Comparing the Accuracy and Precision of SteamVR Tracking 2.0 and Oculus Quest 2 in a Room Scale Setup

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ABSTRACT

Real walking is the most intuitive navigation means to explore large virtual environments. For such a free walking Virtual Reality (VR) experience, large tracking spaces are required as well as dedicated motion tracking systems covering them. In the past, the coverage of large tracking spaces could only be achieved by professional-grade motion tracking systems. Recently, low-cost, consumer-grade motion tracking systems, such as SteamVR Tracking and Oculus Insight, have arisen, which also allow for room scale setups. However, the capability, limitation, and reliability of consumer-grade VR motion tracking systems is not fully understood yet. In this paper, we aim to fill the gap by comparing SteamVR Tracking and Oculus Insight in a 5m $\times$ 5m room scale setup, using state of the art hardware (i.e. the Oculus Quest 2, SteamVR base stations 2.0 and High Tech Computer Corporation (HTC) Vive Trackers Version 2018). The results reveal a significantly higher accuracy for the Oculus Quest 2 compared to SteamVR Tracking in the height of a tracked object. Furthermore, the Oculus Quest 2 tracks its position with substantially higher precision than SteamVR Tracking. Based on the results, we conclude that the Oculus Quest 2 is suitable for a wide range of applications in research and industry, particularly considering its lower acquisition costs, higher mobility and easier setup compared to SteamVR Tracking. However, as this work marks an initial step, more research is needed to fully understand the capabilities and limitations through other metrics (e.g. latency) and other setups (e.g. rooms with fewer landmarks or different lighting conditions).

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; *Mixed / augmented reality*.

KEYWORDS

Tracking system, Inside-out tracking, Motion capture, Head-mounted display

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1 INTRODUCTION

The naturalistic exploration of Virtual Environments through real walking requires large tracking spaces, wherein users can freely navigate. However, large tracking spaces also require motion tracking systems covering them. Besides coverage, tracking systems also need to fulfil certain quality criteria, such as high tracking accuracy and precision, as well as low latency. Through these means, a user's experience can be improved (e.g. by assessing their affective state [3]). Further, possible negative side-effects, such as Virtual Reality (VR) induced symptoms and effects (e.g. simulator sickness) can be mitigated [6]. The awareness of a tracking system's capabilities, as well as of its spatial and temporal reliability is important in order to assess the suitability for the intended application [13]. Professional-grade motion tracking systems fulfil these criteria well, as each system is extensively evaluated by the manufacturer before being shipped to the customer [7]. Furthermore, professional-grade motion tracking systems come with standardized calibration procedures that do not only ensure the system's accuracy and precision, but also reveal its current error [8]. While allowing for sub-millimeter tracking accuracy, low latency and high reliability, professional-grade motion tracking systems also come with some disadvantages: i) their setup and operation is know-how intense and time-consuming, ii) their acquisition cost is high, ranging from tens of thousand to more than a hundred thousand USD.

Recently, consumer-grade motion tracking systems have arisen, which are characterized by simple and fast setup, high mobility, as well as low acquisition cost (i.e. below a thousand USD). Although being initially intended for end-user VR experiences such as gaming and 360°video streaming, consumer-grade tracking systems became highly popular in research. However, the capabilities and

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limitations, as well as the reliability of consumer-grade VR motion tracking systems are not fully understood yet [7].

Thus, the validation of consumer-grade VR motion tracking systems is essential to assess their suitability for clinical, industrial, and research applications [5]. This validation can be carried out through assessing a tracking system's quality metrics, such as positional accuracy and precision [7, 9]. In this paper, we contribute to this discourse by comparing the positional accuracy and precision of two of the most common consumer-grade VR motion tracking systems – SteamVR Tracking and Oculus Insight – in a 5m × 5m room scale setup.

The remainder of this paper is organized as follows: While Section 2 gives an overview on related work of such comparative studies, Section 3 describes our setup for the comparative measures of SteamVR and Oculus Insight tracking in more detail. The achieved results are shown in Section 4, whereas Section 5 concludes our findings and gives an outlook on future work.

2 RELATED WORK

Prior research that explored the capabilities of consumer-grade VR tracking systems mainly focused on SteamVR Tracking, which is part of the widely popular HTC Vive System. In these works, SteamVR Tracking was compared to professional-grade tracking systems, such as Optitrack [1, 8] and Vicon [4, 13]. Furthermore, some studies utilized robotic arms for positioning an HTC Vive Controller [4] or HTC Vive Tracker [12] in repeatable, controlled motion. The main metrics to evaluate motion tracking systems include positional accuracy and precision (i.e. jitter) [7, 9].

Studies, which investigated on the *accuracy* of SteamVR Tracking, reported heterogeneous findings, with positional errors ranging between ≤1mm [1, 4] and 7.5cm [11]. The heterogeneity of these prior findings could be explained by tracking space size and distance between measurement points (i.e. larger tracking spaces and higher distances between measurement points tend to increase the positional error).

Precision is another important metric that was also investigated in prior works. However, the reported values are more homogeneous with sample-to-sample jitter of ≤2mm [9, 12]. It is also worth noting that all prior studies were conducted with first generation SteamVR base stations and thus, precision and accuracy should improve with the current SteamVR base stations 2.0 [12] that are used in this study.

Two prior studies investigated the Oculus Insight tracking system, with the first generation Oculus Quest Head-Mounted Display (HMD) [10] and the Oculus Rift S HMD [5]. Here, the positional accuracy was reported ranging from a mean of 1.66mm for the Oculus Rifts S HMD [5] to a mean of 6.86mm for the first generation Oculus Quest [10]. It is again worth noting that the accuracy is expected to improve with the current Oculus Quest 2 (i.e. second generation) HMD, which is used in this study. Regarding the precision of any device using the Oculus Insight tracking system, no prior works could be found. A technical overview comparing the two tracking systems Oculus Insight and SteamVR Tracking is provided in Table 1.

Table 1: Technical comparison of Oculus Insight and Steam VR Tracking.

	Oculus Insight	SteamVR Tracking
Tracking Paradigm	Inside-out	Inside-out
Degrees of Freedom	6	6
Tracking Data	IMU camera	IMU photo diodes IR lasers
Accuracy [m]	<0.007 [5, 10]	<0.075 [1, 4, 11]
Precision [mm]		≤2 [9, 12]
Room Scale	✓	✓
Standalone VR	✓	
Hand Tracking	✓	(✓)
Add. Tracked Objects		✓

3 MATERIALS AND METHODS

In this section, we outline the apparatus that consists of the SteamVR Tracking and Oculus Insight system, as well as a measuring carriage that we built for this study. Furthermore, we describe the measurement procedure through which the data is collected.

3.1 Apparatus

The apparatus consists of two HTC Vive Trackers and the Oculus Quest 2 that are rigidly mounted on a measuring carriage.

3.1.1 SteamVR Tracking. Steam VR Tracking is a system developed by Valve Corporation that is compatible with numerous consumer-grade VR systems (e.g. HTC Vive, Pimax, Valve Index), as well as professional-grade VR systems (e.g. Varjo, XTAL). Steam VR Tracking consists of a minimum of two base stations – also referred to as lighthouses – that are either permanently or temporarily mounted (e.g. on tripods) in the far corners of the tracking space ideally at a height of 2m. The base stations emit Infrared (IR) light, which is composed of pulses that contain encoded data about the orientation of the pulse relative to the base station and the ID of the emitting base station. These pulses are received by photo diodes arranged in a specific pattern on each tracked object (e.g. HMD, controller, tracker) and then converted into position-indicating digital envelope signals. Furthermore, each tracked object is constantly updated by Inertial Measurement Units (IMUs). Through this process, the system is able to track the position and orientation of the HMD, the controllers, and additional trackers with high update rates.

3.1.2 Oculus Insight. The Oculus Insight tracking system is developed by Facebook Inc. and made exclusively available on the Oculus Rift S, as well as Oculus Quest 1 and 2. Therefore, Oculus Insight does currently not allow to track objects other than its HMD and the two hand-held controllers. Oculus Insight tracking relies on three streams of sensor data: i) IMUs in the HMD and controllers that permanently assess linear acceleration and rotational velocity with low latency, ii) cameras in the HMD that create a 3D map of the room including landmarks (e.g. furniture corners) to compensate IMU drift, iii) IR Light-Emitting Diodes (LEDs) in the controllers that are detected by the HMD [2]. Oculus Insight does not require the setup of auxiliary equipment (e.g. base stations) and has substantially lower acquisition cost with the Oculus Quest 2 starting at 300 USD.

3.1.3 Measurement setup. The measurements were taken in a 7m × 13m room. The room has concrete and white brick walls, a concrete ceiling with a height of 3.6m, and a floor made of black tiles. There is no natural light in the room, the only light sources are the LED lights, which are located at the ceiling and ensure that the room is well lit. Four SteamVR base stations 2.0 (i.e. the lighthouses) are permanently mounted at a height of 3.1m. In the field of view of the four base stations, a 5m × 5m grid was marked on the floor with black points in 1m intervals. This resulted in a 36-point grid shown in Figure 1. The axes x,y, and z represent the three orthogonal unit vectors that span the three dimensional vector room in which the measurements are conducted. In accordance with the coordinate frame used in Unity, the axes x and z are parallel to an ideal, flat floor whereas the y coordinate indicates the height above the floor.

Two HTC Vive Trackers (Version 2018) and the Oculus Quest 2 HMD were rigidly mounted on a carriage, which is shown in Figure 2. The Vive Trackers were mounted on a planar surface 400mm apart from each other. The Oculus Quest 2 HMD was mounted on a foam head in the center between the two trackers which amounted to an additional height of 150mm above the Vive Trackers. Furthermore, we equipped the carriage with a downwards-pointing laser for floor positioning and a VR computer. The VR computer runs an Nvidia GeForce GTX 1070, an Intel i7-8700 and 16 GB of RAM, which fulfills the Oculus Quest 2's hardware requirements. The Oculus Quest 2 was connected to the computer via the Oculus Link USB-C cable. Accordingly, both Vive Trackers were connected to the computer via the supplied HTC Vive USB 2.0 cables. Although one HTC Vive Tracker would have been technically sufficient to conduct the intended measurements, the second Vive Tracker was installed as means to continuously assess the SteamVR Tracking's reliability since the occurrence of tracking losses would distort an entire measurement session.

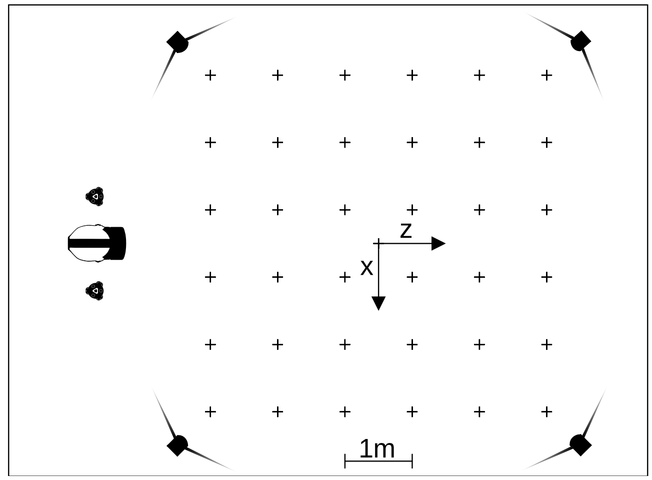

Figure 1: A scaled top-view of the room, in which the measurements were taken, including crosses that indicate grid points, black boxes that indicate base stations, and the HMD facing in z-direction.

Figure 2: The measuring carriage, including the Oculus Quest 2 HMD, 2 HTC Vive Trackers, a computer, and a positioning laser.

3.2 Procedure

For data recording, the Oculus Quest 2 HMD and the Vive Trackers were both registered in the SteamVR Desktop application. Subsequently, a Unity scene was started, which executed a script that recorded the positional data of the Quest 2's HMD and the Vive Trackers in all six degrees of freedom at a sampling rate of 50Hz. The measuring carriage was then moved to the grid's center point for the first measurement. Each of the grid's 36 points was measured by positioning the carriage at the black marker on the floor for 20 seconds (i.e. collecting 1000 measurements for each grid point). Throughout the entire procedure, the measuring carriage was facing in z-direction (see Figure 1).

4 RESULTS

In this section, we analyze the data that was collected through the measurement procedure. Thus, we assess the Vive Trackers' reliability, as well as the accuracy and precision of both, SteamVR Tracking and Oculus Insight.

4.1 HTC Vive Tracker reliability

To assess the Vive Trackers' reliability, the distance between their tracked positions of $|\overrightarrow{T_1T_2}|$ was calculated over the entire measurement session, including the positional data that was recorded while the measuring carriage was moving. Since the trackers were rigidly mounted to the carriage, it was expected that it would not change during the complete measurement procedure. The position of Vive Tracker 1 and Vive Tracker 2 for each sample is given by:

$$\overrightarrow{T_1} = \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} \qquad \overrightarrow{T_2} = \begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix}$$

We then calculate their distance:

$$|\overrightarrow{T_1T_2}| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{1}$$

The closer $|\overrightarrow{T_1T_2}|$ is to the true distance of 0.4m, the better the reliability is of the tracking data obtained by the SteamVR Tracking System within a measurement session. The time series of $|\overrightarrow{T_1T_2}|$ is shown in Figure 3. The Mean (M) of $|\overrightarrow{T_1T_2}|$ calculated to be 0.405m with a Standard Deviation (SD) of 0.135m. While the mean is only 0.005m off, the SD amounts to 33.75% of the true distance. A closer investigation revealed that this relatively large SD can be attributed mainly to a few large outliers and partially to occasional drifting of one of the two trackers. This also visible in Figure 3 between 200s and 400s (outliers), and 1400s and 1600s (drifting) respectively. The outliers could be due to tracking loss and regaining of tracking for one of the Vive trackers. As a consequence, only the better functioning HTC Vive Tracker was used for the consecutive evaluations.

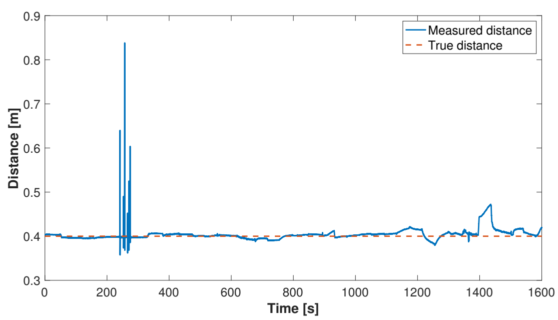

Figure 3: Time series of the distance between tracked positions of the two HTC Vive Trackers $|\overrightarrow{T_1T_2}|$.

4.2 Tracking accuracy

We assess the positional accuracy of both tracking systems by comparing the sample mean error of the tracked objects' heights (i.e. the y-coordinate of the Quest 2's HMD and the HTC Vive Trackers) at each of the 36 grid points (see Figure 1). Each sample consists of 1000 individual measurements taken at a specific physical point on the measurement grid, which in turn results in 36 samples with 1000 measurements each. Since the true object height is known and does not change throughout the measurement session, the positional error can be assessed by subtracting the true value from the mean of the tracked values at each grid position. Thus, a negative error indicates a tracked position, which is lower than the true position, while a positive error indicates a tracked position, which is higher than the true position. Figure 4 shows a comparison of the mean sample errors in the tracked object height between the Oculus Quest 2 HMD and an HTC VIVE Tracker. To ensure that the tracked object height is not affected by floor unevenness, the floor height at the four edge points of the measurement grid was checked with a laser range finder. With this device, we generated a horizontal optical horizon close the floor. Any unevenness would immediately become visible by interfering with the laser beam.

Table 2: Descriptive statistics of mean errors of the tracked object height.

Tracked object	Mean [m]	SD [m]	Min [m]	Max [m]
Oculus Quest 2	-0.001	0.004	-0.006	0.006
HTC Vive Tracker	0.007	0.012	-0.0185	0.030

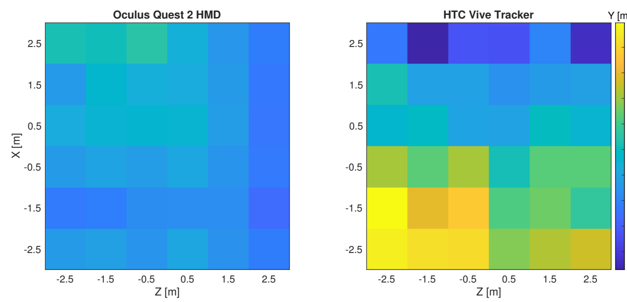

Figure 4: Sample mean errors in the tracked object height of the Oculus Quest 2 HMD and the HTC Vive Tracker.

The descriptive statistics of the sample mean errors shown in Table 2 further confirm the finding that the height tracking accuracy of the Oculus Quest 2 is higher than the tracking accuracy of the HTC Vive Tracker. The SD, minimal value, and maximum value of the sample mean errors for the HTC Vive Tracker are at least one order of magnitude larger than those of the Oculus Quest 2 HMD. Nevertheless, the mean height tracking error for both systems lies in the millimeter range. The mean height tracking error for the HTC Vive Tracker (0.007m) is seven times larger compared to the Oculus Quest 2 HMD (-0.001m). To gain further insights on the this difference, we conduct a paired t-test for the 36 sample points with 1000 measurements each. The analysis reveals a statistically significant difference between the positioning errors of both tracking systems, $t(35) = -3.3$, $p = .002^{**}$.

The height tracking error obtained for the HTC Vive Tracker is in line with the related work. Figure 4 and the comparatively large SD and range of the mean sample errors support the finding of other studies, according to which the ground plane of SteamVR tracking is slightly tilted [7, 9, 11]. In the context of the present study, this implies that the SteamVR ground plane might be tilted around the z-axis by approximately 0.56°. However, for the Oculus Insight tracking system, we could not find any evidence indicating similar phenomena.

4.3 Tracking precision

Tracking precision can be inferred through assessing a tracking system's sample-to-sample jitter by calculating the Root Mean Square (RMS) [9] where n represents the number of samples at a specific location on the grid, and $(P_i - P_{i+1})$ represents the difference between two subsequent samples:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n-1}(P_i - P_{i+1})^2} \qquad (2)$$

The RMS values of the sample-to-sample jitter for each point on the measurement grid are shown in Figure 5. The RMS over all static measurements amount to 0.06mm for the Oculus Quest 2 HMD and 0.18mm for the HTC VIVE Tracker. The results reveal a substantially lower RMS for the Oculus Quest 2 HMD compared to the SteamVR Tracking. Thus, the tracking precision for the Oculus Quest 2 is considerably higher compared to the SteamVR Tracking system.

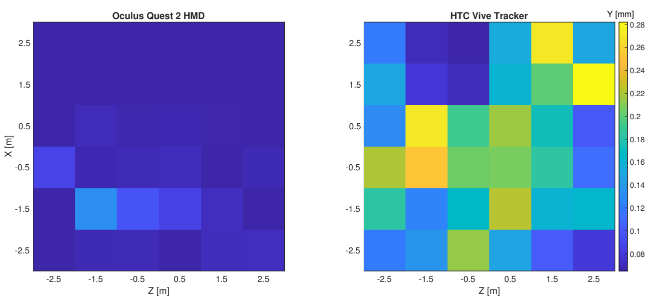

Figure 5: RMS of the Oculus Quest 2 HMD and the HTC Vive Tracker for each point on the measurement grid.

5 CONCLUSION

In this work, we mark an initial step comparing current generation consumer-grade VR motion tracking systems, represented by SteamVR base stations 2.0 (i.e. SteamVR Tracking) and the Oculus Quest 2 VR system (i.e. Oculus Insight tracking). We assess and compare the accuracy and precision of both systems in a 5m × 5m room scale setup.

Our results reveal that the height positioning accuracy (i.e. y-coordinate) of the Oculus Quest 2 is significantly higher compared to the SteamVR Tracking configuration used in this study (i.e. SteamVR base stations 2.0 with HTC Vive Trackers Version 2018). Furthermore, the tracking precision of the Oculus Quest 2 is substantially higher (i.e. the RMS is lower). Based on our findings and in line with other research [5, 10], we argue that the Oculus Insight tracking system is comparable – if not better – than SteamVR Tracking and thus highly interesting for applications in research and industry, due to substantially lower acquisition costs, higher mobility, and faster setup. More work is needed to investigate further on the capabilities and limitations of the Oculus Insight tracking system by investigating other important metrics (e.g. latency) or other setups (e.g. including controllers).

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