COMBINING LARGE-SCALE 3D METROLOGY AND MIXED REALITY FOR ASSEMBLY QUALITY CONTROL IN MODULAR CONSTRUCTION

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ABSTRACT: *The quality control (QC) of assembled modules is an essential process when constructing modular buildings such as hotels and hospitals. Defects that go undetected during module assembly may result in lost productivity in the form of unnecessary transportation, rework or project delays. QC has traditionally been performed using specialized tools and carried out a posteriori in an inspection station dedicated solely to this task. Nowadays, large-scale 3D metrology technology provides a more efficient alternative since it enables accurate measurements to be taken* in situ. *Additionally, mixed reality (MR) supports the immersive projection of information and guidance instructions. This paper introduces a proof of concept of a framework that combines industrial photogrammetry with the HoloLens 2 MR headset to assist with assembly and QC during the off-site construction phase of modular construction. Many tests were conducted in a laboratory and a factory setting to evaluate the system's user-friendliness and possible challenges associated with its future implementation. The experiments conducted confirmed that combining 3D metrology with MR offers an interesting solution for integrating QC into the assembly process. However, further work is needed to enhance the measurement workflow and optimize the measurement system's accuracy.*

KEYWORDS: *3D Metrology, Augmented Reality, Mixed Reality, Modular Construction, Photogrammetry.*

1. INTRODUCTION

In modular construction, volumetric building units, or modules, are factory-built with almost complete interiors including plumbing, electricity, insulation and even furniture. They are then transported to the construction site for final building assembly, which basically involves stacking the pre-assembled modules together. The modules' structure can be made of wood, steel or a combination thereof depending on the customer's requirements and the final height of the assembled building.

During module assembly in the factory, the control of key characteristics (e.g., overall dimensions, squareness error, parallelism of the ceiling and floor) is essential to ensure the module complies with the specifications and estimate the adjustment shims needed when stacking modules on-site. Traditionally, this process has been carried out manually using tools like measuring tapes and levels in the assembly stage and controlled *a posteriori* at an inspection station dedicated solely to this task. If necessary, adjustments and corrections are then made, which leads to lost productivity in the form of unnecessary transportation, rework or project delays.

The advent of contactless 3D metrology provides a valuable alternative since it makes it possible to take accurate measurements *in situ,* while building information modeling (BIM) provides a 3D digital representation of as-designed buildings. This combination of technologies thus automates inspection and digitalizes QC information. QC automation in the prefabricated construction industry has been addressed in recent research. Bae and Han (2021) proposed a vision-based approach to off-site quality inspection that reconstructs 3D point clouds using a projector camera system and computes how much scans deviate from the virtual model to generate quality assessment error maps. Kim et al. (2019) proposed to use a registration-free mirror-aided laser scanning approach to inspect the dimensions and geometric requirements of planar prefabricated elements. Xu, Kang, and Lu (2020) used laser scanning reconstruction technology to inspect surface defects in prefabricated concrete elements. The information they collected during QC was then stored in accordance with the Industry Foundation Classes (IFC) standard and integrated in a BIM platform.

In industry, advances in 3D measurement systems have made it possible to incorporate inspection in the assembly process, which is referred to as measurement-assisted assembly (MAA). The term MAA is used to describe any process that involves measurements being used to guide assembly and QC (Muelaner, Kayani, Martin, & Maropoulos, 2011)

MAA was first introduced as a paradigm shift for the assembly of high-quality large-scale complex structures like aircraft frames to eliminate the monolithic jigs and manual specialized tools that were usually involved in large

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flexible-component assembly (Maropoulos, Muelaner, Summers, & Martin, 2014). This paradigm shift was motivated by advances in large-scale 3D metrology systems that made it possible to take measurements during fabrication or *in situ.* This is particularly beneficial because large-scale structures are often too big to fit into conventional measuring devices or be transported to calibration laboratories (Schmitt et al., 2016). While the construction industry requires less accuracy than the aerospace industry, the same concept can be used to integrate QC in the assembly process of modular and prefabricated structures.

On the other hand, workers need to keep their hands free during assembly to move around and carry their tools. Augmented reality (AR) and mixed reality (MR) technology can make a significant contribution here. They merge computer-generated information with real-world sensations using a device (e.g., a head-mounted screen, a projector, or a tablet) that provides an immersive user experience and eliminates the need to constantly look at fixed screens for information. In the case of MR, the user can interact with the virtual objects (Peddie, 2017). MR can be seen as an evolution of AR that has been made possible by technological advances in sensors and imaging techniques (Park, Bokijonov, & Choi, 2021).

Various studies have evaluated applying AR and MR to assembly tasks and inspection processes. Qin et al. (2021) investigated whether it was possible to use head-mounted AR displays for wood frame assembly tasks. Ahn, Han, and Al-Hussein (2019) proposed to use a projection-based AR system to provide workers with visual guidance during manual panel assembly. Their system projected as-designed models (panel drawings) into the assembly station. Kwiatek et al. (2019) demonstrated that using a mobile AR application in conjunction with 3D scanning during pipe section assembly and inspection improved productivity, reduced the amount of work that needed to be redone, and enhanced workers' spatial skills. Talamas (2017) evaluated using MR interfaces to automate the metrology process flow for in-line assembly process inspection and found that each volunteer made fewer errors when using the MR interface than paper or laptop instruction guides.

The aim of this paper is to propose a proof of concept of a framework that combines 3D measurement technology and MR to integrate QC in off-site module structure assembly. The purpose is to enhance productivity during the assembly process, provide more accurate measurements, and ensure quality output traceability.

2. MATERIALS AND METHODS

2.1 Measurement Equipment

In this research, we focus on assembling a cuboid wood frame structure formed of a floor, four walls and a ceiling. We suppose that the quality of these six parts was previously controlled. To control the quality of the assembly process, we measure the 3D position of a set of points that will make it possible to control the key characteristics, (KCs) the overall dimensions, squareness error, parallelism of the ceiling and floor, etc. These positions will then be compared to the data represented in the computer-aided design (CAD) model. Fig. 1 illustrates the wood frame structure and the set of control points.

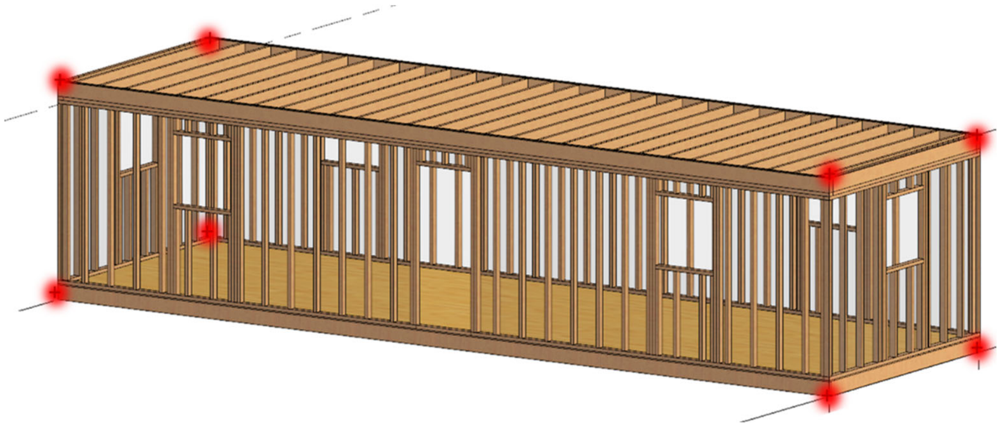


Fig. 1: Wood frame structure

Photogrammetry is a technology that is based on the principle of optical triangulation. An element is positioned in 3D space by at least two cameras that are used to identify targets from different viewpoints. The targets reflect infrared light. The cameras can then capture the position of the targets and position them in relation to the measurement system reference. Multiple targets can be perceived simultaneously, and their positions can be determined dynamically for real-time target tracking (≥ 10 Hz). Photogrammetry is used in many sectors for dimensional inspection. In our research, we use its tracking capability to provide 3D measurement data to assist with the assembly process. C-Track is a photogrammetry device from the company Creaform® that has a measurement volume of up to 16 m^3. Its measurement range can be extended by combining up to four devices to form a measuring system around assembly stations. This eliminates the need to transport measuring equipment from one station to another. Additionally, C-Track can be integrated with portable scanners to probe or scan specific geometric elements as required.

However, the retroreflective targets that are commonly used with C-Track, such as stickers and magnetic artifacts, are unsuitable for wood framing and cannot be accurately calibrated in the CAD model. To address this limitation, customized artifacts have been developed. The artifacts are designed to be easily attached to a wood frame. Each artifact is composed of three retroreflective targets (C1, C2, C3) to locate a point in 3D space. The targets have different spacing to be able to easily differentiate them. Fig. 2 shows a sample artifact developed for tracking the upper corner of a wall.

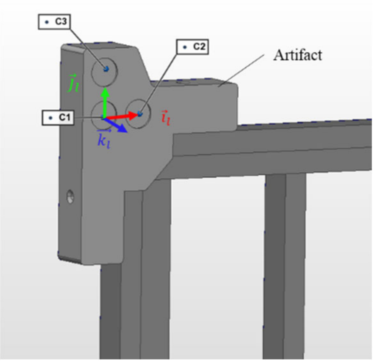


Fig. 2: Sample artifact

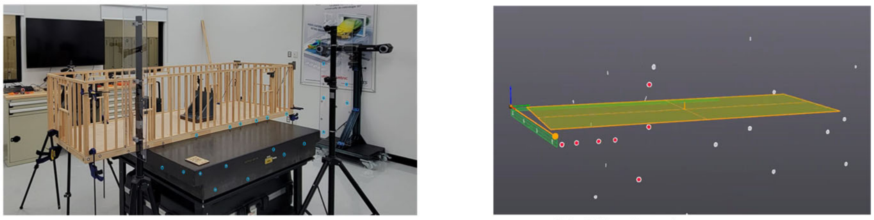
2.2 Measurement System Setup

Prior to initiating the inspection process, certain preliminary operations must be conducted to prepare the measurement system. These operations are: environmental referencing, alignment (or registration), and tracking model creation.

Environmental referencing: This step serves to establish a frame of reference for C-Track within the real environment. The working environment is identified using retroreflective targets (the targets shown in blue in Fig. *3* (a)). These targets are then registered using the primary C-Track (if multiple C-Tracks are used) and exported as a reference file. Once this has been done, measurements can be taken by moving C-Track within the referenced environment.

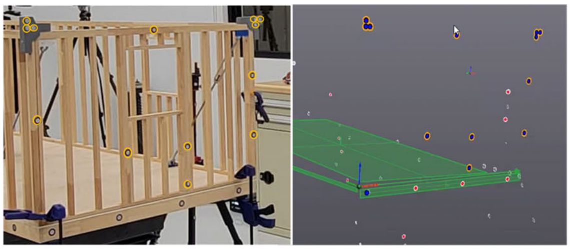
Alignment: To be able to compare measured point coordinates with the CAD model, the C-Track needs to be aligned within the 3D CAD volume. This involves creating reference entities that align the instrument in the metrology software workspace with the real-world instrument. We utilized the floor as a centerpiece. Three perpendicular planes were probed and used to define the measurement coordinate system (as illustrated in Fig. *3* (b)), which was then aligned with the CAD model. Creaform's HandyPROBE portable probe was used with C-Track for this alignment process.

Tracking model creation: The tracking model refers to the collection of retroreflective targets that the C-Track system dynamically tracks. To create this model, the targets comprising the tracked artifacts are registered using the C-Track. Fig. *3* (c) illustrates this process. The acquired targets are then exported as a text file for future use during the inspection process.



(a) Referencing the environment

(b) Aligning the measurement coordinate system with the CAD model



(c) Creating the tracking model

Fig. 3: Measurement system setup

2.3 Data Processing

The raw data collected by C-Track has to be processed and interpreted in order to extract KCs and interpret the measurements in line with the technical specifications. VxElements® software was used with C-Track for data acquisition. For data post-processing, inspection software offers a wider range of tools. In this project, PolyWorks Inspector® was used to extract dimensions from a CAD model, import measurement data and compare the measurement data with the CAD data. Moreover, macro scripting was used to automate the dynamic measurement process workflow.

For each artifact (see Fig. 2), C-Track provides the (x, y, z) positions of the three targets (C1, C2, C3). It is thus possible to create a local coordinate system (ℓ) attached to the artifact. Once the geometry of the artifact is known, the position of a point of interest (for example, an upper corner of a wall) can be determined in the local coordinate system. Geometric transformation makes it possible to determine the point of interest's position in the global coordinate system (the measurement coordinate system). This logic is computed via macro scripts in PolyWorks Inspector®. The detailed method is explained below.

The first step is to identify the targets, which involves associating them with each point of interest and distinguishing each artifact's different targets. To identify the targets that correspond to each artifact, we calculate the Euclidean distances between the nominal position of the corresponding point of interest and the targets. The three targets that lie within a sphere of radius 10 cm around a point of interest are considered the targets associated with the relevant artifact. If one or more targets are missing, an error message is displayed. This approach is based on the assumption that the part (the wall, for example) is positioned roughly at its nominal (CAD) position. Once the three targets associated with each artifact have been identified, the three targets are distinguished by comparing the distances between the targets based on the artifact's geometry. Equation 2.1 provides the vector calculations for creating a local coordinate system $\ell(\vec{\imath}_\ell, \vec{\jmath}_\ell, \overrightarrow{k_\ell})$ around each artifact using the positions of the three targets (C1, C2, C3).

$$\vec{\imath}_\ell = \frac{C_2 - C_1}{\| C_2 - C_1 \|}; \; \vec{\jmath}_\ell = \frac{C_3 - C_1}{\| C_3 - C_1 \|}; \; \overrightarrow{k_\ell} = \vec{\imath}_\ell \wedge \vec{\jmath}_\ell \qquad 2.1$$

The position of the point of interest in the global coordinate system g, $P_g = (x_g, y_g, z_g)$, is calculated by geometric transformation from the position of the point of interest in the local coordinate system ℓ $(P_\ell = (x_\ell, y_\ell, z_\ell))$. This transformation is represented by Equation 2.2:

$$P_g = \mathrm{T}_{g/\ell} \cdot P_\ell \qquad 2.2$$

where $T_{g/\ell}$ is the transformation matrix from the local coordinate system (ℓ) to the global coordinate system (g). To represent this transformation using homogeneous coordinates, Equation 2.2 is equivalently expressed as Equation 2.3:

$$\begin{Bmatrix} x_g \\ y_g \\ z_g \\ 1 \end{Bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} x_l \\ y_l \\ z_l \\ 1 \end{Bmatrix} \qquad 2.3$$

Equation 2.4 donates the rotation matrix:

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = \begin{bmatrix} x\vec{\imath}_g & x\vec{\jmath}_g & x\vec{k}_g \\ y\vec{\imath}_g & y\vec{\jmath}_g & y\vec{k}_g \\ z\vec{\imath}_g & z\vec{\jmath}_g & z\vec{k}_g \end{bmatrix} \qquad 2.4$$

The translation vector corresponds to the coordinate of the origin of the local coordinate system in the global coordinate system as donated by Equation 3.1:

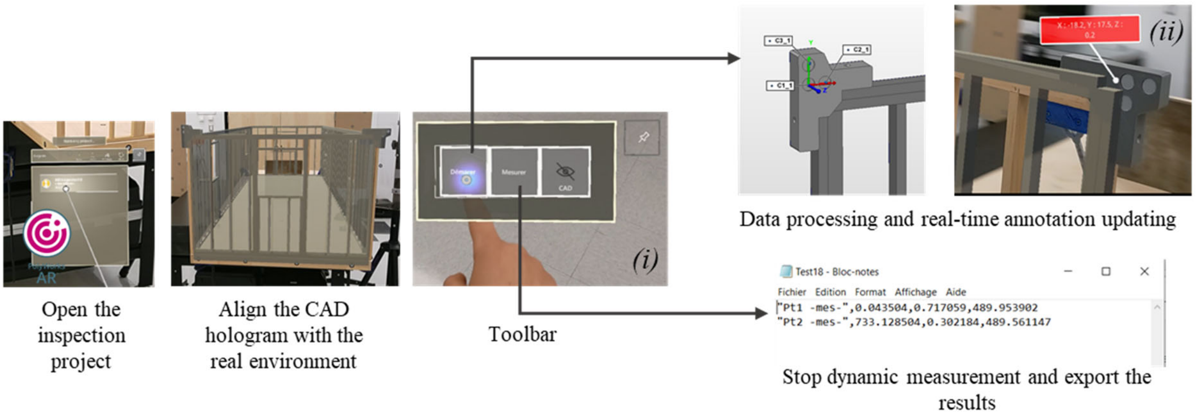
$$\begin{Bmatrix} t_x \\ t_y \\ t_z \end{Bmatrix} = \begin{Bmatrix} xc1_g \\ yc1_g \\ zc1_g \end{Bmatrix} \qquad 2.5$$

2.4 User Interface

As mentioned above, this project uses MR to project dynamic measurements for a user during wood frame structure assembly. The HoloLens 2 headset is a completely standalone head-mounted display (HMD), which means that it doesn't need to be connected to a separate computing device. In addition, it is MR-based, which means that it enables users to interact in real time with digital content that is superimposed on the real world. The content takes the form of holograms, and the holograms interact simultaneously with the user and the real world. Furthermore, HoloLens 2 enables users to interact with holograms using voice commands, hand gestures or eye movement. What's more, the technology makes it possible for two users in different locations to see what the other sees, which enables one to guide the other through a process or simply interact with the world the other sees. This feature has the potential to make remote collaboration easier, more efficient and far more interactive. In addition, an MR plug-in exists for PolyWorks Inspector that makes it possible to manipulate an inspection project directly on HoloLens 2. Macro scripting can also be used to customize the user interface displayed by HoloLens 2.

The user interface must provide the operator with the values of the KCs measured to guide the adjustments to be made and ensure the geometric quality of the assembly. In addition, it must enable the operator to perform certain control commands, such as exporting results and navigating between different inspection stages.

The user interface proposed has two components (Fig. 4): (i) the menu or toolbar, which is composed of three buttons that are each associated with a command Button 1 launches dynamic measurement, Button 2 exports the measurement results, and Button 3 shows or hides the CAD hologram; and (ii) annotations to display the measured value's deviation from the nominal value along the x, y and z axes. The annotations are displayed at the nominal position of the corresponding point of interest and change color depending on whether the measured value is within or outside of the tolerance interval. Note that the functionalities of the PolyWorks AR plug-in for HoloLens 2 were used to align the CAD hologram with the real environment.



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"Pt1 -mes-",0.043504,0.717059,489.953902
"Pt2 -mes-",733.128504,0.302184,489.561147
```

Fig. 4: User interface created for the HoloLens 2 headset

3. LABORATORY TESTING

In order to conduct tests in a laboratory setting, a scaled-down module had to be constructed that adhered to spatial and ergonomic limitations. The scaled module replicates a typical wood frame structure and is around 1/8th the size of an actual module. The module was designed using CAD software. Dimensional and geometric data was present in the CAD model and served as reference information for the nominal (as-designed) model. The measured data was subsequently compared with this nominal data.

3.1 Experimental Setup

The floor was placed on a granite surface plate and secured to the table with a weight to prevent it from moving (see the picture on the right in Fig. 5). Next, we acquired the reference targets, performed alignment and acquired the tracking model as explained in § 2.2.

In an industrial context, adjustable braces are used while assembling walls. A turnbuckle system was built to replicate this for the experiment and allow the operator to easily adjust the position of the wall while tracking the position of the point of interest (see the picture on the left in Fig. 5).

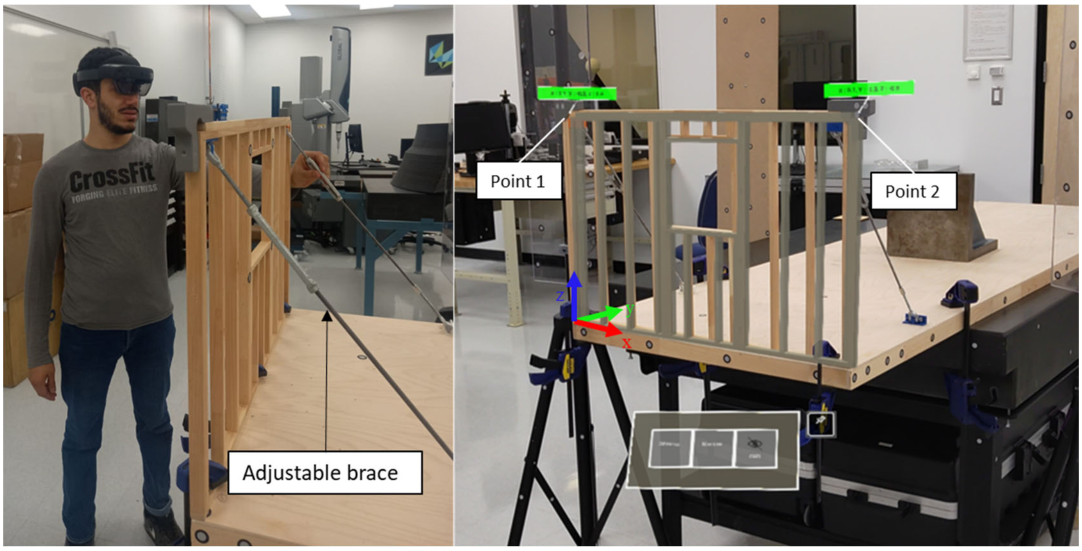

Fig. 5: Experimental setup

3.2 Gage Repeatability and Reproducibility Study

A measurement may be influenced by various sources of variation during the inspection process, which results in there being uncertainty associated with each measurement result. Measurement uncertainty is a quantitative assessment of the unreliability associated with a measurement result based on probability distributions. The dispersion of a set of measurements of a quantity can be characterized using the estimator of its standard deviation, which is also known as standard uncertainty (σ).

Studying the overall uncertainty of the measurement system and evaluating whether the system is able to accurately detect quality defects requires more in-depth study that is beyond the scope of this project. In this study, we intend only to evaluate the amount of variation in the measurement data that is attributable to the measurement system in the configuration proposed. Measurement system variation consists of two important factors, repeatability and reproducibility (R&R). Repeatability is related to equipment variation, whereas reproducibility is related to inspector or operator variation. Measurement system variation can be assessed by conducting a Gage R&R study, which involves data being collected by having multiple operators measure the same set of parts in a random order. Several methodologies can be used for statistical analysis of the data obtained from the Gage R&R study. We chose to use the ANOVA method, which breaks down the sources of measurement system variation as follows:(1) part-to-part: variation originating from the parts being studied; (2) reproducibility: variation originating from the operator(s); (3) operator/part: variation arising from the operator(s) interacting with the parts; and (4) repeatability: variation that originates from the measuring system and cannot be attributable to other sources of variation. The purpose of measuring multiple parts is to evaluate manufacturing method variation, which is also beyond the scope of our research. Therefore, only one part is measured in this study and, thus, variation sources (1) and (3) listed above (which are usually provided by ANOVA) are not taken into consideration in our analysis results.

3.3 Test Sequence

Two operators were asked to repeat the positioning of a wall while tracking the position of the wall's two upper corners. An operator begins by wearing the MR headset and opening the project. The interface displays a hologram of the CAD file with the wall in its nominal position along with a three-button menu, the latter of which is described in § 2.4. The operator then positions the wall approximately in its nominal position and attaches it to the floor and the adjustable assembly brace system. They then fasten the artifacts to the top corners of the wall. Afterwards, they start dynamic measurement by pressing Button 1. The annotations are displayed to indicate each point of interest's positioning error on the x, y and z axes.

The operator begins by adjusting the wall's position along the x-axis in accordance with the deviation values displayed in the annotations for Points 1 and 2 (see Fig. 5). Once the x coordinate is within tolerance, the operator adjusts the position of Point 1 along the y and z axes by adjusting the adjustable brace. When Point 1's position is within tolerance along all three axes, the annotation changes from red to green. The operator then moves on to Point 2 and adjusts its position along the y and z axes. Once both annotations are green (see Fig. 5), the operator stops dynamic measurement by pressing Button 2, which automatically exports the values to a text file. Each operator repeated the sequence 37 times, with six measurements captured each time: *Point1_x*, *Point1_y*, *Point1_z*, *Point2_x*, *Point 2_y* and *Point2 _z*.

3.4 Results and Discussion

The data collected was analyzed using the ANOVA method. Table 1 indicates the repeatability and reproducibility standard deviation of x, y and z for Points 1 and 2. The precision-to-tolerance ratio P/T is expressed by Equation 3.1:

$$P/T = \frac{6\sigma}{USL - LSL} \tag{3.1}$$

where USL is the upper specification limit, LSL is the lower specification limit, and σ is the standard deviation of the measurement error.

Table 1: Gage R&R results

	Point 1			Point 2		
	x	y	z	x	y	z
$\sigma_{\text{repeatability}}$	0.335	0.487	0.152	0.325	0.413	0.089
$\sigma_{\text{reproducibility}}$	0.000	0.019	0.028	0.000	0.237	0.029
$\sigma_{\text{R\&R}}$	0.335	0.487	0.154	0.325	0.476	0.093
P/T	33.5%	49%	15%	33%	48%	9%

The results show that the maximum total standard deviation is 0.487 mm. This means that 95% of the time, the measurement value varies by no more than $4\sigma_{\text{Total}}$ = 1.948 mm ($\pm 2\sigma_{\text{Total}}$ = ±0.974 mm), which is below the maximum allowed tolerance range of 6 mm (±3 mm) indicated in the technical specification. However, for a measurement system to be considered “good”, its precision-to-tolerance ratio must be ≤10%. (Note that 10%<P/T≤30% is borderline, and P/T>30% is unacceptable).

It should be noted, however, that system variation is influenced by the fact that the operator is asked to position each point within an interval of ±1 mm. This can be confirmed by the fact there is less variation along the axis-z since this value is the least impacted by the positioning interval. In fact, when the operator adjusts the braces, the wall’s position along the z-axis almost doesn’t change. In addition, given the experimental setup, the y-axis corresponds to C-Track’s depth axis. A study of the effect C-Track’s depth of field has on measurement system variation showed that the depth of field has a significant effect on system repeatability (Émond-Girard, 2022). In all cases, the system repeatability error is greater than the reproducibility error, which means that the greatest source of variation is the measurement system itself, not operator manipulation.

4. FACTORY TESTING

In order to assess the user-friendliness of the proposed system and to highlight potential constraints linked to its use in an industrial environment, a test was carried out under real working conditions. Below is a description of the experimental setup and test procedure used, as well as the findings and observations noted following the test.

4.1 Experimental Setup and Test Sequence

A near-real-size module was designed to perform factory testing. The artifacts were also adjusted to a true scale. All system setup steps, including referencing the environment, aligning the measurement system with the CAD model’s global coordinate system, creating the tracking model, and aligning the CAD hologram with the real environment were first completed by the research team. Then, we explained to the operators assigned to take part in the tests how the system worked. Three (3) operators then worked together to pre-assemble the module and add the adjustable wall braces. One operator attached the artifacts and put on the MR headset to begin positioning the wall beginning with Point 1. Since the annotation displayed on the MR headset was small, the operator had to climb a ladder to read the value. The other two operators adjusted the position of the wall following the instructions given by the operator wearing the MR headset. The process was repeated until the position of Point 1 was within the desired tolerance range. The process was then repeated for Point 2 following the same procedure. Fig. 6 shows the test sequence.

Fig. 6: Factory testing sequence

4.2 Observations and Discussion

The preliminary actions involved in referencing the environment can be quite demanding in an industrial context. The referencing targets that C-Track requires to locate itself may move due to vibration and operator movement. In addition, during the assembly stage, the floor often moved (drilling of the floor to fix the adjustable wall braces, operator movement, etc.), which made the proposed registration method (alignment of measured data and CAD data) not well suited to the real context. The operator who used the HoloLens 2 headset reported that it was easy to use and comfortable to wear and work with. However, during the test, some drawbacks were noted with the user interface, such as the size of the annotations, which was deemed to be too small. Also, we had to explain to the operator the orientation of the axes and how to interpret the values displayed in the annotation because the coordinate system axes and displacement vectors were not indicated.

5. CONCLUSION

In this research, we were able to achieve a proof of concept of a system that combines industrial photogrammetry and MR to assist operators during the assembly of a wood frame structure. Points of interests were tracked and compared to the nominal data presented in the CAD model. The deviation between the nominal value and the measured value was projected on the real assembly through the MR headset. The proposed solution also supported the documenting of measurement results.

Although the Gage R&R study results showed that the measurement system varied less than the allowed tolerance range indicated in the technical specification, its precision-to-tolerance ratio is still higher than what is recommended. The error associated with artifact fabrication can contribute significantly to the system's variation; thus, further research should work on optimizing the artifact and using the artifact's as-manufactured geometry when computing the measurement data to minimize the amount of variation generated by the artifacts. Further research must be done to evaluate the measurement system's overall uncertainty and validate the system's ability to detect nonconformities.

The test completed in the industrial context helped to identify some drawbacks related to the proposed solution, and, thus, this research serves as a guideline for potential future implementation of a quality control system that combines 3D metrology and MR for integration in an assembly process.

The proposed measurement setup was complex and time-consuming, and keeping the reference targets stable seemed to be a struggle during factory testing. In order to use photogrammetry in *in situ* measurement-assisted assembly, fixed reference entity has to be integrated in the plant layout. Other large-scale technologies like indoor global positioning system (iGPS) could be investigated as an alternative type of measurement equipment. Also, improvements could be made to the user interface to provide the operator with more visual guidance and a more ergonomic way to display the measured values could be sought.

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