Cross-Device Augmented Reality for Fire and Rescue Operations based on Thermal Imaging and Live Tracking

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Abstract

Augmented Reality (AR) has the potential to enhance safety and operational efficiency during firefighting operations. By leveraging modern head-worn AR equipped with embedded sensors and cross-device collaboration, firefighters gain situational awareness, however, fundamental cross-reality interaction challenges exist, in low-visibility, high-temperature, life-threatening conditions. This paper introduces two systems targeting distinct firefighting scenarios employing hands-free gaze-based interaction. The first system named Thermal Imaging System addresses fire and rescue operations when thick smoke is a challenge. By integrating a heat-wavelength infrared camera on the Microsoft HoloLens 2, thermal data can be streamed directly to the operator's field of view, enhancing their visibility. Unlike conventional handheld thermal cameras, this approach maintains the operator's ability to use their hands effectively. The second system named Live Tracking System focuses on wildfire, enabling live tracking of each firefighting team member and displaying their locations on a 3D map, accessible remotely on a computer. An AR headset provides the team captain on the field with real-time visual signals signifying team members' location on the field and in headquarters. A thorough proof-of-concept evaluation with firefighters indicated that the system enabled cross-device collaboration during fire and rescue operations.

Index Terms: Human-centered computing [Human computer interaction (HCI)]: Interaction paradigms—Mixed / augmented reality; Human-centered computing [Human computer interaction (HCI)]: HCI design and evaluation methods—Usability testing; Human-centered computing [Interaction design]: Interaction design process and methods—Scenario-based design

1 Introduction

Cross-Reality systems empower users to collaborate with others along the Reality-Virtuality Continuum [14], [11]. Virtual Reality (VR) is gradually finding its way into firefighting training shown to be effective for simulation purposes [16], [3]. However, obstructing the operator's field of vision limits its practicality in real-world scenarios [4]. Augmented Reality (AR), in turn, allows layers of digital content to overlay physical objects in real-time [20] [8] [12], however, low visibility, smokey and often high temperature environments in fire and rescue demand enhancement of vision and team cross-device collaboration. This may be invaluable in fire and rescue operations, when reliable and continuous communication between teams and control centres is crucial. Fundamental AR interaction challenges exist, in low-visibility, high-temperature, life-threatening conditions. Cross-reality collaboration provides firefighters with access to critical information about environmental conditions, operators' location and related danger, enhancing situational awareness while focusing on fire and rescue.

Thermal Imaging Cameras (TIC) significantly improve the efficiency and safety of fire and rescue operations by recognizing heat sources aiding the rescue of trapped individuals [19]. Firefighters have incorporated TIC in diverse operations [1] mostly through hand-held cameras which, however, limit their hand movements. Moreover, GPS tracking is widely used in fire and rescue operations providing precise location information and real-time situational awareness. Incident commanders could monitor the location of their teams and make informed decisions maintaining personnel accountability, and ensuring the safety of team members during large-scale operations [13]. GPS tracking data serves as valuable documentation for incident analysis, evaluating strategies and improving future response planning [18]. Incorporating live tracking information in real-world, busy and unpredictable fire incidents is crucial, but poses challenges how information is communicated to firefighters in the midst of crisis when, they handle sophisticated apparatus.

This paper presents two innovative cross-device systems, namely a *Thermal Imaging System* and a *Live Tracking System*, with the use of AR technology visualizing thermal heat maps and GPS location data, evaluated by professional high-ranked firefighters. The integration of thermal imaging on head-worn AR provides firefighters with enhanced visibility in low-visibility conditions, enabling them to identify hotspots, victims, and potential hazards. Additionally, by incorporating GPS tracking on head-worn AR, accurate location tracking of individual firefighters is communicated in a cross-device collaborative system, ensuring their safety and facilitating effective team coordination [6].

The *Thermal Imaging System* consists of two components, one running on a laptop and another on the Hololens 2. For this system a small Thermal Imaging Camera (FLIR Lepton 3.5) was mounted on top of the Hololens 2, streaming its content on the headsets' display. Due to lack of ports on the Hololens 2 device the camera could not be connected directly to it. Therefore, the camera is connected on the laptop which is responcible for streaming its content on the Hololens 2. The *Live Tracking System* consists of three components, one running on a PC and acting as a server and two client applications, one for an Android smartphone and another for the Hololens 2. This system provides live tracking of the Android phones connected to the server and a visual representation of their location on PC-based map software in a control room. Lastly, the Hololens 2 operator can view the direction and distance of every connected device in respect to them, in real-time.

This paper contributes to the future development of an AR helmet for firefighters. The specific contributions of this paper include:

- A cross-device AR interaction methodologym hands-free and gaze-based for both presented AR systems operating in low-visibility and smoke, for fire and rescue operations in wild, mountainous and urban settings, based on hand gestures and gaze-enabled interfaces.

- Incorporating thermal vision and GPS tracking of team member location as well as their level of danger superimposed on the real world, enhancing their situational awareness about the

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thermal properties of the environment.

- The components of each system communicates and shares location and emergency signal data, allowing for seamless integration of head-worn AR and mobile platforms to offer a comprehensive overview of the operational environment.
- The systems increase firefighter safety through individual emergency signals turned on by each member and location tracking, enabling rapid response and assistance in critical situations.
- The proposed systems underwent rigorous proof-of-concept testing conducted by professional firefighters, who examined the effectiveness, strengths, and weaknesses of the systems.

2 Related Work

2.1 Head-worn AR

Past work expanded AR headsets' capabilities by embedding various sensors to them [19]. An external camera live streamed the real-world on the Hololens device in order to bring text closer to people with impaired vision [17]. A setup consisting of the HoloLens device combined with two FLIR Lepton 3.5 Radiometric infrared thermal cameras mounted to the top [5]. The system enabled the acquisition of thermal data and stereoscopic thermal overlays on the user's augmented view. Temperature shifts using either heat vision overlays or 3D AR thermal cause-effect relationships (e.g., flames burn and ice cools) were simulated. Estimated temperatures when the stimuli were applied to either the user's body or their environment were investigated in laboratory-based user studies. In the presented Thermal Imaging System evaluated outdoors in real-world smoke, one camera was mounted to capture the thermal properties of the headset operators field of view. Hands-free interaction was paramount, therefore, a gaze-controlled interface is put forward.

AR systems and applications often employ GPS data for Geolocation [15]. The Hololens 2 headset lacks a GPS receiver but that can be solved with the use of a smartphone. In past work, a smartphone ran a server application feeding location data to a Hololens 2 client application [7]. A navigation route is then generated using Google GPS and the smartphone GPS data. The application creates a route graph for the operator and uses the smartphone data to locate itself. The Hololens application then computes the difference between the position of the Hololens and the next position node and generates a line that connects these two coordinates. In the presented Live Tracking System, both the Hololens 2 and the smartphone representing the operators location are connected to a PC server running remotely. Indicators show the direction and distance between constantly moving points forwarded to the Hololens 2 so that team locations are visualized. In fire and rescue gestures are limited and speech also due to noise. In both systems presented here, gaze tracking was selected as the main interaction paradigm [9].

2.2 Systems for Firefighters

C-THRU is a firefighter helmet, in development, equipped with AR technology developed by Qwake Technologies [10]. The helmet provides firefighters with real-time information and visualization overlaid onto their actual view, allowing them to see through smoke, navigate through structures, and access critical information in low visibility environments. The helmet also has thermal imaging capabilities, which can help firefighters locate hot spots and victims in the fire scene. Thermal imaging and AR technology is a promising combination in firefighting operations and a lot of research is taking place in this field. An automated system offers real-time object detection and recognition with the use of a FLIR One G2 camera [2]. The Thermal Imaging System presented has the same goal, while adding gaze-based interaction for optimized functionality.

The ENGAGE Incident Management System (IMS) Computer-Aided Dispatch (CAD) is a software system developed by Satways, designed for emergency response and currently employed by Greek firefighters. The system enables emergency operators to swiftly acquire real-time information pertaining to the incident at hand and dispatch the appropriate resources to the location. Tools encompass incident reporting and tracking, resource management and allocation, mapping and visualization features for enhanced situational awareness, communication and collaboration capabilities for both field teams and command centers, as well as analytics and reporting functionalities facilitating post-incident analysis and planning [13]. The Live Tracker System presented is intended to add functionality by providing AR cross-device collaboration to team captains such as presenting the locations of each operating firefighter on a 3D map with contour lines, suitable for wildfire, urban and rescue missions. The system has a solid data flow and handling so that accurate representation is established.

3 Requirements

This section delineates the general requirements that the proposed systems must meet.

- The AR systems should offer a hands-free user interface.
- Operators should visualize through smoke by presenting infrared data in the visible spectrum hands-free.
- The AR system should display thermal, location and other warnings to the operator's field of view without impeding vision. The interface should be dynamic, allowing operators to activate or deactivate visual elements.
- The AR cross-device collaborative system should display visual signals enabling operators to ascertain the whereabouts of each team member. A visual representation of these locations should be provided to the communication headquarters.
- The AR system should incorporate an individual firefighter emergency signal readily accessible to each team member, allowing them to transmit their location and communicate their situation to all involved in the operation.
- The system should alleviate radio channel congestion by minimizing vocal communication between the Hololens 2 operator and their team. This prevents human error or misunderstanding while communicating critical information.

4 Implementation

4.1 Thermal Imaging System

The *Thermal Imaging System* focuses on urban firefighting while thermal imaging visualizes a smokey environment. A thermal camera was mounted onto the Hololens 2 device capturing the area the operator is facing. The camera feed is then sent to a laptop through a USB cable due to lack of connectivity ports on the Hololens 2 and streamed to the Hololensdevice via WiFi connection. The FLIR Lepton 3.5 is a radiometric-capable long-wave infrared (LWIR) camera solution, smaller than a dime that uses focal plane arrays of 160x120 active pixels on a 57 degree field of view. The PureThermal Mini Pro JST-SR module was used to operate as a plug-and-play UVC 1.0 USB thermal webcam. For the sensor to face the same way as the Hololens 2 operator, a 3D printed mount was designed using SolidWorks and 3D printed. The camera was placed in the 3D printed case and mounted on the Hololens2 using screws as shown in (Figure: 1). The connection was established using a custom JST-SR to USB cable connected to a laptop USB port. The PC software selects between available cameras connected to the computer and streams the desired capture feed to a Hololens 2 device on the internet. The Hololens 2 software connects to the server based on the IP address and port required by the operator. After connecting, the application receives the byte array containing the data of each frame. The application uses that length in a loop to read the camera stream from the server. The camera stream stays in front of the operator no matter their movement in the real world. The streamed frames can be deactivated and reactivated using a small gaze-activated button on the left of the screen (Figure: 4). This allows the operator to show or hide the thermal properties of the environment without any hand movement. Gaze interaction is activated when the operator looks at an object, looks away or stares at it. For this button to be selected, the operator should stare on the button for 2 seconds.

Figure 1: 3D printed case housing FLIR Lepton 3.5 on Hololens 2

4.2 Live Tracking System

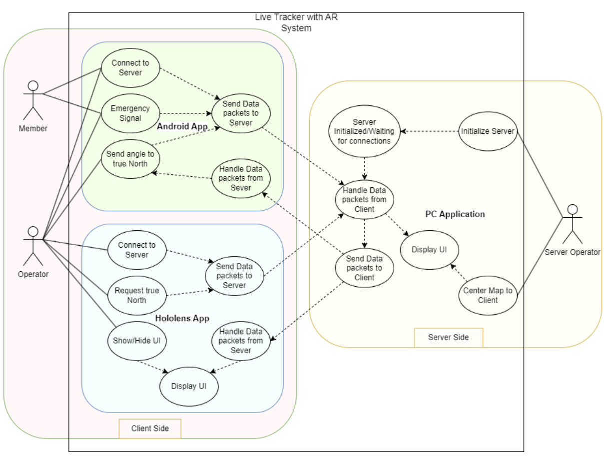

Figure 2: Live Tracker System use case diagram

The *Live Tracker System* is designed to be used in wildfire operations and offers live tracking service, for each individual team member operating. An Android application was built sending the GPS location data of the phone, to a server hosted on PC software. Next, the server forwards location data to the Hololens 2 software running on the headset worn by the operator. For the PC software to receive and send data to both client applications(Android, Hololens2) as shown in (Figure : 2), a client-server communication was implemented using the TCP protocol. A connection between client and server is established before data can be sent. The server must be listening (passive open) for connection requests from clients before a connection is established. To do this the TcpListener Class was used (System.Net.Sockets) to listen for connections on a specified port, with the help of the AsyncCallback delegate in order to asynchronously process incoming connection attempts. Accepting connections asynchronously offers the ability to send and receive data within a separate execution thread. Once a new connection is established the server assigns an id to the client and stores its information on a Client class. A Dictionary<TKey, TValue>helps track the Clients, using the id as a key and each Client as a value. For the application to acquire the GPS data from the Android devices' GPS receiver, a plugin for Unity was implemented using Android Studio accessing native Android data and, thus, is more reliable than the libraries Unity offers. The user interface of the Android application installed on the firefighting team members' mobile phone consists of three screens.

Role Screen: The UI consists of 2 buttons indicating the user role. If the operator, the server forwards the location of the user to the Hololens software with the boolean Op as true, meaning that the Hololens software will consider this as the location of the Hololens.

Connect Screen: The UI consists of 3 input fields and a connect button. After the user enters their username and the IP address and port of the server and presses the connect button, the application begins a connection to the server and if successful, sends a packet of data including their username.

Main Screen: If the Android device establishes a connection with the server then it begins to transmit its location in packets of data that are displayed in the top half of the main screen. Together with the data sent the Android application sends a Boolean called emergency which is set to false. There is an Emergency button, which when pressed changes the value of the emergency Boolean to true. The user needs to press the same button to close the emergency signal. If the application is running in operator role then the operator can send a North Request through the Hololens device which will make the Home screen of the Android application change and a new button appear sending the angle to north of the Android phone orientation when pressed, to the server and forwarded to the Hololens for calibration. There is an red Quit button on the top right of the screen, which when pressed disconnects the client from the server and quits the application.

Figure 3: Live Tracking System on Hololens 2

The Hololens UI (Figure: 3) consists of four main parts:

Virtual Compass: The virtual compass object consists of two textures, compass background and compass which are both 2D sprites that are positioned on top of each other, and a Text UI object that displays the corresponding username and distance in meters.

Virtual indicators that show direction and distance of each member. The arrow prefab is contained in the FirefighterSpawner.cs script instantiating a GameObject for each member Android client.

The coordinates of each Android device EW updated and the direction and distance from the operator's position to each member position is computed. The arrows are contained in a ring around operator, positioned facing the angle to north of each Android device in respect to the Hololens position and virtual north. Bellow the arrow the username of each device and their distance are displayed.

Mini Map. The Mini Map is a GameObject containing the MapSession and MapRenderer scripts, similar to the one described in the PC Application (Server). The only difference is that MiniMap is rendered in 2D and configured to always face the operator.

Gaze-activated button to show/hide virtual indicators. This button is implemented using the same methods described in the Thermal Imaging System. This allows the operator to show or hide the members location indicators without any hand movement. For this button to be selected, the operator should stare on the button for 2 seconds.

5 Evaluation

A group of high-ranked firefighters from the central fire station of Chania, tested the presented proof-of-concept systems and evaluated their effectiveness in real life scenarios.

5.1 Thermal Imaging system

A smoke grenade was activated outdoors. The system was configured so that a connection between the server (PC) and client (Hololens 2) applications was established and the streaming was successful. The Hololens 2 operator recognized human figures on the landscape, through the thick smoke produced by the smoke grenade as well as the environment and the buildings surrounding them (Figure: 4).

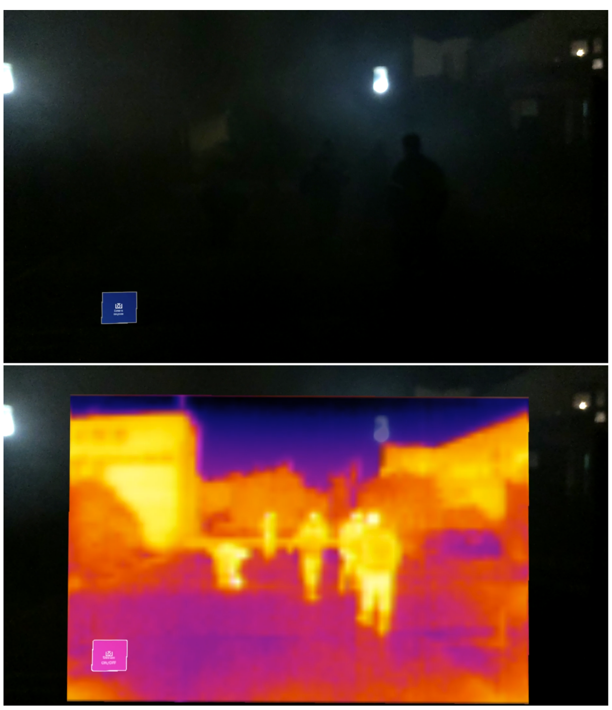

Figure 4: Thermal Imaging System Hololens 2 testing

System Strengths A think aloud evaluation method indicated that the system is effective in providing thermal data to the operator. As shown in (Figure 4) the operator could clearly perceive the environment as well as locate people in the smoke. The system provided thermal imaging of the view of the headset operator directly to the AR headset's display whenever deemed necessary in a hands-free, gaze-activated implementation. The thermal data provided the operator with the thermal properties of humans as well as materials surrounding the operation.

System Weaknesses Good connectivity in fire and rescue is paramount. The streaming latency when sending data was perceptible when the operator was moving. The thermal image quality limited the distance a human person was distinguishable. The Hololens 2 limited contrast in bright environments negatively affected the perceptible contrast of virtual imagery displayed to the operator.

5.2 Live Tracking System

For testing, the firefighters downloaded the Android application on their phones and were connected to the server which was configured on a laptop. Then, a group got in a car and went around the university area while being connected to the server with their Android phones. The firefighters took turns in wearing the Hololens 2 headset which was running the Live Tracker System and was also connected to the server. The headset operator was able to see the car group moving through the campus as well as control some of the virtual objects displayed in the headset display.

System Strengths The system detected group members' and sent corresponding data to the server, which operated successfully in visualizing the received locations on a digital map and forwarding them to Hololens 2. The AR headset indicated the location of the moving firefighters with low latency and showed the orientation the operator was facing. The system tracked moving targets in real-time and displayed the direction and distance, in respect to the operator, on the AR headset. The UI of the server software offered members operating remotely a clear view of team members' location across devices. The server operator had a clear view of each member location. The system did not require any specialized training.

System Weaknesses The Hololens 2 as is cannot function in a real-life firefighting. Hololens 2 provided the operator with visual data only when the environmental lighting was not too bright. Connectivity is paramount and if lost, the system would not be able to function. If one Android application changes IP address during a session by changing connection from a WiFi hot spot to cellular data or vice versa, then the server adds a new client with the new IP and keeps the previous connection of the same application with their last location as static. The accuracy of single frequency GPS data is not ideal for urban firefighting scenarios.

6 Conclusions and Future Work

The systems presented operate in both urban and wild fire operations. The Thermal Imaging System successfully provided thermal data to the operator, improving visibility in smoke-filled environments. The Live Tracker System effectively tracked moving targets in real-time, providing location data to both the server and the operator wearing the AR headset. The proposed systems have the potential to improve firefighting by integrating cross-device and cross-reality systems. By hands-free interaction, enhanced visibility in smoke-filled environments, dynamic and non-intrusive information display, precise location awareness, and efficient communication, the systems can optimize coordination, minimize radio congestion, and enhance situational awareness among firefighters. A future AR headset for fire and rescue should take into account the harsh conditions firefighters operate as well as their helmet equipment which cannot be removed. The Android application running in the Live Tracking System's server could be replaced by a smartwatch including team members' physiological data such as oxygen level and heartbeat. Security and a solid network connection in remote areas is paramount.

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