LocATER: Localization and Accountability Technologies for Emergency Responders

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Abstract—**Over the last decade, there have been several unsuccessful attempts to commercialize indoor localization technology for emergency responders mainly due to a poor product-market fit. This paper describes in detail the findings and conclusions of NSF Innovation Corps (I-Corps) Team 735 (Customer Discovery for Field-Deployable Indoor Localization Technology), part of the Spring 2016 DC-area cohort. As part of the I-Corps curriculum, the team interviewed over 100 relevant stakeholders to better understand the challenges facing the successful commercialization of indoor localization technologies. Throughout the course of these interviews, it became evident that the current solutions available commercially and in research environments did not meet all the requirements needed for effective response in challenging indoor environments. In addition, it is clear that previously demonstrated localization capabilities are sufficient to meet the technical requirements demanded by emergency response scenarios, but have previously not been unified in a holistic system that can be successfully introduced to the market.**

Fig. 1. The view across the Charles River on Mar. 26, 2014 showing the scale of the fire and blustery winds which contributed to the massive 9 alarm blaze on Beacon St.

I. Introduction

March 26, 2014 was a blustery winter day in Boston. The brownstone buildings overlooking the Charles River stood as they have since the 19th century. At 2:41pm, fire alarm box 1579 sent a distress signal to the communications center of the Boston Fire Department starting a sequence of events that would be forever seared in the memories of local community members. At 2:45pm, firefighters from Engine 33 storm into the basement of 298 Beacon St. to find the source of the fire. Only 4 minutes later, at 2:49pm, the mayday radio call comes through. The firefighters in the basement are trapped by the fire with no way out. They call for water to be turned on to the fire hoses they have pulled into the basement, but they are unaware that the fire has burned through them, and they are useless. Their colleagues bravely try to run new, larger fire houses into the basement, but they are met with fierce flames fanned by the winds on that fateful day. Figure 1 shows the scale of the fire. At 3:10pm only 25 minutes after first responding, the deputy fire chief Joseph Finn and acting incident commander deems the fire too dangerous, calls for all firefighters to evacuate the building, and assume defensive firefighting procedures. At 3:15pm, 3:21pm, and 4:14pm, the fire dispatcher makes calls asking if all members have been accounted for. Even an hour after the incident commander ordered an evacuation, dispatch was not able to account for all firefighters at the fireground. That day Boston Fire lost Lieutenant Edward Walsh and Firefighter Michael Kennedy.

During the 2014 Beacon St. fire, despite the modern equipment and dedicated communication center Boston Fire has at its disposal, it took 38 minutes to complete a personal accountability report (PAR) check. A PAR check is essentially a headcount to find out if anyone is missing. Boston Fire normally does PAR checks every 20 minutes during a large incident, but that is impossible if the check itself takes almost double that time. Unfortunately, PAR checks taking longer than 20 minutes are not an uncommon problem at large multialarm fires. On that day, then Deputy Chief Finn was the incident commander and his officers were unsure of who was missing for too long. Chief Finn had to make the most difficult decision of when to scale back rescue efforts based on his years of experience and intuition. Today Finn is Commissioner and Chief of Department at Boston Fire Department and an important champion of improving firefighter safety.

This paper focuses on translating our prior research on localization and navigation of robots in space exploration, assistive, and disaster response environments, to develop a localization and PAR check system integrated within the current gear that firefighters carry. All of these localization efforts have one thing in common: a lack of reliable external reference such as GPS or other predeployed architecture.

As part of our prior research, we have performed a literature survey covering (i) human-motion detection systems especially

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for pose and gait detection and identification, (ii) multi-modal indoor localization systems including IMU-lidar, IMU-camera systems, and IMU-RF systems, and (iii) GPS-less localization algorithms including EKF-based, probabilistic methods and visual SLAM. Competition in the indoor localization space exists but relies either on external infrastructure not amendable to firefighting (NextNav) or is cost prohibitive (TRX Systems), severely limiting adoption within the firefighting community. A localization system that meets the needs of the firefighting community and does not rely on existing infrastructure currently does not exist commercially or in a research setting.

Previous efforts to tackle this problem *are not well aligned with the core needs of the firefighter service, and therefore are on a path to failure.* Current indoor localization efforts assume that the person of interest to track is standing, walking, running, etc. Firefighters, especially in large fires, rarely stand, instead choosing to crawl or walk low to the ground. Our research will focus on adapting our previous efforts in localization algorithms and approaches to be *aware of the way* that firefighters move, reducing tracking error and ultimately reducing cost by eliminating the need for expensive sensor suites.

II. Requirements and Needs

Accurate geolocation in GPS-less environments, particularly inside structures, is one of the two highest priority first responder gaps as reported in multiple working group publications such as Project Responder 4 [1]. During a catastrophic incident, responders operating indoors or over an extensive geographic area without adequate knowledge of the hazards and threats are subject to physical and operational vulnerabilities. Team safety and efficiency relies directly on the location and orientation of each team member. Among other concerns, if the responder is incapacitated, it is imperative to know their location to initiate a rescue operation. Operations in high signal interference areas such as cities, rugged terrain, forest, or indoor spaces deliver intermittent or no GPS signal.

Currently, agencies do not have the capability for real-time automated geolocation of responders on the incident scene. Responders often transmit their location coordinates verbally, using hand-held radios. Most real-time geolocation solutions require the responder to wear a device that broadcasts global positioning system (GPS) coordinates. These signals are not powerful enough to penetrate building walls or even a thin piece of metal, which makes indoor and below ground geolocation very difficult, even with the most sophisticated technology available. Even if a responder knows his or her own GPS coordinates, they must then be transmitted in real time to incident command. Incident commanders generally rely on the last known position (as communicated by the responder or approximated based on tasking) to identify the location of personnel in GPS-denied environments, such as inside buildings. In an emergency situation, it is possible to 'ping' the smartphones carried by many responders to identify their last known position. However, because GPS signals are obstructed indoors, this position may be temporally and geographically out of date. The ability to geolocate responders using a field deployed system would greatly improve the safety of emergency responders and is an excellent example use case of the proposed technology.

Indoor localization for first-responders using multi-modal sensor technologies has been the focus of research and technology development in the past few decades [2]–[6]. [6], [7] provide an in-depth overview of existing localization technologies on their applicability to first responders. It is reported by the 2008 NIST report that first responders strongly demand an indoor tracking system with the following characteristics, (i) location accuracy of 1m, (ii) functionality in all kinds of buildings, (iii) restricted to existing equipment used on site during missions, (iv) requiring minimal training, (v) reliable operation against structural changes, and (vi) cost-effective. Moreover, wearable systems must abide with size, weight, and power restrictions. Existing localization implementations primarily rely on angulation (angle measurements), lateration (distance measurements), fingerprinting (feature matching), inertial and motion sensors and analysis of connectivity. IMU-based techniques have the advantages of being independent of the infrastructure surrounding the first responders, and they do not suffer from multi-path signal propagation. However, the main problem associated with IMU-based techniques is that measurement inaccuracies in acceleration lead to increasing drift errors in localization estimates. In order to mitigate this shortfall, IMU-based techniques have been augmented with visual sensor modalities such as cameras (monocular or stereoscopic) or range sensors. However, these systems require more computational power on board. Furthermore, their accuracy suffers from unsteady motions of the first responders.

Over the course of the I-Corps experience, our team interviewed over 100 firefighters, lieutenants/captains, chiefs, municipal civil servants, manufacturers of firefighting equipment, and regulators from the National Fire Protection Association (NFPA)and Underwriters Laboratories (UL). These interviews significantly changed what we thought were the needs of the firefighting market in terms of indoor localization. After the set of interviews, we realized that firefighters have a significant need for indoor localization, but the localization itself does not need to be all that accurate as long as the floor or elevation of the localization is accurate, as shown in Fig. 2. The most important piece of information about where firefighters are located is their elevation, basically what floor they are on. The ability to tell which quadrant of the building they are on would also be beneficial, but beyond that level of accuracy the benefits do not increase drastically, while the cost associated with systems to deliver that accurate does.

In addition to the localization needs, we discovered that many fire departments have issues with the length of time PAR checks take, with multialarm fires regularly resulting in PAR checks in excess of 20 minutes. The NFPA recommends the checks be done every 20 minutes. This means that at large fires a significant amount of radio traffic is dealing with just PAR checks. The worst part is that if someone is missing or in distress, it may take the entire process of elimination of

Fig. 2. By intervieweing over 100 firefighters, lieutenants/captains, chiefs, municipal civil servants, manufacturers of firefighting equipment, and regulators from the National Fire Protection Association (NFPA)and Underwriters Laboratories (UL), we realized that localization to 3ft accuracy in all cardinal directions (top) is unnecessary, and providing accurate floor and quadrant localization (botton) would be highly beneficial for incident commanders.

the PAR check to figure out who exactly is missing, as was the case in the 2014 Beacon Street fire. The market needs a solution that can streamline PAR checks so that they take less time, more quickly determine who needs help, and ultimately free up radio time to focus on firefighting efforts, not keeping track of firefighters. *As a result, the need quickly emerged for a wearable technology with two main functionalities: (i) the ability to accurately localize firefighters inside a burning building to a quadrant and floor and (ii) provide a method for firefighters to quickly complete a PAR check, reducing radio traffic and overhead associated with PAR checks.*

III. Lesson's Learned through I-Corps Program

The Project Responder 4 Report outlines the applicable goals that are critical for any localization system to be used by first responders. Throughout the process of interacting with firefighters and fire chiefs, we determined that all but one of these requirements are valid requirements, and the accuracy requirement may be relaxed to accuracy on the order of floor and quadrant.

A valid question exists as to why the localization accuracy requirements can be relaxed, and the system will still meet the requirements demanded by the application. The answer is difficult to discover, but trivial to explain. When a group of leaders come together to set out guidelines for future development, such as in the Project Responder 4 workshops, the specifications naturally converge to more and more stringent ones during discussions. In addition, these workshops gathered high level officials and leadership from fire departments, not the operations chiefs, incident commanders, officers, and lieutenants who actually fight fires. It is apparent in talking to those people that the accuracy requirements were lost in translation when discussing the possibility of having to tell which side of 4 cornered intersection a first responder is located in, a rare situation that is taken care of by existing search methods the rescue teams already employ.

Fig. 3. Offensive firefighting (left) focuses on aggressively attacking the fire in order to save people or reduce damages to property. Defensive firefighting (right) focuses on preventing the spread of fire and reducing risk to personell. The incident commander in charge at the scene has to make the decision when to switch to defensive firefighting based on experience and intuition in a highly fluid and rapidly evolving scene.

The 2nd most important decision an incident commander at a large-scale fire has to determine is at what point to switch from offensive firefighting, actively attempting to suppress the fire and save the structure, to defensive firefighting, standing back and putting as much water on the fire from a safe distance, as shown in Fig. 3. The absolutely most important decision, when do rescue efforts (trying to save a firefighter in distress) switch to recovery efforts (they cannot be saved and no more lives should be risked), is closely related to the previous decision. Currently, this decision is made on the basis of years of experience and intuitive understanding of where the venting teams, suppression teams, and rescue teams are within the structure. Our research aims to provide a tool to the incident commander that allows them to make that decision based on more metrics, and less guessing.

One of the most important technical challenges is adding the altitude or elevation information to the localization information in a cost effective manner. It is possible to use a combination of proprioceptive sensor data about how the firefighters are moving through the building and barometric pressure sensors to add the 3rd dimension to the localization data. If a model can be created for the pressure differentials that are sensed, pressure changes throughout a building can be aggregated as collected by the firefighters localization modules, and track their elevation throughout the building. In addition, we have already started preliminary studies to integrate data from accelerometers and gyroscopes, already used for the EKF, to detect if firefighters are crawling/walking over flat terrain or stairs. This semantic information can be used to deduce if elevation changes should be expected depending on the way the firefighters are moving, further reducing the drift that is inherent in inertial localization approaches.

Finally, the last aspect of the system does not present any technical challenges, but provides immense value to the incident commander. A button or other similar interface will be integrated that allows the firefighter to complete a PAR check, checking in and informing the incident commander they are accounted for, without having to stop their current action such as dragging a hose, helping a fellow firefighter, or using an axe for example. This addition will significantly reduce radio traffic due to PAR checks and allow the incident commander to more quickly determine if anyone is in trouble and how to best help them.

IV. Future Work and Conclusions

One of the key challenges that would potentially hinder successful commercialization of indoor localization technology is integration into existing firefighting equipment. Due to safety concerns related to overloading of firefighters, the fire departments and fire unions are very hesitant to the addition of new equipment to firefighters. Therefore our system would need to be integrated within an existing piece of equipment either as an add-on or from the manufacturers themselves for the best chance of commercialization success.

We have identified the most likely candidate for integration as the SCBA, which is the breathing apparatus used by the firefighters to provide fresh air in smoke filled environments. The reason is that SCBAs from MSA and Scott, who cover over 90% of the US SCBA market, already are beginning to implement some limited communications capabilities, and are replaced by fire departments on a regular basis to include new safety features. The SCBA is easily accessible to the firefighter and already includes smart technologies such as PASS devices which sound an alarm if the firefighter stops moving for a given period of time. Addition of new capabilities and technologies in the SCBA will not be unprecedented or surprising to both fire departments and firefighters.

We have identified the relevant stakeholders whose input is critical to successfully transitioning this technology from research labs to use in real-world situations, as shown in Fig. 4. We mapped the people who help make decisions for various fire departments of sizes ranging from just a handful of people to several thousand strong. In addition, the process for approving budget line-items also reveals important stakeholders who would be needed to help introduce localization technology to new departments. Future work needs to focus on engaging these people to better understand the institutional and bureaucratic challenges that may hinder the adoption of localization technology.

Once the large fire departments have proven a piece of technology, the fire departments in the suburban areas of those cities will naturally start to invest in the same technology because of the existing mutual aid agreements in addition to traditional word of mouth marketing. This structure means successful real world introduction of the technology hinges on the ability to convince the larger "beacon" departments in the metropolitan areas to adopt the technology. FDNY is also key fire department acting as a technology evangelist for the firefighting community. Once FDNY adopts a technology across their whole department, fire departments across the whole country consider purchasing the same type of technology.

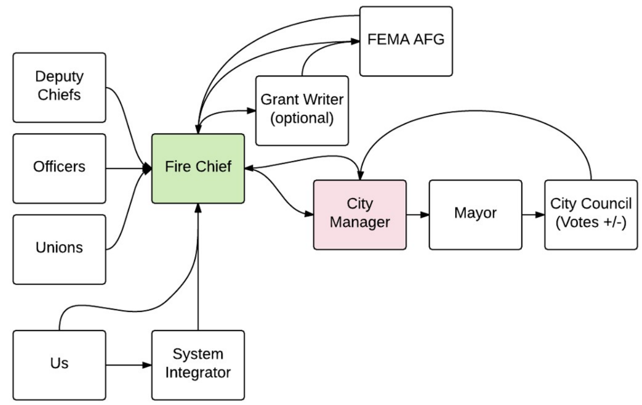

Fig. 4. There are several relevant stakeholders that all need to be engaged in order to successfully transition localization technology from research labs to the real-world. These relevant stakeholders are identified by tracking how decisions and line items for new technology are made by various different fire departments.

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