Integration of a real-time orientation measurement system for a real-time evaluator (RTE) to measure the position and orientation of crane-lifted components

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Abstract -

Prefabrication of building components holds the potential to revolutionize the construction industry. Prefabrication consists of manufacturing building components, modules, and other elements in a factory to be shipped and installed on a construction site. Prefabricated components have been produced for various applications including precast concrete panels for new construction and exterior wall retrofits. The manufacturing process has seen much innovation in recent years; however, the installation process has seen minimal advancements. 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 RTE uses off-the-shelf hardware and novel algorithms to assist erectors with 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 the proposed workflow is presented. Previous on-site demonstrations provided valuable feedback from users on the potential areas for improvement of the system. One common request was real-time measurement of component orientation during lifting, a process that previously required that the component remain stationary while the laser tracker cycled through target prisms. This paper will present the incorporation and testing of a real-time orientation measurement system as it was implemented into the RTE, allowing for measurement of component orientation during movement.

Keywords -

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

1 Introduction

Prefabrication of building components holds the potential to revolutionize the construction industry [1]. Prefabrication consists of manufacturing building components, modules, and other elements in a factory to be shipped and installed on a construction site [2]. Manufacturers can maximize production efficiency and better control quality by constructing elements within a controlled environment [3].

Modern surveying instruments, such as robotic total stations, expedite, automate, and improve the accuracy of building and land surveying. Modern instruments also include reality capture devices such as 3D laser scanners that can accurately measure the surrounding area. However, these devices are more commonly used to survey the as-built conditions after construction is completed. Recent research has developed algorithms to automatically generate as-built 3D models using laser scanning [4, 5, 6]. Methods like these are often utilized immediately after the components are placed and construction is completed. A more proactive use of the technology would be the active monitoring of the quality of construction compared to the design as it is assembled. By addressing errors as they occur in the construction process, the total construction time and cost can be reduced.

An installation tool that provides corrective guidance in real-time to reduce installation time, decrease rework, and reduce cost would revolutionize the construction industry. In other industries such as manufacturing, laser trackers are used to precisely assess and guide the assembly process. For example, in the aviation industry, three laser trackers measuring targets attached to a plane wing have been used to generate real-time guidance during attachment of the wing to the aircraft body [7]. Other machine vision techniques are used during the robotic assembly of cars [8]. Adaptation of these methods in construction applications could enable real-time evaluation of components during placement, providing guidance for users such that errors are addressed in a timely fashion.

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 [9]. 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 prefabricated 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. Previous on-site demonstrations provided valuable feedback from users on the potential areas for improvement of the system. One common request was real-time measurement of component orientation during lifting, a process that previously required that the component remain stationary while the laser tracker cycled through target prisms [10].

This paper will present the incorporation and testing of a real-time orientation measurement system as it was implemented into the RTE, allowing for measurement of component orientation during movement. The paper makes the following primary contributions to the body of knowledge:

- Laboratory experiments show that some off-the-shelf inertial measurement units (IMU) have a high-enough degree of orientation measurement accuracy to provide real-time orientation estimates to guide the crane-positioning of large-scale building components while still meeting typical tolerances. A laser tracker system is still required to meet positional accuracy requirements.
- Comparisons of measured changes in orientation of some off-the-shelf IMUs with advanced laser 6-degree-of-freedom measurement systems show good agreement even during highly dynamic movements.
- Laboratory experiments proved that a system integrating a laser tracker measuring a retroreflector prism position and an IMU measuring orientation can successfully track the position and pose of a rigid-body during typical construction crane-installation processes with an accuracy meeting the typical requirements for tolerances.

1.1 Related Work

This work aims to supplement the prior research work that only utilized a single laser tracker to (1) track a single target during movement with all motion assumed to be rigid body translation and (2) measure three retroreflector targets while stationary within a total time of 10 seconds to determine pose [10]. This paper presents an integrated system that uses (1) a laser tracker to measure the real-time position of a component based on the measured location of a retroreflector prism and (2) an inertial measurement unit (IMU) to measure real-time orientation of the component. The addition of the IMU enables real-time estimation of the pose of the measured component without having to stop motion and wait for approximately 10 seconds.

Prior literature review of work on crane lifting operations has determined that little research is conducted to track the position and orientation of the lifted object specifically for high-precision installation purposes [11]. Prior work has utilized Radio Frequency Identification (RFID), Global Positioning System (GPS), laser scanning, sensors, photogrammetry, and more to estimate the location and orientation of a crane payload. Most applications were for the purposes of path planning, blind lifting, and safety.

For example, previous work utilized GPS and RFID to monitor the position of the crane for safety purposes [12]. However, these systems were not accurate enough for the typical tolerances required for precise installation. Other work consisted of using vision-based systems to determine the 3D position and pose of a component from images [13]. However, the accuracy of the vision-based system depends on the distance per pixel which is affected by camera specifications and distance to target. For large construction applications, sight distances will likely be large (more than 10 meters), and therefore, the accuracy of the vision-based system to determine precise position and pose of the component during lifting may not be adequate without significant investment of multiple camera systems.

For RTE, the system uses an off-the-shelf robotic laser tracker, which many construction companies performing large-scale crane installation of components already have access to. The use of a laser tracker also ensures that positional accuracy of the component location can be measured within 3 mm which is the smallest typical tolerance for the installed position of a component. The addition of the IMU enables real-time estimates of component orientation during movement; however, it is not intended to completely replace the highly-accurate method of measuring component orientation through measurement of three retroreflector targets attached to the component determining pose of the rigid body.

2 Methodology

2.1 System Overview

The existing RTE system utilizes a robotic multi-station controlled by novel software including communication protocols to measure the locations of three reflectors attached at known distances from the corners of the object to be measured. To measure the orientation of the object, the laser tracker sequentially cycles between the three prisms, measuring their positions in 3D space. The time to cycle between all prisms takes roughly 10 seconds. This positional data is then used to establish a frame of reference, allowing for the calculation of the panel's position and orientation [10]. The measured orientation is compared to the target rotation matrix, which is derived from the digital twin model of the expected construction configuration. This difference determines the necessary translations and rotations required for the panel to align with its goal pose.

Figure 1. A real-time evaluator to expedite prefabricated component installation. It provides real-time guidance on installing prefabricated components. [9]

In the current setup for initialization, it is assumed that the panel remains stationary during the orientation measurement cycle, which takes approximately 10 seconds to complete because the total station must turn to, search for, and measure each of the three prisms. This first cycle provides the real-time position and orientation at that time frame. Once the first cycle is completed, the tracker locks on to one of the isolated prisms and updates the real-time translation values from the centroid of the panel assuming all movement is rigid body translation. While this system is highly accurate, it has a significant limitation: it can only update the panel's translation in real time when the panel is moving in 3D space. To calculate the rotation, the panel must be held stationary, and the laser tracker must complete a full cycle through the three prisms again, causing latency. This results in a slower update rate for rotation data and presents a bottleneck in dynamic scenarios where faster orientation updates are necessary. Because of this limitation in measurement speed, all motion is assumed to be rigid body translation while the panel is moving. Additionally, the assumption that the panel remains stationary during cycling through prisms is critical. In reality, if any movement occurs during measurement of the three targets, the calculated component orientation will not be accurate. To address these limitations, there is a need to integrate an Inertial Measurement Unit (IMU) into the system, which can provide approximate orientation estimates in real-time during the panel movement, improving the overall responsiveness of the system.

2.2 Proposed System

2.2.1 IMU Integration

In the proposed system, the IMU is integrated as a complementary sensor to address the limitation of the existing methodology, which requires the object to remain stationary for orientation calculation. The IMU provides approximate orientation updates while the object is in motion, significantly enhancing the system's responsiveness. Our system has two separate coordinate frames (described as RTE and IMU). In order to integrate the IMU's rotation matrix which is determined about its local body frame to the RTE, it is first aligned with the panel to establish the necessary transformation tree (identity matrix in our case). This alignment allows both systems to compute the rotation of the panel with respect to the system RTE frame. The goal pose for the panel is derived from the digital twin model. Once the complete transformation tree is established, the IMU is initialized in the RTE frame using orientation data obtained from the laser tracker and prisms. The algorithm calculates the panel's orientation and reports the difference between its current pose and the goal pose (from the digital twin). This initialization step ensures the IMU's measurements are accurately calibrated and aligned with the reference frame of the system.

The IMU's orientation estimates are fused with the laser tracker's translation data to create a hybrid system. While the panel is in motion, the laser tracker system provides real-time translation measurements but cannot update rotation data due to its reliance on target cycling while the component is stationary. The IMU addresses this gap by providing real-time approximate orientation updates, which are less precise but sufficiently accurate to ensure continuous monitoring of the panel's orientation. The laser tracker, on the other hand, provides precise but intermittent orientation updates when the panel is static. By synchronizing and fusing data from these two sensors, the system benefits from the high accuracy of the laser tracker for precise orientation correction and the IMU's ability to offer continuous updates during motion. This hybrid approach ensures both precision and responsiveness, enabling dynamic tracking and adjustment of the panel's pose in real-time scenarios. In order to fuse the readings from both devices, it has to be calculated on the same reference frame. IMU and RTE's measurements are synchronized using the following transformation tree:

R_{imu} = rotation_imu
$R_{\text{imu\_panel}} = I$
$R_{\text{RTE\_m}} = R_{\text{mat\_RTE}}$
$R_{\text{goal\_m}} = I$
$R_{\text{final\_imu\_m}} = R_{\text{imu}} @ R_{\text{imu\_panel}} @ R_{\text{RTE\_m}} @ R_{\text{goal\_m}}$

2.2.2 Communication System Enhancements

In the previous system, RTE used Bluetooth to communicate between a laptop computer running the software and the MultiStation. However, due to range limitations and constraints of concurrent active connections with Bluetooth, it was decided to switch to a Wireless Local Area Network (WLAN). The switch to WLAN enables seamless, fast, long range communication. Attempts to fuse data collected from the Multistation and IMU simultaneously via Bluetooth encountered communication issues. The switch to WLAN connection facilitates the synchronization and fusion of time-stamped sensor data from both systems thereby enhancing the overall performance of the system for field trials at actual construction sites where the range of Bluetooth could have been a limiting factor.

2.3 Lab Scale Experiments

For sensor selection, tests were conducted to compare the performance of multiple IMUs against the output of a Leica Absolute Tracker AT960 paired with T-probe. However, only the performance of the selected IMU is reported in this paper. The AT960 paired with a T-probe gives highly precise measurements of change in orientation (±15 microns) and translation of any object to which the T-probe is rigidly attached. For a final integration test, the performance of the IMU was evaluated using the Leica Nova MS60 Multi-Station in a lab-scale mockup panel installation setup. The algorithms were written in Python and interfaced with IMU and the robotic total station through WLAN connection automated using Leica GeoCOM commands. The following sections describe the scenarios in which the IMU was tested.

2.3.1 Experimental Setup - Sensor selection

The experimental system consists of a laser tracker and an IMU sensor (x-IMU3) integrated to achieve faster orientation estimation within the semi-loop cycle. The laser tracker is used for precise 3D position and orientation measurements by cycling between three trackable targets. While this method ensures high accuracy, it suffers from an average latency of 10 seconds per update, necessitating the integration of the IMU for quicker approximate orientation estimates.

Table 1. Static accuracy RMS error for a 360° rotation around each axis from the datasheet

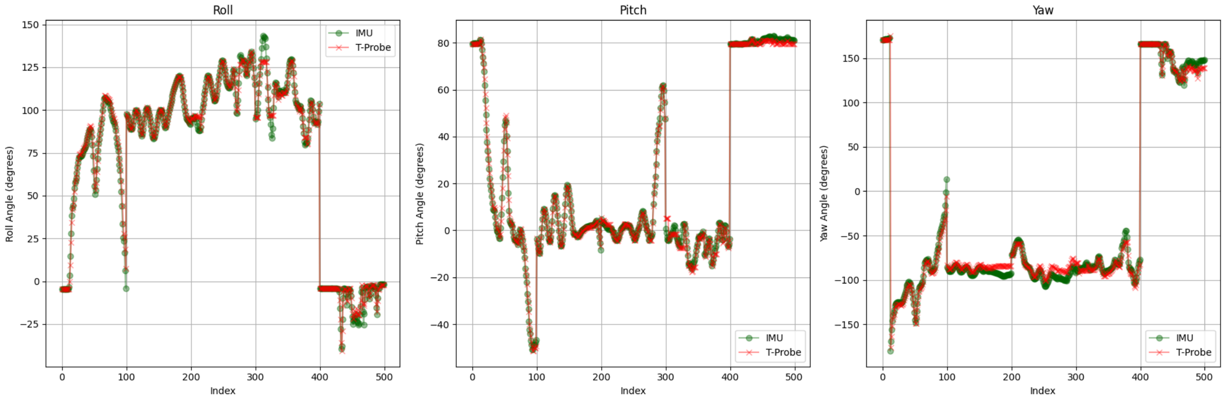
Characteristic	Static Accuracy
Inclination	0.5° RMS
Heading	1° RMS

Table 2. Dynamic error metrics for Roll, Pitch, and Yaw from our lab scale test

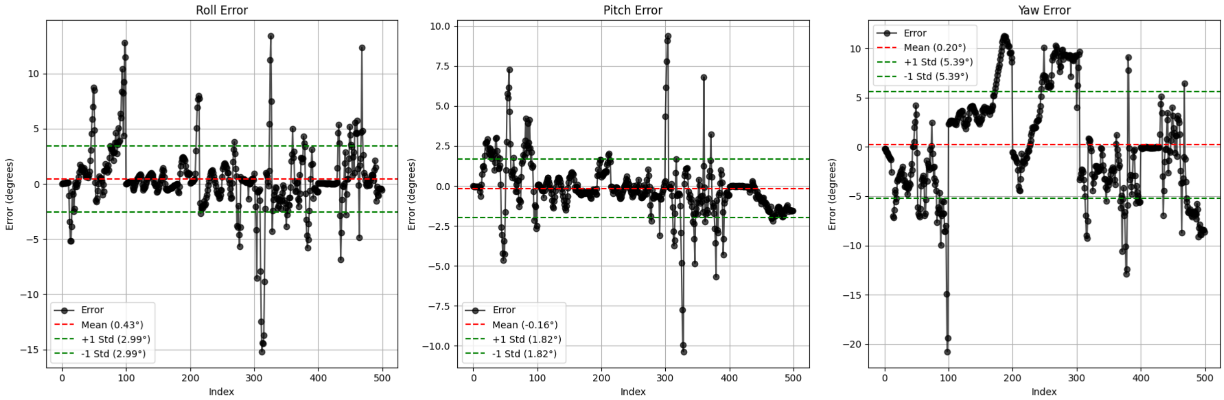
Metric	Roll (°)	Pitch (°)	Yaw (°)
Mean Error	0.43	-0.16	0.20
Standard Deviation	2.99	1.82	5.39

The IMU sensor was chosen based on the following criteria:

- **Accuracy and drift testing:** The IMU demonstrated high static accuracy as seen in Table 1, ensuring reliable orientation measurements during stationary or near-stationary conditions. To evaluate the dynamic accuracy, the IMU was mounted on T-probe and tracked using Leica's Absolute Tracker AT960, a 6DoF laser tracker technology. Data from AT960 and IMU were timestamped and synchronized. A comparison lab scale test between the AT960 and IMU was conducted over a duration of 5 minutes and repeated 3 times. From the results of this test, we concluded that the IMU is reliable enough to provide approximate orientation in highly dynamic scenarios. As shown in Figure 2b the maximum error was observed on the yaw axis, with a standard deviation of



(a) Ground truth vs IMU Data



(b) Error, mean and Standard Deviation

Figure 2. Dynamic accuracy tested using AT960 Laser Tracker as ground truth

5.39. Given that the IMU can provide data at a frequency of 10 Hz or better, it is not expected that the high standard deviation will be an issue since the result will simply be averaged over time. Additionally, the dynamic movements during the test were executed at a significantly higher severity than expected during crane lifting of prefabricated construction elements.

- **Dynamic testing (translation only):** In a translation only dynamic test, the IMU was mounted on a gantry robot system and translated in a square path with zero rotation. The highest average drift was observed in the yaw axis, with an average drift of 2.3 degrees over a period of 10 minutes. For crane-lifted installation of prefabricated components, a drift in yaw axis rotation of over 2.3 degrees in 10 minutes is not insignificant. However, the IMU can be recalibrated to eliminate drift each time the orientation is measured using the object-stationary target-cycling method.

- **Low latent wireless communication and software support:** The x-IMU3 sensor's customizable wireless data stream and its compatibility with Python API simplified its integration into the existing system, allowing seamless data acquisition and processing in rotation matrices, and other formats. Initial tests revealed magnetic drift near ferrous metals, which affected the accuracy of the IMU's rotation values. This issue was subsequently resolved by disabling the magnetometer readings.

2.3.2 IMU integration with RTE:

From the validation tests, we finalized x-imu3 as our choice of sensor for semi-loop integrated real-time orientation approximation. These tests were conducted using a lab-scale setup constructed for previous testing of the RTE system [9]. Figure 3 shows a representation of the lab-scale setup that depicts a 1/3rd scale overclad panel retrofit. Six panels can be assembled on a metal frame that supports a layer of oriented strand board, which serves as a working surface. Twelve connections can be attached to the working surface to serve as hanging points for the six panels. A simulated crane is located on top of the metal frame and can be operated behind the frame to move panels up and down and left and right. While panels are moved with the crane, a set of three retroreflector prisms is attached to the panel. A multi-station is set up at least 5 meters away from the test frame to measure prisms. For the purpose of these experiments, the IMU is rigidly attached directly to the panel to be measured.

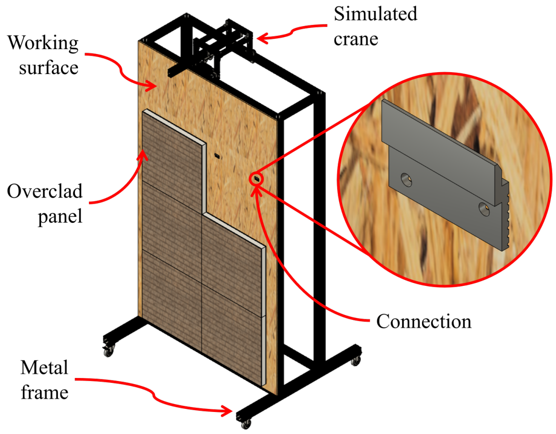


Figure 3. Representation of the lab experiment setup [9]

For the final integration of the IMU into the semi-loop system, a total of five tests were conducted following this procedure:

1. To simplify the test procedure, the panel is attached to a mock crane setup and the experiment begins with the panel located in the goal pose (i.e. the location where the panel should be installed).

2. The coordinates of the three prisms are measured using the multi-station. These measurements provide the position and orientation of the panel required to reach the goal pose based on the digital twin. This initial cycle takes 10 seconds on average.

3. The IMU, which reports orientation in the global frame, is initialized using the previous measurements from the RTE. A coordinate transformation tree is established to align the IMU and RTE's data with the digital twin's reference frame.

4. After initialization, the panel is moved away from its initial pose and RTE tracks a single prism, providing real-time translation updates, while the IMU delivers approximate orientation updates needed to achieve the goal pose.

5. After movement, the panel is brought to a stationary state, and the RTE algorithm commands the multi-station to cycle and measure the coordinates of the three prisms.

6. Upon completing the cycle, the RTE calculates and reports the precise rotation and translation needed to reach the goal pose. Simultaneously, the IMU's readings are timestamped and recorded and the offset value is observed.

The accuracy of the algorithm was evaluated by the difference between the rotation angles calculated from the IMU and those calculated from the RTE algorithm. The measured error in rotation angle was determined by subtracting the angle measured by the RTE in Step 2 from the angle measured by IMU in Step 6. Table 3 below summarizes the resulting Euler Angles observed from our tests, comparing the IMU's performance against precise measurements from the RTE system.

2.4 Results

The results of the experiments highlight the differences between the systems with and without IMU integration. The IMU integration significantly enhances the system's capability by eliminating the need for precise measurements from the RTE mid-cycle while the panel was in motion. Previously, the system did not provide orientation updates when the panel was in dynamic movement, as it required the panel to remain stationary to provide orientation updates. With the IMU integrated, real-time orientation updates became possible even when the panel was in motion, providing a significant improvement in responsiveness.

While the IMU does not reduce the cycle time for precise measurements conducted by the RTE, it complements the system by enabling approximate dynamic orientation updates during motion. This capability ensures that orientation data is continuously available, improving the system's utility in dynamic scenarios. The trade-off between accuracy and speed is analyzed, showing that the IMU effectively supports the laser tracker by maintaining acceptable accuracy levels for dynamic orientation tracking. The integration approach shows promise for scaling the system to larger applications. Future implementations could involve integrating multiple sensors to handle more complex scenarios and adapting the system for deployment in real-world environments.

However, the integration of the IMU introduces challenges such as drift, calibration, and maintaining accuracy under varying conditions. The lab-scale tests were conducted for durations of less than 10 minutes, suggesting that extended testing may help mitigate drift over longer periods. Nonetheless, the accuracy of the IMU is not sufficient enough to replace precise measurements from the RTE system, reinforcing its role as a complementary tool rather than a standalone solution.

Table 3. RTE vs IMU lab scale test results

Test	Angles (°)								
	RTE			IMU			Error		
	Roll	Pitch	Yaw	Roll	Pitch	Yaw	Roll	Pitch	Yaw
Initialization	0.00	0.00	0.00	0.00	0.01	0.01	0.00	-0.01	-0.01
Test 1	-26.05	-0.60	-0.30	-26.77	-1.08	-0.03	0.72	0.48	-0.27
Test 2	-0.09	-15.19	-0.11	0.19	-15.24	-0.56	-0.28	0.05	0.45
Test 3	0.01	25.16	0.06	-0.43	24.98	0.81	0.44	0.18	-0.75
Test 4	1.20	1.03	-21.93	-2.19	2.67	-21.61	3.39	-1.64	-0.32
Test 5	0.33	1.27	-17.78	1.13	1.03	-17.77	-0.80	0.24	-0.01

3 Conclusions

An Inertial Measurement Unit (IMU) was successfully integrated into a Real-Time Evaluator (RTE) system to measure the approximate orientation of crane-lifted components during movement. Previous versions of the RTE required that the component be held stationary to measure the location of three targets attached to the component. After IMU integration, approximate orientation can be measured in real-time without stopping the movement of the component. However, at the current levels of tested accuracy, we do not expect the IMU to completely replace the practice of precisely measuring stationary pose of the component by measuring three targets attached to it's rigid body to determine orientation. Lab experiments were conducted to evaluate IMU performance compared to a highly-accurate six-degree-of-freedom measurement system. Both static and dynamic laboratory experiments showed errors in roll- pitch, and yaw less than 0.5 deg compared to highly-accurate 6DoF laser tracking devices. The IMU was then integrated with the RTE, and an experiment was conducted to verify the integration of the IMU within the workflow of measuring a crane-lifted component as it is installed, providing real-time guidance to installers.

The results of the research prove that IMUs can be used as supplementary devices to measure an approximation of the roll, pitch, and yaw of crane-lifted components. However, for accurate assessments of plumbness and levelness, the IMU measurements alone are not accurate enough to replace conventional methods. Based on these results, the authors see a clear use case for the IMU to approximate orientation while the component is being moved. However, near the final installation point, more accurate methods of orientation measurement such as the previous method of cycled measurements of targets attached to the stationary component are required.

3.1 Future Research

Full-scale demonstrations, both in the laboratory and real-world environments, will be performed to assess the RTE's potential for improving installation efficiency. Future work will include testing the system at an actual construction site to quantify time savings and accuracy improvements on a full scale. Efforts will also focus on refining IMU accuracy over extended period of time, and exploring additional sensor integration to enhance the overall system capability. Additionally, advanced methods using artificial intelligence or machine learning may be explored to improve the accuracy and reliability of the IMU output, which may enable users to install only a single retroreflector on the lifted components and rely entirely on the IMU for orientation measurements, thereby reducing costs.

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