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A FIRST EVALUATION OF THE SEAMLESS MARKERLESS AUGMENTED REALITY REGISTRATION SYSTEM SUPPORTING FACILITY MANAGEMENT

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Abstract

Augmented reality (AR), despite its great potential, still struggles to be widely used in real construction processes due to difficulties in registering holograms in mixed indoor-outdoor scenarios. Since a definitive technological solution for inside-out AR registration does not exist yet, a seamless markerless augmented reality registration system, integrating real-time kinematic positioning (RTK), inertial measurement units (IMU) technologies and image comparison based on convolutional neural networks (CNN), has been proposed by the authors. Experiment results have shown the need to continuously register AR at regular temporal interval within 1 seconds and/or 1 meter to achieve “fine-precision” positional accuracy (i.e., 0.10 m).

Introduction

The architecture, engineering, construction, and operations (AECO) sector, despite its reputation as one of the least digitized industries, is progressively embracing digital technologies to enhance various stages of a building's life cycle (Albahbah, Kıvrak, & Arslan, 2021). Among these stages, the operation and maintenance (O&M) phase in facility management (FM) incurs the most significant costs, accounting for 50–70% of annual facility operating costs and a whopping 85% of the overall lifecycle expense (Salman & Ahmad, 2023). As facilities become increasingly intricate, day-to-day tasks have become more demanding. This heightened complexity has propelled the construction industry pursuit of visualization technologies to facilitate better access to information for evaluation, communication, and collaboration.

Augmented reality (AR) technology emerges as a promising tool for streamlining O&M tasks, bridging the gap between facility managers and field workers, thereby minimizing delays and reducing operational expenses (Salman & Ahmad, 2023). AR technology revolutionizes human-computer interactions by establishing direct links between physical and digital realms. Its ability to overlay virtual objects onto the real world allows for the identification of concealed facilities and provides detailed maintenance guidance for field workers (Salman & Ahmad, 2023). However, integrating AR poses technical challenges. While display technology has made significant strides, achieving precise position tracking remains a major obstacle. Spatial registration, ensuring accurate alignment between virtual and real-world coordinates, stands as a critical aspect of AR functionality (Albahbah et al., 2021; Salman & Ahmad, 2023). Spatial registration methods can be categorized as "marker-based" or "markerless" (Albahbah et al., 2021; El Barhoumi, Hajji, Bouali, Ben Brahim, & Kharroubi, 2022; Salman & Ahmad, 2023). Marker-based approaches register virtual models using some kind of physical or hyperlink markers (El Barhoumi et al., 2022). These solutions can be potentially applied in mixed environments, but they generally require a preliminary survey, a manual setup and markers often generate aesthetic issues (Baek, Ha, & Kim, 2019). On the other hand, markerless methods, such as Global Navigation Satellite Systems (GNSS) or image-based localization, solve the previous gaps automating the AR registration process (Baek et al., 2019). However, the former cannot be applied indoor (Chen et al., 2019) and the latter requires a preliminary survey for collecting reference images (Baek et al., 2019; Messi, Spegni, Vaccarini, Corneli, & Binni, 2023) which restricts its use in large outdoor scenarios.

An innovative seamless inside-out and markerless localization system has been developed by the authors in (Messi et al., 2023), housing GNSS-based and image-based registration engines on an AR cloud platform, complemented by a switch engine managing their priorities. Since initial qualitative testing on a university campus has shown promising outcomes, AR registration performances need to be quantified in terms of drifts from an assumed benchmark. Hence, this paper serves as a follow-up to the one presented by the authors in (Messi et al., 2023) and aims to conduct initial assessments of the tracking engines embedded in the proposed system. These assessments provide a first evaluation of the capabilities of our seamless and markerless AR registration system (Messi et al., 2023). Existing studies report different registration accuracy thresholds, such as the “fine-precision” corresponding to 1°/0.10 m, and “high-precision” corresponding to 2°/0.25 m. The first one is considered as the minimum accuracy required for a good AR user experience in most settings (Sarlin et al., 2022; Sattler et al., 2017).

This paper progresses as follows. The Research questions section formalizes the objectives of the study. Then, the Methodology section presents the proposed system

architecture and the evaluation method. The Experiments section describes the experiments carried out for the assessment of the drift and related results, followed by the Conclusions section that closes the paper.

Research questions

This study, since the seamless and markerless AR registration system presented by the authors has shown promising outcomes (Messi et al., 2023), carries out an accuracy assessment aimed to quantify its reliability. More in detail, the following research questions have been formalized:

RQ.1. What is the drift of the proposed system during FM operations?

RQ.2. What spatial/temporal AR registration frequency should be ensured to optimize the performance of the proposed system?

Methodology

This section presents the methodology applied by this study. To this purpose, the System architecture section will first recap the architecture of the markerless seamless AR system presented in (Messi et al., 2023), whereas the Evaluation method section describes methodology applied to assess drift issues related to the different registration engines embedded by the system.

System architecture

The architecture of the proposed system (Messi et al., 2023) is established on an AR cloud platform housing four essential elements: (i) the graph database, (ii) the GNSS-based AR registration engine, (iii) the image-based AR registration engine, and (iv) the switch engine (Figure 1). Although this system architecture has been defined for Microsoft HoloLens 2, it applies to all AR devices.

The AR cloud platform serves as a centralized resource for data processing, storage, and distribution. It enables precise mapping of virtual assets to real-world locations, crucial for integrating the virtual and physical realms. Images and point clouds are georeferenced and aligned within this platform using absolute world coordinates and accurate rotations. The graph database manages structured and unstructured data storage, allowing AR application accessibility. The GNSS-based AR registration engine utilizes RTK GNSS and IMU systems for open-space challenges, while the image-based AR registration engine employs convolutional neural networks (CNN) for indoor environments lacking reliable GNSS signals. The switch engine integrates the outdoor and indoor registration engines, facilitating uninterrupted AR experiences by dynamically switching between registration approaches.

The process for GNSS-based AR registration involves aligning the HoloLens 2 local frame to global coordinates using RTK measurements. The system computes the device position and orientation relative to geographical coordinates, enabling precise placement of building information models (BIMs), stored within the graph database. This process accounts for changing observer positions and altitudes, ensuring accurate object positioning and alignment with the local frame. Conversely, image-based AR registration relies on image comparison with survey data collected via cameras and LiDAR scanners. The process involves localizing the HoloLens 2 by comparing its current view with referenced images and related point clouds stored in the AR cloud platform (Sarlin, Cadena, Siegwart, & Dymczyk, 2018). CNNs, namely Hierarchical Feature Network (HF-Net) technology (Sarlin, Cadena, Siegwart, & Dymczyk, 2018), and the Perspective-n-Point (PnP) algorithm (OpenCV, 2023) are applied for accurate 6-degrees-of-freedom (6-DoF) localization. In this way, BIM models, stored within the graph database, can be overlapped to real world. The switch engine seamlessly integrates both registration approaches based on the scenario: RTK-only (mainly outdoor), RTK with images (mainly outdoor), and images only (mainly indoor). It identifies and triggers the appropriate registration engine based on available data, ensuring a continuous AR registration experience.

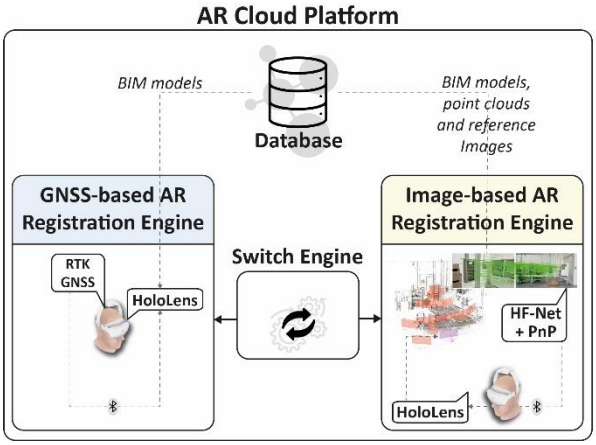

Figure 1: System architecture of the proposed system for seamless inside-out and markerless AR registration.

Evaluation method

For the purpose of a first evaluation of the reliability of the proposed markerless and seamless AR system, a methodology has been defined. It comprises a series of steps aimed at assessing drift values among the tracking engines of the system. More in detail, the methodology defined in this section aims to compare the HoloLens 2 tracking system with both the tracking engines of the system, namely the GNSS-based and the image-based engines. The evaluation steps are reported as follows:

1. **Tracking positions along a route:** this step consists in tracking the AR device position at predefined intervals while navigating a route that includes both outdoors and indoors scenarios. The AR device tracking is carried out using all the different tracking systems described above (i.e., HoloLens 2, GNSS-based, and image-based). The HoloLens 2 and GNSS-RTK tracking devices must be rigidly connected to each other.
2. **Registering HoloLens 2 reference system to the North direction:** this step aims to align the HoloLens 2 system to the North direction using RTK data, by computing the forward azimuth (Movable Type Scripts, 2023) from displacements.

3. **Aligning the image-based cloud system to the HoloLens 2 one:** by aligning the image-based cloud system to the HoloLens 2 one, this step ensures that their x, y, z axes correspond each other and are aligned to the North direction. This alignment is achieved using the position of three reference photos (Schönberger & Frahm, 2016) solely for the purpose of alignment.
4. **Data retrieval of the image-based tracking system:** this step involves calculating displacement vectors (i.e., "tvec" values (OpenCV, 2023; Schönberger & Frahm, 2016) and quaternions (i.e., "qvec" or "rvec" values (OpenCV, 2023; Schönberger & Frahm, 2016)) of the acquired images (i.e., their pose) with reference to the HoloLens 2 reference system.
5. **Data retrieval of the GNSS-RTK tracking system:** this step involves retrieving global coordinates from the GNSS-RTK system, transforming them into x, y, z coordinates using equirectangular projections (ArchGIS Esri, 2023), and computing the forward azimuth (Movable Type Scripts, 2023) of the tracking direction.
6. **Registering and assessing drift between HoloLens 2 and GNSS-RTK tracking:** this step involves calculating the discrepancy between the HoloLens 2 and the GNSS-RTK systems once aligned on the equirectangular projection.
7. **Registering and assessing drift between HoloLens 2 and image-based tracking:** similar to the previous one, this step involves computing the discrepancy between the HoloLens 2 and image-based systems once aligned.
8. **Evaluating drift at regular intervals:** repeating the discrepancy calculations at either specific time intervals (e.g., every 1, 2, 3 s) or distance covered (e.g., every 5, 10, 20 m) to evaluate drift values and assess the best registration frequency.

Experiments

The evaluation method introduced in the previous Evaluation method subsection has been applied to carry out a first reliability assessment of the proposed markerless and seamless AR system. Experiments have been executed assuming a FM use case based on a university campus as a case study. Specifically, the FM of the Digital Construction Capability Centre (DC3) Lab at the Università Politecnica delle Marche has been considered. The DC3 Lab, which covers an area as large as 240 m^2, is composed of a main open space, a changing room, an office, and a restroom. Within this context, the management of the electrical system and, in particular, of the internal electrical panel of the DC3 Lab, has been considered. During this activity, the technician in charge of FM operations spends time first locating the electrical panel. Then, in order to find the root cause of the problem, the technician may be asked to locate cablings associated to the panel, which extend externally to the building. These cablings can be accessed through manholes located on the road in front of the building, connecting it to the rest of the campus (Figure 2).

By testing the system proposed by the authors in (Messi et al., 2023) with the presented FM use case, its reliability in heterogeneous indoor/outdoor scenarios will be evaluated, considering the "fine-precision" positional accuracy threshold (i.e., 0.10 m) and "high-precision" one (i.e., 0.25 m) (Sarlin et al., 2022; Sattler et al., 2017).

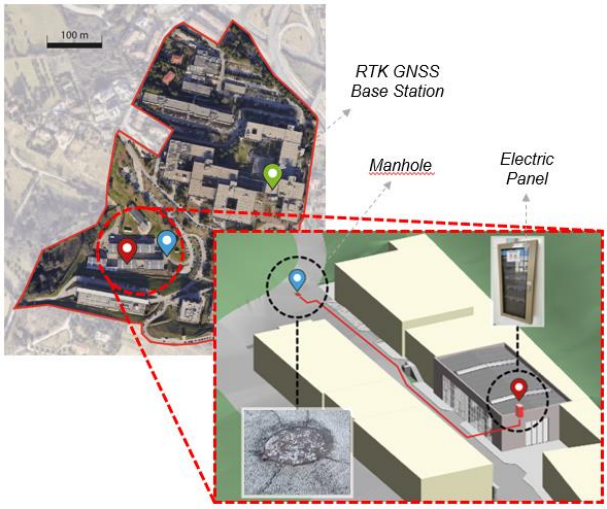

Figure 2: Aerial view of the university campus, assumed as case study, identifying the positions of the DC3 Lab, and the RTK base; The focus on the BIM model of the laboratory shows the positions of the indoor electrical panel and the outdoor manhole cover that are the objective of the simulated FM use case.

Experiments design and execution

In this study, we applied the methodology exposed in the previous Evaluation method subsection to the case study described at the beginning of Experiments section for assessing the outdoor scenario. The indoor scenario and, therefore, the evaluation of drift between the image-based and HoloLens 2 tracking systems will be addressed by future studies. Specifically, in this study, aiming to evaluate drifts between the GNSS-RTK and HoloLens 2 tracking systems (RQ.1) to understand the optimal registration frequency (RQ.2), we implemented points 1, 2, 5, 6, 8 of the proposed methodology (i.e., Evaluation method subsection). Regarding point 1, it should be noted that the conducted experiment simulates the maintenance activity as described at the beginning of Experiments section, following a path in a mixed indoor-outdoor scenario, using the HoloLens 2 device with a rigid add-on hosting the RTK receiver (Figure 3).

With these premises, the experiment was conducted in two parts. The first part involved comparing the GNSS-RTK and HoloLens 2 tracking systems in a mixed indoor-outdoor path, as indicated in point 1 of the methodology. Following point 6 of the methodology, the registration between the tracking systems was initially performed at a single point to assess the order of magnitude of drift over time and space. The second part of the experiment details the first part by comparing the same tracking systems and by following an only-outdoor path, executing multiple registrations at predefined time intervals. Specifically,

registrations were executed each 20 s during the tracked simulation to assess the drift across several samples, aiming to deduce the minimum necessary frequency of tracking system registration while maintaining “fine-precision” or “high-precision” positional accuracy (Sarlin et al., 2022; Sattler et al., 2017).

Figure 3: View of the operator simulating FM activities using the HoloLens 2 with the RTK add-on.

Results and discussion

The results of the first part of the experiment, as described in the Experiments design and execution subsection, are presented in Figure 4 and Figure 5. Figure 4 displays the 2D layout of the DC3 laboratory and the trajectories recorded by both the GNSS-RTK tracking system (depicted in orange) and the HoloLens 2 (depicted in blue) during the simulation of FM tasks conducted by an operator. The size variation of the markers along the GNSS-RTK-traced path signifies positional accuracy, where larger markers correspond to decreased accuracy.

The registration of the two tracking systems occurred solely at point A, i.e. at the beginning of the route, and only once (Figure 4). Subsequent movements within the laboratory space (zone B) revealed notable inadequacies in the GNSS-RTK tracking system indoors, indicating a substantial decline in accuracy. Further observations highlight zone C, illustrating an analogous scenario to an urban-canyon setting, where the GNSS-RTK system exhibited reduced reliability, potentially favoring the application of the image-based registration system [1]. Upon assessing the external trajectory (zone D), where the RTK system has a centimeter-level accuracy as declared by manufacturers (ublox, 2023), the HoloLens 2 system unreliability outdoors became conspicuous. It noticeably diverged from the RTK data when venturing beyond a certain distance from the registration point, indicating a drift of around 1 m each 45 m traversed (Figure 5). Therefore, the first part of the experiment, while answering RQ.1, demonstrates the need for regular registrations of the tracking systems to contain drift.

In the second part of the experiment, whose results are detailed below and in Figure 6, the outdoor operator route mimics the one of zone D in Figure 4. Along this route, the HoloLens 2 tracking system was registered against the GNSS-RTK at 6 subsequent intervals, spaced 20 s apart, creating 6 subsets of the total path. Drift readings for each subset were registered 1 s apart (Figure 6). These recorded subsets are overlaid in Figure 6, displaying a relatively consistent trend. It is worth noting that only the initial 15 m of each subset are depicted in Figure 6, as values beyond this range prove less significant. In Figure 6, the "Subset4” (light green curve), registering the worst performance, shows that the drift remains below 0.10 m (i.e., “fine-precision” positional accuracy threshold) only within about 2 m of covered distance (around 1.5 s of tracking). Instead, on the overall, the trendline of all subsets (red dashed line) shows that the drift remains below 0.10 m within about 4 m of covered distance. Furthermore, the "Subset4” shows that the drift stays below 0.25 m (i.e., “high-precision” positional accuracy threshold) within around 7 m of covered distance (approximately 6 s of tracking). Instead, on the overall, the trendline of all subsets shows that the drift remains below 0.25 m within around 9 m travelled. This result further answers RQ.1.

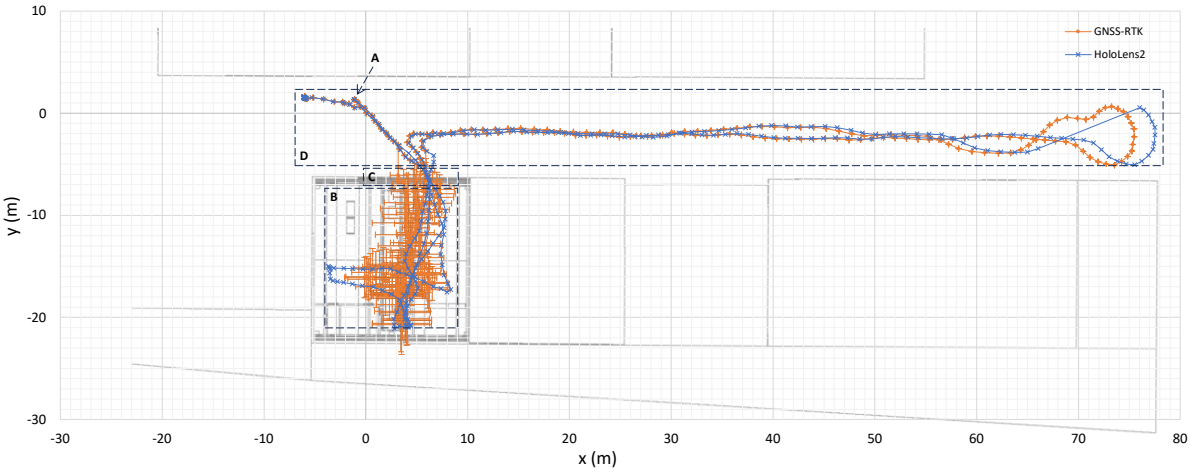

Figure 4: 2D view of the paths travelled by the operator and tracked by the GNSS-RTK (orange) and HoloLens 2 (blue) tracking systems. The grid has a mesh size of 1 m. Smaller orange markers along the GNSS-RTK route indicate higher accuracy of the samples.

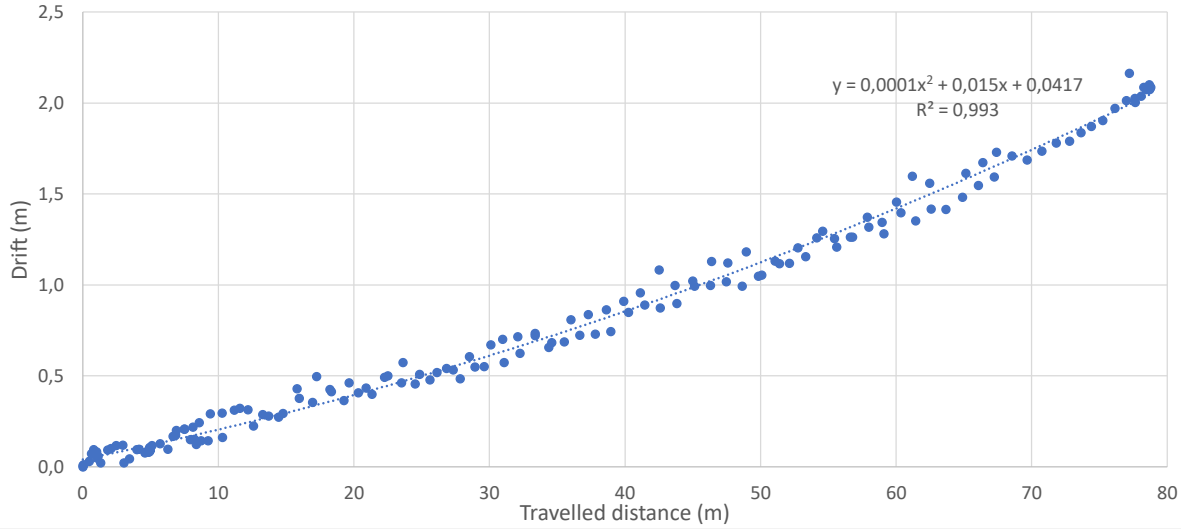

Figure 5: Outdoor assessment of HoloLens 2 drift against GNSS-RTK ground-truth localization (only zone D). The system is spatially registered only once at the beginning of the route.

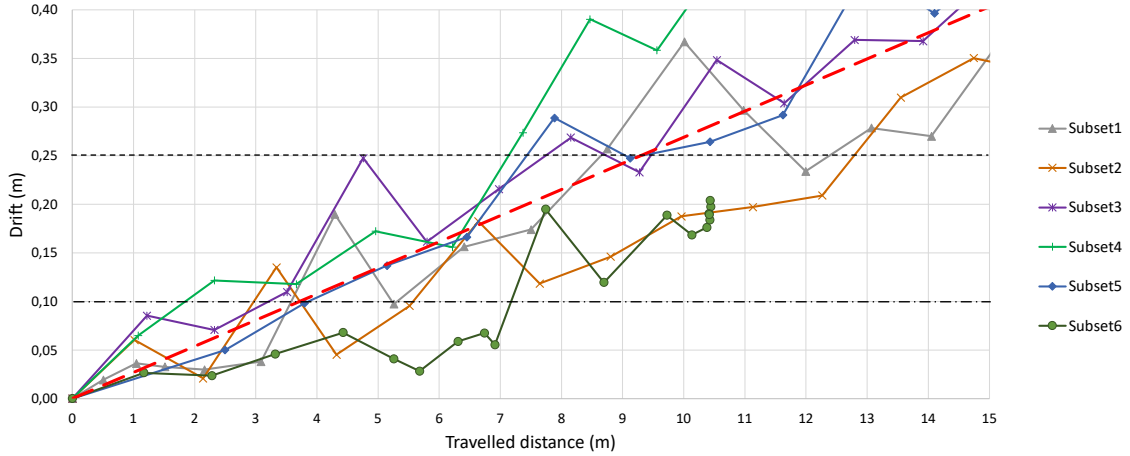

Figure 6: HoloLens 2 drift against GNSS-RTK ground-truth for each subset and trendline (red dashed line), related to the path traversed during the second experiment (only outdoor scenario – zone D). Horizontal dashed and dashed-dotted grey lines represent the "high-precision" and "fine-precision" positional accuracy thresholds at 0.25 m and 0.10 m respectively.

To sum up, for achieving in all outdoor circumstances a "fine-precision" positional accuracy, required for a good AR user experience (Sarlin et al., 2022; Sattler et al., 2017), the results underscore the need of aligning the HoloLens 2 tracking system with the GNSS-RTK approximately every 1.5 s or 2 m of travelled distance. Instead, to ensure the "fine-precision" positional accuracy on the overall, the results underscore the need of aligning the HoloLens 2 tracking system with the GNSS-RTK approximately every 4 m of travelled distance. This result answer RQ.2. It must be noted that, in this study, the RTK time latency was considered and the existing delay between the acquisition of GNSS-RTK samples and those from the HoloLens 2 was compensated.

Conclusions

Despite its immense potential, AR encounters barriers hindering its widespread implementation in real construction processes. One of the primary obstacles lies in the difficulty of aligning and sustaining the stability of holograms in mixed scenarios. The seamless integration of indoor-outdoor AR registration systems is imperative for effective built environment management.

The authors proposed a markerless augmented reality registration system that integrates RTK, IMU technologies, and image comparison based on CNN. Such system was qualitatively tested on a FM use case related to a university campus (Messi et al., 2023). This paper extends preliminary tests conducted on the proposed AR registration system. The aim of this study is quantifying drifts experienced within the different tracking systems embedded in the AR registration engines and determine the optimal registration frequency required for practicality in real FM scenarios. Experiment results have provided insights into the system performance, highlighting its capabilities, limitations, and areas of refinement. Such results can be summarized as follows:

- HoloLens 2 tracking system, as shown by the first part of the experiments, exhibited significant drift outdoors, reaching about 1 m per 45 m traversed

(Figure 4 and Figure 5). This result, while answering RQ.1, confirmed the need of periodic spatial registrations to contain drifts between the tracking systems.

- The second part of the outdoor experiments showed, in the worst subset, drifts below 0.10 m within around 1.5 s or 2 m of travelled distance and below 0.25 m within around 6 s and 7 m traversed (Figure 6). The overall trend of all subsets, instead, shows a drift below 0.10 m within about 4 m and below 0.25 m within about 9 m of travelled distance. These results extend the answer to RQ.1 and highlight the critical need of spatial registration of HoloLens 2 against GNSS-RTK.
- Finally, for achieving in all outdoor circumstances a "fine-precision" positional accuracy, required for a good AR user experience, aligning HoloLens 2 with GNSS-RTK data every 1.5 s or 2 m of travelled distance is crucial. Overall acceptable results can be achieved by aligning HoloLens 2 with GNSS-RTK data every 4 m of travelled distance. These results answer RQ.2.

Future works will focus on the assessment of the drift between image-based and HoloLens 2 tracking systems as explained in point 3, 4 and 7 of the presented methodology (Evaluation method section). Then, data fusion techniques should be applied to combine the different data sources and achieve better results in scenarios served by both the GNSS-RTK and image-based tracking systems.

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References

Albahbah, M., Kıvrak, S., & Arslan, G. (2021). Application areas of augmented reality and virtual reality in construction project management: A scoping review. *Journal of Construction Engineering*, *4*, 151–172. https://doi.org/10.31462/jcemi.2021.03151172

ArchGIS Esri. (2023). Equirectangular. Retrieved December 22, 2023, from https://desktop.arcgis.com/en/arcmap/10.3/guide-books/map-projections/equirectangular.htm

Baek, F., Ha, I., & Kim, H. (2019). Augmented reality system for facility management using image-based indoor localization. *Automation in Construction*, *99*, 18–26. https://doi.org/10.1016/j.autcon.2018.11.034

Chen, K., Chen, W., Fellow, P., Li, C. T., Student, M., & Cheng, J. C. P. (2019). A BIM-based location aware AR collaborative framework for facility maintenance management. In *Journal of Information Technology in Construction (ITcon)* (Vol. 24). Retrieved from http://www.itcon.org/2019/19

El Barhoumi, N., Hajji, R., Bouali, Z., Ben Brahim, Y., & Kharroubi, A. (2022). Assessment of 3D Models Placement Methods in Augmented Reality. *Applied Sciences (Switzerland)*, *12*(20). https://doi.org/10.3390/app122010620

Messi, L., Spegni, F., Vaccarini, M., Corneli, A., & Binni, L. (2023). Seamless Indoor/Outdoor marker-less Augmented Reality registration supporting Facility Management operations. *23° International Conference on Construction Applications of Virtual Reality "Managing the Digital Transformation of Construction Industry."*

Movable Type Scripts. (2023). Calculate distance, bearing and more between Latitude/Longitude points. Retrieved December 23, 2023, from https://www.movable-type.co.uk/scripts/latlong.html

OpenCV. (2023). Perspective-n-Point (PnP) pose computation. Retrieved December 22, 2023, from https://docs.opencv.org/4.x/d5/d1f/calib3d_solvePnP.html

Salman, A., & Ahmad, W. (2023). Implementation of augmented reality and mixed reality applications for smart facilities management: a systematic review. *Smart and Sustainable Built Environment*. https://doi.org/10.1108/SASBE-11-2022-0254

Sarlin, P.-E., Cadena, C., Siegwart, R., & Dymczyk, M. (2018). *From Coarse to Fine: Robust Hierarchical Localization at Large Scale*. Retrieved from http://arxiv.org/abs/1812.03506

Sarlin, P.-E., Dusmanu, M., Schönberger, J. L., Speciale, P., Gruber, L., Larsson, V., … Pollefeys, M. (2022). *LaMAR: Benchmarking Localization and Mapping for Augmented Reality*. Retrieved from http://arxiv.org/abs/2210.10770

Sattler, T., Maddern, W., Toft, C., Torii, A., Hammarstrand, L., Stenborg, E., … Pajdla, T. (2017, July 27). *Benchmarking 6DOF Outdoor Visual Localization in Changing Conditions*. Retrieved from http://arxiv.org/abs/1707.09092

Schönberger, J. L., & Frahm, J.-M. (2016). *Structure-from-Motion Revisited*. Retrieved from https://github.com/colmap/colmap.

ublox. (2023). ZED-F9P module. Retrieved December 22, 2023, from https://www.u-blox.com/en/product/zed-f9p-module