuracy is required, and an orientation measurement time of less than 30 seconds was deemed to most significantly reduce installation time.

2.2 Hardware and software

The real-time evaluator was designed to operate with a robotic total station. For the initial design and prototyping, a Leica Multi-Station 60 (MS60, shown in Figure 2) was selected to use as the base system on which to build the RTE. However, algorithms and software were designed in such a way that the RTE is hardware agnostic, only requiring communication between the software and robotic total station to be established. The survey-grade multi-station acts as a laser tracker to locate, measure, and track targets attached to components.

Modern multi-stations are capable of performing automated searching algorithms for a single retroreflector [8]; however, it is not possible for the multi-station to identify which retroreflector has been located when multiple prisms are present, especially when prisms are attached to movable objects. The novelty of this research includes the development of algorithms which can automate the process of searching, locating, and measuring three retroreflectors attached to a prefabricated component. By using predetermined information about the component and setup of retroreflectors, algorithms were developed to automate the workflow so that a modern multi-station could measure position and orientation of a prefabricated component with little to no human input required.

Multiple types of retroreflector systems and fixtures are used to enable the identification and laser tracking of connections and components. Three target reflectors must be placed on the prefabricated components during installation to track position and orientation. Leica 360° prisms (full size and miniature shown in Figure 2) were used in the design and prototyping of the RTE. These 360° retroreflectors, at any orientation, can be searched for and tracked by the multi-station.

These retroreflectors are intended to be reused and attached to components using a fixture capable of quick-release, rigid attachment. Fixtures, shown in Figure 2, were designed and prototyped for insulated panels. The first prototype is a simple mechanical clamp with an adjustable clamping distance. The second prototype is a clamp that is affixed to a smooth surface using the force of a generated vacuum. The accuracy of retroreflector distance measurements depends on the angle of the reflector in relation to multi-station location; optimal accuracy is achieved when laser-line is as close to perpendicular to the longitudinal axis of 360° prisms. The modular designs allow the 360° retroreflectors to be rigidly attached to wall panels at different orientations to accommodate a variety of station setup distances, locations, and building heights. When installing components near the top floors of a multi-story building, a prism with longitudinal axis angle near to horizontal can be used to accommodate a total station setup close to the building on ground (e.g. total station is looking nearly straight up). Additionally, 360° retroreflectors have been shown to generate small measurement error (in most cases less than 2 mm) when the prism is rotated around the longitudinal axis [9]; however, we expect that prisms will not be rotated more than 15° after attachment to components, and therefore, measured errors will be constant and within specifications of 3 mm.

Disposable tape reflectors (Figure 2) are another reflector option. Unfortunately, tape reflectors differ in function from retroreflectors and cannot be easily searched for or tracked by modern total stations; hence, traditional retroreflectors (prisms) are necessary for the operation of the RTE. However, tape reflectors can be used as control points placed on the existing building structure to orient the station setup in relative space (e.g. to tell where the multi-station is set up relative to the building) which will be required to compare the actual location of a component to the goal location. Future development of cheap, disposable retroreflectors, similar in applicability to tape reflectors, would increase the affordability of RTE.

For this research, the RTE software was written in Python and interfaces with the robotic total station using a Bluetooth connection and Leica GeoCOM commands. Alternatively with some additional development, the software can be installed and operated directly on the total station, However, since different types of laser scanners and trackers use varying communication styles, the responsibility falls to the user to make the connection between the RTE and hardware. For the initial design of the system, the software utilizes a graphical user interface on a personal computer to perform the RTE procedures and monitor component position.

2.3 Autonomous tracking system

The basic function of RTE is the active tracking of components during installation. Using a series of retroreflective prisms, the RTE can autonomously identify and locate each to calculate the component positions and orientations in six degrees of freedom: translation and rotation about each axis. Modern multi-stations can search for, lock on to, and measure prisms. Novel algorithms were created to integrate basic knowledge about the component to automate the location process of the first (isolated) prism. The algorithm then commands the multi-station to turn angles to find and measure the next prism on the component.

The RTE, knowing the dimensions of the prefabricated components, can cycle through prisms and determine coordinates of the component's location and orientation about

Figure 2. Hardware required by the real-time evaluator

primary axes. The frequency of autonomous tracking will depend on the communication settings and hardware capabilities. For the Leica MS60 used in this research, measurement frequency of single prism position was possible to 10 Hz. To calculate orientation, the hardware must turn to and measure the location of a minimum of three prisms. The speed of orientation measurement also depends on the hardware used and is most limited by the speed of motorized turning and searching of the total-station. For the Leica MS60 used in this research, a cycle time of approximately 15 seconds was achievable.

Several assumptions are made to enable simple calculation of component position and orientation:

1. The prefabricated component is a simple rectangular prism with a known width, height, and depth.
2. Reflector targets are rigidly fixed at a known distance from external corners of the component.
3. During initial prism search, the primary measurement face of the component is assumed to be oriented near to perpendicular to the view of the total-station.
4. During measurement of the component position, any motion is assumed to be rigid body translation.
5. During measurement of the component orientation, the component is assumed to be stationary.

Using these assumptions, an automated workflow was developed to calculate and monitor the position and orientation of a component. First, the component must be instrumented with retroreflectors (hereafter referred to as prisms). Three prisms must be rigidly attached to the component so that position and orientation can be calculated. The location of each prism in reference to component corners must be known to calculate the position of the perimeter of the exterior face of the component as shown in Figure 3. Each *prism_offset* is recorded assuming that the component is level and plumb. The layout type of prisms must also be pre-programmed so that the RTE can automate the process of identifying and locating the prisms attached to the component. Four distinct layout types are possible for a set of three reflectors attached to corners of a rectangular prism (i.e. top two corners and bottom left corner, bottom two corners and top right corner, etc.). Each layout produces an isolated reflector that is either on the right or left side of the component. This isolated reflector is what allows the RTE algorithms to be fully automated since it can be uniquely identified by a directional search. Using this layout, RTE can determine from which direction (left or right) the isolated prism can be identified.

The general algorithm to initially find and measure prisms on a component is shown in Algorithm 1. The first, isolated reflector is identified on the stationary component using an automated search procedure. The RTE commands the multi-station to scan either left-to-right or right-to-left depending on the isolated prism location using existing search functions. Horizontal and vertical turn angles are calculated from the positions of measured prisms and known component geometry. RTE commands the multi-station to turn each angle based on the layout of reflectors. After each robotic turn of the multi-station, a spiral search pattern is conducted to locate the prism and acquire a lock before measuring. The entire process takes approximately 30 seconds using the Leica MS60. With the known location of three reflectors attached to the component, the RTE calculates the position and orientation of the component.

After measurement of the three prisms, the RTE automatically enters tracking mode to monitor the real-time position of the component (Algorithm 2. The last prism measured in *find_prisms* will be locked-on and continuous measurements will be collected to determine the rigid body translation of the component. At each measurement cycle, a displacement vector is calculated between two subsequently measured points. This displacement vector is added to the positions of all prisms to determine the new estimated positions of prisms. The frequency of measurement will depend on the multi-station; with the Leica MS60, consistent measurement frequency of up to 10 Hz was possible. During movement, rotations about the X and Y axes of the component (shown in Figure 3) should be small due to the rotational limitations of most rigging configurations for cranes. However, larger rotations about the

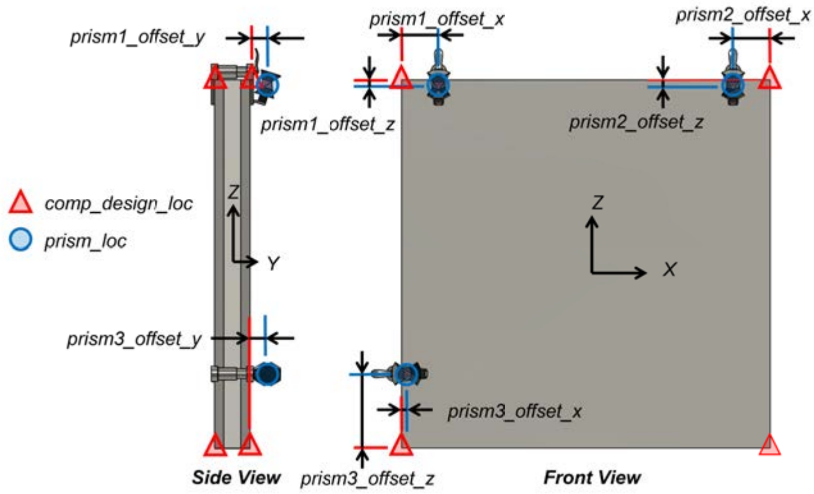

Figure 3. Parameters used to determine the location of components from measured prism locations

Z axis can occur; despite this, the RTE assumes that any movement during active tracking is rigid body translation. As such, the recorded prism locations are simply approximations until another measurement cycle of all prisms is conducted.

After movement, a *cycle_prisms* command (Algorithm 3) can be given to the RTE to measure the real locations of all prisms and determine component positions and orientation. This algorithm is intended to be used when the component is near its design location and only minor adjustments are needed to position, orient, and finalize the placement. Because the *track_position* function assumes rigid body translation of the component, it is possible that prisms are not at exactly their expected locations. Therefore, after each turn, a search is commenced to locate the prism before measurement. This search process allows the RTE to account for minor degrees of rotation of the component about the Z-axis (less than 45°). After returning the three prism locations, the orientation of the component (defined by the Euler angles) can be calculated. The goal of placement is commonly for orientation to be plumb and level; however, RTE can also allow for other solution states defined by the user.

3 Lab-scale demonstration and experiments

Because the autonomous tracking system enables the remainder of the RTE, initial research efforts focused on developing and demonstrating this system. After creation of the algorithms/software and acquisition of hardware, the system configuration was tested using a setup that included a mock-up prefabricated wall panel instrumented with prisms. Both real-time tracking and orientation measurements were achieved in the mock-up, lab-scale test shown in Figure 4.

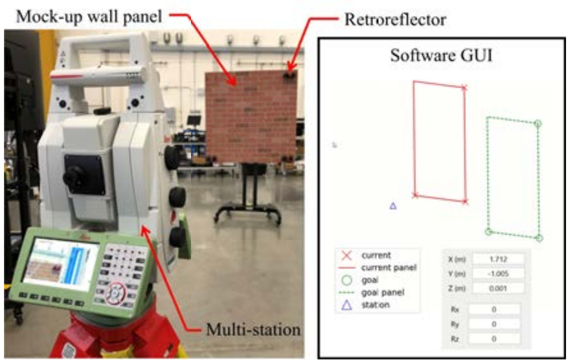

Figure 4. Mock-up lab-scale test of the RTE

A multi-station was set up in a laboratory environment along with a mock-up prefabricated panel on a frame with wheels. Prisms were attached to the mock-up panel at three corners. The RTE software was installed on a personal computer and connected to the multi-station using Bluetooth. The graphical user interface (GUI) was used to control the RTE and track the movement of the panel in real time. The GUI was also set up to simulate the installation of the panel by specifying a design, goal panel location in space, and required movement was given to the installer to move the panel to this goal location.

3.1 Experiments

A series of experiments was performed to determine the performance, repeatability, and limitations of the automated tracking algorithms of the RTE. It is important to note that observed values are dependent on the hardware used and software configurations. The use of different

Algorithm 1: $find\_prisms$: automated initial search and measurement of all prisms attached to component

Data:
Layout of prisms: *prism_layout*
Offsets of prisms: *prism_offset*
Dimensions: *comp_width*, *comp_height*
Result:
Position of prisms: $prism1$, $prism2$, $prism3$

$hz \longleftarrow$ angle from Y-axis (bearing)
$v \longleftarrow$ angle from Z-axis (vertical)

// Find first prism
from $prism\_layout$ determine $approach\_direction$
search($approach\_direction$)
$prism1$ = measure()
set_orientation()

// Find second prism, using a horizontal turn
$prism2.x = prism1.x - prism1\_offset.x + comp\_width + prism2\_offset.x$
hz = atan2($prism2.x/prism1.y$)
if $hz < 0$ **then**
    $hz = 2\pi + hz$
end
turn_to_angle(hz)
search()
$prism2$ = measure()

// Find third prism, using vertical turn
$prism3.z = prism2.z - prism2\_offset.z + comp\_height + prism3\_offset.z$
v = atan2($prism2.y/prism3.z$)
if $v < 0$ **then**
    $v = 2\pi + v$
end
turn_to_angle(v)
search()
$prism3$ = measure()

lock(on)

return $prism1$, $prism2$, $prism3$

models of multi-stations or total-stations will result in different results.

3.1.1 Performance and repeatability

The performance and repeatability of Algorithms 1, 3, and 2 were investigated under standard laboratory conditions. The RTE was commanded to perform each algorithm for a number of iterations. For each iteration, the total time elapsed between start and end of the algorithm was recorded. The same *prism_layout* and *prism_offset* were used for all iterations. The parameters, *comp_width*: 0.7 m and *comp_height*: 0.6 m, were accurately measured manually using the multi-station and used as input for the algorithm. The mock panel was positioned at a distance of 4 m away from the multi-station and was kept stationary for all iterations. First, the RTE was commanded to perform Algorithm 1 a total of 10 times. The time trial results are shown in Table 2. On average, the algorithm was able to meet the required specification of 30 seconds identification time. There were no failed iterations of performance of Algorithm 1 for this setup within the 10 iterations.

Algorithm 2: $track\_position$: automated tracking of position of moving component

Data:
Position of prisms: $prism1$, $prism2$, $prism3$
$V \longleftarrow$ displacement vector of moving prism

// Initialization:
$TargetPrism = prism3$
$TargetPrism0$ = measure()

while *toggle* = *moving* **do**
    $TargetPrism1$ = measure()
    $V = TargetPrism1 - TargetPrism0$
    $prism1 = prism1 + V$
    $prism2 = prism2 + V$
    $prism3 = prism3 + V$
    $TargetPrism0 = TargetPrism1$
    wait X milliseconds
end

return $prism1$, $prism2$, $prism3$

Second, the achievable frequency of Algorithm 2 was experimentally investigated for the software and hardware reported in this study. A similar setup to the previous time trial was used. The mock panel was positioned at a distance of 4 m away from the multi-station and was kept stationary. Algorithm 2 was set to a wait time of 0 milliseconds and allowed to repeat in-loop at maximum speed for 100 repetitions. The amount of time spent within each loop was recorded. Results are shown in Table 3. On average, the algorithm running on specified hardware and software was able to achieve an average tracking measurement frequency of approximately 18 Hz, with maximum frequency of 32 Hz and minimum frequency of 10 Hz for the experiment. However, tracking of crane-installed prefabricated components that are moving slowly will not require high measurement frequency; therefore, it will likely be beneficial to reduce measurement frequency to reduce software and hardware resource requirement.

Next, the RTE was commanded to perform Algorithm 3 a total of 20 times. A similar setup to the previous time trials was used. The mock panel was positioned at a distance of 4 m away from the multi-station and was kept stationary. The time trial results are shown in Table 4. On average, the algorithm completed in nearly half the specified time requirement of 30 seconds cycle time. There were no failed iterations of performance of Algorithm 3 for this setup within the 20 iterations.

To investigate the sensitivity of input data on the repeata-

Algorithm 3: *cycle_prisms*: automated cycling through prisms to measure component position and orientation

Data:
Position of prisms: $prism1$, $prism2$, $prism3$

$hz \longleftarrow$ angle from Y-axis (bearing)
$v \longleftarrow$ angle from Z-axis (vertical)

// At end of tracking, locked-on to prism3:
$prism3$ = measure()
lock(off)

// Turn to estimated position of next prism
hz = atan2$(prism2.x/prism2.y)$
if $hz < 0$ **then**
| $hz = 2\pi + hz$
end
v = atan2$(prism2.y/prism2.z)$
if $v < 0$ **then**
| $v = 2\pi + v$
end
turn_to_angle(hz, v)
search()
$prism2$ = measure()

// Turn to estimated position of last prism
hz = atan2$(prism3.x/prism3.y)$
if $hz < 0$ **then**
| $hz = 2\pi + hz$
end
v = atan2$(prism3.y/prism3.z)$
if $v < 0$ **then**
| $v = 2\pi + v$
end
turn_to_angle(hz, v)
search()
$prism1$ = measure()
lock(on)

// Reverse prism order for next cycle
order = flip(order)

return $prism1$, $prism2$, $prism3$

Table 2. Performance of Algorithm 1: 10 iterations

Parameter	Completion Time (seconds)
Average	26.95
Minimum	26.48
Maximum	27.57
Standard Deviation	0.43

Table 3. Performance of Algorithm 2: 100 iterations

Parameter	Completion Time (milliseconds)
Average	54.4
Minimum	30.7
Maximum	98.9
Standard Deviation	13.6

bility of Algorithm 3, another experiment was performed. A setup similar to the previous time trials was used; the

Table 4. Performance of Algorithm 3: 20 iterations

Parameter	Completion Time (seconds)
Average	13.68
Minimum	13.40
Maximum	14.11
Standard Deviation	0.24

mock panel with prisms was positioned at a distance of 4 m away from the multi-station and was kept stationary. In this experiment, Algorithm 1 was first performed to accurately measure the positions of the three prisms attached to the component. A percent error was applied to the measured width and height of the component, and Algorithm 3 was performed with the error-included *comp_width* and *comp_height*. The completion time of each cycle was recorded. Table 5 shows the setup of the experiment and reported completion times for each iteration. With increasing error up to 30%, the algorithm took longer to complete because more time was spent searching for the prisms. Error beyond 30% caused the algorithm to fail because the prism fell outside of the search radius for the given settings. However, error beyond 5% for the specified component dimensions is unlikely because prefabricated components are often manufactured to dimensional tolerances of millimeters.

Table 5. Sensitivity analysis of Algorithm 3 with errors in component dimensions

Iteration No.	Input Error (%)	Input Width (m)	Input Height (m)	Completion Time (seconds)
1	-30	49.1	39.1	19.19
2	-20	56.1	44.7	18.62
3	-10	63.1	50.2	16.48
4	-5	66.6	53.0	13.58
5	-1	69.4	55.3	13.50
6	**0**	**70.1**	**55.8**	**13.08**
7	1	70.8	56.4	13.40
8	5	73.6	58.6	14.51
9	10	77.2	61.4	17.35
10	20	84.2	67.0	18.73
11	30	91.2	72.6	19.92

3.1.2 Limitations

The limitations of the hardware and algorithms were investigated using simple tests. First, the maximum usable range of the hardware and algorithms were determined. The total-station with RTE software was setup at a great distance away from a full-scale mock-up of a building retrofit. Two prisms were placed at approximately 10 meters apart, and the hardware was instructed to perform a portion of Algorithm 1, which only included the successful identification of the isolated prism on the left from searching. Upon successful completion of the algorithm, the total-station was moved further away from the prisms in increments of approximately 10 meters until the algorithm could not successfully identify the correct prism. Distance between prisms was kept constant during the process. Algorithm 1 failed to complete at a maximum distance of approximately 300 meters. The search function was not able to find the prism at this distance, which aligns with the manufacturers specified maximum prism search distance of 300 meters.

To further expand on the limitations of the algorithm, an experiment was designed to determine the minimum component width that could be tracked at maximum distance. Two prisms were spaced apart at increments of set distance approximately 300 meters away from the total-station. The prisms were progressively moved closer together in increments of approximately 0.5 meters until Algorithm 1 failed to complete. The minimum track-able component width was approximately 2.5 meters at a distance of 300 meters. When two adjacent prisms were spaced at this distance, the algorithm would routinely identify the incorrect prism (i.e. when searching from left-to-right, the search would lock onto the right prism instead of the left prism). This limitation is hypothesized to occur because of the search angle of the hardware. Based on equivalent angles, this minimum component width would translate to 0.84 meter minimum component width at a distance of 100 m which would accommodate most prefabricated elements.

4 Conclusions and next steps

A real-time evaluator (RTE) tool was developed to optimize and automate the process of installing prefabricated components. By actively monitoring the real-time position and orientations of components as they are crane-lifted into position, the real-time evaluator can improve installation speed and quality, increase productivity, and decrease rework. The hardware, software, and algorithms that allow the autonomous tracking of components were detailed. The autonomous tracking algorithms and software can be used as an installation tool to expedite prefabricated construction, reduce errors of installation, and enable complete automation of crane installation.

Future research expanding the RTE is planned in the following areas: 1) development and testing of a connection positioning system, 2) development and testing of an installation assistant system, 3) lab-scale testing of multiple prefabricated elements on a mock-up wall, 4) full-scale testing of a retrofit project utilizing prefabricated overclad wall panels.

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