Ubiquitous Computing for Firefighters: Field Studies and Prototypes of Large Displays for Incident Command

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Abstract

In this paper, we demonstrate how field studies, interviews, and low-fidelity prototypes can be used to inform the design of ubiquitous computing systems for firefighters. We describe the artifacts and processes used by firefighters to assess, plan, and communicate during emergency situations, showing how accountability affects these decisions, how their current Incident Command System supports these tasks, and some drawbacks of existing solutions. These factors informed the design of a large electronic display for supporting the incident commander, the person who coordinates the overall response strategy in an emergency. Although our focus was on firefighters, our results are applicable for other aspects of emergency response as well, due to common procedures and training.

Categories & Subject Descriptors: H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *user-centered design*

General Terms: Human Factors

Keywords: Firefighter, field study, low-fidelity prototypes, emergency response, ubiquitous computing

INTRODUCTION

In the United States, more people are killed by fires than all other natural disasters combined. Each year, there are about 1.9 million fires, killing about 4000 people and injuring 25,000 more, including about 100 firefighters killed in the line of duty. Furthermore, fires cause on the order of $11 billion USD in property damage per year [18, 23].

Firefighting is clearly a dangerous profession. Firefighters must make quick decisions in high-stress environments, constantly assessing the situation, planning their next set of actions, and coordinating with other firefighters, often with an incomplete picture of the situation. One firefighter we interviewed summarized it best: "Firefighting is making a lot of decisions on little information." Improvements in existing tools and practices can help protect civilians and firefighters, as well as minimize property damage.

Currently, firefighters make very little, if any, use of computers when on the scene of a fire, since most commercially available computers are designed for office work. However, ubiquitous computing technologies are providing a remarkable opportunity for change. The convergence of small, cheap sensors (e.g. [12]) coupled with wireless networking and computing devices in a variety of form factors offers the tremendous potential to gather and communicate critical information in real-time—such as temperature, toxicity, and a person's location and health status—at unprecedented levels.

A key question here is how to design systems such that this sensing power can be used effectively. What information should be gathered, who needs to know about it, and how should it be presented and used? To answer these questions, we conducted a series of studies with firefighters, observing a training exercise in the field, carrying out interviews, and iterating on several low-fidelity prototypes. These methods allowed for opportunistic discovery and limited commitment to preconceived notions of this domain. The main goal of these studies was to understand the tacit knowledge about procedures, tools, and dangers that are rarely documented in textbooks, and to use these to inform the design of appropriate ubicomp systems for firefighters.

Firefighters use a para-military organization with well-defined ranks and roles [10]. Ranks are fixed titles, such as battalion chief, captain, and lieutenant. Roles represent a set of responsibilities and help establish the chain of command. While our studies involved firefighters of various ranks, it focused on the role of *incident commander* (IC). The IC is an information intensive position, which involves coordinating the overall response strategy to an emergency and managing available people and resources in real time. This observation led us to focus on supporting ICs early on. Our subsequent field studies influenced the design of our prototype, a large electronic display for supporting ICs.

The rest of this paper is organized as follows. After related work, we provide background information about the organizational structure and procedures used by firefighters. We then present key findings from our studies with firefighters. Next, we discuss how those findings informed our designs, and show how our low-fidelity prototypes

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evolved based on feedback from ICs. We conclude by discussing issues in designing ubicomp applications for firefighters and for emergency response.

RELATED WORK

There is a great deal of existing literature about firefighters, for example, their organizational structure [20, 24], decision-making processes [13], and psychological and health conditions [19, 20]. There have also been several studies of failures, some notable ones being procedural failures in Massachusetts [15], McKinsey and Co.'s report on the World Trade Center attacks [14], and a study of organizational and communication failures at Mann Gulch [24]. While this research informed us, it was limited in helping us understand what kinds of situational information would be useful for firefighters and in designing ubiquitous computing systems for firefighters, especially for incident commanders. Thus, our work here is complementary, concentrating on building appropriate tools for firefighters.

There has been some work in the CHI community that could be used to help firefighters, in mobile and wearable computing (e.g., [17]), hands-free and eyes-free interaction [2], and management of simultaneous conversations [1]. Since the smoke-filled conditions of structure fires significantly decreases visibility, there are also potential overlaps between studies of interfaces for blind users (e.g., [9, 22]) and studies of interfaces for firefighters.

The Command Post of the Future [6] is a set of projects investigating command in battlefield situations. The focus is on developing technologies for mobility and better decision-making, including multimodal interaction, information visualization, and knowledge-based reasoning. We complement this work by looking at user needs for a related but different domain, focusing on information presentation and interface design for large displays.

In the CHI community, our work is most related to Camp et al., who looked at communication issues in emergencies and prototyped a radio system that would reduce congestion while maintaining situational awareness [3]. In contrast, we concentrate more on incident command and how a large display can help support that role.

For the most part, however, there has been relatively little HCI work done on emergency response. While the CHI community has historically focused on non-emergency situations, typically office environments, we see emergency response as an area where the community can contribute significantly. Advances in the state of the art can help save lives as well as minimize injuries and property damage.

The CHI community itself can also benefit from research in this area. The nature of emergency response is fundamentally different from office environments, in terms of physical risk, psychological state, and operating conditions that are dynamic and often extreme. This poses unique challenges for designers and researchers in terms of group awareness, multimodal interaction, and information visualization, to name a few. If we can make an impact in this highly stressful domain, where the systems we offer are secondary to the primary task, we might also be able to apply these results in less extreme environments for a wider audience, such as computing while driving.

BACKGROUND

This section describes background information about the organizational and command structure of firefighters, with an emphasis on incident commanders. This information is part of the standard training for firefighters, and can be found in training textbooks (for example, [10, 21]).

Organizational Structure

The basic unit of organization for firefighters is the *company*, which is "any piece of equipment having a full complement of personnel" [10, 16]. Companies are typically comprised of a captain, a driver or engineer, and one or two firefighters, though this can vary. The *captain* is the officer in charge of a company. The *engineer* operates vehicles, pumps, and other equipment.

A *battalion* is a collection of companies permanently responsible for a geographic area, such as a city or county. A battalion has several *battalion chiefs* (BCs) that are responsible for all operations within a specified timeframe, typically 24 hours. BCs arrive on scene to assume command for structure fires and other large incidents, but are usually not involved with smaller incidents.

If an incident is large enough, firefighters are organized into *divisions*, which operate within a specific geographic region (e.g. north, third floor, or main entrance), and *groups*, which perform specific functions not restricted to a geographic area (e.g., rescue or ventilation).

Incident Command System (ICS)

All emergency responders use some command system to manage the overall response to an incident, the most common of which is the *Incident Command System* (ICS). ICS has been adopted by many local, state, and federal agencies in North America to handle emergencies of all kinds. ICS is also supported by various artifacts and procedures to help the command team assess, plan, and communicate with everyone involved in the incident.

ICS defines five major roles [5, 10]: command, operations, planning, logistics and administration. We only focused on the first three of these in our field studies. *Command* is responsible for all incident activities, including developing and implementing a strategic plan. The person in overall command is the *incident commander*. *Operations* manages tactical operations to implement the overall strategic plan. *Planning* is in charge of collecting, evaluating, and disseminating information such as maps, weather reports, road closures, and status of personnel and resources. These roles are flexible. The ranking officer of the first team on scene might assume the role of IC and carry out all

ICS roles, passing on the role of IC to higher-ranking officers arriving later on and assuming another role.

Firefighters rely on a chain of command where each person reports to exactly one supervisor. The chain of command also describes communication pathways between responders. In small incidents, for example, an IC would send a message directly to the captain of a company, but in large incidents, that message might be relayed from Operations, to the division leader, and then to the captain.

It is also standard procedure for firefighters to maintain a manageable span of control. As one interviewee said, “The idea behind ICS is you break it down so that one person is in charge of one small component. It’s easier to manage that way. It’s based on an old military tradition [of using] the easiest span of control - 5 to 7 [people].” This principle is applied from companies all the way up to ICs. For example, in a small structure fire, the IC might also assume the role of Planning, Operations, and Logistics, but in larger incidents would delegate these roles to other officers, possibly with entire support teams to assist them.

EXAMPLE: A SINGLE-STORY HOUSE FIRE

We present a hypothetical scenario to illustrate some key tasks and procedures involved in responding to a structure fire. After a single-story house fire is reported and confirmed, the 911 dispatcher immediately notifies the nearest fire station. Depending on the perceived scale of the fire, different alarms may be called, which commit a predetermined number of emergency response resources to be dispatched. For example, in a suburban setting, a first alarm might call for three engines, a truck, and a battalion chief, and a second alarm might call for four additional fire engines, another truck, and a hazardous materials team.

When the first engine arrives, its captain takes a quick look around to size-up the situation, taking in such factors as hazards, weather, and safety in developing a plan of attack. At the same time, firefighters are sent out to understand the building layout, surrounding areas, and location and scope of the fire. The engineer is responsible for locating the fire hydrants and setting up the fire hose. The highest ranking member (in this case, the captain) assumes the role of IC.

If the incident is large enough, the on-duty Battalion Chief will also go on scene. BCs often drive a separate vehicle that contains equipment and forms needed for a command post (see Figure 1). A BC will typically set up a command post close enough to see the fire but far enough to maintain safety. Once the BC arrives, the role of IC is passed on to him. The new IC gets a quick status report of what they have, who they have, where they are, what tasks they are doing, where the fire is going, and what else needs to be done. He might also use a grease board (see Figure 2) or some standard forms (see Figures 3a and 3b) to sketch out the local area, help keep track of tasks, communicate information to others, and maintain a record of the incident for post-mortem analysis and training. These tools are often used at the back of the BC’s truck (see Figure 1).

Figure 1. Rearview shot of a Battalion Chief’s truck, which contains many forms and equipment for ICs.

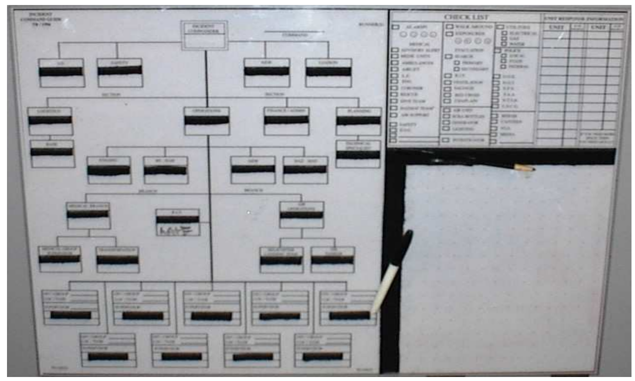


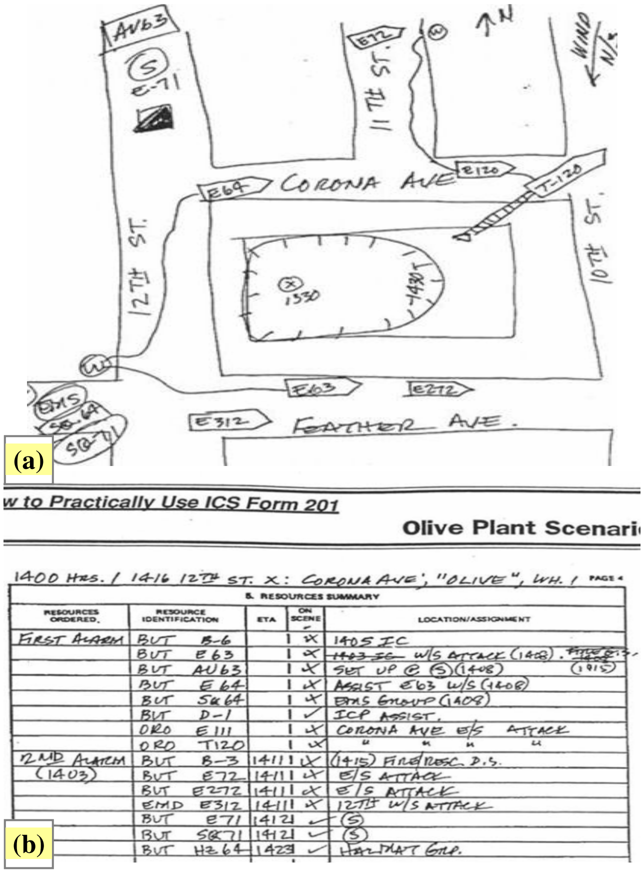
Figure 2. Grease board often used by ICs. The left shows the command hierarchy. The top-right shows a checklist of things to do. The bottom-right is for sketching maps.

ICs develop plans of attack based on information from a variety of sources. The highest level strategy is to go either offensive, fighting the fire directly, or defensive, preventing the fire from spreading. Once the IC is satisfied that the fire has been extinguished, he releases all resources and returns to the fire station.

DESCRIPTION OF FIELD STUDY

Our field study spanned four months and included over 30 hours of interviews and user testing with 14 firefighters in 3 fire departments. Among them were 1 assistant chief, 4 battalion chiefs, 2 captains, 2 engineers and 5 firefighters. We chose to focus on firefighting of structural fires in urban areas, but due to common training methods and standard operating procedures, we believe our findings will be broadly applicable to other types of emergencies. Again, our goal was to understand the tacit knowledge about procedures and problems that are not typically documented.

We conducted interviews at fire stations, which helped us learn about their organizational structure, tools, routines, regular interactions, and typical environment. We also observed one field exercise in which new firefighters were trained on firefighting tactics for urban structures. In addition, we accompanied firefighters on two calls to see first hand how they accomplished their tasks. Throughout,



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5. RESOURCES SUMMARY

RESOURCES ORDERED.	RESOURCE IDENTIFICATION	ETA	ON SCENE ✓	LOCATION/ASSIGNMENT
FIRST ALARM	BUT B-6		✗	1405 IC
	BUT E63		✗	~~1403 IC~~ W/S ATTACK (1408). (1915)
	BUT AU63		✗	SET UP @ (S) (1408)
	BUT E64		✗	ASSIST E63 W/S (1408)
	BUT SQ64		✗	EMS GROUP (1408)
	BUT D-1		✓	ICP ASSIST.
	ORD E111		✗	CORONA AVE E/S ATTACK
	ORD T120		✗	" " " "
2ND ALARM (1403)	BUT B-3	1411	✗	(1415) FIRE/RESC. D.S.
	BUT E72	1411	✗	E/S ATTACK
	BUT E272	1411	✗	E/S ATTACK
	EMD E312	1411	✗	12TH W/S ATTACK
	BUT E71	1412	✓	(S)
	BUT SQ71	1412	✓	(S)
	BUT HZ64	1423	✓	HAZMAT GRP.

Figure 3. Two sample ICS forms from [8]. The top (a) is a sketch of the area and location of resources. The bottom (b) tracks what resources are available, what tasks have been assigned, and what resources are en route.

Figure 4. Passports in a fire station. A tag has the name of a firefighter. Each group of tags represents a company.

we collected artifacts such as actual Incident Action Plans, accountability forms, ICS Forms, ICS booklets, and recordings of radio communication on real incidents.

We began focusing on incident commanders early in our field studies since it was an information intensive position in which computers could help more readily. We discuss our findings most relevant to ICs below.

Accountability

Accountability is pervasive throughout the organizational structure, procedures, and equipment of firefighters. Accountability ensures that there is an accurate count of resources and personnel on scene, with rapid notification if personnel face immediate dangers to their safety. A lack of accountability can lead to dangerous situations (e.g. [14, 15]) where firefighters may not realize that one of their own is missing, or may try to find someone who is not missing.

Our interviewees reported that the most important issues here are knowing what firefighters and equipment are on scene, where they are, and whether or not they are safe. One procedure used to ensure better accountability is conducting periodic roll calls to account for all personnel. Once a roll call has been issued, each team reports back up the chain of command to confirm that all people are accounted for. However, roll calls take some time to complete, and can only be done periodically, creating a time window where firefighters might be missing with no one knowing.

Our interviewees also used a Passport system to track people. A Passport is a plastic tag with an individual's name and rank. These tags are grouped together into companies, and are often attached to a Velcro board in the fire station (see Figure 4). Each engine also has a space to hold the tags of the company currently on duty. Upon arrival at a fire scene, the Passport on the engine is given to the IC, to let the IC know who is on scene. The tags are typically attached to a grease board (see Figure 2).

However, our interviewees reported several problems with the Passport system. One said, "If a captain forgets to change out a tag on the passport or somebody else jumps on the engine, then it's just not accurate information." Another noted, "[t]he Passport will tell you, 'these are the guys on the engine,' but you don't know where they're at."

There are also standardized forms to help keep track of what tasks have been assigned, giving ICs a better idea of who is on scene and what they are doing. For example, ICS form 201 has an area for the IC to sketch a map of the area to help him keep track of the location of all resources (see Figure 3a). Another form in ICS 201 is used to keep track of companies and what tasks they have been assigned (see Figure 3b). These forms are also useful for when command is passed to another person. One weakness, however, is that these forms must be updated manually, and thus might not represent up-to-date or entirely accurate information.

Assessment

ICs make decisions based on many sources of information, including the status of the fire, progress of different companies, condition of the building, location of victims, weather, dangers to nearby buildings, utilities, and so on.

Our interviewees reported that the most important issue here is understanding the overall status of the incident. This is partially addressed by gathering information beforehand as a precautionary measure. For example, fire inspectors collect information about floor plans, hazardous materials, and current number of occupants. Some fire inspections are carried out by firefighters themselves so that they may become familiar with the buildings in their district.

However, our interviewees noted three problems. First, the information might be outdated. Fire inspections are typically conducted annually, but new construction, ownership changes, and movement of hazardous materials can make such information obsolete. Second, the information is often difficult to quickly access. For example, neighborhood maps and floor plans of major buildings are kept in thick binders, but one firefighter commented that it takes too long to find the right page and were thus rarely used. Third, firefighters might not have access to the right information. For example, fire inspectors and environmental agencies file reports, but those reports might not be made available to firefighters.

Collection of information on scene can be difficult and dangerous but is critically important. One BC showed us how he writes notes and fills out forms on his steering wheel while driving himself to the scene because the minutes saved are worth the risk. During an incident, dynamic situational information is communicated over radio or done face-to-face. However, our interviewees noted two problems with radio. The first is noise intensity.

> *There is a lot of noise on the fire ground. You're inside; the fire is burning; it makes noise; there's breaking glass; there's chain saws above your head where they're cutting a hole in the roof; there's other rigs coming in with sirens blaring; lots of radio traffic; everybody trying to radio at the same time.*

This comment also highlights the second problem, which is congestion. Radios are a broadcast channel where everyone can hear everyone else. One BC said that cell phones were often used to contact someone directly, but this did not change the basic problem: "I'm usually listening to at least three [radios]… It's tough, and then you've got people calling on the cell phone at the same time."

Execution

Once tasks have been assigned and resources allocated by the IC, it is up to firefighters to accomplish their assigned task. Although ICs are not directly involved in execution, they noted that there were many kinds of dangers to firefighters, and that being aware of these potential dangers could help them significantly in planning. These include:

- Flashovers, sudden ignition of all contents in a room
- Backdrafts, explosions that occur when an oxygen-starved fire suddenly receives oxygen
- Hidden fires in walls, attics, and other unseen areas
- Structural hazards, including structural collapse and toxic gases from burning hazardous materials
- Personal hazards, including running out of oxygen, getting lost inside a building, and extreme exhaustion

Currently, firefighters do not have any special technologies for helping them avoid the first four problems. However, there are some tools for helping with getting lost. Some departments use thermal imagers that let them "see" in the dark and through smoke, allowing them to scan rooms for people in seconds. However, these are still quite expensive and can sometimes fail due to extreme heat (e.g., [15]).

Firefighters also wear PASS systems, which emit a progressively louder beeping sound when a firefighter has not moved for several minutes, or when a panic button is hit. Our interviewees said that PASS systems go off quite often, due to firefighters standing and talking to one another or pausing for too long. Consequently, other firefighters tend to ignore them unless the alarm is prolonged. Our interviewees also noted that currently, only expensive PASS systems could notify anyone outside of audio range.

Limited audio range highlights another problem, which is the call to abandon a building. When the IC has made this decision, it is broadcast over radio, along with a loud horn blaring outside. However, the abandon call is sometimes missed due to radio dead zones and the loud noise of fires.

FROM THE FIELD TO DESIGN

The main design issues to be taken from the field study for the purposes of design can be summarized as follows:

1. *Accountability* of resources and personnel is crucial and should be as simple and accurate as possible.
2. *Assessment* of the situation through multiple sources of information while avoiding information overload is key.
3. *Resource allocation* is a primary task for ICs and should be a primary focus in designs.
4. *Communication* support should add reliability and/or redundancy to existing communication channels to ensure that important messages reach the right people.

Below, we discuss three iterations of a prototype of a large display for incident command support based on these design issues. As noted by a McKinsey and Co. report, such displays could be more useful than grease boards [14]:

> *[E]lectronic command boards have much greater functionality than magnetic boards. These boards could help communications coordinators and operations chiefs with their tracking, communications and tactical coordination tasks… [They] can store and display maps and multiple building plans.*

We designed and evaluated the first two prototypes in parallel with the field study. This proved to be effective for ensuring that we more closely understood the firefighters' problems, processes, and terminology. For example, as described below, it was not immediately clear to us that resource allocation was a primary concern and problematic issue for ICs until we showed the interviewees the first two prototypes. Designing early prototypes parallel to the field study was also useful as a centerpiece for discussion of design ideas and for quickly getting feedback on new ideas. Our final prototype was done towards the end of the field study and represents our final design.

We also made several assumptions in our design that we believe are plausible given current technology trends. These include the availability and affordability of large displays, widespread deployment and robustness of a wide-range of sensors, and reasonably effective wireless networking.

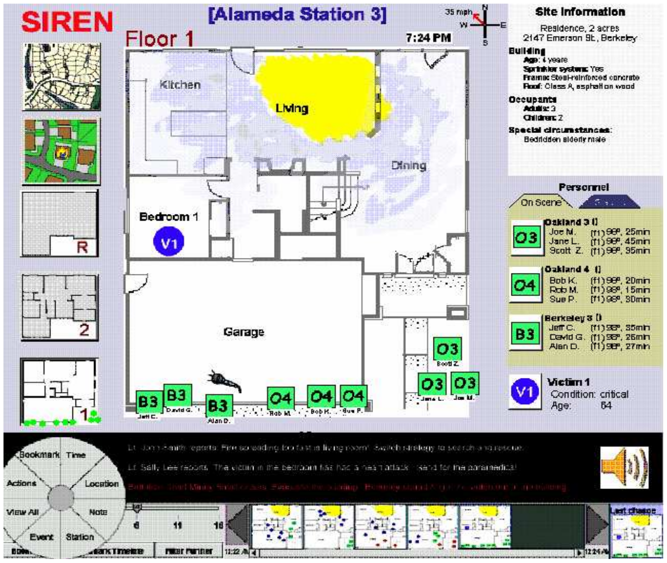

Figure 5. Prototype 1, Firewall, is a wall-sized display to help ICs in small incidents. Sensors show the fire area and the location of firefighters, overlaid on a floor plan.

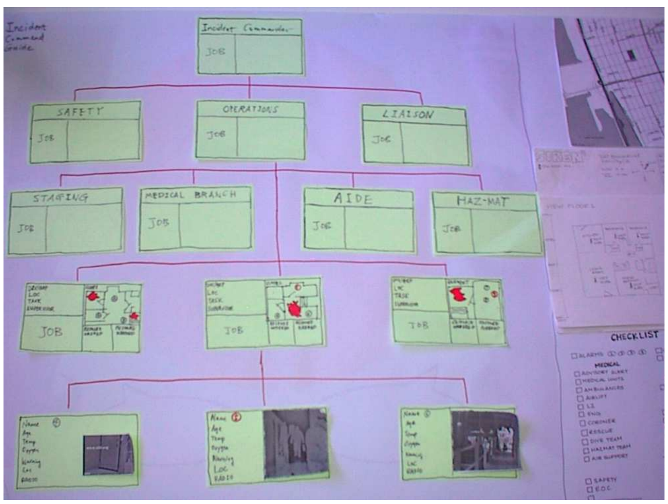

Figure 6. Prototype 2 is a board-sized display based on the grease board in Figure 2. Sensor data from companies and individual firefighters is shown on the bottom-left, and area maps and floor plans are shown on the right.

Prototype 1 – FireWall

Our initial field studies led us to focus the first prototype on accountability and assessment. We based this prototype on a project at Berkeley called FireWall [4], which envisions an IC using a wall-sized display for command and control. This prototype provides a visualization of area maps, floor plans, fires, and locations of firefighters (see Figure 5). ICs assign tasks by using a pie menu to select from a predefined set of commands, such as "attack" or "rescue". Real-time tracking of firefighters addresses accountability weaknesses in the current Passport system. Real-time estimations of the fire and downloadable floor plans addresses assessment problems. This prototype also had tracking of victims, and a history of past events and communications.

While generally positive, firefighters identified three problems. First, tracking individual firefighters is the job of captains and of Operations. So tracking was useful to some extent, but it would be more useful to help ICs comprehend high-level issues and be warned of imminent dangers.

Second, this design put primary focus upon the locations of firefighters in the structure. While this was useful, ICs do not necessarily want this level of detail of information about their crews. Instead, we learned that they are more concerned with the tasks that each crew is assigned.

Third, although useful for post-incident analysis, ICs do not review history or past communications while on scene. This feature was dropped in later prototypes.

Prototype 2 – Tangible Firewall

In the second prototype, we took a step back and used paper prototypes, as high-fidelity prototypes seemed to intimidate some firefighters. We also changed the form factor to be about the size of a grease board, envisioning that it could be stored and used in the back of a BC's truck (see Figure 1).

Our second prototype adopted three new ideas, which were based on observations at fire stations. The first, addressing resource allocation, is a tangible interface inspired by the grease board and ICS command hierarchy (see left side of Figure 6). An IC can assign tasks to a company by attaching an augmented Passport tag to the board, which could be sensed by a computer. The second, addressing assessment, is to present sensor information at different levels of detail. For example, the second lowest level of the hierarchy shows information about companies, such as a floor plan that shows the location of each firefighter in that company. Detailed information about an individual, such as temperature or thermal imaging from the firefighter's perspective, is presented at the lowest level.

There were mixed feelings about these two features. Firefighters liked the use of Passports and how information was presented with successive levels of detail. However, we discovered that the ICS hierarchy on grease boards is not used extensively during incidents. Thus, this prototype wastes a lot screen space. Also, it provides too much detailed information, making it hard to see the overall status. One BC commented, "[This much information] would definitely be an overload for me."

Another issue is that these features do not make it easy to keep track of what tasks have been assigned. One BC said, "As an IC you've got a lot of things going on and you don't remember to go, 'I gave them utilities. Where are they at now?'" This stimulated a conversation about their radio communication standards with regard to resource allocation that were integrated into the next version of the prototype.

Based on discussions with firefighters about the often confusing journey to a fire scene, the third idea was to add a map of the local area, showing streets and nearby fire hydrants (see top-right of Fig. 6), as well as building floor plans (mid-right). These displays could be automatically retrieved from the address data provided by the dispatcher, making it faster than using binders of maps. This feature

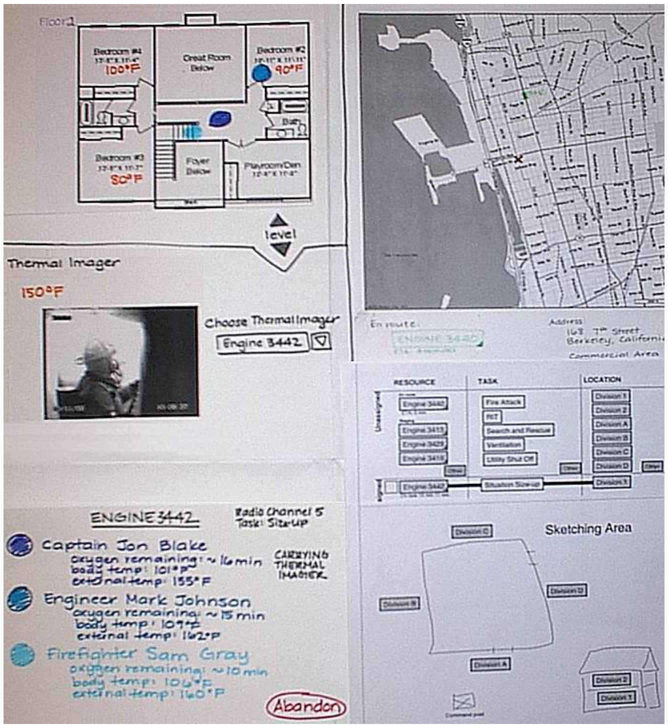

Figure 7. Prototype 3 takes the best features of Prototypes 1 and 2 and adds some new ones. The middle-right screen lets ICs assign tasks and track progress. The bottom-left screen notifies ICs of dangers to individual firefighters.

was very well received by the firefighters, though there were some questions about how to get the floor plans of local residences. One firefighter noted that property deeds often contained floor plans, and that these deeds could be scanned in and associated with the corresponding address.

Prototype 3 – Task Assignment and Management

Prototype 3 kept the form factor design from prototype 2, a grease-board size display located at the rear of a command vehicle, as well as the three most useful features of the initial prototypes: location tracking, area maps, and estimated fire status. It also had three new features. The first is better support for resource allocation, shown in the middle-right screen of Figure 7. This design uses the "resource-task-area" model suggested by firefighters who critiqued Prototype 2. For example, "Assign engine company 4256 to fire attack on the first floor." Our interviewees found that this fit well with their model of assigning tasks (as seen in Figure 3b) and would be useful in accounting for personnel and resources. To help ICs with multitasking and to address the problem of crews neglecting to report their progress, this design keeps track of how long a resource has been on a task and lets ICs add timers to remind him to make progress checks.

The same firefighters told us about FDonScene [7], a laptop application which requires continuous manual input to help ICs in resource accounting. In contrast, our prototype is intended to be a board-sized display and focuses on gathering sensor-data from firefighters in the structure.

The second feature is presenting individual information only when necessary or when explicitly queried. To minimize information overload, detailed information about individuals are displayed in flashing text if a potentially critical danger is detected, such as low levels of oxygen remaining. This feature helps with accountability.

The third feature is an "Abandon" button that an IC could use in the event that all firefighters should leave the building immediately. We imagine that this could work with a firefighter's heads-up display if the environment was too noisy when the announcement was made. Rather than mimicking existing communication, this was to be used for adding redundancy to the communication system.

Summary of Prototype Evolution

Overall, the third prototype best met the 4 design issues that we learned from our field studies.

1. *Accountability*: The first prototype helped by providing real-time location tracking, but required ICs to perform complex mental tasks on sensor visualizations for accountability. This was simplified in the second prototype by tracking resources used by different units during an incident response, though this often provided too much information. The third prototype kept location tracking and simplified accountability by adding notifications of dangers.

2. *Assessment*: Current work practices require firefighters to be sent into unknown situations to size-up the situation. Prototype one introduced the idea of downloadable floor plans, which was kept throughout. In prototypes two and three, we employed the idea of seeing the situation from firefighters' eyes. Images collected by thermal imagers can be wirelessly transmitted back to the IC's command post.

3. *Resource allocation*: Through our field study we learned that resource allocation was a problematic issue for ICs. Based on their feedback, we designed a resource allocation tracker for Prototype 3 that fit well into their current work practices. The "resource-task-area" design also provides some redundancy for accountability.

4. *Communication*: Instead of attempting to record the many conversations juggled by the IC, Prototype 3 has an "Abandon" button that provided a redundant way of signaling the abandon call.

LESSONS ABOUT DESIGN

Through our field studies and prototypes, we learned about some of the major challenges and concerns facing firefighters. The kinds of information ICs needed while on the scene of a fire concerned issues of accountability, assessment, resource allocation, and communication. These issues are also pervasive in other complex situations such as emergency care in hospitals, and response to natural and man-made disasters. We believe lessons learned about designing for firefighters can also help inform these other mission-critical ubicomp applications, especially as it pertains to information displays for command and control.

First, in emergencies, people need to be focused on the people and environment around them rather than on any particular device. Their ability to perform sophisticated tasks is further hampered by demanding operating conditions. As a result, applications should minimize direct interaction. For example, the third prototype automatically displays area maps, updates locations of firefighters, provides notifications of how long groups have been on a task, and provides alerts of dangerous situations. We are also currently investigating software and hardware prototypes supporting spontaneous and opportunistic interactions for firefighters within a structure [11].

Second, while it is not always desirable for consumer applications, redundancy is important for emergency response applications in improving communication and safety. For example, our prototypes present information about individual firefighters in multiple places, including their location on the map, their current task in the task assignment area, and what immediate dangers they face in the notifications area. The abandon button is a redundant form of communication, supplementing their existing radios and abandon horns, helping to ensure that firefighters receive critical messages.

CONCLUSIONS AND FUTURE WORK

In this paper, we describe how the results of field studies, interviews, and low-fi prototypes informed the design of a large electronic display for helping incident commanders to manage issues surrounding accountability, assessment, resource allocations and communication. Two important design issues here include minimizing direct interaction and adding redundancy to improve communications and safety.

There are many opportunities here for improving the effectiveness and safety for emergency responders. Successes here can also help us advance the state of the art in ubiquitous computing, ultimately helping us in designing more reliable and useful applications in other domains. We are continuing this work in developing a mobile messaging system for firefighters inside of a structure [11].

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REFERENCES

[1] Aoki, P.M., *et al.*, The Mad Hatter's Cocktail Party: A Social Mobile Audio Space Supporting Multiple Conversations. *CHI Letters (Human Factors in Computing Systems)*, 2003. **5**(1): pp. 425-432.

[2] Brewster, S., *et al.*, Multimodal 'eyes-free' interaction techniques for wearable devices. *CHI Letters (Human Factors in Computing Systems)*, 2003. **5**(1): pp. 473-480.

[3] Camp, P.J., *et al.* Supporting Communication and Collaboration Practices in Safety-Critical Situations. In Proceedings of *Human Factors in Computing Systems: CHI 2000*. Fort Lauderdale, FL: ACM Press. pp. 249-250 2000.

[4] Chandler, C., *et al.*, The Fire Wall. 2000. http://ratbert.bmrc.berkeley.edu/courseware/cs160/fall00/Projects/firefighting/

[5] City of El Cerrito California Fire Department, Incident Command System. 2002. http://www.el-cerrito.com/fire/incident_command.html

[6] DARPA Information Exploitation Office, Command Post of the Future. http://dtsn.darpa.mil/ixo/programdetail.asp?progid=18

[7] FieldSoft, FDonScene. http://www.fieldsoft.com/fdonscene/fdsoftware.html

[8] Hawkins, J.R., Making a Difference: How to Practically Use ICS Form 201, Incident Briefing, in *California Fire Chief's Association, Fire Instructors' Workshop '92*. 1992.

[9] Helal, A., *et al.* Drishti: An Integrated Navigation System for Visually Impaired and Disabled. In Proceedings of *The 5th International Symposium on Wearable Computers (ISWC 2001)*. Zurich, Switzerland 2001.

[10] International Fire Service Training Association, *Essentials of Fire Fighting*. 4th ed, ed. R. Hall and B. Adams. Stillwater, OK: Fire Protection Publications, Oklahoma State University, 1998.

[11] Jiang, X., *et al.* Siren: Context-aware Computing for Firefighting. In Proceedings of *Second International Conference on Pervasive Computing (Pervasive 2004)*. Vienna, Austria. To Appear 2004.

[12] Kahn, J.M., *et al.* Mobile Networking for Smart Dust. In Proceedings of *MobiCom 1999: The Fifth Annual International Conference on Mobile Computing and Networking*. Seattle, WA: ACM Press. pp. 271-278 1999.

[13] Klein, G., *Sources of Power: How People Make Decisions*. Cambridge, MA: MIT Press, 1998.

[14] McKinsey and Company, Increasing FDNY's Preparedness. 2002. http://www.nyc.gov/html/fdny/html/mck_report/toc.html

[15] National Institute for Occupational Safety and Health (NIOSH), Death in the Line of Duty: Six Career Fire Fighters Killed in Cold-Storage and Warehouse Building Fire - Massachusetts. 2000. http://www.cdc.gov/niosh/face9947.html

[16] National Interagency Incident Management System, Glossary of Terms for the Incident Command System. http://www.acadia.net/mdisar/icsgloss.html

[17] Pascoe, J., *et al.*, Using While Moving: HCI Issues in Fieldwork Environments. *ACM Transactions on Computer Human Interaction* 2000. **7**(3): pp. 417-437.

[18] Paulison, R.D., Working for a Fire Safe America: The United States Fire Administration Challenge. 2002. http://www.usfa.fema.gov/dhtml/inside-usfa/about.cfm

[19] Regehr, C., *et al.*, Individual predictors of traumatic reactions in firefighters. *Journal of of Nervous and Mental Disease* 2000. **188**(6): pp. 333-339.

[20] Regehr, C., *et al.*, Self-Efficacy and Trauma in New Recruits and Experienced Firefighters. *Stress and Health* 2003. **19**: pp. 189-193.

[21] Sneed, M., *Study Guide for Fourth Edition of Essentials of Fire Fighting*: Intl Fire Service Training Assn, 1998.

[22] Strothotte, T., *et al.* Development of dialogue systems for a mobility aid for blind people: Initial design and usability testing. In Proceedings of *The 2nd ACM/SIGCAPH Conference on Assistive Technologies*. Vancouver, Canada: ACM Press. pp. 139-144 1996.

[23] U.S. Fire Administration, F.E.M.A., Facts on Fire. 2003. http://www.usfa.fema.gov/public/factsheets/facts.shtm

[24] Weick, K., The Collapse of Sensemaking in Organizations: The Mann Gulch Disaster. *Administrative Science Quarterly* 1993. **38**(4): pp. 628-652.