User Interface for Supervisory Robot Interactions in Firefighting Operations

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Abstract

Firefighting is a dangerous occupation and several firefighters die in the line of duty every year around the United States. It is important to do all that we can to mitigate these losses. One such method is to develop better tools to aid supervisory personnel at the site of a firefighting incident. The goal of this project, was to develop a user interface that would help visualize data that is made available to firefighters through devices and sensors that they have on them as well as the data from potential robots that are part of such operations. Our interface aggregates important observations made in studies ranging from human-computer-interaction to search-and-rescue with respect to user interface design elements. We also make several recommendations for the development of a fully-working user interface.

Acknowledgements

Our team would like to thank Professor Carlo Pinciroli for his patient guidance on the project. Professor Pinciroli provided some much needed feedback throughout the course of this project despite his busy schedule. We would also like to thank him for accommodating our chaotic schedules, and we could not have completed this project without his much needed help.

We would also like to thank Worcester Fire Department's Deputy Chief, Martin Dyer for taking the time to answer our questions in an interview. He provided us with initial traction that helped plant the seeds for the specific direction we were going to go with this project.

Lastly, we would like to thank Worcester Polytechnic Institute for giving us this opportunity to work on this project for class credits. Without the resources provided by the Institute, we would have had much difficulty in doing the work that we did with the project.

Executive Summary

Firefighting is a dangerous occupation that takes the lives of several firefighters across the United States each year. For example, in 2011 alone, 7090 firefighters were injured in the line of duty (Karter & Molis, 2012). The average number of deaths annually is 75 (National Fire Protection Association, 2018). However, it is not just burn injuries that lead to firefighter casualties. At the site of an incident, firefighters are subject to an immense number of stressors. For example, firefighter fatalities due to sudden cardiac death was found to be responsible for 43.7% of firefighter fatalities over a ten-year period (National Fire Protection Association, 2005). The same study mentions that "firefighting activities are strenuous and often require firefighters to work at near maximal heart rates for long periods (NFPA, 2005). It is evident that the firefighting as a process needs to be improved, and one such method of doing so is by improving the technologies that are accessible to firefighters. This can potentially augment the process in addition to mitigating some of the risks that firefighting personnel are subject to at the incident of a fire.

The constant development of new technologies has made it feasible to collect and process large amounts of data. However, this access to advanced sensors also comes with the challenge of extracting meaning from the data that they deliver. The use of robotic systems in firefighting is being increasingly studied. In order to digest information retrieved by a robot, and this information to be easily digestible at the site of a firefighting incident, it is important to design data interfaces with the user in mind. For example, given the large number of stressors and stimuli that firefighters are exposed to at the incident of a fire, interfaces must be designed to minimize clutter and the potential overloading of information on the screen. At the same time, interfaces must have enough valuable information in order to be of any help to a firefighter. A well-designed display has the ability to increase fire protection and situational awareness for supervisory firefighting personnel at the incident of a fire.

In an interview with Worcester Fire Department's Chief, Martin Dyer, we found that user interfaces that are currently in use, particularly Public Eye, miss some of the requirements of the firefighters. We also gathered that this interface was not well-designed and that firefighters found it difficult to use. Despite this interface not having the additional complexity of robot information on the field, it still poses a challenge to its users. Adding another layer of human-robot interaction only complicates the problem further. The difficulty inherent in human-robot interaction is that the human must be well-versed with the software and hardware architecture of the robotic system. Additionally, interactive interfaces add another dimension of design choices to be made for the interface. Such interactions must be intuitive and have a clear workflow, as well as a deterministic sequence of actions. A well-designed interface, which we seek to prototype, can minimize and at times eliminate the need for users to learn complex commands to make full use of the system in question. The development of our prototype is focused on firefighters in a supervisory setting at a structure fire which includes residential, commercial, and industrial buildings. We intend to borrow ideas and concepts from prior research done in this area, in order to develop a prototype which will then help us make several recommendations for a full-fledged ready-to-use user interface. In order to achieve our goal, we formulated four separate objectives, that together, would help us design an effective user interface of firefighters:

1. Understand and formalize the context in which the user interface will be used
2. Understand the advantages and limitations of user interfaces that have already been studied in similar contexts to our own
3. Develop mockup user interfaces and a corresponding working prototype
4. Make recommendations for future future full-fledged systems to be used in the field

Defining the problem

Our project restricts the range of fire types under study to *structure fires.* These include fires that occur in residential, commercial, and industrial buildings. Examples include home fires and warehouse fires. The main risks that we identify in structure fires are the following:

- Flammable materials
- Toxic gases
- Collapse of floors and ceilings
- Firefighter health

These risks also translate into specific challenges that our user interface needs to address either directly or indirectly:

- Lack of visibility due to smoke and darkness
- Lack of ability to sense and touch things
- Limited awareness of surrounding environment and therefore little navigability

Given these risks and challenges that firefighters face at the site of a fire incident, advanced navigation systems at the site of an incident can provide much needed help. It can also be useful to provide the command operator with all the data that is gathered at the site of an incident. This would aid in, for example, formulating high-level tactics during a fire. For large fires, therefore, it can be empowering for a command-operator to have more than just mapping information during an incident.

We focus on supervisory interactions that involve a firefighting supervisor who is receiving information at the "command center". Therefore, the intended user of our interface is *not* a firefighter who is directly involved in an operation, but rather a firefighter who is a supervisor of the firefighting operations at the site of an incident.

Findings from Existing User Interfaces

The first phase of our development process involved studying existing user interfaces to borrow useful interface elements, and incorporate the limitations that were observed in these interfaces. This phase also involved an interview with Worcester Fire Department's Chief Martin Dyer (Appendix A). In this interview, we gathered that interfaces designed for firefighters must be simple and performant. This was because firefighters will not be willing to use something that could potentially disturb the fast pace at which actions are being taken at the site of an incident. In the same interview, we were also told of an interface that was used by firefighters in a supervisory role to review dispatch information and sites of fire incidents: Public Eye. This helped us understand the level of complexity a firefighter in a supervisory position might be willing to work with.

What was common across all interfaces that we studied was the central role that maps play. This was also consistent with our interview with Deputy Chief Martin Dyer, who had mentioned that at the site of an incident, a map of the building would be very helpful. We also found that the ability to overlay information on top of the map was important and in many of the studies performed, seemed to be approved by firefighting personnel. A few studies also mentioned the importance of having a camera view in the interface because it can aid supervisors in navigation and location awareness of the robots. In order to make the interface as familiar as possible, we borrowed a few ideas from the gameplay of a Massively Multiplayer Online Role Playing Game that had several elements consistent with the requirements of our interface. For example, the minimap in Dota 2 (an MMORPG) was borrowed in order to give firefighting supervisors better situational awareness.

Development of a Methodology

After gathering information from our interview and literature reviews, we were able to extract the main requirements for a supervisory user interface aimed at firefighting in a structure fire. Our first task was to develop mockups before we could develop a working prototype. We accomplished this task of developing mockups by using a free online software called Balsamiq. This helped us concretize the ideas we got from the previous phase. It also helped us in the next step which was the development of a working prototype. The development of the working prototype, which is outlined in more detail in the pages that follow, was done as a web application. The development of this prototype followed several phases. At first, the entire interface was developed using React, but we soon realized that several of the features that we wanted to implement would introduce significant performance limitations because of the conflicting use-case that React is designed for as a framework. Instead, we moved to a more graphics-centric implementation that was based on the HTML5 Canvas. While this meant implementing lower level graphics operations, it also meant more customizability and better performance.

Reflections on the Development Process

Overall, the development process that we followed was inspired by software engineering practices and prior coursework in Human Computer Interaction that some members of our team had completed. The development work of the functioning interface itself was distributed between two team members. Some mistakes were made during the development process. This included not surveying the range of frameworks that are available to us for an application like ours. React was chosen initially because of its ability to separate concerns in the interface, however, we discovered that manipulating the map using React was a difficult task. Therefore, we decided to use d3 within

React to manipulate SVG elements on the map. Testing of the interface quickly revealed to us that it was still not satisfactory. Under the suggestion of our advisor, we moved our implementation of the interface to HTML5 Canvas.

Final Recommendations

After our literature reviews, interview, and the development of the working prototype we noticed important principles that future developers of such an interface would want to keep in mind for their implementation:

- **Interface design must be a function of the user and the setting**

It is important to ensure a user-centric design. For example, in our interview with Deputy Chief Martin Dyer, we found that a lack of attention to the user's requirements and expectations, would lead to a complete abandonment of the system itself. This is also reflected in the reluctance of many of these personnel to adopt new technologies which often come with many unknowns (Appendix A).

- **Interface design must be simple, familiar, and intuitive**

Another important aspect of designing a user interface for firefighters is that these firefighters are already being inundated with a lot of information at the site of a fire. Any new variables that are being introduced into the process such as our intended device, must aim to minimize any further stress that it may cause. Introduction of a cluttered interface can increase stress (Shneiderman and Plaisant, 2010). Therefore, keeping the interface simple, familiar, and intuitive is essential to ensure its continued use.

Future Work

Before an interface like this can be widely adopted in firefighting operations, it is important to conduct user-studies and test the interface out in mock scenarios. Given the high-risk, high-consequence nature of firefighting, it is not recommended to test potential designs prior to several design iterations completed through mock scenarios. It can also be helpful to build a fully native system of the software for the specific devices that firefighters would be comfortable using. The present prototype implementation heavily depends on existing frameworks and libraries that reduce the complexity of our code, but add some performance drawbacks to the application.

Authorship

Kartik Thooppal Vasu, Saina Rezvani, and Nugzar Chkhaidze all contributed to the research and writing of this report. What follows is a breakdown of how the report was written for the project.

All three students contributed towards writing out the paper first in outline form. This was then reviewed with our advisor, Professor Pinciroli to check for meaningful flow in the document. The introduction was first written in bullet points and extended by Kartik Thooppal Vasu and Nugzar Chkhaidze. Following this, the background was written out by Saina Rezvani, Kartik Thooppal Vasu, and Nugzar Chkhaidze and extended based on feedback that was received from our advisor.

The writing of the procedure was split into two sections, one which involved the writing for the procedure's first "Interface Mockup Development" section. This first section was written and extended by Saina Rezvani. The following section about the development of the working prototype was written and extended by Kartik Thooppal Vasu.

In addition to writing individual sections of this report, Kartik Thooppal Vasu, Saina Rezvani, and Nugzar Chkhaidze all edited the paper for grammar, content, and flow as a group.

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1. Introduction

Firefighting is a dangerous occupation. In 2011, 70,090 firefighters were injured in the line of duty (Karter & Molis, 2012). In 2017, 60 firefighters died while on-duty in the US while the annual average number of deaths is 75 (National Fire Protection Association, 2018). *Figure 1* shows the number of firefighter fatalities on-duty. It is therefore imperative to use whatever means possible to help mitigate these losses and aid firefighters that are on-duty. At the same time, it is not just burn injuries that lead to firefighter casualties. At the site of an incident, firefighters are also subject to a large number of stressors. In a study conducted by the National Fire Protection Association, firefighter fatalities due to sudden cardiac death were observed and it was found that this was responsible for 43.7% of firefighter fatalities over a ten-year period (National Fire Protection Association, 2005). The study mentions that "firefighting activities are strenuous and often require firefighters to work at near maximal heart rates for long periods" (NFPA, 2005). Another study found that firefighters have limitations in their tension control (Milen, 2009). Milen concluded that firefighters do not have nearly as much resistance to stress as would be needed in a high-stress scenario. It is clear that the process of firefighting needs to be improved and indeed, could be augmented by the use of technology. Improvements to the process of firefighting can happen in several ways. One such way is in leveraging information that is available to firefighters at an incident.

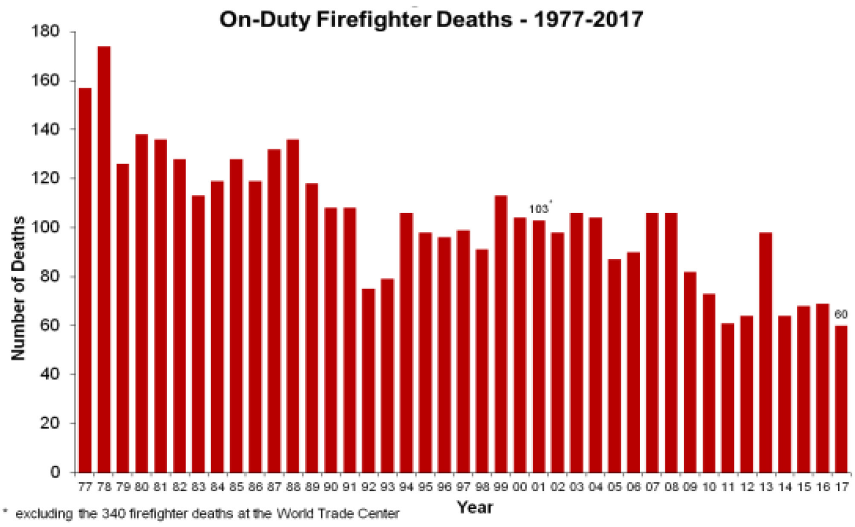

Figure 1: The number of on-duty firefighter deaths between 1977 and 2017 (NFPA, 2018)

The constant development of new technologies has made it feasible to collect and process large amounts of data. As we begin to gain access to more advanced sensors and systems, we can gain knowledge not only about the current situation of an emergency, but also the original condition before the emergency. Specifically, the use of robotic systems in firefighting is being increasingly studied due to firefighters being exposed to dangerous conditions. In general, there are two types of robotic systems that have been developed for firefighting: fixed systems and mobile systems (Lattimer, 2010). The use of robots to navigate unknown spaces is challenging and identifying, localizing, and manipulating objects is a complicated task which necessitates a human operator (Lattimer, 2010). In order for human operators to make the right decisions, they need access to sufficient information.

In order to digest information retrieved by a robot and for this information to be actionable, it is important to design user interfaces for human operators carefully. Data collected from robots and smart visualizations have the potential to increase *fire protection and situational awareness* of firefighters. With the information that is available, we must ensure that we are serving information appropriately by striking a fine balance between too little information which could lead to the interface's use being abandoned and too much information which could lead to information overload. Extreme environmental conditions are known to degrade human performance, and the addition of information overload could lead to unwanted consequences. For example, working memory, which is the capacity to store and employ information over short periods of time, is the function that is known to suffer the most under stress (Staal, 2004). Clearly, knowledge of this would influence the design of a user interface.

However, in an interview with the Worcester Fire Department's Chief Martin Dyer we found that user interfaces, particularly, Public Eye that is currently being used, are not easy to use (Appendix A). Given the large amount of information that firefighters are inundated with at the site of an incident, it is very important to ensure that interfaces are both simple and responsive. Lack of responsiveness in interfaces can lead to frustration, and subsequent termination of their use. The difficulty inherent in human-robot interaction is because the human must be well-versed with the software and hardware architecture of the robotic system. Clearly, there are several challenges when it comes to designing and constructing a user-interface that would work in the real world. Several balances must be struck during the design of an interface such as that between the simplicity of the interface and the large number of features that might be present on a robot. Additionally, interactive interfaces add a new dimension of design choices for the interface. Interactions must be carefully designed to have an intuitive workflow, as well as a deterministic sequence of actions. Interactions must also be responsive. Responsiveness must be ensured at two different levels:

- User interface to user responses
- Robot to user interface responses

A well-designed interface can minimize, and at times eliminate, the need for the users to learn complex theories and commands in order to make full use of the robotic system in question. By making an effective UI, that can successfully eliminate the need of rigorous training and additionally, fully utilizes all the functions and capabilities.

In this paper, we seek to develop a concept for a user interface that will aggregate and present data collected during a firefighting incident. The development of this prototype was focused at firefighters in a supervisory context at a structure fire. In order to achieve this goal, we formulated four different objectives, that together, would inform the design of an effective user interface for firefighters.

These objectives were:

- Understand the context in which the user interface will be used
- Understand the limitations of existing user interfaces being used by firefighting teams.
- Develop mockup user interfaces and a corresponding working prototype
- Make recommendations for future full-fledged systems to be used in the field

The Background section, will cover the background material where we analyze existing interfaces and also formalize the context in which the user interface will be used. We will also attempt to understand the limitations of existing user interfaces. The Methodology section will introduce our mockup user interfaces that were developed as wireframes before we go on to explain the development of a working prototype. Finally, we will address any important takeaways from our project and analyze the limitations of our methodology in the Results and Conclusion section.

2. Background

Before we can begin to study interfaces for the context of our project, it is important to understand the context in which our system will be operating in. First, we will have to understand the problem that we are tacking, and this is covered in Section 2.1 which elucidates structure fires: the specific type of fire that we are dealing with. Second, we will have to understand our intended user and Section 2.2 delineates the types of users that we are designing for. The following sections will elaborate the interfaces that we studied.

2.1 Structure Fires

For the scope of this project, we will be dealing with *structure fires.* Structure fires include fires that occur in residential, commercial, and industrial buildings. Examples include fires in a house or warehouse fires. The National Fire Protection Association has a classification for different types of structure fires as defined below:

1. Type 1: Usually refer to high-rise fires.
2. Type 2: String shopping center malls. Roofs are made out of steel rafters.
3. Type 3: Brick and mortar walls, wood frame floors.
4. Type 4: Churches and other community buildings
5. Type 5: Recent construction of single-family dwellings, apartments with four floors or less. (Structure Fire, n.d.)

The development of our interface will include all these different types of structure fires. While we do not distinguish between these types of fires above, certain interface elements can be adapted to the final in-field implementation of the proposed interface.

The main risks that we identify in structure fires are flammable materials and toxic gases, collapse of building roofs, and firefighter health. These risks put forward important challenges such as a lack of visibility due to smoke and darkness, a lack of ability to sense and touch things, and a general lack of hearing because of the ambient noises that are typical for such incidents. Additionally, firefighters face navigation problems when they are in the structure fire. For example, Worcester, Massachusetts in 1999 saw one of the worst fires that took the lives of 6 firefighters (Carey, 2018). These firefighters were unable to locate their way out of the building because of the disorienting nature of such incidents. Several projects have been proposed to help in such cases such as Jet Propulsion Lab's POINTER system (Good, 2016). These navigation systems can provide much needed help to firefighters on location but it can also be useful to have a centralized "command" unit that is able to review all such location data of firefighters in order to make the right decisions in terms of high-level tactics during a fire. For industrial structures, firefighters therefore need more than just a map that to help them during an incident.

2.2 User Context

Scholtz et al. propose four areas that distinguish the study of human-robot interaction and human-computer interaction. These include the following (Scholtz, 2002):

A. Levels of human interaction
B. Necessity of interaction with the environment
C. Propensity of the robots to develop hardware and software problems
D. Environment in which the interaction occur

In the same paper by Scholtz (2002), three different levels of human-robot interaction, these are:

1. Supervisory: These interactions typically take place between a human and a robot that is in a remote location.
2. Peer to peer: As the name suggests, in this case both the human and the robot are in the same team and contributes to the team according to their respective capabilities.
3. Mechanic: This is the situation where the human requires to be tele operating a robot, thus requiring the user to be skilled.

In the development of our interface, we focus on supervisory interactions where there is a firefighter supervisor that is receiving information at the "command center". This means that the intended user of our system is not a firefighter that is in the location of an incident itself, but rather, a supervisor of the firefighting operations at the site of an incident. As we have suggested earlier, our user interface is also restricted to the domain of *structure fires*.

2.3 State of Current User Interfaces and Their Limitations

In this section, we will be reviewing state-of-the-art user interfaces that are currently being used by firefighters. Each one of the following sections will be named based on whether they were named by the authors in the paper or not. In the latter case, we will be numbering the interfaces for future references.

2.3.1 Public Eye

Figure 2: Public Eye user interface

Public Eye is a mobile platform that is designed for public safety personnel. In our interview with the Worcester Fire Department's Deputy Chief, Martin Dyer, we found that their current use of this interface lacked usability and intuitive operation (Appendix A). Another downside of this user interface is that it is not designed with firefighting operations specifically. But rather, it is a platform that is designed for everyone in public safety including police chiefs (Public Eye, n.d.). As such, Public Eye was a software that the Worcester Fire Department use to review information about potential incidents and also review information about personnel being dispatched into particular locations. It also gives them information about where fire hydrants might be at the site of an incident. While this interface cannot be used directly to manage indoor firefighting operations, it nonetheless gives us an idea about the level of complexity that a supervisory firefighter might be willing to work with in an interface.

2.3.2 User Interface 1 by Gancet et al. (2010)

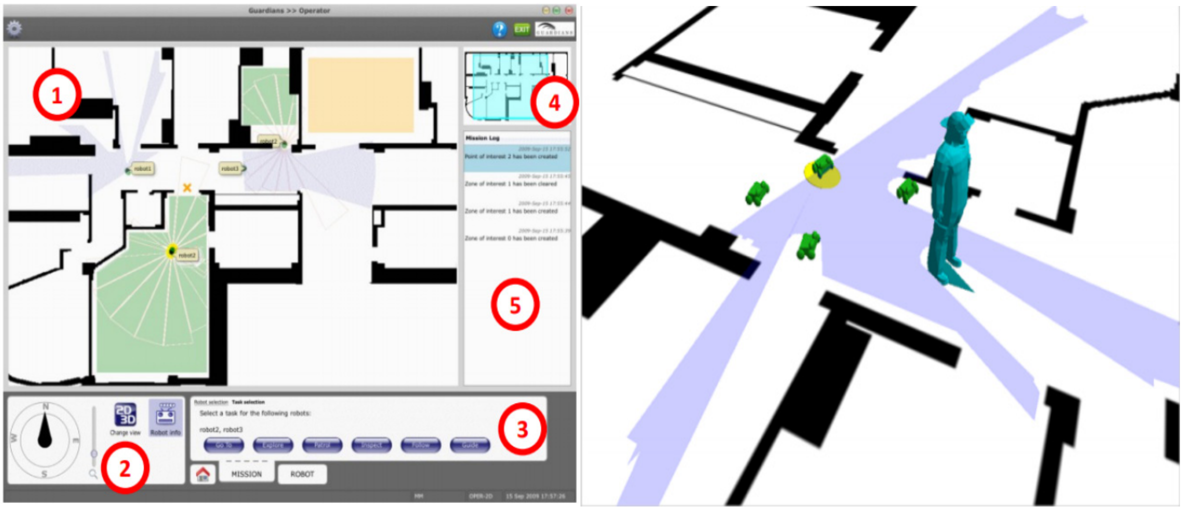

Figure 3: User interface developed by Gancet el al. (2010)

The second user interface (pictured in Figure 3) that we studied in preparation for the design of our own interface was developed by Gancet et al (2010). Their interface was a touch-screen ecological display with Human-Machine interface (HMI) plugins. These HMI plugins correspond to specific events that allow certain interactions. One such event could be a separate window for monitoring a robot's health for example. This interface focused on having as few user inputs as possible. However, there were some suggestions made by the firefighters for the study. For example, firefighters felt that all the information that was being displayed on the interface must be time-tagged or else it would be possible to lose track of the occurrence of events (Gancet et al., 2010). They suggested having different area names in the visualization associated with the commander that is in charge of it. They also suggested color coding already checked areas within a building and alarms based on the chemicals, temperature, remaining time, as well as firefighter and robot health. One particular thing of note is that the firefighters stated that they would spend time learning the ins and outs of the user interface and did not have complaints about the complexity of the interface itself. This was in contrast to the interview that we conducted with Worcester Fire Department's Deputy Chief Martin Dyer who stated that firefighters would benefit from ease of use and a smaller learning curve to the operation of the user interface.

2.3.3 User Interface 2 by Trouvain et al. (2003)

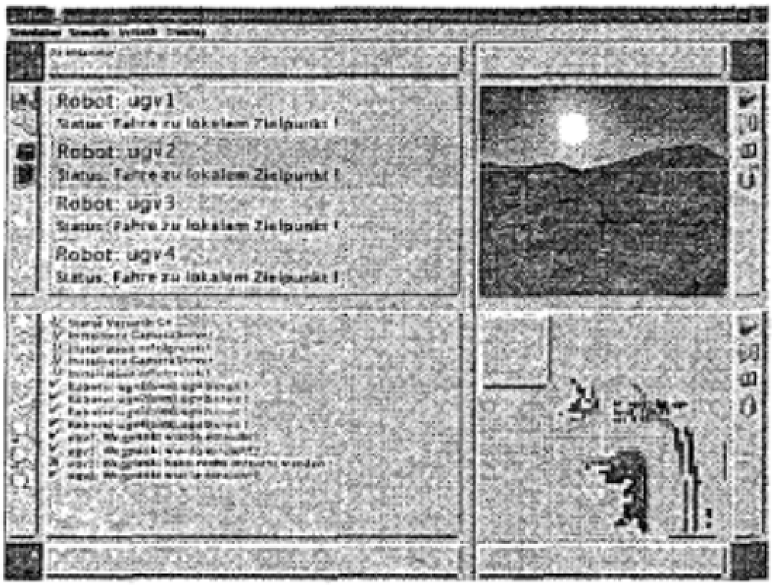

Figure 4: Trouvain et al's (2003) user interface

The user interface developed by Trouvain et al. (2003) was developed for cases of 1, 2, and 4 robots for a semi-autonomous simulated system without any human intervention and no prior map of the environment. The experiments that were conducted to evaluate the interface used the NASA Task Load Index which measured mental demand, physical demand, temporal demand, subjective performance, effort, and frustration level. The user interface also displays general information about all the robots at all times. One of the windows contains a list of robots and each list element has the identifier and a short description of the robot status when the robot is highlighted. There is also a message box that shows warnings or errors and it can have links or buttons. On the top right, there is a camera view and on the bottom left there is compass that is superimposed on the camera image. The interface also has a window for the camera view, a window for the map view and a control panel on either the left or the right side for buttons. There are two navigation modes, one of which is autonomous and another manual. In the case of manual mode, the robot waits for the operator to give commands and performs a command when received. In the autonomous mode the robot can navigate autonomously and then if it receives a command, the robot performs it and then resumes its autonomous movements. The software also has a simulator which provides a birds-eye view of the rendered environment and the corresponding robot accessibility map. On both views, you can see the coordinates and the camera orientation. The paper observed that people typically have a preference to use either a map view or a camera view even if both were available, which indicated the existence of a tunnel-view effect.

However, some of the limitations of the interface included bad performance when more than 2 robots were being visualized on the interface. The interface also was limited in terms of the features and functionalities that was available. For example, there were no events or actions that would be displayed. Also, while newer interfaces incorporate touch screen interfaces, the interface studied in this paper made use of keyboard keys for selected robots. There are also multiple control panels and they are all similar which can cause confusion and make the interface less intuitive than simpler layouts. Finally, a lack of customizability of the user interface meant that users could not alter their views to their own liking.

2.3.4 User Interface 3 by Lewis (2013)

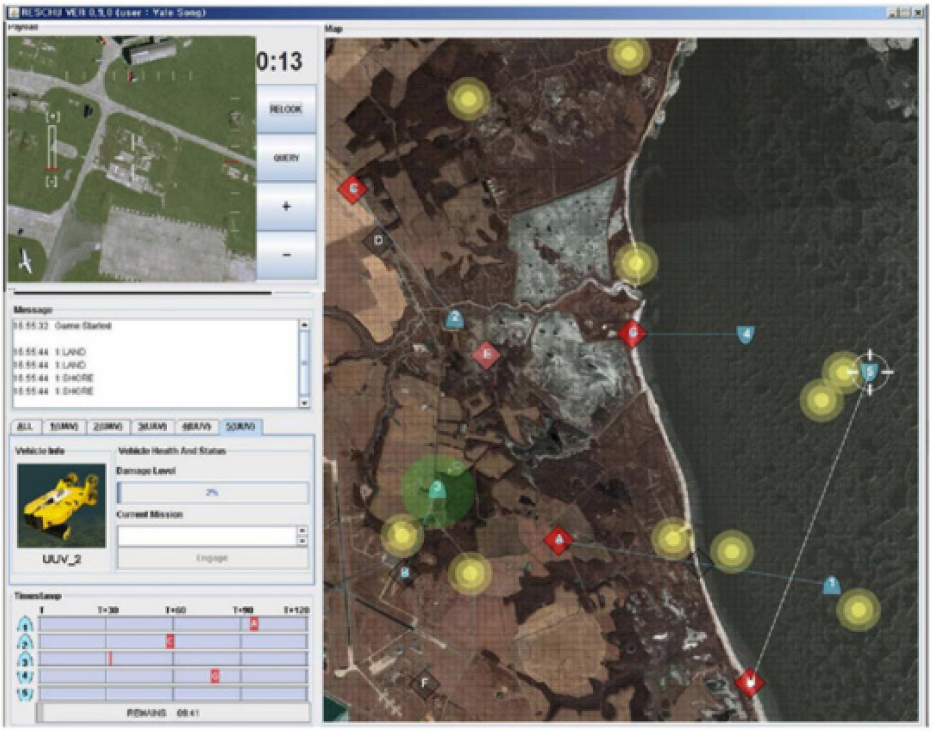

Figure 5: User interface studied by Lewis (2013)

The user interface (RESCHU) proposed by Michael Lewis focused on remote supervision of multiple robots with varied tasks. These tasks could range from foraging, that required little coordination between robots, to formation following. This user interface follows a study by Cunning et al. who developed the OPS-USERS system in 2010 which was used for search-and-rescue simulations.

This user interface has a map for navigation and a window for target search. The robots in this interface travel through a planned path and when they arrive at the target, the operator is required to search for this target locally using the simulated streaming video. This was one of the first interfaces that we studied that included the simultaneous use of the camera as well as a high-level map. The task timeline has the estimated arrival time and it allows for scheduling sensitive automation. The control panel provided by the user interface also allows the operator to see some information about the robot such as the damages on it or the amount of energy being used.

However, the UI was not designed specifically for fire incidents. Rather, it was for general search-and-rescue operations. This meant that we would have to select features from this user interface that only made sense for a fire incident. Additionally, the robots travel through pre-planned paths. Our interface does not take this as an assumption. Finally, we felt that the user-interface was very mission-oriented and had several features that were not necessary for our user interface. This was because our interface is only concerned with displaying information to a command operator about the events in an incident.

2.3.5 User Interface 4 by Schilling et al. (2004)

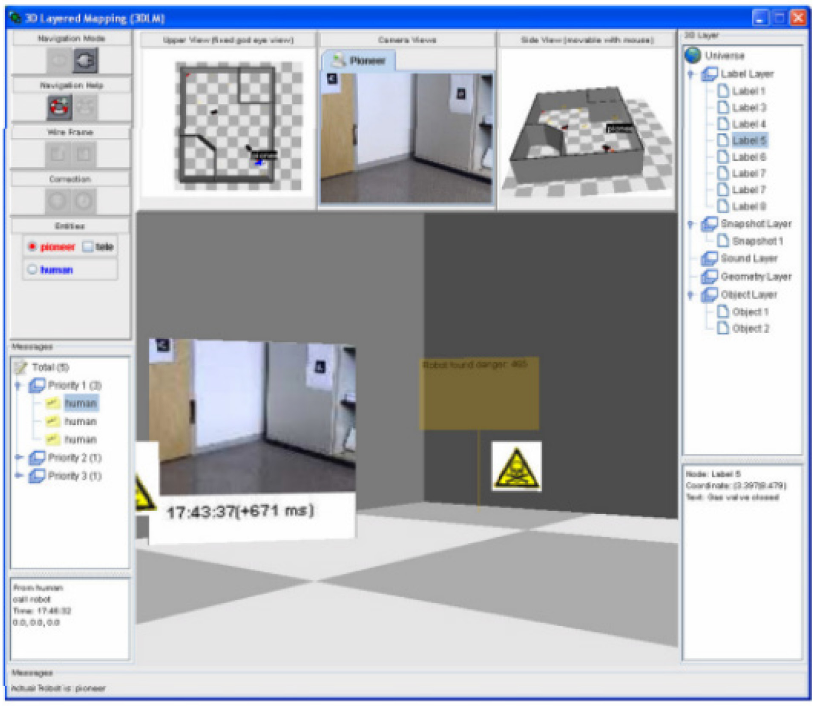

Figure 6: Mixed Reality Interface studied by Schilling et al. (2004)

Similar to our intention for the interface, the system studied by this paper was designed with the needs of a supervisor/command operator in mind who would be supervising a fire rescue team. The robots in this system send messages to the supervisor. These messages are prioritized based on their importance and therefore they are displayed corresponding to the priority levels. For example, some messages regarding a robot's health might occupy a lower priority than when a human member is asking for support. One important takeaway that this paper had was the following insight: “We also observed that a vital role of leaders on extreme teams was to share awareness information about the activities and positions of other team members. It was inefficient for team members to share this information because they did not know who would need it and they did not know how to convey the information from the perspective of the recipient.”

However, one of the challenges that the authors noted was that the usability of the interface required a lot of work. This observation was particularly true for the visualization shown in Figure 6.

3. Methodology

As outlined earlier, we decided to split up our project into the following objectives:

- Understand the context in which the user interface will be used
- Understand the limitations of existing user interfaces being used by firefighting teams.
- Develop mockup user interfaces and the corresponding prototype
- Make recommendations for future future full-fledged systems to be used in the field

In this section, we will be discussing the third objective i.e; the development of the mockup user interfaces and their corresponding prototype. In our work we took inspiration from video game UIs. Video game UIs share several aspects with supervisory interfaces for firefighting situations. These interfaces are designed to provide ease of use and efficient interactions in competitive contexts, which are characterized by the presence of dangerous conditions and the need for time-critical reactions and complex decision-making, albeit in a simulated scenario. We chose Dota 2 as the best design for our purpose. This game has been used in professional gaming tournaments and has been proven to have one of the most effective interface designs. Dota 2 is a multiplayer online battle arena (MOBA) video game. The game is played in matches between two teams of five players. Each player independently controls a powerful character, known as a "hero". These heroes have unique abilities and various styles of play. This design serves our purpose of having swarm robots working together in different teams to perform a mission in a fire incident.

This interface is focused on the player's hero and the surrounding area while the camera can be centered on the hero or moved around freely. Players also have the limited ability to zoom in and out. There are three windows that are always visible on the screen. One is a minimap of the whole area in the bottom left corner which includes all the team members and the opponents. Green dots represent the friendly units and structures and red dots represent the opposing team's units. Teammates are represented by Os and opponents are represented by arrows. The center Bottom window, the hero control console, shows Hero's information including the icon, the skills, levels and stats and the items the hero has. The hero control console has a minimized footprint on the screen, providing maximum vision of the map and terrain, while displaying the hero information. The rest of the windows are hidden and will become visible if the user selects the corresponding button. In the top left corner the user can see the pop-out window with the scoreboard and the list of all the players with their information. Additionally each hero's name, the current level, health and Mana status are on top of the character in the map.

Figure 7: Dota 2 gameplay

3.1 Mockup Interface Development

We created the mockups of our user interface to show the different features we have incorporated in our design. We analyzed the current user interfaces for search-and-rescue procedures in military and fire incidents. Dota 2's user interface combined with interfaces designed for robot and mission operations makes the perfect combination of usability and functionality. We took the best features of every framework that serve our goal and came up with the current design. This design has an intuitive user interface while it is simple enough to be used in a stressful fire incident. It also incorporates suggestions by Deputy chief Martin Dyer and the mission operators.

The main window of our UI is minimalistic to avoid data overload for the user. In a small window on the bottom left corner there is the complete map of the entire area. This idea was inspired from user interface 1 (Gancet et al., 2010). However, for better usability we moved the windows to the current location to keep the user's focus on the main map. A red rectangle shows where the bigger map in main window is relative to the complete map. The map on the main screen zooms in a specific area where the team of the firefighters and robots are located. The red hat symbols represent the firefighters and the robot symbols represent the robots involved in the mission. The bigger map can be zoomed in or out by the scroll button on the mouse or by using two fingers in case of a touch screen.

Figure 8: Minimap box mockup

The robots send different messages to the operator about the state of a robot or regarding the mission as a whole. The top 3 messages show up above the minimap window on a modal screen and disappear after 7 seconds. The idea is to have as little information as possible on the screen to avoid confusion and information overload for the operator. This section was inspired by Dota 2. This feature provides the necessary information to the user without getting in the way of the main task: operating the mission. If the operator wants to see all the messages, s/he can click on the message icon on the top right corner and a window will show all the messages in the order they were sent. Each message includes the date (month and day) and the time it was sent. The operator can scroll through the window and view all the messages. This feature was inspired from user interface 3 (Lewis, 2004) where it keeps a list of all the messages in a window on the left side. However, we believe that having the messages on the screen all the time can be distracting and unnecessary so the user can view this window only when needed.

Figure 9: Messages and communication mockup

In the bottom right corner there is a camera icon. If the user clicks on this icon the camera view will open in a small box. This shows the camera view of a specific robot selected by the operator. If no robot is selected it will randomly choose one of the robots. In the top-left corner there is an expand button which will switch the camera view with the map in the main window. If the operator wants to specifically look at an item or a location this will help him see it on the bigger screen. This idea of the having the camera view was inspired from User Interface 2 (Trouvain et al., 2003).

Figure 10: Camera Window mockup

On the top right corner there is a menu icon. By clicking on it the main menu of all the robots will open. In this window all the robots are listed with their assigned team, their battery and their status. The status represents whether the robot is used and involved in the incident or not with the colors green and red.

Figure 11: Robot menu mockup

The robots are initially not in any teams and work as individual robots. In which case they are under the unassigned category. The user can click on the colored box under the team column for each robot and assign the robot to a team. There will be no team initially and the user can create new teams. In the same way the user can change a robot's team. The menu including all the robots was inspired by Dota 2 where the users are categorized into teams. Similarly we can put our robots into teams and each team performs a specific mission during the incident. Each group is a swarm of robots that can be assigned a range of tasks such as searching for an item or person, collecting environmental information or moving an object.

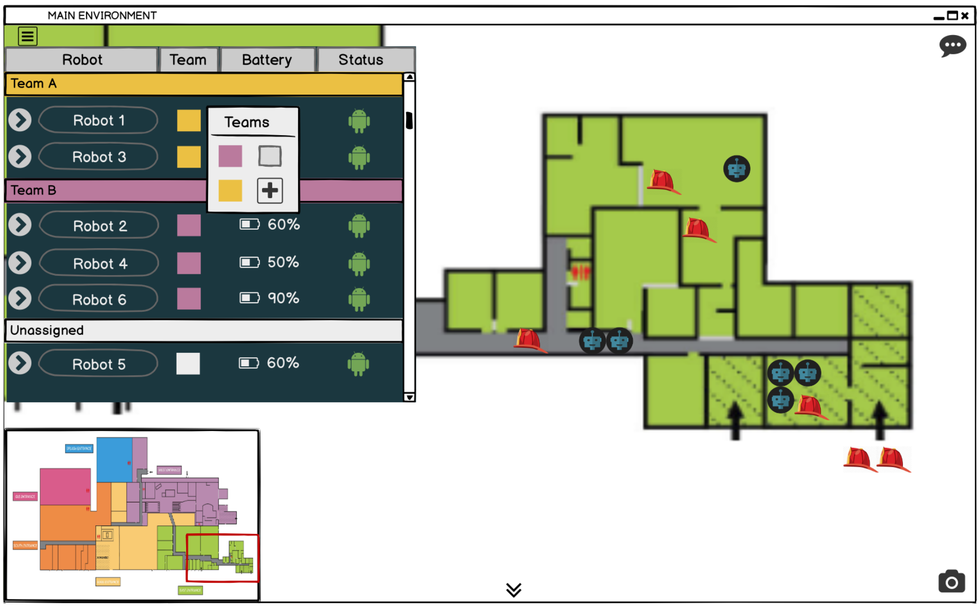

Figure 12: Team assignment 1 mockup

Figure 13: Team assignment 2 mockup

On the top there is a list of the labels for each column. Each label is a button if the user clicks on the robot label, the robot number for all the robots will appear as a little box on top of them or next to them on the map. The same happens for the battery and status. If the user clicks on the team label the color of the box showing their label will change to their team color. Whatever label the user chooses it will lay over the map by each robot. We were inspired to have layers from User Interface 4 (Schilling et al., 2004), but we realized that laying over this information on the map shows the information directly for each robot and the operator does not need to look for the corresponding information for each robot in a separate window. At the same time we made this feature optional, since the operator would be overloaded with too much unnecessary detail.

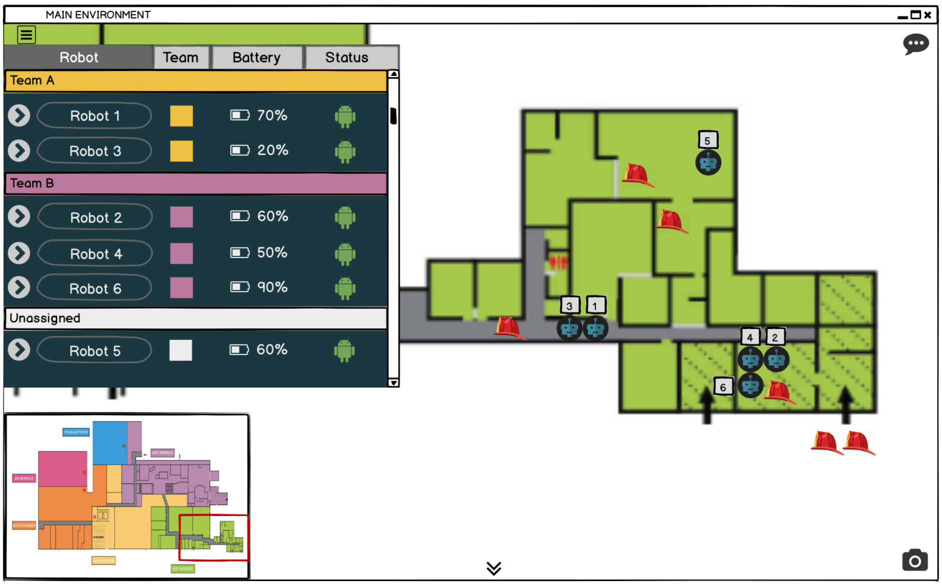

Figure 14: Robot name layover 1 mockup

The user, however, can choose a specific robot to display the labels on top of it. In that case, instead of clicking on the main label, the user can click on the specific robot's info to overlay the map.

Figure 15: Robot name layover 2 mockup

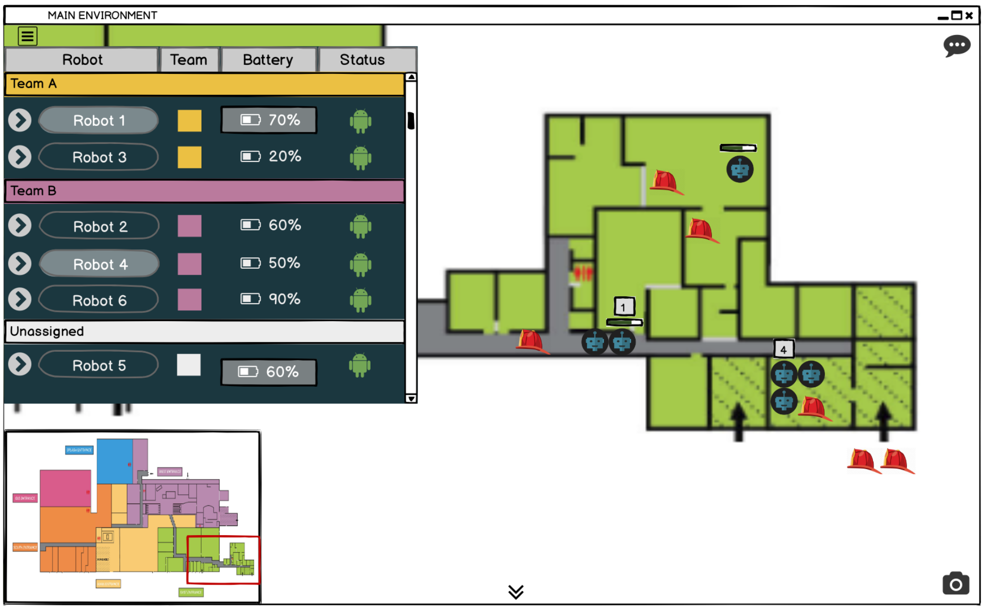

Figure 16: Battery layover mockup

Finally the user can click on the arrow button on the left side of each robot in the menu. This will select the specific robot. This is used to either see the specific robot's camera view or see the information the robot is sending to the operator. Whenever the robot is selected the screen will be centered on the robot. Those information can be seen by clicking on the double arrow icon in the center bottom of the screen. This button will open a little box specific to the robot and show information such as sensor data, coordinates of the robots location on the map, robot's connection quality and its health status. More items such as specific sensor status can be added. This window was inspired by user interface 5, Dota 2 where the user's character information is displayed.

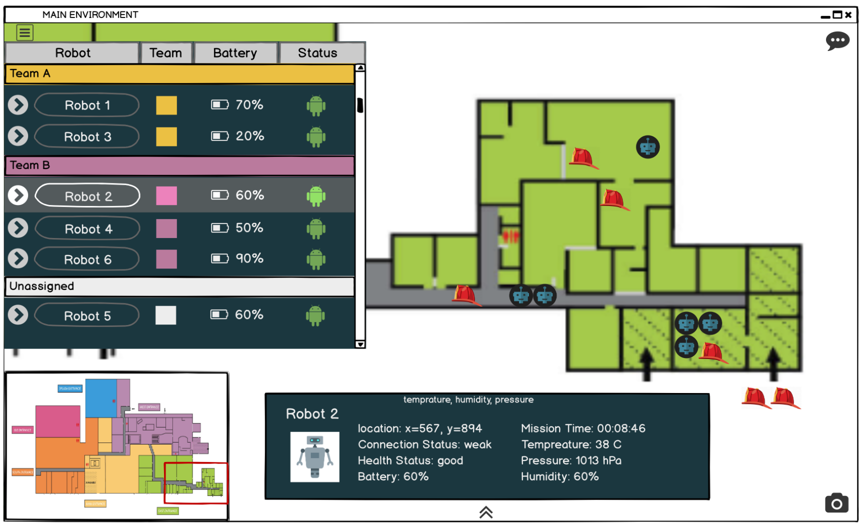

Figure 17: Robot selection and information mockup

3.2 Working Prototype Development[1]

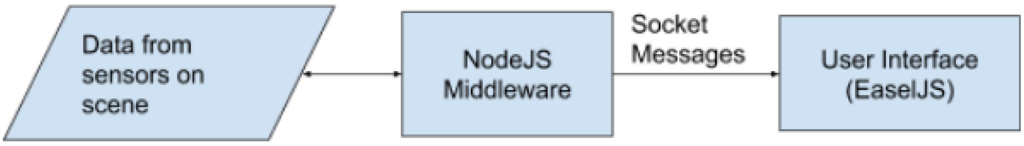

Figure 18: Data flow of the system

In order to build a working prototype of the proposed interface, we had to make several decisions regarding the types of software being used. Since the present application is meant to be used by firefighters at the site of any incident, we decided that our application would be targeted towards a tablet device while also allowing use on a traditional laptop with keyboard and mouse inputs. This decision to design our application towards a tablet/laptop interface, helped narrow down the range of software options available to us. We started with implementing the user interface in ReactJS where each window in the interface was a separate ReactJS element. This meant that we had to treat the map as a distinct window that was independent of the other windows in the image. Any updates made on the individual windows would propagate changes to the abstract "master-parent" class which would then reflect the changes wherever the state changed. This proved to be a challenge and seemed to be violating some of the React recommended rules (propagate state only down the component hierarchy). The map view was initially implemented as DOM elements that formed a grid structure. However, soon we came to the observation that the performance of the software was unsatisfactory. Next, we experimented with using SVG elements for the map graphics that would be manipulated via d3 selections. However, the performance of this system was also lacking. After a discussion, and several design changes to the user interface, we settled on making the entire window a HTML5 Canvas that would be controlled via EaselJS (EaselJS, n.d.).

[1] The program code for the working prototype is available at *https://github.com/kartikvasu/iqp* for reference.

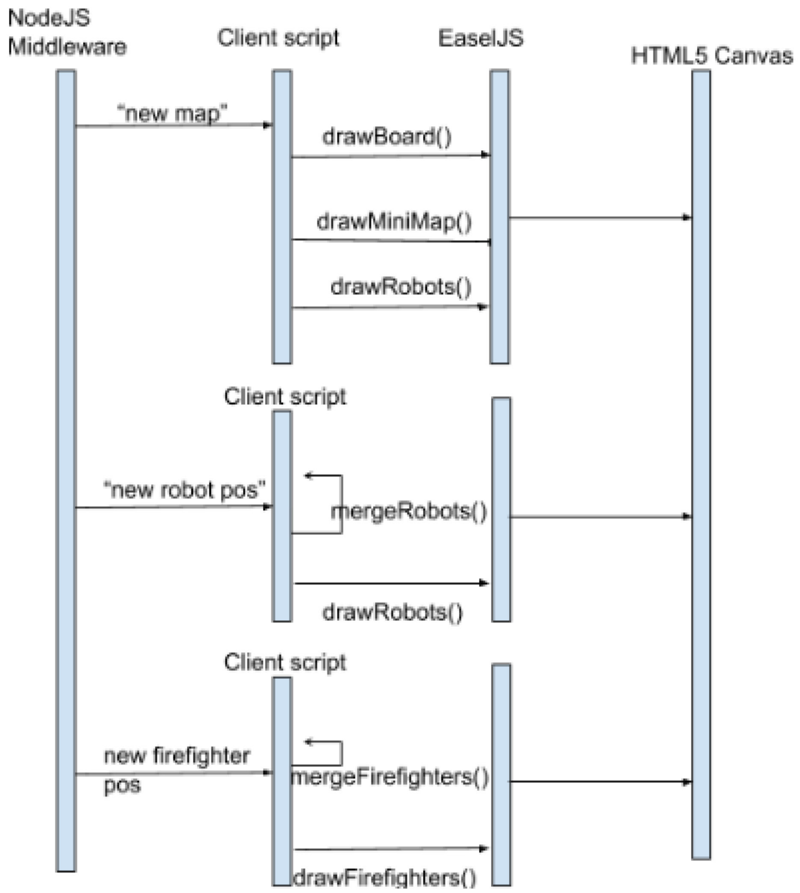

Figure 19: Flow of events in the system

We made use of EaselJS which provided an abstraction over HTML5 Canvas for the development of the front-end of the interface as well as ReactJS for some of the menu items on the interface. ReactJS also can be easily adapted to React Native code which is a popular interface design option chosen by many mobile developers. Our Web application server was NodeJS, and despite it being restricted to Unix operating systems, there exists several examples of its use in embedded systems (Node.js for Embedded Systems, n.d.). This ensured its versatility. The primary goal of the design of this software system is to test the effectiveness and demonstrate the overall user experience. In order to do this, we had to simulate data for a real-world situation. This involved writing a script that simulated a fire incident. This required us to implement the following:

1. A randomized map of the environment
2. A randomized simulation of robot movement within the map
3. Randomized robot messages being generated by the robots in the environment

Robot Map

The current implementation expects the server to send a socket message to the front-end during the initial load of the page with information about the environment in which the robots are in. The robot map was written as a graphic component consisting of several shapes within it. We used EaselJS to render the map and fill the entire screen with it. The entire environment is treated as a collection of objects with locations on the Canvas. This way, whenever a modification is made to the view, the re-render function only needs to look at the set of objects in the map in order to render it on the screen. At the same time, abstracting away the map metadata as a set objects with (x, y) locations is beneficial because incorporating a new map in the screen only needs a user to specify these objects and plug it into the server. This flexibility is important to have so that future implementations can simply replicate our render methods without many changes.

Robot Initialization and Movement

Similar to the way maps are treated by our system, robots are also represented as objects that are reported by the server. In the initial render of the map, the front-end expects a socket broadcast Robot movement has been broken down in steps of 1 second. This means that at each second, the map is updated with new robot positions. This also means that the script that we write has to stream robot position data to the user interface system every second. This is accomplished in an asynchronous manner using SocketIO.

4. Conclusions and Recommendations

After our literature reviews, interview, and the development of the working prototype, we saw a common principles that had to be followed when designing an interface:

- **Interface design must be a function of the user and the setting**

It is important to ensure a user-centric design. For example, in our interview with Deputy Chief Martin Dyer, we found that a lack of attention to the user's requirements and expectations, would lead to a complete abandonment of the system itself. This is also reflected in the reluctance of many of these personnel to adopt new technologies which often come with many unknowns (Appendix A).

- **Interface design must be simple, familiar, and intuitive**

Another important aspect of designing a user interface for firefighters is that these firefighters are already being inundated with a lot of information at the site of a fire. Any new variables that are being introduced into the process such as our intended device, must aim to minimize any further stress that it may cause. Introduction of a cluttered interface can increase stress (Shneiderman and Plaisant, 2010). Therefore, keeping the interface simple, familiar, and intuitive is essential to ensure its continued use.

Finally, we noticed a few important user interface elements that future developers of such an interface would want to keep in mind for their implementation.

- **Map View**

A well-designed map view was the most important user interface element that we found across all the user interfaces we studied. It is also very useful to have the map be navigable and its view easily altered in order for the intended user of the system to reorient themselves when operating the interface in a real setting. Given that our interface is designed for a supervisory setting, a map view helps give our user a more "big-picture" perspective of the scene.

- **Map Overlays**

Having only a map does little to help a supervisory member of personnel at the incident of a fire. It is important to have overlaid information on the map. This can include information such as the position of robots and firefighters within the structure where the operation is occurring. It can also mean overlaying the health information of robots or the information from specific sensors that are present in the site.

- **Camera View**

A camera view can be beneficial for a supervisor to get a better first-person view of a robot. This can be streamed via a camera on a robot for example. However, in order to prevent tunnel vision from occurring, which Deputy Chief Martin Dyer warned us against (Appendix A), it is important to have the camera view be secondary to the map view itself.

- **Minimap View**

Finally, given that any potential user interface is cannot possibly accommodate all possible structures within its window size, it is useful to have a minimap of the scene in the interface itself. This can help keep the user informed of events that might be occurring at locations that are outside the scope of the current window that he or she is viewing.

Future Work

Before our interface can be adopted in firefighting operations, it is important to conduct user-studies and test the interface out in mock scenarios. Given the high-risk, high-consequence nature of firefighting, it is not recommended to test potential designs prior to several design iterations completed through mock scenarios. It can also be helpful to build a fully native system of the software for the specific devices that firefighters would be comfortable using. The present prototype implementation heavily depends on existing frameworks and libraries that reduce the complexity of our code, but add some performance drawbacks to the application.

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Appendix A: Interview Transcript

Interviewer: MQP and IQP teams

Interviewee: Deputy Chief Martin Dyer, Worcester Fire Department

Interview Setting: Interview conducted in office of Atwater Kent.

(Start of interview)

Interviewer: In your experience which fire situations are the most difficult to handle? Are there some situations that make you more reluctant to send personnel?

Interviewee: It is a combination. Size of the fire along with the building both play a role. Used to a typical type of fire. Typical fire is a three-decker fire. Feel very comfortable with them. Probably don't need much technological intervention. An unusual building with "compartmentalization" that you would not expect is what raises the fear-factor.

Interviewer: So what sorts of buildings or is it parts of buildings that are most difficult to deal with?

Interviewee: It could be both. Worcester still has a large amount of old manufacturing buildings. We have a lot of different types of buildings in Worcester. What we have a lot of is a mish-mash of different types. A lot of these Type 4 and Type 5 buildings are being converted into different kinds of living spaces: offices, labs, etc. No idea what's going on behind the walls. Compartmentalization right now is very different than what it was designed for. We don't know what we are getting ourselves into.

Interviewer: Are there certain environments that are more likely to result in firefighter casualties?

Interviewee: Sure, again, compartmentalization. Example of Worcester Cold Storage. Lots of compartmentalization and firefighters were unaware of the lay of the land.

Interviewer: So real-time mapping would help.

Interviewee: So when I hear real-time mapping, I'm thinking having a map prior to the event itself and then overlaying on top of it. So I'm thinking that taking the mapping we have already done and maybe overlay firefighter positioning or whatever.

Interviewer: You mentioned the command board. What sort of tools and technologies does your team use on a regular basis?

Interviewee: So we start off with a clipboard at a fire initially, you know, keeping track for firefighter accountability. That's the first thing. If this is going to be a large incident, they then use a command board which is a large magnetic dry erase board where you can keep track of people. It is very physical. Negatives of that is there is no history that you are building. It would be great to have a history because it will help us with our training and after-actions. Because we can then reason about why things happened the way that they did happen. To give you a little bit more context to the whole thing. When the fire is playing out in real-time, you are just acting. And then afterwards you are relying on everyone's input and information.

Interviewer: We want to make this as appealing to you guys as we can so that it's as helpful for you as it can be. So what can we do when we're making a robot that's gathering information about the fire?

Interviewee: It's hard for me to imagine what's possible and what we don't have. I usually go down to the HAZMAT route when I start thinking about robots rather than structural firefighting. Fire services are like 20 years behind everyone else in the world.When it comes to technology we are still working on getting people comfortable with email. So yuo have to just be careful. We are blue collar workers. We are grunt workers that now require a little bit more technology than we did in the past. That becomes hard, convincing someone that robots can do something. In the structural environment, if we go defensive on the fire, if we don't go in and lob a ton of water. Eventually we have to go in to put the fires out to log events and such. Every bit of water we put in from outside makes it a little more dangerous to go into the building. Maybe some sort of robot that would be able to map the area for you and tell you what the building looks like and reports structure, and damage level and so on. Dangers would be hotspots, holes, ceilings and roofs that are unstable. From the HAZMAT perspective, most fire teams have a state department that has firefighters from all over the state that will respond to HAZMAT situations with enormous number of devices. [He then showed us one device that they use]. It can transmit data back out of the situation and just need to be dropped in. The problem with this is that, for me to get this information. They are meant to drop and go. We'll also use it for area monitoring. We will place these in certain areas and that will help our decision-making and how to respond and so on. A lot of cases requires us to go into the hot zone. This is a perfect example of where a robot could work. It weighs about 5 lbs. Interesting thing with the interface, with this is that the software, I've never once to this system to work. Where I can get it all to come on board and you are seeing everything appropriately. And it's a hard interface in general. You are taking firefighters that are not well-versed with technology to begin with and you give them a difficult interface. I think it's important that the interface should be what they're using everyday, like with their cell phones and your simple apps everyday. That's really what these interfaces should be like for them to have to work.

Interviewer: So it's not familiar to them?

Interviewee: Exactly.

Interviewer: If for instance we had something that integrates with a cellphone and its an app, that is something sophisticated but to you it just feels like an app. That would be a good starting point?

Interviewee: The talent is unbelievable but there is still a resistance to use technology. Every truck has an iPad. It's just that introducing a new technological change has to be done carefully and thoughtfully.

Interviewee: We are using a program called Public Eye so our dispatch system, it automatically assigns which units re going to be going. It will show you the hydrants. We have the capability to show you dangerous buildings and such. A software company called Zico provides this.

Interviewer: Are there any situations you think that happen commonly but that doesn't happen here in Worcester?

Interviewee: Obviously wildfires are a whole different ball game. I think we are unique in that we have a lot of the aforementioned three decker fires. Obviously, going to New York City and places like that, the high-rise problem is different than what we face here. Firefighting is pretty similar from place to place. The fire service is really good at adapting to whatever challenge presents itself.

Interviewer: I'm going to review the main points of our project and curious if any of them stand out individually. Small driving robot that locates fire. Detects human presence. Detecting dangerous conditions.

Interviewee: So detecting human presence not a bad idea. You are doing a virtual search of the building. Mapping depending on the situation it could benefit. Two parts that scare me. 1 it's fast. Depending on which truck I'm in, I'm already planning an action. You're already going through these actions you start on one task complete it and find the next task you have to work on. You are attacking the situation fast, so now I'm thinking of deploying the robot. The fire is growing exponentially. If the robot is actually slowing me down, it hurts the situation more than it helps me. I guess I kind of see these as good applications. But for that off-shoot fire, where it doesn't happen often.

Interviewer: Imagine that you enter with a small group of firefighters initially, and you could deploy the robot to map the place initially and it goes off and maps the region without you. Would that be helpful?

Interviewee: I think so. It's hard for me to envision that. But it probably could be done. We're not arriving with a van of data analysts with us. When you first get to that fire scene, you are task overloaded. The visual stimulants and all that stuff. Have to be careful about the way that you present additional information that may or may not be usable.

Interviewer: What if this information is presented on the outside for instance you, managing the situation. So it's not for the firefighters but for you without intervening in the situation.

Interviewee: yes, I think that is helpful. The more information that you have the better. We have the people that respond to the fires, I don't generally respond. But I listen to every fire. Im on Public Eye listening to information being dispatched. The guy on the street might not be using that information. But I might use it. We should move the department and think about the next generation of command operators.

Interviewer: Is there anything else we should know before we proceed with firefighting?

Interviewee: Just the environment that the robot would be going into. It's very unpredictable. High heat, low visibility, you have to have some kind of way to overcome these things. Whatever it is that happens, it becomes hard.

Interviewer: We're looking at technology from a more general perspective and what possible direction we can take technology in. Specifically in improving the lives of firefighters in dangerous situations, in terms of removing parts of the equation for them to deal with. Do you think there's any part of the firefighting process that's too dangerous to replace with technology?

Interviewee: That's a hard question. It's always going to be a people-based system. You always have firefighters. One thing I get nervous about is people getting too dependent on technology and it inhibiting their decision making process. Lack of experience. Being very careful of getting a tunnel-vision and missing the big picture. We worked with someone that's working on a thermal imager. One thing that's worrisome is focusing on only the thermal imager and getting into a tunnel vision. If that's always in my eye, how does that change my actions.

Interviewer: Do you think there's any part that's very tedious and can be replaced with technology?

Interviewee: The problem now is before the fireground. Most software systems, are built for police departments. Fire departments are the forgotten stepchild. It's very hard to get really good interface programs that will graph the data that's available. We'd love to have a program that assesses data and translate that into our systems. Now when we pull up to a fire, I'm telling everyone else that this is a type 3 building just by what I'm seeing. But I don't have any historical knowledge of that building or what's changed over time and what not. That information should be so easily garnered and delivered to us but its not. It's the hardest problem we have now. If we look at line of duty deaths in situations, it always come down to, the fire department could have had more information that they did not have.

Interviewer; What would you say is the obstacle here?

Interviewee: It's people making good programming and money.

Interviewer: So there's no financial incentive to building these things?

Interviewee: There's people out there that are doing it, they just don't do it well. The integration of the data is the other part of it. I could grab a lot of data from the assessors office. Basically we want an if-then statement, that shows us what type of a building it is.

Interviewer: Was it related to what the city had?

Interviewee: It's a completely different type of database. Which I'm sure is a problem that could be solved but going through all of these buildings in Worcester is- we don't have the manpower for that.

Interviewer: Did anybody ever ask you about the interface? Are you the victim of this interface?

Interviewee: We are pretty much the victim of the interface. We're vetting new companies right now and they have all the promises in the world. But usually, it does not work in practice.

Interviewer: By the way if we make an interface, can we ask you about it?

Interviewee: Of course.

Interviewer: Do you think specifically with respect to stress there's something that technology can help with?

Interviewee: There's people out there that offer things like heart monitors and stuff like that. We don't have a van of data analysts. Where that has a place is after the incident. Where we can look at this to analyze. We had a very hot situation recently it was a very big fire. The guys handled it really well. I was at home I shut my radio off and I got an alert that told me that 2 firefighters were being taken to the hospital from the scene. During the overall process, guys that were heavily involved during the initial attack, went out, got a drink and then got back to work. They worked too hard on a hot day. I look at that as failure of command. We failed by not making sure that this person had the appropriate rehab and did not get hurt. That kind of information having it after the fact, helps you make better decisions and avoid a little bit of oversight.

Interviewer: If we had devices just for the sake of getting information and show you for analysis.

Interviewee: Right, we don't have that at the moment but that would help. We have a policy that disallows cameras. First it's a department issue. You have to be careful who's wearing what.

Interviewer: When was the last time you had a negative experience when you were involved in an incident and do you think that particular information could have helped that situation. What is the information you wish you had in some particularly dangerous situations.

Interviewee: A few years back there was a 2 family house which should have been an easy fire for us but almost killed 3 people. But conditions deteriorated in that building very quickly that it was not normal for that particular situation. It turns out that there was a lot more flammable material in the area than normal it created a much thicker smoke situation. An increasing intensity of heat. That's an example where you have some robot that you throw in and it sends back information.

Interviewer: Let's say it's not a robot that you can throw and someone outside can tell. It's something with a simple interface that does not interfere.

Interviewee: The simple interface that I do not have to necessarily monitor.

Interviewer: How long does it take a firefighter to set up the gear?

Interviewee: It depends on the firefighter and the severity of the event. For the initial heat it is pretty fast. It usually takes 30 seconds.

Interviewer: How helpful would it be if we had a way to assess the structural integrity of the buildings?

Interviewee: That would be great, but how would you do it? There are many components to it. We would love to have an idea of a structural integrity. Worcester has an old housing stock. Each snow season, we have 60-80 inches of snow. How does it affect the integrity of buildings? That kind of information would be great.

Interviewee: I would like to mention that my answers are very specific to Worcester. We run a very aggressive department and we send a lot of resources to each fire. We send 9 units to every reported incident. What works for us may not work for other departments.

Interviewer: If we were to interview someone with a different experience from you to understand how to have a positive impact, what kind of a fire department would you contact, a small one or a big one.

Interviewee: We are mid-sized department. I would suggest both, a rural department and departments in New York, Boston. See how they operate. I can email you some contacts.

Interviewer: How long did it take to introduce tablets into fire trucks?

Interviewee: I started the project in 2013. We had several software failures. We worked with our current vendor. We had to develop the program first and then we tested it using regular laptops, which is what police have. We tried different things to fix issues but it failed. It walked us through the development of the process showed that you have to go through trial and error process. Some people are upset about a failure. We have to keep it through the different iterations of the progress. The part of our problem is not just the software, it is the networking and network security issue. Our technical services department is the one to have a progress. I understand where all security concerns are coming from, but we have to overcome those to make it usable for the people on the field.

Interviewer: How many trucks do you have, how many devices did you buy?

Interviewee: We bought 25. We have 21 frontline apparatus, each one of those has it. Safety officers have it.

Interviewer: Thinking about the cost of the technology that will be built, what is the order of magnitude that the fire department can afford?

Interviewee: We make a case. Usually in 10,000$ dollar range we can make it happen. Above that it gets a lot harder. Our department is personnel based, heavy on labor. We have 40 million $ budget, 38 of which is salary. That gives 2 million to equip, prepare etc.

Interviewer: Thank you so much for your help, it has been really useful.

Interviewee: Anything I can help you with. Do not hesitate to email and contact me.

Appendix B: Working Prototype

Figure 20: Minimap prototype

Figure 21: Robot menu and messages prototype

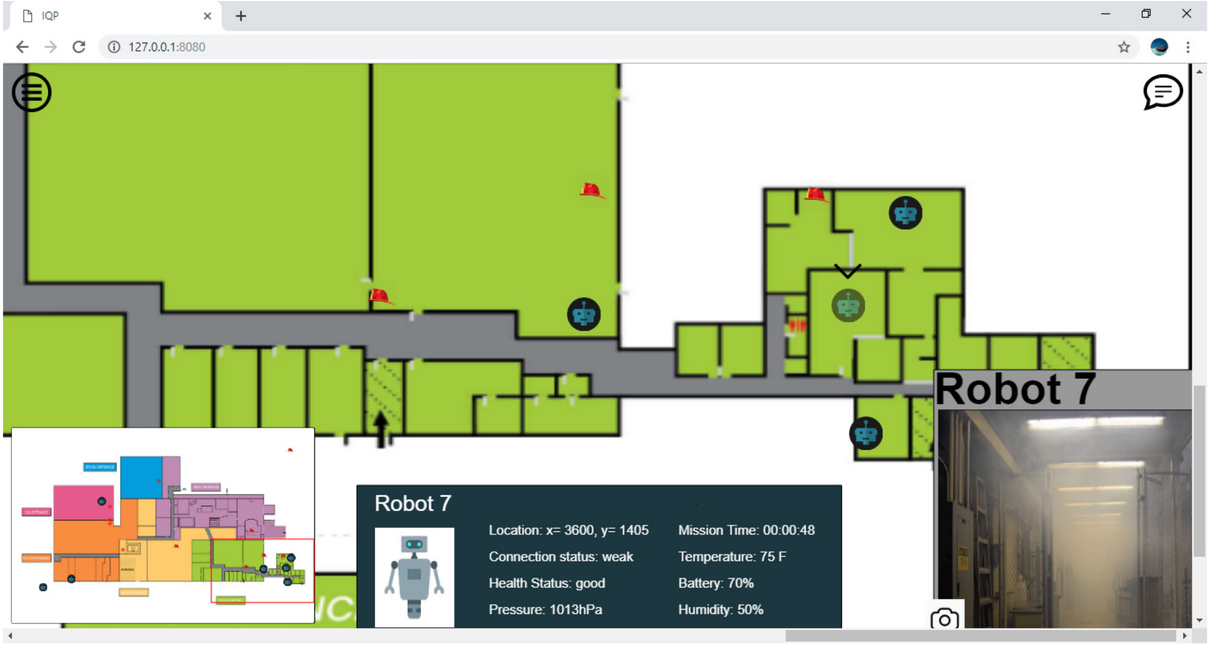

Figure 22: Robot information and camera window prototype

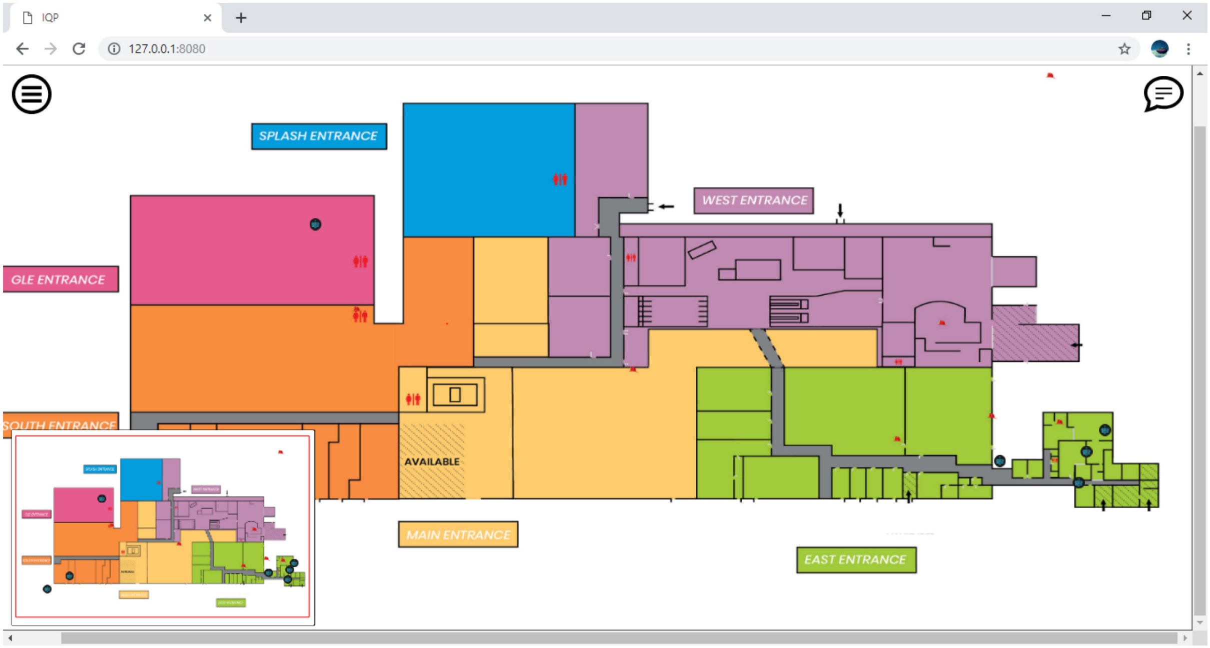

Figure 23: Map zoomed out prototype