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An enhanced system for augmenting urban search and rescue canines

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AN ENHANCED SYSTEM FOR AUGMENTING URBAN SEARCH AND RESCUE CANINES

By

Martin Gerdzhev

Bachelor of Science

in the Program of Computer Science,

Ryerson University 2008

A thesis

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Applied Science

in the Program of

Electrical and Computer Engineering

Toronto, Ontario, Canada, 2011

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ABSTRACT
**AN ENHANCED SYSTEM FOR AUGMENTING URBAN
SEARCH AND RESCUE CANINES**

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MAsc, Electrical and Computer Engineering, Ryerson University, 2011

One of the most critical factors in urban search and rescue is time, as the chances of finding someone alive diminish with time. Emergency responders locate casualties, plan their rescue based on the available information, and then extract them. Measures are taken to do this as safely as possible as the harsh environment may lead to rescuers being injured. Our research demonstrates how emergency responders can obtain more information about the victim and the collapse faster, while potentially increasing their Situational Awareness(SA), and thus decreasing the time to rescue of the casualties. The system described is an enhanced version of Canine Augmentation Technology (CAT) – a telepresence system for augmenting search canines. CAT integrates different technologies like wireless mesh networks, wearable computing, sensors, and software for recording, streaming, and scrubbing of video. The goal of our research is to reduce the time to rescue of victims by providing more relevant information to rescuers faster.

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TABLE OF CONTENTS

ABSTRACT.....	iii
LIST OF TABLES	viii
LIST OF FIGURES	ix
LIST OF APPENDICES	xii
ABBREVIATIONS.....	xiii
CHAPTER 1 INTRODUCTION	1
1.1 Introduction.....	1
1.2 Problem Definition.....	5
1.3 Objectives.....	8
1.4 Thesis Organization	9
CHAPTER 2 BACKGROUND.....	11
2.1 Emergency management	11
2.2 Urban Search And Rescue	13
2.2.1 USAR Rescue Robots	17
2.2.2 USAR Canine team.....	26
2.2.3 Augmenting Animals	30
2.3 Wireless technologies	41
2.3.1 Wireless Mesh Networks	42
2.4 Pattern recognition	43
2.5 Telepresence	45
2.6 Situational Awareness.....	46
2.7 Computational Public Safety	47
2.8 Summary.....	47

CHAPTER 3	MATERIALS AND METHODS.....	49
3.1	Architecture of CAT	49
3.2	CAT Prototypes.....	51
3.2.2	CAT 4.0.....	53
3.2.3	CAT 5.0.....	58
3.3	Automated scrubbing of video	61
3.3.1	Pre-processing.....	64
3.3.2	Isolating regions.....	64
3.3.3	Checking isolated regions	65
3.4	DEX	66
3.4.1	Dimensions	68
3.4.2	Attaching to the dog.....	68
3.4.3	Electronic hardware	70
3.4.4	Control and communication.....	71
CHAPTER 4	EXPERIMENTS AND RESULTS	73
4.1	CAT 4.0 Experiments	73
4.1.1	Preliminary video tests.....	74
4.1.2	Rubble pile tests	74
4.1.3	Experiment Results	75
4.2	Video Scrubbing Tests	76
4.2.1	Test setup	76
4.2.2	Test Results	77
4.3	WMN Deployment Experiments.....	82
4.3.1	Experiment setup	83
4.3.2	Experiment results	84

4.4	CAT 5.0 Experiments	86
4.4.1	CAT Experiments	86
4.4.2	Experiments Results.....	87
4.5	DEX Experiments	90
4.5.1	Experiments setup	91
4.5.2	Experiments Results.....	92
CHAPTER 5	CONCLUSION AND FUTURE WORK.....	97
5.1	Summary of Findings and Conclusions	97
5.2	Future Research	101
5.3	Concluding Remarks	104
APPENDICES	111

LIST OF TABLES

Table 2-1: Comparison of the different 802.11 Standards.....	42
Table 3-1: HSV minimums and maximums	65
Table 3-2: Dimensions of DEX	68
Table 4-1: Approaches and corresponding error	77
Table 4-2: Neural Network's convergence and errors	77

LIST OF FIGURES

Figure 1-1: Earthquake collapse site in the Sichuan Province, China 2008 (Source: National Geographic).....	3
Figure 1-2: Robot stuck at edge of rubble	6
Figure 1-3: Looking for survivors: A rescuer searches for victims at the collapsed site of a school building after an earthquake in Chongqing municipality, China, 2008 (Source: Reuters).....	7
Figure 1-4: One of the first versions of CAT being tested by a canine team	8
Figure 2-1: Emergency Management Cycle	12
Figure 2-2: Condition of Victims vs Emergency Response.....	16
Figure 2-3: BomBot 2 wheeled robot by WVHTC Foundation	18
Figure 2-4: G2Bot tracked robot by Mesa Robotics	19
Figure 2-5: VGTV-Xtreme in its three main positions. In the lowest position for flat surfaces (left), middle position for climbing (center), top position for looking over obstacles (right).	20
Figure 2-6: One robot trapped in the 350mm wide trench.....	21
Figure 2-7: JL-1 in docked state overcoming the same trench	21
Figure 2-8: Large Talon robot unable to cross the gap and wall delivers a small Toughbot (seen in the gripper of Talon) into a roof opening.	22
Figure 2-9: Microbot jumping 38 cm.....	23
Figure 2-10: Robug III rescue robot	24
Figure 2-11: OmniTread OT-4 robot	25
Figure 2-12: Rubble pile at Disaster City	29
Figure 2-13: Following the scent plume to the live victim. This is a simplified diagram, as in rubble the scent might move in various ways.	30
Figure 2-14: CAT 1 tested by a canine team	33
Figure 2-15: USAR Dog wearing CAT 2.0	34
Figure 2-16: CAT Architecture.....	35
Figure 2-17: CAT 3.0 worn by California Task Force 1 (CA-TF1) USAR Dog Freitag	36

Figure 2-18: The CRDS System. From left to right: Harness, CRDS unit, underdog.....	37
Figure 2-19: Canine wearing CRDS with underdog giving a bark indication.....	38
Figure 2-20: The released CRDS leaving the underdog behind.	38
Figure 2-21: USAR Canine Dare wearing CPE device	39
Figure 2-22: CAT attached to CWA.....	40
Figure 2-23: Example of Wireless Mesh Network for Audio communications [84]	43
Figure 3-1: Updated CAT Architecture	50
Figure 3-2: Diagram of ideal CAT.....	51
Figure 3-3: Beagle Board.....	55
Figure 3-4: Block Diagram for CAT 4.0	56
Figure 3-5: Streaming video from CAT.....	57
Figure 3-6: IGEPv2 Board	60
Figure 3-7: Block Diagram for CAT 5.0	60
Figure 3-8: CAT 5.0 with CRDS worn by USAR dog Freitag	61
Figure 3-9: Bag outside in good light conditions.....	63
Figure 3-10: Bag in an enclosed space in poor light conditions	63
Figure 3-11: DEX	67
Figure 3-12: DEX with retractable hooks	69
Figure 3-13: DEX attached with hooks to CRDS	69
Figure 3-14: DEX in underdog attached to CRDS	70
Figure 4-1: Correct classification - Original image	78
Figure 4-2: Image after thresholding	78
Figure 4-3: Image after the ANN filtering.....	79
Figure 4-4: False negative - Original Image	79

Figure 4-5: Image after thresholding	80
Figure 4-6: Image after the ANN filtering.....	80
Figure 4-7: False positive - Original image	81
Figure 4-8: Image after thresholding	81
Figure 4-9: Image after the ANN filtering.....	82
Figure 4-10: Map of tunnels showing victim and router placements.	85
Figure 4-11: Rubble Pile 1 at Disaster City	87
Figure 4-12: CAT 5.0 Failure points.....	88
Figure 4-13: Left camera showing head of the quarry.....	90
Figure 4-14: Right camera showing head of the quarry.	90
Figure 4-15: DEX being thrown from Freitag	93
Figure 4-16: DEX released successfully by the bark barrel	94
Figure 4-17: DEX exploring in the tunnel close to the victim.....	95
Figure 4-18: Image from DEX showing victim and visual acuity markers	95

LIST OF APPENDICES

A.	FOX Board LX832 Specification	111
B.	CAT 2.0 Power consumption break down.....	111
C.	CAT 3.0 Power consumption break down.....	111

ABBREVIATIONS

AI	Artificial Intelligence
ANN	Artificial Neural Network
ASTM	American Society for Testing Material
CAN-TF3	Canada Task Force 3
CAT	Canine Augmentation Technology
CBF	Canine Brain Function
COTS	Common off the Shelf
CPE	Canine Pose Estimation
CPS	Computational Public Safety
CPU	Central Processing Unit
CRDS	Canine Remote Deployment System
CWA	Canine Work Apparel
DEX	Drop and EXplore robot
DHS	Department of Homeland Security
DoF	Degrees of Freedom
EMS	Emergency Medical Service
FEMA	Federal Emergency Management Agency
GPS	Global Positioning Systems
IR	Infrared
LED	Light Emitting Diode
NCART	Network-Centric Applied Research Team
NIST	National Institute of Standards and Technology
OPP	Ontario Provincial Police
PDA	Personal Digital Assistant

PERT	Provincial Emergency Response Team
PSEPC	Public Safety and Emergency Preparedness Canada
RF	Radio Frequency
SA	Situational Awareness
SAR	Search and Rescue
SBC	Single Board Computer
SD	Secure Digital
SDK	Software Development Kit
SSH	Secure Shell
USAR	Urban Search and Rescue
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network

CHAPTER 1 INTRODUCTION

1.1 *Introduction*

Disasters, being unpredictable, can occur anywhere at any given time. Emergency First responders, as the name implies, are those that are first to deal with the immediate aftermath of a calamity. The first priority is to search for, find and rescue live humans trapped within the disaster--these are the goals of any search and rescue (SAR) operation. One type of SAR operation occurs when the disaster has occurred in an urban centre like a city. Urban Search and Rescue (USAR) is a SAR operation that occurs in the rubble and debris of collapsed buildings—adding additional challenges that require special techniques, training and technology. Finding people who are trapped and injured requires caution and speed. The faster a search can proceed, the faster individuals can be found and rescued—increasing survival rates. Thus there is a need for research in this field to try and find new ways or improve existing techniques and technologies to help provide resources that improve search speeds to save lives. This thesis describes an innovative system in the area of urban search and rescue (USAR), which aims to shorten the time to rescue an individual.

Urban disasters are on the rise. We have witnessed the World Trade Center collapse (2001), Hurricane Katrina (2005), the earthquakes in China (2008) and Haiti (2010). All of these disasters occurred in urban areas and resulted in many lives lost. In the years to come, more disasters are bound to occur and their cost will be greater [1]. This is due to a number of reasons including a changing climate, geographical realities and geopolitical forces—including terrorism. In 40 years, the world population is projected to increase by 50%, while the urban population is estimated to double in that same time. We are about to see a shift of

populations from rural areas to urban areas [2]. This increase in population means that even small or moderate disasters can have profound consequences and dealing with the aftermath of such disasters is a difficult job. This makes improving USAR all the more important.

When a disaster strikes, the impact on a city's infrastructure is profound. Many buildings collapse, often creating internal "voids" – pockets of space under the rubble; which may contain live people trapped in them. The purpose of USAR operations is to quickly find, extract and stabilize the trapped people, without jeopardizing the lives of first responders.

The main factor which determines if people will be extracted alive is time. Working under this constraint, emergency personnel need as much information as possible in order to establish situational awareness - an understanding of what is going on around them and what to do about it [3]. This usually means finding the trapped people, determining their condition, and the condition of the surrounding area. This allows emergency personnel to develop better rescue plans that may speed up the rescue operation and thus save more lives.

There are several ways to conduct a search some of which are more dangerous for rescuers than others [4]. Manual search, search with electronic equipment, canine search, and rescue robot search. Manual search involves human search teams going over the collapsed site, visually inspecting voids, listening for the presence of victims and marking the results. Rescuers may also call out to trapped people to knock on a surface so that the knock can be heard. This could be done by anyone, but only gives limited access to voids, can be very dangerous for search personnel, and would not locate unconscious, weak or very young victims. It also tends to be quite slow as the surfaces that searchers must travel over are often difficult to move over and through (Figure 1-1).



Figure 1-1: Earthquake collapse site in the Sichuan Province, China 2008 (Source: National Geographic)

Search using electronic equipment can involve the use of fiberoptic viewers, search cameras and electronic listening devices [4]. Fiberoptic viewers allow for limited assessment of victims that are more easily accessible. Search cameras are more easily understood, and can record the pictures and possibly allow for remote viewing, but are generally limited to straight line-of-sight. Another option is the use of electronic listening devices that can be used to detect sounds from the victim that can be trapped deeper in the collapse. The downside is that unconscious people cannot be detected at all and any noise can interfere with the process of detecting audible signs of life which tend to be faint. To avoid background noise, work must be halted in significant parts of the search area—thus potentially delaying finding other victims. All of these methods require that first responders be on the rubble pile, and at risk.

Another method for information gathering that is extremely effective is canine search. A canine team consists of a canine search specialist and a search dog. Together they can

cover a large area in a relatively short time. The dog, which is trained to find people using its sense of smell, is very agile, fast and reliable. These dogs are able to find unconscious as well as conscious people and are able to identify live humans hidden amongst cadavers.

Even though dogs are very good at locating trapped people, the problem of communicating that information remains. Dogs are trained to bark when they find live people, but they have no other means of communicating information to humans. If the dog is working in an area where the handler cannot follow, a bark may tell us that there is someone alive there, but it may not be possible to determine where the person is or in what condition they are in.

Response or rescue robots are another set of tools that has recently become available to provide data about a disaster environment. These robots are normally teleoperated and can be equipped with a vast array of sensors [5-7]. Some of these sensors are not as good as their equivalent in biological systems, e.g. dogs and their sense of smell. However, other sensor types that can be fitted to robots are not found in nature. The major downside to current robot designs is their limited mobility. Current designs cannot effectively traverse through rubble. Also controlling such a robot can be very challenging as the human operator must take into account angles, position of the robot, as well as carefully plan the path so as to not flip, become stuck or disabled. Until the mobility problems are overcome, use of rescue robots will be limited.

A system combining the best of the natural and artificial systems is described in [8-12]. We propose an enhanced version of this system, which makes it more reliable, more useful, and reduces the time it takes to gain better SA, and thus save more people faster [13-16]. This research falls into the field of Computational Public Safety (CPS), which

encompasses the use of computational resources, theory and practice to support safety processes as well as improve them.

1.2 *Problem Definition*

Whenever a disaster strikes, buildings tend to suffer structural collapse. Such collapsed buildings can be very dangerous because the environment they create is unpredictable, and there is risk of further collapse. Before a human search can occur in such a building, often it must be stabilized which can take a considerable time.

Ideally, first responders would like the locations and conditions of victims as well as the condition of the area around them to gain a better SA before attempting a rescue operation. This is required to ensure the safety of rescuers as well as victims. Thus the rescue effort needs to be carefully planned and executed. Sometimes this process can take a long time depending on the information at hand and the conditions on the ground. A way to gather the information without having to stabilize a building first is required, because stabilizing parts of the building where no survivors are present just wastes time that could be used to find people elsewhere.

Search canines are one of the best options for finding survivors. The dog can be directed by the handler to search a large area in a short time. The dogs can indicate the presence of a survivor by barking, but if the handler is not able to follow the canine due to safety precautions, he may not be able to determine the exact location of the victim. The dogs cannot provide any information on the condition of the survivor nor indicate if there is more than one, or the state of the environment around them.

Response robots are another alternative for searching for victims in rubble from a safe location. They are capable of providing audio, video, and other sensory information that can improve SA. However, finding survivors with such robots is not practical in their current state except in cases where their mobility shortcomings can be replaced by their sensing advantages. In typical urban disasters terrain is often unpredictable. Response robot technology is not currently available that can address even relatively simple obstacles much less the challenges of even a small collapsed building (Figure 1-2). These mobility problems often do not allow robots to explore all the areas that might have survivors, which can often easily be searched by dogs. Another limitation is that most of the robots, despite having numerous potential sensors on-board, rely, almost entirely, on visual cues as presented by video feeds for finding trapped people. This may be problematic as finding a person in debris from visual cues alone is somewhat like finding a needle in the proverbial haystack (Figure 1-3).



Figure 1-2: Robot stuck at edge of rubble



Figure 1-3: Looking for survivors: A rescuer searches for victims at the collapsed site of a school building after an earthquake in Chongqing municipality, China, 2008 (Source: Reuters)

A solution to this problem was originally proposed by Dr. Alexander Ferworn of Ryerson University. The idea was to combine the abilities of canines to find survivors with the strengths of robotics into a system that aids USAR operations. The system is called Canine Augmentation Technology (CAT) [10-12]. A basic CAT system is comprised of a harness equipped with a payload of sensing, actuation and computational equipment, worn by USAR dogs for transmitting audio, video, and other sensory information wirelessly to the handler or other human searchers when they cannot follow the dog during a search [10-12]. The idea behind CAT is to help first responders find people faster and assist them in planning a rescue. It should be noted that the intent of CAT is not to help the dogs—which do very well on their own. The idea was enhanced by the work of Jimmy Tran of Ryerson University [9, 13].

The system has undergone several revisions from a head-mounted wireless analog audio/video camera (Figure 1-4), moving to twin side-mounted digital cameras with an on-dog computer capable of wireless transmission of both camera streams.



Figure 1-4: One of the first versions of CAT being tested by a canine team

1.3 Objectives

The more recent designs of CAT allow for expandability of the sensors and address many dog factor (dogonomic) needs. These designs still leave a lot of room for improvements. A persistent set of problems have been the lack of audio transmission, on-dog recording, user interface, and poor video quality.

The purpose for this thesis is to add to the body of knowledge that supports the effort to make CAT a methodology and suite of technologies that are an alternative to robotic applications. We will show this to be done by demonstrating improvements on the concepts and designs of previous work. Our goal is to improve the SA of the human users of CAT and to reduce the time needed to make an informed decision about where a victim is and how to rescue them.

The contributions of this thesis are the design of a new architecture for CAT that increases the reliability and usability of the system by improving video quality, adding audio

transmission support, on-dog recording for when the dog goes out of wireless range, a basic user interface, as well as reducing the time needed to scrub the video recorded from the dog for signs of life within it.

Furthermore this thesis describes a way of giving more control over what can be seen in the vicinity of a victim within the video stream. It also demonstrates some limitations of the use of wireless transmission that mitigate its usefulness for applications involving fast moving transmitters in rubble. The new design also describes an extensible architecture that can be implemented in a future revision of this work. In other words, one of our contributions is a path forward.

In order to confirm that the goals of this thesis have been met, a number of experiments were designed to test the efficacy of CAT in operation. While none of the testing occurred in real disasters, all tests were conducted in purpose-built facilities similar to those that have been observed in real disasters. To quote Professor Ferworn, “We do not simulate conditions, we make conditions that simulate disasters”.

1.4 *Thesis Organization*

This chapter serves as an introduction to the rest of the thesis. Chapter 2 presents an overview of the field of emergency management and the strategies and technologies that are used in USAR operations. A literature review of related work in augmenting animals with technologies, telepresence, pattern recognition and situational awareness is also provided.

The current architecture of CAT is described in chapter 3. All prototypes from the current generation leading to the latest are described. The algorithm utilizing CAT in canine assisted USAR operations is explored. The use of CAT to overcome robot mobility

problems is also demonstrated. Chapter 4 explains the experimental procedures and presents our results. This is followed by an analysis and discussion of the results. Finally, chapter 5 presents a summary of this thesis and contains a discussion of future research.

CHAPTER 2 BACKGROUND

2.1 *Emergency management*

Hazards, emergencies and disasters threaten us daily. These terms are closely related and their definitions are provided below. According to [18], a **hazard** can be defined as a source of danger or an extreme event that has the potential to affect people, property, and the natural environment in a given location. Hazards can be further classified into natural (earthquakes, floods), technological (malfunctioning machines, industrial explosions), and resulting from deliberate human actions (terrorist attacks, kidnappings).

Emergency has two meanings [18, 19]. The first one describes minor events that cause a few casualties and some property damage (car crash, house fire). These emergencies are unforeseen but with predictable circumstances and results. The second meaning refers to an event that is about to happen in the near future and can have major consequences (a hurricane forecasted to pass in a populated region, weather predictions that favours tornado formation, etc.).

The term **disaster** is reserved for events that produce more losses than a community can handle [1, 18, 19]. They occur when a hazard, or multiple hazards interact with human vulnerability. They can seriously disrupt social routines, cause many deaths, much property damage, or significant environmental damage. Disasters directly impact people or the systems they use– food, natural resources, transportation, etc. A community that has been struck with a disaster can cope only with help from outside – state or federal governments, or other communities. There are many costs associated with a disaster– Direct Financial Costs (repairing infrastructure, rebuilding homes), Long-Term Economic Costs (businesses

closing permanently, employees moving out of the region), Environmental Costs (oil spills, chemicals leaking into rivers), Societal Costs (communities lose sense of place and pride), Human Lives Lost (death of one human being is one death too many) [20].

According to [21], **Emergency management** is “applying science, technology, planning and management to deal with extreme events that can injure or kill large numbers of people, do extensive damage to property, and disrupt community life”. When a disaster strikes, specially trained people – emergency managers must cope with that event. **Emergency managers** are public servants that have the knowledge and expertise to help jurisdictions reduce the liabilities that lead to disasters [1]. Their roles are to prevent or reduce losses that occur due to hazards, disasters, and emergencies [18]. The work of emergency management can be divided into four phases [1,18-20]: mitigation, preparedness, response and recovery. It is also known as the emergency management cycle or disaster life cycle (Figure 2-1).



Figure 2-1: Emergency Management Cycle

Mitigation activities try to eliminate the causes of a disaster. It is accomplished by reducing the possibility of a disaster, or by reducing the loss due to its occurrence. **Preparedness** activities refer to improving the ability to respond quickly in case of an emergency. They include the development of plans and procedures, installation of warning systems as well as training personnel, and stockpiling resources to meet the needs for when a disaster occurs. **Response** activities are actions in the immediate aftermath of a disaster that protect public safety and minimize physical damage. This involves positioning of emergency equipment and personnel. These personnel are normally called “first responders” and consist of fire-fighters, police, and emergency medical services (EMS) teams. They deal with the important operations of search and rescue (SAR), evacuation, providing medical assistance, etc. **Recovery** activities try to return the affected community to pre-disaster or even improved conditions. They occur after the response phase and include the rebuilding and repair of the infrastructure, as well as restoring power, water, etc., and other activities to restore normal operations to a community.

The Emergency Management Cycle is intended to apply to all disasters. Some of the more notable examples of where the cycle can be observed are New Orleans after Hurricane Katrina [8], Kobe Japan [22], Mexico[23] and Haiti [24] after high-magnitude Earthquakes and the World Trade Center [25] after terrorist attacks.

2.2 *Urban Search And Rescue*

Search and rescue (SAR) consists of three separate operations: sizeup, search, and rescue [26]. **Sizeup** involves assessing the situation and determining a safe action plan. **Search** consists of locating victims and documenting their location. **Rescue** involves the procedures and methods required to extricate the victims.

Urban search-and-rescue (USAR) is a "multi-hazard" discipline, as it may be needed as a response for a wide variety of emergencies or disasters. These may include earthquakes, hurricanes, typhoons, storms and tornadoes, floods, dam failures, technological accidents, terrorist activities, and hazardous materials releases [27].

USAR deals with the location, rescue (extrication), and initial medical stabilization of victims who may be trapped in confined spaces. It should be noted that many victims of urban disasters are not trapped and are often found in-situ. Thus search is not required but rescue is. If a victim becomes trapped, it is usually a result of a structural collapse. However, transportation accidents, mine collapses, and collapsed trenches may also result in trapped victims [27].

Due to the multi-hazard nature of USAR, it is organized around the concept of the “**task force**” unit. A USAR task force is a partnership between regional fire departments, law enforcement agencies, federal and local governmental agencies and private companies. Each unit consists of firefighters, engineers, medical professionals, canine/handler teams, emergency managers and other professionals that have been specially trained to deal with USAR environments. A task force is meant to serve as a national resource for disaster response [28] however, there are many examples of task forces that are city or regionally-based¹. In addition to the specialized personnel, each unit has specialized equipment that is not normally available to local responders.

In Canada the organization that is responsible for responding to disasters is called Public Safety Canada (PS). It provides for 5 USAR Task Forces spread from coast to coast

¹ For example, Toronto is served by the city task force called “Heavy Urban Search and Rescue (HUSAR) which also serves the region of Ontario and supports national operations through its designation as one of the 5 Canadian task forces as recognized by Public Safety Canada (CAN-TF3 (Toronto)).

[29]. Similarly to Canada and PSC, in the United States, the equivalent organization is called the Federal Emergency Management Agency (FEMA) of the Department of Homeland Security (DHS). It supports 28 USAR Task Forces that are spread throughout the continental United States [30, 32]. The Task Forces are activated when the regional or federal authority issues a formal declaration of a disaster situation that warrants search and rescue operations.

USAR task force members work in the following four areas of specialization [31]:

- **Search:** find victims trapped after a disaster.
- **Rescue:** includes safely digging victims out of tons of collapsed concrete and metal.
- **Technical:** made up of structural specialists who make rescues safe for the rescuers.
- **Medical:** cares for the victims before and after a rescue, as well as injured task force members.

For large disasters, the emergency response normally occurs in four phases [32]:

- Initial spontaneous response – unskilled persons, neighbours, community response teams rush in to save people
- Planned Community Response – by local trained community response teams. They find people by calling out and through visual search.
- Void Space Rescue – by local emergency services rescue forces. In their searches they use existing cavities, small cut openings and do some shoring to the buildings to use as safe havens for victims and first responders.
- Technical, Urban Search and Rescue – by trained task forces, aided by heavy equipment.

Figure 2-2 illustrates the types of structural collapse rescue [32].

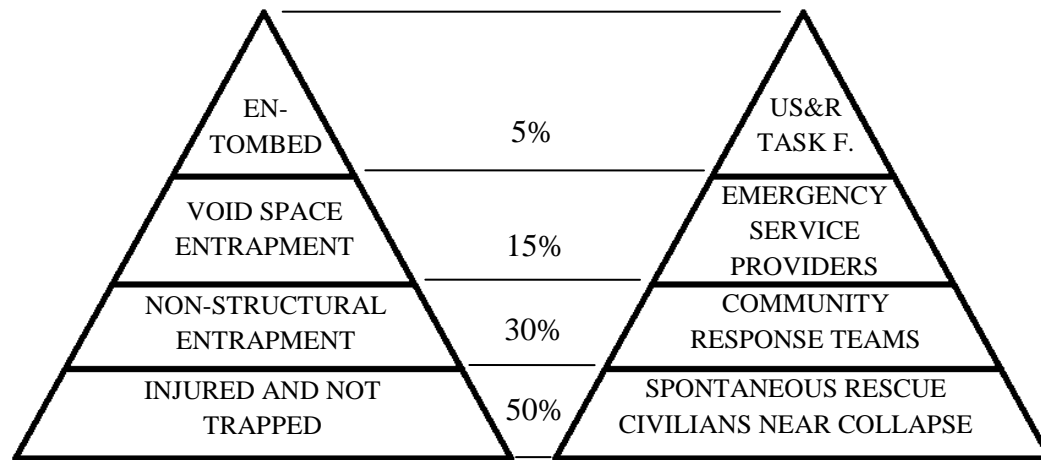


Figure 2-2: Condition of Victims vs Emergency Response

At the disaster scene the goals of the USAR task forces are to rescue the most people in the least amount of time, without becoming victims themselves [26, 33]. This normally means that easily rescued victims would be rescued first. Time is crucial during an USAR operation, as the chances of finding someone alive diminish with time. The first hour gives the best chance for finding live people, but the following day is also critical. The injured and trapped victims have an 80% chance of survival if rescued within the first day [1]. After the first day the chance diminishes rapidly. This doesn't mean that people should just rush into collapsed buildings without an assessment of the situation, as nearly 60% of confined space deaths come from would-be rescuers attempting to re-enter the damaged structure [33]. After arriving at the disaster scene, rescuers would do an initial size-up, where they will identify different buildings. They will then do a general area triage to find the buildings that are most likely to have more trapped people. After that a hazard assessment of the buildings would be done and unsafe buildings would be marked as "NO GO" so people would not enter there. These buildings may be re-evaluated and stabilized after other buildings are

searched. Search operations follow the initial size-up. The search teams would use different techniques to find victims, depending on the situation and equipment available. These would normally include search dogs, specialized listening equipment, viewing devices, perhaps rescue robots, and physical search [5, 6, 7, 34, 35]. Victims that are more easily accessible are extracted and helped first. The ones that require more work to rescue are handled in turn. Quite often it may take hours of digging and cutting through concrete or other building materials to get to a single trapped person. Once they are rescued, victims are stabilized by Emergency Medical Technicians (EMTs), and then evacuated to second line medical facilities [36].

2.2.1 USAR Rescue Robots

The promise of robots used for “response” or “rescue” in USAR operations has seen a lot of interest in the past several years. Most notably, this has occurred after the World Trade Center Disaster of 2001 where they showed some promise as potential tools for finding victims [37]. The robots are typically teleoperated and can be equipped with a vast array of sensors [5-7]. Some of these sensors are not as effective as their biological equivalent systems. Of most interest within this thesis is sensing odour coming from victims which is done extraordinarily well by dogs. However, other sensor types that can be fitted to robots (Ground Penetrating Radars, Gas sensors, etc) are not found in nature.

Robots could prove to be a very useful alternative to human search in environments that are hazardous or inaccessible to humans if it were not for one major limitation – mobility. Disaster environments can be quite unpredictable, with uneven terrain, lots of debris and rubble. Even the best of land robots equipped with tracks or wheels have

difficulty navigating through simple terrain with obstacles as common place as stairs. Traversing terrain that is inevitably present in disaster environments is almost an impossible task. There has been recent progress in robot designs that have attempted to overcome the mobility problem. Architectures, such as shape-shifting or variable geometry [38, 39, 40], marsupial delivery [6, 30, 34, 41, 42], multi-robot force cooperation [43-45], and biologically inspired designs [46-49] are steps forward from traditional designs but are still in their infancy.

2.2.1.1 Traditional tracked and wheeled robots

Traditional tracked or wheeled robots normally consist of a number of fixed wheels or tracks. Control signals are delivered either through wireless or wired data links. Their mobility is normally limited by the size of the wheels or length/height of the tracks. Figure 2-3 and Figure 2-4 show examples of wheeled and tracked robots.



Figure 2-3: BomBot 2 wheeled robot by WVHTC Foundation

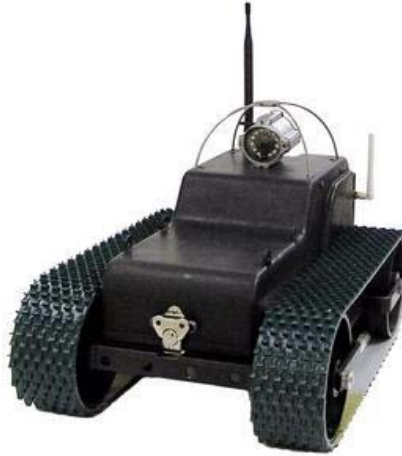


Figure 2-4: G2Bot tracked robot by Mesa Robotics

2.2.1.2 Shape-shifting and Variable geometry robots

Shape-shifting/Variable geometry robots, as the name implies, have the ability to change their shape to better conform to different surfaces or situations where expansion or contraction would aid mobility. This can be a very useful feature, as different configurations allow for the traversal of obstacles where a single fixed-wheels/tracks robot wouldn't be able to move. As shown in Figure 2-5, VGTV-Xtreme by Inuktun is a typical example of a variable-geometry robot that can change shape during operation and is commercially available [40]. Other example robots of this type are Telexmax by TelRob, PackBot from iRobot, as well as a number of research robots like Kenaf [50], Souryu [51], and Helios [52].



Figure 2-5: VGTV-Xtreme in its three main positions. In the lowest position for flat surfaces (left), middle position for climbing (center), top position for looking over obstacles (right).

2.2.1.3 Multi-robot force cooperation

During a rubble search, some surfaces may prove to be a real challenge for a single robot to overcome. If there is a hole that is slightly larger than the robot, it might get stuck while trying to go over it. If a bigger robot is built to cover bigger obstacles, it will have a limited ability to go into smaller voids. Because of this kind of situation, amongst others, multi-robot force cooperation has been suggested as a means of overcoming individual robot shortcomings. This type of robot design incorporates multiple robots cooperating to overcome a specific obstacle by joining together, and then detaching when the obstacle is surmounted. JL-1 is a typical example from this class of robots. Figure 2-6 shows JL-1's attempts to overcome a 350mm wide trench in single-robot state, and Figure 2-7 shows the same robot in docked state overcoming that trench. [45] It should be noted that this form of robot cooperation has never been used operationally (as there just are not that many task forces capable of fielding such teams) thus all the results for this type of deployment is theoretical or done as a demonstration.



Figure 2-6: One robot trapped in the 350mm wide trench



Figure 2-7: JL-1 in docked state overcoming the same trench

2.2.1.4 Marsupial robots

Sometimes a single robot or even a few robots using force cooperation may not be enough to overcome harder terrain such as a low vertical wall. In such a scenario, another form of robot cooperation might be able to accomplish the task.

Marsupial operation is a form of cooperative robotic deployment normally used to deliver USAR assets via the explicit physical interaction of two or more robots to exploit their individual strengths and overcome their individual weaknesses [53]. The term was initially introduced in [41] as a relationship between a “mother” robot that carries and nurtures a smaller “daughter” robot to support USAR operations.

Marsupial robots are often deployed by a mother robot whenever the mother robot cannot navigate over a difficult terrain, or is too big to go through a hole or crack of interest. An example of marsupial delivery can be seen in Figure 2-8 where a Talon robot delivers a

Toughbot robot into a small opening in a roof. Again, this type of robot cooperation has not been greatly used in operations since such different robots are not normally part of a task force's complement of equipment.



Figure 2-8: Large Talon robot unable to cross the gap and wall delivers a small Toughbot (seen in the gripper of Talon) into a roof opening.

2.2.1.5 Biologically inspired robots

Even though marsupial delivery has its benefits, it may still prove to be problematic, as the “mother” robot would normally have mobility problems and delivering the “child” robot at a point where the child robot would only get stuck is useless. Other forms of robots try to move away from tracks and take inspiration from nature.

One such concept is the jumping robot [47, 48]. When an obstacle is met that normally a tracked or wheeled robot cannot go over, these robots can jump over it. Microbot is a concept robot from this type of biologically inspired robot class [48]. It uses a form of mobility where a spring is compressed and released quickly to let it jump some height and distance. Figure 2-9 shows this robot in action.

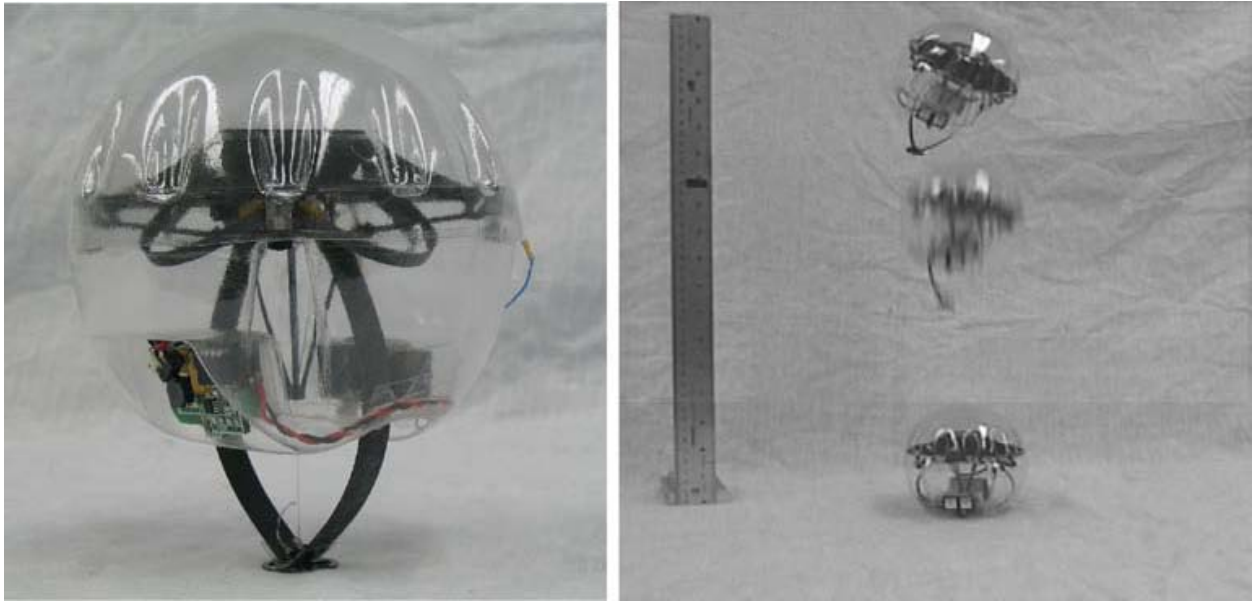


Figure 2-9: Microbot jumping 38 cm.

Even though jumping can be a very useful form of mobility, where you can jump over obstacles, the rough terrain would be very hard to navigate with jumping alone as the robot might still get stuck in places it lands and would be extremely hard to recover. Another line of biologically inspired designs are legged robots. This system exploits the fact that several legs support the robot while others move it over obstacles. Such an example is Robug III – a hexapod spider-like robot designed to enter places too dangerous for humans. It can walk, climb over debris and even scale vertical walls. Figure 2-10 shows a picture of this robot.

Walking robots have a lot of potential. They can potentially climb over debris, but are mostly limited to more predictable environments like the flat floors of labs. Real world environments can be very challenging and there are still many– size, power consumption, balance, stability, and motion challenges. The legs either make the robot too tall, or too wide to fit into tighter places like holes and cracks that are present in a collapsed building. In order to be useful in urban disasters, these issues have to be resolved.

Snake-like robots, which are another type of naturally-inspired robot class, are an attempt to solve the size problem. They consist of many joints, each having multiple degrees of freedom (DoF). This allows them to change form and climb over obstacles and adapt to many potential circumstances. Their size allows them to fit in very tight places. Omnitread OT-4 is one such robot [54]. It has 7 segments each of which is covered by tank tracks. OT-4 can be seen in Figure 2-11.



Figure 2-10: Robug III rescue robot



Figure 2-11: OmniTread OT-4 robot

Although snake-like robots have much potential, there are still problems, including speed, battery life, limited payload capacity, and limited space for sensors.

2.2.1.6 Rescue Robots performance metrics

Based on a review of the locomotion mechanisms of a large number of robots, none of the current USAR robots can practically and autonomously carry out USAR work in a disaster environment [55]. In an attempt to improve this situation, the DHS sponsored Intelligent Systems Division of the National Institute of Science and Technology (NIST) of the U.S. Department of Commerce is looking into the problem of measuring the performance of rescue robots. The approach taken is to create a standard set of tests for robots [56], so that they can be tested against one another for comparison purposes. NIST have developed a variety of performance standards, meant to test many categories of robot characteristics [57-59]. Each robot is evaluated on a range of performance metrics – mobility, sensing, and overall system performance (power, communication and durability).

Another area that is evaluated is “cache packaging” which indicates dimensions and other size and weight characteristics of the robot, as well as any equipment that is needed for it to operate. This is done to give an idea of how the robot and all the equipment for it will be packaged for transportation by a task force. These kinds of tests are important as emergency task forces or any other interested parties can use the evaluations to determine what the capabilities of each robot is, and to better choose ones that suit their needs. Every year there is a DHS/NIST sponsored Response Robot Evaluation Exercise on the grounds of Texas A&M University at their purpose-built training facility - "Disaster City", College Station, Texas. Participants in that exercise consist of first responders, manufacturers and academics from all over the world.

Even though these metrics are driving forward the capabilities of response robots, the improvement of robot mobility is more focused on being able to complete the tests provided in the evaluation exercises. Currently there does not exist a test for robot mobility on rubble, which means that the capabilities required for real disaster situations are not expected to arrive in the near future.

2.2.2 USAR Canine team

The idea of using dogs for finding people is very old. Originally dogs were trained to find people by tracking, but due to a number of limitations with that approach a new method was proposed. In the 1960s it was proposed that dogs be trained for “air scenting” instead of tracking [60]. Unlike tracking dogs, air scenting search dogs do not require scent articles or tracks. The search area does not have to be kept free of other searchers, which means that rescuers can continue their work. Another advantage of air scenting dogs is that they do not require a starting point to find people [60]. A dog’s sense of smell is far keener than that of a

person and it is the primarily sense for identifying items of interest [61]. This ability makes canines quite useful in detecting a variety of scents like the smells of explosives [62], drugs [59] and even cancer [60]. A canine's olfactory system can also be applied to finding people very effectively. The scent of a person is given off by bacteria and vapour living on dead skin cells known as "rafts" that are being shed from our bodies in the thousands per minute, as well as the volatile chemicals that are released from our bodies and our apparel [60, 61, 65].

Regardless of the types of search dogs, they are normally directed by canine handlers which are made up of a number of different professions. In the United States, many canine handlers are volunteers however many are also employed as firefighters and police [66]. Dogs are able to pick up human smell and work their way to the place where the highest concentration of the smell is found. This means that even if a person is buried under rubble, the scent could still escape the confined space and be picked up by an air scenting dog. This is why dogs are invaluable for locating victims at a disaster site.

Before a dog can be employed for actual people searching, both the dog and its handler need to undergo rigorous training. Not all dogs can be trained to become search and rescue dogs. Canines with high "toy drive" (the desire to play with a toy, such as a ball or tug) and nerve strength (the ability to deal with and recover from stress, often caused by threat) are used for USAR [65] work. Most of the U.S. Federal Emergency Management Agency (FEMA) certified dogs are Labrador Retrievers, German Shepherd Dogs, Belgian Malinois, Border Collies and Golden Retrievers [66].

Finding people can be thought of as a game of hide and seek for the dog [66]. During training, people hide from the dog with a toy, then play with the dog with the toy when the

dog finds them. This promise of a reward is quickly learned by dogs and makes them eager to search.

For a disaster environment dogs need to learn a set of skills and pass several certifications before they are allowed to work as USAR dogs. These skills may include obedience, agility, direction and control, and giving a bark indication when a live person is found. FEMA is the agency that designed the evaluation and certification processes for USAR canines [67-69]. One of the most important tests that a canine team must pass is the Rubble Site test. This test is made to simulate a realistic disaster environment where all the skills are put to the test. The canine is supposed to search independently and off-leash. This is done because during an actual disaster, a handler may be precluded from going with the dog due to hazards.

USAR canine teams train on specially built rubble piles if they are available (See Figure 2-12) or even on construction or demolition sites. It is important that different sites are used as the dog will learn all the hiding places and just go to those places instead of doing a thorough search [65].



Figure 2-12: Rubble pile at Disaster City

Regardless of how a rubble pile is created, it closely resembles a real collapse and therefore provides an excellent opportunity for training. Rubble piles can be of any materials that are found in buildings, with the most common materials being steel rebar reinforced concrete and wood. The better purpose-built piles will have a tunnel system underneath for testing in confined spaces and to allow volunteer “victims” to move to different location without being visually detected by observant dogs.

A typical training scenario would involve one or more persons called “quarries” that hide somewhere on or within the pile. Each quarry has a dog toy to give as a reward. After sufficient time has elapsed to allow for the scent of the quarries to build around their hiding places, the handler will direct the canine to look for the quarries. The dog will go across the pile back and forth until it finds the scent plume of a quarry. At this point it will zigzag in and out of the scent going towards the quarry [60]. Figure 2-13 shows an example of the search pattern in action [65].

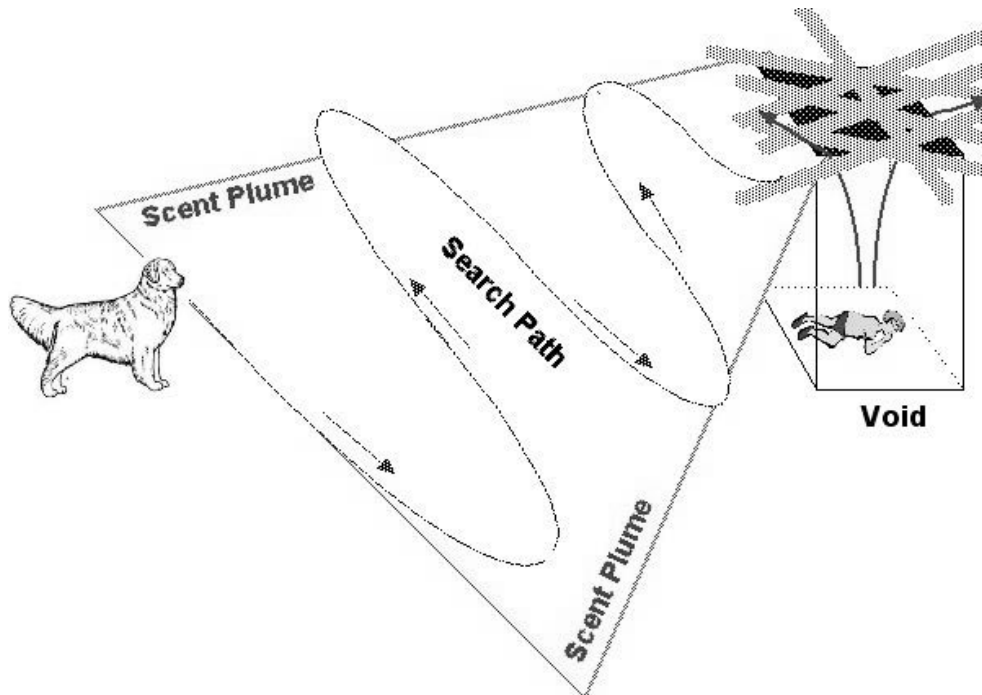


Figure 2-13: Following the scent plume to the live victim. This is a simplified diagram, as in rubble the scent might move in various ways.

When the dog finds the highest concentration of the scent and can go no further, usually very close to the quarry, it will start a sustained barking for a period of time. This is the bark indication for a found live victim. After many barks, the quarry will praise the dog and give the toy to the dog to play with as a reward for finding them. In essence, the dog sees finding people as a form of game that gives a reward in the end when successful. During an actual USAR event, the dog will still be playing the game with the result that lives will be saved.

2.2.3 Augmenting Animals

As can be seen, animals can be very good at some things that would normally be extremely hard for a person or a robot to do. We call this Biological Intelligence [13, 17]. Sometimes we may want to have more information or to do something more than an animal can do on its own. This is where technology can play a role. Technology can be used to

enhance animals so that they can provide that extra information or accomplish tasks previously not possible. This concept is not new and actually has been employed for a long time now. The US Navy use bottlenose dolphins carrying a transponder to find and mark anti-ship mines [70]. Another instance of augmenting an animal is the use of camera systems on sharks for research purposes [71].

From the land animals, dogs have received the most attention for augmentation. This stems from the fact that they can be easily trained for specific tasks. In 1974 a study was conducted that was seeking to develop procedures for a handler to remotely control a trained dog's movements off-leash [72]. The purpose was to use dogs as independent scouts. The results showed the successful conditioning of several dogs to respond to a specific tone which made them change direction. The study showed that it was possible for dogs to be controlled for up to half a mile or more under the control of terrain stimuli and tone signals. A more recent attempt at controlling canine movements autonomously is described in [73]. The author found it possible to control canines autonomously with a success rate of 73% for simple paths and 62% for complex paths.

During the World Trade Center attacks, USAR dogs were equipped with wireless and videotape recording cameras attached to their collars. The dogs would be sent to search for survivors and video from the search would be either streamed live, or would be recorded for later viewing [74]. Another system that is used on dogs is the FIDO Police Dog Camera by Industrial Television Limited of the UK [75]. The system attaches a wireless camera to a harness on the dog's head to be used in weapons seizure operations.

Of particular interest to this thesis is the Canine Augmentation Technology (CAT) project. It was initiated by Dr. Alexander Ferworn in 2005 based on the observation that

walking robots that could traverse common terrain did not exist, would be expensive to build and would likely not work as well as biological systems. He would use the biological intelligence of working dogs to do succeed in walking and augment them with sensors. This work has continued in the Network-Centric Applied Research Team (N-CART) in the Department of Computer Science at Ryerson University [12] since that time. In its present form the project consists of 5 separate subcomponents that have the common goal of improving the situational awareness of the first responders following the USAR dogs. These subcomponents [65] are:

- Canine Augmentation Technology (CAT)
- Canine Remote Deployment System (CRDS)
- Canine Pose Estimation (CPE)
- Canine Work Apparel (CWA), and
- Canine Brain Function (CBF)

The research described in this thesis is based on CAT, CRDS and CWA.

CAT is a wireless video, audio, telemetry, and sensing system that is worn by USAR canines searching for survivors where canine handlers cannot follow. Early prototypes resembled the FIDO Police Dog camera, but it has been refined and altered several times as more was discovered about the dogs' reactions to the system, as well as what could actually be sensed [65].

The first version of CAT used a head mounted wireless analog camera which showed that it was possible to wirelessly transmit the video from the dog, and objects could be identified in the video stream. It had however some severe problems. The dog was uncomfortable with the system and distracted it from the search task. Another problem was

that the placement of the camera on the head showed what the dog was seeing – the ground, as it was using its sense of smell during searches as opposed to vision.



Figure 2-14: CAT 1 tested by a canine team

The second version of CAT replaced the head mounted camera with two side mounted pan/tilt cameras on a harness on the dog's body. The cameras were enclosed in domes to protect them. It moved away from analog cameras to digital cameras, a computing unit and WiFi communication. The move to digital communications and a computing unit allowed for expandability and more control of the information. A new battery pack was designed to increase operation time of the system. With the development of CAT 2.0 [13], the following architecture was adopted (Figure 2-16). Although CAT 2.0 was a significant step up from the first version, it lacked robustness, was very hard to place on the dog, and was very unreliable.



Figure 2-15: USAR Dog wearing CAT 2.0

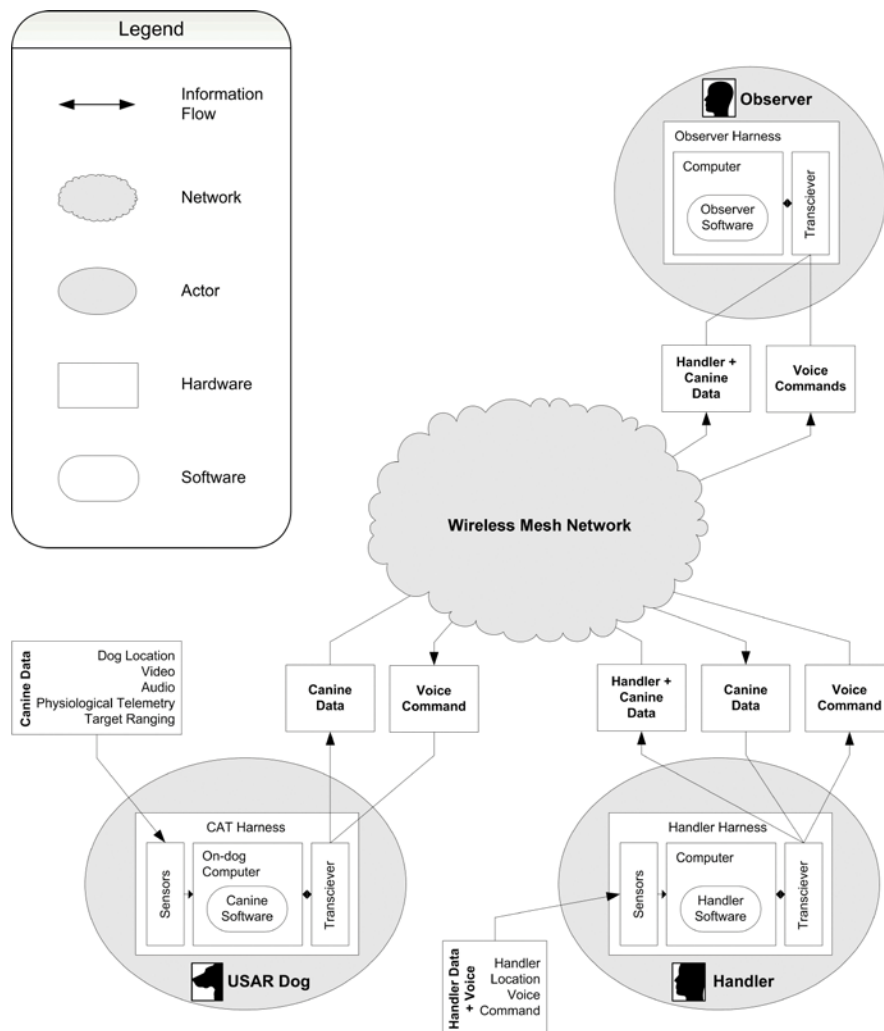


Figure 2-16: CAT Architecture

CAT 3.0 fixed most of the problems with the previous version. It did away with the servos as they kept breaking and were useless in a fast moving dog. They were replaced with wide-angle lens. The cameras and domes were replaced with better versions utilizing commercial domes from security cameras, which had the added benefit of IR illumination for seeing in the dark. The new domes also provided better protection for the cameras and did not break as easily. CAT 3.0 also received a hardware upgrade for the computing unit. It increased the reliability of the system, as well as had the benefit of being more extensible

and had an SDK with drivers for some devices and software readily available. The system was more energy efficient overall than the previous versions.

The problem with the harness of the previous CAT prototypes was addressed with the emergence of the Canine Work Apparel (CWA) sub-project. It was lead by Dr. Lucia Dell’Agnese of the School of Fashion at Ryerson University. Dr. Dell’Agnese designed and made the harness that housed CAT 3.0 and was worn by the dogs (Figure 2-17).



Figure 2-17: CAT 3.0 worn by California Task Force 1 (CA-TF1) USAR Dog Freitag

The garment was designed to address the dogonomic features that could be identified at the time (including heat dissipation, size, flexibility and endurance). It also had a break-away safety feature for the dog’s safety. Virtually every handler requested this feature. Normally dogs search “in the nude” to avoid being snagged by the collar on a piece of debris and thus become trapped where the handler cannot assist the dog. The CAT 3.0 garment was designed to fall apart when the dog became snagged, so that it could escape.

The CRDS is another system that can be integrated with CAT or can be used on its own. It was developed to increase trapped victim survival rates when rescue may be days

away but supplies such as food, water, medical supplies or a radio, can be delivered by the dog [76]. The CRDS utilizes the determination and agility of USAR dogs to deliver these supplies to the victim in places that are inaccessible by human workers. The supplies are put in a bright orange bag called the “underdog” that the canine carries under its belly (Figure 2-18 and Figure 2-19).

When a USAR canine has found a victim, it gives a bark indication, showing that it has found someone. After several barks, the handler triggers the release of the CRDS remotely, and the underdog drops very close to the trapped person’s maximum scent plume (Figure 2-20). Newer versions of the CRDS allow for the automatic release of the underdog triggered by the sustained barking alone—in other words the dog triggers the release itself [77].

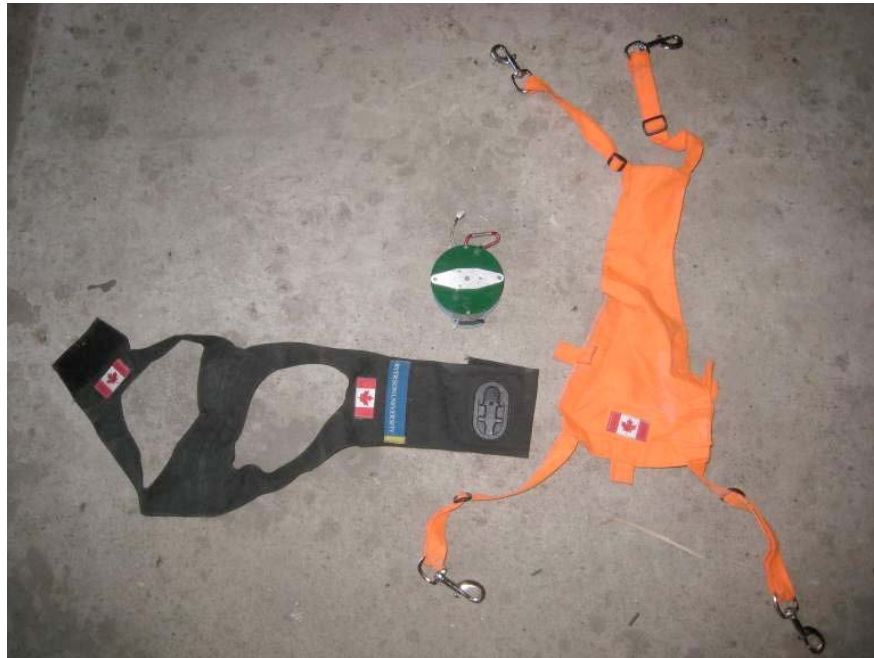


Figure 2-18: The CRDS System. From left to right: Harness, CRDS unit, underdog.



Figure 2-19: Canine wearing CRDS with underdog giving a bark indication.

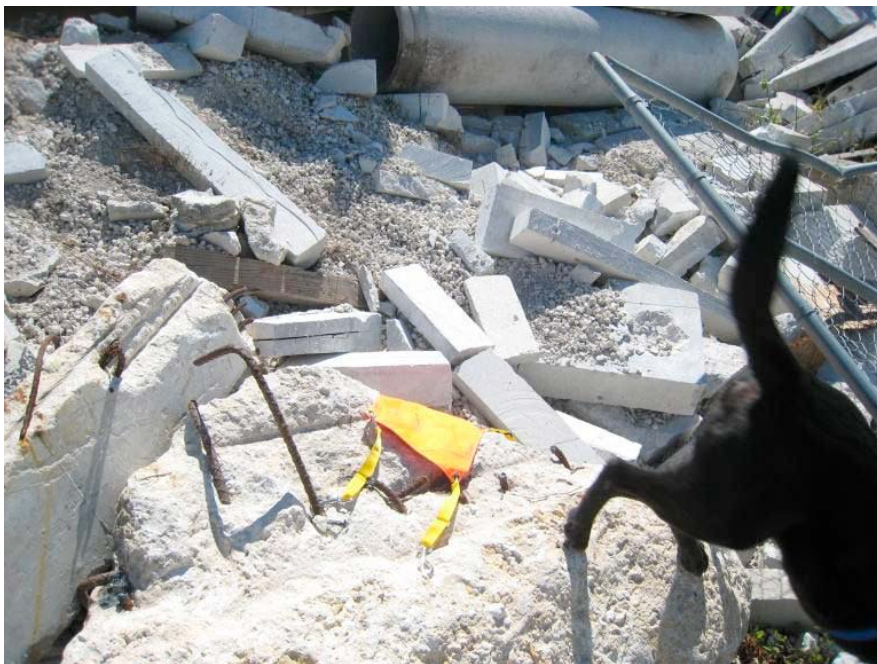


Figure 2-20: The released CRDS leaving the underdog behind.

Canine Pose Estimation is another area of research from N-CART. As the name implies, it strives to estimate the pose of USAR Dogs [78]. It is meant to communicate wirelessly the pose (walking, sitting, standing, etc.) of canines by using accelerometers

mounted on the dog's body (Figure 2-21). This gives the canine handlers another insight as to what their dogs are doing when they are out of sight. This could be beneficial for when dogs work off-leash and out of sight. As some canines are trained for cadaver search, they sit when they find a dead human. If the handlers cannot see this then they will not find the cadaver. Using CPE, handlers can determine the sitting position remotely. Another possible use for CPE is to correct the camera angles of images coming from CAT.



Figure 2-21: USAR Canine Dare wearing CPE device

Canine Work Apparel is a project that aims to design and test prototype canine harnesses that would allow for freedom of movement, comfort and safety of USAR working dogs (Figure 2-22). It is also supposed to provide a stable and reliable platform for the mounting of the CAT sensing components, as well as any of the rest of the subcomponents mentioned earlier. Another reason for designing CWA comes from the United States and the

Canine Search Specialist Certification Process [67] which directs the handlers to remove the leash and collar from dogs at rubble searches. This is done with safety in mind, as the dog may get snagged on a piece of rebar or any other object and it may not be able to escape.



Figure 2-22: CAT attached to CWA

CWA for USAR is designed with this concern in mind. It is meant to tear away when snagged. But unlike other tear-away systems, it is designed to just partially tear away, allowing for the dog to be freed, but also providing a greater chance for the equipment to return together with the dog. This is important for systems like CAT, because if the wireless communication fails, the on-dog recording can provide very useful information.

Another related subcomponent of CAT is Canine Brain Function. This research has found that it is possible to sense what a USAR dog is experiencing, by measuring its physiology during the activity [65, 79]. The experiments use a multi-channel near infrared brain spectroscope [79, 80]. This type of sensor has the capability of measuring brain oxygenation by illuminating the brain tissue within the skull and detecting the reflection.

Many handlers believe that they will be able to determine some aspects of the mental state of their dogs. Using this technology, it may be possible to figure out whether the dog is actually working on the problem of finding people or doing something else.

2.3 *Wireless technologies*

Generally speaking, there are two major types of wireless communication for mobile robotics. The first one is an analog radio frequency (RF). The second is digital wireless communication, of which Wireless Fidelity (WiFi) is the most popular. While RF has a longer range, it may be diminished because there is a lot of interference around disaster sites. When several robots are in the same place in the same frequency band, jamming or interference can occur, leading to loss of signal and loss of control. On the other hand, digital communication gives us the ability to transmit and receive signals in noisy environments with relatively low error rates, and as a result is rapidly replacing analog communication in many fields [81].

This thesis deals with wireless transmissions over a WiFi network. WiFi is used in a variety of electronic products ranging like computers, mobile phones, Personal Digital Assistants (PDA), etc. WiFi enables compatible devices to form a local area network without the need of wires. It provides security of the transmission as well as channel hopping,

which can reduce interference. It consists of several IEEE Wireless Local Area Network (WLAN) 802.11 standards. [82] Table 2-1 shows a comparison between the different 802.11 standards.

Standard	Release date	Frequency Band	Data Rate (Typical)	Data Rate (Maximum)	Range (Indoor)	Range (Outdoor)
802.11a	October 1999	5.0/3.7 GHz	23 Mbit/s	54 Mbit/s	35 m	120/5000 m
802.11b	October 1999	2.4GHz	4.5 Mbit/s	11 Mbit/s	38 m	140 m
802.11g	June 2003	2.4 GHz	19 Mbit/s	54 Mbit/s	38 m	140 m
802.11n	October 2009	2.4/5.0 GHz	74 Mbit/s	600 Mbit/s	70 m	250 m

Table 2-1: Comparison of the different 802.11 Standards

2.3.1 Wireless Mesh Networks

The limited range of the 802.11 WiFi standard means that building a WLAN that covers a large area can be a difficult task. Wireless Mesh Networks (WMN) can overcome this problem. WMNs are available for different wireless technologies, with 802.11 being one of them. In WMNs, there are two types of nodes – mesh routers and mesh clients. Each mesh router operates as both a host and as a router, forwarding packets from other nodes [83]. This allows for multiple routers to connect together and thus form a WLAN that can span a large area. After a mesh network is formed, each mesh client can communicate with any other mesh client regardless of which access point it is connected to.

WMNs have some very useful characteristics. They are dynamically self-forming, self-configuring, and self-healing. The network nodes establish and maintain mesh connectivity automatically among themselves [83]. Self-forming means that as each mesh router node goes on-line, it will automatically connect to other mesh routers to form a network. Self-configuring is the ability of each mesh router to find the fastest and most reliable paths to send data from one client to another. Self-healing means that each mesh router is aware of other routers and whenever one fails, it will reroute the data through

another node [83]. These characteristics provide for robustness, fault tolerance, and easy network deployment, which are all very useful in disaster environments due to the unpredictable conditions.

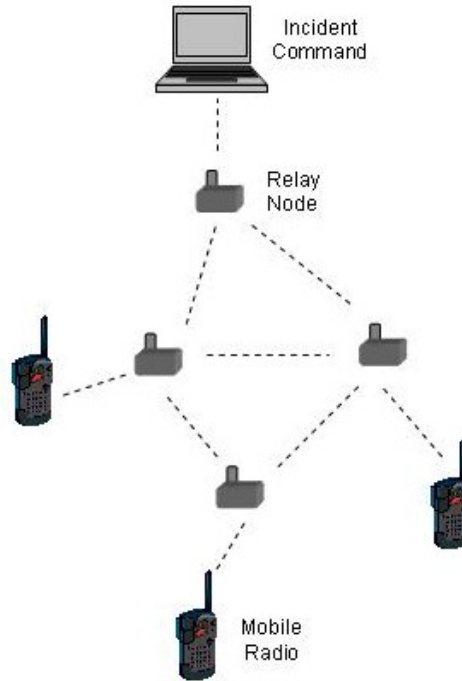


Figure 2-23: Example of Wireless Mesh Network for Audio communications [84]

2.4 *Pattern recognition*

With the increasing use of robots and other remote sensing and telepresence equipment in the USAR field, more emphasis is put on being able to distinguish markers or patterns that signify a human's presence. Even though humans are naturally good at spotting patterns, in a situation where every second counts, first responders could use all the help they can get to aid them in the process. If machines could help with this process it would be extremely beneficial. This is where pattern recognition comes in. Pattern recognition is defined as the study of how machines can observe the environment, learn to distinguish patterns of interest from their background, and make sound and reasonable decisions about

the categories of the patterns [85]. The oxford dictionary defines pattern as “an arrangement or design regularly found in comparable objects” [86], Furthermore, Watanabe defines it as the opposite of chaos, or something that can be given a name [87].

Automatic pattern recognition is normally done in one of two ways – supervised classification, and unsupervised classification. With supervised classification, the pattern is identified as a member of a predefined class. With unsupervised classification on the other hand, the pattern can be assigned to an unknown class. There are several approaches to pattern recognition, with the most prominent being template matching, statistical approach, syntactic approach, and neural networks.

With template matching, a template (usually a shape) is available and patterns are attempted to be matched against that template. The statistical approach assigns features to objects and based on how closely these features match a pattern, it may be classified with some degree of certainty as belonging to one object or another. The syntactic approach attempts to break the pattern into smaller sub-patterns and try to figure out the relationships between the smaller pieces. Neural networks can be viewed as an attempt to mimic the human brain with the key components being learning, generalization, adaptivity, and fault tolerance. Neural networks can be trained to recognize specific objects, and then through generalization they can match other patterns that have similar features [85].

Some example uses of pattern recognition to similar problems are shown in [88] for simple shapes with Artificial Neural Network (ANN), and [89] for search and rescue images from a plane.

2.5 *Telepresence*

Telepresence, or the perception of presence at a remote site is a very important design ideal [90]. It involves the displacement of the user's self perception in a computer mediated environment. Virtual presence (feeling present in a computer generated environment) and telepresence (feeling present in a remote but real environment) have the same psychological effect [91]. Telepresence can be exhibited when an operator remotely controls a machine. There are three main types of telepresence – simple, cybernetic and experiential.

In the simple definition, telepresence is the ability to operate in a computer-mediated environment. This normally involves the control of machines over a distance [91].

With the cybernetic definition, we have telepresence as quality measurement of the human-machine interface. It represents how well a human operator can do the task at hand, by using that interface to teleoperate the machine.

The experiential definition describes telepresence as a mental state, in which the operator feels physically present in the computer-mediated environment. With this type of telepresence it is more like an illusion, where the user thinks that he is there together with all the remote or virtual objects [91].

It is important to make the distinction between the cybernetic definition and the experiential one. Cybernetic telepresence refers more to how effective are the controls and displays in doing the task at hand, while experiential telepresence refers to what is being experienced by the human operator [91]. While the interface contributes to the whole experience, experiential telepresence is something beyond the cybernetic telepresence. It actually involves the projection of human consciousness as opposed to cybernetic

telepresence, which involves the projection of human capability. From this point on when we use the term telepresence, we will mean experiential telepresence.

There are many telepresence systems that are in use in our day-to-day lives. Such systems normally involve the use of a teleoperated robot, and are used when human access to the location is not possible. Such systems include robotic systems for performing remote surgery [92, 93], USAR robots [5, 34, 38], pipeline inspection [94], and deep sea work [95].

2.6 *Situational Awareness*

Situational Awareness (SA) has been defined as “the perception of the elements in the environment within a volume of time and space, the understanding of their meaning and the projection of their status in the near future” [3]. In short, SA means understanding what is going on around you and what can you do about it.

SA would be different for different domains, and could have some variations within those domains based on the different roles of people. Most of the time, SA is used as an operational term, as a person doesn’t always need to know everything that is happening around them, but mostly just the information that is needed to complete the task at hand.

For USAR in general, besides having the right gear, rescuers also need to be aware of their surroundings. Different buildings might have different number of people in them. Also, elderly people would be harder to rescue than younger people who can more easily move [1]. It is also important to know the condition a person is in, so that first responders would know how to move him, or whether he would need to be medically stabilized before extracting. Another important thing for emergency personnel is to be aware of the conditions of the building – how stable is it, does it need shoring, etc. FEMA advises rescuers to “Be

alert for hazards (e.g., power lines, natural gas leaks, hazardous materials, sharp objects, etc.)” [26].

On top of these, the more specialized tasks might require some more things to consider. E.g. a robot operator might need to consider things like the condition of the robot, its location, angle etc. A canine handler might be more concerned for the dog that he is directing while still taking into account other relevant things.

2.7 *Computational Public Safety*

Computational Public Safety (CPS) is a field that encompasses the use of computational resources, theory and practice to support safety processes, as well as improve them [96]. Examples of systems in this area include response robots, CAT and its sub-projects CRDS, CPE, CWA and CBF. These systems are meant to provide rescuers with a better SA, so that they can make an informed decision with respect to rescuing trapped victims in minimal time.

2.8 *Summary*

To gain a better understanding of the motivation for the thesis, some background information on USAR and Emergency Management operations were provided. The information provided described USAR operations, why are they needed, how are they normally carried out, as well as challenges that may be encountered in the process. Other key technologies and research having similar goals, such as rescue robots and animal augmentation were also described. This chapter also provided literature review on wireless technologies and pattern recognition and its applications for USAR operations. Furthermore this chapter explained some key processes, concepts and terminology used in this work.

CHAPTER 3 MATERIALS AND METHODS

3.1 *Architecture of CAT*

The CAT project has seen numerous improvements since its initial development. It has gone through several prototypes, while taking into account lessons learned from them, with each one building on the previous one. The first few prototypes leading to CAT 2.0 have been developed in an ad-hoc manner, without adhering to any architecture or plan. With the development of CAT 2.0 [13], the architecture shown in Chapter 2 was adopted (Figure 2-16).

This was a necessary next step that addresses the long-term vision for what the ideal CAT should be. It set some goals for future versions to accomplish. This section suggests some additions to this architecture, as well as example designs of how the CAT harness would look like.

During the course of this thesis, it was postulated that another useful kind of information could be collected using dogs as the transportation mechanism. Environmental sensory data like air quality, concentration of different gases, temperature, etc. can also be collected. The above architecture has been slightly modified to reflect this addition (Figure 3-1).

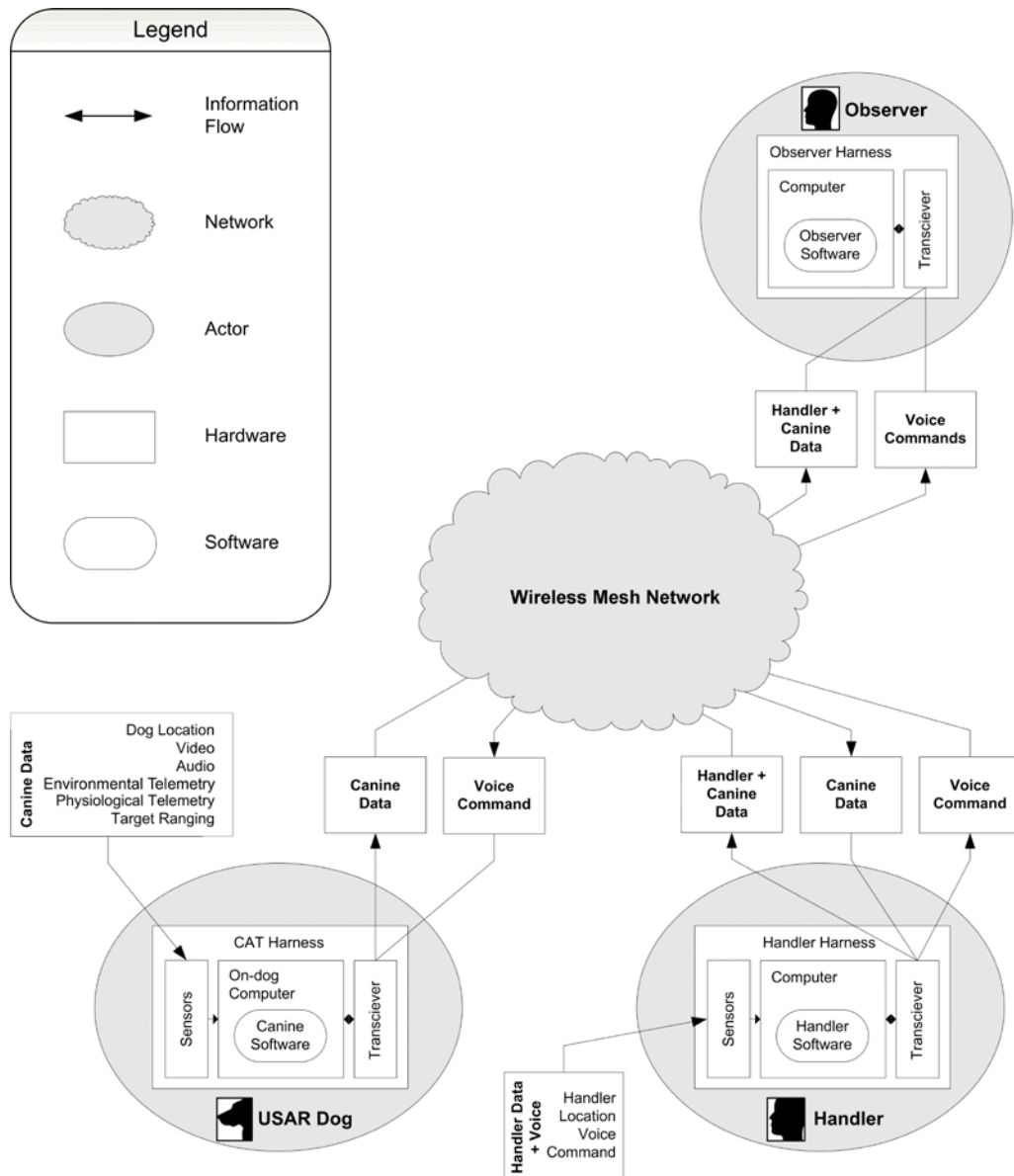


Figure 3-1: Updated CAT Architecture

Through careful consideration a more detailed diagram of how the ideal CAT might look like was created. It is presented in Figure 3-2.

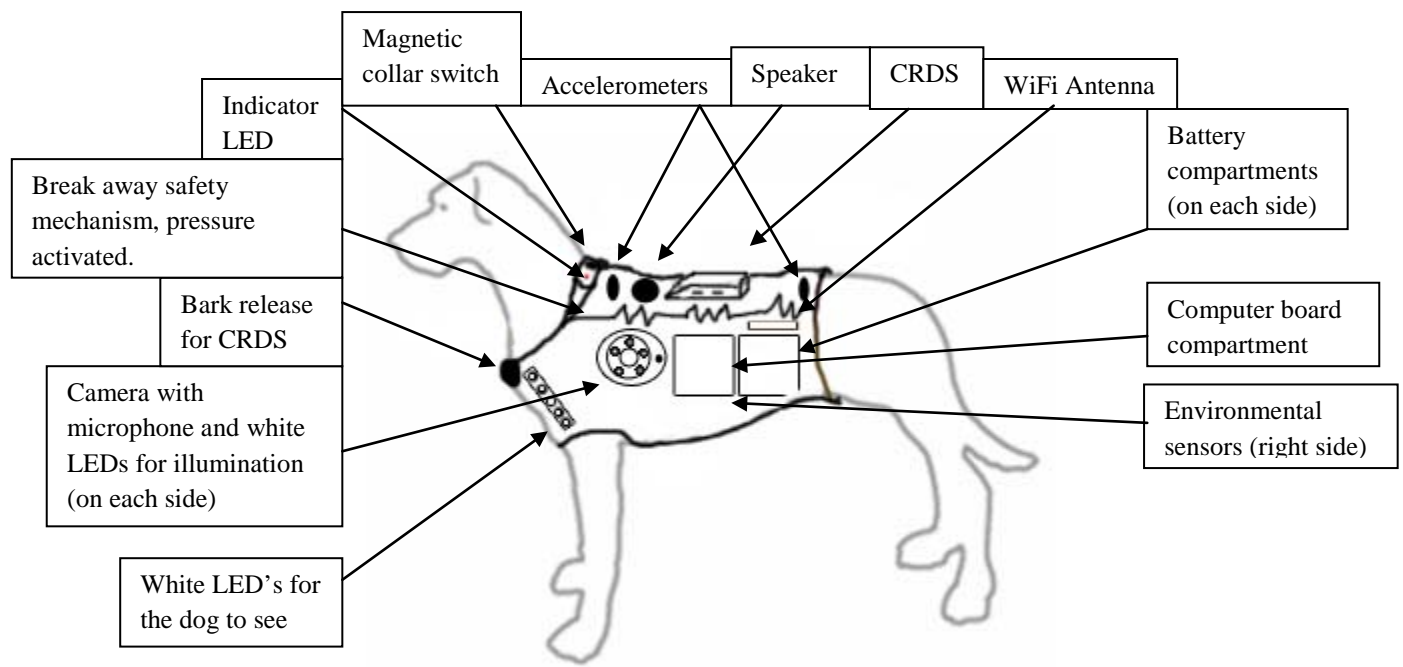


Figure 3-2: Diagram of ideal CAT

The harness would have all the wires sewn in the fabric to prevent snagging. Components attached to CAT should be as flush to the dog as possible, so that they are better protected. White light LEDs should be used to allow the cameras to be effective in low-light conditions as well as record in colour. A speaker would allow for bi-directional communication. Accelerometers to establish the pose of the dog can be integrated on the harness. Environmental sensors would give a better understanding of the conditions in areas that the dog is moving through. An external WiFi antenna that is sewn into the harness might extend the range of the dog. The indicator LED could blink different colors to visually indicate states like on/off, low battery, connected to WiFi node, etc. Batteries should be hot-swappable so that the system could operate for longer periods of time.

3.2 CAT Prototypes

The CAT prototypes starting from CAT 2.0 follow the new architecture which has four critical features:

1. Capturing the local situation of the dog

2. Providing a means of transmitting this integrated information
3. Integrating the data into a single separable stream, and
4. Allowing for the system to be expandable.

In order to achieve the goals of the thesis and demonstrate an enhanced dog-based telepresence system, a prototype that builds on previous designs and incorporates the four critical features of the design needs to be shown.

Capturing the local state of the dog through CAT must provide sufficient feedback to the human observers, allowing them to feel like they are present at the location where the dog is. We do this by using simple cameras, microphones, as well as other sensors.

Another key feature that should be present in the system is that it should provide a means of transmitting the integrated information that is being collected. WiFi is being used as the primary means of communication with the handlers and observers. It was chosen for its simplicity and even though it has a fairly short range, it can be expanded easily when a WMN is used. We cannot expect to have a constant wireless connection with the dog as disaster sites are unpredictable, and rebar-reinforced concrete especially can block WiFi very effectively. That is why the necessity of having an on-dog recording is apparent.

Integrating all the data streams into one is another important architectural feature. Some of the reasons behind this are the limited bandwidth that is normal in a disaster environment; and the fact that the data being transmitted is related, but specific to the needs of the end observers. Different observers will make use of this information in different ways. For example, the handler may be more interested in the information about the dog – temperature, pose, physiological features, etc. The structural engineers would be looking to secure the buildings for humans to attempt a rescue. Search personnel might be interested in

the locations of the victims and the path to them. This will allow for them to build a map of where survivors are located on the disaster area.

Expandability is a key feature of CAT, considering that it is a work in progress. Being able to integrate more sensors as the need for them arises, or incorporating the different sub-components of CAT – CRDS, CBF, and CPE is very important. As other sub-projects arise, they can be integrated into the system, while other pieces can be removed if they are found to be ineffective.

The following sections describe the new CAT prototypes from the oldest to the newest one. It is important to show them as they show how lessons learned from older prototypes were used to create newer ones.

3.2.2 CAT 4.0

CAT 3.0 was a major step from the previous designs but still had limitations that needed to be overcome.

One such limitation was the lack of CPU power. The FOX boards could only stream one camera due to the slow CPU. This meant that nothing else could be accomplished as it would require additional computing power.

Another problem with the CAT 3.0 boards was the limited hardware support. The drivers for it only supported a very limited number of chipsets of specific cameras and WiFi adapters. Even newer revisions of the same cameras that were used were not supported. The hardware used in CAT 3.0 has become obsolete and thus extremely difficult to replace if a problem occurred.

Furthermore a problem was discovered with the recording mechanism over WiFi. If the dog roams out of wireless range, the data was lost, meaning that in some places deeper

into the rubble piles it would be impossible to see what was happening. Also the video feed coming from the dog and recorded wirelessly was too choppy and hard to watch. That meant that when the video was reviewed it would take a substantial amount of time to find the few useful frames where the survivor can be seen, as well as the immediate area around them.

Another problem that was identified was the fact that canine handlers often would forget to turn on the equipment when sending the dog to a search. A better way of switching on/off the system was required.

CAT 4.0 was designed to address all of the above issues. The FOX boards were replaced with a powerful low-cost Linux-based Single Board Computer (SBC) called a Beagle board (Figure 3-17). Because it had a single USB port, a powered USB hub was required to connect all the remaining components. The same two USB Logitech cameras and WiFi adapter were used and the block diagram for CAT reflects that (Figure 3-5). The Beagle board boasted a 600MHz ARM CPU and a Digital Signal Processing (DSP) core allowing it to handle the two camera streams easily, as well as have spare CPU cycles for other things. It had an SD card slot that could expand the space to 16GB that allowed for recording the camera feeds on the dog, as well as streaming them simultaneously. This allowed recording data in places with no wireless signal and had a constant frame rate with better quality and less choppiness.

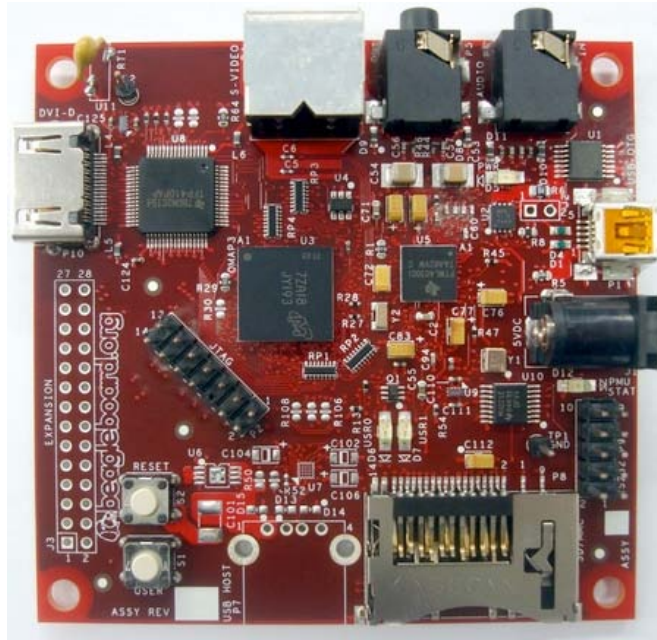


Figure 3-3: Beagle Board

The main benefit of using this SBC was the fact that it could run a full Linux distribution with full hardware support for any peripherals desired. This allowed for using any new camera or WiFi adapter available. The board also featured a serial port, as well as several Input/Output (I/O) pins for communicating with other embedded sensors and devices. In essence the possibilities become limitless as to what can be connected to CAT.

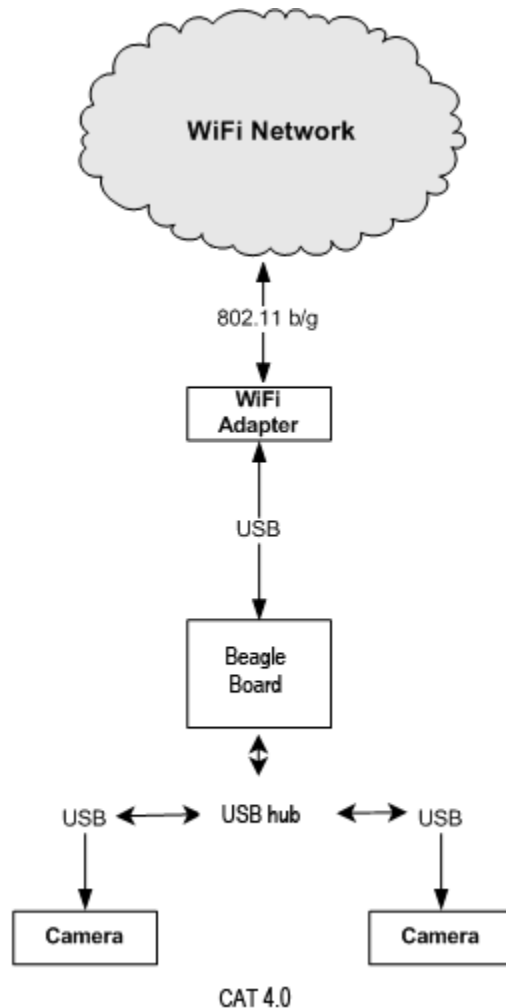


Figure 3-4: Block Diagram for CAT 4.0

Having a full-fledged Linux distribution also meant that developing software for CAT would be just as easy as developing for any other computer. Thus software for streaming and recording the two video streams was written in the C language and utilized the Gstreamer multimedia libraries for Linux. Utilizing these libraries allowed for compression of the data to save bandwidth, and opened up the possibility of recording at higher resolution than transmitting. Different software was made for the computer that would connect to view the streams from CAT. This made it possible to easily connect and view the camera streams on the screen (Figure 3-19). The client application was written in Java, thus allowing for easily

creating a Graphical User Interface. It also utilized the Gstreamer multimedia libraries. Java and Gstreamer were specifically chosen as they are both platform independent and allowed the software to be run on any computer. The software for CAT could be very easily adapted to work with any embedded Linux computer and enable for the streaming and recording of any number of cameras, as well as controlling servos and motors, and reading input from sensors. One such other embedded device that benefited from the software was DEX, which is described in Chapter 3.4.

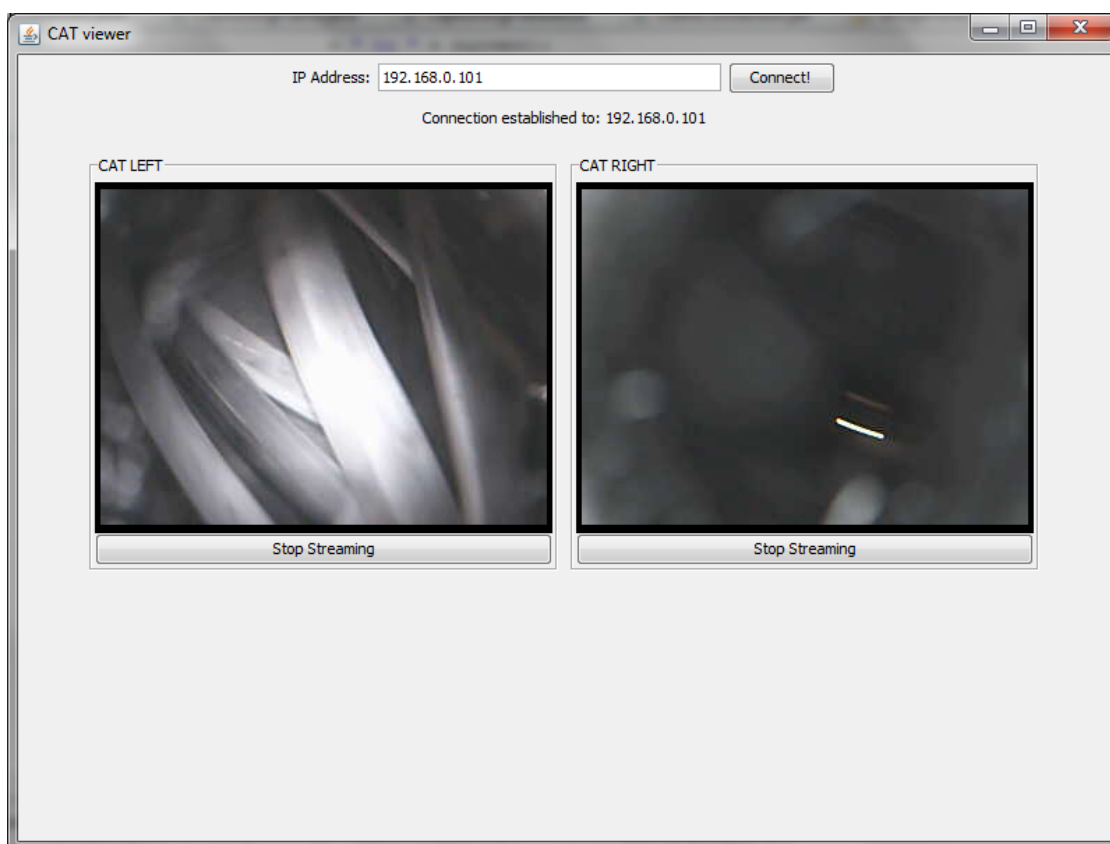


Figure 3-5: Streaming video from CAT.

The power consumption of the board itself was comparable of that of the two FOX boards combined – 2W. This meant that power-wise no sacrifice was made to achieve such benefits as the Beagle board provided. Additional details on the board are provided in [97].

It was identified however from the previous version of CAT that the IR LEDs in each dome would consume 3W peak each. Thus the power consumption of the entire system came up to be 10W. This necessitated the change of battery pack to a higher capacity one. The resulting battery pack provided 7.4V and 2Ah and thus allowing for up to 1 hour of continuous operation.

The ability to record on the dog allowed for the use of software to speed up the search in the video streams to find the important segments where the victim is supposed to be [14]. More details on this are provided in Section 3.3.

To address the issue of having an extra step of switching the equipment on, a different type of switch was used. Instead of having the canine handler physically flipping a switch, a magnetic switch was introduced. It was attached with a string to the dog collar, so whenever the dog was to be sent on a search, the collar was removed and with that the magnetic switch activated the device.

The only downside that was introduced with this iteration of CAT was the size of the computing box actually increased compared with previous versions of CAT.

3.2.3 CAT 5.0

CAT 4.0 was a good architecture, but it brought some issues that needed to be addressed. CAT 5.0 was designed to take those issues into account.

One of the major issues that were encountered with CAT 4.0 was the size of the main computing unit. The added USB hub, as well as the mechanism for switching it on increased the size of the computing unit. Thus having brought the architecture to only one SBC actually increased the size of the box that housed the electronics.

The problem with the increased size became clear as soon as we put the unit on the dog. The harness was designed for a smaller computing unit. When the dog started running and jumping off rubble, the unit fell off the pouch that was housing it and it was dragged on the ground by the connecting cables. Even though the problem could be partially fixed by adjusting the pouch size, it could be seen that it was still bulky and uncomfortable for the dog. It became clear that a smaller unit was needed.

Also the camera domes relied on an off-the-shelf security camera domes that also were a bit big and could swivel when hit. This meant, that if the dog rubs onto something, the camera could be dislodged and remain in a position that it is looking at the back of the dog, or at the ceiling.

Another problem with the domes was that they didn't let sound in. This meant that even though CAT 4.0 had the ability to record audio, the microphones from the USB cameras in the domes could not pick up any sound.

These issues were addressed with the design of CAT 5.0. To reduce the size of the unit, the platform was moved to a Beagle board clone called IGEPv2 board (Figure 3-6). It incorporated Bluetooth and WiFi on the board itself, as well as two USB host ports and thus eliminating the need for a USB hub and an external USB WiFi adapter. The switch to the new SBC brought in a performance boost as well. The new IGEPv2 board had a 720MHz ARM based CPU with the same DSP chip and more on-board RAM and NAND Flash, which could allow for the entire operating system to run on the built-in memory rather than on the microSD card. Additional details on the board are provided in [98]. This simplified our block diagram for the system as can be seen in Figure 3-7.

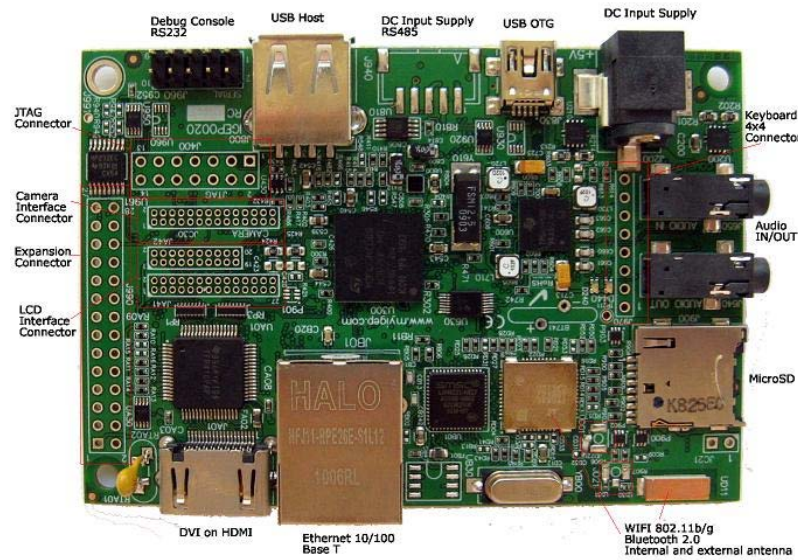


Figure 3-6: IGEPv2 Board

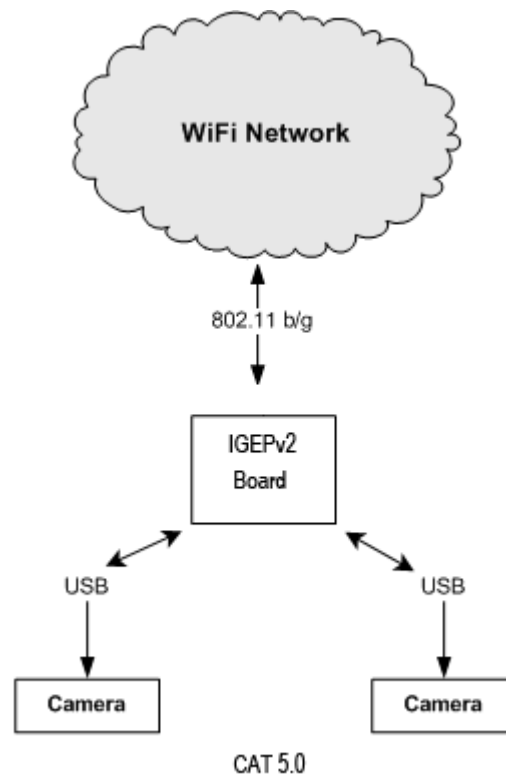


Figure 3-7: Block Diagram for CAT 5.0

The camera domes were redesigned to take into account the issues discovered in the previous CAT prototypes. The outer shell was made of a sturdy material that housed the

inner shell which was made from aluminum with a clear plastic cover at the front of the camera. The inner shell was positioned at an angle facing forward to allow for a better frontal view from the dog. This design also allowed for adjusting of the inner shell for several angles depending on the dog that the CAT system is placed on. The newly designed camera domes included housings for the microphones which were attached to the webcams. Thus bringing back audio sensing which has been missing since CAT 2.0. Figure 3-8 shows the CAT 5.0 prototype.



Figure 3-8: CAT 5.0 with CRDS worn by USAR dog Freitag

3.3 *Automated scrubbing of video*

Since the development of CAT 4.0 and the ability to record the video streams from the dog, it became possible to develop video processing algorithms. These algorithms would allow for tagging the video where interesting things appear. One such algorithm has been

developed for finding times in the video where the victim is most likely to appear [14]. This algorithm is described in this section.

The algorithm for automated scrubbing of video relies on a protocol called the 3-Dog protocol that has been previously developed for situations where CAT and CRDS would be used together [76]. This protocol involving three steps is used whenever a handler cannot accompany the dog in its search:

- A dog is sent without any equipment to search and find a human in the regular way.
- If the first dog gets a “hit”, a second dog is sent with a Canine Remote Deployment System (CRDS) [76] that is capable of automatically dropping a marker when the dog barks. The bag (called the underdog) is orange (containing supplies, radio, etc.) and is usually within 1 meter from the scent plume the dog has detected.
- Finally, a third dog equipped with CAT is sent in to collect video of the area and possibly of the trapped person and their surroundings and condition.

The dropped bag is the key to video processing as the bag is a colour which is different from the surrounding debris. Thus a technique used by a human scrubbing the video is to look for the orange bag to appear - the video depicting the victim is likely to be near this location in the video stream.

The scrubbed images can then be analyzed by structural engineers and rescuers to plan how to best save the person. We should take into account that going through the video and analyzing the video frames is a very time-consuming process which adds to the delay before a rescue can be attempted. Since the underdog may appear in one or two video frames for a fraction of a second, a person might easily miss seeing it.

Software was developed that is able to analyze the video stream, either in real time or after the video has been extracted, and to tag the video where the orange bag appears. To accomplish this, each frame is checked for the presence of the orange bag. Thus the problem becomes finding the bag in an image, as a video is a sequence of images. Because the bag is not a rigid object (shape recognition cannot be applied) and can appear in the image in different orientations and distances from the camera, and in different light conditions, thus the problem becomes quite difficult (See Figure 3-9 and Figure 3-10).



Figure 3-9: Bag outside in good light conditions



Figure 3-10: Bag in an enclosed space in poor light conditions

In solving this problem several approaches were tried. One such approach was the use of the SIFT method [99] to find similar features between the database of trained images and the test images. The problem with this was that many images of rubble, especially in dark places look the same, and the key points selected normally would not contain the orange bag at all. This led to incorrect classification every time and the method was abandoned.

Another approach that proved to be effective is described below.

The problem was split into three parts: pre-processing, isolating regions of the image that contain an orange coloured blob (based on a threshold), and checking if that region contains the orange bag (using an Artificial Neural Network). The Software was implemented in the C language. The libraries used were the OpenCV (Open Computer Vision) library for image processing and FANN (Fast Artificial Neural Network) library for the ANN part.

3.3.1 Pre-processing

The pre-processing consisted of converting from the RGB colour space to the HSV colour space. This was done because the HSV colour space describes perceptual colour relationships more accurately than RGB, and allows us to more easily find colours that are very similar [100].

3.3.2 Isolating regions

For finding the regions with the orange blob, thresholds were selected for the Hue, Saturation and Value that best capture the colour that was sought in different light conditions. The values were found to be the following:

Table 3-1: HSV minimums and maximums

Hue		Saturation		Value	
<i>Min</i>	<i>Max</i>	<i>Min</i>	<i>Max</i>	<i>Min</i>	<i>Max</i>
0°	24°	0.44	0.75	0.35	1.00

A second black and white image is created, so that it can be shown which parts of the image are detected in the colour that is sought. We then go through each pixel in the image and if it has values within that threshold, we change the corresponding pixel in the black/white image white, and black otherwise. We then perform an “erosion”² on the black and white image to remove any stray pixels that might be detected by accident and then several “dilations”³, to get a slightly bigger region that we can use for the ANN step.

What we are left with at the end of this step is one or more regions that were determined as probably showing the orange bag. If no regions were detected, then the orange bag was not found, we discard the image, and we check the next image. If one or more regions are found, they are each scaled to 30x30 pixels and the HSV values for the 900 pixels are given as an input to the Neural Network in the next step.

3.3.3 Checking isolated regions

A standard back propagation Artificial Neural Network was trained on 200 30x30 images to recognize the orange bag. It consists of 2700 inputs (900 pixels with HSV values for each) and 1 output – whether it is the bag or not. Best results were achieved with 2

² Erosion is a basic operator in mathematical morphology. When used in binary images, it erodes away the boundary of regions of foreground pixels.

³ Dilation is a basic operator in mathematical morphology. When used in binary images, it enlarges the boundaries of regions of foreground pixels

hidden layers of 150 neurons each. The Sigmoid Symmetric activation function and a learning rate of 0.7 were used for all the neurons. When a 30x30 region is given to the ANN, it provides a floating point result between -1 and 1 depending on how sure the ANN is of the match. If the result is greater than 0 we assume that it is a positive match and when it is less than or equal to 0 it is a negative match. Based on these results, we can filter each image and remove some or all of the regions that were given as part of the previous step and therefore produce a more accurate result concerning the presence or absence of the orange bag in the image.

This approach could be used to produce timing information where it detected the presence of the underdog. This timing information could be used as a marker in the software for playing the video feeds from the dog. The person reviewing the video feeds would then be able to just jump to that position in the video where the orange bag has been spotted and thus find the victim in the video significantly faster than the manual approach.

3.4 DEX

Although CAT provides really important information like path to the victim, a view of the area around the victim, it does not provide any form of control over where the cameras would be pointed. In most situations the victim can be seen only very briefly, or some areas may not be seen at all. Sometimes a more detailed examination of the victim and the immediate area around them is needed. Since dogs cannot be finely controlled, the ideal situation would allow the search specialist fine control over what can be seen. Robots would be ideal in a situation like this where the operator has complete control over everything. The problem with the robots though is that they cannot get to where the person is trapped. As previously discussed in Chapter 2.2.1 their mobility is very limited. The question then came,

what if we can bypass the terrain traversal and put a robot where the victim is? As previously noted in Chapter 2.2.1, there exist some designs where one robot can carry another robot in a form of marsupial symbiosis. But these designs also are limited by the mobility of the “mother” robot. Then the idea occurred that we know that the dog has no mobility limitations and can easily find the victims. It could also deliver packages to the survivors through the use of CRDS. So why not deliver a small robot to the victim instead of a radio? This idea led to the development of Drop and EXplore (DEX) – the first robot in a new class called Canine-Delivered Marsupial Robot (CDMR). CDMRs can be defined as robots that are designed to be deployed from search dogs [13, 16].

DEX is a prototype robot that was built specifically to be deployed by a dog (Figure 3-11). As such it was built with several constraints in mind. The first is that it must be able to fit under the dog well. We suspected that a flat top would fit flush to the dog’s underbelly making it more acceptable for the dog to carry.

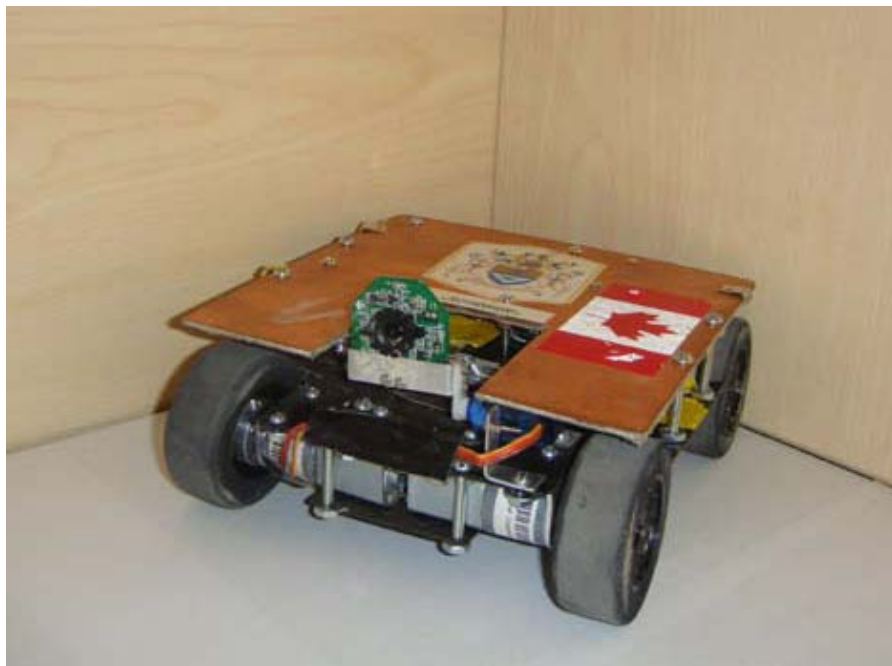


Figure 3-11: DEX

It should also be “dogonomic” – ergonomic for dogs. This is important since the dog must concentrate on its task and not be distracted by the equipment.

These constraints limited the choices for all the other components, such as small wheels size. This reduced the robot’s mobility over a rougher terrain but was still acceptable since the robot would be dropped very close to the casualty. DEX also would not need to move very far to capture the data required. We designed DEX to be a 4 wheeled drive vehicle to enhance its mobility.

DEX’s small footprint also limits the electronics that can be fitted inside. Hence processing power is reduced. More details about the robot are presented below.

3.4.1 Dimensions

As noted above, dogonomics is an important consideration and thus we tried to minimize the physical size of DEX. In reality, not all dogs are suitable for this type of work. We have found that USAR dogs come in many shapes and sizes. As a rough gauge Labrador and Shepherd breeds work very well in terms of size and build. Table 3-2 lists the dimensions in detail. The larger the size is the less accepting the dog is likely to be and the robot will also encumber the dog’s mobility.

Table 3-2: Dimensions of DEX

Length (cm)	Width (cm)	Height (cm)	Wheel Diameter (cm)
18	15.5	6.5	5.5

3.4.2 Attaching to the dog

We used the CRDS as the deploying mechanism so another design issue that we had to consider was how the CRDS, the dog and DEX would be attached. We developed two methods for attaching DEX to the release mechanism.

3.4.2.1 Method 1: We used retractable cable mechanisms, attached hooks to the ends and mounted them on top of the robot. Figure 3-12 shows this on the robot and Figure 3-13 shows how the system is attached.



Figure 3-12: DEX with retractable hooks

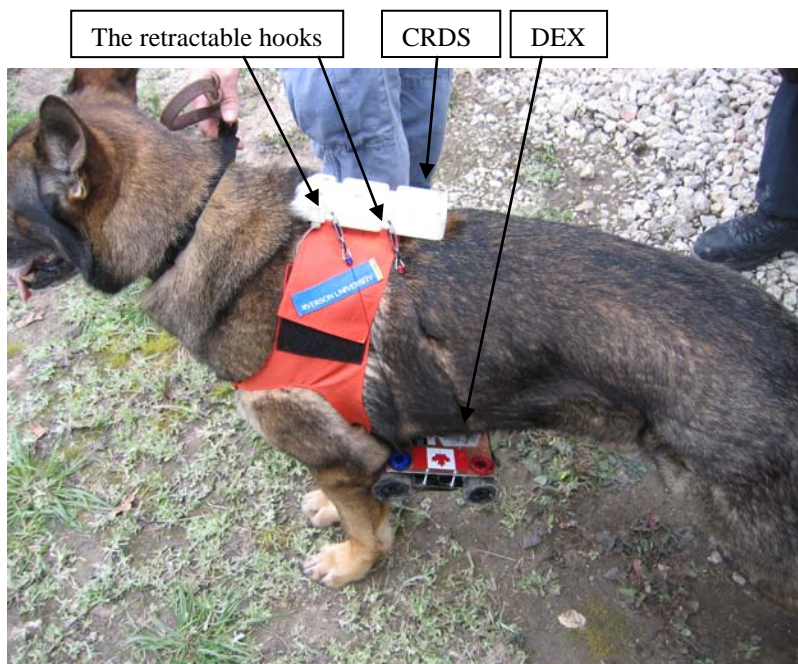


Figure 3-13: DEX attached with hooks to CRDS

3.4.2.2 Method 2: The robot was nestled inside the underdog. When the CRDS is triggered, the bag is released along with DEX (Figure 3-14).

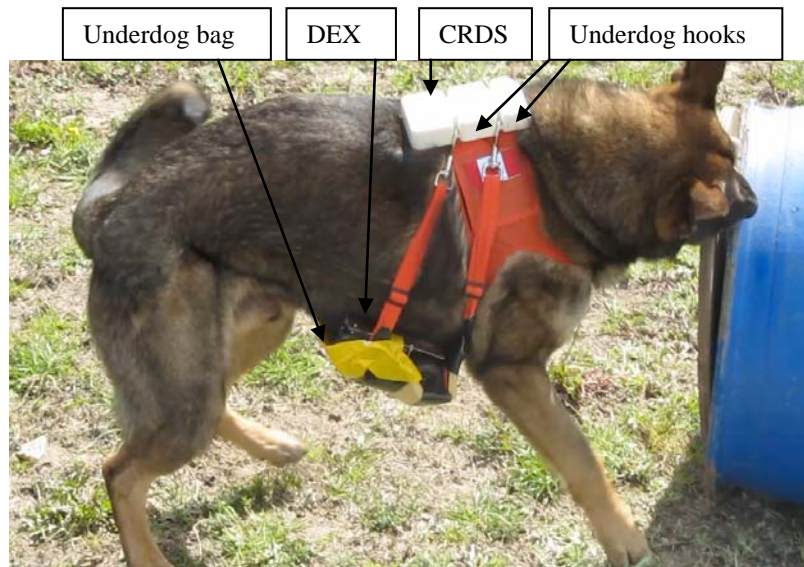


Figure 3-14: DEX in underdog attached to CRDS

3.4.3 Electronic hardware

The electronic components of DEX include:

- SBC – Beagleboard
- Camera – Logitech C200 webcam
- 4 ports USB Hub
- WiFi adapter – D-Link DWL-G122
- Switching voltage regulator
- Microcontroller board based on Atmel's ATMega328
- Motor driver – Pololu TB6612FNG Dual Driver
- Lithium Polymer (Li-Po) batteries

The main control unit – the Beagle board was the same as the one that was used in CAT 4.0. It was used to capture the video from the camera and transmit it over a WiFi WMN. It was also responsible for receiving control signals from another computer and passing it on to the microcontroller for mechanical functions.

The microcontroller was also connected to the motor driver which provided power to four geared motors. Aside from the drive motors, a servo motor was used to raise and lower the camera. The servo motor was controlled by the microcontroller.

DEX was powered by two separate packs of Li-Po batteries. Each batteries pack was made from two cells in series providing a nominal voltage of 7.4V and has the capacity of 2000mAh. Since all the electronics operated on a 5V logic level, a switching power regulator was used. The second batteries pack was used just to power the motors. This design of two separate packs helped reduce the electrical noise from the motors.

3.4.4 Control and communication

The robot is controlled through 802.11 standard over a WMN. Our reasoning is that the network can be easily extended by dropping more nodes, and thus allowing for connectivity in places where normally no wireless signal could penetrate, such as around bends in rubble made out of reinforced concrete.

The robot is controlled from a laptop on which the user interface displays a live audio/video stream from the camera. A joystick-like interface is used for easier control of the robot movement and 2 buttons for tilting the camera up and down. When a command is sent to move the robot, it goes through several “hops” of the mesh network to the robot’s computer which, in turn, interprets the command and sends it to the microcontroller via a serial interface that controls the individual motors.

The video feed from the camera is recorded on a local flash drive, specifically a Secure Digital (SD) card on the Beagleboard. The video is also streamed through the WMN to be displayed on the laptop screen where first responders can analyze the information.

The automated video scrubbing, detailed CAT architecture design, the software for DEX, as well as CAT 4.0/5.0 are the contributions of this research. The next chapter presents the experiments that test the theories of these developments. The results of those experiments will show that these contributions satisfy the requirements to achieve the goal of this thesis.

CHAPTER 4 EXPERIMENTS AND RESULTS

This section explains the experiments and results obtained from each stage of CAT's development. It is meant to complement Chapter 3 and the designs of each prototype. Each stage was done with the knowledge obtained from the previous stages. The experiments can be classified in the following sections in chronological order:

- CAT 4.0 Experiments
- Video Scrubbing Tests
- WMN Deployment Experiments
- CAT 5.0 Experiments
- DEX Experiments

In the final sections we will discuss how the captured video and audio through the different CAT systems, as well as from DEX demonstrated the ability of the systems to further enhance the situational awareness of an observer when compared to previous CAT systems. Also we will discuss how the video scrubbing software can reduce the time needed to locate key frames within a CAT video feed which may ultimately reduce the time needed to rescue someone.

4.1 CAT 4.0 Experiments

CAT 4.0 was designed to make the CAT system more expandable by allowing for more sensor attachments and to allow recording video on the dog (On-dog recording) for later review and processing. On-dog recording was a pragmatic response to difficulty of maintaining a wireless network link with a moving dog in some of the worst radio communication settings.

4.1.1 Preliminary video tests

Based on the new hardware and software, CAT 4.0 had the ability to transmit and record the two camera streams simultaneously. The equipment was first tested in-lab to determine the performance of recording and streaming the two video feeds. The results from this test were very encouraging.

The live video feeds showed very good quality at resolutions of 320x240. The video streams showed almost no lag and little choppiness. The on-board recording showed no problems whatsoever. There was no lag and the pictures had good quality.

4.1.2 Rubble pile tests

With the collaboration of the Ontario Provincial Emergency Response Team (PERT) of the Ontario Provincial Police (OPP), a purpose-built rubble pile and “confined space” training and testing facility used as a simulated disaster site was made available for the experiments.

With the help of Canadian certified and U.S. FEMA certified canine teams⁴, two experiments were conducted. In the first experiment, the canine “Dare” was equipped with CAT 4.0 and the canine handler Const. Kevin Barnum walked him around the PERT headquarters. The video feed from the CAT system was recorded, as well as observations made as to how the new system fit on the dog.

The second experiment involved a simulated search for a victim on the rubble pile. A person acting as a quarry was hidden somewhere in the rubble while Dare had to find him. One WiFi router was placed on the pile at a strategic location, so that it could provide coverage for a large area. This test would give us an indication of how the video feeds would

⁴ Provincial Constable Kevin Barnum and the Black Labrador Retriever “Dare”

look during an actual deployment, as well as tell us how well the system could be worn and accepted by a dog. It would also show us how having on-dog recording compared to video over WiFi transmission.

4.1.3 Experiment Results

The video recorded from the first experiment showed us that recording on the dog is better than the streamed video. It produced no lag or interruptions. A perennial problem—that of shaky video, was addressed. When the dog was moving the shaking was noticeably reduced. We noted that the main computing unit was not ideally suited for a dog's comfort and movement appeared awkward for the dog.

Because the box that housed the computing unit was a little larger than on the previous version of CAT it did not fit as snugly as before. In addition, the unit placed additional strain on the harness quick release points which sometime gave way reducing the effectiveness of CAT. As the computing unit was larger than previous units, it had a tendency to sway in sympathetic harmony with the dogs motion which several dogs clearly did not like. A field expedient was used to resolve this issue by snugly duct taping the unit in place against the harness. Clearly, there were still issues associated with harness comfort and efficacy. However, these are beyond the scope of this thesis.

Previous CAT units had a very cumbersome method of turning on the various components. Canine Handlers hated this. The canine handlers appreciated a new method for turning CAT on. A magnetic switch was incorporated into the harness in proximity to the D-ring intended for a leash. When a handler removed a leash—readying the dog for a search, the unit was turned on.

In the second experiment, within the first minute of the search Dare started jumping from place to place on the pile and the box for the computing unit fell out of its pouch. The unit was then dragged by the dog for several meters hanging by the cable harnesses for the cameras. It became apparent that the harness would have to be modified to accommodate the change to a bigger computing box. After duct tape was applied, the box no longer was falling off and the experiment could be resumed. Dare was able to find the victim in a very short amount of time. During that time, the wireless connection to CAT had disconnected multiple times and thus lost parts of the transmitted video information. When the search was complete and Dare returned, the SD card with the camera feeds was extracted from the dog and the videos were reviewed. This showed us that on-dog recording was far more reliable than the WiFi transmission which experienced numerous disconnects.

4.2 Video Scrubbing Tests

One of the main benefits that came with the ability to record video streams with CAT was the possibility to run pattern recognition software on the video feeds to allow for easier victim location⁵. The software that was developed and presented in Chapter 3.3 was then tested [14] to determine efficacy.

4.2.1 Test setup

A series of tests were conducted on the pattern recognition software for the thresholding part, the ANN part and the combination of both. The thresholding part and the combination of thresholding and ANN were tested on a series of 20 images, while the ANN part was trained on 200 images and tested on 135 images.

⁵ We refer to finding the victim within the video stream only. Finding the victim in reality is done by the dog.

4.2.2 Test Results

The error for the ANN converged quickly after only 41 epochs and produced minimal errors on the testing data as well. The results are presented in Table 4-1 and Table 4-2.

Table 4-1: Approaches and corresponding error

	Thresholding	Thresholding + ANN
Error	15%	15%

Table 4-2: Neural Network's convergence and errors

Epochs	Training Error	Testing Error
41	0.001813	0.067022

While the thresholding approach yielded a 15% error, it actually recognized all the images that had the orange bag in them, but also picked up some false positives. The two approaches combined still exhibited 15% errors which means that 15% of the time a false indications of an orange bag that was not present at a particular location in the image was produced. Figures 4-1- 4-9 provides examples of correct classifications, false negatives, and false positives.

As false positive errors are generally far more acceptable than false negatives given that we are trying to find indirect signs of a trapped human being in the rubble. False positives can quickly be ruled out by a human observer however a false negative—a failure to indicate the presence of a colour—could mean our system would miss them completely.



Figure 4-1: Correct classification - Original image

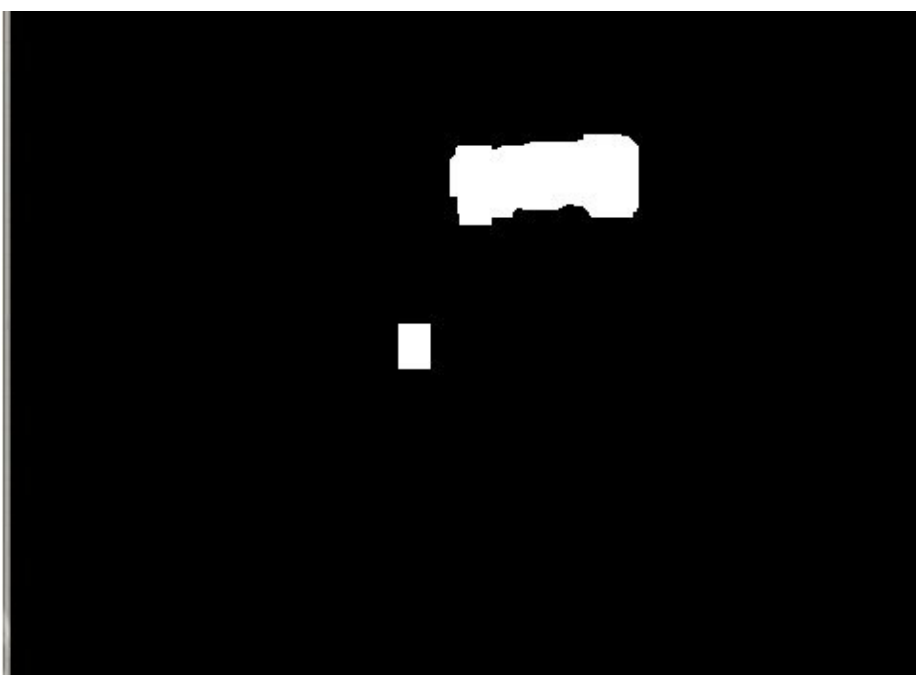


Figure 4-2: Image after thresholding

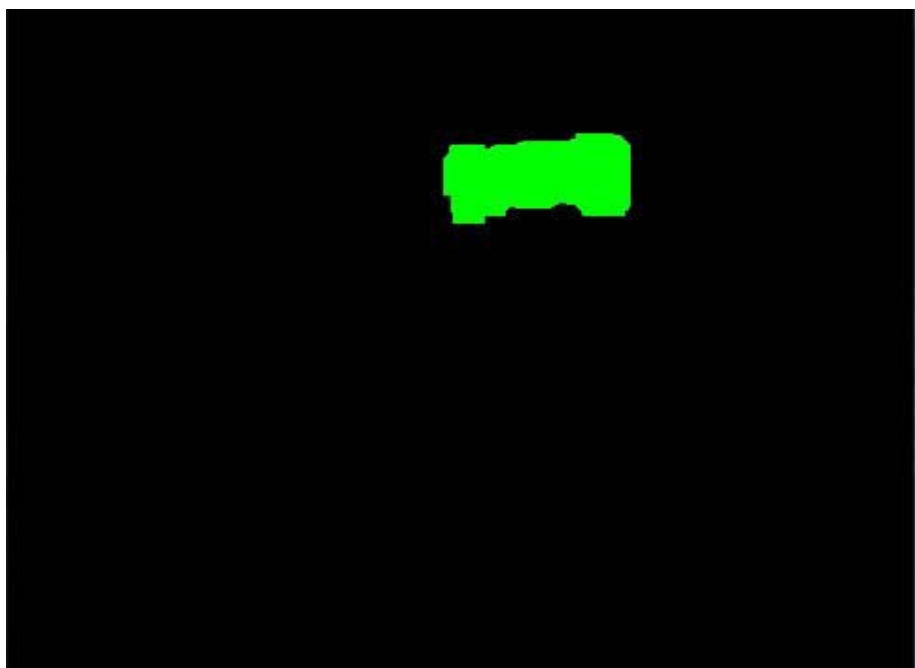


Figure 4-3: Image after the ANN filtering

In Figures 4-1 - 4-3 the thresholding function detected 2 regions, one of which was a false positive. After filtering the 2 regions through the ANN only the correct region remains.



Figure 4-4: False negative - Original Image

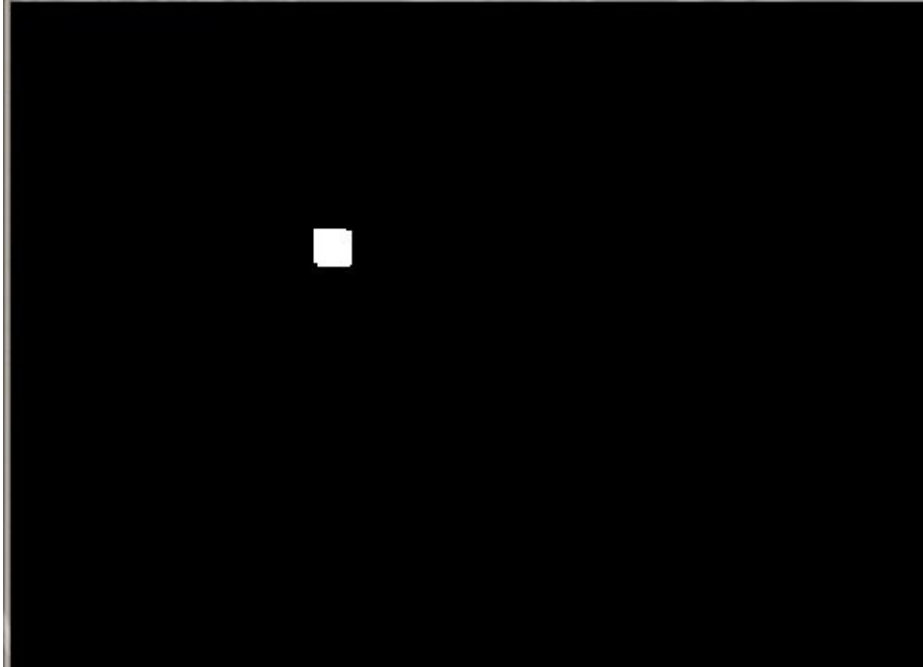


Figure 4-5: Image after thresholding

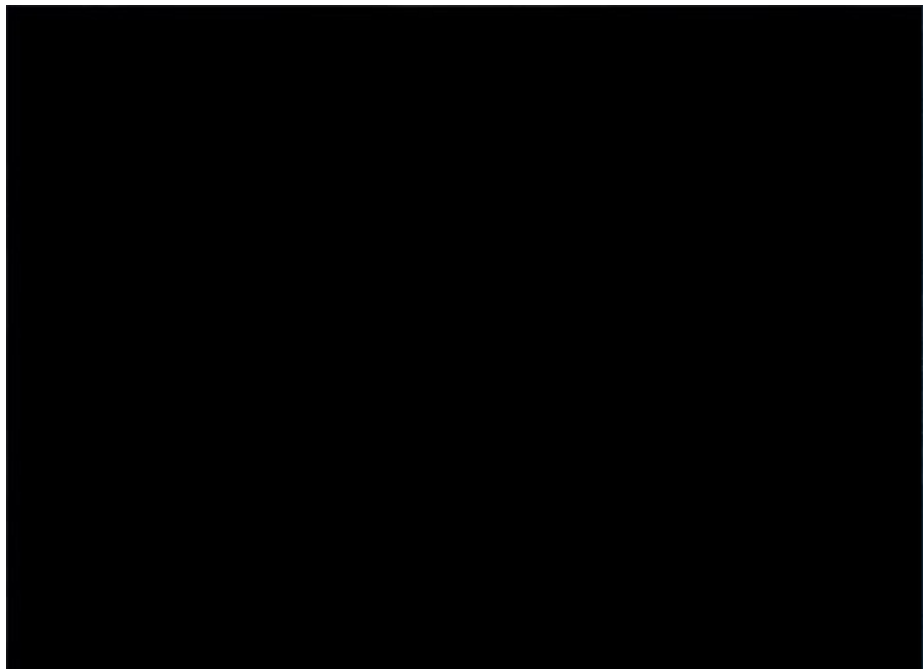


Figure 4-6: Image after the ANN filtering

In Figures 4-4 - 4-6 the thresholding function detects 1 region which shows the bag. After the ANN filtering, that region is ignored and gives a false negative.



Figure 4-7: False positive - Original image



Figure 4-8: Image after thresholding

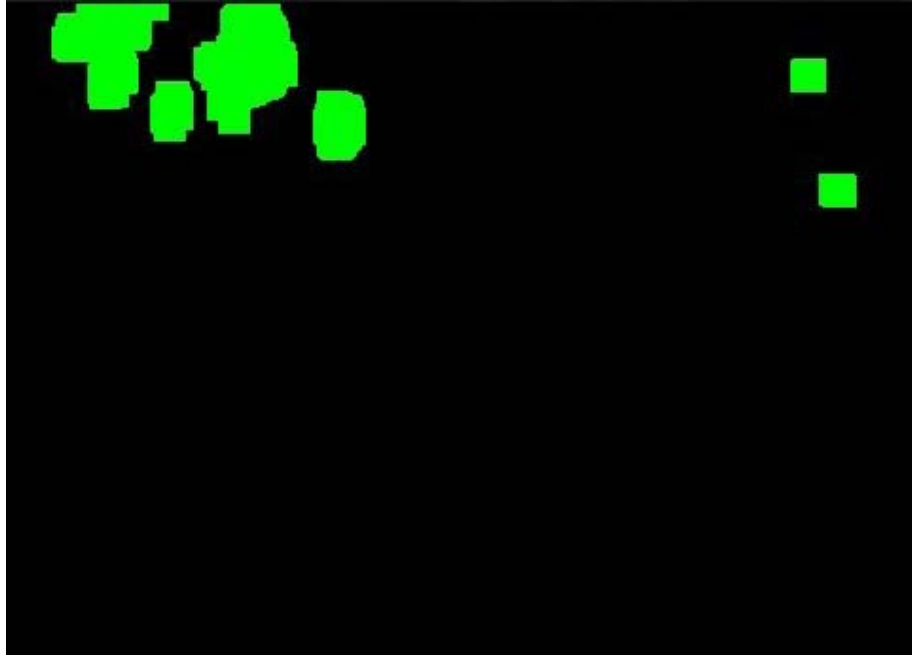


Figure 4-9: Image after the ANN filtering

In Figures 4-7 - 4-9 the thresholding function detects 8 regions, all of which are false positives. These are due to the orange colour of hanging insulation in a partially collapsed parking garage. After the ANN filtering, 2 of these regions are ignored but still provide a false positive. This image is particularly difficult to process in order to find the orange bag, because most of the image has orange shapes most of which look like the bag. It is almost impossible even for a human looking at the image to figure out whether the bag is present in it.

4.3 WMN Deployment Experiments

When first responders arrive at the scene of a disaster, they need to build the wireless network on which CAT will run. This has to be done in a way that does not endanger them. This section describes one way of deploying a WMN.

The experiment was conducted in the tunnel system under Rubble Pile 1 (Figure 4-11) at Disaster City of Texas A&M University, College Station, Texas. It involved the

placement of several WMN routers at strategic locations so that wireless connectivity is maintained throughout the tunnels.

Normally WMN's are set up by dropping off access nodes around the rubble in question. This can be problematic as there is no knowing what connectivity is available in the midst of debris which cannot be traversed by a human. Our experiments indicate how a network can be extended into debris without endangering humans.

4.3.1 Experiment setup

To simulate a real environment, a “quarry” was hidden somewhere in the tunnels under the rubble pile. The intent was to place a person in a location that was deep within the tunnel system, so that it would necessitate the placement of several WMN nodes in order to establish a connection. The tunnels were made out of reinforced concrete with 90 degree turns, which limited wireless range significantly (Figure 4-11). The goal was to build the network without any previous knowledge of where a victim might be located. To do this, we started with placing a WMN router near the entrance to the tunnels at a distance of 3m. The remainder of the network was to be built by utilizing a USAR dog and a response robot. The dog was equipped with a CRDS with a WMN node placed in the “underdog”. The goal was for the dog to find a victim, bark until the CRDS was activated and the router would be deployed. Then a person would walk on top of the rubble pile with a WiFi detector to try and locate where the dog has released the mesh router and give us an approximate location. A response robot would then be sent in to build the network to the victim. The robot used in the experiment was a Matilda by Mesa Robotics. It carried another mesh node in its gripper. This node was to be released when the signal to the node at the entrance to the tunnels was very weak. The network was to be extended by dropping extra mesh nodes with the Matilda

robot until a connection was made to the last node located in the vicinity of the victim (dropped by the dog).

4.3.2 Experiment results

The experiment proved to be a success. The dog that was sent in found the victim, gave a bark indication and the CRDS released the underdog containing the WMN router. A walk on top of the rubble pile with a WiFi signal detector gave us an approximate location of the WNM node. At this point the Matilda robot carrying the second mesh router was sent in. We had determined that the best position to drop off the second mesh router was at the second tunnel intersection. Anything further than this would have required more WMN nodes to be deployed. The Matilda dropped off the mesh node at that location. The mesh network was formed and within seconds we were able to ping the router that was dropped off by the dog near the victim. A map of the locations of the victim and the routers is shown in Figure 4-10.

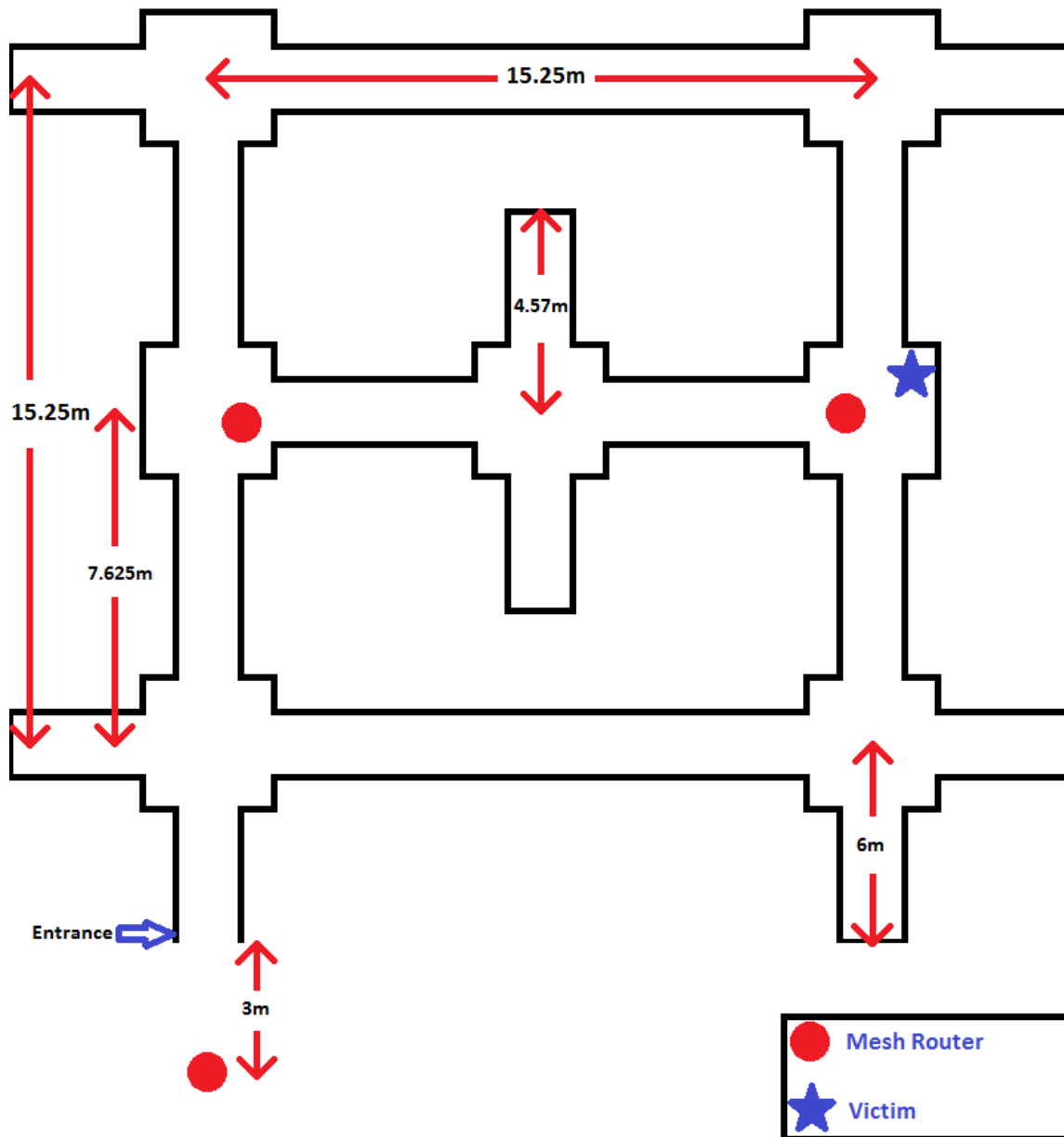


Figure 4-10: Map of tunnels showing victim and router placements.

This network was used in the experiments described in Chapters 4.4 and 4.5.

4.4 CAT 5.0 Experiments

The main focus of the experiments for CAT 5.0 was testing the video streaming capabilities of the system in an actual disaster environment. We also wished to confirm how well the system interacted with the dog.

4.4.1 CAT Experiments

Again, our experiments were conducted at Disaster City, College Station, Texas with the help of FEMA canine handlers Tom Haus and Athena Haus (FEMA CA-TF2) and their USAR German⁶ shepherd Freitag.

For the first experiment, Freitag was equipped with the CAT 5.0 system and the handlers Tom and Athena Haus took turns walking him on the grounds of Disaster City. In this experiment Freitag also had to traverse challenging terrain like a rubble pile (Figure 4-11) and different obstacles that existed on the test location. We carried a WiFi router near the dog to test the streaming and recording capabilities of the system in different conditions. Special attention was also put on how the new camera domes and the system performed as a whole.

The second experiment involved looking for a “quarry” in the tunnel system underneath Rubble Pile 1 (Figure 4-11). A WMN was previously established (Chapter 4.3) that covered the whole path to the victim. This test was performed to measure the viability of streaming the video feeds from the dog through the WMN. Another measure was how fast would the dog find the victim, come back and all the information is retrieved from it.

⁶ German in the sense that Freitag only understands commands given in the German language.



Figure 4-11: Rubble Pile 1 at Disaster City

4.4.2 Experiments Results

The results of the experiments were very interesting. The first experiment showed the reliability of the new camera domes. There were no abrasions or cracks to the domes after thirty minutes of testing. The domes remained in operational condition in almost any situation. However one problem that was discovered was the latching mechanism. The inner shell housing the camera was secured to the harness via a magnet. In certain situations, when the dog was jumping up or down, the force from the landing would make the magnet slip and the cameras would pop out of the harness. Another problem that once again stemmed from the domes was that they were heavy. In some conditions when the dog would run and shake too much, the safety features of the harness would trigger. This led to the release of the CAT system when there was no danger of the dog being trapped. The failure points were marked and temporarily fixed with yellow duct tape. Some of the failure points can be seen

inFigure 4-12. The streaming and recording software developed as part of this thesis worked quite well. The streaming video was a bit choppy and at times had significant delay. Some network disconnections also occurred. On the other hand, the recording part of the software performed without any problems. The recorded videos had a constant frame rate, no choppiness or delays. That meant that regardless of the conditions and network communication problems, the recorded video can always be extracted and show us good quality footage from the dog. This test uncovered a problem with our cameras that came from our assumption that the dog would normally operate in low light conditions. We had removed the infra-red filters from our cameras so that we can get a better video in the dark when the IR LEDs turn on. That however meant that in brighter locations like outside the tunnels, or on top of the rubble pile the cameras would show just a white picture. Other than these problems, the system performed well.



Figure 4-12: CAT 5.0 Failure points

The second experiment showed us some more interesting results. Even though there were several WMN router nodes covering the whole area through the victim, connection to the dog was lost several meters after going into the tunnel system. The reason for this was that at that point, CAT was out of range from the router that was located at the entrance to the tunnel and was trying to roam to the next router. It was not successful as the dog was moving so fast that it was already out of range from it before being able to connect. The same thing was repeated for all the nodes on the network. A short time after finding the victim, the dog was back out of the tunnels. The SD card from CAT was retrieved and the videos downloaded to a laptop. The whole process from beginning to having the videos downloaded on the laptop took less than 4 minutes. The experiment was repeated several times with the same outcome. Almost no video was available from the wireless transmission, while the video from the on-dog recording showed a view of the quarry many times and the routes the dog took in and out. (Figure 4-13 and Figure 4-14). From this result we can see that the upgraded system presented in this thesis has a far greater potential for improving SA, as it now allows for video to be recorded despite connectivity problems. Unfortunately this could not be tested as there is no proper user interface available.



Figure 4-13: Left camera showing head of the quarry.



Figure 4-14: Right camera showing head of the quarry.

4.5 DEX Experiments

Although information provided by CAT can be very useful, it is still fairly limited. The video is shaky from the running of the dog and limited around the victim as we would get a brief view of the victim and their surroundings. Since we do not have control of the dog's movements we cannot obtain more information on the trapped person. To give us a better SA, we needed more control of the cameras that could be obtained by using a robot. This is why DEX was introduced. One major concern in the development of DEX was determining if dogs would accept having a robot attached to them. The dog cannot be distracted from its task of performing searches and this was a real concern whenever we attach anything to a dog. Another concern was determining if DEX could be successfully deployed from a search dog and remain operational. In past testing we determined that most items that were in any way fragile would be broken by an USAR dog eventually. A successful deployment of DEX would mean that it would maintain all its functionality, such

as mobility and video broadcasting after being dropped from the dog. Our first set of experiments tested these concerns.

4.5.1 Experiments setup

The CAT 5.0 experiments were followed by the DEX experiments. A typical exercise in the training of USAR dogs is called the “bark barrel”. A “quarry” is placed inside a large barrel and hidden from view. The purpose of the bark barrel is to get a dog to bark when it smells the human in the barrel. Eventually, the barrel is moved to a rubble pile and then removed altogether as the dog becomes used to finding hidden humans in voids and hidden spaces in rubble piles.

We adopted the bark barrel exercise for our experiment to familiarize the dog with wearing the equipment. In our experiments we equipped Freitag with the CRDS equipment and DEX attached to its underbelly, and then the handler guided the dog to do the bark barrel exercise. Several trials were conducted using both methods of attaching DEX to the dog. Observations were made to see if having all the equipment on would affect Freitag’s performance in the bark barrel exercise. Failure points in the deployment of DEX were also observed.

The second experiment was done at the same rubble pile as the CAT 5.0 and WMN experiments and used the already established network and “quarry” location from the previous experiments.

This experiment was designed to test DEX’s ability to capture videos of the victim and overall visual acuity. A “quarry” was hidden in the same location as the previous experiments. Visual acuity stickers were placed around the location of the quarry. After the quarry was placed, the dog was to be sent in to find the quarry. When the dog barked

indicating that it has found a casualty, the robot would be deployed. The robot then was to explore the area trying to capture videos of the casualty and find as many of the stickers as it can.

4.5.2 Experiments Results

The results from the first method of attaching the robot to the CRDS showed us that that method was a complete failure. Due to the weight of the robot, the cables were sagging and were getting kicked around by the canine. It seemed to be extremely uncomfortable to the dog and on one of the trials the retracting cables mechanisms tore off from the robot body because of the jerking motion of the running dog and the weight of the robot. Figure 4-15 shows DEX being thrown when Freitag was running towards the barrel. It was surprising that DEX was able to drive off after that but another method of releasing the robot was needed.



Figure 4-15: DEX being thrown from Freitag

For the second method of release, the underdog had to be slightly modified to include bends of the material at the back and sides of the bag, so that the robot wouldn't fall off while the dog is running as in the previous method. The underdog was then cinched flush against the dog's underbelly, so that it held firmly in place. We observed that the dog was able to do the barrel exercise as if it was not wearing anything. This indicates that this method was much more suitable than the first one. Figure 4-16 shows DEX successfully released by the bark barrel. We tried this test multiple times with this release method and we were able to reproduce the same results every time.



Figure 4-16: DEX released successfully by the bark barrel

For the second experiment we managed to deliver DEX successfully in the tunnel system within a meter of the victim. The video streaming system designed as part of this thesis performed quite well. DEX successfully connected to the WMN and we were able to see a live video stream and control the robot and the camera without any problems. With a little exploration we were able to spot the victim and some of the visual acuity markers in the vicinity. See Figure 4-17 and Figure 4-18 for images in the tunnel.



Figure 4-17: DEX exploring in the tunnel close to the victim



Figure 4-18: Image from DEX showing victim and visual acuity markers

In this test we also quickly ran into the main limitation of the robot – mobility. Due to the small size of the tires and the small clearance, DEX got caught behind large wooden

blocks and could not navigate around or over them. Despite that we were able to obtain useful information as can be seen in Figure 4-18.

CHAPTER 5 CONCLUSION AND FUTURE WORK

5.1 *Summary of Findings and Conclusions*

Disasters are occurring more frequently, have a greater cost and have devastating impacts on more people than ever before. Many lives are lost in these disasters, but some of them can be saved. To do this we need the right technology. A lot of the victims survive the initial building collapses, but then die because they are not found and rescued in timely manner. Adding technology to the search dogs in order to improve the speed of the Urban Search and Rescue effort could lead to saving more lives.

The goal of this thesis is to improve various aspects of CAT in order to reduce the time needed to make an informed decision about where a victim is and how to rescue them. This thesis introduced a method for automatically scrubbing the video coming from CAT, overcame the video streaming problems by recording on the dog, enhanced the capabilities of CAT by providing a better computation platform, developed a streaming and recording software that can be used on different embedded platforms like CAT and DEX, as well as helped pave the way in deploying a network in a structural collapse. It also helped to deliver a robot to a victim. This chapter provides a summary of the findings of this research, conclusions drawn from them, and suggests some topics that need further work.

When disasters occur in an urban environment, it is quite common for buildings to suffer structural collapse. Finding survivors other than the lightly trapped ones means that rescuers need to search deeper into a collapsed building. Those areas however could be very dangerous for humans to enter, as the damaged structures tend to be very unstable and there is risk of a secondary collapse. To continue the search, some parts of the wreckage need to

be stabilized and made safe. But not knowing if there are survivors in those parts of the collapse means that valuable time can be wasted stabilizing an area that contains no survivors, while other survivors continue to wait to be found.

There are several methods available for remotely searching for trapped people in areas still too dangerous for rescuers to go in – manual search, manual search with electronic equipment, rescue/response robots, and canine search. The manual search can be very dangerous to rescuers and also allows for a very limited access to voids. Manual search with electronic equipment is more effective than manual search alone, but still places the rescuers on the rubble pile, directly in the way of danger. A safer approach is to use rescue/response robots. However, due to their limitations (see section 2.2.1) like the inability to traverse rubble and the reliance on visual cues for finding people, they cannot be used effectively in the search process. The last method is to use specially trained USAR dogs guided by their handlers. Dogs are very agile and can quickly traverse rubble and find survivors by using their excellent sense of smell. The problem however arises when dogs work off-leash in places where the handlers cannot follow. If a canine finds a victim, it gives off a barking indication. This only alerts the handlers that there is a survivor, but nothing can be determined about the condition of the victim or the surrounding area. A way of obtaining more information is needed to better plan the rescue effort.

Operating under the assumption that dogs are capable of finding any survivors, we can rely on their biological intelligence to get them to the survivors. There is a lot of evidence to support their ability to find victims effectively. Thus equipping them with a telepresence system would allow them to provide more valuable information. We have demonstrated how we can improve the information available to rescuers by equipping dogs with technology.

We have provided a more robust system that addresses the needs of the dog – dogonomics, and is able to sense and convey more information than before. We have shown that with the improvements in CAT with versions 4.0 and 5.0, the successful deployment of a WMN in a structural collapse, as well as the work on DEX, we have significantly reduced the time to make an informed decision about rescuing victims. Although it is not possible to describe the comfort experienced by a dog while wearing the system, we have determined through observation that our system is more practical to wear, as seen in the experiments described in 4.4. When wearing CAT, the dog was able to move quickly, without any hindrance from the equipment, and was able to perform searches without any apparent discomfort.

The CAT 4.0 prototype described in 3.2.2 introduced many improvements over the previous prototype versions. With the introduction of the new hardware platform, CAT 4.0 was able to support any new hardware components, such as cameras, microphones, and other sensors. It also allowed for the easier development of software, as it was able to run a full Linux distribution. Another major step up with this prototype was the ability to record the sensed information on the dog.

The improvements from CAT 4.0 allowed for the easier development of software for the platform. Thus a versatile video recording and streaming application was developed, that could be easily adapted to other embedded telepresence systems. One such system, described in 3.4 was DEX, a robot that could be delivered to the victim by a USAR dog. The work on DEX helps to address the limited view of the victim and their surroundings by giving a live feed of the victim that rescuers can control and obtain more information in order to improve their SA.

The ability to record on the dog, spurred the development of another software that was meant to speed up the process of extracting useful information from the recorded videos. It did that by scrubbing the video for the presence of a marker previously dropped by the victim and noting the time in the video. Further details were provided in 3.3.

The on-dog recording proved to be a highly beneficial feature, as the experiments on WMN, described in 4.3 and 4.4, showed us that this type of network was not very effective for the use with a dog. The reason for that was because the dog was moving so fast, that by the time it roamed to another node, it was already out of range of it.

The CAT 5.0 prototype, described in 3.2.3, was a refinement of the CAT 4.0 prototype. As was discovered from the experiments shown in 4.1, the previous prototype was a bit bulky and felt cumbersome for the dog. CAT 5.0 addressed that by selecting a better hardware that was smaller in size and eliminated several components that were no longer needed. That resulted in improved dogonomics as seen in 4.4. Another improvement was seen in the improvement of the camera domes, which were made stronger and more robust. The new prototype also allowed for the recording of audio on the dog, which would further improve the SA of rescuers.

The purpose of this research was not to provide an ideal telepresence system. This work has added to the body of knowledge that supports the effort to make CAT a methodology and suite of technologies that are an alternative to robotic applications. This research has provided functioning prototypes that improve on the work done in previous iterations of the system. The results of the experiments conducted in this research show that the goal of improving the SA of human users of CAT and reducing the time needed to make an informed decision about where a victim is and how to rescue them has been achieved.

Furthermore, without the use of CAT and the streaming and recording software used for it and DEX, it would not have been possible to obtain the video information extracted from the experiments described in 4.4 and 4.5.

5.2 *Future Research*

Although CAT 5.0 is the most reliable, robust, and feature rich prototype so far, CAT is still far from ready to be deployed effectively in real disasters. Many areas still need to be improved and further research is required.

While CAT 5.0 addresses several problems present in previous prototypes, it still needs many improvements. The camera domes is one area that needs further research. They are very durable, but a bit heavy and the latching mechanism relies on a single magnet, which was not very effective of keeping them in place.

Another issue is the use of IR LEDs. There was no real reason behind this, and using white light LEDs can bring several benefits. The first one being that the dog would see better when there is some illumination in the dark. Another one being that the video turns black and white when recording in the dark. Moving to white light LEDs could keep the colour of the video, which would help the video scrubbing software that relies on colour to spot the “underdog”.

The video scrubbing software can see improvements as well. In its current state it could give many false positive or false negative results. The accuracy of the detection was 85% for either method attempted, meaning that in 15% of the results it could give a false positive result if using the thresholding function alone. If we combine it with the ANN, 15% of the results could be false negative or false positive. In most cases the orange bag would be present in several consecutive frames, which would improve the chances of successfully

recognizing it in at least 1 or 2 frames. Incorporating bark detection in the software could help eliminate most of the wrong results.

Another area of improvement is the user interface. At the moment, the only user interface is meant for the streaming of the videos and it is very basic. It would need to be improved to incorporate other sensory information. Since streaming may not be such a viable solution, another UI is needed for recorded audio/video and sensory information. Also further investigation is needed to determine what exactly would be appropriate for use by canine handlers, as they are averse to any form of interface that might jeopardize their interaction with their dog. A hardware and software solution designed specifically for their needs would be the best option.

Reliability of the system is still something that is not up to par. We have seen several prototypes destroyed from electrical sparks. A secondary voltage regulator system should be put into place to prevent such problems. Sometimes the cameras would stop working after a fashion and need to be restarted. When there is no wireless connection to the dog, the on-dog software would need to determine if something has happened and take the appropriate action.

Dogonomics could still be improved. The placement of the main computing box underneath the dog is not the best from a dogonomic perspective. This can be seen especially when using CAT and CRDS at the same time. The “underdog” adds to the bulk of the computing box and makes it a little awkward for the dog to move. Newer hardware that is a fraction of the size would mean that the computing box can be placed on the side of the dog without problems.

Modularizing the design of CAT is also a desirable option. Having different self-contained components in separate locations on the harness would mean easier replacement if some of them failed.

More work is needed to reduce the size of the different components and make them in such a way that when placed on the dog, they would protrude only minimally. This way if the dog brushes against debris it would not be able to break the equipment or tear the harness.

Tracking the dog's precise location in the collapsed structure has been on the wish list of canine handlers for some time. This has the potential of providing rescue workers with a map showing the dog's path to a survivor. Since Global Positioning Systems (GPS) do not work indoors, much less under rubble, this is an open area in research where a lot of work needs to be done.

A similar function is the ability to map the environment. This technology exists in rescue robots. Some systems are able to create a 3D map of the environment as it is traversed. However robots traverse areas very slowly, sometimes stopping to process data. This is problematic when using a dog as transportation.

The CWA would need to be redesigned to take into account all the necessary changes. A diagram of the ideal CAT was provided in 3.1.

Another area that could be explored is the improvement of DEX. Since it could provide a better view of the victims and can be dropped from a dog equipped with CAT and CRDS, it could be a very good solution to the incomplete video information of the victim and surrounding area. The mobility of DEX would need to be improved, so that it could

navigate around simple obstacles. Better video compression on the video stream from DEX would allow for using a higher resolution to improve the clarity of the image.

5.3 *Concluding Remarks*

The intent of this thesis is to improve upon the previous work in the augmentation of search dogs with technological components, and thus create a useful telepresence system for remote viewers. We hope that we have provided a good stepping stone for future work and the system could be expanded and improved upon. Since disasters cannot be predicted, we can at least be more prepared to respond to them. Giving first responders the best available tools to support them in the search and rescue effort can help them significantly. We hope that through further research, one day we could see versions of CAT deployed in actual disasters, where they would enable rescuers to save more lives.

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APPENDICES

A. FOX Board LX832 Specification

Manufacturer	Acme Systems
Operating system	Linux kernel 2.6.19
Power consumption	5V at 280mA (1W)
CPU	100MIPS Axis ETRAX 100LX 32 bit, RISC, 100MHz
Memory	32MB RAM, 8MB Flash
Ports	1 Ethernet (10/100 Mb/s) 2 USB 1.1 1 serial console port
Extension	2 extension sockets with IDE, SCSI, 2 serial lines, parallel ports, I/O lines, I2C bus interface
Dimension	6.6 x 7.2 (cm)

B. CAT 2.0 Power consumption break down

Component	Current Draw (A)	Voltage	Power Consumption (W)
La Fonera Router	1.0	5	5
IP Video Server	0.6	5	3
Serial Servo Controller	0.4	5	2
Servo (4)	$0.1 \times 4 = 0.4$	5	2
Total	2.2	5	12

C. CAT 3.0 Power consumption break down

	Current Draw (A)	Voltage	Power Consumption (W)
Single FOX Board	0.28	5	1
Single FOX Board + USB camera + WiFi Adapter	0.40	5	2
Complete CAT 3.0 Hardware	0.80	5	4