Study of HMD Tracking Systems Accuracy Applied to Short Head Displacements

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Abstract *– The aim of this experiment was to characterize and compare the tracking systems of 5 HMDs (Microsoft Hololens 2; Vive Pro 2; Vive Focus 3; Varjo XR-3 with Vive lighthouse; Varjo XR-3 in standalone mode) on short distance displacements (max 50cm) for phygital applications. A UR5 robotic arm was used to move HMDs along square and round trajectories, at slow speeds, high speeds, and variable speeds. To study the accuracy of HMDs, their position data were compared to position data recorded by an external robust passive infrared tracking system which serves as a groundtruth. The results shown that the Varjo XR-3 has the best accuracy with an average error of 0.23 cm. The HMD with the worst accuracy is the Vive Pro 2 with an average error of 1.24 cm, followed by the Hololens 2, the Vive Focus 3 and the Varjo XR-3 SLAM with an average error of 1.22 cm, 0.58 cm, and 0.54 cm respectively. The analysis of the results shown that in the case of phygital applications in driving cockpits with a high demand of accuracy (up to 1mm), the Varjo XR-3 with Vive lighthouse or other optical tracking systems is a good solution. In the case of larger scale phygital applications such as vehicle exterior reviews, which require larger movements and lower levels of accuracy (up to 1cm), standalone HMDs such as the Vive Focus 3 are more beneficial.*

Keywords: *Head Mounted Displays; Tracking Systems; Virtual Reality; Augmented Reality; Phygital Simulation*

1. Introduction

Nowadays, virtual reality is more and more used for assessment phases during vehicle design. Virtual reality helps to shorten the validation loops and the number of physical prototypes produced. To carry on this dynamic, Renault Group is exploring on the development of “phygital” simulation platforms. These platforms are composed of few physical parts of the vehicle that users interact with, completed with the rest of the vehicle model in virtual reality.

However, for this workflow to be viable, it is necessary to ensure that the platform reaches a level of immersion and realism close to the real, or at least high enough to allow correct validation of design of the future vehicles. The imbrication of these worlds is possible thanks to high tracking accuracy and known system errors.

The experimentation described in this paper aims to study and compare the accuracy of 5 different virtual/augmented/mixed reality HMDs (Head Mounted Displays) using different technologies and tracking systems. To do this, we compared the position data recorded by the native tracking systems of the HMDs with position data recorded by an external infrared optical tracking system that have served as a reference.

1.1 Previous and related work

Several studies have been conducted to characterize tracking systems used in virtual reality. Although those studies are quite recent, from 3 to 5 years, they focus on first generation VR HMDs such as the HTC Vive Pro, the Oculus rift, the Oculus Quest and the Vive Tracker. The data measured in these studies were accuracy error (expressed in distance), tracking latency, refresh rate as well as tracking jitter (ability to remain static). Overall, the measurement methods were similar: an external position measurement system was used as a reference and compared with the position recorded by the head-mounted display (HMD) tracking system. 3 different reference measurement systems were employed.

The first tracking system most used as a ground truth in literature are passive infrared optical tracking system (as ART or Optitrack motion capture systems). Studies have been conducted on the tracking of the Oculus Rift S (Jost, et al., 2019; Monica and Aleotti, 2022). They compared the outside-in tracking of the HMD with an optical tracking system and used a robotic arm to move the HMD. Results shown good accuracy for translations (1.66 ± 0.74 mm) and rotations ((0.34 ± 0.38◦). Ameler, et al. (2019) and Lubetzky, et al. (2019) conducted similar studies to compare the performance of the Oculus Rift, the HTC Vive Pro and the HTC Vive Tracker and found better results for lighthouse tracked Vive products with an accuracy of 1mm. However, Bauer, et al. (2021) conducted a study on the HTC Vive Pro with HTC Vive lighthouses, in which the experimental protocol consisted of sliding the HMD, controllers and trackers on a linear bench. Results shown a good reproducibility of a few centimeters although it revealed a drift problem when using multiple lighthouses. Finally, Van der Veen, et al. (2019) also used an optical tracking system as a reference coupled with a robot to obtain known and repeatable trajectories. The results shown an error of 6.8mm with the optical tracking system.

The use of collaborative robots as reference tracking is also common in the literature, both robot arms and mobile robots. Ikbal, et al. (2021) studied the accuracy of an HTC Vive Pro and found an error of 1mm in static and 3mm in motion. Borges, et al. (2018) also used a robot as a reference to characterize the motion of the HTC Vive Tracker, they found similar results to the HTC Vive Pro with a static accuracy greater than 1mm. Lwowski, et al. (2020) conducted a similar study, however the Vive Tracker tracking results were impacted by a drift.

Finally, some papers present experimental protocols where physical markers such as checkerboards on the floor are used as a reference to characterize VR HMD accuracy. Niehorster, et al. (2017) characterized the accuracy of an HTC Vive Pro using static poses with a grid of known dimension on the ground. Then, they compared the positions recorded by the HMD with the positions of the HMD on the grid. Results shown good tracking accuracy as well as low latency of the tracking system (22ms). However, each time a drift occurred, the tracking accuracy was lost unless the system was recalibrated, making it too unstable to conduct scientific studies requiring accurate tracking, according to the authors. Borrego, et al. (2018) conducted similar study to compare the accuracy of an HTC Vive Pro to that of an Oculus Rift, with a physical grid as the reference tracking. Results shown similar performance for the 2 HMDs with an accuracy of approximately 1cm and a jittering error of 0.35mm. Holzwarth, et al. (2021) conducted a study using a physical grid on the ground to compare the accuracy of an Oculus Quest 2 with a Vive tracker. Results shown the standalone HMD to be much more accurate and stable with a position error of 1mm, compared to the Vive Tracker with a position error of 7mm.

1.2. Research Question

Today, several tracking technologies of new generation are available for virtual reality, each with its own advantages and disadvantages. The purpose of this study is to evaluate and compare the performances of 5 different tracking systems for short displacements (less than 50cm) for use in phygital platforms dedicated to automotive cockpit studies.

2. Method

2.1. Experimental setup

2.1.1. Measurement platform

As shown in Fig. 1, HMDs were installed on a 3D printed human like head of mean proportions.

Figure 1: Picture of the 3D printed head installed on the UR5 with a Hololens 2 mounted on it.

HMDs movements were operated by a UR5 (Universal Robot 5) robotic arm, which has a precision of 0.1mm. The robot has a maximum payload of 5Kg, which was under the weight of the HMD + 3D Printed skull. The head was fixed to the end of the arm using screws.

2.1.2 Head-mounted displays

5 different HMDs were tested during the experimentation, all with different tracking systems:

- Hololens 2: a Microsoft SLAM (Simultaneous Localization and Tracking) algorithm.
- Vive focus 3: a Vive SLAM algorithm.
- Vive Pro 2: Vive's Lighthouses.
- Varjo XR3 SLAM: a Varjo SLAM algorithm.
- Varjo XR3 LH: Vive's Lighthouses.

The reference tracking system used to analyze the precision of the VR HMDs tracking systems was a passive infrared optical tracking system called ART Trackpack. This system had a precision of 0.1mm and a frequency of 60Hz (ART Technical datasheet TrackPack). The ART installation consisted of 4 cameras, distributed in a CAVE area as indicated in Fig. 2.

2.1.3. Experimental environment

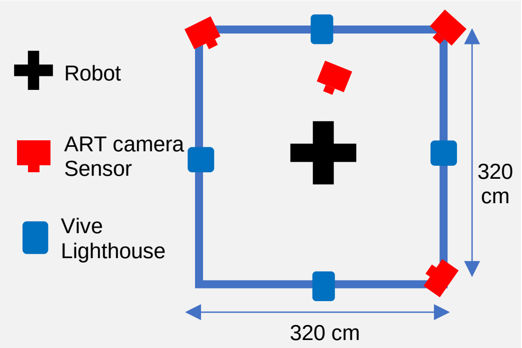

Figure 2: Map of the room scale environment used for the experimental setup.

The robot was positioned in a CAVE (dimensions: 320mm x 320mm x 270mm), 160mm away from all the sides (Fig. 2) and at 130cm high. Black and white grid patterns were displayed on the surfaces of the CAVE using projectors, and furniture were added to help SLAM algorithms to better map space. Same area had 4 Vive's Lighthouses to use Steam VR tracking system. They were distributed in the area as indicated in Fig. 2. Furthermore, the light conditions and the placement of the elements in the CAVE were the same for all the HMDs and during the whole experimentation.

The desktop computer used for the experimentation included an Intel® Xeon® Gold 5120 CPU @ 2.20GHz, 64GB of RAM and an Nvidia RTX 6000 GPU.

2.2. Experimental procedure

2.2.1. Trajectories

The robot performed multiple calibration trajectories, as shown in Fig. 3, for each HMD, which consisted of 3 translations of 10 cm along the 3 main axes. These trajectories were done at the beginning and during the experiment between all the measurement trajectories. Then, they were being used later during data processing to compare the HMDs to the ART tracking recorded positions.

All the movements realized during the different trajectories were translations, HMDs faced the same direction throughout the measurements and the HMD rotation did not change at any time.

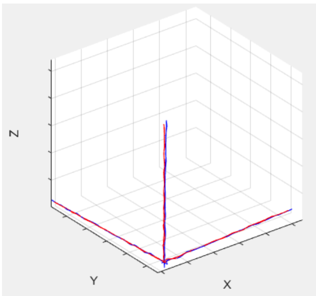

Figure 3: Calibration diagram path.

For the measurements, the robot performed 2 trajectories, as shown on Fig. 4:

- Square trajectory : 4 straight translations of 14cm composed of ± 10 cm on X and Y axis, and ± 5cm on the Z axis.
- Circle trajectory : 4 curves of 90° with a radius of 10 cm composed of ± 10cm on X and Y axis and ± 5cm on the Zaxis.

The robot repeated the measurement trajectories under 3 speed conditions :

- Low speed: speed = 50mm/s, acceleration = 2000mm/s^2 and completion time = 21s.
- High speed: speed = 300mm/s, acceleration = 2000mm/s^2 and completion time = 12s.
- Acceleration/deceleration: speed = 300mm/s, acceleration = 15mm/s^2 and completion time = 40s.

Finally, at the end of the experiment, a static position measurement was done, lasting t = 10s. This static position measurement was intended to measure both the stability and the drift of HMDs.

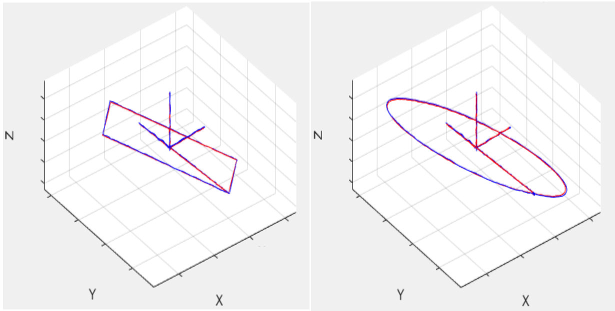

Figure 4: Square and circle measurement diagram paths.

2.2.2. Data acquisition

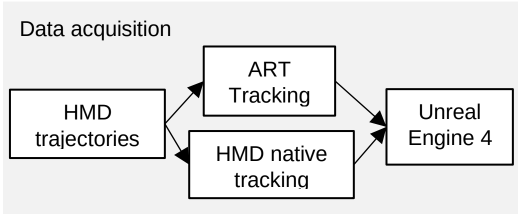

Figure 5: Data acquisition process.

The data acquisition process is described in Fig. 5. In a first step, the HMD which was mounted on the robotic arm, performed a calibration trajectory. Then several measurement trajectories were carried out by the robot thank to an URP script wrote on and executed by the robot controller. Tracking data of HMDs were recorded a first time by Steam VR v1.23.7 software which receive the data provided by the sensors of the HMD. Then, tracking data of the HMD were recorded a second time by Dtrack 2.0 software which received the tracking data recorded by the trackpack camera. These 2 softwares sent their data to Unreal engine 4.27, thanks to Unreal Engine plugins, which expressed their positions as X, Y and Z coordinates each frame at 60 frames per second. Then the data were exported in a text document thanks to an Unreal Engine script.

2.2.3. Data processing

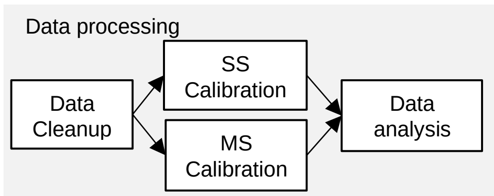

Figure 6: Data treatment process.

The data treatment process is described in Fig. 6. The data were first automatically cleaned in excel to remove any capture error that could distort the results. Then different calibration methods were used with MATLAB r2020 to study the recorded motion curves. Details of the calibration procedures are defined in the paragraph below. Finally, data were analyzed with MATLAB r2020 to determine the tracking errors of each trajectory for each HMDs, as described in section 5.

HMDs and ART tracking data were calibrated, processed, and analyzed in MATLAB R2020b using 2 distinct methods that are represented in Fig. 7 (Zhang and Scaramuzza, 2018):

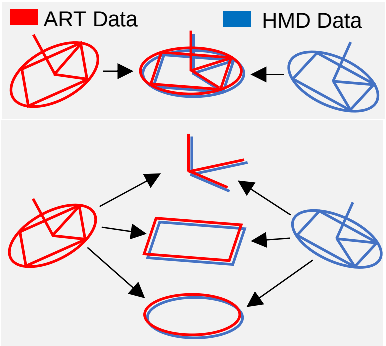

Figure 7: Single State (SS) and Multiple state (MS) calibration representation.

- SS (Single State): a single calibration with a calibration trajectory operated at the beginning of the experimentation to compare all the measurement trajectories of the 2 tracking systems.
- MS (Multiple State): multiple calibration with multiple calibration trajectory operated during all the experiment at the beginning of each measurement trajectory to compare the measurement trajectory of the 2 tracking systems.

Because of the MS calibration method which divides a curve into several pieces to compare them to each other, the difference between the calibration methods allows to cancel or not the effect of drift which can occur during the measurements. Also, depending on the calibration method used, the static position measurement can be used to measure the drift of a tracking system as well as its stability.

3. Results

Results are presented one by one for each HMD and show the mean tracking error for each trajectory and speed condition for both SS and MS calibration methods. The mean accuracy error of the HMDs, expressed in cm, is calculated as the mean of the distance at each frame between the point recorded by the HMD's origin tracking system and the point recorded by the reference tracking system. Results also presents the standard deviation and the maximum error for each trajectory performed by the HMD.

3.1. Hololens 2

Fig. 8 left shows that the largest mean error of the HoloLens 2 was obtained during the square trajectory at high speed, with a maximum recorded error of 5.24 cm in SS calibration. We also observe in Fig. 8 that the Hololens 2 drifted a little during the measurements and is rather stable in static position. However, the overall mean error of the HoloLens 2 is 1.22 cm in SS calibration despite a little drift (0.31 cm) and a good stability (0.11 cm). These results are confirmed by the small difference between the values obtained with the MS calibration and the SS calibration. Finally, there is a significant difference (p=0.04) between the high-speed trajectories and the low-speed trajectories, which can be explained by the low frequency of the Hololens 2 depth sensor (30fps).

3.2. Vive Focus 3

The lowest mean error (0.38 cm), presented in the Fig. 8 right, was recorded for the square trajectory at low speed, and the highest mean error (0.72 cm) was recorded during the circle trajectory at high speed. The drift measurement in SS calibration shows a value of 0.6 cm throughout the experiment, and the stability measurement in the MS calibration shows a value of 0.04 cm. The SS calibration data shows a larger and increasing mean error compared to the MS calibration data, which can be explained by the drift that occurred during the experiment, especially during the acceleration and deceleration trajectories. This drift, which can be caused by the inertial sensors of the Vive Focus 3, remains nevertheless under the centimeter.

3.3. Varjo XR-3 SLAM

Fig. 9 left shows the results of the varjo XR3 set in SLAM mode. The highest mean error recorded during the square trajectory at high speed was 0.69 cm and the lowest mean error recorded during the square trajectory at low speed was 0.45 cm. There is little difference between the SS and MS calibrations, which is explained by a reliable drift during the measurements and is confirmed by the 0.1cm drift measurement. However, a large error of 0.28cm can be observed in the stability measurement. Nevertheless, the mean error of 0.54cm show this HMD as a material with a precision below the centimeter.

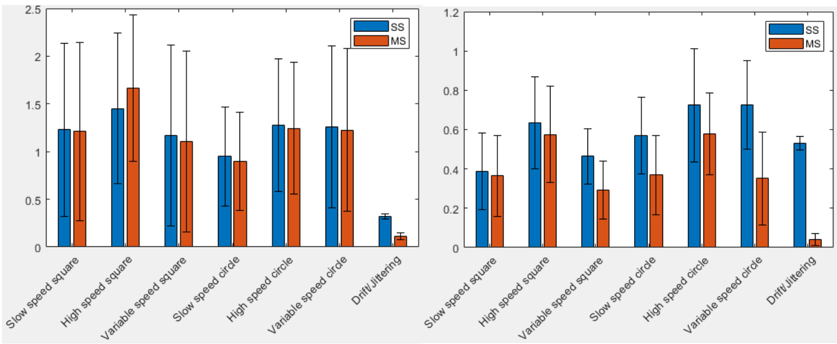

Figure 8: Mean tracking error in cm and standard deviation of the Hololens 2 (left) and Vive Focus 3 (right) for all measurement trajectories.

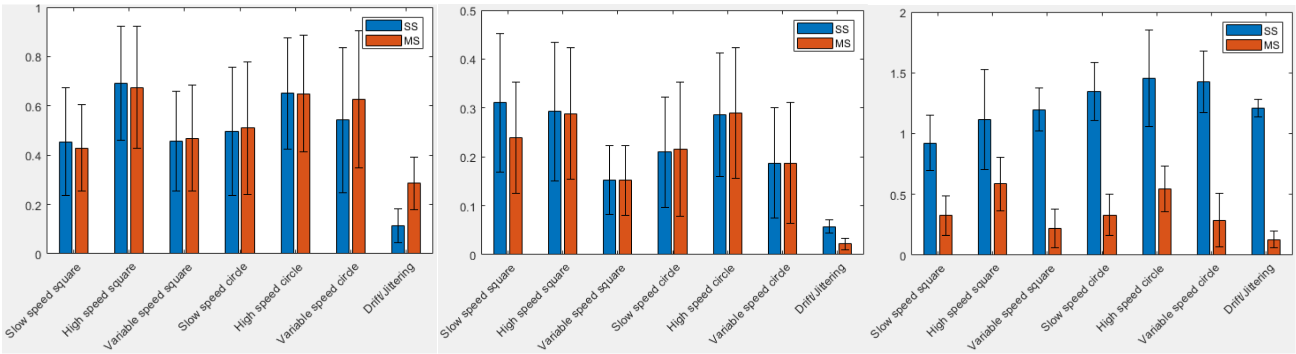

Figure 9: Mean tracking error in cm and standard deviation of the Varjo XR-3 SLAM (left), Varjo XR-3 with Vive Lighthouse (middle) and Vive Pro 2 (right) for all measurement trajectories.

3.4. Varjo XR-3 with Vive Lighthouse

Fig. 9 middle shows that the Varjo XR-3 tracked by the Vive Lighthouses obtains mean tracking error of 0.23 cm. We observe that the maximum error recorded (1.54 cm) comes from the circle trajectory at low speeds, and the highest mean error recorded (0.31 cm) comes from the square trajectory at low speeds. The lowest mean error measured (0.15 cm) is obtained during the square trajectory in acceleration/deceleration. Finally, we observe a very small drift of 0.05cm supported by a very small difference between the SS calibration values and the MS calibration. We also observe a very high stability, with an error of 0.04cm. These results show that the Varjo XR-3 with the Vive Lighthouse is a very robust tracking system with an accuracy in the millimeter range.

3.5. Vive Pro 2

We observe a significant difference (p=0.000006) between the results obtained with the SS calibration method and those obtained with the MS calibration method, as well as a significant difference (p=0.01) between the square trajectories and the circle trajectories with the SS calibration (Fig. 9 right). These values are explained by a large drift of 1.2cm occurred throughout the measurements. However, we observe with the MS calibration values that the maximum average tracking errors occurred during the high-speed trajectories, and the minimum average errors during slow speed trajectories. Finally, we observe a good stability value of the system of 0.12cm.

4. Discussion

4.1. Comparison of HMD's results

Analysis of HMDs results was done with ANOVA test, to find significant differences in the results according to the different experimental conditions. The results used for the comparison are those obtained with the SS calibration method, because it is the one that is the closest to the use of HMDs in real conditions.

4.1.1. SLAM vs Vive Lighthouse HMD's

For this first comparison SLAM HMDs are compared to Vive Lighthouse HMDs. As shown on Fig. 10 left, we observe a non-significant difference (p=0.28), the SLAM HMDs having obtained a lower mean tracking error compared to the HMDs tracked with Vive lighthouse. This non-significant difference can be explained by the drift recorded during Vive Pro 2 measurements, which increases the error of HMDs tracked by the Vive Lighthouse.

4.1.2. Square trajectory vs circle trajectory

There is a non-significant difference (p=0.62) between the mean errors of the tracking systems for the square and circle trajectories (Fig. 10 middle). HMDs are more accurate during straight movements than when performing curves. This can be explained by the simplicity of the rectilinear movement compared to the circle trajectory.

4.1.3. Slow speed vs high speed vs acceleration/deceleration

Finally, Fig. 10 right presents a comparison of the average tracking errors obtained according to different speeds. We observe non-significant differences (p=0.48) between all the speeds conditions. The tracking systems made less error when moving at slow speeds than high speeds. This result can be explained by the slow speeds trajectories longer recording time (t=21s) compared to the high-speed trajectories recording time (t=12s). It is also observed that the mean tracking error obtained during trajectories with accelerations and decelerations is included between the mean tracking errors of slow and high speeds.

4.2. Discussion on tracking accuracy for phygital and virtual uses cases

Some phygital uses cases require more precise interactions with physical objects such as tactile interfaces or control buttons and will require a more precise level of tracking up to the millimeter. This is the case for driver cockpit simulation, where the user is seated and needs to have a physical and virtual match on the seat, steering wheel, switches, and tactile screen control interfaces. In these use cases,

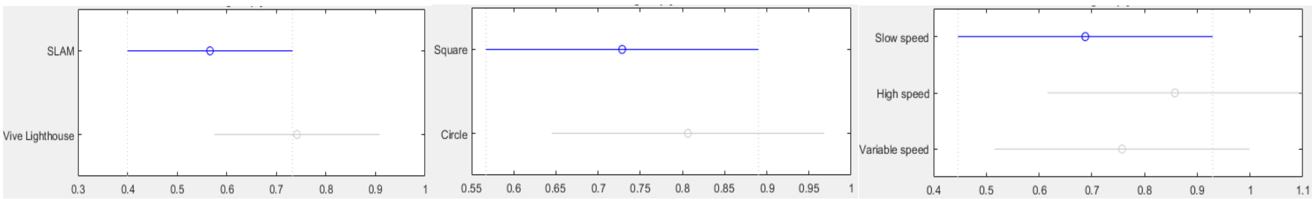

Figure 10: Left: Mean ranking of SLAM HMD's vs Vive Lighthouse HMD's, based on mean tracking errors in cm (p=0.28). Middle: Mean ranking of square trajectory vs circle trajectory, based on mean tracking errors (p=0.62). Right: Mean ranking of Slow Speed vs High Speed vs Acceleration/deceleration, based on mean tracking errors in cm (p=0.28).

the user's movements are small and not very fast due to his seated position. Therefore, HMDs tracking systems with a high level of precision will be required, such as the Varjo XR-3 with Vive lighthouse, or HMD with passive infrared optical tracking systems.

Other phygital uses cases require less precise physical interactions such as simple palpations of physical surfaces like the body of a car, the contours of a dashboard, or a seat, with a centimeter precision needed. In these use cases, which usually are reviews of outdoor vehicles, user's movements have a greater amplitude up to several meters, with strong accelerations and decelerations. These uses cases are more suited to standalone HMDs, which track themselves such as the Vive Focus 3 or the Oculus Quest 2 (Holzwarth, et al., 2021), to avoid wires during large movements around a mockup. However, wired HMDs such as the Varjo XR3 in SLAM mode or the Vive Pro 1 (Bauer, et al., 2021; Ikbal, et al., 2021; Lubetzky, et al., 2019; Borrego, et al., 2018) and the Vive Pro 2 with Vive lighthouses are also adapted.

Finally, some HMD can be used for VR and AR applications to visualize models or virtual interactions, but in the case of phygital applications where the slightest gap between physical and virtual objects can reduce the feeling of presence of users, the choice of tracking system is more demanding. Therefore, the use of HMDs like HoloLens or Oculus Rift S (Monica and Aleotti, 2022) is not suited for phygital applications.

5. Conclusion

This paper presented an evaluation and comparison of the accuracy of tracking systems of 5 virtual, mixed, and augmented reality HMDs on small distances. The native tracking systems of the HMDs were compared with an external optical tracking system that served as a reference. The results shown that the Varjo XR-3 has the best accuracy with an average error of 0.23 cm. The HMD with the worst accuracy is the Vive Pro 2 with an average error of 1.24 cm, followed by the Hololens 2, the Vive Focus 3 and the Varjo XR-3 SLAM with an average error of 1.22 cm, 0.58 cm, and 0.54 cm respectively. The analysis of the results shown that depending on the phygital applications, the needs on the quality of the tracking could be constraining. In the case of phygital applications in driving cockpits, where the type of motion and interactions require a high level of accuracy, the Varjo XR-3 with Vive lighthouse or other optical tracking systems is a good solution. In the case of larger scale phygital applications such as vehicle exterior reviews, which require larger movements and weaker level of interactions with lower accuracy, standalone HMDs such as the Vive Focus 3 are more beneficial.

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