Towards Outdoor Collaborative Mixed Reality: Lessons Learnt from a Prototype System

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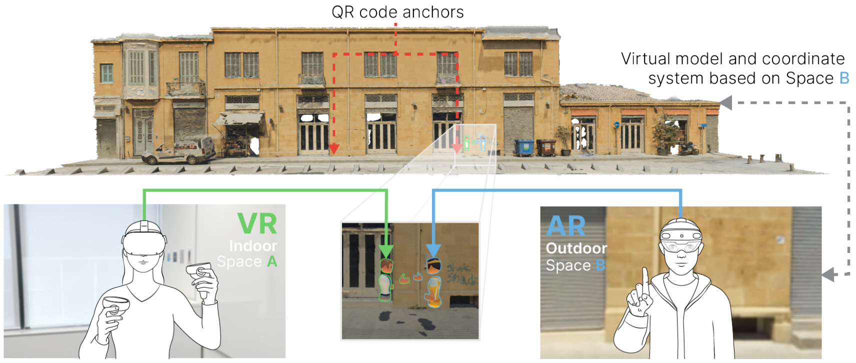

Figure 1: Conceptual overview of our outdoor CMR system showing a detailed 3D model of a street that a local AR user can experience in collaboration with a remote VR user. The virtual coordinate space of the shared virtual environment is aligned to the real-world surroundings of the AR user (Space B) with QR code markers. Line illustrations by Suhyun Park (artist).

ABSTRACT

Most research on collaborative mixed reality (CMR) has focused on indoor spaces. In this paper, we present our ongoing work aimed at investigating the potential of CMR in outdoor spaces. These spaces present unique challenges due to their larger and more complex nature, particularly in terms of reconstruction, tracking, and interaction. Our prototype system utilises a photorealistic model to facilitate collaboration between remote virtual reality (VR) users and a local augmented reality (AR) user. We discuss our design considerations, lessons learnt, and areas for future work.

Keywords: mixed reality, augmented reality, virtual reality, collaboration, outdoor, city-scale, reconstruction, registration

Index Terms: Human-centered computing—Collaborative and social computing systems and tools; Human-centered computing—Ubiquitous and mobile computing systems and tools;

1 INTRODUCTION

Collaborative mixed reality (CMR) is a rapidly evolving field that has the potential to fundamentally change the way we interact with each other and with our surroundings. Although current research in CMR has focused mostly on collaboration in indoor spaces, there are many opportunities for it to be applied in outdoor spaces. Outdoor CMR systems enable new forms of games [4, 17, 35], tourism [7, 16], and navigation [22]. Other applications, which have been thoroughly investigated in indoor settings, may find wider or new applications in outdoor spaces such as visualisation and design [36, 37], training and education [15, 28, 29], and remote assistance [11, 14].

However, to achieve a seamless and fully consistent outdoor CMR experience, several challenges must be overcome. The majority of outdoor CMR applications rely on an accurate digital representation of the real-world environment. A key challenge is model registration, which refers to the accurate alignment of virtual objects with respect to the tracked physical environment. This includes both static registration, such as georeferencing for large-scale models, and dynamic registration, also known as the tracking problem, which usually involves estimating the transformation between the user and the world in real-time using vision-based tracking methods. For outdoor CMR systems, tracking techniques must be able to handle large-scale environments, variable lighting conditions, and complex compositions of moving (e.g. cars), reflective (e.g. windows), and visually repetitive (e.g. façades) objects. Furthermore, outdoor CMR systems require different approaches to user interface and interaction than indoor systems, as users may be physically moving over long distances and have different needs in outdoor environments. Moreover, due to the complex and dynamic nature of outdoor environments, it is challenging to create highly realistic and coherent experiences, which commonly has been found to contribute to the sense of presence and engagement of users [20, 23, 30].

In this work-in-progress paper, we explore the challenges of building outdoor CMR systems for large areas by developing a prototype in which a local outdoor augmented reality (AR) user collaborates with remote virtual reality (VR) users located in a large-scale 3D model of the AR user's physical space. In this system, we employ a brute-force alignment method based on QR codes, the built-in HoloLens 2 tracking system, and the World Locking Tools (WLT) [21] library. We used this prototype as a testbed for exploration and experimentation, allowing us to gain insight into the challenges of outdoor CMR and to devise plans for future work

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to address these. By releasing our prototype's source code and discussing our system design considerations, recommendations, and plans for future work, we aim to inspire further research in this area.

2 RELATED WORK

One of the first systems for collaboration between remote outdoor AR users and local VR users was presented by Piekarski et al. [26]. Their proposed system allowed multiple AR users to interact with a user in a stationary VR system. In the VR environment, real-time information indicating the AR users' whereabouts with respect to the real world was used to render an avatar in the corresponding virtual location. In the same year, Höllerer et al. [12] demonstrated collaboration between an indoor desktop user and an outdoor AR user using their MARS backpack. Although these early systems demonstrated the potential of CMR, they were limited by hardware constraints [8, 12, 26]. For example, differential GPS systems had to be used for position tracking, which were expensive, bulky, and required a clear view of the sky. Furthermore, interaction capabilities were limited as they relied on tablet computers or keyboards.

A recent example that addressed some of these limitations, but still is based on a relatively bulky and expensive system, is DreamWalker [38]. This VR system allows a single user to observe a large dynamic virtual environment while walking to a destination in the real world. The system used GPS coordinates, inside-out tracking, and RGB-D sensors to accurately detect walkable paths and represent them in VR through a dynamic scene to guide the user to their destination.

Others have explored the implementation of relatively compact outdoor CMR systems, such as GIBSON [34], a system that allows remote VR users to join the walking experience of a local AR user through a combination of a 3D city model and a live video stream of the AR user's view. This system used a Nreal Light for the AR user combined with a third-party visual positioning system (VPS) for localisation, and a Meta Quest 2 for the VR user.

Furthermore, Rompapas et al. [31] introduced a collaborative AR system called HoloRoyale. This system extended a HoloLens with an external software framework which improved user pose accuracy and provided synchronisation among users. As the HoloLens has a limited trackable area ($100\,\mathrm{m}^2$, according to the authors), individual scans were merged using an iterative closest point (ICP) method so that the alignment between each pair of submaps and the world was established. In our prototype, we do not exceed the limit of a single HoloLens map, and the registration between the mesh model and the real world is established and maintained through the WLT library [21].

Our proposed system is unique in that it provides an open-source implementation, allowing for experimentation and inspiration for future work. Unlike GIBSON [34], however, our system does not rely on a VPS and requires manual preparation of the model and manual actions to align the model at runtime. The improvement of registration methods is a subject of future work and is discussed in Section 4. Our system enables collaboration between remote VR users and a local AR user through Ubiq [9], with support for voice communication and basic gestures. Additionally, it provides a high-fidelity large-scale model for the remote VR user to accommodate tasks that require precision or an accurate view of the real-world environment, such as architectural design and city planning.

3 OUTDOOR CMR SYSTEM

Our prototype system is built using the open-source social VR framework Ubiq [9] (Unity version 2020.3.40f1) and is based on an existing implementation of an asymmetric CMR system [25]. Our system supports collaboration between a local outdoor AR user and remote VR users. Users are represented as randomly assigned avatars from the Ubiq platform, featuring a head, an upper torso, and floating hands with a hand-closing animation. They experience the CMR environment from an egocentric point of view, are scaled to their normal height and are able to move independently within the environment. The avatar movement of users is networked through a TCP connection with Ubiq's `Networking` module. They can communicate through a voice over IP (VoIP) connection established through Ubiq, using spatialised audio. Controller-based interactions are implemented through the Ubiq controller components.

Figure 2: A VR user placing greenery and a shaded park bench in the collaborative virtual environment.

We utilise the Microsoft HoloLens 2 (HL2) for the AR user and the Meta Quest 2 (MQ2) for VR users. Avatar hands are controlled through hand-tracking for AR users and through controllers for VR users. For the AR user, an internet connection is established over a wireless 5G mobile hotspot created with an iPhone 13, whereas VR users connect to the internet through a wireless network. The source code of our prototype system has been made available publicly[1].

3.1 Interactions

Our prototype system provides remote VR users with a detailed reconstruction of the local AR user's environment, allowing them to effectively navigate and interact with the shared space as if they were physically present. This is particularly useful for applications such as city planning, construction, and emergency response, where the ability to accurately visualise and interact with the physical environment is crucial for effective decision-making.

As a demonstrative example, we implemented an application utilising our prototype for the collaborative placement of greenery and basic street furniture, such as trees, flowers, and park benches (Figure 2). In this application, users can tap one of three cubes placed on the ground while holding their controller's trigger button to spawn an object. Each box spawns one of three types of objects: trees, flowers, or benches. Utilising an accurate model of the street, remote and local stakeholders, such as landscapers and urban planners, can collaborate in real-time to optimise the placement of greenery while being able to consider factors such as traffic, shading, and aesthetics.

3.2 3D Reconstruction

For VR users, the CMR environment contained a 3D model of the physical space of the AR user, which was a street in Nicosia, Cyprus. Terrestrial laser scans are commonly used in 3D reconstruction to provide comprehensive and accurate models of the scene, with high-density point clouds as well as RGB colour information. However, models based on laser scans are typically less appealing due to the presence of shadows representing occlusion boundaries and gaps between individual scans (as shown in Figure 4). Although additional scans could be registered to mitigate this issue, we found that photogrammetry methods demonstrated greater efficiency and better visual quality. For this reason, in our prototype system, we opted to create a detailed model of a section of the street using photogrammetry software. We used an offline method for this, as online capture methods are not suitable for large areas and usually sacrifice model quality to achieve real-time performance. To make the model

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[1] `https://github.com/UCL-VR/outdoorCMR-prototype`

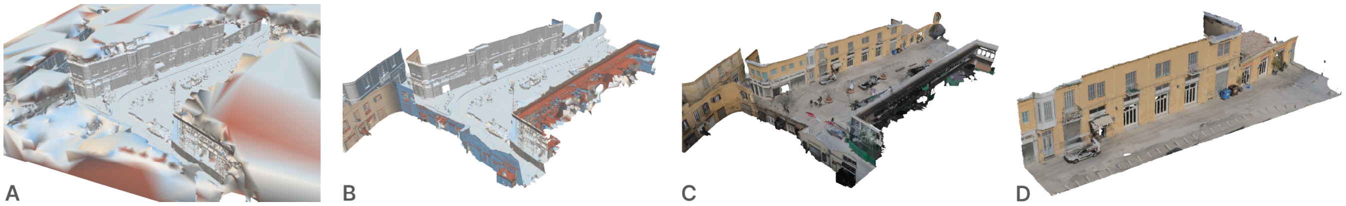

Figure 3: Overview of the decimation and cleaning process of the photogrammetry model. From left to right: (A) Raw mesh produced by RealityCapture containing around 30 million polygons; (B) Initial cleaned-up mesh removing bridge edges between the vertices; (C) Initial cleaned-up mesh with vertex colours; (D) Final mesh including texture, with only a restricted area remaining to ensure it could be rendered on untethered mixed reality (MR) devices.

Figure 4: Photogrammetry point cloud model with image poses.

Figure 5: Dense laser point cloud model from a FARO scanner.

suitable for real-time on-device rendering on the employed head-mounted displays (HMDs), we simplified and cropped the model. In the remainder of this subsection, we discuss the reconstruction process of the model used in our prototype.

First, we took 376 photographs of the target area from multiple angles using a Sony Alpha 7 III camera with a Sony FE 24-70mm F2.8 GM lens at 29mm and f/8. Each patch of the target area was captured from several vertical positions, approximately one metre apart from each other horizontally, and maintaining sufficient overlap. These images were then processed through the RealityCapture [2] photogrammetry software, which reconstructed a sparse model using 296 of all images. In this process, images are aligned by feature matching, and camera poses are triangulated and optimised to produce the best alignment (see Figure 5). From there, a dense point cloud was generated from the sparse model. From the dense point cloud, a polygonal model (mesh) was produced.

In its medium or high quality configuration, RealityCapture produces very large models based on the volume of images we captured (Figure 3A), which requires further processing. The resulting high poly mesh was cleaned up (Figures 3B and 3C) and decimated through a geometry-aware polygon reduction process to retain its shape while reducing complexity. Following this, the lower-poly mesh was exported and cut up to cover a smaller area, and finally cleaned up manually in Blender [5]. The final mesh model contained around 350K polygons. Finally, back in RealityCapture, the original texture and normal maps were baked onto the mesh (Figure 3D).

3.3 Coordinate Space

As our 3D model is not georeferenced to a global coordinate system and lacks scale information, we registered the model to the AR user's surroundings through a two-step process. Firstly, when putting together the CMR environment, we estimated and corrected the scale of the mesh model. While scaling could have been achieved using QR codes, we opted to use an available laser point cloud for this purpose, as it provides a more reliable and accurate scaling method. The scale factor was estimated by comparing sample points in the laser scan model (Figure 4) at metric scale and the corresponding points in the mesh model. Secondly, at runtime, a shared coordinate space was created for AR and VR users by aligning the CMR environment with the real world. This procedure was based on two known points marked with QR codes, located in two known places in the physical space (shown in Figure 1), based on a calculation described by McGill et al. [19].

An initial calibration was required for the HL2 user to perform the alignment. This involved walking up to each QR code and looking at them until they were successfully scanned, indicated by an overlaid green square. In each of the two virtual positions, *Space Pins* from the WLT library [21] were set to lock the virtual coordinate space to the real world. While the alignment persisted across sessions, drift made it necessary to periodically recalibrate the coordinate space to ensure proper alignment. This was done by repeating the above-mentioned QR code scanning process.

4 DISCUSSION

In the process of designing, implementing, and testing the described prototype system, we identified several key areas for improvement and further research, including model registration, AR tracking, 3D reconstruction, model management, applications, and evaluation. We describe these findings in this section with the aim of providing valuable information for the future development and optimisation of similar systems that target large-scale outdoor CMR.

Visual Evaluation To visually evaluate the limitations of the system with respect to model registration, we overlaid the mesh model on the view of the AR user, as shown in Figure 6. If registration were perfect, a coherently registered semitransparent virtual replica of the real world would be observable from the AR user's perspective. This technique allowed us to visually evaluate the prototype system in terms of static registration error, runtime tracking quality, and other observed differences between the captured model and real-world scene at runtime.

In our visual examination, we observed spatial inconsistencies between the real-world environment and the mesh model caused by dynamic objects in the scene. For example, in Figure 6A, a car is present in the mesh model but is no longer present in the real world. This divergence may confuse users and cause spatial referencing issues during collaboration, as the user's views of the environment do not match. To address this, object and motion segmentation techniques [1] could be applied to the model to distinguish regions of the model that are not expected to change. This could result in a more consistent representation of the environment and would therefore form a better base for CMR. Furthermore, future work could investigate the potential of real-time components of models based on real-time mapping or semantic segmentation methods that could use imagery captured by the AR user at runtime.

Additionally, we observed jittering in tracking, causing misalignment between the model and the real scene (Figure 6B). In future prototypes, we aim to replace the WLT library and QR code alignment with one of the vision-based localisation methods mentioned

(A) A car captured in the mesh model which was no longer on-site at the time of the our test.

(B) An extreme case of poor tracking causing misalignment between the model and the real building

Figure 6: Two screenshots of a recording of the AR user's perspective where the mesh model is overlaid onto the real world, showcasing issues we encountered during test time.

above to simplify setup, improve robustness, and mitigate drift.

Ultimately, the requirements of CMR systems are highly dependent on their application, and further evaluation is needed to explore the requirements of environmental representations, such as model accuracy and update frequency. For example, in some cases, a static high-accuracy model may be sufficient, while a low-accuracy model with a high update frequency may be required in other cases. Future work should thoroughly examine the requirements of CMR systems in various domains and explore the trade-offs between these factors.

Registration and Tracking Improvements

Accurate localisation requires precise registration of the 3D model in the global coordinate frame. However, in our prototype system, the 3D model is not georeferenced, and we used the WLT library and QR markers as a brute-force method to achieve a simple and reliable way to register the model in the real world. This process requires manual intervention and is not always robust or consistent. Furthermore, drift may occur when the QR code is out of sight of the AR user and, as a result, the virtual position of the AR user may jump when a QR code is re-observed. Although more QR codes could help mitigate this and may improve model registration overall, this is impractical for large areas. Additionally, since we had access to a point cloud of metric laser scan, a possible improvement in the manual steps of the registration process could be the usage of an ICP method [33] to align the laser scan model with the 3D model for georeferencing.

If we instead had a 3D model that is georeferenced, we could leverage other methods for more robust and accurate localisation and tracking. Ideally, this process could be simplified using image-based localisation on the 3D model [32] with respect to the real world. With this, local SLAM tracking could take over after localisation, similar to those mentioned in the work of Lynen et al. [18], and practical systems such as the one proposed by Platinsky et al. [27] and Niantic Lightship [24]. In those systems, the local device localises in the global 3D model at set time intervals to reduce local drift.

Large-scale 3D Reconstruction

Our prototype system used a relatively small subsection of a city, which limits its applications in terms of the CMR scenarios described in Section 1. To have the ability to cover larger and more complex areas in shorter amounts of time, we are exploring the usage of alternative capturing methods such as Velodyne-style LiDAR and drone-based camera systems. However, each type of capture method has its strengths and shortcomings with respect to aspects such as speed, accuracy, coverage, privacy, and safety concerns. For instance, drone-based camera systems are well suited for large-scale image-based reconstruction but may not be viable in crowded urban areas due to safety concerns. In contrast, non-RGB LiDAR-based systems are inherently more immune to privacy concerns but are limited in their ability to provide a detailed geometry model of the environment.

Therefore, in capturing a large area (e.g. cities) with different types of terrain and restrictions, it is common to have models of the same place from different providers with various types of input captured at different times. Furthermore, differences in the pipeline and any manual intervention could induce further variations within a large set of overlapping captured data. This has important implications for the management and combination of models across different dimensions, such as sensing modality, time of capture lighting conditions, and accuracy.

On the other hand, large variations also exist on the side of consuming applications. Applications that strictly visualise data have different requirements than CMR environments, especially if they are used for localisation and tracking. One potential use case for alternative models is to instead use low-fidelity models, which may reduce rendering and bandwidth requirements for displaying and retrieving models. The MLIT city model used in the GIBSON system, as described by Takeuchi et al. [34], exemplifies the potential of using a low-fidelity model instead of a photorealistic model. More research is needed to find the best balance of model fidelity and performance, depending on its use case.

To address model management and fusion in this situation, we are currently exploring to address this problem by using geospatial platforms (e.g. Cesium [3]) for distributing the model, providing flexibility for applications such as variable polygon complexity or requesting specific model chunks. The use of geospatial platforms also contributes to model fusion as they force georeferencing of each model. Georeferencing of the model provides a useful common ground for merging and distinguishing changes in the model and can provide good initial measurements for appearance-based and geometry-based fine-registration methods. A similar problem has been examined in the robotics field through the concept of lifelong SLAM [13]. One example of this is autonomous driving [10], where a map supporting multiple representations of the same place is established from maps captured by different robots over time. This type of map supports asynchronous contribution from different mapping sessions, allows simultaneous mapping from multiple agents, and thus achieves higher mapping efficiency and maintains robustness for localisation. This concept could be applied to our model fusion techniques to unify data captured at different times.

This effort is part of a large ongoing project focused on the creation of a digital twin of Nicosia, Cyprus, called *iNicosia* [6].

5 CONCLUSION

This work-in-progress paper describes our investigation into the difficulties of developing CMR systems. We gained valuable insights into the difficulties that arise in the design of outdoor CMR systems by implementing a prototype that allows a local outdoor AR user to collaborate with remote VR users in a large-scale 3D model of the AR user's physical space. Our prototype, based on a brute-force alignment technique that uses QR codes, the built-in HoloLens 2 tracking system, and the WLT library, served as a testing ground for experimentation and exploration. Our findings cover key areas that require additional research and development to address the challenges of outdoor CMR. Among them are registration, AR tracking, 3D reconstruction, model management, and evaluation. We hope to inspire further research and advancements in this field by releasing the source code of our prototype and sharing our system design considerations, recommendations, and plans for future work.

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