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Evaluating the Tracking Abilities of Microsoft HoloLens-1 for Small-Scale Industrial Processes

Kuhelee Chandel, Julia Åhlén, Stefan Seipel

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***Abstract*—**This study evaluates the accuracy of Microsoft HoloLens (Version 1) for small-scale industrial activities, comparing its measurements to ground truth data from a Kuka Robotics arm. Two experiments were conducted to assess its position-tracking capabilities, revealing that the HoloLens device is effective for measuring the position of dynamic objects with small dimensions. However, its precision is affected by the velocity of the trajectory and its position within the device's field of view. While the HoloLens device may be suitable for small-scale tasks, its limitations for more complex and demanding applications requiring high precision and accuracy must be considered. The findings can guide the use of HoloLens devices in industrial applications and contribute to the development of more effective and reliable position-tracking systems.

***Keywords*—**Augmented Reality, AR, Microsoft HoloLens, object tracking, industrial processes.

I. INTRODUCTION

THE advancements in augmented reality (AR) technology have opened numerous opportunities for its utilization across various industries, including industrial applications. AR enables physical interaction with virtual objects [1]. In recent years, there has been a marked increase in interest towards the utilization of AR technology within the realm of intelligent or smart manufacturing. Recent research suggests that AR technology and its hardware have yet to reach their full potential in intelligent manufacturing [28]-[30]. Limitations in display resolution, battery life, and field-of-view of AR hardware, as well as the need for more advanced AR software capable of real-time object detection and integration with AI and IoT technologies, have been identified as areas for improvement [31].

As a result, many industries are now exploring the potential use cases of AR to determine how it can improve their processes, increase efficiency, and enhance customer experiences. The goal is to identify specific areas where AR can bring significant value and improve outcomes. AR has several applications in the industrial sector, such as improving precision, quality control, and safety. It provides real-time guidance and instructions, facilitates 3D product visualization, and enables remote collaboration. Overall, AR is a valuable tool for enhancing productivity, efficiency, and quality in industrial settings. Devices such as Google Glass, Vuzix Blade, Epson Moverio, and Microsoft HoloLens are commonly used for AR, with HoloLens being a mixed reality (MR) device. MR devices enable users to interact with digital objects that appear as if they are part of the real world, creating an immersive experience. AR has the potential to reduce errors, waste, and manufacturing costs while improving product quality and performance [2], [3]. AR can assist workers during assembly and maintenance processes by providing them with real-time guidance and visual cues, reducing errors and improving efficiency. For instance, a study by [4] showed that AR-based guidance improved the assembly time and accuracy of a toy car compared to traditional assembly methods. AR has been used to provide assembly assistance to workers by overlaying digital information on top of real-world objects. This helps workers to perform assembly tasks more efficiently and with fewer errors. One of the recent studies [5] shows that incorporating AR into assembly tasks can lead to a reduction in execution time and errors while improving the accurate understanding of instructions. Also, as illustrated by a prototype for AR-based tape drawing presented in another study [6], AR technology has the potential to reduce design and redesign time exposure in the context of product development. AR can also aid in quality control and inspection by providing real-time feedback on the product's dimensions, surface quality, and other characteristics. For example, according to a recent article [7], AR technology has been integrated into quality control and maintenance processes, leading to significant improvements in manufacturing efficiency and product quality. The adoption of AR systems in the manufacturing industry has the potential to save time, reduce costs, and minimize the production of defective products. By using AR, manufacturers can identify and correct issues in real-time, resulting in fewer errors and increased productivity.

The Microsoft HoloLens is a device that uses advanced sensors, such as tracking cameras and a Time-of-Flight (ToF) range camera, to map and navigate the surrounding environment in real-time [8]. This enables virtual objects to be placed with precision and accuracy in the real world. The ToF range camera collects range data, which are used to construct detailed representations of the environment using triangle meshes. While the HoloLens offers a unique and powerful solution for tracking and mapping scenarios, there are several challenges that need to be addressed.

One of the challenges is the level of knowledge required to operate the device. Complex technologies like spatial mapping and gesture recognition also add to the complexity. There are also display issues that can impact the accuracy of positioning virtual objects in the real world. Another concern is the precision of the device, particularly for tasks that require a high level of accuracy, such as manufacturing. Even small errors in

Kuhelee Chandel is with University of Gävle, Sweden (e-mail: kuhelee.chandel@hig.se).

the spatial co-registration between the HoloLens with the real world can have a compounding effect on the accuracy of object tracking over time, resulting in increasing misalignment between virtual and real objects [9]. To effectively use the HoloLens for precision tasks in industrial settings, it is crucial to address issues related to its accuracy and precision. Calibrating and tracking the HoloLens in real-world environments can help maintain accurate object tracking, with techniques such as SLAM being particularly effective in achieving this. Researchers have emphasized the importance of such techniques in improving the HoloLens' accuracy for precision tasks [8].

II. BACKGROUND

The Microsoft HoloLens is a MR headset that has garnered significant attention in the manufacturing industry due to its self-tracking capabilities. Equipped with an optical tracking system, the device can determine its position in a room and track the movements of the user [2], [10]. This system creates a map of the environment, allowing the HoloLens to accurately place virtual objects relative to the user, making it suitable for a wide range of applications in product design, production, maintenance, and employee training [11].

Object detection and tracking is another key feature of the HoloLens, achieved using computer vision algorithms that run on the device [12]. The device's onboard cameras, microphones, and sensors enable real-time object detection and tracking, which can be leveraged for a variety of applications such as hands-free interaction, remote assistance, and industrial maintenance. To facilitate the development of real-time object detection and tracking applications for the HoloLens, Microsoft provides the HoloLens development kit, which includes tools, libraries, and APIs for building MR experiences [13]. With the increasing popularity of the HoloLens and the growing potential for innovation in the manufacturing industry, it is expected that the use of this device for real-time object detection and tracking will continue to grow and evolve soon [11].

Real-time object detection and tracking using Microsoft HoloLens is a challenging task due to the device's limited processing power and memory. However, recent research has made significant progress in developing innovative techniques to address these challenges and improve the accuracy of object detection and tracking in dynamic and cluttered environments. One approach is the use of deep learning-based object detection and tracking systems, such as the work in [14]. Their system achieved real-time object detection and tracking performance with high accuracy, even in complex environments with multiple objects and occlusions. In a very interesting article, researchers proposed a solution for tracking IR marker targets with the HoloLens, achieving a tracking accuracy of 0.76 mm at 40-60 cm distance and high frame rates of 55-60 fps [15]. Their study compared two approaches for tracking IR marker targets and demonstrated the potential for using well-established medical IR markers for AR in the operating room.

However, despite these advancements, accuracy remains a challenge for real-time object detection and tracking using HoloLens. The device's limited field of view and resolution can make it difficult to detect and track objects accurately, particularly in complex environments. Additionally, the device's processing power and memory limitations can make it challenging to run complex object detection and tracking algorithms in real-time [11]. Overall, the progress made in developing new techniques for real-time object detection and tracking using HoloLens shows great potential and opens new possibilities for using AR technology in various fields. However, to fully leverage this potential, it is essential to prioritize research efforts toward developing more efficient and accurate algorithms for real-time object detection and tracking on HoloLens.

Studies have shown that using HoloLens in manufacturing can reduce production time and errors [16]. However, the existing simultaneous localization and mapping (SLAM) technology used in HoloLens has limitations in tracking moving objects, which can result in inaccuracies and drift in the spatial relationship between virtual objects and the real world [8]. Researchers are exploring alternative tracking methods, including sensor fusion and machine/deep learning algorithms, to improve the accuracy and robustness of object tracking [12], [17], [19]. The current SLAM implementation in HoloLens relies heavily on visual odometry, which is not accurate enough to track fast-moving or occluded objects, leading to drift and inaccuracies [19].

Overall, researchers are actively exploring alternative tracking methods to improve the accuracy and robustness of object tracking in HoloLens and other applications. The HoloLens has been evaluated in various ways for its suitability in industrial applications, including its use as an AR device, the perceived spatial stability of holographic displays, and the quality of the user experience enabled by the HoloLens. For example, in an article titled "Hologram stability evaluation for Microsoft$^{(R)}$ HoloLens" authors investigate holographic perceived spatial stability [20]. One study investigates into the quality of the HoloLens-enabled user experience [21], while in another, the HoloLens tracking system is compared to ground truth data from a motion capture system for human-robot interaction application scenarios [22]. Two recent studies have examined the spatial accuracy of HoloLens-captured triangular meshes for indoor mapping. One study compared HoloLens-captured data to ground truth data from terrestrial laser scanners, and was the first quantitative investigation of HoloLens accuracy for this purpose [8]. Another study conducted a geometric evaluation of HoloLens's spatial mapping capability [23]. While there is research on various aspects of this technology, we did not encounter specific investigations focused solely on the device's object-tracking accuracy within the scope of our research.

In the context of Microsoft HoloLens, object tracking refers to the process of continuously monitoring the movement and position of real-world objects and maintaining their spatial relationship with respect to the virtual objects in a MR scene. This is typically done through computer vision techniques that rely on the device's sensors, such as the depth camera and inertial measurement unit (IMU), to estimate the 3D position and orientation of objects in the user's environment. Knowing the position and orientation of virtual and physical objects allows them to be aligned. The posture is obtained by the HoloLens to calculate and render virtual models from the correct viewpoint [24].

Real-time spatial context is a critical aspect of industrial digitalization as it enables manufacturers to accurately locate and track physical assets in their manufacturing environment. This, in turn, facilitates the real-time monitoring of their physical properties and operational attributes, leading to improved efficiency and reduced errors. To achieve this, it is necessary to determine the spatial relationships between assets with precision.

Our study aims to comprehensively evaluate the accuracy and precision of the HoloLens tracking capabilities in providing real-time spatial context. Specifically, we will compare it with the ground truth obtained through a Kuka Robotic arm to identify potential limitations of the HoloLens tracking system. The goal is to determine specific applications where the HoloLens can be effectively used despite these constraints and provide insights into opportunities for improvement of the HoloLens system.

The purpose of this study is to contribute to the development of more efficient and safe small-scale industrial operations. This includes assembling small parts with high precision, conducting maintenance on complex machinery, and training new operators in a simulated environment. By improving the accuracy and precision of the HoloLens tracking system, we can enable more effective digitalization of industrial processes, leading to improved operational efficiency and reduced errors.

III. METHODS

This section outlines the key components and procedures used in two experiments. Both experiments employed a marker-tracking approach to identify the position of a tracking target relative to the HoloLens camera. ARToolkit 5.3 and Unity 2017.1 were utilized as the marker tracking framework. An LED was installed on a robotic arm, acting as an active optical target for tracking, and the built-in RGB camera at the center front of the HoloLens captured images of this target.

The experiments were conducted in a controlled laboratory environment. Standardized protocols ensured the accuracy and reliability of results. Potential sources of error were minimized by careful calibration of the marker tracking system. Established procedures, like the use of calibration objects to provide known reference points, and tracking algorithm optimization were adopted to reduce errors. Experiments adhered to established scientific standards, controlling for variables like lighting and using analytical tools to manage data variability. All experimental procedures were documented to promote reproducibility by other researchers.

A. Experiment 1

In the first experiment of this study, the setup comprised a Microsoft HoloLens 1 mounted on a tripod and a small battery box with an infrared light emitting diode (IRLED) attached to the robotic arm as the optical target. Fig. 1 shows the technical apparatus in our experiment. The HoloLens device was affixed to a tripod and oriented towards the robotic arm, with the IRLED target affixed to it. The tripod was situated at 1 meter from the robotic arm. The HoloLens device's field of view at this distance encompasses approximately 33 centimeters in the horizontal direction and 24 centimeters in the vertical direction.

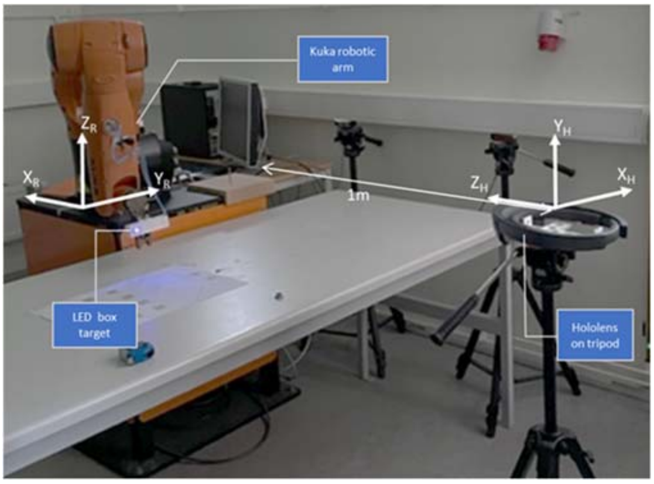

Fig. 1 Experiment 1 & 2 Setup

In experiment 1, the accuracy of the Microsoft HoloLens as a 3D positional measurement instrument was evaluated for static targets using a systematic approach. A 2-dimensional rectangular grid of equally spaced reference positions was first pre-computed. To physically realize those reference positions for the LED target a very high-precision industrial robotic arm (Kuka KR 6 R900) [25] was programmed. Due to the industrial robot's high accuracy and precision, physical positions of the LED were considered as ground truths. The grid consisted of 91 reference positions arranged in 7 rows and 13 columns. The distance between columns and rows was 25 millimeters. HoloLens was subsequently used to record spatial coordinates at each of the 91 points, one at a time. Each point was measured 50 times with no motion of the robotic arm between individual recordings to exclude potential repositioning errors. Multiple readings at each point were taken to allow for statistical analysis of accuracy and precision of the measurements. In the first experiment, accuracy of HoloLens based measurements was evaluated in terms of the known distances between reference points on the grid i.e., we analyzed accuracy for pairwise relative positions (distances) between adjacent points on the grid. In this way, any minor translational or rotational alignment errors (offsets) between the robotic coordinate system and the HoloLens's internal coordinate system could be neglected. This approach allowed for a straightforward systematic evaluation of the HoloLens as a measurement instrument and provided valuable insights into the accuracy and suitability of the device for various applications requiring precise measurements.

The HoloLens device used in the experiments is equipped with a depth sensor that helps in determining the 3D position of the robotic arm. The depth sensor is a ToF camera that works by emitting infrared (IR) light signals and measuring the time it

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takes for the signals to bounce back from the surrounding objects. Distance (range) measures are instantaneously measured for all pixels of the depth sensor. Based on the range image, the 3D locations of objects in the field of view of the camera can be determined per pixel.

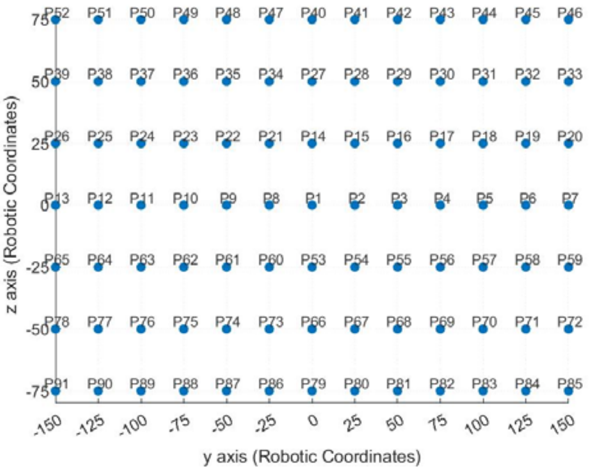

Fig. 2 2-D rectangular grid of equally spaced 91 reference positions

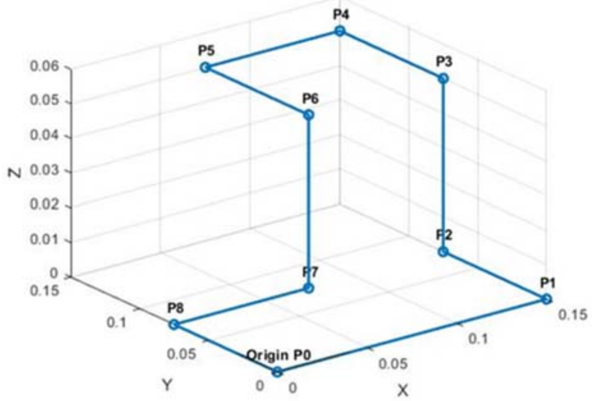

Fig. 3 Predefined reference 3D trajectory

In the experiments, an IRLED target was attached to the robotic arm, and the HoloLens device was positioned 1 meter in front of the arm. As the arm moved along the programmed trajectory, the visible light camera of the HoloLens device captured the IR signal reflected from the IRLED target. After identification of the IRLED position within the field of view of the camera, the pixel location was used to retrieve the ToF measurement from the range image of the depth sensor to calculate the distance from the device to the IRLED target. Knowing the intrinsic camera parameters of the depth sensor, the HoloLens device then calculates the 3D position of the target, which corresponds to the position of the robotic arm.

B. *Experiment 2*

The second experiment aimed to test the HoloLens device's ability to capture the position of a moving object under dynamic tracking conditions. The robotic arm was programmed to follow a piecewise linear trajectory at different speeds, and an IRLED target was attached to it. The HoloLens device was positioned in front of the robotic arm to capture the x, y, and z measurements of the target at discrete intervals. The experiment aimed to evaluate the accuracy of the HoloLens device in capturing the position of a moving object at different speeds. The findings from this study could have practical implications for the development of real-time monitoring systems for moving objects in manufacturing settings. The trajectory used in the experiment was carefully planned and consisted of nine linear segments, involving changes in the x, y, and z directions. The trajectory covered a total path length of 750 mm and allowed for measurements at different speeds.

The trajectory was divided into nine displacements, with the initial displacement being 150 mm in the positive x-direction. Subsequent movements involved displacements of 75 mm in the positive y-direction, 50 mm in the positive z-direction, 75 mm in the negative x-direction, 75 mm in the negative y-direction, 50 mm in the negative z-direction, 75 mm in the negative x-direction, and 75 mm in the negative y-direction. Seven different speeds were tested, ranging from 75 mm/s to 3.75 mm/s, with a gradual reduction in speed from 100% to 75%, 50%, 25%, 20%, 10%, and 5%. These speeds were chosen to evaluate the device's performance in capturing the position of a moving object at a range of speeds commonly found in manufacturing settings. Overall, the experiment provided valuable insights into the performance of positional tracking under dynamic conditions and highlighted the potential of the HoloLens device as a tool for capturing the position of moving objects.

C. *Coordinate Systems*

Fig. 1 illustrates that in both experiments, the coordinate axes of the industrial robot and the local HoloLens coordinate system were manually axis-aligned with the best effort. In experiment 1, the center of the 7x13 grid of reference points was chosen to coincide with the z-axis of the HoloLens coordinate system at 1 meter along the z-axis. Additionally, columns and rows were aligned with the x-axis and the y-axis, respectively. Essentially, the 2D grid of reference points was placed on the image plane of the HoloLens camera at 1 meter.

It is important to note that due to the error analysis design based on pairwise distances, a more sophisticated co-registration of the robotic coordinate system with the HoloLens internal coordinate system was not necessary. Therefore, all coordinates presented in the results section refer to the HoloLens with respect to the position of the center of the 7x13 grid of reference points, as described above. This alignment is on the image plane of the HoloLens at a 1-meter displacement along the z-axis. These details provide a clear understanding of the experimental setup and the reference points used for analysis.

IV. RESULTS AND ANALYSIS

The accuracy of the HoloLens in the first experiment was evaluated based on the agreement of the measured pairwise horizontal distances between positions with the established ground-truth distances according to the 7x13 grid definition.

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The deviations of measured distances from the reference distances were considered as the error metric in our analysis to assess HoloLens relative positional accuracy. The statistical and spatial analysis of observed errors reveals insights to characterize position tracking quantitatively and qualitatively within the field of view of the HoloLens. They provide an understanding and give implications in various applications that require accurate object tracking, such as in industrial production scenarios.

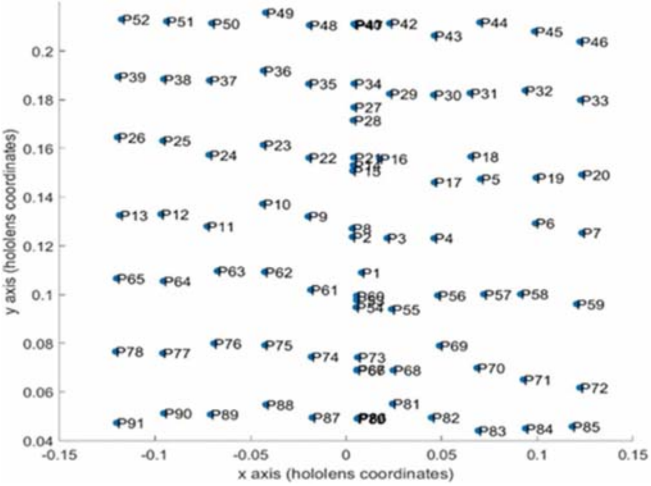
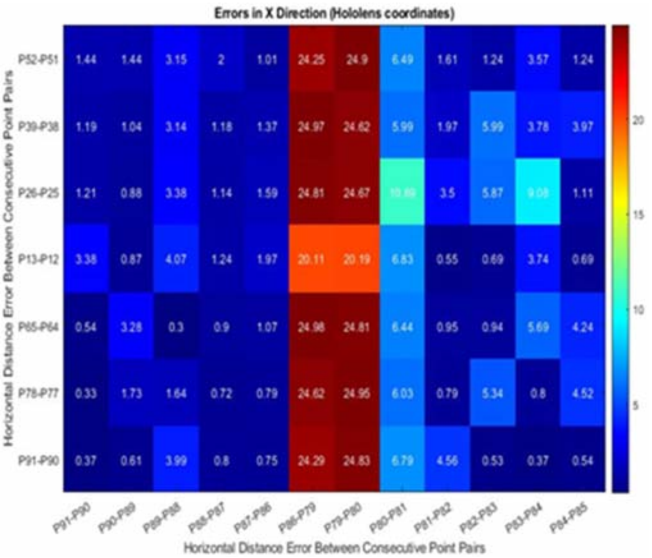


Fig. 4 2-D Scatter plot of 91 points measured with Microsoft HoloLens (median values)

In this study, a 2-D matrix of 91 points in both x and y directions was generated, and each point was measured 50 times using Microsoft HoloLens to obtain the y and z coordinate values. The median values of these measurements were then used to create a 2-D plot that showed a similar matrix to the original one. Fig. 4 illustrates this plot of the 91 positions derived from the HoloLens 50 observations at each of the 91 static positions of the target mounted on the robotic arm. The use of median values from the 50 observations for each of the 91 static positions minimized any outliers or inaccuracies in the measurements, providing a more accurate representation of the spatial coordinates of each point. The study aimed to evaluate the accuracy of distance measurements obtained using the Microsoft HoloLens in both the horizontal and vertical directions.

The results of the study revealed that the average error value in the horizontal direction was 6.18 mm, with a maximum error value of 24.98 mm. The data points closest to the center of the matrix in the lateral direction contributed the most inaccuracy in the horizontal direction. These findings provide important insights into the limitations of the Microsoft HoloLens in accurately measuring distances in industrial settings. To further analyze the accuracy of the measurements in the horizontal direction, a heat map (Fig. 5) was created to illustrate the distribution of distance measurement accuracies across the field of view of the HoloLens. The color scale indicates the level of accuracy, with warmer colors (red) indicating less accuracy and cooler colors (blue) indicating more accuracy. Interestingly, it was found that the measurements were least accurate in the central region of the field of view, where the colors were warmest. As we moved further away from this central region in either direction, the accuracy of the measurements gradually increased, as indicated by the shift towards cooler colors. This trend was consistent in both the negative and positive x directions, as demonstrated by the similar patterns in the two halves of the heat map.


Errors in X Direction (Hololens coordinates)

	P91-P90	P90-P89	P89-P88	P88-P87	P87-P86	P86-P79	P79-P80	P80-P81	P81-P82	P82-P83	P83-P84	P84-P85
P52-P51	1.44	1.44	3.15	2	1.01	24.25	24.9	6.49	1.61	1.24	3.57	1.24
P39-P38	1.19	1.04	3.14	1.18	1.37	24.97	24.62	5.99	1.97	5.99	3.78	3.97
P26-P25	1.21	0.88	3.38	1.14	1.59	24.81	24.67	10.69	3.5	5.87	9.08	1.11
P13-P12	3.38	0.87	4.07	1.24	1.97	20.11	20.19	6.83	0.55	0.69	3.74	0.69
P65-P64	0.54	3.28	0.3	0.9	1.07	24.98	24.81	6.44	0.95	0.94	5.69	4.24
P78-P77	0.33	1.73	1.64	0.72	0.79	24.62	24.95	6.03	0.79	5.34	0.8	4.52
P91-P90	0.37	0.61	3.99	0.8	0.75	24.29	24.83	6.79	4.56	0.53	0.37	0.54

Fig. 5 Error values in distances measured in x-direction between consecutive points

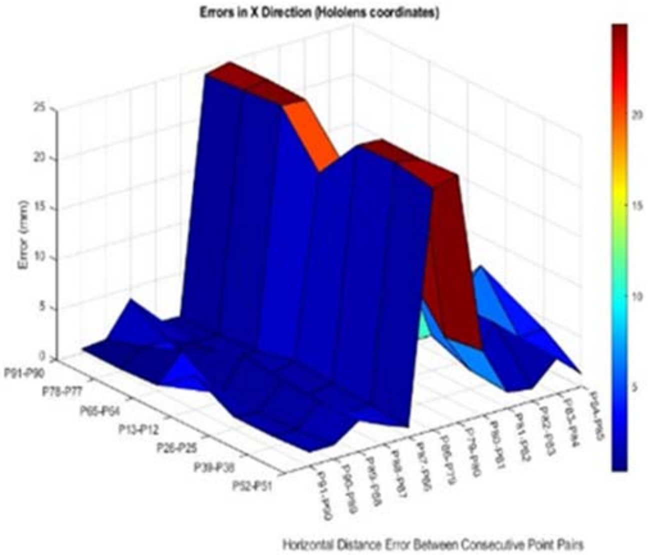
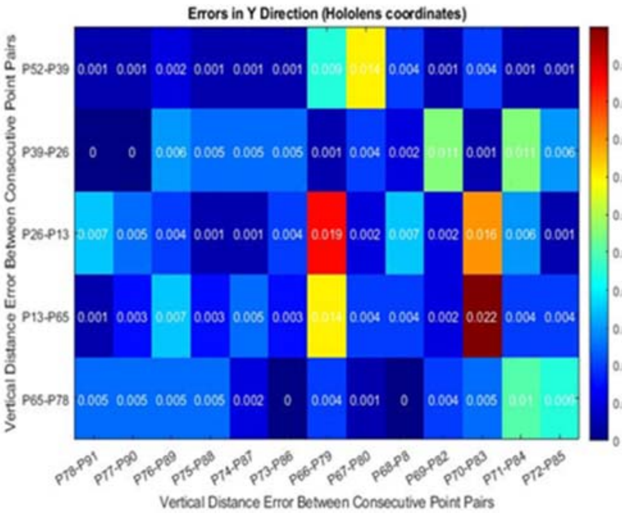


Fig. 6 Error analysis of distance measurements in x-direction between consecutive points

The surface plot (Fig. 6) provided a visual representation of the distribution of distance measurement accuracies across the vertical field of view of the HoloLens. In both the heatmap and surface plot, colors were used to represent the magnitude of the errors, with red indicating the highest error values and blue representing the lowest error values. The visualizations revealed that the highest error values were concentrated in the center of the plot, where the colors were mostly red, indicating that errors were maximum at the center. This information is crucial for identifying the areas where errors are most prevalent and for adjusting the system to improve the accuracy of the data.



	P78-P91	P77-P90	P76-P89	P75-P88	P74-P87	P73-P86	P66-P79	P67-P80	P68-P8	P69-P82	P70-P83	P71-P84	P72-P85
P52-P39	0.001	0.001	0.002	0.001	0.001	0.001	0.009	0.014	0.004	0.001	0.004	0.001	0.001
P39-P26	0	0	0.006	0.005	0.005	0.005	0.001	0.004	0.002	0.011	0.001	0.011	0.006
P26-P13	0.007	0.005	0.004	0.001	0.001	0.004	0.019	0.002	0.007	0.002	0.016	0.006	0.001
P13-P65	0.001	0.003	0.007	0.003	0.005	0.003	0.014	0.004	0.004	0.002	0.022	0.004	0.004
P65-P78	0.005	0.005	0.005	0.005	0.002	0	0.004	0.001	0	0.004	0.005	0.01	0.006

Fig. 7 Error values in distances measured in y-direction between consecutive points

Fig. 7 shows a scatter plot of the measured data points in the y direction. The average error value in this direction was found to be 0.005 mm, with a maximum error value of 0.022 mm in distances measured in the y direction. Unlike in the x direction, there was no evident pattern in the distribution of errors in the y direction. Clearly, the accuracy is much higher in the coordinate measurements in the y direction. The results highlight the significance of considering the field of vision when using the HoloLens for spatial measurements. Further research is necessary to verify these findings in other applications and to determine the full potential of HoloLens as a precision measurement tool.

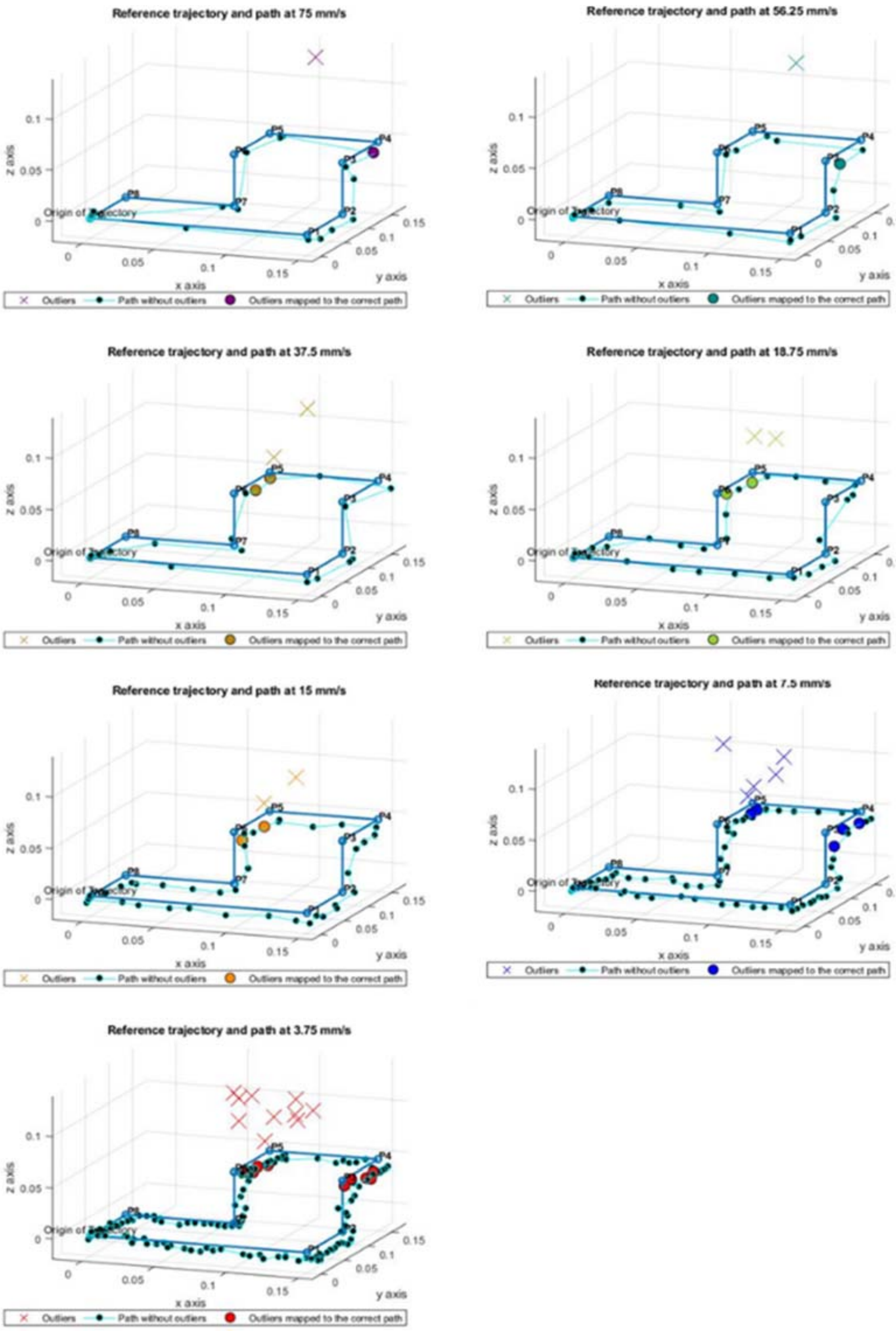
The second experiment aimed to test the ability of the HoloLens device to capture the position of a moving object under dynamic tracking conditions. The accuracy of the device was influenced by the speed of the object's trajectory and the position of the HoloLens in the field of view. The accuracy was quantified using root mean square error (RMSE) calculations, and the results showed that the accuracy generally decreased as the speed of the object increased. To improve the accuracy of the measurements, it is important to consider these factors and optimize the position and orientation of the HoloLens device. The analysis of the data showed that the HoloLens device was able to accurately capture the position of the moving object, with varying degrees of accuracy depending on the speed of the target. The mean distance between the reference trajectory and the observed trajectory (as measured by the HoloLens device) ranged from 0.42 mm for the slowest speed to 0.62 mm for the fastest speed. The RMSE distances between the two trajectories ranged from 0.47 mm to 0.71 mm, respectively. The output of the accuracy analysis suggests that the accuracy of the observed paths generally decreases as the speed of the object decreases. This indicates that the path at the highest speed had the most deviation from the reference path.

In addition to our observations of path data at various velocities, we performed a comprehensive analysis of the obtained coordinate values. Using the x, y, and z values of each path plot, we identified the presence of outliers. We plotted these outliers alongside the originally observed paths to gain a clearer understanding of their significance, as illustrated in Fig. 8. Additionally, we employed a mapping technique to reassign each aberration to its correct position on the respective observed path for the corresponding velocity. This was accomplished by calculating interpolations based on the x, y, and z coordinates of the closest neighboring points. Upon further analysis of the outlier locations, we discovered a consistent pattern. The outliers were frequently located near two specific segments, as illustrated in Fig. 9. The highlighted segments revealed that the outliers were concentrated in a nearly identical region, regardless of the measurement speed. This region was where the HoloLens was positioned perpendicularly at 1 meter away. This finding provides significant information that could help improve the accuracy of distance measurements by identifying a specific area where the HoloLens may require calibration or further optimization.

V. DISCUSSIONS AND CONCLUSIONS

The study sought to assess Microsoft HoloLens (Version 1) tracking capabilities for small-scale activities often found in industrial applications, such as component assembly, quality control inspection, and maintenance operations. The findings of the two experiments shed light on the performance of the HoloLens device for location tracking in industrial applications. In Experiment 1, the accuracy of the HoloLens device in measuring the position of static points inside a 3D matrix was evaluated. It was discovered that as distance from the core portion of the HoloLens field of view rose, accuracy improved. Median values were found to be more helpful than mean values in decreasing the effects of skewed or outlier distributions on measurement accuracy.

Experiment 2 tested the performance of the HoloLens device in tracking the position of a robotic arm as it followed a linear route at varied speeds. The accuracy of HoloLens measurements was influenced by trajectory speed and device position in the field of vision. Furthermore, the study discovered that outliers in the data were concentrated in the central region of the field of view. Some of the outliers noticed in the core region could be due to limitations or mistakes in the HoloLens device itself. For example, the HoloLens' limited range of view may result in insufficient or inconsistent data in particular places, resulting to outliers. Also, the HoloLens may have depth perception issues or calibration errors, which could lead to inaccuracies in the position and orientation of virtual objects, contributing to outliers in the data.



Reference trajectory and path at 75 mm/s

Reference trajectory and path at 56.25 mm/s

Reference trajectory and path at 37.5 mm/s

Reference trajectory and path at 18.75 mm/s

Reference trajectory and path at 15 mm/s

Reference trajectory and path at 7.5 mm/s

Reference trajectory and path at 3.75 mm/s

Fig. 8 Plots depicting the reference trajectory, observation outliers, and corrected path outliers

However, environmental factors such as lighting or other visual obstructions could also be contributing to the concentration of outliers in the central region of the field of view. As a result, it is critical to properly study the data and consider all conceivable factors that could be influencing the reported outliers. This may entail modifying data collection methods or adding additional efforts to reduce the effects of environmental factors or inherent HoloLens flaws. Microsoft notes in its HoloLens documentation that changes in lighting conditions might compromise the accuracy of the HoloLens device's tracking, particularly in low-light situations, although it does not specify at what light levels the difficulties may arise [26]. Visual occlusions, such as objects covering the view of the HoloLens cameras, can also reduce tracking accuracy, according to the similar documentation [27]. As a result, while the HoloLens device has the potential to be a helpful tool for location monitoring in a variety of applications, its limits in particular circumstances and potential environmental considerations must be considered when contemplating its use.

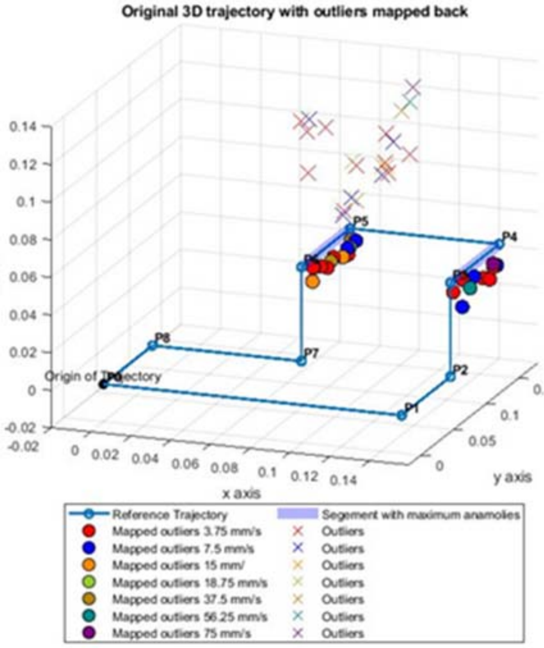


Fig. 9 Plot highlighting the segments of significant outlier locations

The study's limitations include a controlled laboratory setting and linear trajectories with tiny dimensions. Future research should investigate the HoloLens device's ability to track more complex trajectories and compare it to other devices.

The study emphasizes the limitations of Microsoft HoloLens (Version 1) tracking capabilities, particularly in complex and dynamic industrial contexts. The device may be appropriate for small-scale operations, but it may not be reliable for more sophisticated and demanding applications that require great precision and accuracy. It is critical to continue assessing the performance of the HoloLens device in various configurations and circumstances, as well as comparing its performance to that of other devices, to develop more effective and dependable position tracking systems. Furthermore, the effect of depth sensor frame rate on measurement accuracy should be investigated.

The study reveals that the HoloLens device can be utilized well for position tracking in dynamic circumstances where the target moves in linear trajectories of modest dimensions, although caution should be exercised when the angle of view is critical. This discovery could have implications in numerous small-scale industrial operations, such as assembly line production, robotic welding, and packaging, where accurate location tracking is critical for ensuring that components or products are integrated or packaged correctly. However, when precise measurements from specific angles are required, the HoloLens device may not be suitable for such applications. In other scenarios, such as medical procedures, construction and architecture, and training and simulation, the HoloLens device's positional tracking accuracy and precision are critical for creating realistic virtual environments or accurately aligning virtual objects with physical ones. As a result, while the HoloLens device has the potential to be a helpful tool in a variety of industries, its limits in particular contexts must be considered when evaluating its application. More research is needed to optimize the experimental setup and improve measurement accuracy, particularly in scenarios involving faster trajectories and larger objects.

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