Design and Simulation of Next-Generation Augmented Reality User Interfaces in Virtual Reality

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Abstract

We present a methodology for the simulation of next-generation Augmented Reality (AR) User Interfaces (UIs) within immersive Virtual Reality (VR). We use a user-centered model to support design decisions for specialized operations in high stakes fields, and present augmented reality user interface designs for two use cases in public safety: a law enforcement traffic stop and a firefighting search and rescue scenario. By utilizing VR to simulate AR, we can design and evaluate the benefits of idealized UIs that are unencumbered by hardware limitations. We discuss the trade-offs of Virtual Reality as a medium for simulation and training of next-generation Augmented Reality User Interfaces.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality, Mixed / augmented reality

1 Introduction

The development of future User Interfaces (UIs) depends on proactively anticipating and accommodating the needs of the user. The potential of incipient Augmented Reality (AR) interfaces can be evaluated in Virtual Reality (VR), obtaining important feedback while other aspects of the AR technology may still be unavailable. In other words, as soon as it is possible to envision how a future technology might evolve, designers can create UIs that take advantage of its potential features. It is no longer necessary to wait for the technology to be fully functional leverage its capabilities. One classic example of such an exercise comes from the Knowledge Navigator [10] conceptual video, which was developed by Apple Computer in 1987. The video demonstrates the concept of a future office interface, with which the user naturally commands the UI through voice and gestures. The audience of the video was presented with a dynamic, highly responsive, conceptualized system, allowing them to envision the UI decades before it would become technologically feasible. Conducting such exercises is important when considering the opportunities and limitations that may exist when the technology is fully realized.

Augmented Reality technologies are still in active research and development. Key parameters such as field-of-view (FOV), display brightness, tracking, and battery robustness must be improved before being deployed to high stakes fields such as military, medical, and public safety. As such, the adoption of AR technology in real world production contexts can take several years. It can be argued that AR UI design is best applied to current AR technology, and immediately evaluated on the target platform. Developing under current technological constraints is valuable, allowing for real-time application of proposed UIs. However, if we intend to account for future capabilities, when current constraints are not a factor, existing AR hardware may not be able to support novel designs. VR, on the other hand, is well suited for this task. It can be leveraged to obviate present AR constraints. Not only to imagine and passively visualize the likely direction of next generation AR UIs, such as in the Knowledge Navigator concept, but to realistically and precisely interact with the proposed interfaces. Preparing us anticipate and take advantage of future AR features, improving current processes while remaining unbound by contemporary technological limitations.

Virtual Reality offers several advantages over directly designing under specific constraints imposed by current technology. The simulation of next-generation AR UIs in VR allows for a much wider design space. For instance, in VR, we can have complete control over several AR parameters including FOV [28,34], latency [22], and visual realism [23]. The complete control over all AR parameters gives us the ability to simulate AR that has perfect image registration and large FOV, and focus on the design of user interfaces that would not be possible if developing with current hardware specifications in mind. Beyond the design of the interface itself, simulations in VR can also replicate existing AR systems [27]. Serving as a benchmark against which real AR hardware and interfaces can be compared, and allowing prototypes to be evaluated in a high-fidelity context, where all simulated elements are tightly controlled. Such experiments can be easily reproduced with consistent testing variables, and can be performed in a safe environment. This level of control would be hard to achieve in field test setups.

In this paper, we present a user-centred methodology with the goal of leveraging VR as a tool to design and simulate next-generation AR User Interfaces (UIs) (Sect. 3). The methodology aims at maximizing user acceptance of the interfaces in high stakes fields once the technology is available. We describe the application of the methodology for the design of AR UIs focused on two use cases: a law enforcement traffic stop and a firefighting search and rescue scenarios (Sect. 5). We discuss how simulation of AR user interfaces in VR can potentially impact sensitive operations and reduce the burden of technology transfer to real world applications (Sect. 6) and conclude by laying out a research agenda for the application of VR simulation towards the design of next-generation AR UIs (Sect. 7).

2 Related Work

2.1 Mixed Reality Simulation

VR has proven to be an effective simulation platform to address mixed reality (MR) development issues [22]. It provides a safe and controlled environment that is consistent within itself where experiments can be easily designed and replicated [27]. For instance, replication studies aiming to validate MR simulations have successfully demonstrated comparable results against OST-HMD systems in interaction with virtual objects [21] and visual realism [23].

Other MR simulation work focuses on recreating the characteristics of AR hardware in VR, to assess the intrinsic issues of AR. Terrier et al. [33] observed that registration errors typically found in AR hardware affects user behavior during object manipulation tasks, Nabiyouni et al. [25] investigated the effects of latency on AR

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simulations and Bowman et al. [4] proposed a display simulator in VR to study the effects of display fidelity.

MR simulation has also been used to explore futuristic AR features that current devices can not provide. One of the limitations of current OST-HMDs is restricted FOV. Ren et al. [29] and Ragan et al. [28] showed that wider FOV can lead to better performance in searching tasks comparing a range of different simulated FOVs in VR. Another issue of current AR technology pertains to interactivity with augmented content. Alce et al. [1] describe a methodology for prototyping interaction concepts for OST-HMDs. Burova et al. [5] prototyped futuristic AR guidance and awareness features for industrial maintenance. The work described in this paper also aims at designing futuristic AR user interfaces for specialized tasks. But, instead of focusing on a specific field, we describe a generic methodology that can be applied for designing effective and efficient AR solutions for any field.

Design methodologies and prototyping techniques have already been proposed to assist with the designing of AR user interfaces. Like ours, they are often based on consolidated HCI methodologies, such as the WoZARd [24] that adapted the Wizard of OZ (WOZ) but with specific elements to cover the particularities of wearable AR designs, the work by De Sa et al. [9] that proposed a user-centred approach adapted for mobile augmented reality design and the ExProtoVAR [26] that adapted a double diamond process to create virtual prototypes of AR applications.

Our methodology differs from previous work. We focus on proposing user interaction designs for the next-generation interfaces, aimed at highly specialized task requirements. In Sect. 3, we detail the methodology and apply it to two use case scenarios.

2.2 VR Training and Simulation for Public Safety

The demand for new technologies that enhance training and public safety operations is a common sentiment among first responders [7, 8]. However, the successful adoption of novel user interfaces relies on a clear understanding of first responders' needs, requirements, and contexts of use [18]. The use of methodologies that actively seek first responders' feedback aid in the understanding of their procedures and practices. Making the design of training simulations suited for their needs [11, 15], while revealing opportunities for which next-generation user interfaces can be designed [2, 14].

The effectiveness of VR simulation for public safety has been discussed [17] and demonstrated [3] since the late 1990s. The technological advancements made in recent decades have allowed for the growth of immersive AR/VR simulations and training to mimic a variety of public safety operations [36]. For instance, VR training for law enforcement has been explored as a platform where specific procedures can be configured and simulated [16]. Saunders et al. [31] focused on the validation of VR training against traditional live training exercises. They reported comparable results for both settings, similar to the results of non-immersive VR training [3]. Fire emergencies have also been replicated in VR. Research has focused on training systems capable of simulating realistic fire [6] and smoke [35] hazard situations. Simulation of real fire pump panel in VR with passive haptics [32] and assessments of VR training effectiveness against real firefighting procedures.

While previous works focus on the simulation of current training procedures in VR, the goal of our methodology is to effectively propose novel interfaces that will eventually be available for use. Training with next-generation interfaces in simulated VR environments will help prepare first responders to use the technology when they are ready for real-world implementation.

3 METHODOLOGY

Our proposed method follows a user-centred design methodology, to identify current limitations and opportunities for future technology. It employs the following phases: requirement analysis, prototyping, implementation and evaluation.

3.1 Requirement Analysis

Each user population has specific needs and characteristics that should be prioritized during the design process. In our user-centered approach, input from end-users is crucial for identifying gaps and opportunities to improve next-generation technology. By gaining a better understanding of what the user needs, we can contribute AR solutions that supplement, rather than simply replace, time-proven processes. What needs are not currently being met? What already works well? What solutions might be implemented if current technology was not a limiting factor? By asking our users about their specific needs, unencumbered by the limitations of preexisting systems and current technology, we gain deeper insight into what the next generation UI technology might look like and how we might bring these concepts to life in VR.

We conduct requirement analyses to gain insight into the needs of our users. Our requirement analysis methodology involves performing field research in which we closely observe and learn about existing user processes and practices. The goal being to identify opportunities and gaps where next-generation UIs stand to produce the greatest benefit. Our initial meetings with the users establish rapport and provide context, before progressing to semi-structured interviews. We also accompany the users to gain a more thorough understanding of routine activities, procedures, and systems involved in completing their daily tasks. Through observing their real-world routines and challenges, we can identify problems and deliver next-generation solutions to streamline and improve their workflow.

3.2 Prototyping

For the prototyping phase, we start with knowledge gained during the requirement analysis. Our prototypes are incrementally developed using an iterative approach. Gradually progressing from rough low-fidelity concepts, sketches, and storyboards to working mock-ups (see Fig. 1(a)(c) and Fig. 2(a)(b)). We obtain feedback from the users early in the process, discuss possible scenarios, and progressively refine our designs. Fidelity is increased with each iteration, leaving the smaller details for the end. This practice allows us to readily change the early models at low cost when large modifications are likely, and concentrate programming effort with interactive demonstrations at later stages when changes tend to be minimal.

3.3 Implementation

The implementation phase involves transferring design prototypes into a fully functional VR simulation. In our process, we use VR to simulate real-world interactions while simultaneously simulating AR interfaces within the virtual world. This allows us to develop and evaluate hardware and software that may not otherwise exist yet, within a flexible and controlled context. This phase also includes the design of the virtual environment, implementation of scenario progression, and system control mechanisms, e.g. menu interfaces.

3D printing allows us to rapidly prototype props, including novel tracked input devices. This gives us more flexibility to evaluate and modify the custom hardware as we go. Our iterative design process is accelerated by using these quickly developed experimental prototypes, providing additional opportunities to obtain feedback from users. For instance, we might find that the shape of an object interferes with the performance of a task under certain conditions. Its geometry can then be revised to resolve the previously unknown problem, within a short time frame. It also provides us with the flexibility to adapt as new AR and VR systems become available.

3.4 Evaluation

Evaluation of the proposed designs aims at assessing the effectiveness of the simulated AR user interfaces. Quantitative feedback and user studies with the experts can guarantee the validity of designs and transferability of simulated UIs into the real world.

The studies completed in this phase can assist in the identification and understanding of human factors that affect the tasks aided by the AR UI and inform the redesign of observed usability problems.

During the prototyping and implementation phases, we also might detect opportunities where user experiments would provide answers to specific design elements. For example, a user study could help us find the best setting for an alert system so that the alerts would be easily noticed, easily interpreted, but at the same time not too intrusive that it would affect the main task.

4 Technical Approach

To help us simulate high fidelity AR in VR, we are using the HTC Vive Pro headset with eye-tracking and its lighthouse tracking system. Active gaze-based interaction enables the user to toggle elements of the HUD and make hands-free point-and-click selections while simultaneously performing other tasks. Vive controllers are used for standard interaction with the VR environment and simulated augmented reality interfaces.

We have also created custom tracked hardware to simulate a device intended for use in conjunction with real-world AR displays. This custom hardware can serve multiple purposes. For instance, the custom tracker can have the shape of specific real-world devices [12] to provide passive haptics or it can be used to track specific body parts. A trackpad and buttons can also be incorporated into the design, creating novel controllers to meet our specific needs.

The form factor is an important consideration when developing hardware for 3D user interfaces. Attention must be paid to the circumstances under which the interface will be used, along with how the device itself influences the user's behavior. It should be robust and simple to operate, yet unobtrusive. Achieving desired results without detracting from other aspects of task performance.

Our tracked devices incorporate infrared sensors using the Virtual Builds Pebble sensor kit [1], SteamVR tracking HDK [2], an add-on board with haptic motors, and a custom 3D printed PLA plastic shell. Sensor locations are optimized to enable reliable tracking through high visibility to base stations. Tracking performance is comparable to that of an HTC Vive trackers [3].

5 Use Cases

We demonstrate the potential benefits of designing and prototyping AR UIs in use cases for specialized domains. Due to the high risk of operations involved, these domains tend to require established procedures that are proven to be safe and effective. UI designs for specialized tasks have the potential to improve processes but need to be carefully designed to produce a positive outcome. So, along with the wide design space that VR provides, it also offers a simulation platform where testing prototypes and training for risky and costly operations can be done safely and at low cost.

We have chosen public safety as the domain to which apply our AR simulation methodology. The public safety field has specific demands that need to be captured and placed at the center of the design process. We applied our methodology to identify opportunities where next-generation UIs would have a potential impact on first responder operations. We started the process by studying the public safety domain and by gathering data from first responders. Then, we performed an iterative participatory design process to prototype low-fidelity UIs for scenarios chosen to have the most opportunities of benefiting from a next-generation UI. When the technology is ready, adoption of the interfaces proposed in VR will be expedited as the design and validation steps will have already been completed.

[1] https://www.virtualbuilds.com/product-page/pebble-kit
[2] https://partner.steamgames.com/vrlicensing
[3] https://www.vive.com/us/accessory/vive-tracker/

The field research conducted counted with the participation of three public safety organizations (PSOs) and took about six months to be completed. A total of fifteen first responders contributed with their expertise throughout this phase (6 from Law Enforcement, 5 from Firefighting, and 4 from Emergency Medical Services).

The analysis of the data collected revealed that personal safety is a big concern among first responders in the field. Awareness of the situation and communication are key to mitigate operational mistakes. We present the AR user interface designed specifically to enhance situational awareness in two simulated use cases: a traffic stop (Sect. 5.1) and a search and rescue scenario (Sect. 5.2).

5.1 Law Enforcement Traffic Stop

We considered a few different law enforcement scenarios centered on the data collected in the requirement analysis. After group discussions with first responders, we agreed to explore the contributions of next-generation user interfaces in traffic stops. Traffic stop operations represent one of the most common interactions between police officers and civilians. They are often a low-risk routine but have the potential of risk escalation due to operational uncertainties that may trigger situations that can compromise both officer and civilian safety. These uncertainties are caused by the time gap between gathering the data about the vehicle and its occupants and verifying the received information. The officer needs to approach the driver, ask for documents and run the data in various databases to fully identify the situation. In some cases, the officer can be dealing with a criminal and only realize it when it is too late. Moreover, the officer might lose track of the vehicle's occupants when he needs to use the in-car computer to verify the information.

We conceived a next-generation AR UI to assist police officers in a traffic stop operation. The design leveraged knowledge that we gathered in the requirement analysis, leading us to prototype a system with two high-level features: a situational awareness interface and an on-demand information display. Used together, these features facilitate quick and easy access to information while minimizing the risks involved. Our designs envision technology that performs real-time scanning and searching of vehicle's plate, driver's license, facial recognition, and object detection, as it is reasonable to assume that such these are features will be supported by future technology.

5.1.1 Traffic Stop Simulation

We created a traffic stop scene (Fig. 1), with three procedures in mind: inspecting and approach the vehicle, interviewing the driver and checking documents, and proceeding with warnings, tickets, or severe/escalating actions. The proposed simulated AR UI is intended to support these tasks. The simulation starts with the suspect's vehicle pulled over and the officer approaching it from behind, a common procedure that exposes the officer to a high degree of risk. We describe the details of each action below:

Vehicle approach: While approaching the vehicle, the officer performs a visual inspection looking for suspicious movements and illegal objects inside the vehicle.

Driver interview: The officer interacts with a virtual avatar. The avatar can understand natural language and will answer to predetermined questions. For example, the driver will hand their driver's license upon request. Alternatively, a system control UI enable the interaction if voice commands are not possible or desirable.

Information verification: Once the officer is in possession of the driver's documents, the information about the driver is searched.

5.1.2 Situational Awareness Interface

The situational awareness interface is designed to help the officer perceive key elements in the environment and to assess potential risk escalation. Simulated pattern recognition tags key elements, such as plates, driver's license, and suspicious objects in the scene

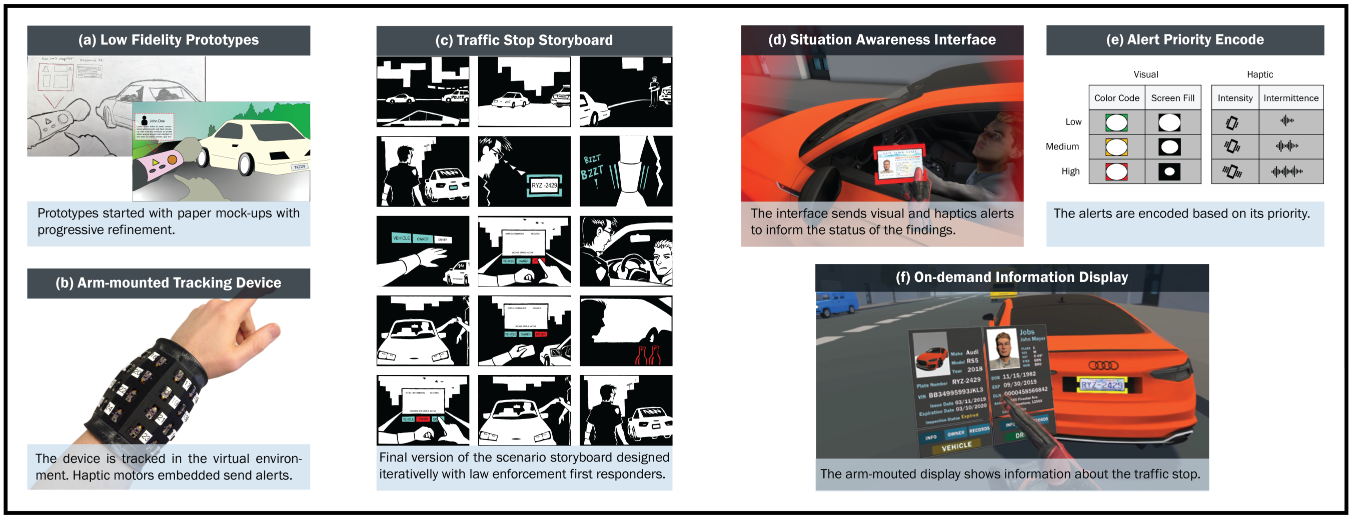

Figure 1: The traffic stop scenario design process. Low-fidelity designs evolved until the functional implementations of the AR UI interface.

(Fig. 1(d)). An alert system provides a status update when the information searched in the background is ready. The alert system works at three distinct levels: low priority, medium priority, and high priority. Low priority alerts are informational. They notify that the data about a query was fetched and no irregularities were found. Medium priority alerts may require attention but are not time-sensitive. For instance, this kind of alert may indicate an expired vehicle registration. With high priority alerts, however, immediate action must be taken as the situation may put the officer in danger. Normally, after a high priority alert, no further information is needed. Sufficient evidence is likely available to support a warrant for arrest (or to execute an existing one).

The alert's intensities have distinct encoding so it is easy to understand the severity of the alert. We support the delivery of alerts through the visual and haptic channels. Visual alerts are delivered as color-coded signals in the officer's peripheral view, and vibrations are encoded by frequency and intensity to express each alert priority level, as seen in Fig. 1(e).

5.1.3 On-demand Information Display

Using feedback gathered from law enforcement officers during the requirement analysis phase, we designed an on-demand information display that follows a physical armband mounted on the non-dominant forearm and is activated on demand through glance (Fig. 1(f)). This arm-mounted display interface is always within reach, yet readily removed from view without needing to divert attention from other high priority concerns. Both hands, therefore, remain free to perform other crucial tasks as new information is delivered and the traffic stop runs its process. This way, the officer can focus on the traffic stop procedures without being overwhelmed with information. The information display interfaces with the car's computer system and provides a summary of relevant data about individuals and vehicles encountered during the traffic stop. Information is grouped into two categories. One for the vehicle, and another for the driver. It is possible to navigate through the categories by pressing virtual buttons on the display's graphical user interface (GUI). The situational awareness interface alerts the officer when new data is available so that they can choose to verify the info through the arm-mounted display.

We designed and prototyped a 3D-printed tracked armband (Fig. 1(b)) to properly track the forearm in the virtual space. The device is worn near the wrist, much like a wristwatch, by the hand where a phone or radio might also be held. As such, this is a natural place to look for information. Wrists are highly sensitive to vibrations [19], followed by the arms. Bony areas are best suited for detecting vibrotactile stimuli [13].

The armband's haptic system uses two linear resonant actuators (LRA) vibration motors for alerts and notifications. Haptic alerts are adjustable for amplitude, frequency, and duration. With a low-profile design and adjustable strap, rotational forces are effectively distributed while remaining in close contact with the wrist.

5.1.4 Traffic Stop Design Considerations

We designed the AR interface to assist in a specific stage of a traffic stop, where the officer already pulled over the suspect vehicle and is starting the approaching and interrogation of its occupants. The scenario also assumes that the officer has no prior knowledge about the situation. In circumstances, we can demonstrate all the benefits of the proposed interface. While pulling over a car and interrogation can happen without a prior check on the vehicle's information, commonly the officer would run the vehicle's plate before living the patrol vehicle. During the discussion with law enforcement agents, we prototyped an in-car interface that could assist the officer while patrolling the streets. While we acknowledge that an in-car UI would complete the traffic stop scenario experience, based on the discussions, we decided to focus on the second stage since it is where the agent is most vulnerable.

5.2 Firefighting Search and Rescue

During search and rescue operations, firefighters encounter a wide variety of hazards that potentially put their lives in danger. In a burning building, for instance, risks can quickly escalate. On the scene, a firefighter may encounter blocked passages, harmful gasses, high temperatures, toxic smoke, and various combinations of risk factors. Each incident is unique. Firefighters often navigate buildings blind, with a variety of floor plans, and must monitor the presence of hazards for the operation to succeed.

Moreover, firefighter heat-tolerant gloves limit their ability to perform fine-grained interactions. Along with that, the nature of their operation requires a high level of attention to observe hazards in a dynamic changing environment, constant use of their hands for navigation, debris removal and victim rescue, and non-traditional locomotion style for indoor navigation in smoke-filled rooms. All of these factors pose design challenges when interacting with the UI.

By adopting next-generation AR UIs, environmental perception is enhanced and uncertainties are reduced. For the search and rescue

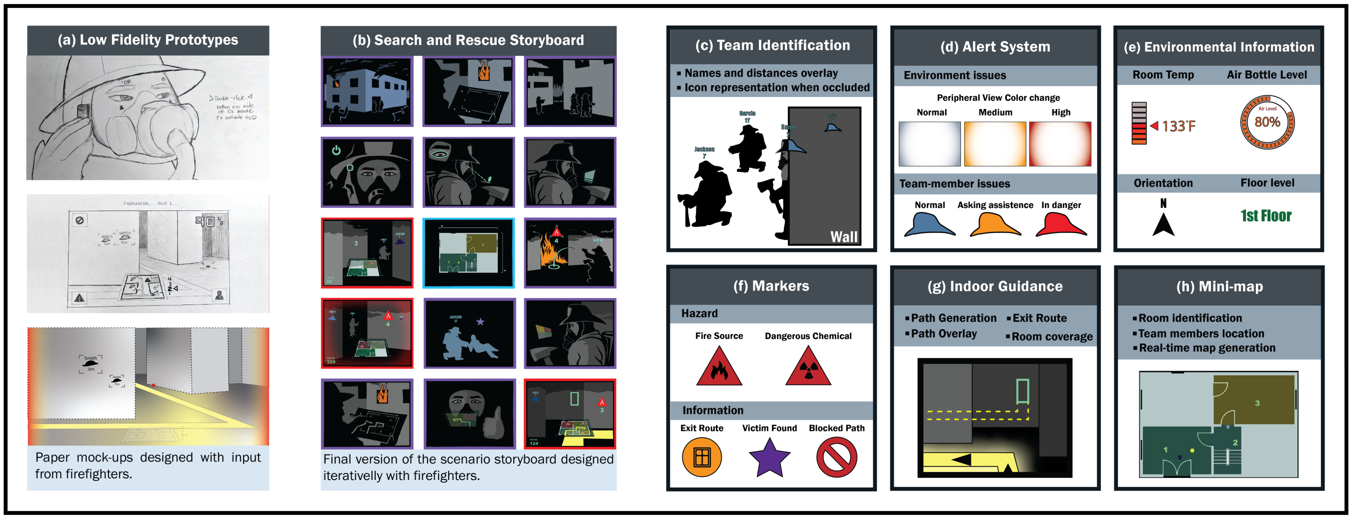

Figure 2: The design process of the search and rescue scenario. The designs were informed by a group of firefighters.

scenario, we designed AR UIs for three high-level functions: indoor guidance, teammate identification, and situational awareness.

5.2.1 Indoor Guidance

On-site communication poses one of the greatest challenges for search and rescue teams. It can be difficult, at times, for a team leader–a firefighter who commands the operation from outside the burning building–to accurately convey directions and describe threatening situations via radio. Likewise, firefighters may struggle to articulate their predicaments to teammates.

Unfortunately, firefighters are rarely provided with detailed floor plans of the buildings they enter. And even when they have a floor plan, it may be outdated and not account for remodeling or other changes. Beyond what can be observed by assessing the outside of the structure, along with possible firsthand accounts from people on the scene, there is no guarantee that firefighters will have detailed information. Also, there may be structural damage or changes caused by the fire. As such, firefighters at the scene are likely to deal with these uncertainties and risks. Next-generation UIs have the potential to provide a more intuitive approach to relaying such information.

Our indoor guidance system includes two key functions: dynamically path generation and mini-map. The path generation function enables the request for directions for a remote team leader. When the path is received, it appears on the mini-map and HUD. The application simulates the function of the team leader.

The indoor guidance mini-map automatically updates a functional floor plan as firefighters explore the structure. The VR simulation assumes that simultaneous localization and mapping (SLAM) will be robust enough in the future to support real-time identification in dynamic environments.

As illustrated in Fig. 2(h), the mini-map reveals the floor plan while firefighters explore the structure. When a new room or hallway is entered, the room is automatically scanned and added to the map. It also depicts real-time data about firefighter's position, the presence of hazards, the victims' location, and the path to a particular area. Real-time updates of the environment and the team help avoid repeated searches, ensuring that other teammates have instant access to the latest information. The mini-map is activated on-demand by eye-gaze. Gazing downward, and focusing on a virtual tab for a specified time, the mini-map rises into view.

When exploring the burning building, due to the low visibility, it needs plenty of efforts to find a doorway. This could cause unnecessary risks when the firefighter or victim needs to be evacuated or found as soon as possible. The next-generation UIs outline the structure of each explored region and display the room number on the walls (see Fig. 2(e)). Combining this system with the mini-map, firefighters can easily know their positions and easily communicate directions with other team members.

5.2.2 Team Identification

Firefighting search and rescue operations require a high level of communication and cooperation among teammates. Next-generation UIs must provide firefighters with access to real-time information. This may include the names, distance, and status of nearby firefighters along with other crucial data. Team members should be able to share information and request assistance as needed.

The system tags the firefighters and shows their location in the environment. We use icons floating over the teammates where we display their information (see Fig. 2(c)). The tag contains the firefighter's name and distance. Each firefighter's tag has a different color to easily distinguish them. The tag is visible through walls and barriers, and its size is consistent with the firefighter's distance. The mini-map also displays the same tag representing each firefighter and their accurate location in the building.

5.2.3 Situation Awareness Interface

Most risks encountered in firefighting search and rescue operations are due to a lack of situational awareness. For example, the unexpected spread of fire could block the planned evacuation route putting the firefighters at risk. To improve awareness of environmental factors, our next-generation UIs implements a situation awareness interface, which consists of a hazard marker system, an alert system, and an environmental information display.

Hazard Marker System: The system allows for the deployment of markers around the hazardous area to alert teammates. There are two marker deployment modes: precise deployment and quick deployment. In the precise deployment the hazardous region is explicitly specified by choosing the type of marker from the menu and placing it near the source of the hazard (see Fig. 2(b)). In the quick deployment method, suspicious regions are quickly labeled while the firefighters exploring the space. The virtual markers placed on the environment are displayed both in the AR display and on the mini-map. The markers also have distance information similar to the team identification feature.

Alert System: The alert system sends a color-code-based warning to the peripheral view if the firefighter is confronting some danger (Fig. 2(d)). For example, when the environment temperature is unusually high, the system can send an alert to notify the change.

Environmental Information: Two fundamental information that firefighters need when exploring the building are oxygen level and room temperature. These information are displayed in the HUD display in the peripheral vision for quick access.

5.2.4 Search and Rescue Design Considerations

Typically, search and rescue are cooperative operations that require the coordination of several firefighters. While the scenario exemplified in this paper count with an exchange of information with other firefighters in the team, the interactions with other team members and team leader are simulated and only allow for a limited set of options that are predetermined based on the current simulation phase. The advantage of doing that is that we can guide the user through the scenario and impose the use of the user interfaces.

6 Discussion

Simulating AR interfaces in VR allows us to design ideal user experiences unconstrained by current technology limitations. While VR simulations are limited in recreating the full real-world experience, VR is consistent within itself. This means that, even though VR technology presents display limitations, such as graphics realism, resolution, accommodation mismatch, latency, and tracking quality, all simulated elements, both real and virtual, follow the same rules within the simulated reality. For example, any computer-generated graphics environment that renders based on tracked input will inherently contain latency due to processing and physical constraints. Within optical see-through head-mounted displays (OST-HMDs), the real-world is always zero latency, but the virtual augmentations will be subject to a delay which can hinder the user experience. Within a VR simulation, the latency of the simulated real and the simulated virtual is always the same, and the visual environment will be consistent throughout. Moreover, other limitations from OST-HMDs, such as display brightness and opacity, robustness in outdoor environments, and tracking in dynamic environments cause many potential design features to be left out of consideration. By using VR simulation, we remove these handicaps and can experience the potential impact that next-generation UIs can produce before the technology to support it becomes available. Once AR UIs become available, they will add a new complexity layer that needs to be mastered to enhance the standard procedures. VR simulations can serve as a platform for training operations aided by future technology even before the AR UIs reach maturity level and become widely available for public safety agencies. Training with anticipated UIs can prepare first responders for possible future procedures and reduce the burden of technology transfer to real-world applications.

Even though our user-centered design methodology used throughout the entire process aims at maximizing user acceptance of the interfaces, to investigate the real benefits of simulated AR, the UIs need to be validated with the end-user of the application. Our methodology includes the assessment of the simulated UIs Sect. 3 by proposing empirical studies, through the collection of performance data, observation of user reactions, and gathering of feedback and usability metrics. This approach is useful to understand if and how the UIs are improving the current processes and to analyze design flaws. However, assessments done solely on VR simulation may not answer if the UI designs would transfer to real AR UIs.

Virtual Reality has its own limitations and just as a VR experience may not always transfer to the real world, a simulated AR interface may not transfer to a real-world AR experience. We identified two potential risks with transferring simulated AR to real-world AR: intrinsic VR issues, and low interaction fidelity. First, the effect of the simulated AR interface may not be equivalent to the effect of the same interface in a real AR application. For example, due to intrinsic features of VR, such as FOV currently limited to around 100°; hardware encumbrance; and graphics realism, the user response in simulated AR may be different from the user response in real-world AR. To counter this risk, there is evidence in the literature that VR experiences successfully transfer to the real world, for example, for motor skill acquisition [20], for social behavior [30] and for AR simulation [22]. The second risk relates to the interaction limitations that a VR experience poses to the user experience. For example, it is not practical to physically walk in VR through a large building such as in our search and rescue use case scenario, and an indirect locomotion needs to be used. Further, interactions with real-world actors, such as calling for backup in the traffic stop need to be simulated through system control. These simulations add a layer that is not present in real-world. Luckily, there is a vast body of VR interaction research from which simulated AR designers can draw for techniques that are most likely to cause the least amount of interruption to the user experience. Further research is needed to indicate to what extent such control and locomotion interfaces affect the user experience beyond the main experience of the simulated AR UIs.

The comparison of simulated AR with implementations in real hardware would establish the validity of our methodology. If usability and performance are similar in both conditions we could assume that the methodology is effective. Previous works have reported positive results on the validation of simulated AR against real hardware in specific contexts [21, 23]. However, such validation would many times not be possible under our proposed methodology because the designs do not take into account AR hardware limitations. Only at a point in the future, when the technology to support the simulated AR UIs is available that transfer could ultimately be tested. Instead, the simulated AR designs could serve as reference points to which interfaces implemented in actual AR devices could be compared. This way, it would be possible to follow the evolution of AR devices using the AR simulations as the gold standard. The process goes as follows. The rigorous participatory design process of our methodology ensures that the outcome will be highly usable interfaces that are likely to succeed if fully implemented in real-world AR. Because AR technology will likely not support all features proposed by the simulated AR UI, as new AR hardware becomes available, developers can implement the closest approximation to the idealized design under the new technology constraints. Finally, a comparative study between the idealized simulated AR interface and the concrete closest approximation is performed. Results from this evaluation can point to how far any new technology is from the *ultimate* interface.

7 Conclusion and Future Work

In this paper, we discussed how the simulation of next-generation AR user interfaces in VR can anticipate the technology uses and possibly validate such UIs before they reach the consumer level. We highlighted the importance of considering the specific requirements of the target population and presented a user-centered methodology that, through an iterative process, aims at producing the *ultimate* UI without constraining the design space to the technology currently available. We applied our methodology to two use cases in public safety where future AR UIs can be integrated into field operations to potentially increase safety and improve decision making.

Future work includes the validation of the user interfaces designed for the public safety use cases with first responders and the creation of an evaluation protocol that addresses the comparison of UIs implemented in newer AR hardware with their simulated counterparts. These formal comparisons would create a better understanding of how the AR technology is advancing and how far it is from the idealized simulated interfaces.

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