Real-Time Kinematic Positioning and Optical See-Through Head-Mounted Display for Outdoor Tracking: Hybrid System and Preliminary Assessment

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Abstract: This paper presents an outdoor tracking system using Real-Time Kinematic (RTK) positioning and Optical See-Through Head Mounted Display(s) (OST-HMD(s)) in urban areas where the accurate tracking of objects is critical and where displaying occluded information is important for safety reasons. The approach presented here replaces 2D screens/tablets and offers distinct advantages, particularly in scenarios demanding hands-free operation. The integration of RTK, which provides centimeter-level accuracy of tracked objects, with OST-HMD represents a promising solution for outdoor applications. This paper provides valuable insights into leveraging the combined potential of RTK and OST-HMD for outdoor tracking tasks from the perspectives of systems integration, performance optimization, and usability. The main contributions of this paper are: **1)** a system for seamlessly merging RTK systems with OST-HMD to enable relatively precise and intuitive outdoor tracking, **2)** an approach to determine a global location to achieve the position relative to the world, **3)** an approach referred to as 'semi-dynamic' for system assessment.

1 INTRODUCTION

The primary motivation of this work is to explore the integration of OST-HMD and RTK systems for outdoor tracking, particularly in the context of managing CBRN (Chemical, Biological, Radiological, and Nuclear) incidents. Our focus here is on radiological incidents. Incident management involves numerous first responder organizations, as well as potentially the military and other agencies. Those involved in responding to such incidents require accurate, real-time information regarding the risks present and the positioning and utilization of assets such as Unmanned Aerial and Ground Vehicles (UAVs, UGVs) to detect and identify sources of contamination.

Leveraging OST-HMD with RTK systems for real-time outdoor tracking could significantly enhance situational awareness during radiological incidents. By providing first responders with the ability to perceive, comprehend, and plan appropriate courses of action based on real-time accurate information, this technology can help mitigate risks and manage incidents more effectively. However, radiological incidents can occur in diverse environments, including densely populated urban areas, under various lighting conditions, and in different weather conditions.

Most contemporary technologies designed for outdoor object tracking with high precision primarily rely on image inputs. The utilization of machine learning approaches, such as YOLOv5 (Benjumea et al., 2021), facilitates the detection and tracking of various objects. Nevertheless, these methods encounter challenges when objects are concealed by obstacles, in adverse weather conditions, or during nighttime. Consequently, their effectiveness diminishes under such conditions. In response to these limitations, alternative methods incorporating GPS signals have been employed, offering estimations with limited precision (Stranner et al., 2019). However, certain applications demand even greater accuracy, prompting the utilization of RTK systems to achieve enhanced tracking precision.

To visualize the tracking information obtained from GPS or RTK systems, conventional approaches employ tablets or 2D screens. Advancements in OST-HMDs technology have paved the way for novel applications that capitalize on the benefits of observing

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tracked objects through OST-HMDs. These devices are based on the half-silvered mirrors technique to merge the view of virtual and real objects. The advantage of this technique is the ability to directly view the real world as is and not via a computer rendering as is the case with **V**ideo **S**ee **T**hrough HMDs (VST-HMDs). This avoids problems with lag, and often reduces other ergonomic issues associated with VSTs, such as discomfort and heat.

Despite their impressive capabilities for blending digital content with the real world, OST-HMDs are not recommended for outdoor scenarios. Most OST-HMDs rely on depth-sensing cameras to map the user's environment and interact with virtual objects. While they can work outdoors, the performance of depth sensing may degrade in bright sunlight or on highly reflective surfaces, leading to less precise spatial mapping and interaction. Moreover in bright sunlight, the display may appear less vibrant, and the virtual objects content may be less visible compared to indoor environments.

However, OST-HMDs offer several advantages over traditional 2D visualization: 1) spatial awareness supported by OST-HMDs allows to tracked objects in their actual surroundings, making it easier to comprehend their positions and movements; 2) users can interact with the tracked objects in a hands-free manner. This is particularly beneficial in scenarios where users need to focus on tasks or have limited physical mobility; 3) OST-HMDs can offer intuitive navigation assistance by overlaying visual cues or directions onto the real-world environment. This can be particularly useful for guiding users to specific tracked objects or locations.

Despite the fact that OST-HMDs are not fully adapted for outdoor use, these advantages have attracted numerous researchers (Ling et al., 2019; Satheesan, 2024; Oskiper et al., 2012) to analyze potential scenarios for their application such as tracking real object in outdoor environment. In this paper, we suggest a system that integrates the RTK system with OST-HMD for outdoor scenario. We integrated an RTK system and a Raspberry Pi into a UGV, connected to the proposed web-based server. Moreover, a semi-dynamic approach is proposed to evaluate the system and illustrated in Section 4. The paper presents preliminary results, shedding light on the potential of this integrated system, while also highlighting the myriad challenges associated with its implementation. Hence, in this paper, we aim to address the following research questions:

- RQ1: how can UGVs be effectively visualized using OST-HMD when obstacles obstruct the view of objects as illustrated in Figure 1?
- RQ2: how can data from RTK systems be seamlessly integrated into OST-HMD?
- RQ3: how well does the semi-dynamic approach adapt to the challenges of real-world UGV tracking evaluation compared to the static and dynamic methods?

2 BACKGROUND

We review the related works in three main paragraphs, each corresponding to one of our key contributions.

RTK system with OST-HMD. RTK systems overcome GPS limitations, achieving centimeter-level accuracy through base station corrections (Gan-Mor et al., 2007). However, urban environments reduce RTK performance due to signal obstructions and multipath interference (De Pace and Kaufmann, 2023). Large-size RTK systems provide extended baselines and high accuracy, while small, portable devices prioritize usability for mobile applications (De Pace and Kaufmann, 2023). For instance, a smartphone-based RTK device achieved 1 cm accuracy in open-sky areas but showed significant accuracy degradation near buildings (De Pace and Kaufmann, 2023).

Augmented Reality (AR) with GPS or RTK on handheld devices has been extensively studied (Schall et al., 2009; Stranner et al., 2019). However, integrating these systems with OST-HMDs remains underexplored. Early works (Roberts et al., 2002) proposed combining AR and RTK for underground feature visualization, but lacked implementation details or robust outdoor adaptability. Recent hybrid approaches use multiple sensors, including RTK and visual SLAM (vSLAM). For example, (Satheesan, 2024) developed a proof-of-concept combining RTK with vSLAM for OST-HMDs, achieving partial success but requiring external antennas and frequent RTK updates. Another hybrid system using RTK with vSLAM for outdoor tracking on Microsoft HoloLens (Ling et al., 2019) shares similarities with our approach but has notable limitations. It lacks formal performance benchmarking, requires an external antenna on the HMD, reducing mobility, and relies on frequent RTK updates, which can introduce latency due to signal delays. In contrast, Our approach integrates RTK for initial reference positioning with vSLAM for continuous tracking, reducing dependency on RTK updates and enhancing portability.

Global Locations. vSLAM can create a local map of traversed areas but cannot provide a global po-

Figure 1: Tracking UGV using RTK systems. F_n, F_{n+i} and F_{n+i+j} are captured frames from Microsoft HoloLens v2. The white virtual rectangle refers to the RTK information derived from RTK rover system located on UGV. A detailed demonstration of the experiment setup is available in the video: https://youtu.be/cqJEJmuMtsg.

sition relative to the world. Methods like matching observed data to geotagged datasets (Zhang and Kosecka, 2006) or using pre-built 2.5D models with GPS alignment (Arth et al., 2015) offer solutions but require substantial initial preparation. Similarly, deep learning approaches, such as SSD-based object detection (Rao et al., 2017), combine rough GPS data with sensor inputs for near real-time positioning. In this paper, we propose using an RTK-equipped UGV to establish a reference point, aligning the OST-HMD coordinate frame with the world frame. This enables accurate tracking of the UGV's position on the OST-HMD, as detailed in Section 3.5.

Accuracy Evaluation. The accuracy of a system containing RTK or GPS can be evaluated in static or dynamic scenarios. The RTK or GPS systems remain fixed at a specific location (Wiśniewski et al., 2013; Safrel et al., 2018) in static conditions, while it keeps changing its physical location in dynamic conditions (Kluga et al., 2014; Tomaszewski et al., 2020). In this paper, a semi-dynamic method is proposed, capturing UGV positions at specific locations along a trajectory (Tomaszewski et al., 2020). Unlike traditional static or dynamic evaluations, this approach balances real-world relevance with methodological rigor, providing insights into system accuracy under varying conditions. Details are provided in Section 4.

3 SYSTEM

3.1 Scenario

As highlighted in the introduction, the focus of this work revolves around enhancing the management of CBRN incidents through the visualization of tracked a UGV. First responders, including firefighters, military personnel, and other emergency teams, often face critical situations where they must intervene to neutralize, for example, a source of radiation in an urban area. In these scenarios, the initial step involves deploying a UGV equipped with a specialized gamma camera (Gal et al., 2001). This camera is designed to detect and pinpoint the exact location of the radiation source, enabling the team to address the threat effectively.

The key advantage of utilizing a UGV lies in its ability to perform reconnaissance and intervention tasks without putting human lives at risk. By keeping first responders at a safe distance, the UGV minimizes their exposure to dangerous levels of radiation and other associated hazards. This approach not only enhances the safety of emergency personnel but also improves the efficiency and precision of the intervention.

To further augment situational awareness and operational effectiveness, we propose that first responders wear OST-HMD. These can overlay critical information directly into the responders' field of vision, including real-time data on the UGV's position, radiation levels, and other vital metrics. This integrated system ensures that first responders have immediate access to comprehensive information, facilitating informed decision-making and coordinated actions during the intervention.

Hence, we hypothesize that by combining the capabilities of UGV with OST-HMD, we can significantly enhance the safety, accuracy, and efficiency of radiation neutralization efforts in urban environments. Consequently, in this investigation, we propose a system to visualize tracked UGVs in outdoor environments via OST-HMD. This system addresses the initial research question *RQ1: how can UGVs be effectively visualized using OST-HMD when obstacles obstruct the view of object?* To answer this question, the system includes three main components, which are detailed in the following Sections:

- The server application receives the positions of the UGV and transmits this data to the OST-HMD.
- Sensors in our scenario are UGVs equipped with an RTK system. This system is composed of an RTK rover and an RTK station. The position of the RTK rover is corrected using the RTK station, as will be illustrated later in Section 3.4. The choice of the RTK system, as mentioned in the introduction, offers significant advantages over image-based tracking in scenarios involving obstacles, adverse weather, or nighttime conditions.
- The AR application deployed on OST-HMD serves as an interface for visualizing information provided by the RTK rover.

3.2 Assess System Requirements

In CBRN management, free-hand operation for first responders is essential. For this reason, OST-HMDs were selected rather than handheld AR devices. A Continuously Operating Reference Station (CORS) network consists of a series of fixed reference stations that continuously collect GNSS data. In such a system, the rover corrects its position often via an internet connection through a remote station provided by the CORS network. Some countries around the world provide CORS networks. In our case, the system was not supported by CORS; hence a local station was chosen. Furthermore, we opted for large-size RTK systems to achieve the highest possible positional accuracy. CBRN incidents often occur in urban areas, so we evaluated the system in these areas (see Figure 2). Despite the fact that the RTK system provides less accuracy and precision compared to open-sky conditions.

3.3 Server Application

We utilized Tomcat, a web hosting service built around the Java programming language. It offers a REST API as well as socket connections. This server is hosted on a web-based platform known as (Anonymous web server). The server receives the message from sensors and broadcasts to the OST-HMD. Since real-time communication is required, raw socket connections are used. This offers lower latency compared to HTTPS due to reduced protocol overhead and encryption.

3.4 Sensors

Sensors such as UAVs, UGVs, or other types can be used in CBRN management. In the scenario pre-

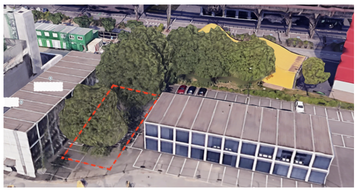

Figure 2: Picture captured from Google Earth. The area highlighted in red is where the experimental test is conducted.

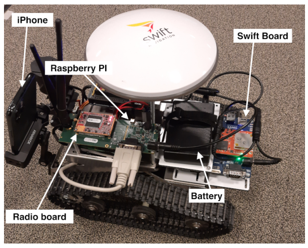

Figure 3: UGV consists of an antenna, Swift Navigation Piksi board, Radio board, battery, phone holder, iPhone 11 Pro, and Raspberry Pi, which is hidden by a radio board that receives the correct position of the UGV using information derived from the RTK station.

sented in Section 3.1, the sensor specifically refers to one mounted on a UGV [1]. This latter operates through a specialized application that communicates via a dedicated WiFi network. This application serves as the control interface, enabling users to remotely manage and command the UGV's movements. We customized the UGV to fit our requirements, incorporating components such as an RTK rover (an antenna, Swift Navigation Piksi board [2], Radio board), phone holder, iPhone 11 Pro and Raspberry Pi on the UGV (see Figure 3). Moreover, an RTK station (see Figure 5) is used to transmit GNSS correction data over the radio link to the RTK rover. The RTK station position known as the "surveyed position" is determined manually or automatically. The surveyed position will be used to correct the position derived from RTK rover. In our case, the surveyed position was not available, therefore, we used automatic surveyed position which is generated using average of the last 1000 Single Point Positioning (SPP) position solutions. Furthermore, RTK rover interfaces with the Raspberry Pi, which facilitates the transmission of the UGV's position data to a web server known as (Anonymous web server). Moreover, an iOS application is developed and deployed on iPhone 11 Pro. The application provides GPS capabilities for location tracking and navigation using the CLLocationManager class. This information is then sent to the web server, similar to the information sent from the Raspberry Pi. Utilizing lo-

[1] https://www.xiaorgeek.net
[2] https://www.swiftnav.com

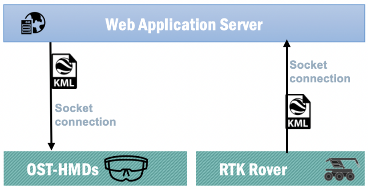

Figure 4: General schema of the proposed system.

cation information derived from the iPhone provides us with the opportunity to compare it with RTK location information, as illustrated in Section 4.

3.5 AR Application

In this investigation, HoloLens version 2 is used. An AR application is developed using Unity3D. It's connected with UGV via the server application (see Figure 4). Moreover, we propose to utilize sun protection filter [3] to reduce some of the effects of bright sunlight on the outdoor experience. The HoloLens app is based on vSLAM to generate a map of the surroundings and find its own location within it. Our main contribution in this application is to respond to the *RQ2: how can data from RTK systems be seamlessly integrated into OST-HMD?* To answer this question, the application contains two main functionalities: 1) calibration to obtain a global location, and 2) location update, as described below:

3.5.1 Calibration

Global location consists of finding the correct position and orientation of the person wearing the HoloLens relative to the world.

User's Position. At the start, the person wearing the HoloLens stands in the same location as the UGV. This location is considered as the reference point. Hence, the position P_{ref}^{world} derived from the RTK rover is the same as the position of the HoloLens device $P_{ref}^{HoloLens}$, but in different coordinate frames. The first is in the World coordinate frame, and the second is in the HoloLens coordinate frame. The two positions P_{ref}^{World}, $P_{ref}^{HoloLens}$ are saved to calculate the updated positions.

User's Orientation. The bearing angle indicates the angle between the reference position P_{ref}^{World} and the UGV's position P^{World} relative to the north direction. This angle is crucial for navigation and positioning tasks. If the OST-HMD coordinate frame is aligned with the World coordinate frame, meaning that the negative z-axis of the HoloLens aligns with the north direction, then the bearing angles calculated in the World coordinate frame will match those in the HoloLens coordinate frame. This alignment ensures consistency in directional references across both systems. To achieve this alignment, at the beginning, the user's head direction, while wearing the OST-HMD, should face the north direction. This initial orientation aligns the user's perspective with the World coordinate frame, facilitating accurate bearing angle measurements and consistent spatial orientation.

3.5.2 Update Position

Keyhole Markup Language (KML) messages are composed of the coordinates of the UGV in World coordinate frame are transmitted to the server application via the detected Wi-Fi network. The server relays this data to the AR application, which then displays the relevant information on OST-HMD. As mentioned previously, sockets are employed to enable multiple simultaneous messages between the various system components. Therefore, to compute the position of UGV in the HoloLens coordinate frame, we follow these steps

- Computing the distance δ between UGV's position P^{World} and reference position P_{ref}^{World} which refers to the previously saved reference position from the calibration step
- Calculating the bearing angles between the reference position P_{ref}^{World} and the UGV's position P_{ref}^{World} in the World coordinate frame. This angle will be the same in the HoloLens coordinate frame thanks to the calibration step, which aligns the negative z-axis of the HoloLens with the north direction

Hence, the position $P_{v}^{HoloLens}$ of the virtual object corresponding to the position of UGV in HoloLens coordinate frame is computed as follows:

$$P_{v}^{HoloLens} = P_{ref}^{HoloLens} + P_{\delta}^{HoloLens} \tag{1}$$

$$P_{\delta}^{HoloLens} = \begin{pmatrix} \delta \cdot \cos(\beta) \\ \delta \cdot \sin(\beta) \\ 0 \end{pmatrix} \tag{2}$$

Where $P_{\delta}^{hololens}$ refers to the position after the rotate of point $(\delta, 0, 0)^T$ by the bearing angle β which indicates the angle between the reference and UGV positions according to north direction. Knowing that the negative z axes of HoloLens coordinates system is aligned with north direction via calibration steps as mentioned previously. Hence, the AR application transforms the RTK coordinates of UGV derived from KML file into the HoloLens coordinate frame using

[3] https://www.realsim.info/en-gb/hololens-2-sonnenschutzfolie

the reference position $P_{ref}^{HoloLens}$. Therefore, the proposed approach isn't required to update the position of the user wearing the HoloLens in each frame, as in (Ling et al., 2019), thus avoiding noisy information and providing more stable results.

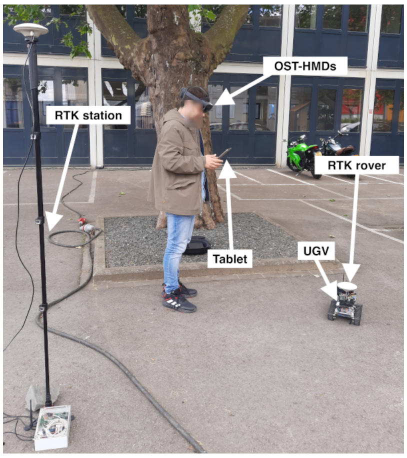

Figure 5: A prototype consisting of a UGV, RTK rover (including an antenna, Swift Navigation Piksi board, and Radio board), RTK station, tablet with a specific application enabling users to remotely command the UGV's movements, and OST-HMD such as the HoloLens v2.

4 RESULTS

To accurately simulate a real-world scenario involving a CBRN incident in an urban environment, the system as illustrated in Figure 5 was thoroughly evaluated in a mixed use urban area containing a diverse array of structures such as multiple buildings, trees, and various other environmental elements that would typically surround the UGV. This complex and realistic urban landscape is illustrated in Figure 2. One advantage of this system is that it can still track objects even when they're not directly in sight, unlike systems that rely on images. As illustrated in Figure 1, when the UGV is occluded by the tree, it can still be tracked via the AR application. This can be useful, especially in situations where you need to see past obstacles. For example, in the context of a radiological incident and the management of CBRN, the utilization of OST-HMD by first responders could significantly enhance their situational awareness. These devices would enable them to gain a comprehensive understanding of the scenario, facilitating real-time observation of various elements, such as the location of the UGV. Notably, the latter could be equipped with systems similar to those integrated into our prototype UGV, thereby extending the capabilities of the response team to effectively assess and mitigate the situation.

However, in this paper, we provide a preliminary evaluation of the system from the perspectives of functionality and accuracy. Further study is required to evaluate the system with end users, specifically first responders.

The experimental test begins by locating the RTK station and automatically determining its surveyed position using more than 1,000 positions of the SPP solution. This functionality is provided by the Swift Navigation Piksi Multi RTK GNSS system. Afterward, the UGV is positioned at a predetermined reference point. To calibrate the system, the person wearing the OST-HMD stands as close as possible to the UGV, holding a tablet to drive the UGV via a detected WiFi network. Both the person and the UGV face the north direction. Subsequently, the person wearing the OST-HMD turns on the HoloLens and runs the application. After the calibration step is complete, the person starts driving the UGV via the tablet and is free to move without any restrictions. A virtual object representing the UGV follows the physical UGV, visualized through the HoloLens. As mentioned in Section 2, in assessing GPS and RTK accuracy (see Figure 6), two main methods are used: a) static: this involves comparing specific GPS/RTK location data with the real-world coordinates. It helps understand accuracy in fixed positions. b) dynamic: unlike static, dynamic analysis looks at the entire trajectory from GPS/RTK against real-world movement. This helps assess accuracy while in motion, useful for tasks like navigation and tracking. However, in our proposed methodology for system evaluation, applying the dynamic method has proven challenging. Synchronizing the movement of both the UGV and the HoloLens wearer to capture a full trajectory for error distance evaluation has presented difficulties. As a result, we propose a "semi-dynamic" approach, addressing *RQ3: how well does the semi-dynamic approach adapt to the challenges of real-world UGV tracking evaluation compared to static and dynamic methods?* In this method, the UGV is driven and paused at various locations to measure error distances before completing the route for a more comprehensive evaluation.

To measure the error distance, our approach (semi-dynamic) is grounded on the hypothesis that the distance between the physical camera position of the HoloLens and the virtual tracked object should ideally be zero when the wearer of the HoloLens stands in the same position as the UGV simultaneously precisely in same position of RTK rover, disregarding any height difference. We conducted multiple iterations of this process, ensuring that error distances were recorded while standing as close as possible to the RTK rover antenna. Figure 7 illustrates the absolute error distances between the positions UGV measured using RTK information and GPS information derived from iPhone and the HoloLens camera position, knowing that the y-axis of the HoloLens is set to zero, as our aim is to calculate the error in a 2D plane without considering height.

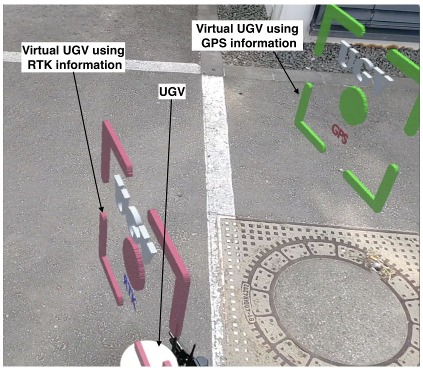

Figure 6: Tracking a UGV using RTK and GPS. Frame is captured from HoloLens v2. The virtual objects (rose and green rectangles) should be in the same position as the UGV such that the green rectangle represents the GPS value derived from the iPhone, and the rose rectangle represents the RTK value derived from RTK rover.

As expected, we observe that the position of the virtual object using GPS values is jumping and unstable in densely populated urban areas. In our experiment, the standard deviation for the different positions of a trajectory was approximately 7.453 meters. Consequently, it's necessary to apply a filter to these data to reduce the jumping behavior. Conversely, RTK values exhibit a standard deviation of 0.126 meters and provide more stable results. As shown in the Figure 7, a shifted offset value between the real object and the virtual one provided by RTK is approximately constant observed. In line with expectations, RTK offers greater precision than GPS, with an average of 0.745

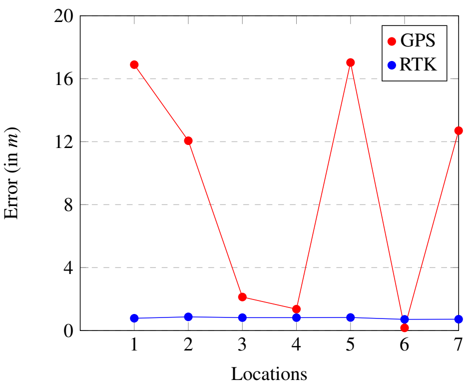

Figure 7: Scatter plot illustrating the errors in distance measurements for several UGV locations obtained using both RTK and GPS systems.

meters compared to 8.907 meters provided by GPS.

Although it is well known that RTK offers significantly higher accuracy than standard GPS, the primary objective of this experimental test is to demonstrate that our methodology for the hybrid system of OST-HMD and RTK—specifically the processes of calibration and location updating—functions effectively, while maintaining the high accuracy provided by RTK.

5 LIMITATIONS AND FUTURE DIRECTIONS

To optimize the OST-HMD and RTK system for outdoor tracking, key areas of improvement include:
Accuracy Enhancements. Leveraging RTK stations with surveyed positions can simplify calibration and improve accuracy. Adding sensors like a compass to OST-HMDs could aid orientation calibration, while improving depth sensors for outdoor conditions can enhance vSLAM performance.
Network Latency. Reducing latency can be achieved through multi-threading, network optimization, and using UDP for faster communication. Predictive rendering on OST-HMDs can also compensate for delays by anticipating object movements.
Visualization. Challenges in aligning virtual objects with real-world counterparts in outdoor environments remain. Research is needed on optimal virtual object shapes, perception changes with distance, maintaining alignment across terrains, and the impact of lighting and weather. Using sun filters and adapting to outdoor lighting conditions can enhance visibility, while exploring sensory augmentations like sound could improve usability. Addressing these challenges could significantly improve OST-HMD and RTK integration for real-world applications.

6 CONCLUSION

Current OST-HMDs overcome many limitations of VST-HMDs but still face challenges when used in outdoor environments. This paper proposes an approach to integrate data from an RTK system and track this information using the vSLAM algorithm in OST-HMD. We hypothesize that combining UGV, OST-HMD, and accurate positioning can enhance the ability of first responders to manage incidents, particularly by improving their capability to visualize occluded information, thereby increasing situational awareness and safety.

Our system consists of three core components: (1) a web server that receives data from a UGV and transmits it to OST-HMD via a socket connection; (2) a UGV equipped with an RTK rover system; and (3) the HoloLens 2, serving as the OST-HMD. A detailed calibration step, which ensures accurate global tracking of the user's position and orientation, is illustrated.

In this paper, we present a preliminary evaluation of the system in terms of functionality and accuracy. Further research is necessary to assess the system with end users, specifically first responders. In conclusion, this paper advances the state of the art in outdoor RTK positioning with OST-HMD, proposing a comprehensive system for visualizing UGV data via OST-HMD while also highlighting areas for future research.

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