"SIZING UP" EMERGING TECHNOLOGY FOR FIREFIGHTING: AUGMENTED REALITY FOR INCIDENT ASSESSMENT

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Every year, structure fires account for billions of dollars in property damage and injuries to firefighters and civilians. Emerging technologies, such as augmented and virtual reality (AR/VR) have been identified to assist in mitigating the loss of life and property, but they have not been fully evaluated. The goal of this work is to clearly identify how AR can enhance fire suppression operations by mapping feedback from a needs assessment conducted with firefighters to the areas where technology could be leveraged to support an initial incident assessment (*size up*), demonstrating the practical use of AR for the fire service.

INTRODUCTION & RELATED WORK

Despite a downward trend in the overall number of fires reported over the last decade in the United States, the number of structure fires remains relatively constant (Haynes, 2017). A structure fire is defined as any reported fire that involves the architectural aspects of a residential, industrial, or commercial building (Klaene, 2014). These types of fires accounted for over 74% of all fires reported last year, resulting in approximately 7.9 billion dollars in damage, 2,950 civilian deaths, and 12, 755 civilian injuries (Haynes, 2017). Due to the frequency and varying severity of structure fires, it is important that the *incident commander*, the fire officer in charge of directing fire suppression operations, can gather information quickly to formulate strategies and tactics, mitigating the loss of life and property. However, this information is typically incomplete and often lacks enough detail to be useful until the unit arrives on scene and can assess the operational environment.

Due to the shared characteristics of complex, time sensitive, and dangerous operational environments, the fireground has been used an analog for the battleground (Klein, Calderwood, & Clinton-Cirocco, 1986). Because of this intersection in research, adapting technologies from the military to the firefighting domain is not in itself a novel approach. Virtual environments (VEs) have been used for training in the fire domain for over 20 years (Bliss, Tidwell, Guest, 1997; Carnegie Mellon University, 2005; Gillespie (2013); Tarr, Smith, Totten, Carney, & Wadja, 2014). Additional research focuses on integrating Augmented Reality (AR) and VEs not only for training, but for navigation, locating victims, and physiological monitoring (Bailie et al., 2016; Liu et al., 2010; Prasanna, Yang, & King, 2013; Ramirez et al., 2012; Siu & Herskovic, 2014). AR integrates the physical and virtual worlds using computer generated images overlaid on a real-world environment (Billinghurst, Clark, & Lee, 2015). It is ideal for showing information in context and has been successfully implemented to support military operations (Yohan et al., 2000).

Gasaway (2009) identified the major barriers to incident command decision making, citing the ability to collect accurate information and data as critical to successful incident management. To aid incident commanders in handling information on the fireground, emerging technologies such as specialized wearables, unmanned aerial vehicles (UAVs), and AR displays are being evaluated for efficacy and safety (Klann, 2008; Quaritsch et al., 2011).

Given the needs of the fire service and their reliance on technology in dynamic life or death situations, AR seems to be a promising and practical tool for fire suppression activities. Yet, there is a gap in the literature that explicitly outlines the advantages of AR during initial stages of incident response when the fireground is assessed, also referred to as a "*size up*." In this paper, we evaluate how AR could be leveraged to support initial on-scene incident assessments. Our research was guided by the following questions:

- How do firefighters perform routine tasks and what equipment do they use? Do these tasks and tools differ across ranks?
- What sources of information are necessary to support firefighters of all ranks engaging in fire suppression tasks?
- What are the benefits of current technology used? Are there any capability gaps or bottlenecks related to technology that prevent firefighters from doing their job?
- What are the advantages of using Augmented Reality (AR) for firefighting and how can we explicitly map these advantages to the tasks and technology used in modern firefighting practices?

PRACTICE INNOVATION

We present an analysis focused on identifying areas where AR technology could potentially support engine crews during the *size up* phase of fire suppression response. We combined this analysis with a technology-focused needs assessment (field study) to elicit information requirements for a fire department. The goal of this work is two-fold: 1) propose an initial framework for identifying best practices related to the use of AR in the fire response domain and 2) demonstrate the applicability of this framework using data from our field study approach.

Participant Profile

The participant sample consisted of n = 35 (32 male, 3 female) firefighters and n = 3 (3 male) emergency management personnel; n = 38 total. In this study, an *engine crew* is composed of at least one firefighter, one lieutenant, and one engineer that all ride in the fire engine. *Line officers/incident commanders* include most firefighters with the rank Lieutenant, Captain, or Battalion Chief (see Table 1).

Table 1.
Firefighting Command Structure

Rank	Role
Probational Firefighter	Newly Trained
Firefighter	Fire Suppression
Engineer/Driver	Drives Vehicle & Operates Engine Equipment
Lieutenant	Crew Supervisor
Captain	Directs fire and/or emergency medical operations
Battalion/District Chief	Highest ranking officer on duty
Assistant/Deputy Chief	Operations/Administration
Division/Fire Chief	Operations/Administration

The fire service, while grounded in a para-military structure, has local and regional variations across the United States. For example, a battalion chief in one region may be referred to as a district chief in another.

Methods

The field study was completed in three separate portions (see Table 2). The first focus group was transcribed from an audio recording. Subsequent focus groups were not audio recorded due to the nature of incident response. All medical calls are subject to Health Insurance Portability and Accountability Act (HIPPA) regulations and patient privacy protections. Therefore, the first author took field notes for the remaining focus groups (2-10).

The first author coded the interview data. This coding process was completed by uploading all transcripts into MAXQDA 12. Two senior researchers reviewed random samples of this coding to ensure interrater agreement prior to the completion of all coding. Coding was divided into categories: command structure, roles, incident needs, and technology capabilities/gaps/failures.

Table 2.
Field Study Summary

Study Phase	Participants
Focus Group 1	Emergency Management Personnel
Focus Group 2	Various Fire Chiefs
Focus Groups 3-10 (Combination Field Study/Focus Groups)	Engine Crews Across 6 Fire Stations; conducted during 10-Hour Ride-Along

PRACTICE APPLICATION

For the purposes of our research, we are focusing on the the initial information management phase of incident response, known as a "*size up*" (Brunacini, 2002; Norman, 2005). This phase can be conceptualized as a checklist; like the types of checklists pilots use to prepare an aircraft for landing or how surgeons prepare the operating room.

Understanding Firefighter Tasks and Technology

Given that emergencies require responses in seconds, the steps taken from leaving the station to completing the size up are all crucial. *Pre-incident planning* involves information capture that is typically handled when not responding to emergencies (see Table 3). Depending upon department needs, state employees, agencies, or fire departments will carry out those efforts. Therefore, alternative solutions must be proposed to maximize this type of information on scene, especially if the first-due officer or crew is not familiar with the area. Ideally, some of this size up information would be available, but as we learned in our study, these pre-incident plans may not be entirely accessible on scene, or the responding unit may not be the same unit that collected the information.

"You have 45 seconds to understand information from several disparate systems, you are flipping screens, switching back and forth from the mapping screen and the incident screen…"-Lieutenant

"The MDC printout has more information than someone can read in 30 seconds..."-Firefighter

"The point is you cannot get there quick enough with all the information you need, yet we are putting first responders in this role, this is high consequence decision making..."-Emergency Operations Center

These quotes illustrate the importance of understanding information needs on the fireground. The National Institute for Standards and Technology (NIST) envisions a future in which emerging technologies are integrated to create "smart firefighting," providing firefighters with updated and intelligent technology to better support their mission. However, transitioning this vision into reality requires an understanding of the current systems firefighters use to obtain information. Table 3 captures the main tools used by the fire battalion we interviewed. Please note this is not an exhaustive list; rather, it serves as a foundation for understanding participant feedback and details regarding size up.

Table 3.
Core Tools Used by Firefighters

Technology/ Tool	Use	Users	Type
Mobile Data Computer/ Terminal (MDC/MDT)	Incident information, reports, logs	All	Laptop
Global Positioning System (GPS)	Navigation	All	Standalone device
Radio/ Portable Radio	Communication	All	Standalone Device
Pre-Incident Plan (PIP)	Information captured prior to emergencies (typically include maps, pictures, facility information, contacts, etc.)	Incident Command	Depending upon department/region can be paper or digital, often contain information in 2D
Air Pack & Air Pack Tracker	Supply of air to prevent contamination	All/ Incident Command	Backpack/Tablet Interface

Through our study and a critical review of relevant literature, we demonstrate how AR lends well to each of these areas, particularly for the structure fire use-case. We comment on these different technologies by using quotes from the interviews to *identify participant needs* and to *illustrate where AR could be leveraged*. We also discuss where research has implemented or studied AR in certain use-cases or other safety-critical occupations to leverage what we already know from the literature and translate this to the fire domain.

Thirteen-Point Size Up

Multiple models exist for size up; however, Norman (2005) is credited with the original thirteen-point size up commonly used in modern fire departments. Although it is the incident commander's job to direct operations and fire suppression, crews may be assigned to participate in various aspects of the size up. For example, two firefighters may be assigned to evaluate the posterior (charlie side) of a building. It is also critical to note that the thirteen-point size up *does not have to be completed in order*; rather, it touches on these aspects to ensure no valuable information is overlooked. We outline these thirteen points below:

Construction (1). Each type of building falls within a construction class that designates how flammable the material is, ranging from Class 1 to Class 5 (Klaene, 2014). The construction and engineering industries have adopted AR to integrate plans, blueprints and other ways to collaborate and share awareness throughout the design and construction phase, demonstrating the use of AR in visualizing and reconstructing buildings, bridges, and other structures (Bae, Golparvar-Fard, & White, 2013; Irizarry, Gheisari, Williams, & Walker, 2013). Similarly, this information could direct a line officer about how to handle an incident by providing "on the fly" knowledge of the building's materials and key features directly available in the environment.

Occupancy (2). Determining occupancy load and collecting clues about the underlying structure is a critical portion of size up. For example, a shopping mall will have both open floor space and compartmentalized areas and will likely be multiple floors. Ideally this information would be accessed using pre-incident plans, but this is not always possible, as summarized in the quote below:

"It's an issue of accessibility. I need to pull up a separate network just to access these plans. You don't have that kind of time to spend 15 minutes trying to get to a plan." -Captain

Apparatus and Staffing (3). Chosen tactics will depend on the type of apparatus that responds. In addition to engine companies, there are tower trucks that have different capabilities. Depending on the severity or the location of the fire, different resources, trucks, or staffing requirements may be necessary. A participant succinctly summarized this below:

"*The expectation for the IC [incident commander] is that he/she prioritizes accountability. They need to know where everyone is and what they are doing at the scene from start to finish."* -Chief

Life Hazards (4). Knowing how to handle materials in each environment is of critical importance (Bevelacqua, Hildebrand, & Noll, 2005). The NFPA mandates departments continually catalog and capture information about buildings, structures, and hazards to enhance emergency preparedness and provide fire departments with information in the event of an emergency (NFPA, 2003). This information is stored in the form of *pre-incident plans*. Hazardous materials teams train for these incidents, but the tools they have on scene are often limited. For example, teams will typically use a database of chemicals found in a mobile application, or in some cases from a paperback book, which contains important chemical properties and other vital details. AR provides a way for this information to be accessed on scene without the need to flip through a book or access a separate application. As one participant explained:

"I have to keep a separate flash drive with information about local schools on them. Relying on technology that typically fails [the MDC] is not a good plan." -Chief

Experienced staff express knowledge and know-how, they find ways to adapt to the information retrieval problem. However, this forced adaption also creates stress and requires another system—they must maintain their own "database" and regularly update it for it to remain effective.

Water Supply (5). Across the battalion we interviewed, firefighters indicated that the technology *did meet some more critical needs.* For example, on the mapping system in the MDC, there are icons that represent nearby fire hydrants. This aids the commander and engine crew in determining the logistics of water supply on scene. In addition to hydrants, hose lays/stretches are crucial for water supply, and may involve combining and connecting hoses. As a result, *distance, volume, and friction loss* are all important calculations that need to be done quickly and accurately.

"One major concern with recently developed communities is the lack of fire hydrants. They are typically expensive, and some developers complete the bare minimum for coding and zoning. As a consequence, the logistics of putting out a house fire may be compromised by lack of water and you have to move to plan B." -Engineer

Auxiliary appliances (6). Due to advances in building construction and continual updates of fire codes to increase safety, integrated fire suppression systems are more numerous than ever before. AR allows for the overlay of important building information, such as construction materials, utility shut offs, overhead loads, ingress and egress points.

Street Conditions (7) & Weather (8). Street conditions refer to traffic flow during working hours, cars parked on the street, and other types of situations will impact the ability for crews to situate themselves in the environment. Weather includes factors like temperature, humidity, and precipitation that will affect how fast materials combust and how quickly the fire spreads.

Exposures (9). Exposure refers to the potential for a fire to spread to other buildings. Some head mounted AR devices allow for photographs or video capture. This could assist an incident commander in capturing vital details as fire conditions change, allowing them to send information to other responders or officers.

Table 4.
Mapping Information Needs to AR Capabilities

Information Need (Maps to Size Up Numbers)	***Example***	***AR Capabilities***
Minimizing Required User Input (All; 1-13)	Incident commanders already use multiple devices (captured in Table 3). Input needs to be minimal to avoid distraction and maximize time for decision-making and coordination.	Gesture-based commands and the integration of pre-incident plans superimposed onto the environment eliminate a need for multiple devices.
Multi-perspective views (3, 10)	An overhead view, view of all building sides (360°), and the ability to see the perspective of other crew members can enhance the incident commander's understanding of the incident scene.	From our interview data, we conclude that firefighters use both *primary (the surrounding environment) and secondary (pre-incident plans, maps, etc.) sources* to size up an incident scene (Darken & Peterson, 2001). AR leverages the ability to view both at once, or the ability to switch seamlessly between views.
Visualization of spatial information (4, 5, 10, 13)	Judging height distances for a multiple story structure requires time and effort. If a hydrant does not work, this also requires reconfiguration of the incident scene.	Distances for height and from the hydrant to the scene are easier to calculate and comprehend. This kind of information is already available in the construction and engineering domains through BIMs (Bae et al., 2013).
Critical Cues (4, 9, 13)	Signs of a potential flashover (when a fire becomes fully involved very quickly due to thermal radiation) can be easily overlooked. Additionally, ***mental models*** (mental representations of current and future states of an emergency scene) may not be correct prior to arrival (Gasaway, 2013).	Similar research has already demonstrated that AR has been successful for a military use case and in visual search tasks (Yohan et al., 2000; Lu, Duh, & Feiner, 2012). Since technology continues to improve, dynamic cues can be captured and tracked. The AR system can focus the incident commander's attention *to enhance cue detection and support reconciliation of pre-arrival mental models with information they capture during the size up*.
Information Filtering (4, 5, 10)	The incident commander is bombarded with radio conversations about irrelevant information, particularly when multi-agency response is required.	Configure the display to show only necessary information or allow for customization according to incident commander's preferences (Julier et al., 2002). The AR system has the potential to reduce distracting information, such as unnecessary radio traffic.
Video/Image Capture (6, 9)	The first-due officer wants to show the next due officer changes in conditions, so that he/she can strategize, and change courses of action as needed upon arrival.	Incident commanders can view multiple images or videos to compare critical cues and changing conditions. This can give the incoming officers an advantage over current technology.
Predicting future states (All)	Exposures (9) and changes in the conditions require careful consideration as these changes may require a change in fire suppression tactics.	To be successful, incident commanders must think ahead. AR can scaffold an incident commander's mental model by reducing demands on memory and enhancing coordination, by allowing them to manipulate information that is superimposed on the real-world environment.

This table captures how information needs identified in our field study map to the capabilities of AR technology now and in the future.

Area/potential (10). Firefighting involves tasks that require heavy reliance on visual information in denied and degraded environments. This includes line of sight information, as well artifacts and interfaces that manage the number of people on scene, air pack utilization, etc. Most officers agreed that a summary of information is needed to support decision making. The command staff frequently indicated that they needed some information that was not readily available for sizing up an incident scene:

"It would be beneficial to have a quick picture and summary for size up. If there was a way to summarize this information, more people would use it."-Captain

"*Something that gives an overhead view would be important, but it does not exist. I can pull an overhead view on Google maps, but it's usually a picture from two years ago…*"-Chief

As denoted in these two pieces of feedback from participants, commanding officers struggle to get the information they need about an area quickly. It takes effort to be able to discern and filter which information is important. More importantly, this ties up working memory and cognitive resources. If an incident commander needs to recall a piece of information, he or she must write it down or pull from memory, taking time away from the incident to ensure facts are not missed. This is also problematic for the first-due officer (the first to arrive on scene) who may transfer command once a more senior officer arrives.

Location and extent of fire (11). This portion of size up involves making inferences about where the fire is, how quickly it will spread, and what tactics should be used, depending on these two factors.

Time (12). This encompasses not only time of incident to determine how long a structure has been burning, but also refers to time of day and seasons, which may be referenced in the earlier "weather" (8) portion of the size up.

Height (13). Building height will determine what kind of crew is needed to perform any victim extraction or to reach a fire. This requires strategic placement of the fire engine or vehicle.

DISCUSSION

From our data and from the literature, we have summarized the principal areas where AR could replace current interaction methods and interfaces to enhance efficacy of fire service operations (see Table 4). AR has the potential to:

- Minimize required user input
- Increase data sharing across the command
- Support visualization of spatial information
- Emphasize critical cues for size up
- Filter and customize information presented to the incident commander
- Allow for the prediction of future states and dynamic incident changes

CONCLUSION & FUTURE DIRECTIONS

We have outlined major areas above that could leverage AR technology to better support line officers and other firefighters on the scene of an emergency. With this work as a foundation we contend that practitioners, developers, and human factors professionals can use the following information to better design and evaluate AR tools for firefighting. However, there are several limitations of this work that impact the generalizable content of our results. First, we have not validated this framework with testing. We contend this framework serves as a foundation for better understanding how emerging technologies explicitly link to supporting fire engine crews. Second, we did not survey multiple fire departments across the United States. We recognize that this does not necessary mean our work generalizes to all U.S. fire departments. In less populated areas, volunteer firefighters are more prevalent. Further research must be conducted to determine how the needs of volunteer fire departments can be addressed.

We recognize that AR technology has not yet reached a level of maturity that will meet all the needs of the fire service in current off-the-shelf devices. Tracking and registration problems still plague AR in its present commercial state. We foresee this being implemented in portable, head-mounted AR glasses, but we acknowledge that future directions might include other types of displays. In our future studies, we plan to extend this framework beyond a structure fire use-case to encompass more scenarios. We also plan to assess different agencies across the nation to better understand the needs of the fire service more broadly, including tower truck crews and special operations teams. This data will inform the design process for both hardware and software prototypes in the next iteration of our study.

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