Evaluation of Low-Cost/High-Accuracy Indoor Positioning Systems

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***Abstract*—Indoor positioning is a challenging research topic. Over the years, many different measurement principles and algorithms have been proposed. Each system has its own advantages and drawbacks, therefore trade-offs have to be made. For example, one generally needs to make a trade-off between cost and accuracy. However, recent developments in sensing technology have led to commercial systems that advertise sub-decimeter positioning accuracy for less than €1k. In this paper, we benchmark the accuracy of indoor positioning systems by Pozyx labs and Marvelmind robotics, as well as the VIVE tracker by HTC and Aruco Marker tracking in OpenCV. Results show that these systems achieve an average dynamic positioning accuracy of approximately 150 mm, 20 mm, 8 mm and 100 mm, respectively.**

Keywords*–*Indoor positioning; benchmarking; accuracy

I. INTRODUCTION

Positioning is not a particularly new problem. Mankind has attempted to determine his position for centuries, using instruments such as sextants, clocks, almanacs, maps, etc., One of the largest revolutions in this field is probably the advent of the Global Positioning System (GPS), which can provide position information almost anywhere on earth to anyone with a receiver. However, GPS often does not work in indoor environments, as the signals of the satellites lose much strength when penetrating the walls of buildings [1], making it difficult to receive them with traditional, low-cost sensors. Moreover, the accuracy (that is, the Euclidean distance between the true and the reported position) of such sensors is limited to a couple of meters, which is insufficient for many indoor applications. A study performed by the National Exposure Research Laboratory indicates that most people spend about 90% of their time indoors [2]. Therefore, indoor location information provides many business opportunities. This is illustrated by the fact that the indoor mapping market is rapidly increasing in size, and is estimated to be worth about $10 billion by 2020 [3]. As GPS cannot be used for indoor environments, different technologies are required to obtain this position information. While GPS has become the de facto standard for outdoor environments, no such standard exists for indoor spaces [4]. The wide variety of indoor environments has prompted an equally wide variety of Indoor Positioning Systems (IPS), each with their own advantages and drawbacks. Usually, a trade-off has to be made between accuracy and cost. In the past, this trade-off was quite significant. However, in recent years, a number of positioning systems have come to market that should provide high accuracy ($\leq$ 10 cm) at relatively low-cost ($\leq$ € 1k), potentially bridging the gap that existed before. In this paper, we evaluate several commercially available high-accuracy/low-cost indoor positioning systems. Different measurement principles are represented, namely ultrasound, ultrawideband radio, infrared light and computer vision. A highly accurate (sub-millimeter) infrared measurement system is used as a ground truth reference. The positioning systems are benchmarked in the same environment, thus enabling an objective comparison.

The rest of the paper is structured as follows; Section II presents related work and the main contributions of this paper. Section III elaborates on the different positioning systems that were considered. The experimental setup is explained in Section IV, and results are presented in Section V. Finally, a conclusion is drawn in Section VI.

II. RELATED WORK

Van Haute et al. [5] benchmarked several indoor positioning systems in a healthcare environment. Low-cost technologies like Wi-Fi, ZigBee and bluetooth low-energy (BLE) were used. Accuracy of static measurements in the order of 1 to 4 meters was obtained. These kinds of radio-frequency (RF) based systems are relatively popular for indoor localization, due to the widespread availability of the hardware. However, accuracy is rarely below 1 meter [1].

Ultrawideband (UWB) has been an increasingly important topic in indoor positioning research in recent years. Typically, UWB positioning systems determine the distance between static anchors and a mobile node based on signal travel time. A position estimate is then obtained via triangulation. Ruiz and Seco [6] compared the commercial UWB systems sold by DecaWave (the Pozyx system uses DecaWave transceivers) and BeSpoon. Manual measurements with a ruler were used as ground truth. Ruiz and Granja [7] added the Ubisense system to this comparison, and extended the testing space to a larger industrial warehouse as well (rather than the lab environment as in [6]). A comparison was made based on the ranging accuracy and positioning accuracy with a particle filter. An overview of the positioning results of these papers can be found in Table I. The Ubisense system was evaluated separately as well by Maleek and Sadeghpour [8]. The focus of their work was dynamic positioning and localization of factory workers in order to increase safety. A number of experiments were performed by placing a tag on a Lego track, as well as experiments where the tag was used to localize a person. Ground truth locations are calculated based on the starting time and the known layout of the lego track for the first set

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of experiments. For the experiments on worker localization, the real position was determined with a robotics total station (Leica iCON Robot 50). Their findings indicate 2D accuracy of 15-31 cm depending on the experiment. Dabove et al. evaluated the Pozyx system in [9]. In an office environment, the average 3D positioning accuracy was 100 mm, and the accuracy of the range measurements was found to be 320 mm. In a narrow corridor, the horizontal accuracy and range error were determined to be 87.4 mm and 225 mm, respectively. Surveying equipment was used as ground truth reference for static range measurements, and a grid pattern was used for static positioning ground truth measurements. Finally, Ridolfi et al. [10] evaluated the Pozyx kit as a positioning technology for sports postures. Average positioning errors of 200 mm were recorded (depending on tag placement and activity) and the authors propose several implementations of filtering algorithms to reduce this error. A motion capture system (MOCAP) was used as ground truth.

TABLE I. OVERVIEW OF PREVIOUS UWB BENCHMARKING RESULTS REPORTED IN [6] AND [7]. P90 REPRESENTS THE 90% INTERVAL OF THE CUMULATIVE ERROR DISTRIBUTION

	DecaWave	BeSpoon	Ubisense
Mean accuracy (office) [m]	0.24	0.51	/
P90 (office) [m]	0.51	0.99	/
Mean accuracy (factory) [m]	0.49	0.71	1.1
P90 (factory) [m]	1.09	1.16	2.39

The ranging of the Marvelmind system was, to the best of our knowledge, only benchmarked by Cernohorsk and Novk [11]. The error of the range measurements was found to be in the order of a few centimeters, though some outliers exist in absence of a direct line of sight. The absolute positioning error was not evaluated.

The HTC VIVE is a relatively new system, and thus little research about it is available. Chang et al. [12] compared several head-mounted virtual reality systems, namely the 3Glasses D2, Oculus Rift DK2, Google Cardboard and Samsung Gear VR based on metrics such as positioning precision and sensitivity. One degree of freedom motion was considered by mounting the headsets on a servo motor. However, the HTC VIVE was not considered. Niehorster et al. [13] did evaluate the precision and latency of the HTC VIVE specifically. Latency is conservatively estimated to be 22 ms, significantly less than the latency of the 3Glasses D2 (44 ms) and Oculus Rift DK2 (48 ms) measured by Chang et al. [12]. Niehorster et al. concluded that the VIVE measures at a tilted reference plane relative to the ground plane. However, the angles and positions reported by the VIVE are consistent as long as the system does not lose tracking. Positioning accuracy was not reported.

It is clear that while some of these systems have been evaluated in previous publications, further work is still required. For example, position accuracy is not always specified and even when reported, this is often the average value. In the context of, for example, autonomous operation of mobile robots, one is often also interested in the P95, that is, the 95% interval of cumulative error distribution. These results are usually not included ([6] and [7] do report 90% intervals, as shown in Table I). Additionally, static grid measurements or measurements with a ruler are often used as a ground truth reference. A survey of papers published in the proceedings of the International Conference on Indoor Positioning and Indoor Navigation (IPIN) concludes that this method is used quite often in indoor positioning research [14]. In this work, we perform ground truth measurements with a highly (sub-millimeter) accurate positioning system with a relatively high update rate (50 Hz, see Section IV). This allows better characterization of the dynamic performance of the considered indoor positioning systems.

In summary, our main contributions are:

- Evaluation of several measurement principles in the same environment.
- Measurements of moving receivers are compared with a highly accurate, fast-measuring ground truth reference.
- Evaluation of positioning accuracy, rather than ranging distance.
- Reporting of mean accuracy and P95 values, to provide both an overview of normal performance and worst case scenarios.

III. SYSTEMS UNDER EVALUATION

Table II provides an overview of the main specifications of the IPS considered in this paper. The system cost includes value added tax, and the specifications for the Aruco system are based on the camera used in this work (Logitech HD webcam). Scalability refers to whether a particular system can easily be extended up to larger environments.

The indoor positioning system by Marvelmind robotics uses ultrasound ranging to determine the position of one or more mobile sensor modules (referred to as hedgehogs). Ultrasound ranging is also used by the transmitters (referred to as beacons) to determine their relative position. Therefore, the Marvelmind system is self-calibrating. The sensor modules have built-in rechargeable batteries, and whether a module is a beacon or hedgehog can be selected in the software and changed at will. The maximum update rate for tracking a single hedgehog is 16 Hz. The system uses time division multiplexing, so if multiple hedgehogs are tracked, the update rate becomes:

$$F_{update} = \frac{16}{n_{hedgehog}} \quad (1)$$

With F_{update} the update rate of every hedgehog and $n_{hedgehog}$ the number of tracked hedgehogs.

The indoor positioning system by Pozyx labs uses ultrawideband radio as a distance estimation principle. Additionally, data from a 9-axis Inertial Measurement Unit (IMU) is fused in order to improve the position estimate. The advantage of ultrawideband over other RF technologies is that the increased bandwidth makes it more likely that at least some of the transmitted frequencies will go through or around obstacles [15]. Therefore, accuracy can be significantly higher than, for example, Bluetooth or Wi-Fi based positioning [4]. The system has the option to self-calibrate, but we performed a manual calibration to improve accuracy [16] (see Section V-B).

The HTC VIVE is sold as a virtual reality headset, and ships with a Head-Mounted Display (HMD), two controllers with infrared receivers and two infrared transmitters (called lighthouses). Recently, a standalone tracker module has also been released to enable simpler tracking of objects [17]. It is the positioning of the tracker that was evaluated in this paper. Each lighthouse is equipped with two lasers, which sweep across its horizontal and vertical axes. The infrared laser sweeps are detected by photodiodes which are mounted on the controllers, headset or tracker modules. The difference between arrival times of the laser at the photodiodes is used to determine the position and orientation of the modules [13]. These laser measurements function mostly as drift correction. In between sweeps, positions are estimated with IMU-based dead-reckoning [18]. Contrary to the other systems considered in this paper, the VIVE was not originally designed to be a standalone positioning system. However, accurate position and orientation tracking is required to provide a good virtual reality user experience. As the OpenVR Software Development Kit (SDK) has a published driver for the tracking hardware [19], it is possible to access all the tracking information outside a gaming environment, thus opening the door for a wide range of other applications. As a positioning system, however, the user experience is not as smooth as the Pozyx or Marvelmind systems. For example, steamVR needs to be continuously running in the background and the controllers need to be connected even if one only wants to know the position of the tracker. At the time of writing, it is also not possible to utilize more than 2 lighthouses, thus limiting the operating space.

The final positioning system considered in this work is based on Aruco marker detection [20] with a webcam and OpenCV. The field of computer vision has many examples of marker tracking, the implementation in this paper is likely not the most accurate or user friendly system available. For example, a calibration procedure is required to compensate for the effects of lens distortion and to convert the measured coordinates from pixels to meters [21]. The system is nonetheless included in this comparison as a representative example of what a novice in the field could reasonably implement themselves, and represents one of the lowest cost IPS that can achieve sub-decimeter accuracy. The system returns z-coordinates, but these should not be used as it is challenging to estimate depth with a monocular camera.

TABLE II. SPECIFICATIONS OF THE CONSIDERED IPS.

Positioning system	Marvelmind	HTC VIVE	Pozyx	Aruco
Update rate (max) [Hz]	16	120	138	30
Approximate system cost [€]	400	700	600	70
Measurement range [m]	50	5	30	
Scalable ?	Yes	No	Yes	No

IV. EXPERIMENTAL SETUP

Experiments were conducted in a lab environment of approximately 5 meters by 5 meters. All beacons were mounted at the edges of the test space. The Pozyx beacons are mounted vertically at approximately the height of the receiver (see Section V-B). The lighthouses for the VIVE are attached to metal poles and pointed slightly downwards. Both the Marvelmind beacons and the webcam are attached to the ceiling at a height of approximately 2.8 meters. Figure 1 shows the experimental setup. The receivers of the various positioning systems are mounted on top of a mobile robot with a custom sensor platform (see Figure 2). The Pozyx tag is mounted vertically to improve accuracy [16]. The tag is connected to a raspberry pi 3 that also controls the robot. Measurements for the HTC VIVE, Marvelmind and camera system are received on a laptop. The robot moves at varying speeds during the experiments, occasionally stopping to turn. The maximum speed of the platform is about 0.2 m/s.

As a ground truth reference, the Krypton K600 coordinate measurement machine (CMM) was used. This system is equipped with 3 infrared cameras, which track the positions of infrared LEDs that can be attached to objects. The accuracy of the system is between 60 μm and 190 μm, depending on the distance to the camera [22]. The krypton CMM is controlled with and measurements are stored on a separate computer.

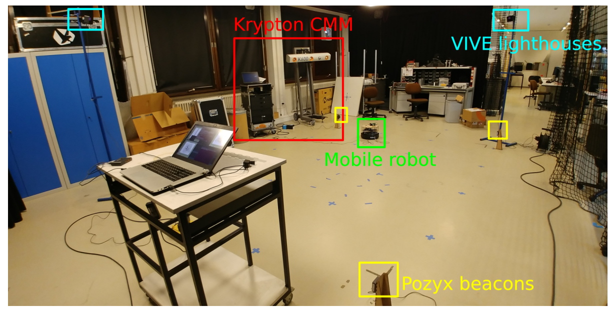

Figure 1. Experimental setup. One more Pozyx beacon is present but cannot be seen on this perspective.

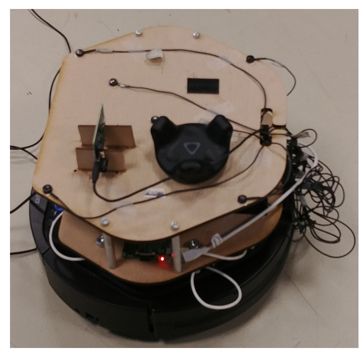

Figure 2. Robot platform used in the experiments

A. *Data processing*

Data from the systems under testing (SUT) are returned in different formats (e.g., a .txt file for the HTC VIVE and as a rosbag for the Marvelmind system). In order to compare data from different systems, all the output is first converted to a CSV file containing the timestamped positions. It is assumed that timestamps recorded by different computers only have an offset difference.

Following conversion, both the CSV data from the Krypton CMM and the SUT are loaded into memory. The positions of the infrared LEDs relative to the robot center are used to determine the robot pose via Procrustes analysis [23] and Kabsch algorithm [24], which determines the least-squares solution for the pose matrix. Next, these pose matrices and the position of the evaluation system relative to the robot center are used to calculate the equivalent trajectory of the SUT (that is, the trajectory that the SUT would report if it was placed at the location of the krypton markers). However, this equivalent trajectory can still be rotated or translated in space, and have an offset time difference relative to the SUT. Additionally, the sampling frequency of the krypton measurement system is not necessarily the same as the SUT. To determine the points that can be compared, virtual timestamps of the Krypton CMM that provide the best match for the SUT are selected, based on the assumption of a constant 50 Hz sampling rate and the starting time of the experiment. Out of these timestamps, those that overlap are selected for evaluation (see Figure 3). At this stage in the post-processing, we have two datasets of equal length (one equivalent dataset for the Krypton CMM and one for the SUT). The position data can still be rotated and translated relative to each other, and the time vectors can have an offset difference. We therefore calculate the transformation matrix that provides the best fit of the position data. The SUT data is then transformed to the Krypton coordinate frame with this matrix. Next, we shift the timestamps of the evaluation samples with a period of the reference system and calculate the transformed dataset. The time shift that provides the smallest error is assumed to be the offset difference between the clock. The result of this process is a reference dataset and an evaluation dataset that is aligned in space and in time, from which the accuracy can now be computed.

One might argue that the method described above provides the smallest possible positioning errors as the data is transformed to provide the best fit. Therefore, the entire length of the datasets are not fitted to each other. Rather, for each experiment approximately half of the data is used for fitting, and the rest is used for evaluation.

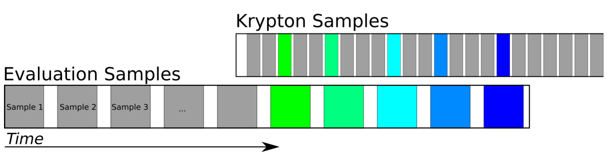

Figure 3. Procedure for determining overlapping samples in the krypton and SUT datasets. Samples in the same color are assumed to represent the same timestep

V. Experimental results

Table III provides an overview of the measured accuracies of the different positioning systems. The following Sections will elaborate on these results. Accuracy is defined as follows:

$$\varepsilon = \sqrt{(x_{ref} - x_{SUT})^2 + (y_{ref} - y_{SUT})^2 + (z_{ref} - z_{SUT})^2} \quad (2)$$

Where x, y and z are used to denote the different coordinate axes, and the subscripts ref and SUT indicate the ground truth and the system under testing, respectively.

TABLE III. ACCURACY OF THE CONSIDERED POSITIONING SYSTEMS

	Marvelmind	HTC VIVE	Pozyx	Aruco
Accuracy (mean) [mm]	19,62	8,05	150,73	99,15
Accuracy (P95) [mm]	33,28	12,62	283,21	177,09

A. Marvelmind

Figure 4 shows the Marvelmind positioning results together with the ground truth reference. It is clear that both trajectories are a close match. At certain sections it can be challenging to distinguish the two from one another. The mean accuracy with respect to the ground truth reference is 19,62 mm. The 95% interval of the cumulative error distribution was determined to be 33,28 mm. Therefore, it appears that the advertised accuracy of 2 cm is consistent with the average observed accuracy. However, it should be noted that the CMM has a relatively limited measurement range (as can be seen in Figure 4). When performing experiments in larger space, there inexplicably exists a region where the Marvelmind system does not measure at all. We were unable to determine the cause of this signal loss, as the beacons were not obstructed in this space nor were there any apparent sources of interference present.

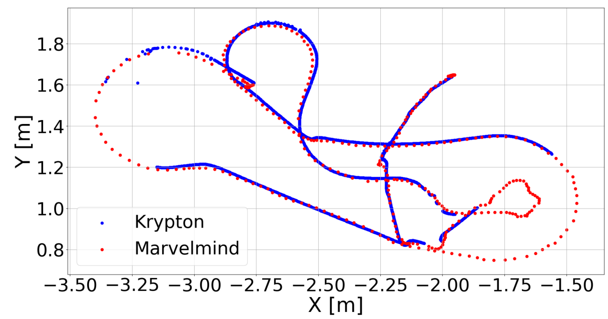

Figure 4. Marvelmind positioning results alongside Krypton CMM measurements.

B. Pozyx

The Pozyx beacons were placed at an equal height in an approximate square. In order to improve accuracy, the distances between the beacons were determined based on manual measurements rather than using the self-calibration function (this is also recommended in the documentation [16]). The relative distances can be used to calculate the angles of the approximate square (see Figure 5), these angles should then sum to 360 degrees. If this is the case, the beacon angles and distances can be used to determine the beacon locations in any coordinate system. In this paper, one beacon is selected as the origin, and the other beacons are defined relative to it.

Positioning results were not as expected. The large degree of noise in positioning data means determining the best fit is challenging. When a fit is possible, positioning errors are on average around 150 mm, with a P95 value of 233 mm (see Figure 6). These results can likely be attributed to the large amounts of metal present in the lab environment, which reduces the accuracy of UWB ranging. Therefore, a measurement was also performed with a static receiver in an open outdoor area. The results of this experiment are shown in Figure 7. The measured positions are spread over an area of approximately 20 cm, thus implying that the maximum (static) accuracy of the system is 10 cm.

Our results are slightly better than the evaluation in [10], where a mean accuracy of 20 cm was obtained. However, a P95 value was not specified. Our analysis reaches significantly different results than those in [9]. However, we suspect the authors may have used a different definition for accuracy. Negative values for 3D accuracy are present in some of the figures, which is impossible in the definition in (2). The definition that the authors did use is not specified. The obtained mean accuracy is significantly better than that of the DecaWave kit benchmarking in [6]. Additionally, our obtained P95 value is much better than even the 90% interval measured by the authors. Since the Pozyx developers kit used in this paper makes use of DecaWave transceivers, we can therefore conclude that their additions such as machine learning and sensor fusion improve performance, particularly at high intervals of the cumulative probability function.

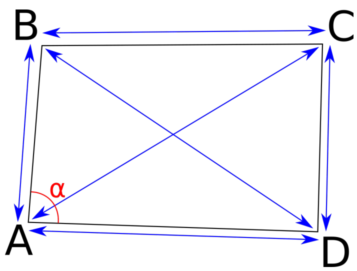

Figure 5. Calibration of Pozyx beacon positions

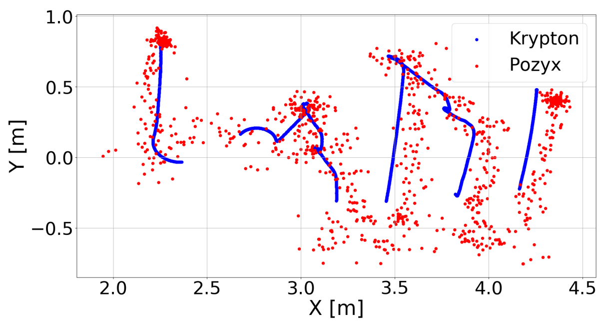

Figure 6. Pozyx positioning results (red) alongside Krypton CMM measurements (blue).

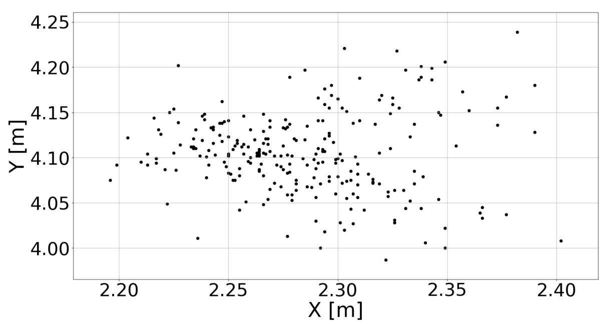

Figure 7. Reported positions by pozyx when the receiver remains static in an outdoor environment. Beacons were placed approximately 5 meters apart.

C. Aruco marker tracking

Positioning results from the computer vision system show significantly less noise than the Pozyx system. Accuracy is relatively high in the center of the test space. However, this accuracy decreases towards the edge of the image (see Figure 8), possibly due to a small degree of image distortion that remains even after calibration. Accuracy relative to the krypton ground truth is around 100 mm on average, with a P95 value of 177 mm.

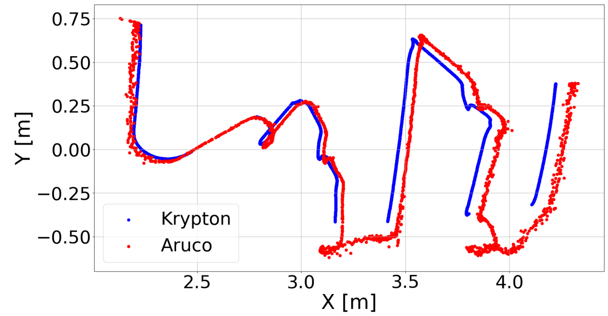

Figure 8. Camera positioning results (red) alongside Krypton CMM measurements (blue). Data was fitted to the left side of the figure, which is why deviation is smallest in this region. Evaluation is performed on the rest of the dataset which was not fitted.

D. HTC VIVE tracker

The HTC VIVE proves to be the most accurate system out of all the experiments. As can be seen on Figure 9, the two datasets match very closely, in fact it is challenging to observe any difference. Therefore, these results are also shown in a different perspective in Figure 10. Small variations in the z-coordinate of the reference system are present. These variations can likely be attributed to a non-perfect smoothness of the floor or roundness of the robot wheels. The average positioning error relative to the ground truth is 8 mm, with a P95 value of 12 mm.

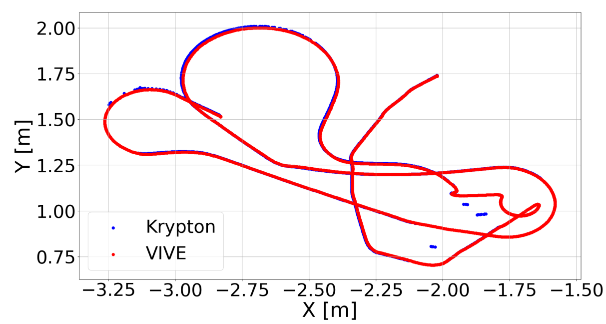

Figure 9. HTC VIVE positioning results (red) alongside Krypton CMM measurements (blue).

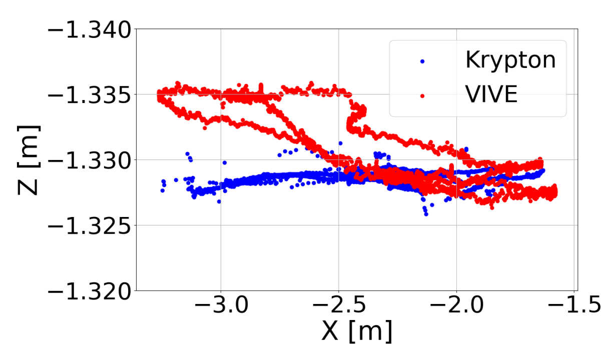

Figure 10. Side view of the HTC VIVE positioning results (red) alongside the Krypton CMM measurements (blue)

VI. Conclusion

In this paper, we benchmarked a number of low-cost indoor positioning systems. We used a highly accurate reference system rather than conventional grid measurements or measurements with a ruler as a ground truth. Additionally, we measure the ground truth position at a high rate to better characterize dynamic performance. While there likely will never be a single 'best' indoor positioning system, it is clear from our results that significant progress has been made in recent years. For just a few hundred euros, it is now possible to purchase a positioning system that delivers accuracy of a few centimeters out of the box. If one has more technical expertise, then the HTC VIVE can provide even higher accuracy. It is even possible to use the VIVE as a ground truth reference for positioning systems that have an accuracy that is one order of magnitude less than 1 cm. In this case, the VIVE can be a more interesting option than the krypton CMM due the drastic reduction in cost and the larger measurement space. When a very low-cost positioning solution is required, it is possible to achieve, on average, sub-decimeter accuracy for the price of an webcam. However, both the HTC VIVE and the camera based solution do not scale to larger environments, unlike for the Marvelmind or Pozyx systems.

Future work can extend this analysis to include more positioning systems. For example by including commercially available optical tracking systems. Additional performance metrics such as precision and power use could also be evaluated, to provide a more complete assessment of the IPS. Finally, the experiments in this paper were performed at approximately the same movement speed. An evaluation at a range of velocities could be useful for highly dynamic applications (e.g., drones).

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