NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

GUIDED SEARCH: EXPLORING TECHNOLOGICAL SOLUTIONS FOR INTERIOR NAVIGATION IN THE STRUCTURAL FIRE ENVIRONMENT

by

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September 2019

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE September 2019	3. REPORT TYPE AND DATES COVERED Master's thesis

4. TITLE AND SUBTITLE GUIDED SEARCH: EXPLORING TECHNOLOGICAL SOLUTIONS FOR INTERIOR NAVIGATION IN THE STRUCTURAL FIRE ENVIRONMENT	5. FUNDING NUMBERS
6. AUTHOR(S) Kenneth A. Pravetz	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	12b. DISTRIBUTION CODE A

13. ABSTRACT (maximum 200 words)

The structural fire environment is hazardous and challenging to firefighters who are operating in unknown locations with zero visibility. Many firefighters lose spatial awareness and get lost, leading to inefficient operations as well as deaths and injuries. This research was designed to reveal which technology has the highest potential to provide interior navigation for firefighters in such an environment. This thesis used the exploratory research method to identify and appraise existing indoor navigation technology. The mission model canvas was applied to determine the business potential of each alternative and identified one potential solution to the problem that is a good market fit and has a high chance of adoption. Spectral image fusion technology augments spatial awareness and will help firefighters perform more efficiently. However, this technology will not provide navigation, so it is an incremental enhancement to the existing thermal image capability. Terrestrial transmitters are likely to have high adoption rates, appear able to achieve the mission, and are a viable solution. This thesis recommends that the fire service continue to push for more evaluation and testing of terrestrial transmitters. Fire service leaders should work with and encourage vendors to set up trials to develop additional interior navigation solutions that can be implemented.

14. SUBJECT TERMS technology, indoor navigation, public safety, emergency management, firefighting, situational awareness, augmented reality, spatial awareness	15. NUMBER OF PAGES 117
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

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GUIDED SEARCH: EXPLORING TECHNOLOGICAL SOLUTIONS FOR INTERIOR NAVIGATION IN THE STRUCTURAL FIRE ENVIRONMENT

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Submitted in partial fulfillment of the
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MASTER OF ARTS IN SECURITY STUDIES
(HOMELAND SECURITY AND DEFENSE)

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

The structural fire environment is hazardous and challenging to firefighters who are operating in unknown locations with zero visibility. Many firefighters lose spatial awareness and get lost, leading to inefficient operations as well as deaths and injuries. This research was designed to reveal which technology has the highest potential to provide interior navigation for firefighters in such an environment. This thesis used the exploratory research method to identify and appraise existing indoor navigation technology. The mission model canvas was applied to determine the business potential of each alternative and identified one potential solution to the problem that is a good market fit and has a high chance of adoption. Spectral image fusion technology augments spatial awareness and will help firefighters perform more efficiently. However, this technology will not provide navigation, so it is an incremental enhancement to the existing thermal image capability. Terrestrial transmitters are likely to have high adoption rates, appear able to achieve the mission, and are a viable solution. This thesis recommends that the fire service continue to push for more evaluation and testing of terrestrial transmitters. Fire service leaders should work with and encourage vendors to set up trials to develop additional interior navigation solutions that can be implemented.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three dimensional
AP	access point
BLE	Bluetooth low energy
BMC	business model canvas
CAD	computer-aided design
DHS	Department of Homeland Security
EPC	electronic product code
GDP	gross domestic product
GPS	Global Positioning System
HF	high frequency
IEEE	Institute of Electrical and Electronics Engineers
ISO	Insurance Service Organization
LODD	line-of-duty death
LPS	local positioning system
MBS	Metropolitan Beacon System
MMC	mission model canvas
NFPA	National Fire Protection Association
OSHA	Occupational Safety and Health Administration
PCII	Protected Critical Infrastructure Information
PDR	pedestrian dead reckoning
RF	radio frequency
RFID	radio-frequency identification
RSS	received signal strength
SA	situational awareness
SCBA	self-contained breathing apparatus
SSID	service set identifier
TDOA	time difference of arrival
UHF	ultra-high frequency
VR	virtual reality
VSL	value of statistical life

WAP	wireless access point
Wi-Fi	wireless fidelity

EXECUTIVE SUMMARY

Firefighters operate in zero visibility, high heat, and toxic environments. Firefighters work in unfamiliar structures and must quickly and efficiently search these structures for lost victims. These challenges lead many firefighters to lose situational and spatial awareness and then get lost. The National Institute of Health and Occupational Safety Firefighter's line-of-duty death investigations point to this loss of awareness as a contributing factor to many firefighter deaths. Firefighters inside buildings lose their ability to share their locations with incident commanders and would-be rescuers. There is an opportunity to improve survivability by providing a navigation system for the structural fire environment.

Navigation is the process of moving from one point to another. Technology has advanced in this area from navigating by stars using the sextant to the Global Positioning System (GPS) using satellites. Navigational aids have improved travel around the world, and technology can guide the way. Unfortunately, GPS does not function indoors because devices cannot communicate with satellites. Navigation is a large part of searching for victims and locating the source of a fire. The problem is that firefighters get lost while searching in thick smoke and darkness. The fire service is seeking a reliable system that will provide the ability for firefighters to navigate an unknown structure to improve the mission of saving lives.

This thesis was designed to answer the following question: What technology has the highest potential to be adopted to provide interior navigation for firefighters in a structural fire environment? The duration of the program at the Center for Homeland Defense and Security limited the project, so there was not enough time to conduct actual tests or trials. Therefore, an exploratory method was used to evaluate previous research done in other industries to develop indoor navigation systems. The literature review identified that existing radio frequency technology might provide a reliable system to support interior navigation. This thesis explored the scholarly literature, and the knowledge gained helped define the technologies examined in this thesis. An evaluation of the fire problem was conducted to estimate the annual costs of fire losses in the U.S. The

information for each technology was then applied to the mission model canvas (MMC). In the book *Business Model Generation: A Handbook for Visionaries*, Alexander Osterwalder and Yves Pigneur describe a canvas as a tool to help innovators visualize information and identify unknowns. The MMC compares alternatives from a public sector perspective.

Indoor navigation is a complex challenge. Leonardo Ramirez et al. point out that firefighting intervention makes interior navigation solutions more challenging to design.[1] As quoted in Karimi's work, Prashant Krishnamurthy claims, "Building an entirely new infrastructure for positioning in indoor areas would incur substantial cost in a variety of ways."[2] For this reason, many researchers have tested the highly dispersed existing radio-frequency technology found in most structures. Wireless fidelity (Wi-Fi), Bluetooth, and radio frequency identification are all possible ways to define location inside a structure. Hui Liu explains that there are many ways to identify a location: physical location, symbolic location, or absolute location. Each definition is useful in different situations. When sharing a position with another individual, both must be using the same reference system for the transfer of information to be helpful.

Indoor navigation systems use triangulation, fingerprinting, and proximity to measure the distance from a known point to calculate a precise location. Triangulation uses measurements from multiple sources to identify the angles and determine a location. Fingerprinting matches the measurements to previously identified reference points. Proximity also uses reference points, and the closest source defines the relative position.

All of the technologies have different advantages and disadvantages. Wi-Fi is a technology that is in most public spaces in the United States. Wireless access points supply the service, and these broadcast a service set identifier to define the network. This broadcast signal speed between the wireless access point and the receiver is measured to calculate a location. Bluetooth technology has evolved to be more reliable and more powerful. A Bluetooth system consists of positioning servers and receivers (or beacons). Bluetooth

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[1] Leonardo Ramirez et al., "Landmarke: An Ad Hoc Deployable Ubicomp Infrastructure to Support Indoor Navigation of Firefighters," *Personal and Ubiquitous Computing* 16, no. 8 (December 2012), https://doi.org/10.1007/s00779-011-0462-5.

[2] Hassan A. Karimi, *Indoor Wayfinding and Navigation* (Boca Raton, FL: CRC Press, 2015), 314.

proximity systems have been successfully installed in specific retailers and large commercial spaces. In these systems, a user can open an application on a mobile device to gather information about one's proximal space and the items in the area. Radio-frequency identification (RFID) systems utilize tags and receivers, and these devices typically have less power than other technologies. RFID is not a standard technology in mobile devices, but many RFID tracking systems have been developed to find items with RFID tags. The terrestrial transmitter system functions differently. It uses transmitters engineered to cover a metropolitan area. These transmitters operate just like GPS and leverage GPS hardware to define the location and assist in navigation accurately. This system works indoors and can account for changes in elevation to assist in high-rise operations. Each of these technologies may serve as a feasible solution to the problem.

Augmented reality and spectral image fusion are two alternative technologies that may assist in maintaining spatial awareness. Augmented reality is a complex solution that requires a known location, travel direction, and direction of the user's gaze. To function correctly, the user will need a camera, display, and gyroscope, not to mention a system that defines his location. Spectral edge image fusion is a technology that combines multiple camera lenses into one view to enhance the user's view of items. This technology can leverage the deployment of the fire service thermal image cameras.

The thesis identified the cost of loss of life and property to fire in the United States. Fires have a significant impact on the U.S. economy—in the form of direct and indirect costs. This expenditure equals 1.9 percent of the gross domestic product. The majority of fires occur in residential structures, and this is also where the majority of deaths occur. The National Fire Protection Agency defines the value of statistical life as $9.4 million, which leads to an annual cost of human life lost to fire in the United States of $43 billion per year.[3]

The MMC was used to identify the business potential for each technology. The value proposition helps innovators solve customer problems. The innovator must be able

[3] Jun Zhuang et al., *Total Cost of Fire in the United States* (Quincy, MA: Fire Protection Research Foundation, October 2017), 2, 25.

to solve the problem and have a viable business opportunity. Indoor navigation will involve many key partners and key activities. Ron Adner refers to this as an innovation ecosystem. He goes on to point out that this type of interdependence brings additional development risk.[4] The final aspect of the MMC is mission achievement, which defines whether all other parts of the canvas will result in success.

Out of all of the technologies evaluated, spectral image fusion is going to be the solution to support the mission and help with navigation. It is likely to be adopted and will improve survival. Spectral image fusion is an incremental step as this technology will not provide navigation but will enhance spatial and situational awareness. The terrestrial transmitters are a longer-term option that will require innovation before they will be a viable solution. The other technologies—Wi-Fi, Bluetooth, RFID, and augmented reality—all present too many challenges to achieve the mission and have a low potential for being adopted.

Incorporating additional training into the national standards for a firefighter to maintain situational and spatial awareness is an alternative finding that can support technology solutions.

Finally, the thesis discovered that there is a need for additional testing and trials, including some in real live-fire situations, to test the potential for many of these systems.

[4] Ron Adner, "Match Your Innovation Strategy to Your Innovation Ecosystem," *Harvard Business Review*, April 2006, 8.

ACKNOWLEDGMENTS

I want to thank my wonderful wife for supporting me through my life and this project. She has always encouraged me to push for my goals and has given up more than is fair. Marcy, I love you! I am thankful for the support of my daughter, Rachel, and my son, Shawn, who are wonderful people, despite my constant distractions from school and work. I am so proud of you both, and I love you. Thank you!

I want to thank all of the professors and staff at the Center for Homeland Defense and Security for allowing me the opportunity to be part of the program and learn from the best. Thank you, Marianne Taflinger, for suggesting great ways to improve my research and this thesis. Finally, I want to acknowledge my thesis advisors, Dr. Cristiana Matei and Dr. Nicholas Dew, for providing great feedback and guiding me through this process. Thank you both very much!

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I. INTRODUCTION

A. PROBLEM STATEMENT

Firefighters operate in zero visibility, high heat, and toxic environments that require an air supply. These operational challenges require proficiency from the firefighters in every task to be effective. For example, firefighters must train to work without the ability to see, to communicate through a mask, and to move through an unfamiliar structure quickly in protective clothing, searching all areas. Identification of solutions to zero visibility and high competence is important because the loss of spatial awareness is a contributing factor to firefighter deaths.[1] Many firefighter injuries and fatalities occur on structural fire scenes (89 percent), and the majority of these are residential structures (73 percent).[2] A common theme of line-of-duty death and near-miss investigative reports include firefighter and incident commanders' loss of situational awareness as a contributing factor.[3] The structural fire environment is volatile, containing zero visibility in entirely unfamiliar structures. Firefighters must navigate through these structures to find victims and locate the source of the fire. Firefighters become disoriented, and their air supply reaches depletion, leading to unconsciousness and death.

Navigation began by using landmarks on the earth. People traveled from landmark to landmark. The sextant changed this and allowed stars to be terrestrial landmarks.[4] The development of the Global Positioning System (GPS) created the opportunity to reference location relative to a known object. Unfortunately, GPS does not work indoors because the

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[1] National Fire Protection Association, "Patterns of Firefighter Fireground Injuries," accessed May 28, 2018, https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Emergency-responders/ospatterns.pdf.

[2] "Home Page," National Fire Protection Association, accessed May 10, 2018, https://www.nfpa.org/.

[3] National Fire Protection Association.

[4] Christien Kluwe and Andrew D. Ellington, "RNA GPS," *Science* 330, no. 6002 (2010): 2, http://www.jstor.org/stable/40931604.

devices cannot get a line-of-sight connection to the satellite.[5] With the lack of visual landmarks and no functional GPS, firefighters cannot navigate the interior of structures.

Technology continues to advance, and alternatives to GPS devices may offer opportunities to assist firefighters. Thermal cameras, which create an image through the smoke and dark, have become standard tools for firefighters. Developers have explored augmenting the firefighter's view with a thermal image in the mask.[6] As an alternative, some researchers have tested local positioning systems (LPSs). An LPS can use many different technologies, such as Bluetooth, WiFi, ultra-wideband, and radio-frequency identification (RFID), but is costly and must be pre-installed.[7] Some commercial facilities, warehouses, and hospitals have LPS for business efficiency. These systems could provide a framework for a standard public safety system because they use various networking technologies to reference location. An LPS must also be compatible with any system that the firefighters are using. When talking about all the different requirements of an indoor navigation system, Valérie Renaudin, a specialist in real-time positioning, states that "it seems almost impossible to design a solution that answers all these features."[8] Another area of research being conducted to perform indoor navigation is creating systems that track the gait and movement of people from a known point.[9] Augmented reality and edge detection systems can also provide universal clues to one's location, as demonstrated by studies conducted by the Menlo Park Fire Department.[10]

This research seeks to identify technological solutions to provide indoor spatial guidance for firefighters. This study aims to explore research in the indoor navigation field and correlate it with applications in the fire service. Its goal is to identify technologies that

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[5] Valérie Renaudin et al., "Indoor Navigation of Emergency Agents," *European Journal of Navigation* 5, no. 3 (2007): 10.

[6] Jon Peddie, *Augmented Reality: Where We Will All Live* (Cham, Switzerland: Springer, 2017), 116.

[7] Renaudin et al., "Indoor Navigation of Emergency Agents," 2.

[8] Renaudin et al., 4.

[9] Jiuchao Qian et al., "An Improved Indoor Localization Method Using Smartphone Inertial Sensors," in *Proceedings of the International Conference on Indoor Positioning and Indoor Navigation* (Montbeliard, France: IEEE, 2013), 1–7, https://doi.org/10.1109/IPIN.2013.6817854.

[10] "Home Page," Qwake Technologies, accessed June 20, 2018, https://www.qwake.tech.

are showing the most promise and encouraging development, leading to the adoption of standards in this area. Finding technologies that can increase spatial awareness will improve firefighters' performance.[11]

Specifically, this research aspires to define the operational variables that make indoor public-safety navigation systems function. It also seeks to define the variables in the structural fire environment and compare them to the alternatives studied in other settings.

B. RESEARCH QUESTION

What technology has the highest potential to be adopted to provide indoor navigation for firefighters in a structural fire environment?

C. RESEARCH DESIGN

The study tries to answer the research question of which technology has the highest potential for adoption to provide reliable indoor navigation. Due to time limitations, the research did not involve any field testing but used an exploratory research method to identify previous research done in other industries to help define the operation of each technology.

The literature review is used to define the complexity of indoor navigation and to discuss existing radio frequency technology that may provide a reliable system to support indoor navigation. Scholars somewhat agree that existing radio-frequency (RF) systems could be used to help identify a location within structures because many occupancies have these systems, and they have been successfully deployed to accomplish similar tasks.[12] The literature review also highlights alternatives to RF technology tested for indoor navigation: augmented reality using edge detection and dead-reckoning, which measures an individual's movement from a known point.

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[11] Qwake Technologies.

[12] He Xu et al., "An RFID Indoor Positioning Algorithm Based on Support Vector Regression," *Sensors* 18, no. 5 (2018): 1504, http://dx.doi.org/10.3390/s18051504.

The research began with describing the technology. It explored the technical requirements and operational challenges of each type of system. This information was used to help define the likelihood that the RF system could meet the needs of the fire service. The data came from scholarly research that had been done to solve the problem of indoor navigation in various industries. The process involved identifying existing research through Dudley Knox Library and affiliated databases as well as the Homeland Security Digital Library.

The technology was only half of the answer; getting a product to market that functioned and met the needs of the stakeholders was a more significant challenge. In the book *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers* Osterwalder and Pigneur explore innovation and design thinking. They state, "A business model describes the rationale of how an organization creates, delivers and captures value."[13] Osterwalder and Pigneur further note that the business model canvas (BMC) is an excellent tool for determining the market fit and creating stakeholder value. They conceptualize this model as an assembly of nine blocks that help define all variables in any business innovation.[14] The BMC is a Lean Startup tool designed to help identify the unknown aspects of business needs. It helps to visualize the information and the change in assumptions over a project's history. The authors point out that the model can also be used to define the value proposition, which is the solution to a problem.[15] The relationship between the value proposition and the beneficiaries is called the product/market fit. The product/service must match the needs of the beneficiary in a way perceived to be a solution to the problem.[16] This methodology helped us compare and contrast the alternatives and test hypotheses without developing fully operational systems.

As this was exploratory research, a canvas was used as an evaluative tool to compare each potential solution. The tool selected was a variant of BMC. In government

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[13] Alexander Osterwalder and Yves Pigneur, *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers* (New York: Wiley, 2013), 15.

[14] Osterwalder and Pigneur.

[15] Osterwalder and Pigneur.

[16] Osterwalder and Pigneur.

situations where mission accomplishment rather than profit motivates behavior, the BMC can be modified. The modified version is called the mission model canvas (MMC).[17] MMC also has nine key areas: value proposition, beneficiaries, buy-in/support, deployment, key partners, key activities, key resources, costs, and mission achievement.[18] The model starts with the value proposition, which is used to define the service or problem being addressed. Next, the beneficiaries most likely affected by each alternative are described. The model helps to identify the deployment options for each of the solutions evaluated. The potential buy-in or support for each option is considered in the model's matrix. The MMC helps to identify whether each technology can successfully reach mission achievement (fulfillment or impact). The second half of the model is used to help define the key partners, key activities, and essential resources to make a successful solution for indoor navigation. Finally, a budget estimate is established for a typical deployment in a business occupancy to compare the costs of each solution.[19] Thus, this evaluation separated the ideas from potential solutions that were viable and had a reasonable return on investment.

This model was a comparative tool for different technologies. Since much of the deployment of this technology was unknown, the MMC was a useful tool to evaluate assumptions related to each type of solution. The MMC is a Lean Startup tool to explore possible alternatives without the expense and time constraints of establishing live testing. Although live testing would have provided more accurate results, the limited time for this research aligned better with the assumptions made through talking with subject-matter experts.

One critical element of the Lean Startup methodology is to get out and speak with potential users and partners.[20] This was not done as part of this research project; however, the results will be shared to encourage further research and development in this area. The

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[17] Steve Blank, "The Mission Model Canvas – An Adapted Business Model Canvas for Mission-Driven Organizations," *Steve Blank* (blog) February 23, 2016, https://steveblank.com/2016/02/23/the-mission-model-canvas-an-adapted-business-model-canvas-for-mission-driven-organizations/.

[18] Blank.

[19] Blank.

[20] "How to Build a Startup," Udacity, accessed December 8, 2018, https://classroom.udacity.com/courses/ep245.

Department of Homeland Security (DHS)'s Science & Technology Directorate is an important agency that can help promote the exploration of indoor navigation for public safety. Another agency is the Smart Cities Initiative, and they will be lobbied to promote the idea of a standardized indoor navigation system for public safety.

The final step in the thesis was to make recommendations based on the findings of the exploratory steps. Each level helped to define the opportunities and challenges of all technologies. The canvas provided a way to compare the results and identify the potential systems that could fill this life-safety gap for firefighters.

II. LITERATURE REVIEW

The purpose of this literature review is to identify scholarly works in the field of indoor navigation for the fire service and to define research that has been conducted on the effectiveness of global positioning systems (GPS) indoors. The literature review also explores alternative indoor navigation technology, and it expands the knowledge of existing radio-frequency technology, which may serve as an alternative for indoor navigation for the fire service. This literature helps to define systems that may correlate with the needs of the fire service.

A. INDOOR NAVIGATION IS CHALLENGING

Ramirez et al. highlight the necessary yet challenging trait of indoor navigation for firefighters. They state, "The circumstances in which a firefighting intervention occurs represents a rather complex challenge for the design of supporting technology."[21] Hassan Karimi—who obtained his doctorate in geomatics engineering and has conducted extensive research in navigation location-based systems—tends to agree.[22] In the book *Indoor Navigation and Wayfinding*, Karimi, who defines navigation as the process of traveling and receiving continuous feedback as to location and route, points out that indoor navigation is more complicated because it takes place in three-dimensional space as most buildings have multiple floors.[23] Indoor navigation is achieved without the help of GPS, which dominates the technology for exterior positioning. In this context, Prashant Krishnamurthy, a researcher working to find indoor navigation solutions, notes, "There is no preferred positioning technology choice for indoor navigation."[24] Krishnamurthy goes on to say that indoor navigation requires more accuracy up to a meter or better, but

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[21] Leonardo Ramirez et al., "Landmarke: An Ad Hoc Deployable Ubicomp Infrastructure to Support Indoor Navigation of Firefighters," *Personal and Ubiquitous Computing* 16, no. 8 (December 2012): 1025, https://doi.org/10.1007/s00779-011-0462-5.

[22] Hassan A. Karimi, *Indoor Wayfinding and Navigation* (Boca Raton, FL: CRC Press, 2015).

[23] Karimi.

[24] Prashant Krishnamurthy, "Technologies for Positioning in Indoor Areas," in *Indoor Wayfinding and Navigation* (Boca Raton, FL: CRC Press, 2015), 36.

pedestrians tend to move more slowly than vehicular-borne navigation systems, so this allows for alternative systems.[25]

Krishnamurthy further notes, "Building an entirely new infrastructure for positioning in indoor areas would incur substantial cost in a variety of ways."[26] In this context, he posits that a navigation system would require installing hardware in mobile devices and base stations in structures. This expense has led to extensive research in using existing RF technology installed in most structures and many mobile devices.[27] Research conducted by Karimi and Krishnamurthy on wireless fidelity (Wi-Fi), Bluetooth, and RFID concluded that the latter is the most affordable because it is already in place.

B. EMPLOYING EXISTING RADIO-FREQUENCY TECHNOLOGY

Perahia and Stacey explain that Wi-Fi has become widespread in modern society, is found in most public facilities, and could be an excellent alternative for positioning systems. [28] Karimi mentions that the Institute of Electrical and Electronics Engineers (IEEE) standardized WiFi, currently defined by the 802.11 nomenclature. The 802.11ac standard can transfer 100s of Mbps, but this evolution of Wi-Fi uses multiple-inputs and multiple-outputs, meaning it can send and receive data simultaneously. Wi-Fi positioning systems are tested in two different approaches: proximity and fingerprinting. The positioning model uses the known position of the Wi-Fi access point (AP) to indicate the location of the device/person. Krishnamurthy warns that this approach is prone to error as walls or RF shadows may prevent connection to the closest AP, and architectural features may shield the closest point.[29] In contrast, Krishnamurthy notes that the fingerprinting model uses a mapped area inside a structure in which all spaces are identified, and a grid is established to the closest three or four APs in that area. It has the advantage of measuring

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[25] Karimi, *Indoor Wayfinding and Navigation*, 36.

[26] Krishnamurthy, "Technologies for Positioning in Indoor Areas," 36.

[27] Karimi, *Indoor Wayfinding and Navigation*, 39.

[28] Eldad Perahia and Robert Stacey, *Next Generation Wireless LANs: Throughput, Robustness, and Reliability in 802.11n* (Cambridge: Cambridge University Press, 2008), 2, https://doi.org/10.1017/CBO9780511541032.

[29] Krishnamurthy, "Technologies for Positioning in Indoor Areas," 49.

the received signal strength (RSS) for each access point to the device. He further discusses that a device reports the RSS to each AP, and that record is compared to the mapped locations to estimate the location.[30] The consensus in the literature indicates that RF technology can serve as an excellent indoor navigation guide.

Gabriel Deak, Kevin Curran, and Joan Condell surveyed other technologies for indoor navigation, two of which are Bluetooth and RFID.[31] Deak describes Bluetooth as a personal-area networking technology. Bluetooth technology enables the connection of a device without additional hardware.[32] Karimi opines that like Wi-Fi, Bluetooth navigation systems use the connection status to identify the location as devices move and connect to different coverage areas, yet Bluetooth transmits at much lower power and range than Wi-Fi.[33] In 2006, Garfinkel and Rosenberg's testing of RFID use in proximity-based navigation systems found that passive and active tags can be placed indoors to work in a fingerprint layout system. RFID readers are indexed from the known location of the tags. This known waypoint inside a structure can be triangulated with other RFID tags to help a reader determine its relative location to the tags.[34] This literature demonstrates that RF technology can be used for indoor navigation. Bluetooth has demonstrated the ability for proximate distances whereas RFID and WiFi have more significant potential for longer distances and larger applications.[35]

C. ALTERNATIVES

As an alternative to RF technology, Jiuchao Qian et al. researched dead reckoning. Dead reckoning is the study of navigation through the tracked movement of the person's gait or stride using smartphone sensors. Their report states,

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[30] Krishnamurthy.

[31] Gabriel Deak, Kevin Curran, and Joan Condell, "A Survey of Active and Passive Indoor Localisation Systems," *Computer Communications* 35, no. 16 (September 2012): 1939–54, https://doi.org/10.1016/j.comcom.2012.06.004.

[32] Deak, Curran, and Condell.

[33] Karimi, *Indoor Wayfinding and Navigation*, 44.

[34] Karimi.

[35] Krishnamurthy, "Technologies for Positioning in Indoor Areas."

> The localization method is the core constituent of an indoor navigation system. According to various basic measuring principles, localization method can be divided into four main categories: triangulation, direct sensing, pattern recognition, and dead reckoning.[36]

Pedestrian dead reckoning (PDR) is the study of people walking. This localization method takes a standard smartphone and combines it with a PDR algorithm to determine indoor location. The paper contrasts the technology of radio signals and WiFi, which have been used to determine an indoor location in an exciting new way. The authors propose that multiple uses of a phone during a typical day be evaluated to identify how to develop a standard algorithm to estimate distance and direction traveled.[37] The researchers noted that this method could be useful for limited applications of indoor navigation, where algorithms and estimates from the sensors in the devices calculate the distance from a known point. Jiuchao et al. note that the algorithms are not accurate enough for long-term indoor navigation but "could be a promising scheme."[38]

Dead reckoning uses inertial sensors from smart devices and can be used to estimate the distance from a known point. The algorithms are becoming more accurate; however, additional research is needed to make this method more reliable for longer distances.[39] This methodology has the potential for upright people inside large buildings for short periods. Unfortunately, when conditions are at their worst, firefighters are often crawling due to high heat and low visibility. This change in position disrupts the estimates of gait. There is also the reality of performing work while moving about the building, searching, and moving hoses and other equipment—each of these tasks decreases the accuracy.

Leonardo Ramirez and his team took a different approach from all the others identified in this literature review by using illuminated pucks deployed by firefighters to establish waypoints. This concept used breadcrumbing systems—firefighters deploying

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[36] Jiuchao et al., "An Improved Indoor Localization Method."

[37] Jiuchao et al.

[38] Jiuchao et al., 1–7.

[39] Jiuchao et al.

colored tags at notable landmarks—to create a virtual chain.[40] The method took advantage of the firefighters' strengths in identifying important landmarks while searching and provided a means to reference and share that location through illuminated pucks. The testing did not help with navigation on the way into a structure for the initial crews. The testing also raised questions for additional research opportunities: using the pucks to serve as radio repeaters and environmental sensors to expand functions. This method did not leverage pre-installed RF technology, but it used a system deployed by firefighters at the time of entry. Ramirez et al. believe that it is a step in the right direction, but additional research is needed. [41] This procedure will alter the typical operations of the firefighters and require additional personnel on scene to deploy and monitor the system. The ability to identify known points and share this information is critical to any indoor navigation system; regrettably, at the time of an emergency, all hands are needed to solve the problem. More tasks and distractions lead to lower efficiency and higher risk.

D. SUMMARY

The literature of Ramirez et al. and Karimi supports the concept that firefighting can be improved and made safer by providing indoor navigation systems. GPS technology dominates the outdoor positioning field, but indoor navigation lacks an accepted standard.[42] RF-based systems found in many structures may serve as a technology that can be used to build a system. Wi-Fi is the most distributed RF technology, but its current distribution model has limited access points. Bluetooth and RFID, however, both serve as emerging technologies in the field of indoor navigation.[43] Alternatively, many researchers are exploring leveraging the sensors on mobile devices to improve dead reckoning for indoor navigation. Illuminated waypoints deployed by firefighters in the first wave of entry can improve operations for the crews that follow. Unfortunately, little scholarly research

[40] Ramirez et al., "Landmarke," 1026.

[41] Ramirez et al., "Landmarke."

[42] Karimi, *Indoor Wayfinding and Navigation*, 49.

[43] Deak, Curran, and Condell, "Active and Passive Indoor Localisation Systems."

has evaluated the technology specifically for fire service indoor navigation, so this thesis aspires to fill this gap in the literature.

III. INTERIOR NAVIGATION TECHNOLOGY

The purpose of this chapter is to define indoor navigation in the context of this research as well as explain the various technologies being evaluated. Across academia and industry, researchers are exploring indoor navigation for numerous commercial and government applications. Various technologies have been tested to develop interior navigation systems, and the majority use radio frequency connectivity. The fire service is one small part of this research, but the impact may be significant in the number of lives saved and the amount of property preserved. Each technology offers benefits and challenges that must be compared to determine the feasibility for public safety.

A. LOCATION

Location may be defined in several ways. The physical location of a person, place, or thing may be expressed using coordinates: degree decimal minutes, minutes and seconds, or the Universal Transverse Mercator system.[44] People use points of reference and plain language to identify a symbolic location: they are at the Naval Postgraduate School, for example. In contrast, using a shared reference grid allows the absolute location to be identified. For example, the Washington Monument is at 38.8895° N, 77.0353° W. Figuring distance or proximity from a known point is called relative location: the climbers are 1200' from the top of the mountain. In sum, as Adam Hernod Olevall and Mathieu Fuchs, researchers from Uppsala University, conclude, "The evolution of the various navigation techniques have helped the human species spread across the planet."[45] All these terms help people determine their location, communicate locations of items, and navigate in the world. Defining one's location is a critical piece of information. If the sender and receiver have an agreed reference system, then any one of the methods above can be useful. If there is not a shared understanding, then the exchange of information is useless: a

[44] Hui Liu et al., "Survey of Wireless Indoor Positioning Techniques and Systems," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 37, no. 6 (November 2007): 1067, https://doi.org/10.1109/TSMCC.2007.905750.

[45] Adam Hernod Olevall and Mathieu Fuchs, *Indoor Navigation and Personal Tracking System Using Bluetooth Low Energy Beacons* (Uppsala, Sweden: Uppsala University, October 2017), 18.

firefighter telling the incident commander that he is in the kitchen brings no value if the rest of the team does not know where that room is located in the facility.

B. INDOOR NAVIGATION TECHNOLOGY

GPS has empowered humans to traverse the world efficiently, and the next evolution is defining the system for indoor navigation. Indoor navigation systems gain their intelligence by using transmitters and sensors (receivers) that exchange signals. Many types of systems have been developed using various algorithms to calculate location. There are four types of positioning systems: remote positioning; self-positioning; indirect, remote positioning; and indirect self-positioning.[46] The difference between these types of positioning systems relates to the location of the transmitter and measuring units. Where the measurements take place is also important. In remote positioning systems, the transmitter is mobile, but the measuring devices are fixed. In self-positioning systems, the measuring unit is mobile while the transmitter is fixed. The two indirect methods use a data connection to obtain the measurement result from the opposite side of the system.[47] All of the RF systems under development use transmitters, receivers, and one of these typologies to function.

Once the devices exchange signals, triangulation, fingerprinting, and proximity enable calculation.[48] Triangulation uses two derivatives: the measurement of the distance from known reference points and the angles that these measurements form.[49] Fingerprinting or "scene analysis" matches the estimated location to previously calculated points to determine the best match.[50] Proximity systems use a dense spread of receivers with well-established locations, and the antenna/receiver with the most robust connection to the mobile device is considered the reference point for the object being tracked.[51] These

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[46] Hui et al., "Wireless Indoor Positioning Techniques and Systems," 1067.

[47] Hui et al., 1067.

[48] Olevall and Fuchs, *Indoor Navigation and Personal Tracking System*, 23.

[49] Hui et al., "Wireless Indoor Positioning Techniques and Systems," 1068.

[50] Hui et al., 1070.

[51] Hui et al., 1071.

three algorithms have advantages and disadvantages that must be considered when designing a system.

Indoor navigation systems tend to be designed to operate over Wi-Fi, Bluetooth, RFID ultra-high frequency radio, or cellular communication channels. Each of these operating environments is explored in the following sections. Some designs take advantage of existing network infrastructure while others are built independently and specifically for navigation. Independent systems are more expensive to design.[52] Some modern systems have begun to incorporate combinations of RF technology to improve performance.

Industry insiders evaluate and compare indoor navigation systems based on their complexity, robustness, precision, accuracy, scalability, and—of course—financial commitment. The complexity is an evaluation of hardware and software and the computing power necessary to complete the algorithm. Robustness is measured by the ability to operate with limited or partial signal strength. Precision is based on the consistency of the distance error between the actual location and the estimated one. Accuracy is the most critical performance indicator and is measured by comparing the average estimated location with a known location. Scalability measures the ability to cover large areas, maintain performance, and handle a high volume of measurements consecutively. Finally, the cost defines the system and its return on investment. Using established infrastructure can reduce the required investment but this infrastructure may come with reductions in other performance measures.[53]

C. WIRELESS FIDELITY

The widespread distribution of Wi-Fi in public places makes it a popular choice for indoor navigation systems. Most public spaces in the United States have wireless access points (WAPs) installed.[54] The service set identifier (SSID) is typically broadcast from the access point to allow devices to see the network and connect if authorized. This

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[52] Olevall and Fuchs, *Indoor Navigation and Personal Tracking System*.

[53] Hui et al., "Wireless Indoor Positioning Techniques and Systems," 1072.

[54] Karimi, *Indoor Wayfinding and Navigation*, 316.

identification of the AP and the SSID can be used to support navigation technology. Once the location of the AP is known, Wi-Fi-based systems use proximity, time difference of arrival (TDOA), or fingerprinting, as defined earlier, to estimate the location.[55] Proximity systems are less accurate than fingerprint systems because access points cover areas of hundreds of square feet, including the predicted location. Fingerprinting uses signal strength by mapping the different RSS from multiple WAPs and plotting the exact match to a known reference point. Any device that sees the same signal strength combination is expected to be in the same spot.[56] Reducing the range of the WAP and increasing the distribution density of the hardware can increase the accuracy of a fingerprint-based system. The precision of three to six meters of error can be achieved in an area within a direct line of sight of four WAPs.[57] TDOA systems calculate location by triangulating the distance from multiple WAPs. The advantage of a Wi-Fi-based system is the dual purpose of the infrastructure, which reduces the cost. For large public spaces where navigation does not need to be exact, this system may be a "good enough" level of performance that does not require any other hardware investment.

Designing a Wi-Fi-based system requires a great deal of work. The following case study defines the steps necessary to build a Wi-Fi-based system. Dongsoo Han et al. designed a Wi-Fi navigation system in the COEX complex, the largest indoor mall in Seoul, South Korea.[58] The first step was to analyze the AP environment and then establish design goals. With goals established, the team developed indoor maps to achieve the desired outcome of the system. Using the new maps, the team collected the Wi-Fi data to gather fingerprints of all areas of the occupancy. The COEX project identified over 10,000 measurement points, leading to over 200,000 total data points, collecting 20 Wi-Fi fingerprints at each measurement point. A total of 15 people worked for more than two

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[55] Deak, Curran, and Condell, "Active and Passive Indoor Localisation Systems."

[56] Karimi, *Indoor Wayfinding and Navigation*, 316.

[57] Karimi.

[58] Dongsoo Han et al., "Building a Practical Wi-Fi-Based Indoor Navigation System," *IEEE Pervasive Computing* 13, no. 2 (June 2014): 72, https://doi.org/10.1109/MPRV.2014.24.

weeks to gather these data.[59] After collecting the data, the fingerprints were correlated to the map, indexed to a known coordinate. The team then developed the application and built and tested the system. The Wi-Fi environment constantly changed, and the system required ongoing maintenance to maintain accuracy within the goals. Another challenge was to reconfigure spaces in the mall and make seasonal adjustments that distorted the fingerprint information and reduced the performance. This project demonstrates the extensive work required to map one facility and to keep that map valid and reliable. It did create demand in the market: "More than 200,000 users downloaded the system in its first year of use."[60] Mapping the system took considerable design work and extensive human effort that was dedicated to this specific environment. This work did not carry over to the next occupancy, so each Wi-Fi system required a similar level of effort.

Wi-Fi systems have a set of drawbacks. One significant disadvantage is the signal loss and interference from structural elements. Precision is lost if walls block wireless signals. Another challenge is the lack of accurate time-syncing between the WAPs, leading to some calculation errors when estimating the time of arrival. Wi-Fi-based systems—to be of any value for navigation—will require mobile applications with maps and building plans.

D. BLUETOOTH

Bluetooth is another networking technology that has been used to develop indoor navigation systems. It consists of low-power-consumption devices that can communicate over RF without direct line-of-sight connections.[61] All Bluetooth devices are approved by a qualification test facility and meet established industry protocols. Industry standards require that all new Bluetooth protocols are backward compatible with older devices.[62] The

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[59] Han et al., 76.

[60] Han et al., 79.

[61] Martin Sauter, *From GSM to LTE-Advanced: An Introduction to Mobile Networks and Mobile Broadband* (New York: Wiley, 2014), 1, ProQuest.

[62] Sauter, 2.

ability for this technology to adapt but maintain compatibility with older devices adds value to these types of systems.

Bluetooth networks are sophisticated systems. Bluetooth devices operate on the 2.4-GHz radio frequency band. To avoid interference with other devices in that frequency, designers developed a frequency-hopping spread spectrum in which the frequency changes after each data packet is passed. Bluetooth technology is continually evolving and advancing. Bluetooth Low Energy (BLE), a relatively new Bluetooth technology developed in 2011, uses less energy and significantly extends battery life.[63] While Bluetooth systems operate over 79 channels in the frequency ranges, BLE operates over 40 channels in the frequency range. [64] Bluetooth 5.0, the next generation after BLE's development, has twice the network speed and four times the range of previous versions.[65] A Bluetooth network of devices, called a piconet, consists of up to eight devices—one master and seven others connected.[66] A typical deployment example is a laptop computer with a wireless mouse, a pointer, and headphones. The ability of a master to support and connect to multiple devices is an advantage in navigation system capabilities.

The technology has been considered a promising network to leverage for indoor navigation over other RF systems. Bluetooth has become a standard network system that is found in all mobile phones and laptop computers, making it highly distributed.[67] Figure 1 shows the broad spectrum of Bluetooth enabled devices. Bluetooth indoor navigation systems consist of positioning servers, small transceivers (beacons) with unique identifications that can broadcast their identification and location to a nearby device. Bluetooth-enabled devices recognize signals from paired hardware but ignore all other signals in the area. Because of this limitation, users have to opt in or allow a connection to the beacons in the area. System designers find ways to entice people to accept the connection. Retail stores use mobile customer applications to help customers locate

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[63] Olevall and Fuchs, *Indoor Navigation and Personal Tracking System*, 18.

[64] Olevall and Fuchs, 28.

[65] Olevall and Fuchs, 28.

[66] Sauter, *From GSM to LTE-Advanced*, 4–5.

[67] Hui et al., "Wireless Indoor Positioning Techniques and Systems," 1075.

products in stores. Apple developed the iBeacon protocol based on BLE in 2013; it can transmit advertising information as a consumer comes in range with the appropriate mobile application open. Airport systems help travelers find their gates. These Bluetooth indoor navigation systems have seen some success and have been deployed in shopping malls and numerous other environments.[68] The widespread availability of this technology makes it a good choice at a lower cost as most people already have an enabled device.

Figure 1. Bluetooth-Enabled Devices[69]

[68] Olevall and Fuchs, *Indoor Navigation and Personal Tracking System*, 3.

[69] Source: Hui et al., "Wireless Indoor Positioning Techniques and Systems."

E. RADIO-FREQUENCY IDENTIFICATION

New devices are being developed to improve and expand the capabilities of RFID systems. Technology is quickly replacing barcodes as a rapid way to identify items, track things, and to control access. These devices are electronic labels, adhesive chips, or cards that can be read or written to using the appropriate RF devices.[70] The shipping, banking, and retail industries are the leading users of this technology, and significant innovation continues to expand the use of RFID devices.

RFID comes in two systems: ultra-high frequency (UHF) and high frequency (HF). These chips can be further separated by how they function: active, passive, or semi-passive. Active tags have their own power supply and are the most expensive. Active tags are used on substantial assets such as rail cars and cargo containers, which must be tracked repeatedly over long distances. Active tags have a readability distance of 60–300 feet.[71] Active tags come in two configurations: beacons or transponders. Transponders are dormant until awakened by a reader, where beacons emit a signal at set intervals.[72] An external power supply stimulated by RF waves causes passive RFID chips to wake.[73] Semi-passive chips can function either way. All the chips have an antenna, electronic product code (EPC), and a digital memory chip installed in them. The system uses a reader that allows the activation of the chip and the transfer of data from the chip to the reader. The readers act as interrogators to stimulate the antenna and wake up the chip. The EPC is then shared, and if the correct connection is established between the chip and the reader, information can be exchanged. The chip then transmits the information it is programmed to broadcast or receives new information to store.[74] Passive low-frequency tags can be read from about 12 inches whereas high-frequency tags can be read from three feet, and ultra-

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[70] Eric Puffenbarger et al., "RFID: New Technology on the Horizon for IT Majors," in *Information Communication Technologies: Concepts, Methodologies, Tools, and Applications*, ed. Craig Van Slyke (Hershey, PA: Information Science Reference, 2008), 30, https://doi.org/10.4018/978-1-59904-949-6.ch261.

[71] Bob Violino, "The Basics of RFID Technology," *RFID Journal*, January 16, 2005, 4, https://www.rfidjournal.com/articles/view?1337.

[72] Violino, 4.

[73] Puffenbarger et al., "RFID," 30.

[74] Puffenbarger et al.

high frequency can be read from 10 feet or more.[75] The type of use defines the RFID system that will best suit the application. The critical components of an RFID system are shown in Figure 2.

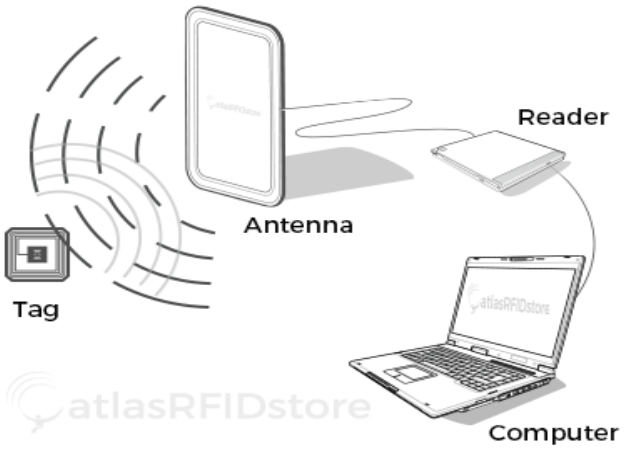

Figure 2. RFID Components[76]

Innovation and increased availability are expanding the applications of these systems. RFID systems are being used in new ways, such as in disaster mitigation to identify and tag disaster victims. Medical equipment is tagged to ensure that all tools are accounted for after surgery. Patients receive an RFID bracelet to reduce pharmaceutical errors and to track their location in a facility. The auto industry is using RFID tags in manufacturing lines of vehicles to track parts and inventory levels. The electronic toll industry is almost exclusively operated by issuing active transponders to vehicles for activation as the vehicles pass under the readers. The chips have voluntarily been implanted in humans for making purchases, gaining access, and storing medical information. Animals are also increasingly being tagged with RFID chips to identify breeding history as well as medical and owner information. New RFID readers are being developed to increase the

[75] Violino, "The Basics of RFID Technology," 5.

[76] Source: "What Is RFID?: The Beginner's Guide to RFID Systems," Atlas RFID Store, accessed October 12, 2018, https://www.atlasrfidstore.com/rfid-beginners-guide.

capabilities of the systems. Glove- and bracelet-style readers can detect an RFID tag that the user grasps or moves to reduce the manipulation of the reader.[77]

The final two components of an RFID system are the middleware and the database. The middleware is the software that runs on the host computer and exchanges the information between the tag, the reader, and the database.[78] The database is what makes the RFID system useful. This system holds the encryption keys and the information about each tag. Using the shipping industry as an example, a tag is applied to a package and scanned, and information about the package is entered into the database. The package then moves through a series of readers that report the package's location as it progresses through its travels. The tag is read as it leaves the point of origin, as it gets loaded onto a vehicle, when it is taken off the vehicle, and again in the sorting process so that it gets directed to the appropriate next location. This process continues until it arrives at its destination. The database has a history of each scan, the date, the location, and what vehicles it was on, who delivered it, and who signed for it.

RFID systems may help address the indoor navigation problem discussed at the beginning of this thesis. A few potential RFID system deployments may be viable solutions to help with firefighter spatial awareness. One model would be deployed upon the arrival of the firefighters. The firefighters would bring the system and all the components with them during the response. The RFID tags could be attached to the firefighters' equipment or on their protective clothing. Alternatively, a system may be installed during construction or retrofitted into existing structures. Both systems would use RFID tags placed inside the structure, and firefighters would be provided readers that reference the tags to help determine the location. Firefighters' locations would be triangulated from the referenced tags.

RFID is the technology of choice in the firefighter-tracking technology developed as a result of a significant fire service tragedy. In 1999, six firefighters were killed in the line of duty fighting a cold storage warehouse fire in Worcester, Massachusetts. The

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[77] Puffenbarger et al., "RFID," 30.

[78] Puffenbarger et al., 31.

firefighters became disoriented and lost inside the building. In 2003, Worcester Polytechnic Institute tested the firefighter-tracking system Q-Track, which used RFID tags attached to firefighters and an RFID reader to locate missing firefighters (see Figure 3). During this test, a missing firefighter was located within seven minutes with the RFID system versus 24 minutes without the system.[79] The test used RFID tags operating at low-frequency 1MhZ. This frequency was used because it penetrates walls and structures more efficiently, and it has less signal reflection and bouncing, allowing for more precise location determination. This system does not help the lost firefighter with navigation, nor does it provide the incident commander with better accountability. This test proved the potential application of RFID systems to assist firefighters in locating their peers, but more work is needed to provide indoor navigation with RFID.[80]

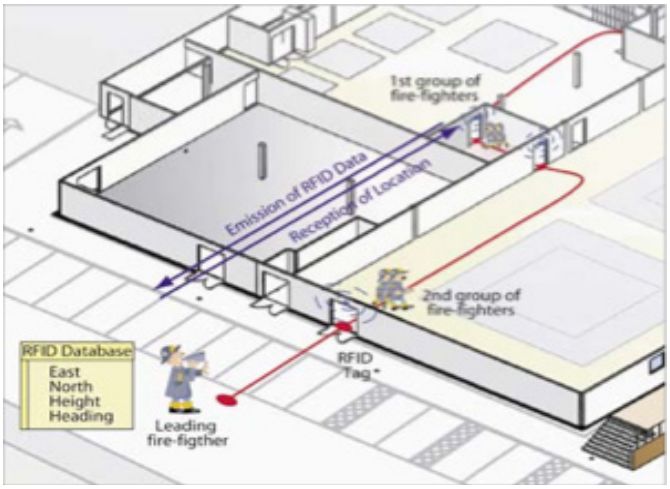

Figure 3. RFID System Deployed by Firefighters on Scene[81]

Hong Kong University has done extensive research on RFID as a tool for indoor location sensing. It uses triangulation, proximity, and scene analysis (evaluating the dynamics of the environment) to test the ability to locate objects equipped with RFID tags

[79] Mark Roberti, "Locating Firefighters with RFID," *RFID Journal*, October 1, 2010, 10, https://www.rfidjournal.com/purchase-access?type=Article&id=7915&r=%2Farticles%2Fview%3F7915.

[80] Roberti.

[81] Source: Renaudin et al., "Indoor Navigation of Emergency Agents."

within a reliable level of accuracy. Researchers developed a system called LANDMARK, which uses reference tags to increase accuracy without having to increase the number of readers.[82] The researchers dispersed RFID readers with known power levels across a region in the test facility. These readers activated tags within that region, and each region was monitored for RFID tags that entered or exited that region. Reference tags were placed in the region in known locations to help provide landmarks for the analysis to increase accuracy.[83] Additional research, completed in March 2018, improved the accuracy of LANDMARK using support vector regression and the Gaussian-Kalman filter to reduce noise in the algorithm.[84] The author of the most recent study, He Xu, concluded that this system would be accurate enough to "locate a book in a library, a patient in the hospital or . . . trapped people in a fire."[85] Another type of RFID deployment to consider is one installed by firefighters as they go to work inside a structure—a type of breadcrumb system. Firefighters drop RFID disks as they enter a structure. Similarly, RFID technology can be installed in the fire hose or search rope. Firefighters have readers that can activate and read the tags. This type of system provides visual points of reference for firefighters.[86] They will have some known location that they can visualize to help track their locations. This is much better than the method of keeping a hand on the wall. These RFID systems do not help firefighters navigate unknown spaces, but they represent an improvement over getting lost and having no point of reference.

RFID technology can be used as an indoor location system. Engineering a solution for the fire service will produce challenges, but through additional research and testing, a viable system can be developed. The real challenge will be the standardization of RFID systems, the middleware, and the methodology to deploy such systems for navigation. If testing reveals that the most efficient model is a pre-installed system, working through the

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[82] Lionel M. Ni et al., "LANDMARC: Indoor Location Sensing Using Active RFID," *Wireless Networks* 10, no. 6 (November 2004): 701–10, ProQuest.

[83] Ni et al., 703.

[84] He et al., "An RFID Indoor Positioning Algorithm."

[85] He et al., 1504.

[86] Renaudin et al., "Indoor Navigation of Emergency Agents," 30.

standard and building code changes to require installation will be a significant undertaking. Research is confirming this proof of concept, and many public safety agencies would benefit from this type of technology. Even the consumer industry would benefit. If the mobile phone industry installed RFID readers in devices, Google and Apple Maps would help people navigate indoor spaces such as malls, hospitals, and large business complexes. RFID is a possible solution to indoor navigation for the fire service, and more research is needed to define the best application of this technology.

F. METROPOLITAN BEACON SYSTEM

NextNav's Metropolitan Beacon System (MBS) is a proprietary network that functions like GPS, except it functions indoors and has been designed to support urban applications (see Figure 4).[87] This terrestrial-transmitter system reports high accuracy and reliability inside and operates faster than the typical GPS infrastructure.[88] The system is designed and built for the customer and has been successfully tested in the San Francisco area. Transmitters cover the area where the technology is needed; these devices are networked and synchronized to provide high accuracy. The transmitters are one-way devices that cryptically broadcast their location and time. The user's device receives this information, and the device determines its location and altitude from onboard sensors and calculations.

[87] "Technology," NextNav, accessed January 2, 2019, http://www.nextnav.com/technology#psbn.

[88] NextNav.

Figure 4. NextNav Terrestrial Transmitters[89]

The technology for this system is no more complicated than the outdoor positioning system. This system functions over a licensed cellular network frequency, and on the device side, it mimics GPS. The available literature indicates that devices may be programmed to use either GPS or NextNav MBS transmitters to determine location. This makes programming less challenging and creates the opportunity for developing more applications.[90] Receivers that function with GPS can incorporate the technology so that numerous other devices can take advantage of the location accuracy.

The applications of this system for public safety are significant. The system is designed to cover an entire municipality, not just a specific building or structure. The 9-1-1 system using MBS will be able to pinpoint the location of callers to buildings and floor level. First responders can be tracked throughout buildings and across the municipality. NextNav claims that floor plans can be incorporated when they are available.[91] Current

[89] Source: NextNav, "Technology."

[90] NextNav.

[91] NextNav, "NextNav MBS - First Responder," Vimeo, video, 2:27, June 20, 2017, https://vimeo.com/222454215.

GPS applications struggle indoors and fail at predicting height. Consistently knowing the floor level of people in need and tracking responders through a building at all levels are essential for firefighters.

G. AUGMENTED REALITY AS AN ALTERNATIVE TO RADIO FREQUENCY SYSTEMS

Augmented reality (AR) is the addition of computer-assisted contextual layers over the real-world image. The technology can help to solve problems and make our lives easier. Imagine a scenario as described by Abraham and Annunziata: "Workers being guided through a repair, step-by-step repair instructions hovering over a machine part, visually guiding a worker through the job."[92] AR is often associated with the discovery that fulfills curiosity through relevant content. Imagine an enhanced view of the world with information in one's line of sight that helps one accomplish a mission. David Mizell and Thomas P. Caudell, who worked for Boeing research, helped to define the expression *augmented reality*. According to Ronald Azuma's definition, it has three characteristics: "1) It unites real and virtual worlds. 2) It is interactive in real time 3) It permits movement in three dimensions (3D)." [93] The description that Azuma developed is consistent with the needs in the fire service. Jon Peddie, a researcher and author of the book *Augmented Reality: Where We all Live*, argues, "I genuinely and truly believe we will all use AR and that it will alter our lives forever. . . . It will be omnipresent in our lives." AR is often called the intermediate space between the authentic world and the synthetic one.[94]

Using images of the environment around a user's AR enhances views by overlaying additional images on top. It can include images of sounds and haptic feedback (physical stimulation of the senses like vibration or tapping). These devices work by taking any digital source and putting it in view in a 3D format on top of an image of the real world. To ascertain the orientation and the position of the camera, a computer calculates its

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[92] Magid Abraham and Marco Annunziata, "Augmented Reality Is Already Improving Worker Performance," *Harvard Business Review*, March 13, 2017, https://hbr.org/2017/03/augmented-reality-is-already-improving-worker-performance.

[93] Peddie, *Augmented Reality*, 105.

[94] Peddie, 35.

location and the movement of the hardware. The computer then renders the 3D information in the user's view.[95] As shown in Figure 5, a model is on the table, and then an augmented image displays on the iPad being held by the user. The image illustrates the enhanced detail that AR can provide. Trees, roads, and building features are all displayed as if they are in the model in the appropriate relation to the model.

Figure 5. Image on Tablet Enhanced by Augmented Reality[96]

This technology is not simple to generate; in fact, it is much harder than virtual reality (VR). In VR, the developer controls the entire pallet, size, orientation, and brightness because it is a complete scene. In AR, the developer is only enhancing a real image by applying virtual images and information into the view of the user referenced to the viewer's direction. The images displayed must be proportional and consistent with the correct size, orientation, lighting, and shading as the rest of the user's view. Peddie states that more than one supplier had commented that "it was the most difficult thing they had ever done."[97] This technology requires several components to function: a graphics-processing unit, a display or projector, and a computer to process the information. Other

[95] Peddie, 56.

[96] Source: "Augmented Reality," Apple, accessed June 25, 2018, https://www.apple.com/ios/augmented-reality/.

[97] Peddie, *Augmented Reality*, 38.

hardware that may be required includes GPS, gyroscope, accelerometer, barometer, depth sensor, cameras, eye-tracking devices, microphones, local storage, power supply, Bluetooth, Wi-Fi cellular, bio-sensors, ambient light sensors, and speakers. The intended use of the device makes a significant difference in the complexity of the device, but even consumer-grade AR glasses have 10 or more sensors to provide the appropriate information to the user. This demonstrates that even simple, consumer-grade AR products are complex computers.

Although AR and VR share common technology, AR is different from VR in many ways. Both technologies stimulate one's senses through computer inputs. Peddie states, "VR replaces the real world with a simulated one."[98] The user does not see or interact with the real world while in a virtual environment. The real world is totally obscured, and if done correctly, the user has no reference to his actual place or time. VR gives the user three degrees of freedom while AR provides six degrees of freedom.[99] "Six degrees of freedom" refer to the ability to move in the *x*, *y*, *z* planes as well as pitch, yaw, and roll, which means rotation around and across the axis. Usually, in a virtual environment, the user can only view in three rotational movements but cannot move physically about the virtual space. The examples of Google Cardboard or a 360-degree visual photograph depict three degrees of freedom.[100] The ability to move physically about in a virtual world is limited whereas an AR environment is unlimited. VR is useful in training when it is necessary to create a fully immersive situation and all of the elements that the person would encounter. AR is more appropriate than VR when the person's focus on the real world must be maintained. In a virtual training situation in which participants across the globe using different systems are participating in the same simulation, VR distributed mission training could be used to feed everyone the same scenario at the same time, but an AR training situation could include moving through a real environment with augmented variables to which the participant reacts.

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[98] Peddie, 20.

[99] Peddie, 55.

[100] Christiane Snyder, "Part 3: Degrees of Freedom," Leading Ones, July 4, 2016, http://www.leadingones.com/articles/intro-to-vr-4.html.

This technology is not new to developers and researchers. In the 1970s, government research was taking place at NASA's Ames Research Center, the United States Air Force Armstrong Laboratory, and Wright-Patterson Air Force Base in Ohio.[101] The Air Force of South Africa first deployed gunsight technology mounted in the helmet. The United States Navy was the first to field the Visual Target Acquisition System, an operational helmet-mounted sight system in a fighter jet. These researchers worked to connect aircraft operators with weapon systems and aircraft controls using AR to supplement the aircrew's view of the world with flight information and targeting tools in the line of sight.

The corporate world has invested a great deal in AR research. Newport News Shipbuilding developed a project to design and build ships using AR. The company called it Drawingless Deckplate, and by 2017, the developers had more than 30 projects completed or in the pipeline.[102] The development of AR solutions is becoming less technical. Apple has recently released ARkit, a developer package for coders to develop AR solutions for Apple IOS devices. This provides a toolbox to guide developers through the process. As a result, Apple's App Store includes AR-enabled applications from IKEA, American Airlines, and hundreds of others. Innovators have released AR ski goggles and motorcycle helmets with heads-up displays that show navigation, messaging, and other relevant information to the user.[103]

With all this development, the fire service has not yet leveraged AR technology. Firefighters almost always wear a mask when involved in a structural firefight. AR technology may provide information in this mask view that helps firefighters know their location and the environmental conditions. Fire officers almost always temporarily give up the use of one hand to utilize a thermal camera to guide their crews.[104] Incident

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[101] John W. Lyons, "Reflections on Over Fifty Years in Research and Development: Some Lessons Learned" (Washington, DC: National Defense University, February 2012), https://doi.org/10.21236/ADA559598.

[102] Peddie, *Augmented Reality*, 133.

[103] "RideOn - The AR Lifestyle," RideOn, accessed June 25, 2018, https://www.rideonvision.com/new/.

[104] Qwake Technologies, "Home Page."

commanders use building floor plans at the command post to guide interior crews. The opportunities are great to use AR in the structural fire environment.

H. SPECTRAL EDGE IMAGE FUSION

Thermal image technology has been widespread in the fire service, and as mentioned in the AR section, the thermal image can display in the head mask. An enhancement of the thermal image has been developed to improve the information in the display. This enhancement, called spectral image fusion, combines multiple images into one to augment the view. Spectral edge image fusion uses an algorithm to combine multispectral input images into a visual spectrum that enhances imagery by defining the outlines of items in the field of view. Figure 6 shows the three different spectral images. The visible, thermal, and enhanced detail from the algorithm combine to produce the far right image, bringing all the data together. This technology is used to detect edges and bring more clarity to the thermal image.[105] FLIR, a leading manufacturer of thermal imagery, is using a multi-spectral dynamic imaging type of intelligence in its FLIR MSX. The increased definition of the image improves navigation for the user as it diminishes the challenges of darkness and depth.

[105] Alex E. Hayes, Roberto Montagna, and Graham D. Finlayson, "New Applications of Spectral Edge Image Fusion," in *Proceedings of the Society of Photo-Optical Instrumentation Engineers 9840, Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery*, ed. Miguel Velez-Reyes and David W. Messinger (Baltimore: Society of Photo-Optical Instrumentation Engineers, 2016), 984009, https://doi.org/10.1117/12.2223703.

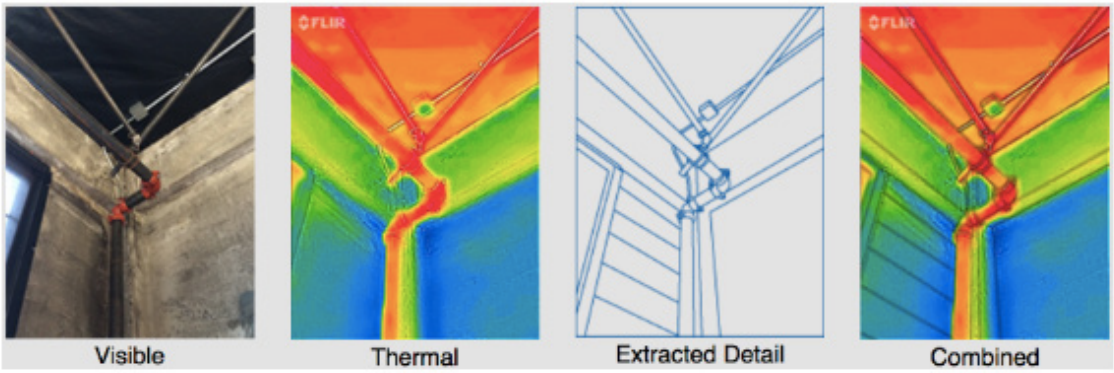

Figure 6. MSX Technology[106]

Qwake Technology has developed the C-Thru operating system to improve situational awareness in fire environments. The company has created a solution to assist in navigation through zero-visibility environments that incorporates a thermal camera, a high-speed camera, edge detection, and data streaming into a heads-up display that fits into the firefighters' self-contained breathing apparatus (SCBA) masks. The system connects the interior crews with incident command, providing the firefighter's point of view and location to command. In testing done by the Menlo Park Fire Department in California, crews using the system navigated the test environment 267 percent faster than the control group.[107] Thus, the optical clarity in places with obscured visibility can be enhanced. The enhanced visual features are an incremental step in bringing awareness to responders. Incorporating this technology into handheld thermal image cameras will be a step toward a solution.

I. CONCLUSION

There are different ways to define a location, and each one is useful in a specific context. Two parties must have a shared understanding of the reference system being used for the position transmitted to be meaningful to the party receiving the information. In navigation, moving from one point to another can be assisted with technology. If the two

[106] Source: "FLIR E75 Termocamera," Batter Fly, accessed March 27, 2019, https://www.batterfly.com/shop/flir-e75-42.

[107] Qwake Technologies, "Home Page."

points are also known to the technology, a person can be routed between these two points. The most widely distributed navigation system is GPS; this technology uses absolute location.

Technology needs reference locations to run algorithms to help in calculating the new position as the device moves. Many interior navigation systems are built around RF-enabled devices; reference points must be identified and distributed in a high enough density to be useful. These systems are dependent on fingerprinting or signal-speed measurements. Wi-Fi navigation systems are built around the location of access points that transmit their signal to a receiving device. Bluetooth systems require the distribution of enabled beacons; once again, the density of these beacons determines the accuracy of the system. RFID location systems use tags, which come in numerous types and capabilities: active, passive, HF, and UHF. These tags must be deployed in the space. Researchers have tested both pre-deployed and actively deployed systems. The difference is that pre-deployed systems are established and set up whereas responders complete actively deployed systems by dropping reference pucks that define different landmarks. As with all systems, the density of the distribution matters, and in actively deployed systems, the density of the deployment is minimal.

The NextNav system is different from the aforementioned systems as it works with exterior-located transmitters on a frequency that can penetrate interior spaces and supplement GPS-enabled devices. The system is constructed in a community with specific goals and functional areas defined at the time of design, and the system uses cellular signals to communicate with the transmitters. Signal speed and accurate time syncing are used to determine the location on the x, y, and z planes. This system has been demonstrated to accurately predict the location in high-rise buildings, meaning it can determine what floor a device is on. Another advantage of this system is the lower distribution density required to build the system.

AR is not a navigation system but a useful tool in allowing a person to have visual clarity in a space. AR systems require complex image processing. Sensors must be used to determine the exact direction the viewer is looking and depend on precise locations. Spectral edge image fusion is similar to AR systems in bringing visual clarity but needs

fewer accurate sensors and less location information. This system takes the advantages of cameras on the device; it still requires complex image processing but allows responders to visualize the spaces they are in more clearly.

Each one of these systems has advantages and disadvantages; all of the RF systems share the need for accurate floor plans and building plans. The distribution and plotting of devices for Bluetooth and RFID systems will require extensive person-hours, and any changes in a building's layout will require the replication of the process. Wi-Fi networks will also require a comprehensive mapping of signal strength, which will require follow-up measurements on a schedule to maintain the accuracy of any system that is developed. Opportunities to create a viable interior navigation system for the fire service are present in these technologies. Unfortunately, they also come with significant challenges.

IV. INTERIOR NAVIGATION APPLIED TO THE FIRE SERVICE

What does interior navigation mean to the fire service? This chapter explores the opportunities created by this technology. The chapter outlines the fire problem in the United States and describes how navigation deficiencies are leading to the loss of life and property loss. It starts with operational considerations, such as situational and spatial awareness, and then moves into the economic and training impacts that will be faced in implementing this new technology. Any one of the technologies discussed—Bluetooth, RFID, Wi-Fi, terrestrial transmitters, or AR—will create significant shifts in the fire service. If successful, the technology can create a safer work environment and reduce fire fatalities.

A. SITUATIONAL AWARENESS

Situational awareness is important for understanding what is going on and what is likely to occur next, and it is vital for preventing situations from escalating. Situational awareness is not new and has been studied extensively in the aviation industry. Oswald Boelke first acknowledged the importance of situational awareness (SA) in "gaining awareness of the enemy before the enemy gained the same advantage."[108] The aviation industry, where air traffic controllers and pilots were pressured to gain better SA, heartily embraced the idea. According to Kaber and Endsley, three characteristics relate to a loss of SA: "multiple goals pursued simultaneously[,] . . . multiple tasks having different relevance to goals competing for [the] operator's attention[, and] . . . performance under stress and negative consequences associated with poor performance."[109] Some of the failure factors of SA include the absence of communication, the failure of humans to perceive clues as serious, the failure to decipher information perceived, and the failure to comprehend individual tasks and the responsibilities of others.[110] Maintaining SA is a

[108] N. A. Stanton, P. R. G. Chambers, and J. Piggott, "Situational Awareness and Safety," *Safety Science* 39, no. 3 (December 2001): 189, https://doi.org/10.1016/S0925-7535(01)00010-8.

[109] Stanton, Chambers, and Piggott, 191.

[110] Stanton, Chambers, and Piggott, 191.

three-step hierarchical process: perception, comprehension, and prediction. The operator perceives the environment, comprehends what is happening, and predicts what is likely to happen based on the information gained in the first two steps. People who have lost SA are slower to detect problems, require additional time to diagnose problems, and cannot perform remedial activities.[111]

Effective fire operations require good situational awareness. Similar to aviators, firefighters must know where the problem is located, who is responding, where the other operators are located, and what the objectives are of each company on scene. Firefighters must perceive the environment, comprehend what is happening, and make predictions about what will happen in the future. Decisions must be based on reliable and timely information. Responders face dangers every day, and they manage complex events with uncertainty.[112] The responders communicate the details of incidents as they occur to share what is happening and what is anticipated. The purpose of this exchange is to protect life, property, and the well-being of the community.[113] Demarco points out in his thesis that miscommunication and confusion "contribute to the loss of life [and] property, and squandering [of] resources," despite improvements in wireless communication.[114] In his research to identify a visual language for situational awareness, David De Marco warns, "Responders['] reliance on voice communication for information exchange has repeatedly failed to provide the necessary situational awareness required to support decision making."[115]

Some steps to improve SA include the following: reducing the need for operators to make calculations; presenting data that make understanding and prediction easier; organizing information in relation to assigned goals; providing critical clues to capture attention; sharing goals globally across all involved parties; providing data multi-modally,

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[111] Stanton, Chambers, and Piggott, 199.

[112] David L. De Marco, "A Visual Language for Situational Awareness" (master's thesis, Naval Postgraduate School, December 2016), 1, https://www.hsdl.org/?view&did=798788.

[113] De Marco, 1.

[114] De Marco, xvii.

[115] De Marco, xvii.

not sequentially; and assisting in prediction.[116] Indoor navigation can assist responders in maintaining situational awareness. Removing the stress of navigation without sight—improving routing and allowing responders to focus on other critical tasks—will improve performance.

B. SPATIAL AWARENESS AND LOST FIREFIGHTERS

Firefighting is high-risk work. Since 1977, there have been 4,580 line-of-duty deaths of firefighters.[117] There have also been 3,184,930 firefighter injuries in the line of duty since 1981. Of those injuries, 229,395 were on the emergency fire scene during fire operations from 2010 to 2017.[118] The National Institute of Health and Occupational Safety maintains a database of firefighter line-of-duty death (LODD) investigations. As of April 2019, NIOSH had published 660 such reports. A query of this dataset resulted in 207 reports that contain "lost" in the description of the death.[119] Many of these events included multiple firefighter deaths.[120] Significant events that resulted in multiple firefighter deaths as a result of firefighters getting lost include the July 1, 1988, auto dealership fire in Hackensack, New Jersey, where five firefighters were killed. A supermarket fire in New York, New York, on August 2, 1978, resulted in six firefighter deaths. A December 3, 1999, fire in a Worcester, Massachusetts, warehouse, as mentioned earlier, resulted in six fatalities. Nine firefighters were killed in Charleston, South Carolina, on June 18, 2007, in a furniture store fire. Firefighting is high risk, and the environment in large complex structures makes it even more dangerous.

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[116] Stanton, Chambers, and Piggott, "Situational Awareness and Safety," 202.

[117] "Firefighter Deaths," National Fire Protection Association, accessed April 18, 2019, https://www.nfpa.org/News-and-Research/Data-research-and-tools/Emergency-Responders/Firefighter-fatalities-in-the-United-States/Firefighter-deaths.

[118] National Fire Protection Association.

[119] "207 Results Returned for Lost," Centers for Disease Control and Prevention, accessed July 11, 2019, https://search.cdc.gov/search/?affiliate=cdc-main&query=Lost&sitelimit=www.cdc.gov%2Fniosh%2Ffire%2F&dpage=1.

[120] "Deadliest Fires with 5 or More Firefighter Deaths at the Fire Ground: 1977–2016," National Fire Protection Association, accessed April 18, 2019, https://www.nfpa.org/News-and-Research/Data-research-and-tools/Emergency-Responders/Firefighter-fatalities-in-the-United-States/Deadliest-fires-with-5-or-more-firefighter-deaths-at-the-fire-ground.

Firefighters getting lost is a significant problem for the industry. The following summaries from the NIOSH reports reveal some of the findings.

> On December 9, 2014, a 37-year-old female career fire fighter/EMT died after becoming lost and running out of air in a residential structure fire. The fire fighter/EMT was the third fire fighter on a hoseline crew attacking the fire when the fire overran their position. One fire fighter and the officer escaped, but the fire fighter/EMT was trapped and radioed a Mayday. However, before she could be located, her buddy breather hoseline burnt through and she lost her available air.[121]

This firefighter radioed to her peers and informed them that she was lost inside the structure, looking for assistance. They had some time to assist her before her air system was compromised. Unfortunately, they did not know her location, and she was unable to give a better location to her would-be rescuers.

The summaries are replete with examples of firefighters getting lost and requesting assistance.

> On October 29, 2008, a 24-year old male volunteer fire fighter (the victim) was fatally injured while fighting a residential structure fire. The victim, one of three fire fighters on scene, entered the residential structure by himself through a carport door with a partially charged 1½-in hose line; he became lost in thick black smoke. The victim radioed individuals on the fireground to get him out. Fire fighters were unable to locate the victim after he entered the structure which became engulfed in flames. The victim was caught in a flashover and was unable to escape the fire. Approximately an hour after the victim entered the structure alone, a police officer looking through the kitchen window noticed the victim's hand resting on a kitchen counter; the victim was nine feet from the carport door he had entered. The victim was removed from the structure and pronounced dead at the scene by emergency medical services.[122]

Once again, in the 2008 example, the firefighter knew he was in trouble, and he radioed for assistance. The crew attempting to rescue him did not know his location and was unable

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[121] National Institute for Occupational Safety and Health, *Career Female Fire Fighter Dies after Becoming Lost and Running Out of Air in a Residential Structure Fire—Pennsylvania*, Report F2014-15 (Washington, DC: National Institute for Occupational Safety and Health, March 21, 2017), https://doi.org/10.26616/NIOSHFFFACEF201425.

[122] National Institute for Occupational Safety and Health, *Volunteer Fire Fighter Dies while Lost in Residential Structure Fire—Alabama*, Report F2008-34 (Washington, DC: National Institute for Occupational Safety and Health, June 11, 2009), https://www.cdc.gov/niosh/fire/reports/face200834.html.

to gather that information in a timely fashion.[123] Case after case demonstrated similar findings—a firefighter became disoriented in the space, lost spatial awareness, ran out of air supply, and called for help as the conditions deteriorated. The firefighters attempting the rescue tried to determine the missing firefighter's location to focus rescue efforts, but they did not know where to search.

The findings of the Worcester incident were even more troubling. On December 3, 1999, a fire was reported in a warehouse structure; two firefighters were ordered in to look for homeless people that were believed to be inside. These firefighters got lost; they were unsure of their location, but they were able to call for help. Four more firefighters lost their way searching for the original homeless and the lost firefighters. These firefighters also radioed to command that they were lost and running out of air. They needed assistance quickly. Help never arrived as nobody knew how to navigate the building, and the lost firefighters were unable to report their location accurately.[124]

NIOSH describes simply the case known among the fire service as the Charleston Nine: "On June 18, 2007, nine career fire fighters (all males, ages 27–56) died when they became disoriented and ran out of air in rapidly deteriorating conditions inside a burning commercial furniture showroom and warehouse facility."[125] Had these firefighters had navigational tools, they may have been able to navigate to an egress point. The list of LODD reports covering lost firefighters appears in Appendix A.

The problem is not always getting lost. In a 2015 case study, NIOSH found, "A firefighter fell down an unsecured elevator shaft while searching for a smoldering fire in a

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[123] National Institute for Occupational Safety and Health.

[124] National Institute for Occupational Safety and Health, *Six Career Fire Fighters Killed in Cold-Storage and Warehouse Building Fire—Massachusetts*, Report F99-47 (Washington, DC: National Institute for Occupational Safety and Health, September 27, 2000), https://www.cdc.gov/niosh/fire/reports/face9947.html.

[125] National Institute for Occupational Safety and Health, *Nine Career Fire Fighters Die in Rapid Fire Progression at Commercial Furniture Showroom—South Carolina*, Report F2007-18 (Washington, DC: National Institute for Occupational Safety and Health, February 11, 2009), https://www.cdc.gov/niosh/fire/reports/face200718.html.

two story warehouse."[126] There were radio reports about the hole and hazard 90 seconds before this firefighter fell.[127] Operating in zero visibility is a risk even when the location is known. One of the recommendations from this investigation was that "fire departments, cities, and authorities having jurisdiction should consider developing systems that allow the integration of building information into the information available to responding crews during the initial dispatch."[128] Unfortunately, this is not an isolated event. The database has numerous other findings of firefighters falling through openings.

C. THE FIRE PROBLEM

The frequency of U.S. fires in residential structures is much greater than that of all other occupancy types. Between 2012 and 2016, more than 382,800 fires occurred in residential properties. This figure can be subdivided to provide a little more clarity: 246,203 of these fires were in single- and dual-family dwellings, and 109,202 were in apartments or multi-family structures.[129] The remainder were in other residential property types such as hotels or dormitories. Non-residential fires, including those outside or on special properties, totaled 24,207 during this period. Storage properties had 21,750 fires, and business/mercantile properties totaled 17,932. The next largest property type involved places of assembly with 15,009 reported fires between 2012 and 2016.[130] As a point of reference, the total reported fires for this period was 487,798. Fires occur frequently; in the United States, they are a problem that kills firefighters and citizens alike.

Fire departments' performance measures often include fire deaths. The loss of life from fires has decreased in the United States. In the early 1980s, the country averaged

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[126] National Institute for Occupational Safety and Health, *Career Fire Fighter Dies after Falling Down Unsecured Elevator Shaft while Searching for the Seat of a Smoldering Fire—Illinois*, Report F2015-18 (Washington, DC: National Institute for Occupational Safety and Health, June 26, 2017), 1, https://www.cdc.gov/niosh/fire/reports/face201518.html.

[127] National Institute for Occupational Safety and Health, i.

[128] National Institute for Occupational Safety and Health, 34.

[129] "Fires by Occupancy or Property Type," National Fire Protection Association, accessed April 18, 2019, https://www.nfpa.org/News-and-Research/Data-research-and-tools/US-Fire-Problem/Fires-by-occupancy-or-property-type.

[130] National Fire Protection Association.

5,712 fire deaths per year. Between 2012 and 2016, the average was 3,082 civilian fire deaths per year compared to the prior period of 2007–2011 when the average was 3,266 deaths.[131] Unfortunately, the downward trend has reversed, and since hitting a low of 2,855 deaths in 2012, the numbers have steadily increased.[132] In 2017, U.S. fire deaths climbed to a high of 3,400 for the decade.[133] The trend is evaluated in Figure 7. Time is a critical measure in survivability. If firefighters can locate fire victims more quickly, lives can be saved.

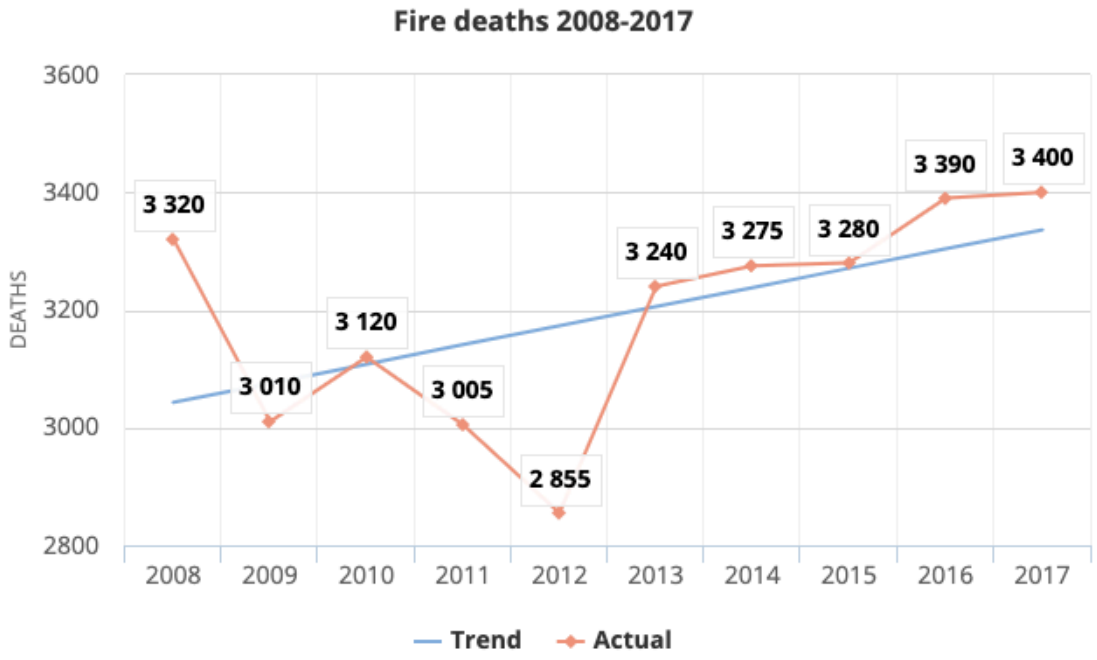

Figure 7. Fire Deaths per Year[134]

[131] National Fire Protection Association, "Firefighter Deaths."

[132] "U.S. Fire Statistics," U.S. Fire Administration, accessed February 11, 2019, https://www.usfa.fema.gov/data/statistics/index.html.

[133] U.S. Fire Administration.

[134] Source: U.S. Fire Administration, "U.S. Fire Statistics."

Firefighters are being killed and injured in the line of duty. One significant reason for these deaths, as identified by independent case studies, is that firefighters are getting lost. These lost firefighters can neither find an exit nor inform their rescuers of their location accurately enough to affect extrication. Residential fires account for the majority of firefighter deaths; however, business and mercantile structures seem to correlate with a higher risk for multiple firefighter death events.

D. ECONOMIC IMPACTS

The cost of fire in the United States has a significant economic impact. Can interior navigation technology for firefighters reduce the cost for the country? In 2017, the National Fire Protection Association (NFPA) published a comprehensive breakdown of the cost of fire in the United States. For this report, the authors defined the total cost of fire "as the collective of all net expenditures on fire protection and all net losses due to fire incidents."[135] The report evaluated the cost of fire between 1980 and 2104, as this was the most comprehensive dataset available. The findings of the NFPA report demonstrate the significant impact of fires in the country. Expenditures and losses account for 1.9 percent of the 2014 gross domestic product (GDP), or $328.5 billion.[136] Expenditures consist of $273.1 billion. Direct costs, including the cost of providing fire protection, equal $90.1 billion. Indirect costs include passive fire protection expenditures and insurance costs, including claims, premiums, and processing, totaling $183 billion. Active and passive fire protection measures make up the majority of these costs with the fire insurance costs accounting for $23.6 billion. [137] Figure 8 shows that the cost of fire in the United States has climbed over the years (50.3 percent), but as a percentage of the GDP, it has fallen by 75.3 percent.

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[135] Jun Zhuang et al., *Total Cost of Fire in the United States* (Quincy, MA: Fire Protection Research Foundation, October 2017), 7.

[136] Zhuang et al.

[137] Zhuang et al., 1.

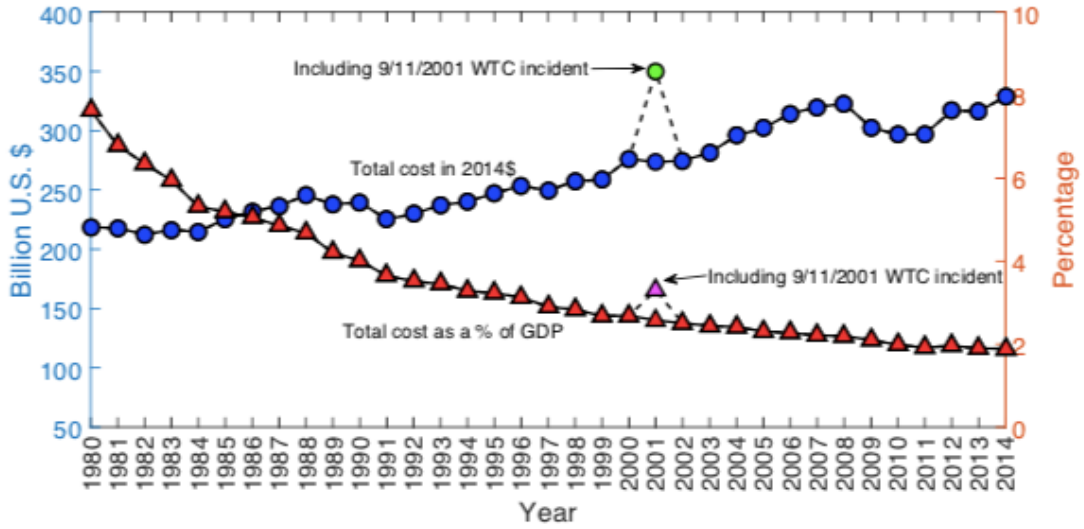

Figure 8. Changes in the Total Cost of Fire as a Percentage of the GDP over Time[138]

Economic losses have another substantial impact on society. When exploring the loss of fire in the United States, the report identifies direct and indirect losses. The authors define direct losses as human and property losses, and indirect losses are the "economic impact of fire."[139] Human economic losses are calculated using the value of statistical life (VSL), as defined by Anderson and Treich: "the monetary value of a mortality risk reduction that would prevent one statistical death."[140] NFPA researchers have also used the U.S. Department of Transportation's guidance for the VSL. The Department of Transportation defines the VSL "as the additional cost that individuals would be willing to bear for improvements in safety (that is, reductions in risks) that, in the aggregate, reduce the expected number of fatalities by one." [141] The VSL used in the researcher's calculations is $9.4 million, based on the Department of Transportation's revised guidance. Comparing

[138] Source: Zhuang et al., *Total Cost of Fire in the United States*, 4.

[139] Zhuang et al., 27.

[140] Henrik Andersson and Nicolas Treich, *The Value of a Statistical Life* (Linköping, Sweden: Swedish National Road and Transport Research Institute, 2008), 26.

[141] "Revised Departmental Guidance on Valuation of a Statistical Life in Economic Analysis," U.S. Department of Transportation, August 22, 2016, https://www.transportation.gov/office-policy/transportation-policy/revised-departmental-guidance-on-valuation-of-a-statistical-life-in-economic-analysis.

the NFPA statistics on fire deaths, both of civilians and responders, the average cost of human life due to fires between 1980 and 2014 was $43 billion per year. The total cost for the same period was $150.59 billion in direct human loss of life.[142] The trend line in Figure 9 clearly shows a positive trend in the rate of deaths from fire. However, more recent statistics show that the trend has reversed; since 2012, the United States has seen an increase in deaths once again.[143] The economic impact is still a significant cost to the U.S. economy.

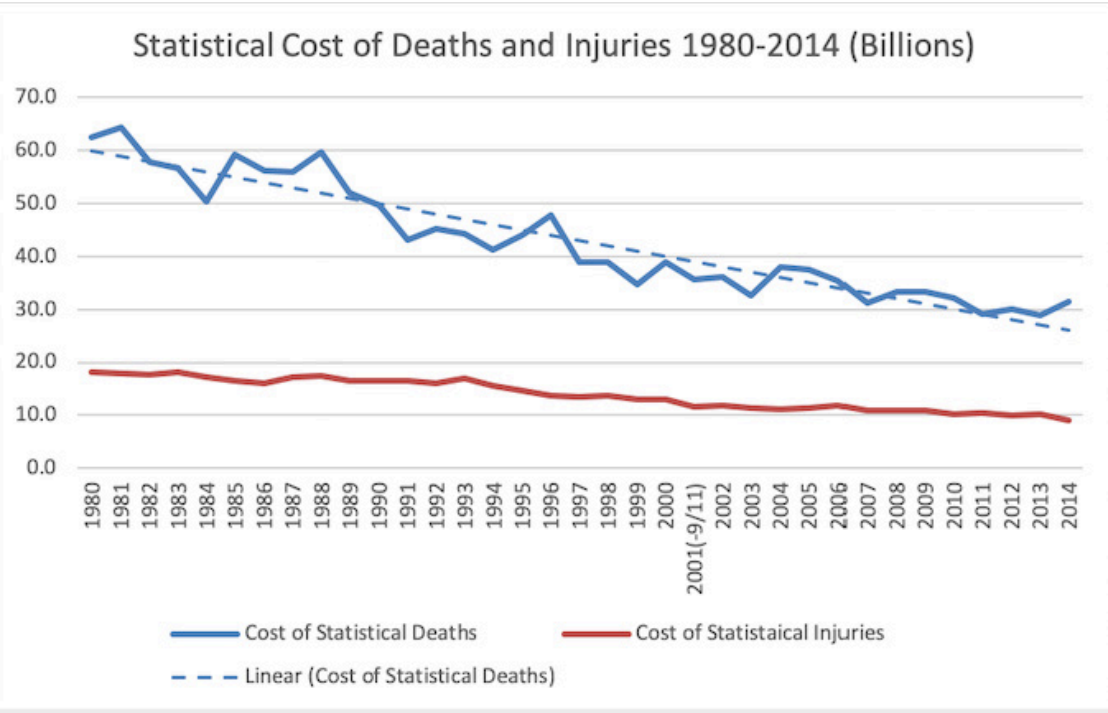

Figure 9. Statistical Cost of Death and Injuries[144]

Injuries from fires also have a high cost to the economy. When calculating the cost of fire-related injuries, NFPA researchers developed a similar value index called the value of statistical injury. This index helps to calculate the cost of preventing injuries. Each type

[142] Zhuang et al., *Total Cost of Fire in the United States*, 30.

[143] U.S. Fire Administration, "U.S. Fire Statistics."

[144] Source: Zhuang et al., *Total Cost of Fire in the United States*.

of accidental injury is rated using a scale of quality-adjusted life years compared to perfect health. An internationally recognized metric to determine injury severity is called the maximum abbreviated injury scale. This scale has six levels of injury: minor, moderate, serious, severe, critical, and unsurvivable.[145] Each of these levels of injury has a coefficient that can be applied to the VSL to determine a cost for each injury type. The civilian and firefighter injury statistics were broken down into levels based on the severity and duration. This measurement was calculated to find the impacts of these fire injuries. Injuries from fire average $13.9 billion in each of the years studied. Figure 10 shows the trend over time—it is also on a downward path. The total cost of fire injuries between 1980 and 2014 was $487.5 billion. Although the trend has gone in the correct direction, fire injuries to civilians and firefighters remain a significant cost to the U.S. economy.

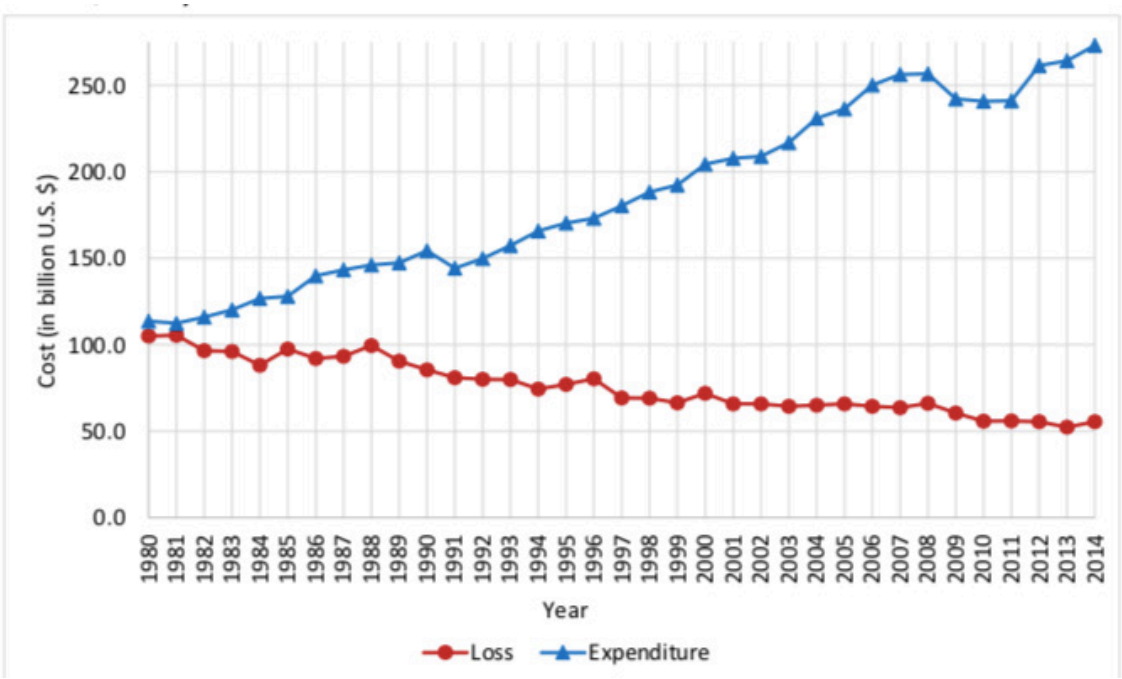

Figure 10. Trends of Expenditures and Losses[146]

[145] Suzanne Polinder et al., "Burden of Road Traffic Injuries: Disability-Adjusted Life Years in Relation to Hospitalization and the Maximum Abbreviated Injury Scale," *Accident Analysis & Prevention* 80 (July 2015): 193–200, https://doi.org/10.1016/j.aap.2015.04.013.

[146] Zhuang et al., *Total Cost of Fire in the United States*, 5.

One final point of discussion related to the economic cost of fire on society is the comparison of expenditures to losses. There has been an increasing gap between expenditures and losses. Figure 10 demonstrates the divergence of these two trend lines. Expenditures in 2014 were 1.9 percent of the GDP; this was a significant investment, and the opposing trend line in losses was a positive trend. Unfortunately, the research did not quantify whether the reductions in losses were from more effective fire operations and intervention or preventive expenditures. Zhuang et al. state, "The decreasing losses may be attributed, at least partly, to increasing successful fire interventions."[147] Having a better understanding of this correlation would allow fire departments to calculate the effectiveness of their expenditures in fire protection services, using this information to demonstrate the value the organization brings to the community.

The economic impacts are worth reviewing, as they are a considerable driver of the industry. There is a correlation between investments in fire protection and the reduction in lives and property lost. The NFPA researchers also associated improved fire intervention strategies as a means to reduce losses. Although the losses have gone in the desired direction, considerable impacts to the economy remain—$328.5 billion in 2014 alone. If indoor navigation can improve performance on the fireground, helping firefighters find victims sooner and control the fire earlier, these economic impacts will decrease even further.[148]

E. TRAINING

Firefighter training is an area that is evaluated in this thesis to discover areas for improvement. Firefighter training requirements are covered under numerous standards and are evaluated by these same agencies to ensure compliance. The standards define subjects that must be taught. Firefighter training requirements are set by the Occupational Safety and Health Administrations (OSHA), the National Fire Protection Association, and the

[147] Zhuang et al., 44.

[148] Zhuang et al.

Insurance Service Organization.[149] Navigation training and situational awareness receive little coverage within these standards, and there is little emphasis on the importance of firefighters maintaining awareness of their locations and routes through a building. This area, nevertheless, is often scrutinized when an accident or death occurs. NIOSH investigators review training records for all people involved in any firefighter death.

NFPA 1001 is the national standard for professional firefighter qualifications. This standard defines performance for uniformed fire service personnel. This standard defines the minimum job performance requirements, knowledge, skills, and abilities for anyone serving as a firefighter I or firefighter II. Section 4.3.9 defines the requirements for search and rescue operations. This standard requires that firefighters, as part of a team, conduct a search with obscured vision and wear personal protective clothing, a flashlight, forcible entry tool, and hose lines, or ladders if necessary. The objective is to search all areas of the structure, maintain safety, and remove all victims. The standard also requires the team to stay together and keep in communication. The NFPA standards refer to this as team integrity.[150] The supplemental information in the appendix of the NFPA standard discusses best practices for teaching these search and rescue skills. It states that more emphasis should be put on teaching avoidance of being trapped as opposed to self-survival techniques. NFPA 1001 mentions nothing else on how to maintain SA or ways to train firefighters to keep from getting lost.

NFPA 1410 establishes the training requirements for emergency scene operations. Section 3.3.43 of NFPA 1410 defines SA as the "ongoing activity of assessing what is going on during the complex and dynamic environment of a fire incident."[151] The supplemental information in the appendix expands on the requirement to state that

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[149] International Society of Fire Service Instructors, *Fire Department Required Training Self-Assessment Guide* (Centreville, VA: International Society of Fire Service Instructors, March 2015), https://www.fireengineering.com/content/dam/fe/online-articles/documents/2015/isfsi-2015-self-assessment-guide.pdf.

[150] National Fire Protection Association, *Standard for Fire Fighter Professional Qualifications*, NFPA 1001 (Quincy, MA: National Fire Protection Association, 2019), 3, https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=1001.

[151] National Fire Protection Association, *Standard on Training for Emergency Scene Operations*, NFPA 1410 (Quincy, MA: National Fire Protection Association, 2015), https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=1410.

"Operations are more effective and safer with continual observation of surroundings, communicating conditions to other members, and monitoring communications."[152] Section 11.4 of the same standard speaks to the required training for conducting search and rescue operations. The standard focuses on identifying areas of immediate attention: performing in a team of two people as well as training to use a rope or tagline, to use the vent-enter-isolate-search technique, and to remove victims. NFPA 1410 does not mention any other techniques to teach firefighters how to keep from getting disoriented. The standard does not require any training in SA; it only defines it in the list of definitions.

NFPA, OSHA, and ISO all require firefighters to be trained and tested on the NFPA 1001 standard before engaging in fireground operations. The minimum is 240 hours of training. The organizations also require ongoing training for firefighters to be compliant with best practices. According to the standards, firefighters must engage in company-level training, multi-company drills, night drills, and drills on structural firefighting.[153] Firefighters are not required to be trained or tested on any navigation skills before they engage in firefighting operations. In light of previous accidental deaths, this is a problem that needs to be addressed in future training schemes.

F. SUMMARY

This chapter explored the importance of indoor navigation to the fire service. Navigation and spatial awareness are essential survival skills for firefighters. Situational awareness is the knowledge of what is happening and what is likely to happen next. The term originates from the aviation industry, which has trained pilots to be more efficient in difficult situations. The industry also develops systems to prevent pilots from getting confused and squandering mental effort while determining what is occurring and what are the best steps to counteract the disruption. The loss of spatial awareness—or "getting lost"—is a real problem in the fire service. A query of NIOSH's LODD investigative reports identified more than 200 incidents in which firefighters were lost or disoriented before their deaths. In many of these incidents, multiple firefighters were lost. In case after

[152] National Fire Protection Association, 34.

[153] International Society of Fire Service Instructors, *Fire Department Required Training*.

case, firefighters reported that they were lost and in trouble, so incident commanders deployed rescue teams, but firefighters could not locate their peers. The frequency of firefighter deaths has been on a positive trend and slowly reducing since the 1990s. Since 2009, fewer than 100 firefighters per year have died in the line of duty.[154]

The fire problem in the United States is located predominately in residential structures; more fires occur in these types of occupancies than any other. Civilians are still dying in fires, most frequently in residential structures. The economic impacts of the U.S. fire problem are significant. The expenditures and losses equate to 1.9 percent of the GDP. While the expenditures have increased, the losses have also demonstrated a positive trend in reductions in direct and indirect losses. The VSL of $9.4 million leads to an average $43 billion per year in economic impacts from fire deaths and $13.9 billion in fire injury costs. Although the increase in expenditures is going up, the losses are going down. Nevertheless, there is insufficient evidence to determine whether intervention has contributed to this decline. However, the researchers did indicate there was at least a causal relationship between improved fire operations and reductions in fire losses.

Between the big three fire service regulatory and standard-making organizations—the NFPA, OSHA, and the Insurance Service Organization (ISO)—there are no explicit requirements that firefighters receive initial or ongoing training on maintaining situational awareness or interior navigation. NFPA 1410 does mention SA in section 3.3.43, which is a list of definitions, but no specific performance measure is defined in any of the documents. While the risk to the fire service comes in many areas, firefighters are getting lost in residential structure fires. These lost firefighters do not have a shared reference system to indicate to the crews outside where they are located. Some of them are dying. Even with this as a known problem in the industry, there is no formal training standard that discusses maintaining SA or navigation inside structures. The impact of this lack of training standards may be significant on the economy.

[154] National Fire Protection Association, "Firefighter Deaths."

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V. APPLICATION OF THE MISSION MODEL CANVAS

The MMC is a Lean Startup tool used to help visualize various aspects of innovation. This canvas is used in this thesis to identify which technology has the greatest chance of meeting the requirements of the fire service (the value proposition) and is assessed to have a high chance of being adopted. The canvas uses nine segments: buy-in, beneficiaries, deployment, mission achievement, value proposition, key partners, key activities, key resources, and mission cost. The nine segments encourage a deeper understanding of the customer, the problems being evaluated, and the solutions being suggested. This tool is innovative and allows comparisons of different solutions to the same problem. The specific details of every technology explored are beyond the scope of this endeavor. As each system will be custom designed and deployed for the specific situation, exploring every technology is not feasible. However, this research provides an initial analysis. The MMC helps to compare solutions to see which one has the broadest market fit. Under these circumstances, this chapter defines the segments and establishes the relationship of each segment to the fire service. It starts with the value proposition and beneficiaries followed by each of the other segments and ends with the mission cost.

A. VALUE PROPOSITION AND BENEFICIARIES

As discussed in *Business Model Generation*, a book by Osterwalder and Pigneur, the value proposition is a segment that is used to help innovators solve customer problems.[155] In the MMC, beneficiaries replace the customer segment. To identify the beneficiaries' problems, the customer must be clearly understood. For example, by applying the canvas, the jobs, pains, and gains of the fire service can be identified. The higher-level responsibility of the typical fire agency includes fire and emergency medical response and mitigation, prevention activities, specialized technical and hazardous response, prevention activities, inspections, and code enforcement. The pains associated with inadequate indoor navigation include loss of civilian and firefighter lives, reduced

[155] Osterwalder and Pigneur, *Business Model Generation*, 16.

efficiency in conducting search and rescue operations, poor situational awareness, longer response times, and poor planning. Line-of-duty death statistics have established these known pains.[156] The value proposition is the total package that provides the solution to the customer's problem.[157] For example, the value provided by indoor navigation systems addresses these pain points. Improved indoor navigation can provide shorter response times, improve efficiency and situational awareness, and save lives.

The public is another segment that needs to be considered vis-à-vis the financing of technological investment. Public money predominantly funds the fire service, through either direct tax expenditures or donations to support volunteer organizations. The public has a vested interest in any investment the fire service makes. This customer segment demands fiduciary responsibility, which is the appropriate expenditure of government funds. The general public supports safety, yet when expenditures are questionable, that support can erode quickly. Numerous fraud investigations have placed local fire agencies in an undesirable status with the public.[158] The public's confidence in government officials is crucial in supporting any investment in technology. No project will be implemented without the support of the public and consideration of their motivations.

Other beneficiaries with interest in this technology include the property owners, insurance industry, and municipal government. Property owners want to build safe, secure structures that will have full occupancies to generate the highest income or efficiency for the occupants. They typically want to build the structures for the lowest cost to meet the need of the space as designed by the architect. Introducing a large amount of technology that does not directly benefit the owner or the occupants is typically not supported by the builder's associations. The debate over the installation of fire sprinkler systems is an example. When Chicago mandated the installation of sprinkler systems in high-rise buildings, one Alderman stated that "the cost of installing fire sprinkler systems is a major

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[156] National Fire Protection Association, "Patterns of Firefighter Fireground Injuries."

[157] Osterwalder and Pigneur, *Business Model Generation*, 22.

[158] "Fraud Archives," *Fire Law Blog*, accessed January 25, 2019, http://www.firelawblog.com/tag/fraud/.

concern of property managers."[159] Many real estate professionals pushed for incentives or property tax relief versus mandates for this life safety equipment. The insurance industry was also a major player in this debate. In 1991, a high-rise structure in Philadelphia, One Meridian Plaza, burned. This fire on the 38th story burned to the only level of the operational sprinkler system, where it was finally extinguished. Three firefighters lost their lives, and it resulted in over one billion dollars in insurance claims. Damages from this event were in the hundreds of millions. Sprinkler systems reduce liability, and the insurance industry became an advocate for the protective systems.[160] The insurance industry wants to have the lowest possible level of risk. Each customer segment has an interest in innovation and has its own perspective. Property owners and government bodies often debate the extra cost while the insurance industry is interested in reducing losses. These customer segments will have a significant impact on the adoption of any technology.

All of the technology explored in Chapter III can provide some value and relief to the pains identified for the fire service. All the interior navigation systems based on RF technology provide some measure of accuracy that will inform responders about their location. The two predominant methods for calculating location—fingerprinting and triangulation—are affected greatly by the infrastructure. Each RF technology will improve in accuracy with more infrastructure and more reference devices installed. The system that provides the greatest value for one party may not be acceptable to the others based on different primary interests.

B. DEPLOYMENT

The way innovative projects are deployed is critical to their diffusion in the market. Any innovation must gain momentum to move across the continuum of diffusion. Everett Rodgers and Geoffrey Moore discuss the five categories of adoption: "innovators, early adopters, early majority, late majority, and laggards."[161] All innovations need champions

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[159] Institute of Real Estate Management, *Life Safety Laws: Sprinklers in High Rise Buildings* (Chicago: Institute of Real Estate Management, August 12, 2013), 17.

[160] Institute of Real Estate Management, 17.

[161] John T. Gourville, "Note on Innovation Diffusion: Rogers' Five Factors" (Boston: Harvard Business School, April 7, 2006), 6.

to help gain momentum for adoption. These champions are typically discovered at the beginning of the innovative process. Innovators and early adopters are more willing to try new things, even if they are slightly flawed. The two authors disagree about the next step: Rodgers believes that diffusion moves across the spectrum of adoption smoothly, but Moore concludes that a gap exists between the early adopters and the early majority. This gap is a big failure point for many innovations. After crossing between early adopters and the early majority, the rest of the diffusion follows the typical bell curve.[162]

To achieve deployment to the industry, Osterwalder and Pigneur explain that the startup must take the buyer through five phases: awareness, evaluation, purchase, delivery, and post-delivery. The buyer can be taken through the phases via different channels for each customer segment.[163] Awareness uses typical fire service models of trade shows and journal articles. Professional associations, including the International Association of Firefighters, the International Association of Fire Chiefs, the DHS Science and Technology Directorate, and the National Institute of Standards and Technology, all have an interest in helping to encourage awareness in reducing injuries and deaths. An evaluation of the technology across public safety and municipal government is critical to deployment. Test sites, pilot systems, and virtual demonstrations of the capabilities will facilitate evaluation for all potential users.

Completing a large purchase in the bureaucracy of government is not a quick, easy process. All state and local governments have different procurement laws. However, most large purchases require a request-for-proposal process or established contract. The U.S. General Services Administration is another purchasing mechanism that many state and local governments use to make large capital investments.[164] To facilitate a purchase, system providers need to establish open contracts with early adopters that can assist other agencies with completing the purchasing process.

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[162] Gourville.

[163] Osterwalder and Pigneur, *Business Model Generation*, 27.

[164] "Technology," U.S. General Services Administration, accessed February 18, 2019, https://www.gsa.gov/technology.

The final two phases of the deployment process—delivery and post-delivery—are most important in the future adoption of the technology. Too often, technology projects perform poorly, are over budget, or take years to complete. Ryan Nelson, a professor at the University of Virginia's Center for the Management of Information Technology, claims, "Two out of three IT projects fail."[165] He further contents that "this trend is not improving, and the failure rate is not decreasing."[166] Innovators and early adopters are tolerant of a few implementation hurdles. However, if any technology is going to be successfully deployed in the market, the implementation for the early majority must be painless and on budget. Post-delivery support must be aggressive at ensuring customer satisfaction and maintaining the operation of the system.

One of the challenges in this indoor navigation technology is gathering the data of the structures. The floor plans or visual maps are a critical component of the navigation system.[167] The deployment will be hampered by the availability of current floor plans of the structures. Most building departments require a set of plans at the time of construction and major renovation. These documents are normally paper copies delivered to the permit office. Older plans are rarely digitized, and the files are not maintained. It will be a significant undertaking to gather all floor plans in a community, determine whether the plans are current, and legislate a process to improve this information sharing. There are also risks to having floor plans readily available in semi-public databases. Nefarious actors might take advantage of these documents, using them to plan attacks. Most fire departments perform pre-fire planning visits and building inspections as well as inform the owners of the advantages of a rapid response. Many are provided structural plans upon request for this purpose. The digitizing of floor plans will lead to a large dataset that will have to be available to the devices that need the data. Downloading this information will require significant bandwidth and connectivity. If the floor plan data cannot be gathered, deployment of the technology will be significantly hampered. Navigating requires both a

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[165] R. Ryan Nelson, "Failures, Classic Mistakes, and Best Practices," *IT Project Management* (2007), 67.

[166] Nelson, 1.

[167] Markus Mild and Alexis Määttä Vinkler, "An Explorative Usability Study of Smartphone-Based Indoor Navigation" (master's thesis, KTH Royal Institute of Technology, 2013).

location and a reference point or map. Gathering all the required maps and floor plans will be a hindrance for the majority of the technologies identified as possible solutions. Public safety agencies will see this as a significant challenge to deployment.

C. BUY-IN/SUPPORT

Buying into the technology is critical in deployment and mission achievement. Steve Blank has advised, "Customer discovery helps you understand whose buy-in is needed in order to deploy the product/service . . . and how to get those beneficiaries to buy-in."[168] The public safety market is limited because the equipment for this market is highly specialized. The specialized market potentially reduces innovation as it is often not profitable due to the narrow customer base. Many innovators in this sector are already vested in the market, either offering new capabilities to their line or trying to increase penetration. Others are motivated by some intrinsic need to solve a public safety challenge.

Buy-in is created by establishing relationships with customers. In the public safety field, this relationship is established by placing one reliable piece of equipment into the field and then adapting that equipment to bring new and improved options. For example, the SCBA worn by all firefighters is a crucial part of any additional products. The Scott SCBA system is supported by the Pac-tracker, an RFID locating system mentioned earlier, as well as the face-mounted voice amplifier. The Mine Safety Appliance Company (MSA) SCBA is supported by system-mounted thermal image cameras on the air whip, and the A2 software allows incident commanders to monitor air levels of the responders on scene remotely. The users identify challenges and work with the vendors to find solutions to these problems. This co-creation builds lasting relationships as the customer becomes a part of the business team and vested in its success. Once a customer commits to a breathing apparatus, the operational dependencies with these other systems make breaking these relationships more difficult.[169]

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[168] Blank, "The Mission Model Canvas."

[169] Osterwalder and Pigneur, *Business Model Generation*, 29.

Constantly being supportive of the customer strengthens that relationship. Numerous standards govern the industry, easing the burden for the customer to stay in compliance with these standards and driving the demand for product replacement. Offering ways to reduce risk by improving safety is another way to build support. Brand loyalty is very much alive in the public safety industry; this loyalty is also built around user communities. Users come together for product discussions, product enhancement prioritization, road mapping, and innovation evaluations. The customer feels supported and included and also meets like-minded customers, which encourages acceptance of that technology or product line. Relationships with the customer are critical for building support and getting buy-in for new products.

D. MISSION ACHIEVEMENT

Mission achievement in the arena of indoor navigation means creating a system that allows public safety officials to navigate while indoors and have fixed reference points that can be shared with others. In Figure 11, a user device with a map and a route is shown in the bottom middle while the command view of all team members on a tablet is shown on the bottom left. Providing spatial awareness and the shortest route to a point is a critical capability for emergency response. Stopping firefighters from getting lost in structures and decreasing response times will save lives, especially in complex structures.[170] Once operational, the indoor navigation system must be reliable, accurate, and functional in hostile environments. The solution must be intuitive and easy to implement and require little maintenance.

[170] Uwe Rueppel and Kai Marcus Stuebbe, "BIM-Based Indoor-Emergency-Navigation-System for Complex Buildings," *Tsinghua Science and Technology* 13, no. S1 (October 2008): 362, https://doi.org/10.1016/S1007-0214(08)70175-5.

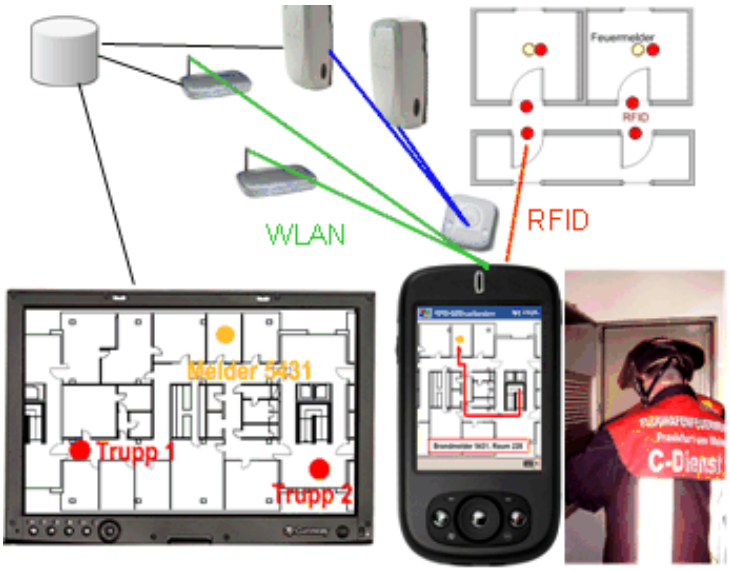

Figure 11. Indoor Navigation System (Command and User Devices)[171]

E. KEY RESOURCES/ASSETS/FINANCE

Key resources of the MMC are defined as physical, intellectual, human, and financial.[172] The physical resources are the equipment to make the system work, including the hardware, networks, displays, mobile devices, towers, and beacons. The intellectual property is the software and algorithms developed to make the system function. It is the knowledge needed to create a solution. Sometimes, this is sold as part of the purchasing process, but often, the software is licensed for use under the terms of the agreement, and the rights end when the contract term ends. The human resources necessary for the indoor navigation system will include engineers of various specializations; it will include subject-matter experts from the fire service. The software designers and coders will have a major role in the development and maintenance of the system. The system will also need trainers, a sales force, and legal and marketing support. If the solution requires the installation of equipment in private structures, legislative action may be necessary, requiring political action and lobbyists to assist in widespread deployment.

[171] Source: Rueppel and Stuebbe, "BIM-Based Indoor-Emergency-Navigation-System."

[172] Osterwalder and Pigneur, *Business Model Generation*, 34.

When considering finances, the system must be affordable. The municipal fire service is largely funded through tax dollars.[173] Expenditures must be weighed against all other community priorities. If the government ends up directly paying the costs, the deployment will be significantly delayed as capital funds are built up. The fire service will likely seek grant funding to support deployment. If legislative action requires that building owners install these systems, then the cost will be seen as an increased tax. This is where using existing systems may ease deployment and the burden on the financier of the project.

F. KEY PARTNERS AND SUPPLIERS

Key partnerships are critical to the successful implementation of a project of this scope. The fire service has numerous suppliers in the public safety equipment manufacturing business, and these suppliers tend to provide a broad scope of equipment to the public safety industry. A specialized public safety market supplier sells everything from fire apparatuses to gloves and everything in between. The technology industry is not as involved, but increasingly, more technology is being used in public safety. The need for intelligence gathering, police cameras, and microphone systems to pinpoint active shooting locations are bringing new technology partners to the industry.[174] The development of the First Responder Network Authority, a national public-safety broadband system that helps transfer data, has also increased the technology's investment in public safety.[175] Many new partnerships will be required for success. For indoor navigation, the wireless networking industry, as well as mobile device manufacturers, will need to be brought into the solution. All of the partners that can bring human resources with the knowledge to create a viable solution must be identified.

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[173] "Funding Alternatives for Emergency Medical and Fire Services," International Association of Fire Chiefs, accessed March 8, 2019, https://www.iafc.org/topics-and-tools/resources/resource/funding-alternatives-for-emergency-medical-and-fire-services.

[174] Chris Weller, "There's a Secret Technology in 90 US Cities That Listens for Gunfire 24/7," *Business Insider*, June 27, 2017, https://www.businessinsider.com/how-shotspotter-works-microphones-detecting-gunshots-2017-6.

[175] Linda K. Moore, *The First Responder Network (FirstNet) and Next-Generation Communications for Public Safety: Issues for Congress*, Report No. 7-5700 (Washington, DC: Congressional Research Service, June 17, 2016), 29.

The owners of structures will have to partner with public safety agencies to make floorplans and maps of complex buildings available for system success. Builders must submit plans upon construction and major renovations, and most municipal governments have a review process that involves the fire department. These plan reviews predominantly involve paper copies.[176] The paper review process could be streamlined for innovation that serves two purposes. Partnering with the building officials to gather these plans in a computer-aided design (CAD) file will reduce the burden on builders to produce numerous copies of plans and provide the information necessary for all future construction to assist in mapping and navigation. The International Alliance for Interoperability has developed standards for an information exchange format for buildings. The Industry Foundation Classes and green building eXtensible Markup Language were developed specifically for transferring building information in CAD files.[177] If the files are still available, they will be an efficient way to gather the necessary information. This will also reduce the burden on the development of a system. It will take strong partnerships to gather the information and to keep it accurate.

The Protected Critical Infrastructure Information (PCII) Program was established as part of the DHS's efforts to partner with the private sector to share critical information to protect essential systems and services. Under this framework, the private sector shares risk and protective measures with the government to improve situational awareness.[178] The same type of framework will be required at the state or local level to allow mapping information to be shared but protected from misappropriation. Once information is shared, the public sector will expect data privacy. Using a model such as the PCII system will help alleviate concerns of public-release Freedom of Information Act requirements that most governments must comply with. This methodology is a way to bring in partners.

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[176] "Fire Protection Systems Plans Review," Alexandria Fire Department, accessed March 8, 2019, https://www.alexandriava.gov/code/info/default.aspx?id=8892.

[177] Rueppel and Stuebbe, "BIM-Based Indoor-Emergency-Navigation-System," 366.

[178] "Protected Critical Infrastructure Information (PCII) Program," Department of Homeland Security, October 4, 2018, https://www.dhs.gov/pcii-program.

A project like indoor navigation is complex, and it will require participation from many different groups. Influencers will have to step up to bring others into the fold. Innovative organizations are recognizing the high risk of this environment, and the call for testing in the fire service is growing. Public safety equipment dealers will need to partner with the technology industry to bring a viable system to market. The partnerships that develop as a result of the convergence of different industries are likely to create numerous innovative systems to serve public safety.

G. INNOVATION ECOSYSTEM

The innovation process is rarely done in isolation; many improvements happen as a result of others' advancements. An ecosystem of innovation will be required to move any indoor navigation system to the consumer. This means that innovators will be obligated to partner with—or expand on the work of—other innovators until the solution is ready for the market. Ron Adner refers to this as complementary innovation. While this concept is not explicitly identified as part of the MMC, it is a substantial part of measuring the likelihood of success for all technology. This requirement for others to be successful brings risk to all the partners and the project success. Some of the risks that must be considered include how likely the project will encourage complementary development, what other development solutions must occur first, and who else must adopt or opt into the solution before it can be deployed to a broader market. More dependencies increase the likelihood that a project will be delayed or fail. After measuring these risks, the innovator can evaluate whether success is likely with the current plan or the scope of the project should be changed to reduce the dependencies and risks. The innovator can also determine whether the timing of the project is appropriate; otherwise, success may be more likely if the solution is delayed until partners complete their development.[179]

In applying the ecosystem concept to indoor navigation, it is clear that all of the technologies evaluated have several dependencies. The offerings are contingent on expert

[179] Ron Adner, "Match Your Innovation Strategy to Your Innovation Ecosystem," *Harvard Business Review*, April 2006, 12.

development and the deployment of other incremental solutions.[180] First, a system that accurately defines locations inside buildings must be developed. Once the absolute location is known, a shared reference system can be used to design a navigation system inside buildings. The devices that process the location data with a map will require an accessible database of floor plans based on location. Once the hardware is developed, it will need to be hardened to survive the structural fire environment. From there, a head-up display can be developed to provide navigation inside the firefighter's mask. Each of these incremental innovations will likely come from different sources. The synergy of a solution will come from the modernization of existing hardware and software as well as future development. Leaning further forward, new systems and technology may be developed to help citizens escape. Imagine a system similar to the Waze Traffic application that defines the safe way out of a structure based on sensor technology. Citizens might safely escape without the help of firefighters, and the system would inform firefighters of remaining occupants' locations. This technology would reduce the need for firefighters to search some occupancies. In sum, in a system with many dependencies, incremental innovation is the more likely way the whole ecosystem solution for indoor navigation will materialize.

H. KEY ACTIVITIES

In the key activities section of the MMC, Lean Startup defines critical activities that the company must perform to be successful. The BMC defines the main categories of key activities as production, problem-solving, and network/platform. The production area focuses on design and manufacturing. The problem-solving area focuses on knowledge management or finding new solutions to customer challenges. Finally, the network platform management category allocates delivery-of-services provisioning or promotes the platform. [181]

The fire service will not directly develop the indoor navigation system. The key activities for the fire service are to encourage others to invest in this area and to support research and testing until a viable solution emerges. By partnering with innovators, the fire

[180] Adner.

[181] Osterwalder and Pigneur, *Business Model Generation*, 37.

service can bring subject-matter expertise to the discussion. Most state procurement laws prohibit the development of products by government employees, so the fire service must be open to many companies and share information freely with all vendors that seek information and support. This will lead to better outcomes by leveraging advancements across a broader spectrum of companies. The fire service must push the government to invest in technology.

The municipal building and planning processes are areas where change will pave the way for easier data collection and more rapid deployment. A principal activity is to commit to the development of the electronic planning process and archival of planning documents.

I. MISSION COST

In the MMC, costs are described as the price of doing business and bringing products or services to market. Lean startups are either cost- or value-driven. Cost-driven businesses work to contain costs in all aspects of the business plan. In value, driving business costs is not as critical as creating value for the customer base. Both models have fixed and variable elements of the cost structure. Fixed costs do not change as the business scales up; for example, the rent and salaries of staff remain constant. Variable costs, on the other hand, fluctuate based on the volume of the operations. The economy of scale can lead to variability in pricing as larger purchases tend to get a lower price per piece for volume discounts. There is also an economy of scope whereby companies in broader markets can leverage existing core business services to support new business lines. In the public safety sector, this increase in scope occurs quite frequently. Manufacturers of one core product invest in new lines to expand the scope of the business.

J. CONCLUSION

The value proposition helps innovators solve problems for defined beneficiaries. In applying the MMC, the following beneficiaries were identified: the fire service, the public, property owners, the insurance industry, and local government. Each one of these can see some benefit from the development of interior navigation systems. Unfortunately, many will not see the value in the system as the problem will not be perceived in the same way

by each party. Few people recognize that they are likely to experience a fire in their building, so designing a system will not appear a viable investment.

Bureaucratic systems and logistical challenges will hamper the deployment of navigation systems. Innovators and early adopters will help bring awareness, but the government is not known for the quick adoption of new technologies. The distribution of public funds in government is often regulated, and the government is risk intolerant. Given that government projects have high rates of failure with significant cost overruns, it will be more challenging to shift to higher adoption rates.[182]

Buy-in within the fire service centers around relationships with product vendors. These relationships lead to joint product development and experimentation. Many of the products used in the industry are multi-functional or depend on other systems, such as the SCBA. Looking at technology development from an ecosystem approach, it is clear that incremental innovation is necessary. The partners in the system each bring more risk, add more time, and increase the failure rates. Building interest and showing a demand for the key fire service vendors that deal in technology and equipment will help create innovation in the field of navigation. The deaths in Worcester, in part, led to the testing and development of the PAK Tracker RFID system. It will take an industry push to encourage the market to experiment more in the area of interior navigation. The goal is to achieve the mission of developing an interior navigation system for public safety. The system needs to help responders define their location and navigate through structures quickly and safely. To achieve this mission, key resources like intellectual property, technology hardware, and financing will be required. The financial implications must be weighed against the other expenditures of government.

The public safety industry has started to embrace technology in other areas of operations. For example, incident and patient care reporting has been done on tablet computers. Law enforcement agencies have adopted license plate readers, body cameras, and e-ticketing; this expansion of technology is establishing new partnerships with different suppliers. Mobile devices are an instrumental part of this new technology. Mobile

[182] Nelson, "Failures, Classic Mistakes, and Best Practices."

devices are more likely to have components that are needed to support interior navigation. These suppliers are also more likely to have the developers on staff to build the code necessary to implement a solution. The building floor plans are also going to be required to overlay the location information for public safety to make use of the data. A system to securely share building floor plan information with developers and the government will require policy decisions that build trust with partners. The PCII system would be a good starting point for this data exchange.

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VI. FINDINGS AND RECOMMENDATIONS

Interior navigation for firefighters is a tool that can improve survivability for the public and firefighters. Several different technologies were explored in this research. The MMC was used to explore the likelihood of success for a technology of this type. If a company cannot create value and solve stakeholder problems, the product will never make it to market. The viability of developing a technology depends on a product's market fit and shared value between a beneficiary and the provider. This chapter begins with recommendations and answers the research questions. It goes on to discuss the limitations of this research and makes suggestions for future research.

A. FINDINGS

The literature review identified that interior navigation is a complex problem, and there are many ways to solve it. Ramirez et al. explained that the challenges created by firefighting operations compound this problem.[183] Many other scholars agree with this assessment, claiming that building out the infrastructure to support interior navigation will be very expensive.[184] The existing technology that is best suited to support navigation appears to come in the radio spectrum. Wi-Fi, Bluetooth, and RFID are all well distributed in the country and already used in many applications to track the location of physical devices.[185] RF systems are not the only options, and additional research is ongoing in the field of dead reckoning and movement tracking of humans. There appears to be a consensus that an indoor navigation system is technically possible, and the research, functional environmental systems have been developed.

Chapter III defined location as it relates to the fire service and explored different technologies identified as possible solutions to the problem. The review of these

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[183] Leonardo Ramirez, Sebastian Denef, and Tobias Dyrks, "Towards Human-Centered Support for Indoor Navigation," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York: ACM Press, 2009), 1279, https://doi.org/10.1145/1518701.1518893.

[184] Krishnamurthy, "Technologies for Positioning in Indoor Areas."

[185] Deak, Curran, and Condell, "Active and Passive Indoor Localisation Systems."

technologies noted that location is defined differently when communicated between individuals. Relative, symbolic, and absolute location can all be used to describe a place. If the sender of a message does not have a common reference system with the receiver, then a shared understanding of that place cannot be established.[186] In the fire service, a common understanding of the interior fire conditions and the locations of the crews must be established between the interior and exterior crews. The lack of accurately reported firefighter locations has led to many firefighter deaths.

Indoor navigation technology uses the same methodology as GPS. A transmitter and receiver exchange signals, and algorithms calculate the distance between the devices to determine the location. This location is then compared via scene fingerprinting, triangulation, and proximity to pre-established models to define the location on a visual indicator like a map. When comparing the different technologies, researchers use the system complexity, robustness, precision, accuracy, scalability, and financial implications to evaluate the differences. [187]

Wi-Fi navigation systems have received much attention because wireless access points are widely distributed in public places, and this density helps to support a system. The explosion of wireless networked devices is increasing, and the majority of U.S. citizens now have a Wi-Fi-enabled device with them at all times.[188] Building and maintaining a system using this technology is labor intensive. Han et al. needed to map over 200,000 points in a large mall to develop a viable system, and it took more than 15 people two weeks to do so. Once completed, the researchers said they lost accuracy within six months as the networks that had been mapped changed in strength and name, and some were no longer operational. In addition, building modifications changed the layout.[189] Thus, although this technology might be technically functional, it will not be a supported system due to the high implementation requirements and lack of dependability.

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[186] Hui et al., "Wireless Indoor Positioning Techniques and Systems."

[187] Hui et al.

[188] Karimi, *Indoor Wayfinding and Navigation*.

[189] Han et al., "Building a Practical Wi-Fi-Based Indoor Navigation System."

Bluetooth is another technology that has seen significant development and distribution in mobile devices. Bluetooth is highly standardized, so different manufacturers' devices can communicate with others. The performance and reliability are constantly evolving; the latest version of Bluetooth has twice the communication speed of previous versions.[190] Many retailers have explored using Bluetooth beacons inside stores to identify location and items of interest to shoppers if they have an app open while shopping.[191] Retailers place Bluetooth beacons in known locations, so the consumers' mobile devices can identify their relative locations in the store. This allows retailers to target ads or information to the customers based on their locations in the store. To deploy this type of system, beacons must be installed and mapped inside a space. Bluetooth systems also have maintenance issues, as the devices have batteries that need replacing. Bluetooth is an option that may help the firefighters find their relative location in a space, but once again, there are high implementation and maintenance requirements.

RFID navigation systems operate similarly to Bluetooth except that RFID tags (active or passive) replace the beacons. RFID is not as widely distributed in mobile devices, and most portable phones support only near-field communication in a short-distance RFID technology used for mobile payment applications.[192] There has been some development in RFID tracking systems for firefighters. After the Worcester event, Worcester Polytechnic Institute tested the Q-Track RFID reader as a firefighter-locating tool. Scott developed and brought to market the Pak Tracker, an RFID-enabled tracking device that can be used to locate a missing SCBA. In essence, this is a firefighter locating system. The system will help someone find a lost SCBA. All firefighters working in an environment that is immediately dangerous to life and health will be wearing an SCBA. The tracking device is a UHF proprietary device that points the user toward the RFID signal—think of the

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[190] Olevall and Fuchs, *Indoor Navigation and Personal Tracking System*.

[191] Olevall and Fuchs.

[192] James Thrasher, "RFID versus NFC: What's the Difference between NFC and RFID?," *RFID Insider* (blog), October 11, 2013, https://blog.atlasrfidstore.com/rfid-vs-nfc.

divining rod concept.[193] It does not help the firefighter know where he is. The location is not transmitted or provided to anyone to share a common reference point.

RFID tags are relatively inexpensive, so there is much exploration in this area. Researchers have developed pucks that can be dropped to mark waypoints for firefighters using the same concept as the Q-Track: firefighters are equipped with a reader to find the puck. In theory, if a firefighter knows where he dropped the puck, he can navigate the space.[194] RFID seems to have a high likelihood of producing a firefighter navigation system if standards can be developed and the industry embraces the concept. This type of system will also require significant effort to deploy and map, but maintenance will be less than a Wi-Fi or Bluetooth system. If the fire industry developed a standard that all doors, windows, and exits have a tag with specific signal indicators, firefighters across the country could be equipped with standard readers to find key landmarks. Eventually, the reader display would work its way in the display of the SCBA mask.

NextNav (terrestrial transmitter) is a relatively new system to hit the industry. This system boosts the capability of GPS and GPS-enabled devices. All mobile devices are already equipped to use GPS. The system requires that transmitters be installed in a community and coverage of the area is engineered for performance standards. This system can also accurately predict elevation, which is critical to urban and suburban fire departments.[195] The deployment of this type of system will require much less labor—and this system shows significant promise.

Augmented reality initially seemed like the right answer—putting the head-up display in the mask and providing a map—but the technical challenges were soon apparent. The device must know where the user is and what direction she is moving and looking. AR requires cameras and gyroscopes that must process the view to combine the images and make it relative to the scene.[196] In reality, AR is likely one of the most complex solutions.

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[193] Roberti, "Locating Firefighters with RFID."

[194] Ni et al., "LANDMARC."

[195] NextNav, "Technology."

[196] Peddie, *Augmented Reality*.

Providing accurate image processing based on complex sensors will require a great deal of computer equipment to be mounted on the firefighter, including on the head and mask. The AR will not work effectively in a hostile fire environment. Firefighters will not want to add more weight to their protective ensembles or their helmets.

Spectral edge image fusion is a middle-ground solution. This technology takes existing fire service equipment, mainly the thermal image camera that is widely distributed in the industry, and uses camera technology to enhance the image. Two manufacturers, Qwake and FLIR, have developed systems that leverage this technology. Both have demonstrated great success in enhancing SA in the fire environment. Qwake testing revealed significant reductions in search times in testing at Menlo Park. The wearer's view is also projected to the command post for incident commanders to share the view or point of reference.[197]

When the research explored the Lean Startup model to evaluate the business opportunity, some interesting things were discovered. The MMC helped identify the potential for any product to make it to market. The developer and the buyer must be able to generate value, and the other stakeholders will need to provide support. Indoor navigation system development will involve many stakeholders with divergent needs and desires. Identifying the beneficiaries and balancing these differences will be a significant challenge. The service will want to improve operations and save lives; building owners will want lower insurance premiums. One major participant will be the government, possibly multiple levels of government, but such participation will delay any project, and the government will want fiscal responsibility. As the fire service pushes for this technology, vendors in the industry will be the first to explore opportunities in the area of indoor navigation. This is the typical development routing. Similar to the RFID tracking systems that were developed after a tragedy, industry responds to a need. Once a product is developed, it will have to move through the product diffusion phases, innovators will help improve the technology and, eventually, the new product may become adopted in the marketplace.

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[197] Qwake Technologies, "Home Page."

Product delivery and post-delivery support will be crucial; the RF technologies will require extensive maintenance, ongoing support, and improvement as technology continues to evolve. Technological products have developed a history of coming in late and performing poorly.[198] If the deployment does not go well, the relationship will weaken, and support will drop. Buy-in is critical for increasing deployment and generating value. Innovators and early adopters need to be satisfied. To reach mission achievement, the system developed must be functional—it must allow firefighters to identify where they are and share that location through a common reference system.

The second half of the exploration of the model looked at all key elements of the innovation. The key resources are the intellectual property to make the system work as well as the funding to support development. Finances will be a big part of the challenge. It will take considerable investment to create the technology. These funds will need to be available upfront. Research grants may be a good option to secure this type of development. The key partners outside of the public safety equipment manufacturers will be property owners if systems need to be installed in public property. The DHS Science and Technology Directorate and the Defense Advanced Research Projects Agency may be good places to look for assistance with the research and development. The government will also be a key partner; if building owners are required to share private information about their structures, legislation will be needed to define how this information should be collected stored and utilized. The PCII system may be a good model to explore. The key activity for the fire service at this point is to share the challenges and the impacts of poor SA in the industry, point out the challenges faced by the fire service, and explain the impact on the community. Innovators need to know there is a problem, and the push needs to come from the industry so it can connect with an entity that wants to solve it.

Chapter IV explored the problem of poor navigation in the structural fire environment and why it is relevant. Firefighters can work more effectively if they maintain awareness of their location. Outside incident commanders can function more efficiently if they know where crews are working and what areas are being searched, extinguished, and

[198] Nelson, "Failures, Classic Mistakes, and Best Practices."

occupied. They can also deploy assistance to the proper location when things go wrong. Situational awareness mistakes were first addressed in the aviation industry, which quickly adopted tools and training to eliminate the breakdown of good SA. Firefighters become lost in buildings; all references to space are eliminated by smoke and darkness. Spatial awareness is critical to maintaining the ability to predict what is likely to happen next. When firefighters are lost, they often call for help, but they are unable to share their general location to receive appropriate assistance.[199] NIOSH's reports have identified incidents of routine calls going terribly wrong, and case after case has indicated similar problems. Interior navigation tools will reduce these events.

The fire problem in the United States is a significant cost to society. Firefighters and civilians are dying; the trend was on a downward path, but in the last decade, it has started to reverse.[200] At a VSL of $9.6 million, each death and injury has a significant impact on the economy. The expenditures on fire protection have continued to climb and are a significant part of the GPD. Fire losses had also headed in the appropriate direction, but recent history has tracked an increase in this area.

With all the lives lost and the investigative reporting completed, one might think the industry would mandate some training in response to these problems. A review of the training requirements has revealed that three significant fire service agencies—NFPA, OSHA, and ISO—have failed to require specific training on maintaining SA. They require no recurring training on the subject, but they do cover search procedures. The industry needs to add formal training on interior navigation and strategies for maintaining situational and spatial awareness. If more firefighters are tasked with exploring this problem, more innovation in how to tackle it will be encouraged.

There is a solution to this problem. Interior navigation is an item of considerable interest in the research and business fields. The fire service must encourage more research in this area, specifically for its needs. The industry must demonstrate the real cost in lives

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[199] Centers for Disease Control and Prevention, "207 Results Returned for Lost."

[200] U.S. Fire Administration, "U.S. Fire Statistics."

that this vulnerability has brought to the United States and its citizens. Even incremental steps to improve vision with an understanding of the space will make a difference.

B. RECOMMENDATIONS

What technology has the highest potential to be adopted to provide indoor navigation for firefighters in a structural fire environment? Spectral edge image fusion is the most likely market-ready solution to improve situational awareness and provide better spatial awareness. Unfortunately, all the other technologies explored are too complex or have extensive dependencies that prevent them from being market-ready investments. Manufacturers have taken the spectral image fusion as well as edge detection to the industry for field testing.[201] These field tests and demonstrations are generating more market push and encouraging development into products for deployment into the industry. Although these enhanced images do not provide navigation, they will improve vision, which will keep firefighters from getting lost. This will also provide disoriented firefighters the ability to describe their location to rescuers better. These appear to be excellent tools that can fill the gap sooner than any other system explored in this research. An SCBA mask with a display that uses edge detection has been developed. The company is advertising that sensor technology and artificial intelligence will be the next steps in bringing improved spatial knowledge to the responder.[202] The possibilities for incremental innovation in this area creates an ecosystem with less risk and better predictions for success. Thus, this technology is a good option to improve the situation, but it will not fix indoor navigation in the truest sense.

Another recommendation generated by this research is that additional training should serve as an alternative way to improve the situation in the short term. Changing the firefighter training standards is the path to improving efficiency and saving lives. The fire service is aware of the issue of firefighters getting lost—it has been identified in hundreds of LODD investigative reports. Increasing the mandatory training on the subject of spatial awareness and maintaining situational awareness is a non-technical complement to the

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[201] "Home Page," Smart Firefighting, accessed July 15, 2018, https://www.smartfirefighting.com/.

[202] Smart Firefighting.

alternatives proposed in this thesis. Firefighters need to be made aware of the best practices to maintain SA and spatial awareness. Improving predictions of what the conditions are indicating and taking actions based on likely outcomes is another way to reduce firefighter loss of life. Adding mandatory training into the national standards at basic levels for firefighter standards, including refresher training and continuing education, can supplement all of the technology.

The longer-term solution that is not quite market-ready involves the GPS supplemental systems using terrestrial transmitters.[203] These systems can improve functions and help firefighters know where they are. The altitude information provided by the terrestrial transmitters is essential for firefighters to identify building floor levels. The hardware to utilize this type of system is available in most mobile devices today. This system does not require any installation of location markers inside buildings or mapping of building interiors, and it will cover an entire community or vast areas. Maintenance of the system, of the transmitters, is the manufacturers' responsibility. The terrestrial transmitter technology is the one most likely to gain support with the least labor impact, so it may be financially reasonable. The challenge to this system, which has yet to be overcome, is the floor plans that will have to be provided or created for complex structures. These floor plans will then need to be geo-coded to be pulled from the database when used in that area. The technology will need to be incorporated into firefighters' gear, most likely with the other electronics in the SCBA. A supplemental display will need to be added to the mask. As the navigation will be needed when a firefighter is on and off air, the mask display may be similar to a video game map that is brought up to show the field of play. This will require the terrestrial transmitter manufacturers to partner with SCBA or thermal image manufacturers to break into the market. GPS supplemental systems appear to be a viable business opportunity to create value, solve a problem, save lives, and affect the U.S. economy. Table 1 summarizes the technological strengths and weaknesses as well as the potential for mission success from a business perspective.

[203] NextNav, "Technology."

Table 1. Recommendation Summary

Technology	Technical		Business
	Strengths	Weaknesses	Achieve Mission Success
Spectral Fusion	Easy addition to current technology	Does not provide actual navigation	Does provide spatial awareness that will improve navigation but does not provide any mapping or guidance
Terrestrial Transmitters	Support GPS signals and function like outdoor navigation systems	Expensive; limited to designed area; still need floorplans. Ecosystem not ready.	Yes, with additional development and testing. Boost existing systems and leverage current hardware.
RFID	Capable of providing location data	High implementation and high hardware requirements	Not without significant time and labor investment, continued maintenance
Wi-Fi			
Bluetooth	Beacons have been successfully deployed in retail.	Weak signals, high deployment, and set-up requirements	Not on a wide scale, could fill the gap in particular instances but unlikely to be adopted in the fire service
Augmented Reality	Provides visual guides relative to space	High technology demands and requires specific location	Will not solve the problem independently. Could be used if other systems are developed.

RFID and Bluetooth have more challenges to overcome and are not likely to gain much of the market. RFID technology is in use in the industry, and the tracking/divining rod example demonstrates that a successful application to find lost teammates is achievable. Unfortunately, this solution will not prevent the firefighter from getting lost. The deployable pucks with readers also have the potential to help firefighters leave and share landmarks or waypoints. This maintains some knowledge of the space and may be another way to break into the market. Finally, the idea of creating a standard for all doors, windows, and exits to be tagged presents a system to improve movement. This concept is not likely to gain traction as a value-producing business plan or from the industry. The idea of deploying hundreds of tags inside a structure and then mapping them will not garner much support for the fire service. The taxpayers or the public will not likely support the

cost of labor to develop and maintain such systems. Bluetooth has all the same challenges of RFID, and because it is built intentionally with a limited range, it is not likely to produce any new alternatives to serve as a navigation system. Beacons may be used in the same way as RFID pucks are deployed. Bluetooth technology has made its way into the SCBA for radio communication, so there are some opportunities for this technology to improve fire operations—but it is unlikely to be a good market fit as a navigational tool.

While conducting this research, it became apparent that this is a more complicated matter than initially believed. Exploring technology and business tools to encourage innovation in the field of indoor navigation revealed that there are many significant hurdles to develop a model that will generate value. Installing hundreds of location-marking devices in someone's building or occupancy may not be a popular idea. Having firefighters spend hundreds of hours installing and mapping structures will not be popular in the industry. Asking building owners to share floor plans in a government database for use by public safety will also not likely generate a great deal of buy-in or support. The ongoing maintenance needs for all of these RF systems is going to burdensome. There are real challenges to defining an indoor navigation system that will solve the fire service problem, which will generate profit for a business. One way to continue to keep the idea of a technological solution moving forward is to encourage strategic communications moving in the fire service community. The challenge will take many partners working together to create an innovation ecosystem that encourages complementary innovations.[204]

C. LIMITATIONS OF THE RESEARCH

This was exploratory research and, as such, did not involve actual trials and tests. Due mostly to time constraints, the research was kept at the theoretical level. Exploring others' research and working to gain an understanding of how the different technologies worked without using them in trials led to some suppositions. The research design was tailored to account for this weakness from the beginning. In order to devise a means for comparing technologies, a business model was applied from the Lean Startup business

[204] Adner, "Match Your Innovation Strategy to Your Innovation Ecosystem."

perspective. Identifying the technology that may solve customers' problems—and with which the company can make money—allowed the question to be answered about which technology offers the best market fit.

Much of the research evaluated was conducted in the testing environment, which might mean poor transportability to the structural fire environment. Setting up a testing scenario that included limited visibility, high noise, the wearing of an SCBA, and high heat would be a better model to test technological solutions to operate in that situation. Once again, time limitations prevented that type of research. At this time, the goal was to gather technical information to determine the needs of each system to compare them. The proper application of the MMC would have been to get out and speak with customers and key partners as well as evaluate and reevaluate the assumptions and market fit. As this was a theoretical evaluation, no product was being pitched, and neither was there a supplier to work with nor a model to show and try.

The use of NIOSH line-of-duty death investigative reports provided a post-incident analysis that also made assumptions about information that may not have been available. I know two of the investigators; they do everything possible to prevent filling in any gaps in the facts. If the information is not available, NIOSH reports just that. Unfortunately, the investigations are taking place because the primary witnesses are deceased. The reports cannot with absolute certainly define when the firefighters knew they were lost or what drove them to ignore a warning about a hole in the floor. Firefighter survivors, in similar situations, often report that they tried to solve the problem for a while before calling for help. The LODD reports give details as best as they can be ascertained.

The economics of the problem are based on assumptions and standard ways to calculate financial information. These standards have changed over the years; the further away from the current date, the greater the variability in the data. Which data are included in the last five years may be different from what was counted in the past. The value of statistical injury used to determine the cost of injuries is a relatively new methodology, and its accuracy is likely subject to greater variability as injuries have to be classified across

two different rating systems. The National Fire Incident Reporting System and the Maximum Abbreviated Injury Scale both classify injury data a little differently.[205]

Exploratory research is just that—it discovers a relatively new subject. This type of research helps to start conversations. It opens doors to evaluate what can be done next to start more in-depth research. The findings were that there are possible solutions and more immediate opportunities to make conditions better for firefighters working in this environment. Innovation and development are incremental processes, and the solution to indoor navigation is at the early stages of this process. Synthesis of a technological system is a few generations away from being field-tested in the fire service. The fire service needs to call out for help to solve this problem.

D. ADDITIONAL RESEARCH

This thesis was another step on the path to interior navigation in the structural fire environment—to solve this problem, save lives, and provide a business solution that was both possible and profitable. The application of terrestrial transmitters that enhance GPS signals and allow devices to index off these towers when they cannot communicate with satellites seems to be a potential leap forward. Research should be done to evaluate the capabilities of these systems in typical environments. Once they function in normal structures, the interior fire environment should be simulated. Finally, research that takes this capability to a display in the SCBA mask or on the handheld thermal image device must be done to implement a solution fully.

While the research in terrestrial systems takes place, spectral edge image fusion systems may continue to be pushed as a more immediate solution to saving lives. This technology has already been added to a firefighting mask and validated to deliver more rapid search times. More testing will create market demand and will lead to distribution in the industry.

[205] Zhuang et al., *Total Cost of Fire in the United States*.

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APPENDIX A. NIOSH LODD QUERY RESULTS

This table was generated using data from the Centers for Disease Control and Prevention, which hosts the National Institute for Occupational Safety and Health (NIOSH) Fire Fighter Fatality Investigation and Prevention Program reports at the following website: https://wwwn.cdc.gov/NIOSH-fire-fighter-face/Default.cshtml?state=ALL&Incident_Year=ALL&Submit=Submit. The data were filtered for reports that were relevant to the thesis subjects of navigation, lost firefighters, and situational awareness.

F2016-07	Apr 30, 2016	Volunteer fire fighter dies after running out of air and becoming disoriented in retail store in strip mall fire - North Carolina.	PDF
F2015-20	Dec 09, 2015	Volunteer fire fighter dies after inhaling super-heated gases at a residential structure fire - New York.	PDF
F2015-19	Dec 28, 2015	Fire fighter falls through floor and dies at residential structure fire - Ohio.	PDF
F2015-18	Dec 14, 2015	Career fire fighter dies after falling down unsecured elevator shaft while searching for the seat of a smoldering fire - Illinois.	PDF
F2015-13	Jun 28, 2015	Career fire fighter/engineer dies after falling through translucent corrugated roof panel while searching for fire extension - Colorado.	PDF
F2015-08	May 23, 2015	Career fire captain drowns after stepping into flooded storm drain during floodwater rescue - Oklahoma.	PDF
F2015-06	Mar 26, 2015	Career fire apparatus operator dies after falling down an unsecured elevator shaft at a 5-story residential structure - Ohio.	PDF
F2014-25	Dec 09, 2014	Career female fire fighter dies after becoming lost and running out of air in a residential structure fire - Pennsylvania.	PDF
F2014-24	Nov 12, 2014	Shift safety officer falls through hole in floor into basement of vacant row house and dies from smoke inhalation - Maryland.	PDF
F2014-19	Oct 07, 2014	Career fire fighter dies from an out-of-air emergency in an apartment building fire - Connecticut.	PDF
F2014-15	Jul 09, 2014	Career fire fighter dies in heavy smoke on second floor of a residential structure - Texas.	PDF
F2014-14	Jul 05, 2014	Career fire lieutenant dies in cluttered apartment fire on 19th floor of high-rise residential apartment building - New York.	PDF
F2014-02	Jan 26, 2014	Two career fire fighters die in a rapid fire progression while searching for tenants - Ohio.	PDF
F2013-17	May 20, 2013	Career fire fighter killed by structure collapse while conducting interior search for occupants following 4th alarm - Texas.	PDF
F2013-16	May 31, 2013	4 Career fire fighters killed and 16 fire fighters injured at commercial structure fire - Texas (revised).	PDF
F2013-14	May 08, 2013	Career probationary fire fighter runs out of air and dies in commercial structure fire - Michigan.	PDF
F2013-13	Apr 24, 2013	Volunteer fire fighter found unresponsive with his facepiece off dies eight days later - Maryland.	PDF

F2013-07	Apr 06, 2013	Career captain dies conducting roof operations at a commercial structure fire - Pennsylvania.	PDF
F2013-02	Jan 22, 2013	Volunteer captain dies after floor collapse traps him in basement - New York.	PDF
F2011-20	Aug 14, 2011	Career lieutenant dies after being trapped in the attic after falling through a roof while conducting ventilation - Texas.	PDF
F2011-18	Jul 28, 2011	Career captain dies and 9 fire fighters injured in a multistory medical building fire - North Carolina.	PDF
F2011-13	Jun 02, 2011	A career lieutenant and fire fighter/paramedic die in a hillside residential house fire - California.	PDF
F2011-02	Jan 19, 2011	Volunteer fire fighter caught in a rapid fire event during unprotected search, dies after facepiece lens melts - Maryland.	PDF
F2010-30	Jul 13, 2010	Seven career fire fighters injured at a metal recycling facility fire - California.	PDF
F2010-18	Jul 24, 2010	A career lieutenant and a career fire fighter found unresponsive at a residential structure fire - Connecticut.	PDF
F2010-16	Jul 03, 2010	Volunteer captain runs low on air, becomes disoriented, and dies while attempting to exit a large commercial structure - Texas.	PDF
F2010-13	May 22, 2010	Career fire fighter dies while conducting a search in a residential house fire - Kansas.	PDF
F2010-10	Mar 30, 2010	One career fire fighter/paramedic dies and a part-time fire fighter/paramedic is injured when caught in a residential structure flashover - Illinois.	PDF
F2009-23	Aug 24, 2009	Career lieutenant dies following floor collapse into basement fire and a career fire fighter dies attempting to rescue the career lieutenant - New York.	PDF
F2008-34	Oct 29, 2008	Volunteer fire fighter dies while lost in residential structure fire - Alabama.	PDF
F2008-08	Mar 05, 2008	Volunteer fire lieutenant killed while fighting a basement fire - Pennsylvania.	PDF
F2008-07	Mar 07, 2008	Two career fire fighters die and captain is burned when trapped during fire suppression operations at a millwork facility - North Carolina.	PDF
F2008-06	Feb 29, 2008	Volunteer fire fighter and trapped resident die and a volunteer lieutenant is injured following a duplex fire - Pennsylvania.	PDF
F2007-37	Aug 18, 2007	Two career fire fighters die following a seven-alarm fire in a high-rise building undergoing simultaneous deconstruction and asbestos abatement - New York.	PDF
F2007-32	Aug 29, 2007	Two career fire fighters die while making initial attack on a restaurant fire - Massachusetts.	PDF
F2007-29	Aug 03, 2007	A volunteer mutual aid captain and fire fighter die in a remodeled residential structure fire - Texas.	PDF
F2007-28	Jul 21, 2007	A career captain and an engineer die while conducting a primary search at a residential structure fire - California.	PDF
F2007-18	Jun 18, 2007	Nine career fire fighters die in rapid fire progression at commercial furniture showroom - South Carolina.	PDF
F2007-12	Apr 16, 2007	Career fire fighter dies in wind driven residential structure fire - Virginia.	PDF
F2007-09	Feb 09, 2007	Career probationary fire fighter dies while participating in a live-fire training evolution at an acquired structure - Maryland.	PDF
F2007-07	Nov 16, 2007	Volunteer fire fighter dies after falling through floor supported by engineered wooden-I beams at residential structure fire - Tennessee.	PDF
F2006-28	Oct 10, 2006	Career fire fighter dies in residential row house structure fire - Maryland.	PDF
F2006-27	Aug 27, 2006	Floor collapse at commercial structure fire claims the lives of one career lieutenant and one career fire fighter - New York.	PDF

F2006-26	Aug 13, 2006	Career engineer dies and fire fighter injured after falling through floor while conducting a primary search at a residential structure fire - Wisconsin.	PDF
F2006-24	Jun 25, 2006	Volunteer deputy fire chief dies after falling through floor hole in residential structure during fire attack - Indiana.	PDF
F2006-19	May 14, 2006	Career Lieutenant dies in residential structure fire - Colorado.	PDF
F2005-09	Feb 19, 2005	Career fire captain dies when trapped by partial roof collapse in a vacant house fire - Texas.	PDF
F2005-05	Jan 20, 2005	Career captain dies after running out of air at a residential structure fire - Michigan.	PDF
F2005-04	Jan 23, 2005	Career fire fighter dies while exiting residential basement fire - New York.	PDF
F2005-03	Jan 23, 2005	Career lieutenant and career fire fighter die and four career fire fighters are seriously injured during a three alarm apartment fire - New York.	PDF
F2005-02	Dec 20, 2004	One probationary career firefighter dies and four career firefighters are injured at a two - alarm residential structure fire - Texas.	PDF
F2004-17	Mar 13, 2004	Career battalion chief and career master fire fighter die and twenty-nine career fire fighters are injured during a five alarm church fire - Pennsylvania.	PDF
F2004-14	Apr 04, 2004	Career fire fighter dies and two career captains are injured while fighting night club arson fire - Texas.	PDF
F2004-05	Jan 09, 2004	Residential basement fire claims the life of career lieutenant - Pennsylvania.	PDF
F2004-04	Dec 16, 2003	Career fire fighter dies of carbon monoxide poisoning after becoming lost while searching for the seat of a fire in warehouse - New York.	PDF
F2004-02	Nov 29, 2003	Basement fire claims the life of volunteer fire fighter - Massachusetts.	PDF
F2003-28	Aug 08, 2003	Live-fire training exercise claims the life of one recruit fire fighter and injures four others - Florida.	PDF
F2003-12	Mar 31, 2003	Career fire fighter dies and two career fire fighters injured in a flashover during a house fire - Ohio.	PDF
F2002-43	Oct 09, 2002	Fire fighter dies after collapse at apartment building fire - Kentucky.	PDF
F2002-40	Sep 14, 2002	Career fire fighter dies after roof collapse following roof ventilation - Iowa.	PDF
F2002-34	Jul 30, 2002	Career lieutenant and fire fighter die in a flashover during a live-fire training evolution - Florida.	PDF
F2002-32	Jul 04, 2002	Structural collapse at residential fire claims lives of two volunteer fire chiefs and one career fire fighter - New Jersey.	PDF
F2002-20	May 03, 2002	Two career fire fighters die in four-alarm fire at two-story brick structure - Missouri.	PDF
F2002-19	Apr 10, 2002	Fire fighter dies during live fire training - North Carolina.	PDF
F2002-12	Mar 01, 2002	Volunteer fire fighter killed and career chief injured during residential house fire - Tennessee.	PDF
F2002-11	Mar 04, 2002	One career fire fighter dies and a captain is hospitalized after floor collapses in residential fire - North Carolina.	PDF
F2002-08	Aug 09, 2000	Fire fighter dies at kitchen fire - North Carolina.	PDF
F2002-07	Feb 11, 2002	One career fire fighter dies and another is injured after partial structural collapse - Texas.	PDF
F2002-06	Mar 07, 2002	First-floor collapse during residential basement fire claims the life of two fire fighters (career and volunteer) and injures a career fire fighter captain - New York.	PDF
F2001-38	Sep 25, 2001	Volunteer fire fighter dies and two others are injured during live-burn training - New York.	PDF
F2001-33	Oct 13, 2001	High-rise apartment fire claims the life of one career fire fighter (captain) and injures another career fire fighter (captain) - Texas.	PDF

F2001-27	Jun 16, 2001	Career fire fighter dies after single-family-residence house fire - South Carolina.	PDF
F2001-23	Jun 17, 2001	Hardware store explosion claims the lives of three career fire fighters - New York.	PDF
F2001-18	May 09, 2001	Career fire fighter dies after becoming trapped by fire in apartment building - New Jersey.	PDF
F2001-16	Mar 08, 2001	Career fire fighter dies after falling through the floor fighting a structure fire at a local residence - Ohio.	PDF
F2001-15	Mar 18, 2001	Residential fire claims the lives of two volunteer fire fighters and seriously injures an assistant chief - Missouri.	PDF
F2001-13	Mar 14, 2001	Supermarket fire claims the life of one career fire fighter and critically injures another career fire fighter - Arizona.	PDF
F2001-10	Dec 23, 2000	Fire fighter dies at house fire - New Hampshire.	PDF
F2001-08	Feb 17, 2001	Two volunteer fire fighters die fighting a basement fire - Illinois.	PDF
F2001-04	Jan 11, 2001	Volunteer fire fighter (lieutenant) killed and one fire fighter injured during mobile home fire - Pennsylvania.	PDF
F2000-44	Nov 25, 2000	Residential house fire claims the life of one career fire fighter - Florida.	PDF
F2000-43	Oct 29, 2000	A volunteer assistant chief was seriously injured and two volunteer fire fighters were injured while fighting a townhouse fire - Delaware.	PDF
F2000-34	Apr 26, 2000	Lieutenant dies at a fire in a one-and-one-half story dwelling - West Virginia.	PDF
F2000-26	Apr 20, 2000	Residential structure fire claims the life of one career fire fighter - Alabama.	PDF
F2000-24	Apr 11, 2000	Fire fighter dies during search-and-rescue training - Ohio.	PDF
F2000-23	Mar 31, 2000	Career fire fighter dies and three are injured in a residential garage fire - Utah.	PDF
F2000-16	Mar 03, 2000	Arson fire claims the life of one volunteer fire fighter and one civilian and severely injures another volunteer fire fighter - Michigan.	PDF
F2000-14	Feb 06, 2000	Fire fighter dies at a single-family dwelling fire - Iowa.	PDF
F2000-13	Feb 14, 2000	Restaurant fire claims the life of two career fire fighters - Texas.	PDF
F2000-09	Jan 27, 2000	Volunteer fire fighter dies fighting a structure fire at a local residence - Texas.	PDF
F2000-05	Dec 13, 1999	Fire fighter dies at a barn fire - Ohio.	PDF
F2000-04	Dec 22, 1999	Structure fire claims the lives of three career fire fighters and three children - Iowa.	PDF
99-F48	Dec 18, 1999	Warehouse fire claims the life of a battalion chief - Missouri.	PDF
99-F47	Dec 03, 1999	Six career fire fighters killed in cold-storage and warehouse building fire - Massachusetts.	PDF
99-F34	Aug 08, 1999	Recreational vehicle fire claims the life of one fire fighter and injures two other fire fighters - Arkansas.	PDF
99-F33	Aug 31, 1999	Motor-vehicle incident claims the life of a volunteer fire fighter and injures a lieutenant and another fire fighter - South Carolina.	PDF
99-F22	Jun 17, 1999	Fire fighter dies during operations at a fire in a three-story structure - Pennsylvania.	PDF
99-F21	May 30, 1999	Two fire fighters die and two are injured in townhouse fire - District of Columbia.	PDF
99-F18	Mar 17, 1999	Fire fighter dies at the scene of a small fire in an apartment building - Connecticut.	PDF
99-F04	Dec 31, 1998	Roof collapse in arson church fire claims the life of volunteer fire fighter - Georgia.	PDF
99-F03	Jan 10, 1999	Floor collapse claims the life of one fire fighter and injures two - California.	PDF

99-F02	Jan 09, 1999	Single-family dwelling fire claims the life of a volunteer fire fighter - Indiana.	PDF
99-F01	Dec 18, 1998	Three fire fighters die in a 10-story high-rise apartment building - New York.	PDF
98-F32	Nov 06, 1998	Two volunteer fire fighters were killed and one fire fighter and one civilian were injured during an interior fire attack in an auto salvage storage building - North Carolina.	PDF
98-F26	Oct 12, 1998	Eight-alarm fire in a 27-story high-rise apartment building for the elderly nearly claims the life of one fire fighter - Missouri.	PDF
98-F21	Aug 29, 1998	Commercial building fire claims the lives of two volunteer fire fighters - Mississippi.	PDF
98-F18	Jul 11, 1998	Vacant dwelling fire injures two fire fighters - Virginia.	PDF
98-F17	Jun 05, 1998	Sudden floor collapse claims the lives of two fire fighters and four are hospitalized with serious burns in a five-alarm fire - New York.	PDF
98-F07	Mar 08, 1998	Commercial structure fire claims the life of one fire fighter - California.	PDF
98-F06	Feb 05, 1998	Single-family dwelling fire claims the lives of two volunteer fire fighters - Ohio.	PDF
98-F05	Feb 11, 1998	Backdraft in commercial building claims the lives of two fire fighters, injures three, and five fire fighters barely escape - Illinois.	PDF
98-F04	Jan 21, 1998	Supermarket Fire Claims the Life of Volunteer Fire Fighter - West Virginia.	PDF
98-03	Oct 27, 1997	Two fire fighters die of smoke and soot inhalation in residential fire - Pennsylvania.	PDF
97-09	Aug 19, 1997	Restaurant/tavern fire results in the death of one fire fighter and serious injuries to three other fire fighters - Indiana.	PDF
96-17	Mar 18, 1996	Sudden roof collapse of a burning auto parts store claims the lives of two fire fighters - Virginia, March 18, 1996.	PDF

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APPENDIX B. TOTAL COST OF FIRE BY YEAR

Table 2. Total Cost of Fire by Year, 1980–2014[206]

Year	Total Cost of Fire		U.S. GDP		Total Cost of Fire as a Percentage of GDP
	actual $	2014 $	actual $	2014 $	
1980	75.9	218.5	993.9	2,862.5	7.6%
1981	83.8	217.9	1,235.0	3,211.0	6.8%
1982	87.1	212.4	1,370.9	3,345.0	6.4%
1983	90.8	216.2	1,528.6	3,638.1	5.9%
1984	93.8	214.8	1,764.5	4,040.7	5.3%
1985	102.0	225.4	1,966.8	4,346.7	5.2%
1986	106.3	231.8	2,105.6	4,590.2	5.1%
1987	113.2	236.5	2,330.2	4,870.2	4.9%
1988	122.1	245.5	2,613.2	5,252.6	4.7%
1989	123.9	237.8	2,946.7	5,657.7	4.2%
1990	131.0	239.7	3,267.5	5,979.6	4.0%
1991	128.6	225.1	3,528.0	6,174.0	3.6%
1992	135.2	229.8	3,846.6	6,539.3	3.5%
1993	143.7	237.1	4,168.9	6,878.7	3.4%
1994	149.1	240.0	4,539.6	7,308.8	3.3%
1995	158.5	247.3	4,912.9	7,664.1	3.2%
1996	166.7	253.4	5,329.1	8,100.2	3.1%
1997	168.6	249.5	5,816.6	8,608.5	2.9%
1998	176.3	257.4	6,225.5	9,089.2	2.8%
1999	180.9	258.6	6,755.7	9,660.6	2.7%
2000	200.1	276.1	7,452.7	10,284.8	2.7%
2001 (9/11 included)	261.3	350.1	7,926.7	10,621.8	3.3%
2001 (9/11 excluded)	203.3	273.4	7,926.7	10,621.8	2.6%
2002	208.1	274.7	8,316.3	10,977.5	2.5%
2003	216.4	281.3	8,854.4	11,510.7	2.4%
2004	234.8	295.8	9,742.0	12,274.9	2.4%
2005	247.6	302.1	10,732.6	13,093.7	2.3%
2006	268.7	314.4	11,842.6	13,855.9	2.3%
2007	280.5	319.8	12,699.7	14,477.6	2.2%
2008	298.9	322.8	13,628.3	14,718.6	2.2%
2009	272.7	302.7	12,989.9	14,418.7	2.1%
2010	272.1	296.6	13,728.8	14,964.4	2.0%
2011	282.9	297.0	14,779.0	15,517.9	1.9%
2012	304.6	316.8	15,533.9	16,155.3	2.0%
2013	310.2	316.4	16,364.2	16,691.5	1.9%
2014	328.5	328.5	17393.1	17,393.1	1.9%

Notes: All values are in billion U.S. dollars. "Actual$" gives the actual cost in the corresponding year, and "2014$" gives the cost adjusted to inflation, in 2014 dollar equivalents. Refer to the report: *The Total Cost of Fire in the United States* (2017), for calculation methodology, changes from previous version of this report (2014), data sources used for calculation, and other details.

[206] Source: Zhuang et al., *Total Cost of Fire in the United States*, 38.

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