

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

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## ABSTRACT

Augmented Reality (AR) may 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. Cross-reality interaction challenges still 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 are streamed directly to the operator's field of view, enhancing their visibility. Unlike conventional handheld thermal cameras, this approach allows hands-free operation. 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 [17], [14]. Virtual Reality (VR) is shown to be effective in firefighting training for simulation [19], [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 [23] [10] [15], however, low visibility, smokey and often high temperature environments in fire and rescue demand enhancement of vision and team cross-device collaboration. This is 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.

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Thermal Imaging Cameras (TIC) recognize heat sources aiding the rescue of trapped individuals [22]. Firefighters have incorporated TIC [1] mostly through hand-held cameras which, however, limit their hand movements. Moreover, GPS tracking is used in fire and rescue providing precise location and real-time situational awareness. Incident commanders monitor the location of their teams and make informed decisions maintaining personnel accountability, and ensuring the safety of team members during large-scale operations [16]. GPS tracking data serves as valuable documentation for incident analysis, evaluating strategies and improving future response planning [21]. Incorporating live tracking information in real-world, busy and unpredictable fire incidents is crucial, but poses challenges in relation to 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 AR visualizing thermal heat maps and GPS location, 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 hot-spots, 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 [7].

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, the camera was not connected directly to it. Instead, the camera is connected on the laptop responsible for streaming its content on the HoloLens 2. The *Live Tracking System* consists of three components, one application on a PC acting as a server as well as visualizing the teams real-life location on a 3D map, and two client applications, one on Android smartphones 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 3D map software in a control room. Lastly, the HoloLens 2 operator views 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 methodology, hands-free, gesture-driven and gaze-based for both presented AR systems operating in low-visibility and smoke, for fire and rescue in wild, mountainous and urban settings.
- 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 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 as well as location tracking, enabling rapid response while in crisis.
- 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 head-worn AR by embedding sensors. An external camera live-streamed the real-world on the HoloLens device bringing text closer to people with impaired vision [20]. A HoloLens device was combined with two FLIR Lepton 3.5 Radiometric infrared thermal cameras mounted on the top [6]. 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. Also, a FLIR Boson ADK thermal camera was mounted on top of a HoloLens 2, analyzing thermal properties of energy systems and identify energy related vulnerabilities [9]. In the presented *Thermal Imaging System*, a thermal camera was mounted to capture the thermal properties of the headset operator's field of view. Hands-free interaction was paramount, therefore, a gaze-controlled interface is put forward.

AR systems often employ GPS data for geo-location [18]. The HoloLens 2 lacks a GPS receiver, to be derived from a smartphone. In past work, a smartphone ran a server feeding location data to a HoloLens 2 client [8]. A navigation route was generated using Google GPS and the smartphone's GPS. The application created a route graph for the operator and used the smartphone data to locate itself. The HoloLens app then computed the difference between the position of the HoloLens and the next position node and generated a line that connected these two coordinates. In the presented *Live Tracking System*, both HoloLens 2 and a smartphone representing the operator's location were 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, hands carry apparatus and speech-driven interfaces cannot be employed due to noise. In both systems here, efficient interaction is facilitated by gaze tracking [11] [12] [5].

### 2.2 Systems for Firefighters

C-THRU is a firefighter helmet, in development, equipped with AR technology, by Qwake Technologies [13]. The helmet provides real-time visualization overlaid onto firefighters' actual view, allowing them to see through smoke and structures, and access critical information in low visibility. The helmet, also, includes thermal imaging locating hot spots and potential victims in the fire scene. Thermal imaging and AR technology is a promising combination in firefighting. An automated system offered real-time object detection and recognition with the use of a FLIR One G2 camera [2]. The *Thermal Imaging System* presented here has the same goal, while adding gaze-based interaction for optimized functionality.

The ENGAGE Incident Management System (IMS) for Computer-Aided Dispatch (CAD) is a software system by Satways for emergency response employed by Greek firefighters. The system enables emergency operators to swiftly acquire real-time information pertaining to an incident and dispatch the appropriate resources to 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 [16]. The *Live Tracker System* presented adds 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 lists the requirements the systems, here, must meet.

- The AR systems should offer a hands-free user interface.
- Operators should be able to view 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 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 HoloLens device 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: 5). 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

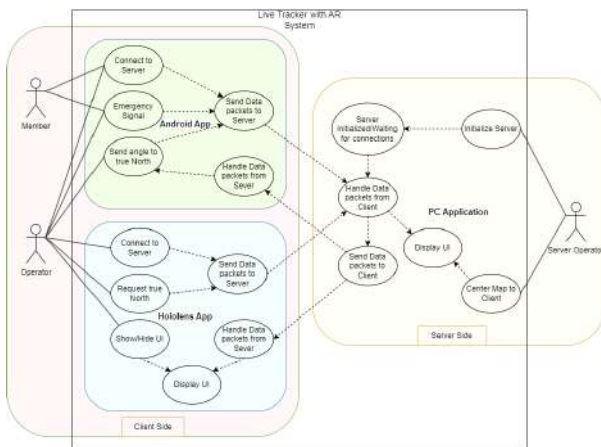


Figure 2: Live Tracker System use case diagram

The *Live Tracker System* could be used in wildfire operations and offers live tracking service, for individual team members. An Android application sends 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 TCP. 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) listening for connections on a specified port, with the help of the AsyncCallback delegate in order to asynchronously process incoming connection attempts. Accepting connections asynchronously sends and receives 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. The server application shown in (Figure: 3) also provides visual

representation of each member's location on a 3D map that is easily controlled by the PC operator. For the application to acquire 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 (UI) of the Android application installed on the firefighting team members' mobile phone consists of three screens:



Figure 3: Live Tracking System server screenshot

**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 entering a username and the IP and server port and pressing 'connect', the application begins a connection to the server and if successful, sends a packet of data including the username.

**Main Screen:** If the Android device establishes a connection with the server, it begins to transmit its location in packets of data displayed on 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 presses the same button to close the emergency signal. If the application is running in operator role, then the operator sends a North request through the Android application. This action will change the home screen of the Hololens device. A new button will appear sending the angle to north of the Android phone orientation, when pressed, to the server and forwarded to the Hololens for calibration. Pressing a red Quit button on the top right of the screen will disconnect the client from the server and the application will close.

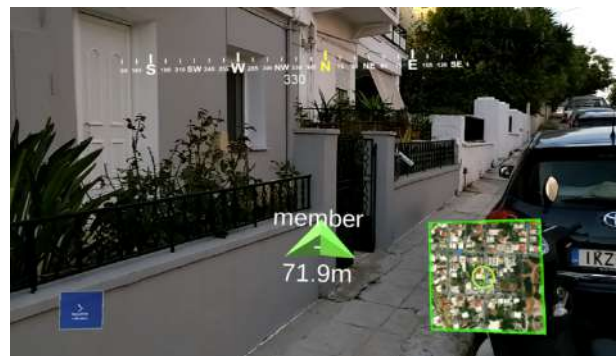


Figure 4: Live Tracking System on Hololens 2

The Hololens UI (Figure 4) consists of four main parts:

*Virtual Compass:* The virtual compass object consists of two textures; the compass background and actual compass which are both 2D sprites positioned on top of each other. A text UI object displays the corresponding username and distance in meters.

*Virtual indicators showing 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 are 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 the operator, positioned facing the angle to north of each Android device in respect to the Hololens position and virtual north. Below the arrow, both 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 member's location indicators without any hand movement. To be selected, the operator should stare on the button for 2 seconds.

## 5 EVALUATION

High-ranked firefighters from the central fire station of Chania, Crete, Greece, tested the proof-of-concept systems and evaluated their effectiveness in real-life, simulated, scenarios in a safe space.

### 5.1 Thermal Imaging system

A smoke grenade was activated outdoors. A connection between the server (PC) and client (Hololens 2) applications was established and the streaming was successful. The Hololens 2 operator recognized and tracked 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: 5).



Figure 5: Thermal Imaging System on Hololens 2

**System Strengths** A think aloud evaluation indicated that the system is effective in providing thermal data to the operator. As shown in (Figure 5), the operator clearly perceived the environment, locating people in the smoke. The system provided thermal imaging of the view of the headset operator directly to the AR headset's display whenever 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

Firefighters downloaded the Android application on their phones and were connected to the server configured on a laptop. Then, a group drove around the university, while being connected to the server through their smartphones. Firefighters wore the Hololens 2 running the *Live Tracker System*, also connected to the server. The headset operator viewed the group driving through the campus as well as control virtual objects displayed on the headset display.

**System Strengths** The system detected group members and sent data to the server, successfully visualizing the received locations on a digital map and forwarding them to Hololens 2. The AR headset indicated the moving firefighters' location and operator's orientation with low latency. 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 real-life firefighting. Hololens 2 provided the operator with visual data only when the environmental lighting was not too bright. If connectivity is lost, the system would not function. If an Android application changes IP address during a session by changing connection from WiFi to cellular 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 may 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 optimize coordination, minimize radio congestion, and enhance situational awareness. A future AR headset for fire and rescue should take into account the harsh conditions firefighters operate as well as their helmet equipment. 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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