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Metrological Analysis of HoloLens 2 for Visual Marker-Based Surgical Navigation

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***Abstract*—Although the research on medical navigation systems dates back to the second half of the 20th century, the emergence of modern technologies offers new prospects for their application. One of the technologies that has been investigated in recent years for its potential in clinician support systems is augmented reality. Many AR solutions utilize head-mounted displays, allowing for the integration during medical procedures. These displays are equipped with cameras that can provide data for marker-based navigation. However, before implementing such approaches in real-world applications, it is crucial to assess the precision of marker detection. Therefore, in this paper we present a metrological analysis of the detection of two most common marker types, namely QR codes and ArUco markers, using Hololens 2 and dedicated algorithms designed for this specific purpose. Our study consisted of two different measuring setups: one to investigate the effect of different distances and the other to investigate the effect of angles on position error. The results showed that QR codes can be detected from a maximum distance of 750mm (for a 75mm size marker), while ArUco markers can be detected from distances as far as 1250mm, even for a marker as small as 2.3 cm. However, the standard deviation of the average measurement of ArUco marker size is greater than that of QR codes. The results obtained suggest that it is possible to detect ArUco markers in sizes and distances suitable for medical settings using HoloLens 2 and dedicated software. Therefore, the results of this study could potentially pave the way for the development of a marker-based method for medical navigation in the future.**

***Index Terms*—Augmented reality, marker registration error, marker tracking, surgical navigation, Microsoft Hololens 2**

I. Introduction

Medical navigation systems, which had their origins in the late 1980s, are now being rapidly developed. Medical navigation, in its broadest sense, can be defined as the attempt to determine the position of a medical instrument in the space of the surrounding environment. Such an instrument can then be tracked, and its position can be superimposed on another modality giving the doctor real-time information. In most current medical navigation systems, stereoscopic infrared cameras are being used, which record the position of characteristic markers to determine the position of a surgical instrument in space. However, this solution requires the use of additional markers attached to medical instruments, which, among other things, alter the center of gravity of the device.

Surgical navigation is used in neurosurgery, orthopedic surgery, spinal surgery, and oral surgery. The increase in popularity of medical navigation systems is a direct result of several of their advantages. Firstly, by combining patient imaging studies with intraoperative real-time data, they improve surgical precision and accuracy. They also became a valuable tool to confirm the surgeon's understanding of anatomy, resulting in fewer intraoperative complications and better patient outcomes. Secondly, they allow for preoperative diagnosis, operation path planning, registration, and intraoperative navigation, making the operation more accurate, rapid, and safe [1]. Lastly, surgical navigation enables the surgeon to process data from preoperative and intraoperative sources, with the aim of condensing available information by presenting only the most relevant ones. Despite the benefits, practical usage remains relatively low due to long setup and registration times, steep learning curves, and workflow disruptions.

These disadvantages can be mitigated by using augmented reality (AR) technology, especially AR glasses worn by the surgeon. AR technology provides a more intuitive way to perform marker-based navigation during surgical procedures [2]. Moreover, AR-based surgical navigation systems provide more visual information during surgeries. The positional relationship between the surgical field and organs is visualized based on preoperative medical images of a patient in 3D using holographic view. However, the accuracy of the AR-based navigation systems in a real-life scenario still needs to be validated, which is the topic of this article.

This paper is arranged as follows. Section 2. comprises

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the classification of surgical navigation systems and describes some recent studies related to the accuracy of image overlay and marker registration. Section 3. briefly explains the proposed detection algorithms and measuring techniques. The experimental result and analysis are highlighted in Section 4. Their implications are discussed in Section 5. Finally, Section 6. describes the conlusion and future development.

II. Tracking systems in surgical navigation

The main component of a surgical navigation system is the tracking method that determines the pose and orientation of the surgical instrument related to the patient. We can distinguish marker-based methods where artificial visual markers are attached to the surgical tool and marker-less ones that use computer vision algorithms to obtain tracing features from intraoperative images.

Apart from the above classification, we can divide surgical tracking methods into the following types [3], [4]:

- Mechanical - consist in attaching rigid mounting frames to the patient's organs. The advantage of this method is a high accuracy but it suffers from the difficulty of the procedure and high invasiveness.
- Electromagnetic - such systems consist of a magnetic field generator placed at a specific location and electromagnetic sensors that are attached to the surgical instrument. The magnetic field produced by the generator induces a voltage on the sensors that is used for pose estimation [5]. However, the measurements are sensitive to random noise and artifacts.
- Optical - measure light either transmitted or reflected by an object. They are the most common solutions and can be divided according to the wavelength used: Infra-Red (IR), Videometric (visible light) and laser.

In the last few years, the development of surgical navigation systems has become popular. We can observe two main trends: using external sensors like ClaroNav or using head mounted displays equipped with cameras like Microsoft HoloLens 2. The second approach expands the possibilities of applying additional features that make surgical navigation more intuitive and reliable. For example, by aligning a hologram generated using preoperative CT or MRI images to the patient's body. [2], [6]

A. Image overlay accuracy

Our study focuses on surgical navigation system with the use of augmented reality headset for gathering data from sensors and visualization.

One of the state-of-the-art approaches involves AR-based patient positioning using Microsoft HoloLens 2 headset and three-dimensional QR code (QR cube) [7]. While viewing the QR code directly, the hologram is placed at the appropriate location. The registration accuracy was reported to be of the order of 3.0 ± 1.5 mm. However, when the user does not directly view the marker, the hologram tends to shift as the tracking algorithm struggles to interpret the QR-code.

In [8] authors present another solution that also uses the Microsoft HoloLens 2 headset but tracks ArUco codes instead. Tracking is done using Vuforia SDK. The best achieved perceptual registration accuracy was 0.98 ± 0.5 mm. This result was obtained in the repeatability study, where each user performed the pupillary calibration procedure.

A different approach worth mentioning is a system that utilizes the Magic Leap 1 headset and the external Brainlab Curve navigation platform [9]. The authors used an optical reference array attached to a needle to track its position, radiopaque markers for registration of the CT data with a phantom model, and a custom disposable hybrid marker to align coordinate systems of the headset and navigation system camera. The registration of the phantom model with the virtual one was achieved in all of the cases. The positional error of needle placement was measured in the axial and sagittal planes. The median axial positional error and the median sagittal positional error were 1.0 mm and 1.1 mm, respectively.

It can be observed that the accuracy of surgical navigation is strictly dependent on the tracking accuracy of marker positions. In conclusion,it is crucial to recognize markers as accurately as possible.

B. Marker registration accuracy

When measuring the accuracy of marker registration, key factors considered include marker size, position, distance, and angle between marker and sensor. Similar aspects were examined in research on the registration accuracy of HoloLens in nonclinical settings for high-precision surgical tasks in [10].

A recent study has investigated the accuracy of ArUco marker tracking using mono and stereo vision from the Microsoft HoloLens 2 headset [11]. They have considered different mono camera resolutions while stereo camera have only one resolution available. For their experiment, three different marker sizes were evaluated at four distances from the headset. The results have shown that the translational error decreases while increasing the marker size and decreasing distance from camera for all setups. The lowest error was 2.8 ± 1.7 mm which was reported for the mono camera with the highest resolution using a marker of size 10 cm that was viewed from a distance of 50 cm. The stereo tracking error was relatively low at close distances (3.3 ± 0.2 mm for marker of size 10cm viewed from a distance of 50cm) but it was rising exponentially with increasing distance (56.9 ± 5.0 mm for the same marker viewed from a distance of 140 cm). They have tested also a combination of mono and stereo tracking by taking the average of the z-axis translational component from those two approaches. The lowest possible resolution of a mono camera was used. This method outperformed other approaches with an accuracy comparable to that obtained with a mono camera at the highest resolution.

III. Methods and Metodology

For this experiment, a marker-based approach was used. The measurement sequence consisted of setting up a selected marker on a measurement station at a designated location.

The user then put on a Microsoft Hololens 2 headset and positioned themselves at the specified measurement distance. This approach enables detecting the markers and obtaining information about the position error from different distances and angles.

A. Markers and detection techniques

Two frequently used marker types, namely QR Code and ArUco marker, were used to analyze marker registration accuracy. The selection of these particular markers was determined by the widespread availability of their recognition methods. On the one hand, the Microsoft Hololens 2 headset has a built-in package dedicated to QR Code recognition. On the other hand, there is the open-source ArUco library that allows for tracking of square fiducial markers.

1) QR Codes: To investigate the accuracy of QR Code registration, a custom application was developed using the Microsoft.MixedReality.QR package. The marker detection process provides information about the size of the marker and the position of its upper left corner (Fig. **??**). Then, it is possible to create bounding box around the marker. Thus, it is crucial to analyze the detected size and position error of the upper left corner. The documentation provides the declared error ranges of the Microsoft.MixedReality.QR package. Firstly, the error in detecting the size of a marker is up to 1% of the actual size of the marker. Secondly, under continuous detection, the placement of a code might deviate by a maximum of $\pm$ 2.5 mm. Furthermore, Microsoft states that the tested marker must have a minimum side size of 4-5 cm, and under such conditions, it can be detected from distances of up to 50 cm. Whereas, larger markers with side lengths of up to 25 cm can be detected from up to 2 meters [12].

This study focuses on verifying Microsoft's stated error ranges and analyzing the detection of smaller markers, as they may be more suitable and useful for medical navigation systems.

2) ArUco marker: In order to detect ArUco markers, a custom algorithm based on the OpenCV library was created. The implemented application receives input from the RGB camera and depth camera streams. The output of the system consists of the coordinates of the four corners and the central point of the marker.

B. Measuring stations

Figure 1 shows two measuring stations that were created to enable imitation of the doctor's posture while operating. At the measurement station A the effect of distance was investigated with a fixed angle α of 90 degrees. Whereas, at measuring station B the effect of angle on detection results was additionally observed. The angle value α was defined by the height of the user and his distance from the marker.

1) Marker sizes: The study examined and compared the detection capabilities of markers of 4 sizes: 75mm, 65mm, 37mm and 23mm Such sizes were chosen because of their usefulness in the context of medical navigation systems.

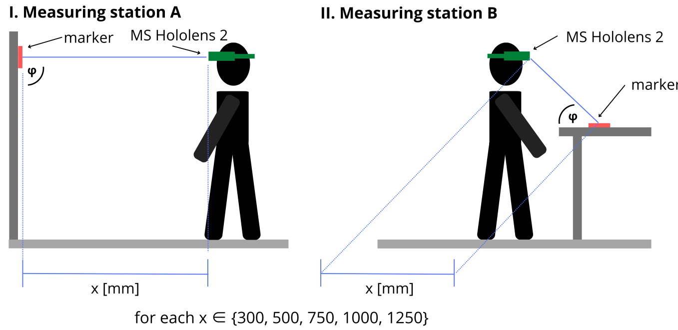

Fig. 1: Schematic diagram of the measuring stations.

2) Marker positions relative to the Microsoft Hololens 2: At each measurement station, measurement locations were set so that the distance between the marker and the headset sensor was equal to 300, 500, 750, 1000 and 1250 mm, respectively. The selected distances correspond to the typical distances at which physicians are positioned during medical procedures.

C. Measuring techniques

The proper measurement method was chosen depending on the analyzed aspect and marker type. All procedures used are described below. The measurements at both stations were repeated 10 times for each marker size from each measurement distance.

1) Detection of the QR Codes size: After each successful detection, the size of the recognized QR code was recorded. Finally, data was averaged for each QR Code size.

2) Marker registration accuracy: Measurements were taken for each type of marker: QR Code and ArUco using a certified INSIZE 1111-100A Mini Digital Caliper that meets the DIN862 standard [13]. The position error was calculated as the distance between the actual point and its hologram. For the QR Code, the position error of the top left corner was examined (Fig. 2), while for the ArUco marker, the central point and four corners were analyzed (Fig. 3).

IV. Results

This section presents the results of the QR code size measurements and the analysis of the effect of distance, marker position, and angle between the marker and the sensor on registration accuracy.

Fig. 2: QR Code.

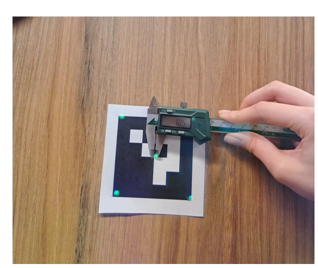

Fig. 3: ArUco marker.

TABLE I: Detection of the QR Codes size.

	Actual marker size ∼75 mm [mm]		Actual marker size ∼65 mm [mm]		Actual marker size ∼37 mm [mm]		Actual marker size ∼23 mm [mm]	
Max. size error tolerance according to Microsoft *	0.747		0.645		0.365		0.220	
	Mean with std [mm]	**Median [mm]**	**Mean with std [mm]**	**Median [mm]**	**Mean with std [mm]**	**Median [mm]**	**Mean with std [mm]**	**Median [mm]**
measured using caliper	74.68 ± 0.21	74.66	64.532 ± 0.064	64.530	36.490 ± 0.077	36.485	21.992 ± 0.066	21.990
detected by Hololens 2	74.638 ± 0.022	74.631	64.524 ± 0.045	64.524	36.526 ± 0.017	36.523	-	-

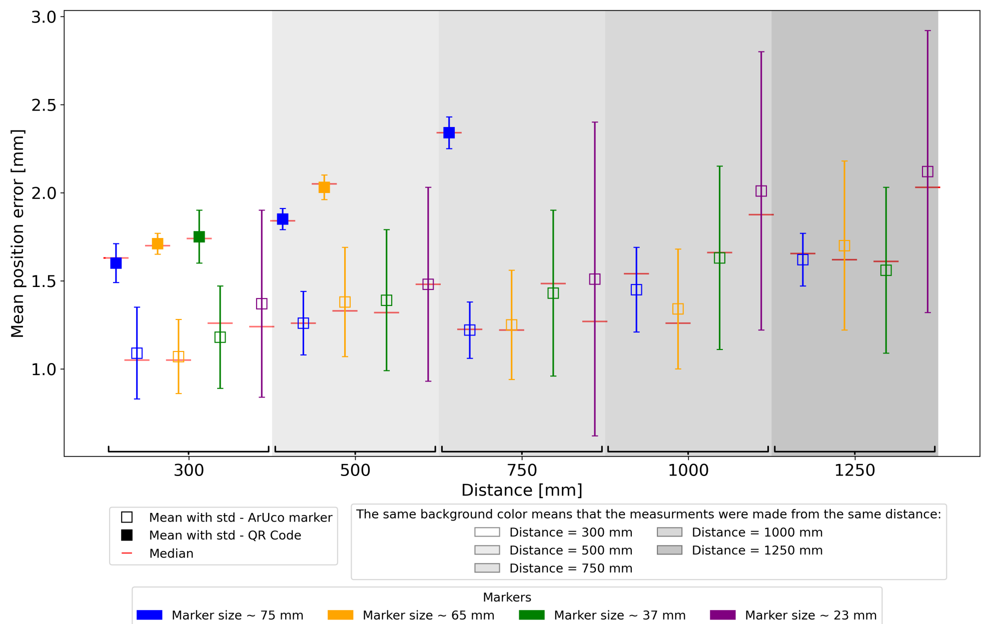

Fig. 4: Effect of distance on QRCode and ArUco registration accuracy.

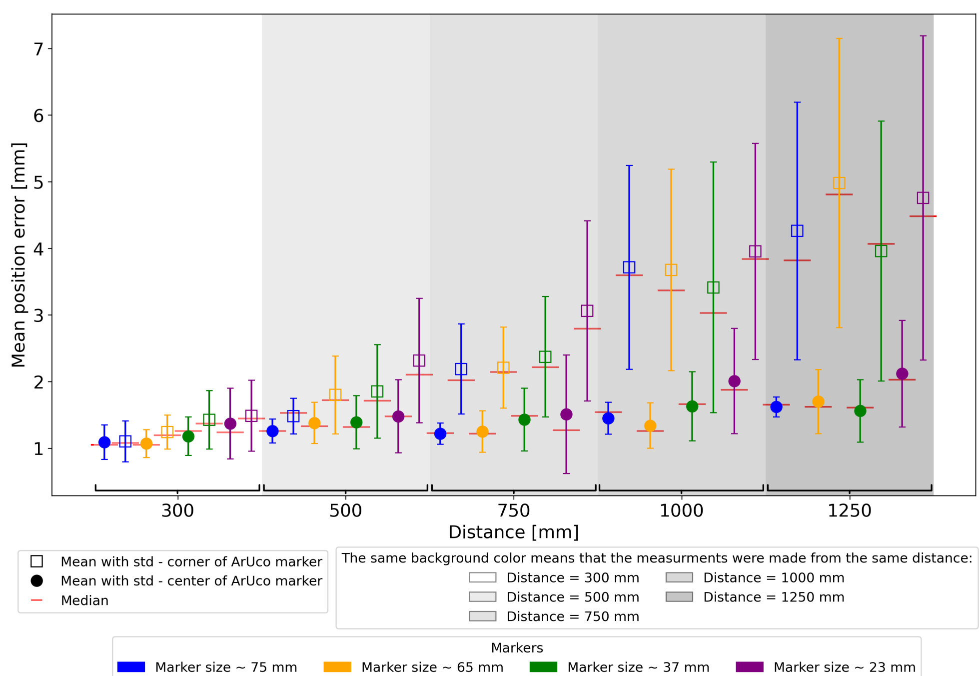

Fig. 5: Effect of distance on ArUco center and its corners registration accuracy.

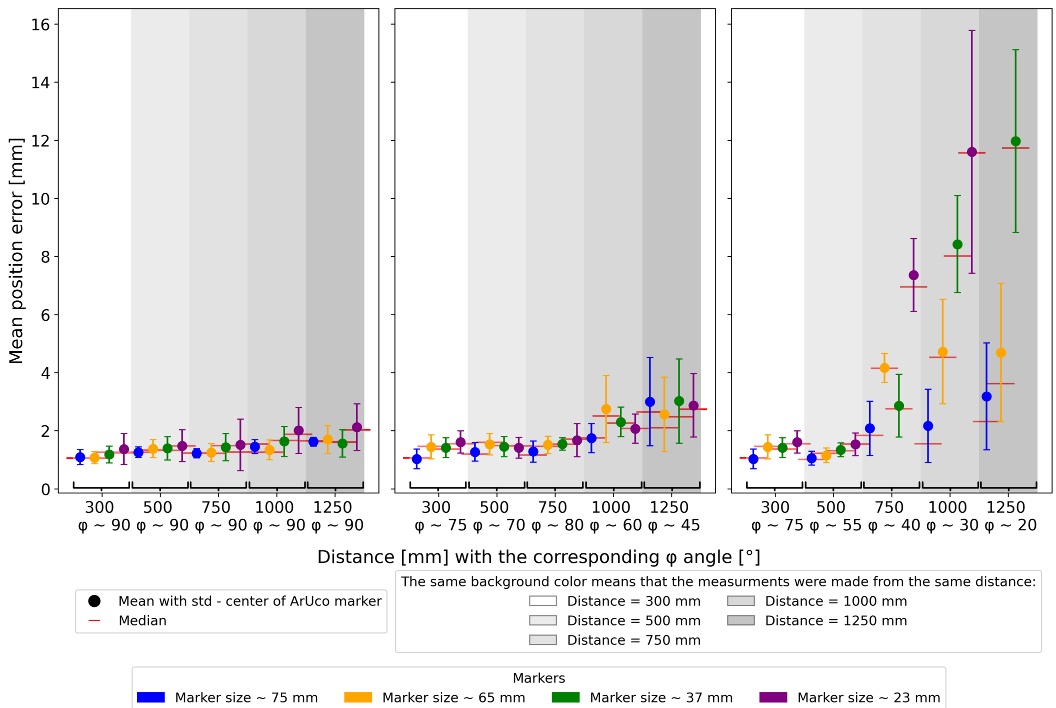

Fig. 6: Effect of angle and distance on ArUco center registration accuracy.

A. Detection of the QR Codes size

Table I compares the marker side size: measured manually with a caliper and detected by the Hololens 2 headset. The results are comparable. However, the smallest marker, with a side size of 23 mm, could not be detected regardless of the measuring distance.

B. Effect of distance on QR Code and ArUco registration accuracy

Figure 4 shows the effect of distance on the ability to detect QR codes and ArUco markers. The maximum distance from which the QR Code of size 75mm could be detected was found to be 750mm. Detection of 65mm and 37mm size codes were possible from closer distances, 500mm and 300mm respectively. However, measurement of the 37mm size marker proved to be more difficult to detect, making the process longer. In contrast, all sizes of ArUco markers could be detected from all distances considered. Furthermore, it can be observed that the standard deviations of the QR code position errors are similar and smaller than those of the ArUco markers. The results of ArUco's marker position error seem promising for each marker size, up to 1.5mm up to a distance of 750mm and up to 2mm up to 1250mm.

C. Effect of distance on ArUco center and its corners registration accuracy

ArUco markers have achieved satisfactory results, so it was decided to dive deeper into them. Figure 5 compares the position error of the center and corners of the ArUco marker. In both cases, the error increases with greater distances and as the size of the marker decreases. However, this phenomenon occurs much faster for the corners than for the center. Similarly, the standard deviation of position errors are also much larger for the corners than for the center of the marker. Position error of corners is up to 2mm only from a distance of 300mm for all marker sizes.

D. Effect of angles and distance on ArUco center registration accuracy

The accuracy of detecting the center of the marker is much higher than that of the corners. Therefore, it was determined to investigate the effect of angles (ranging from 20° to 90°) on the results (Fig. 6). The position error of the central point increases as the value of the alpha angle decreases. For an angle equal to 45 degrees, the error is about 3 mm for each marker size. For degrees less than 45 degrees, a significant increase in position error was observed.

V. Discussion

The measurement stations used in this article were designed to replicate the working conditions of a doctor in an operating room. Accordingly, we obtained a number of practical conclusions:

- Our experiments confirmed the size and translation error ranges given by Microsoft documentation. The maximum detection distance for QR Codes was achieved for a marker of size 7.5cm, reaching a distance of 75cm. However, the smallest QR Code, measuring 2.3cm, proved to be too small to be recognized. Based on the results obtained, it can be concluded that QR codes do not

meet the necessary requirements for their use in medical navigation systems.
- ArUco markers of all the sizes considered were successfully detected across all the measurement distances examined in the study. These results indicate that the detection of ArUco markers is comparatively easier than the detection of QR codes, especially at distances greater than 50 cm. This fact can be attributed to the difference in the amount of information represented by each code and thus to the lower resolution of the marker. QR codes at distances greater than 50 cm need to be much larger to be detected, which is a limiting factor for their potential use in the operating room.
- Detection errors for the centers of ArUco markers are much smaller than detection errors for their corners. Moreover, these errors are of the same order of magnitude regardless of distance.
- There is a correlation between the decrease in registration angle and the increase in position error. For angles smaller than 45 degrees, this error reaches unacceptable values (above 3mm). However, it should be noted that, in the intended use of the device, during operations, such angles should not occur.
- The deformation of the marker geometry increases with the registration distance and decreasing angle to the marker plane. In the case of ArUco markers, this is due to the detection of each corner of the marker and its center separately. For QR markers, this is caused by detecting only the upper left corner of the marker and using a bounding box of the set dimensions.
- Due to the geometric deformations described above, it is necessary to treat the marker as a point and not as a plane.

In summary, the results presented in this paper suggest that it is possible to detect markers of suitable sizes for use in AR-based surgical navigation systems. Such systems, in addition to all the advantages of traditional tracking systems, can provide physicians with additional information about the anatomy of the patient without leaving the sterile field. However, the measurements described above clearly show that the use of markers and AR set for medical navigation is not a solution without drawbacks. Nevertheless, taking into consideration the convenience of using AR systems in comparison to traditional medical navigation, the relatively low cost of such solutions, and potential possible integrations, further development in this direction should be considered. Of course, technical limitations should be taken into account and the system used should be appropriately adapted to specific medical procedures in terms of the required precision of navigation. The main constraints of the current solution are hardware capabilities. Therefore, utilizing cameras with higher resolution will probably lead to improved overall accuracy.

VI. Conclusion

The article addresses the accuracy of the detection of ArUco markers and QR codes using the AR kit for medical navigation. Despite existing similar studies, the novelty of our work was the use of measurement scenarios that reproduce the real conditions of a surgeon. The tests carried out showed that ArUco markers are detected with higher accuracy, more stably, and at longer distances, which is critical in the operating room in terms of ensuring sterility. The tests we conducted can serve as a reference for many different applications of AR googles in the context of optical-marker based medical navigation.

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