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ANALYSIS OF THE ROBOTIC-ASSISTED SEARCH AND RESCUE RESPONSE TO THE WORLD TRADE CENTER DISASTER

by

MARK MICIRE

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Computer Science
Department of Computer Science and Engineering
College of Engineering
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July 17, 2002

Major Professor: Robin Murphy, Ph.D.

DEDICATION

To my parents.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ANALYSIS OF THE ROBOTIC-ASSISTED SEARCH AND RESCUE RESPONSE TO THE WORLD TRADE CENTER DISASTER

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An Abstract

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The World Trade Center disaster was significant in that, prior to these events, no urban search and rescue response had used robotic technology in the technical search process. The activities performed by the Center for Robot Assisted Search and Rescue in response to this disaster aided in the two week rescue phase after the initial strike. The data collected during the response are presented herein, along with an analysis providing insights into the robot failures and the impact of these failures. The analysis shows that the robot required assistance through the tether an average of 2.8 times per minute over 8 attempts. The robot lost 11% of the search time on average due to traction slippage, 18% on average due to camera occlusion, and 6% on average due to lighting adjustments. Seven findings and a detailed taxonomy of the environmental and robot relationships are then presented from this data. These findings are intended to guide further research and development of search and rescue systems.

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Major Professor: Robin Murphy, Ph.D.
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Date Approved: ______________________________

CHAPTER 1

INTRODUCTION

The attack on the World Trade Center complex on September 11, 2001 resulted in the largest loss of life from any single building collapse in the United States of America. This disaster tested the endurance and expertise of firefighters, police officers, FEMA urban search and rescue teams, and volunteer civilian agencies in an effort to comb through the rubble and search for potential victims. One of the civilian agencies that responded was the Center for Robot assisted Search and Rescue, or CRASAR, headed by John Blitch. The group was activated for deployment under a standing invitation from Ray Downey, the Chief of Special Operations for the Fire Department of New York (FDNY). Four CRASAR teams from across the country converged upon New York, including the University of South Florida, Foster-Miller Inc., iRobot Inc., and the Space and Naval Warfare Systems Center (SPAWAR). The resulting cache of robots and personnel was involved throughout the entire rescue effort. An additional group from the Army Explosive Ordnance Disposal relieved the groups during the recovery effort. During the recovery effort, CRASAR was able to assist the structural and safety engineers in exploring the damaged building structure without endangering human lives.

The collapse of the World Trade Center and the surrounding structures is particularly significant in that, prior to these events, no urban search and rescue response had used robot technology to aid in the search process. As with any first time event, difficulties and relationships within the environment need to be identified for any useful information to be extracted. With this purpose in mind, a detailed failure analysis of the robot performance has been created. This information can provide insight and structure to engineering and professional organizations pursuing research and future applications in urban search and rescue. This also develops and formalizes observations and procedures that will improve future emergency responses that require the aid of robotic systems.

1.1 World Trade Center Disaster

On the morning of September 11, 2001, two commercial airliners were hijacked and flown into the upper floors of World Trade Center Towers located in lower Manhattan, New York. Each of the two large airplanes were Boeing 767-200ER series aircraft with 24,000 gallons of fuel to supply the transcontinental flight to Los Angeles. At 08:46 EST, American Airlines Flight 11 from Boston, crashed into the north tower (World Trade Center 1) between floors 94 and 98. The aircraft impacted the the north face traveling approximately 470 miles per hour, resulting in a large explosion and fireball that impacted multiple floors and surrounding buildings. United Airlines Flight 175 from Boston collided with the east side of the south face of the south tower (World Trade Center 2) at 09:03 EST traveling an estimated 570 miles per hour. Like the first impact, this damage caused multiple floor damage to the structure [1].

At 09:59 EST the south tower collapsed. This was to the astonishment of most observers, including knowledgeable structural engineers at the site. The north tower remained standing for 1 hour and 43 minutes after the initial strike, but eventually collapsed at 10:29 EST. Fire and debris rained down on surrounding buildings, damaging all seven buildings in the 16 acre World Trade Center complex and surrounding structures. Additional damage was encumbered by the Marriot Hotel (World Trade Center 3), the South Plaza Building (World Trade Center 4), the U.S. Customs building (World Trade Center 6), the Winter Garden, and the St. Nicholas Greek Church.

At 17:20 EST, World Trade Center 7 collapsed due to fires that had burned unattended during the rescue effort [1].

Fire rescue personnel responded immediately to the disaster. Of the estimated 58,000 people occupying the World Trade Center complex, 2,270 lost their lives that morning. The lives of 157 airplane passengers and 403 emergency responders were also lost due to this terrorist attack [1]. The resulting search and rescue effort was one of the most challenging ever experienced. FEMA task forces and CRASAR arrived on the scene in the evening of Septemper 11 and began to activate a response to the disaster. This response continued for more than a month after the collapse occurred.

1.2 Research Question

What failures, both hardware and operator, occurred during rescue operations on the rubble pile at robot-assisted rescue response at the World Trade Center?

Accurate analysis of robot failures during a search and rescue disaster requires the robot to have been deployed in an unstaged response. Prior to September 11, this had not been possible due to insufficient robotic platforms for this task. The data collected at the World Trade Center now provides a starting point on which analyze these failures. This can help ensure that the failures encountered and the lessons learnt are not lost to future researchers who may benefit from this information for their own system design considerations.

In addition to guiding better designs in search and rescue related tasks, this work impacts other robotic communities. Virtually any robotic domain that deals in unstructured and unconstrained environments can use the information within this document to gain a better understanding of the problems that can occur. For example, Military Operations in Urban Terrain (MOUT) such as Afghanistan is an example of where this failure information can can be used to their benefit [2].

1.3 Contribution

Three contributions have resulted from this work that will aid the field of urban search and rescue robotics. First, a detailed account of the events gives researchers a historical account of the types of equipment that was used and the conditions under which they were used. Second, a classification of robot systems and void types contributes a common vernacular and grouping that can be used to describe the equipment needs of a disaster event. This taxonomy provides a framework for future findings and recommendations. Finally, findings specific to this disaster are provided to contribute to the future advancement of robotic systems.

The focus of this work is to present how the robots failed or underperformed during an unstaged urban search and rescue response and present findings that reveal real deficiencies in current robotic systems. For the purposes of this thesis, a *robot* is defined both as the deployment vehicle and the operator interaction. A *robot failure* is classified into two instances. A *catastrophic robot failure* is one that terminates the run, and a *significant failure* is one that introduced sub-optimal performance. These failures may have been caused by a hardware deficiency, operator errors, or both.

1.4 Thesis Organization

The remainder of this document is organized as follows. Chapter 2 will cover previous research related to robot-assisted search and rescue. Chapter 3 describes the classification of equipment and deployments experienced at the response. The chapter introduces a taxonomy that is used to provide a context for the failures observed. Chapter 4 documents the failures that occurred and provides a classification for their analysis. Chapter 5 enumerates seven findings that are based on the failures examined in Chapter 4 and operator observations after the disaster. Chapter 6 provides recommendations for future work in this evolving field.

CHAPTER 2
RELATED LITERATURE

This chapter discusses previous research work in the area of urban search and rescue platforms, software and their classifications. Prior to September 11, 2001, there appears to be only a limited examination of rescue robotics subject matter with expert data or field studies. The few field studies reported were carried out by the University of South Florida Perceptual Robotics Lab, often with the author. Because training exercises may differ from unstaged events, many failures or errors observed at the World Trade Center did not show up.

Work done by Blitch in 1996 was one of the first attempts to create a knowledge-based system for disaster site resource allocation. In [3] an expert system was designed to benefit the rescue community by decreasing the expertise the incident commander was required to have in robotics. One effect of designing an expert system is the detailed classification of the elements that will be evaluated in the system. As a result of this work, a very good breakdown of the robots, environment, and tasks is created. The work provides the basis for many of the sections in this thesis.

A natural partitioning of the urban search and rescue domain emerged that split the research tasks into hardware, software and human interaction. Two relatively new concepts in rescue robotics were explored in [4] and [5]. In [4], the concept of shape shifting, or polymorphic robots was explored by Murphy. This allows the robot to adapt physically to the changing environment. In [5], a formal establishment of marsupial robots was researched by Murphy and Martinez. In this multi-robot configuration, a larger mother robot was used to carry smaller daughter robots to the disaster site for deployment. Hirose explored the use of a snake-inspired platform design in [6]. The focus in this research comes from a snake's ability to navigate through highly unstructured and non-horizontal environments. Fire rescue robots are explored by Kobayashi and Nakamura in [7] and Amano, Osuka and Tarn in [8].

The second partition of the urban search and rescue domain resides in the software aspects of the robot. The research in this area has focused primarily on human assistance, multi-agent collaboration, robot control, and sensor control. Human assistance related to resource allocation was explored by Blitch and Mauer in [9] and Blitch in [10]. Additionally, in [11] Murphy, Casper, Micire, and Hyams explored the use of mixed-initiative systems for aiding in the identification of victims. This was tested at the AAAI robot rescue competition in 2000 and was shown useful in this artificial search and rescue environment. This system used the affordances of heat, color, motion, and color difference to establish the probability of a positive identification. Multi-agent collaboration has been explored by Jennings, Whelan, and Evans [12] and multi-sensor control was presented by Masuda, Oinuma, and Muramatsu [13].

Human interaction studies by Casper and Murphy [14] showed that robots can surpass humans in some current rescue techniques. This study was staged in a realistic building environment with the assistance of Hillsborough County Fire Rescue personnel. Vertical exploration through breached floor structures and victim search was shown to be superior to human methods in many respects. However, it was also found that stairwell search by a robot was not superior to a human executed search. This human interaction study provides a detailed breakdown of the patterns that make up a search operation.

In an effort to encourage research in this domain, NIST established a USAR test course in 2000 [15] [16] [17]. The test course was broken into areas by difficulty to allow technologies to evolve through increasingly difficult search and rescue scenarios.

The test course is available year round to researchers wishing to test their technologies and it is used yearly at the Robotcup/AAAI Urban Search and Rescue competition. Most of the participants in this competition are university students and researchers wishing to demonstrate their solutions to the search and rescue problems [18] [19]. It was argued by Murphy, Casper, Micire, Hyams and Blitch [20] [21] that this course is not sufficient and does not present a realistic test bed for a search and rescue site. This claim was reinforced in [19] when Casper and Murphy explored the 2001 RoboCup/AAAI competition and find inconclusive results regarding the performance of the teams.

Failure detection and diagnosis in mobile robotics has had limited exploration in the literature. In [22], Lamine and Kabanza implement a system that detected failures in control programs of behavior based robots. This was accomplished through the use of temporal fuzzy based logic to monitor distributes real-time systems. Makey, James, Park, and Zak present an architecture for failure prediction, detection, and isolation in [23] along with performance metrics. Soika in [24] presents work using the correlation between redundant sensor readings to form a failure detection framework. In [25], Visinsky, Cavallaro, and Walker present a system that uses mathematical models of the sensor dynamics to monitor the state of the robot and detect failures. Washington in [26] attempts to create a fault detection system for rovers that is based on Markov models and Kalman filters. A system that helps to detect and diagnose navigational mistakes is presented in [27] by Stuck. None of these efforts identified and quantified the frequency of occurrences of failures in the field.

Most recently, Casper examined the human-robot interactions at the World Trade Center disaster [28]. This work is important because it is the first research related to an actual unstaged urban search and rescue response that used robot technologies. The thesis provides detailed findings and recommendations regarding observations at the World Trade Center disaster and two additional training exercises.

Finally, it gives recommendations for future research. The findings presented can eventually be used as guidelines for future robotic rescue systems.

CHAPTER 3

EQUIPMENT AND DEPLOYMENTS

This chapter documents the classification of equipment and deployments that were experienced at the World Trade Center response. The descriptions and classification of failures presented in this chapter are vital to the understanding of the failures presented in chapter 4 and the findings conveyed in chapter 5. This documentation is based on the field notes and digital media recorded at the time of the disaster. This material was correlated post-response to create a coherent inventory and timeline of the emergency response. The gathered material presented in this chapter provides a foundation for the classifications.

The coverage in this chapter is limited to the events and robots that were used at the World Trade Center rescue operation. The events and equipment are taken from the first two weeks of the response. CRASAR was involved in the rescue effort from September 12 through September 20. Additional documentation from September 21 to October 1 was available, but was not used in this analysis since CRASAR was assisting in a recovery mode throughout these dates and not a rescue mode. The only robots evaluated in this analysis are the robots that were in the CRASAR cache. The scope of this analysis does not encompass other experimental platform related technology that was not available at the time of the response.

The chapter introduces a taxonomy that is used to provide a context for the failures observed. This taxonomy breaks the characteristics of the voids and the robots used into elemental units, and explores the relationships between them. Finally, the reasons behind these links are discussed.

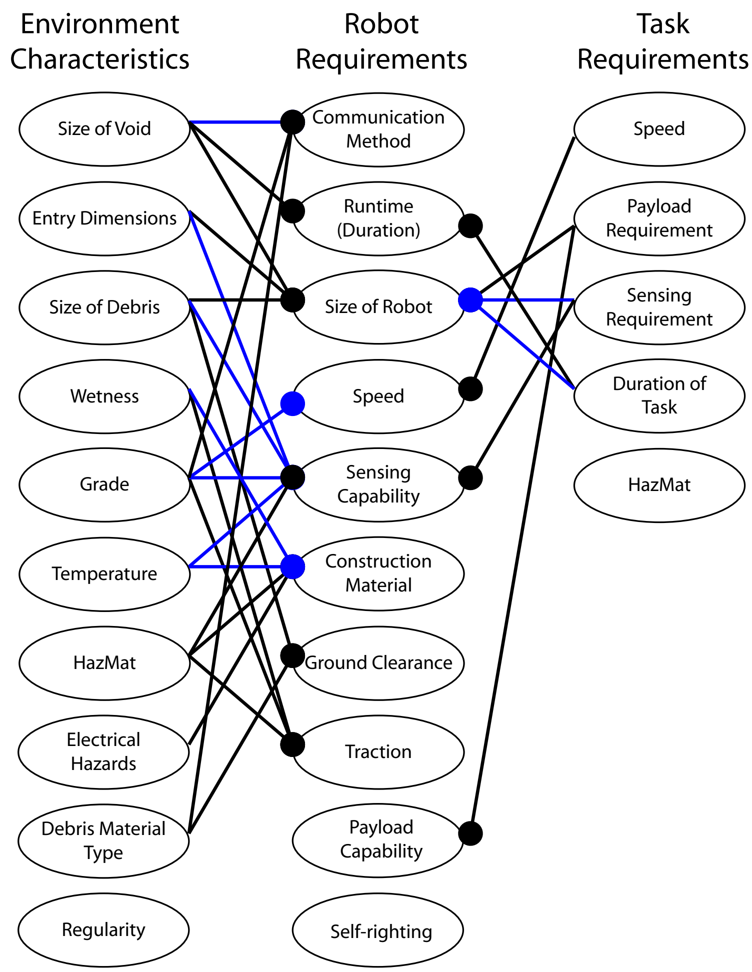
The remaining portions of the chapter are organized as follows. First, the characteristics of a void, robot, and task in a USAR environment are explored. This is then followed by a description of the robots and equipment used during the first two weeks of the response. The robot descriptions then provide a foundation for grouping the robots into four categories. Finally a breakdown of void characteristics and a record of the voids encountered at the World Trade Center is presented.

3.1 Overall USAR Characteristics Analysis

Classification of the robot deployment characteristics at the World Trade Center form three main categories. *Environment characteristics* describe the nature of voids and the key traits that can be used to describe voids. This is important to the analysis because it is the characteristics of the void that will provide the minimum requirements of the robot platform. *Robot requirements* break down the key robot qualities useful for search and rescue. The importance in this category is showing the minimum range of characteristics that a USAR robot should provide. Finally, *task requirements* include potential task requirements that must be satisfied for mission completion. To speak of a USAR response only in terms of debris and equipment would be incomplete. Therefore, this category is a list of elements that are not physical characteristics, but characteristics of the mission. These mission requirements will place additional requirements on the robot platform. A listing of each of these categories can be seen in Figure 3.1.

The taxonomy created by Blitch in [9] provided a first attempt at breaking the task and environment of USAR into its atomic units. This taxonomy was used to establish a knowledge-based system for resource allocation in USAR events. A comparison of the data generated at the World Trade Center found this breakdown to be incomplete. The classifications in most cases were not granular enough to properly

Figure 1. Relationship of the Environment, Robot, and Task characteristics in USAR.



describe all of the characteristics in the environment. To this end, a taxonomy is created to extend, refine, and update the classifications to current data and robots.

For this taxonomy, the environmental characteristics were broken into ten elements.

- *Size of void* is the internal volume of the void to be searched. A cross section of this volume gives an indication of how much area the robot will be required to travel for a complete search.

- *Entry dimensions* refers to the minimum cross section through which the robot can enter the void space. This is often different from the size of the void since the entry point may be a small breach of a wall or floor.

- *Size of debris* is the size of the loose rubble and construction material that the robot will need to navigate to inspect the void space.

- *Wetness* is the amount of moisture in the void.

- *Grade* is the angle of the floor surface that the robot is required to travel.

- *Temperature* is the maximum amount of heat or cold in the void space.

- *HazMat* refers to any hazardous material that may be present in the void which the robot will need to travel through or interact with.

- *Electrical Hazards* are any loose wires that can shock or harm people or robots in the environment.

- *Debris material type* describes the primary material composition of the debris surrounding the robot platform.

- *Regularity* is the amount of change in the environment that the robot might experience. This change may be in the form of temperature, void size, or grade to give some examples.

The robot characteristics were also broken down into ten elements.

- *Communication Method* is the medium by which the robot communicates to and from the operator control unit. This is broken into two categories. Tethered communication is conducted through a cable, and wireless communication is conducted over radio frequencies.

- *Runtime* is the duration of time that the robot can operate before requiring the removal of the robot from the void for recharging or changing of the batteries.
- *Size of robot* is the physical volume of space that the robot occupies in a deployable state.
- *Speed* is the maximum ground velocity that the robot can achieve during a deployment.
- *Sensing capability* indicates the amount and quality of sensors that can be attached to the robot platform.
- *Construction material* defines the primary material of which the robot is built.
- *Ground clearance* is the minimum distance from the bottom of the robot to the ground plane.
- *Traction* refers to the robot's ability to grip the surface on which it is moving.
- *Payload capability* is the amount of additional sensors, manipulators, or equipment the robot can carry.
- *Self-righting* refers to the robot's ability to flip itself over without direct assistance from an operator or the environment.

Finally, task requirements are broken into five elements.

- *Speed* refers to the urgency of the task.
- *Payload requirement* is the amount of additional payload that the task requires the robot to carry.
- *Sensing requirement* is the amount of sensing information the task requires.
- *Duration of the task* is the estimated time the task is believed to take.

- *HazMat* refers to any hazardous material cautions or actions that are associated with the task.

The relationships between the elements in Figure 3.1 were considered as follows. Each of these elements was considered for its relationship to the other elements. If the element had a substantial impact on another in the graph, then a connection was made. This was repeated for every element in the graph. The highest scoring element was the one that was the most connected. Elements with the highest score would presumably be the most important and dependent elements in USAR robotics.

Each of the relationships shown in figure 3.1 came from two sources. First, prior work by Blitch [3] was used to provide a starting point. Unfortunately, the detail and relationships presented in this work were not as granular as this analysis required. As a result, the second source for the links between elements was four of the CRASAR operators that were involved in the rescue effort at the World Trade Center. These operators also had USAR training outside of the World Trade Center response and were considered expert robot operators.

3.1.1 Environmental Characteristic Relationships

An evaluation of the Environmental Characteristic connection scores in Figure 3.1 shows important relationships between the top scoring elements. In the Environmental Characteristics category, four elements tie for the most connections. *Size of Void*, *Size of Debris* and *Grade* were the three characteristics with the high score of 3 connections. These elements were related to navigating inside the void space. This indicates that the structure of the void is very important to the robot's design characteristics. Specifically, the void size will greatly determine the robot that will be used, the debris size will place restrictions on the minimum robot clearance that will be useful to the search, and the grade of the void will require specific robot features to overcome traction deficiencies. *Hazmat* also received a high score with 3 connections, but unlike the other categories, this class was related to robot material and safety considerations in the engineering of the robot platform. This is an applied material engineering issue that is important due to the safety requirements of equipment used in hazardous environments.

The lower scoring groups in the Environmental Characteristics category show characteristics that are important, but not as highly dependent on multiple elements in the Robot Requirement category. Elements scoring 2 connections were *Entry Dimensions*, *Wetness*, *Temperature*, and *Debris Material Type*. *Entry Dimensions* may not be a high scorer because the robot's ability to enter a void is only reliant on its sensing the opening and having a size sufficient for it to fit through the void. *Wetness* is not highly connected due to this placing requirements only on the traction and construction material on the robot platform. *Temperature* can be an important aspect of a deployment, but it does not require more than two elements of the robots design. Sensing and construction material are the only two elements that are effected by this environmental characteristic. *Debris Material Type* places only two requirements on the robot platform. First, the communication method must be such that it can transmit through the debris to the operator unit, and second, the ground clearance on the robot must be high enough to navigate the material on the void floor.

The lowest scoring elements show their non-reliance on platform related requirements. These two low scoring elements were *electrical hazards* with 1 connection and *regularity* with no connections. *Electrical hazards* is a characteristic that can only be related to one robot characteristic. Namely, the construction material of the robot must be non-conductive to limit the damage of this hazard in the environment. Finally, *regularity* appears to have no relation to robot requirements. The regularity of the void can help determine the robot's actions, but there is no platform requirement that can specifically fulfill this environmental characteristic.

3.1.2 Robot Requirement Relationships

In the Robot Requirement category, *Size of robot* has a total of six connections and is tied with *Sensing capability* as the most connected element in the graph. These two characteristics are normally very closely tied in field practice. Specifically, the larger the robot, the more sensors that can be placed on it. Conversely, the more sensing requirements placed on the robot, the larger the robot will become. This important relationship will be more closely examined in Section 3.3. *Construction material* was also a high scoring element, with a total of four connections. This is due to the need for the robot to have proper material characteristics for its environment. Corrosive hazardous material and high temperatures are two examples of environmental characteristics that stress the material characteristics of a robot.

Lower scoring elements in this category included *Communication Method* and *Traction* with three links to other elements. These elements are vital to the sucess of the robot platform, but are not highly reliant on many other categories. *Communication Method* is currently a binary selection between tethered or wireless operation, and is therefore limited in its relationships to other elements. Likewise, *traction* is related to only three of the environmental characteristics due to the limited scope of the traction design in current robot platforms.

The lowest scoring elements in robot requirements are *runtime*, *speed*, *ground clearance*, *payload capability*, and *self righting* with two or less connections. Four of these elements suffer from the binary relationship observed with the communication method element. Specifically, *runtime*, *speed*, *ground clearance*, and *payload capability* are elements that do not have many relationships to other elements because the requirement can either be satisfied directly or it cannot. If the void is too large for the robot to search or the duration of the task is too long for the robot, then the *robot runtime* will not be sufficient. The *speed* of the robot is only dependent on the grade of the void and the speed requirement of the task. The robot requirement of *ground clearance* is only related to the debris size and material type. As a result, the robot either has the ability to travel over the debris in the environment, or it does not. *Payload capability* is the final characteristic that is weakly connected. This is due to the robot either satisfying the tasks payload requirements or not satisfying them.

Self-righting did not have any links to the other characteristics. While the logic described may be deceiving, the ability for a robot to operate inverted or to self right is such a fundamental characteristic that it is loosely and fundamentally connected to every operation in robotic USAR. While each individual link to the various nodes in the graph may be too weak to explicitly represent, the sum of all of the weak links makes this a fundamental feature of robots for USAR.

3.1.3 Task Requirement Relationships

Finally, the number of connections from Task Requirements is tied across three of the five elements. The top three elements each have two links. These nodes are *payload requirement*, *sensing requirement*, and *duration of task*. As discussed with previously connected elements, these three are binary in nature. *Payload requirement* is only related to the robot's size and payload capability. *Sensing Requirements* of the task are only related to the robot size and sensing capability. In both of these elements, the robot does or it does not have the ability to carry the payload or sensors. Finally, *duration of task* is only related to the size of the robot and the runtime that the robot can provide. In this case, the relationship is closely tied to the batteries that are powering the robot. If these batteries are on-board the robot, then a longer runtime will require an increase in the size of the platform.

The lowest scoring elements in this graph are *Speed* and *HazMat*. Task speed is only related to the speed of the robot because the robot must satisfy the minimum speed requirement for the task or it is insufficient. This feature is not dependent on any other element in the robot feature space. The task requirement of *HazMat* is unrelated to the elements of the robot due to the wide variety of hazardous material characteristics that may occur. Much like the regularity category discussed previously, this task element does not place a specific requirements on the platform due to the extremely wide range of characteristics that hazardous materials encompasses. To adequately classify the hazardous material task space would need to be a class of requirements in itself, and this falls outside of the scope of the data set gathered at the World Trade Center disaster.

3.2 Description of Robots

This section describes the robots from three manufacturers that were available for the rescue response at the World Trade Center. These robots are described in the context of the *robot requirement* category described in Section 3.1. The organization of this chapter places the robots into three sections relative to the manufacturer of the robot. Additional information unique to each individual platform is detailed in that particular sub-section. Section 3.3 will explore the robots' relationships to each other in terms of characteristics.

All of the robots available were military robots and all but one was actively involved in DARPA's Tactical Mobile Robotics program for research purposes. These robots were released by DARPA for use at this disaster operation. Of the robots in CRASAR's cache, none were specifically designed for search and rescue operations. The original purposes of the robots included unexploded ordnance removal, military reconnaissance, and confined space remote inspection. Only four of the smallest robots were used on the rubble pile, but all of the following equipment was cached during the rescue. An overview of the robot characteristics is shown in Table 1. The "sensing" characteristic is not included in the table due to the availability of multiple sensor configurations on each of these platforms. Additionally, "material type" is not included since all of the robots are manufactured from aluminum and contain plastic parts in sensor components.

Table 1. Overview of robot characteristics

	Communication	Runtime (hr)	Size (in)	Speed (ft/sec)	Grnd Clearance (in)	Traction Method	Payload Capacity	Self-Righting
MicroVGTV	Teth	6+	6x12x2	.25	.75	Trk	Poor	N
MicroTracs	Teth	6+	7x6x5	.5	2	Trk	Fair	N
MiniTracs	Teth	6+	15x21x5	.53	1.25	Trk	Fair	N
Talon	Both	1-4	34x24x11	6	4	Trk	Exc.	N
SOLEM	Both	1-4	20x14x8	1.5	3	Trk	Fair	N
Urbot	Wless	1+	33x?x11	1.5	5	Trk	Fair	Y
Packbot	Both	1-4	24x20x7	7.2	2	Trk	Exc.	Y
ATRV Jr.	Both	3-6	30x25x21	3.3	3	Whl	Exc.	N
ATRV	Both	3-6	41x32x25	6.6	4.5	Whl	Exc.	N

3.2.1 Inuktun Family of Robots

The Inuktun group of robots was most used on the rubble pile due to their small size and low weight. The members of this family consists of three models: the *VGTV*, *MicroTrac*, and *MiniTrac*. Of these three, the VGTV and MicroTrac proved to be the most useful to the rescue operation. The MiniTrac was available and considered for use on the pile, but did not actually get deployed into a void. Each of these robots can be seen in Figure 3.2.1.

3.2.1.1 Micro Variable Geometry Tracked Vehicle The *Micro Variable Geometry Tracked Vehicle*, or *VGTV*, is a small tethered tracked vehicle. Its unique feature is that it has the ability to adjust the shape of the platform's chassis to raise

Figure 2. Examples of the Inuktun brand of robots and OCU available at the World Trade Center disaster including the VGTV (left), Microtracs (center), and Minitracs (right). Left two photos are courtesy of Inuktun Services Ltd.

or lower the sensor pod located at the front of the vehicle. This ability to change shape, or polymorphism, is achieved through the use of an accordion-like outer chassis that can push the inner structure upward while reducing the track footprint. The raised position has the advantage of increasing the viewpoint height, but this also decreases the platform stability due to the higher center of gravity, or high-centering. Conversely, the lower position is highly stable on angled terrain, but suffers from a limited camera viewpoint.

Specifications relative to the ten robot requirements in Section 3.1 enumerate this robot model's capabilities. The communication method for this robot is through a 100 foot tether. Since the battery is provided outside of the robot chassis, the runtime is only limited by the longevity of the power source. This can be in the form of three twelve volt batteries or an AC to DC power supply. In the robot's lowered tank-like position, the VGTV's height is 2.5 inches and it has a footprint of 6.5 by 12.5 inches. In the raised triangular position, the footprint is reduced to 6.5 by 7.5 inches and the height is increased to 10 inches. Two drive motors allow it to operate at speeds up to 15 feet per minute. The sensor suite includes a microphone, speaker, a motor-driven manual-focus CCD camera, and a camera tilt unit that incorporates halogen lighting. The chassis is manufactured out of milled aluminum, the tracks are rubber belt material, and multiple components contain molded plastic coverings.

This platform has less than 3/4 of an inch ground clearance in either polymorphic configuration. Traction is provided via two rubber belt tracks with cleats added for additional traction. Payload capability is severely limited to packages less than the size of the inner chassis. This limitation is due to its polymorphic nature restricting the mounting space available. Finally, this robot has no self righting features.

3.2.1.2 MicroTracs Robot The *MicroTracs* vehicle is the smallest vehicle for remote inspection in confined space environments. Although it is small, one of its unique features is the amount of strength that the two MicroTrac drive units can produce given their size and weight. These drive units are attached to the bottom of the chassis plate. The track units provide 15 pounds of force per track and can operate at speeds up to 30 feet per minute. Compared to the small VGTV platform, this is twice the speed capability and much more torque. The VGTV is not rated for pulling capability, so any task requirements that mandate a strong and small robot will be best served by this platform.

Specifications relative to the ten robot requirements in Section 3.1 enumerate this robot model's capabilities. The unit is typically deployed using a 100 foot tether for communication, but has the strength to pull longer lengths if needed. Since the battery is provided outside of the robot chassis, the runtime is only limited by the longevity of the power source. This can be in the form or three twelve volt batteries or a AC to DC power supply. The MicroTrac's height is 5 inches and the platform's fixed shape and size and occupies a 7 by 6 inch footprint. Two MicroTrac drive units allow it to operate at speeds of up to 30 feet per minute. The sensor suite includes a microphone, speaker, a motor-driven manual-focus CCD camera, and a camera tilt unit that incorporates halogen lighting. The camera, lights, and microphone are enclosed in a cylindrical tilt unit on the top front of the vehicle. The chassis is manufactured out of milled aluminum, the tracks are rubber belt material, and multiple components contain molded plastic coverings. This platform has 2.25 inches of ground clearance. Traction is provided via two rubber belt tracks with cleats added for additional traction. Payload capability is limited limited only by weight and balance constraints. The flat control box on top of the robot provides adaptability for multiple payload configurations. Finally, this robot has no self righting features.

3.2.1.3 MiniTracs Robot The *MiniTracs* is larger than its two *Micro* counterparts and is a slow, powerful robot. This unit is unique in that it weighs slightly over 50 pounds. This weight helps to counteract the potential recoil from the 12.5mm water jet disruptor that can be installed on the unit's tilt mast. It uses two MiniTrac drive units for mobility that provide 50 pounds of pull per track and can easily accommodate 100 pounds of payload on each track. This is the largest and most powerful robots of the Inuktun brand used by CRASAR.

Specifications relative to the ten robot requirements in Section 3.1 enumerate this robot model's capabilities. A 100 foot tether is typically used for CRASAR operations, but the system can be upgraded to accommodate up to 1,500 feet of tether. Since the battery is provided outside of the robot chassis, the runtime is only limited by the longevity of the power source. This can be in the form or three twelve volt batteries or an AC to DC power supply. The MiniTrac's height is 5 inches and the footprint is 15 by 21.5 inches. Two MiniTrac drive units allow it to operate at speeds of up to 32 feet per minute. The sensor suite includes a microphone, speaker, a motor-driven manual-focus CCD camera, and a camera tilt unit that incorporates halogen lighting. The camera, lights, and microphone are enclosed in a cylindrical tilt unit on the front of the vehicle. The chassis is manufactured out of milled aluminum, the tracks are rubber belt material, and multiple components contain molded plastic coverings. This platform has a 1.25 inch ground clearance. Traction is provided via two rubber belt tracks with cleats added for additional traction. Payload capability is limited only by weight and balance constraints. The flat upper chassis provides adaptability for multiple payload configurations. Finally, this robot has no self righting features.

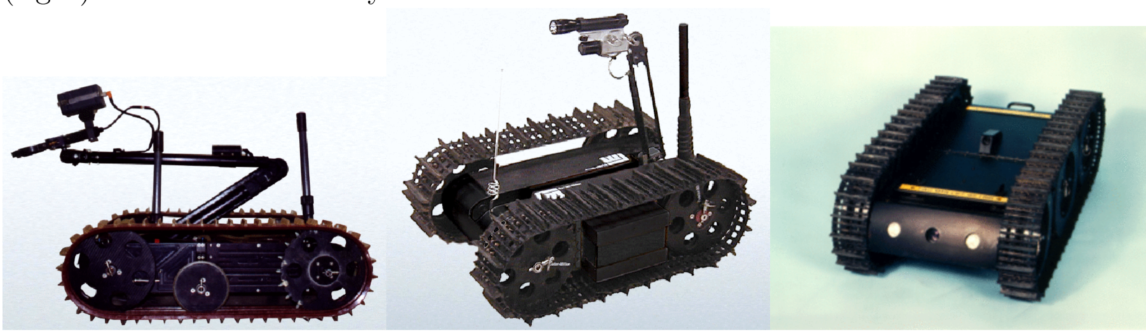
3.2.1.4 Inuktun Operator Control Units These three platforms are controlled through identical *operator control units* or OCUs that provide the operator with video feedback and two-way audio. A joystick provides the interface to the robot's translational and directional movement. Toggle switches on the console also provide light adjustment, focus adjustment, tilt of the sensor pod, and an adjustment for platform polymorphism in the case of the VGTV. The OCU has external jacks that accommodate video output, power input, and the robot tether connection. This unit can be hung around the operator's neck with an optional neck strap. Power is supplied through three 12 volt batteries connected in series or a 36 volt power supply unit.

3.2.2 Foster-Miller Family of Robots

The Foster-Miller family of robots consists of three models that were used at the World Trade Center response. These are the *Talon*, *SOLEM*, and *Urbot* models of robots. These robots are larger than the previously described Inuktun family, but are more flexible in their sensor and payload capabilities. These systems are also much faster than the Inuktuns. This increase in speed is due to their initial design criteria that required their use in time-dependent military operations. The SOLEM platform is the only robot out of this family that was used on the pile at the World Trade Center. The other two platforms were used to inspect building structures adjacent to Ground Zero. Examples of the three platforms can be seen in Figure 3.

3.2.2.1 Talon Robot The *Talon* robot is a robust vehicle for long range reconnaissance and weapons removal or delivery. It is unique in that it is the heaviest of the Foster-Miller platforms weighing 85 pounds before mission specific configuration. Additionally, it has a 200 pound pull capacity and accommodates 300 pounds of payload. This is larger than any of the other platforms by this manufacturer.

Figure 3. Examples of the Foster-Miller Talon (left), SOLEM (center), and Urbot (right). Photos are courtesy of Foster-Miller.



Talon is watertight up to a depth of 100 feet, easing decontamination and making it a candidate for maritime operations. It also has the ability to navigate up and down stairways.

Specifications relative to the ten robot requirements in Section 3.1 enumerate this robot model's capabilities. A two watt wireless connection provides one mile line of sight operation. This communication method is typically used for CRASAR operations, but the system can be adapted for tethered communication of up to 300 feet. The platform carries its own batteries inside the chassis and it has a runtime of 1 to 4 hours depending on mission characteristics. The Talon's height is 11 inches and the footprint is 34 by 24 inches. It can be driven at 6 feet per second, making it an ideal platform for quick down-range assessment. The standard sensor suite includes a microphone, speaker, two stationary cameras, and a camera unit that is mounted on a movable gripper arm. The chassis is manufactured out of milled aluminum, the tracks are riveted plastic material, and multiple components contain molded plastic coverings. This platform has a 4 inch ground clearance. Traction is provided via two riveted plastic tracks with cleats added for additional traction. The platform has a modular cargo bay that can accommodate field-swappable payloads. Payload capabilities can include multiple cameras, a two-stage arm, grippers, hazardous material sensors, munitions-placement modules, breaching tools, communication equipment, and disruptors. Finally, this robot has no self righting features.

3.2.2.2 SOLEM Robot A smaller implementation of the Talon robot is the *Special Operations Lemming* (SOLEM) platform that can be used for short range or confined space reconnaissance. This unit is the only one in the Foster-Miller group that is man-packable due to the lower unit weight of 33 lbs. Much like its larger Talon counterpart, the SOLEM has a wide range of mission specific sensing and payload options, including cameras, gripper arms, and hazardous material sensing. It is also watertight which enables it to operate in all-weather and amphibious deployments.

Specifications relative to the ten robot requirements in Section 3.1 enumerate this robot model's capabilities. A one watt wireless connection provides one mile line of sight operation. This communication method is typically used for CRASAR operations, but the system can be adapted for tethered communication of up to 300 feet. The platform carries four nickel metal hydride batteries inside the chassis and it has a runtime of 1 to 4 hours depending on mission characteristics. The SOLEM's height is 8 inches and the footprint is 20 by 14.75 inches. It can operate at 1.5 feet per second. The standard sensor suite includes a microphone, speaker, and a camera unit that is mounted on a movable sensor arm. The chassis is manufactured out of milled aluminum, the tracks are riveted plastic material, and multiple components contain molded plastic coverings. This platform has a 3 inch ground clearance. Traction is provided via two riveted plastic tracks with cleats added for additional traction. The platform has a modular cargo bay that can accommodate field-swappable payloads. Payload capabilities can include multiple cameras, gripper claw, hazardous material sensors, night vision camera, thermal camera, communication equipment, and unexploded ordnance sensors. Finally, this robot has no self righting features.

3.2.2.3 SPAWAR Urbot Robot The SPAWAR *Urbot* is a custom manufactured robot for ground warfare reconnaissance. The chassis is based on the Foster-Miller

Tactical Adjustable Robot design, was upgraded by the SPAWAR Systems Center. This platform is unique in its ability to fully operate in an inverted position. When the platform becomes inverted, the robot detects this condition and adjusts the camera and controls to the new orientation.

Specifications relative to the ten robot requirements in Section 3.1 enumerate this robot model's capabilities. A 2.4Ghz wireless connection provides the communication channel. The platform carries batteries inside the chassis and it has a runtime of over 1 hour depending on mission characteristics. The Urbot's height is 13 inches and the platform is 33 inches long. It can operate at greater than 1.5 feet per second. Sensory upgrades to the platform include a 24x zoom camera, two low-silhouetted cameras, attitude sensor, compass, temperature sensor, and two-way audio. The chassis is manufactured out of milled aluminum, the tracks are flexible plastic material, and multiple components contain molded plastic coverings. This platform has a 5 inch ground clearance. Traction is provided via two flexible plastic tracks with cleats added for additional traction. The platform has a modular cargo bay that can accommodate field-changable payloads. Finally, this robot can operate in both an upright and inverted position, so no self righting capabilities are needed.

3.2.2.4 Foster-Miller Operator Control Units The Talon, SOLEM, and Urbot use virtually identical *operator control units* for their operations. These control units are either a 20 pound suitcase sized unit or a wearable OCU. The case based OCU uses a joystick for position control, toggle switches for arm or payload control, camera selector dial, gripper control, and video overlay switch. Both units provide the same functionality to the operator, but the wearable unit has the above features incorporated into a handheld control unit and a VR goggle for displaying video and status information in a heads-up fashion. The Urbot operator control unit is much like the wearable control unit for the Talon and SOLEM, but it implements a different radio and control methodology and is therefore incompatible with other vehicles. The Urbot unit also does not use a VR headset. Instead, a small, watertight liquid-crystal display provides video and text feedback to the operator. This feature retains the portability of the system while allowing a person other than the operator to simultaneously view the display unit.

3.2.3 iRobot Family of Robots

The iRobot family of robots includes four models of robots that were not used on the rubble pile at the World Trade Center disaster. Three of the platforms were available at the time of the disaster, but only the Packbot platform was used to inspect building structures around the disaster site. The Packbot and Urban are tracked vehicles with unique traction and self-righting abilities. The ATRV and ATRV-Jr platforms are large wheeled vehicles that have high configurability. Due to the high similarity between the two groups of robots, they are described in pairs in the following two sections. Examples of the platforms can be seen in Figure 4.

Figure 4. Examples of the iRobot Packbot (left) and ATRV (right). Photos are courtesy of iRobot.

3.2.3.1 Packbot and Urban Robots The *Packbot* and *Urban* platforms are two DARPA funded vehicles that were designed for high mobility in military operations in urban terrain (MOUT). The Urban was a precursor to the Packbot platform. Both have the unique feature of “flippers” on the front drive axle of their differential track drive. This feature gives them higher mobility in environments that contain vertical components such as stairs and debris.

Specifications relative to the ten robot requirements in Section 3.1 enumerate this robot model's capabilities. A 2.4Ghz IEEE 802.11 wireless Ethernet connection provides the communication channel to the operator. This communication method is typically used for CRASAR operations, but the systems can be adapted for tethered communication of up to 1500 feet via wired Ethernet. The platforms carry their own batteries inside the chassis and they have a runtime of 1 to 4 hours depending on mission characteristics. They both have a footprint of approximately 24 by 20 inches, with the Packbot being slightly larger. The Packbot can operate at 7.2 feet per second, while the Urban is considerably slower depending on the motor condition and age. The large payload area on both of these robots allows them to be adapted to a wide variety of sensors. The most basic sensor suite configuration on these platforms include cameras and lighting. Each can be modified to support two-way audio, sonar ranging, thermal imaging, low-light cameras, GPS, attitude, compass, chemical sensors, and manipulators. The electrical and sensing system on these platforms uses the proprietary rFLEX sensor communication architecture in conjunction with miniaturized mobile Pentium II and III class processing units. The chassis is manufactured out of milled aluminum, the tracks are injection molded plastic material, and multiple components contain molded plastic coverings. The platforms have a 2 inch ground clearance. Traction is provided via two injection molded plastic tracks with cleats added for additional traction. The platforms have large payload capabilities that account for approximately half of their volume. Payload capabilities can include multiple cameras, a 2 degree of freedom manipulators, and hazardous material sensors. Finally, these robots have self righting features via the flipper mechanisms on the front drive axles.

3.2.3.2 ARTV and ATRV-Jr Robots

The *ATRV* and *ATRV-Jr* are large-wheeled, mobile robots designed for flexible off-road configurations and enhanced sensing capabilities. Compared to the rest of the CRASAR robots, these two platforms are large and less agile in highly unstructured domains. The ATRV weighs 260 pounds or more and the ATRV-Jr weighs 110 pounds. Unlike their smaller tracked counterparts, these platforms have the ability to carry multiple desktop-class PC units inside their chassis. Because of their size, speed, and strength, these robot platforms can be adapted to carry the other smaller robot platforms in a marsupial configuration. CRASAR currently maintains an ATRV that can move three Urban platforms quickly down-range and deploy them for their short-range mission goals. This provides the benefit of longer mission time on the smaller robots, as they do not need to expend energy during the movement to the mission site.

Specifications relative to the ten robot requirements in Section 3.1 enumerate this robot model's capabilities. A 2.4Ghz IEEE 802.11 wireless Ethernet connection provides the communication channel to the operator. This communication method is typically used for CRASAR operations, but the systems can be adapted for tethered communication of up to 1500 feet via wired Ethernet. The platforms carry their own batteries inside the chassis and it has a runtime of 3 to 6 hours depending on mission characteristics. The footprint for the ATRV is 41 by 32 inches and the ATRV Jr is 30 by 25 inches. The ATRV can operate at 6.6 feet per second and the ATRV-Jr can operate at 3.3. The large payload area on both of these robots allows them to be adapted to a wide variety of sensors. The most basic sensor suite configuration on these platforms include cameras and lighting. Both can be adapted to support two-way audio, sonar ranging, laser ranging, thermal imaging, low-light cameras, GPS, attitude, compass, chemical sensors, and manipulators. The electrical and sensing system on these platforms uses the proprietary rFLEX sensor communication architecture in conjunction with ATX desktop class Pentium II and

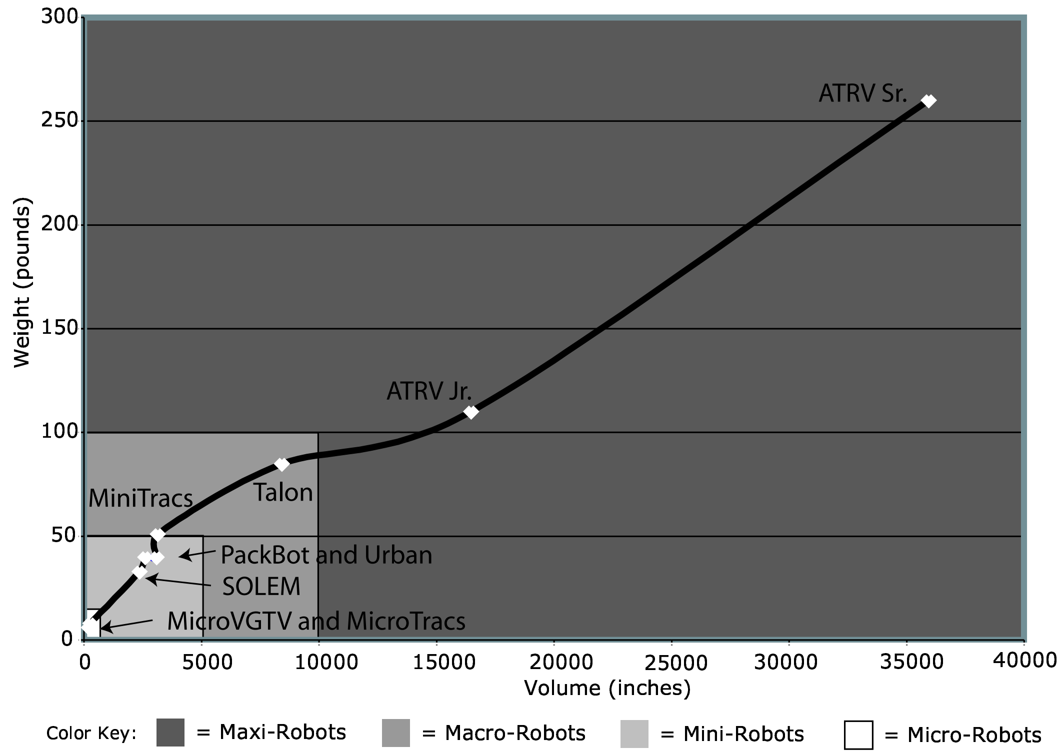
III class processing units. The chassis are manufactured out of aluminum, the tracks are rubber tires, and multiple components contain molded plastic coverings. The ATRV-Jr platform has a 3 inch ground clearance and the ATRV has 4.5 inches. The differential wheeled drive system uses pneumatic knobby tires for mobility. The platforms have large payload capabilities. Payload capabilities can include multiple cameras, laser range finders, and hazardous material sensors. Finally, these robots have no self righting capabilities.

3.3 Robot Classification

The robots available at the time of the World Trade Center disaster can be broken into four classes based on the robot's size and weight. This partitioning is based on the high dependency on robot size, sensing capability, and construction material in the robot requirements category shown Section 3.1. The size of the robot will determine six of the environmental and task level requirements. This makes it a good candidate as a classification variable. An increase in the robots sensing and construction material are typically attributed to the larger robots because of their large sensor and battery payloads. As a result, weight makes a good second variable by which to classify robot platforms. A graph of the robot classifications is shown in Figure 5. Each classifications' definition, costs, and benefits are detailed below:

- *Micro-Robots* are robots with a volume less than 1,000 cubic inches and a weight of less than 10 pounds. This is the smallest class of robots which has typically been used for confined space inspection. These platforms were used the most on the pile at the World Trade Center due to their small size. Within the CRASAR cache of robots, the Inuktun "Micro" line of robots are the platforms that fall into this category. This includes the two MicroVGTV and the two MicroTrac units. Characteristics of this size of platform typically include tethered communication and control, no on-board batteries, less than two inches grounds

Figure 5. Classification of robots in the CRASAR cache



clearance, and limited sensing capability. Cameras and two-way audio are the typical sensors on these robots. Speed and deployable distance are two shortcomings of these platforms. The speed is limited due to the miniature motors that must be used. Distance is limited by the tether length and weight. These robots can be considered safely man-packable in a 1:1 man-to-robot configuration. [28]

- *Mini-Robots* are robots that have a volume greater than 1,000 cubic inches and less than 5,000 cubic inches. Their weight falls between 10 and 50 pounds. This second class of robots have been used for short-range reconnaissance and semi-structured building inspection. Their weight and size attributes make them a good choice for small environments that require more speed or ground clearance than their smaller Micro-Robot counterparts. The iRobot Urban, iRobot Packbot, Inuktun MiniTracs, and Foster-Miller SOLEM platforms are robots of this type in the CRASAR cache. These platforms can be tethered or wireless, may contain on-board or off-board batteries, have two or more inches of ground clearance, and have a larger sensor suite than the *Micro*-class of robots. The flexibility in characteristics is due to their ability to carry a larger payload and increased computational resources. Speed is an advantage that this class provides due to the use of larger motors. Additionally, the operating distance can be extended by using wireless communications. These robots approach the maximum of what can be considered safely man-packable. Typically a 2:1 man-to-robot ratio is utilized for transportation. [28]

- *Macro-Robots* have a volume between 5,000 and 10,000 cubic inches and a weight between 50 and 100 pounds. This is a large class of robots that have been effectively used for explosive ordnance removal and medium-range reconnaissance. The Foster-Miller Talon and SPAWAR Urbot are examples of CRASAR robots that fit into this category. Wireless communications, onboard batteries, two or more inches of ground clearance, and the ability to have enhanced sensing payloads are some of the typical characteristics of these platforms. All of the enhanced characteristics are due to the robot's increased size and payload capability. These robots are not safely man-packable and may be in excess of a 3:1 man-to-robot ratio. [28]

- *Maxi-Robots* are the largest class of robots that are classified for USAR. Their volume is between 10,000 and 40,000 cubic inches and their weight is between 100 and 300 pounds. The robots are typically wireless, have large battery reserves, two or more inches of ground clearance, and can be equipped with large, diverse arrays of sensing equipment. These robots have not been shown to be effective for search tasks, but their increased size and power capability make them useful for carrying the other smaller robot classes as payload, or carrying rescue gear. In the first role, the robot acts as a marsuipal mother that can carry the smaller robots down-range into the disaster area and deploy them with fresh resources. After the small robots have performed their assigned search functions, they can return to the larger mother robot and be carried back up-range. The mother's long runtime and increased sensing capabilities make her a valuable asset to a larger robot team. [4] In the second role described, the large Maxi-Robot can be used as a "robot mule" that can carry supplies and equipment. This can lessen the physical fatigue on the rescue workers by manually teleoperating the robot, or idealistically by the robot autonomously following the rescue worker. CRASAR currently caches two models of robots that fit into this category. The ATRV-Jr and ATRV are the platforms being researched in this regard.

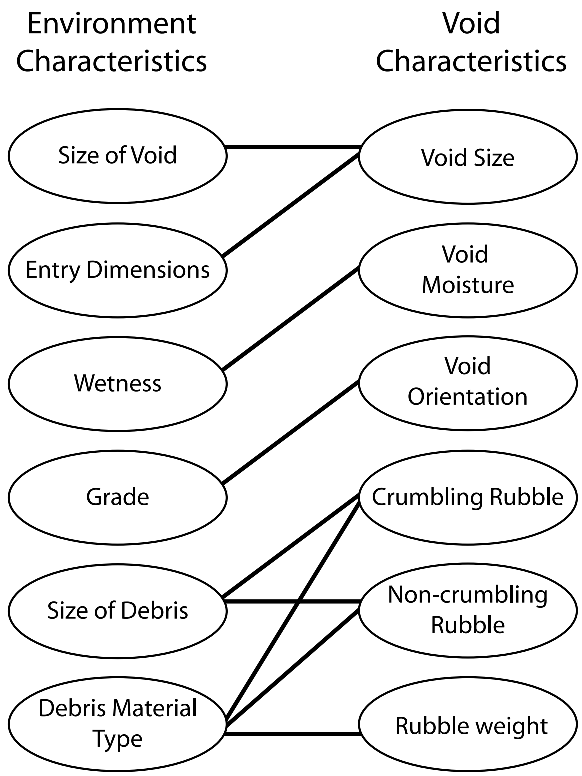
Larger robots than the ones described above are in excess of 10,000 cubic inches and 300 pounds. These could be used for structural shoring or large debris removal in the future, but their effectiveness has not currently been proven in the field. The size and weight of the larger robots require special vehicles and specialized non-commercial equipment for use and maintenance. As a result, highly specialized training and a support staff are typically needed. CRASAR currently does not cache robots larger than the Maxi-Robot category.

3.4 Void Classification

Classification of voids in structural collapses creates seven main characteristic categories. *Void size, void moisture, void orientation, crumbling rubble size, non-crumbling rubble size,* and *rubble weight* are all observable features of a void that a commanding officer can use to classify the void before inserting a robot. This selection of characteristics is based on the environmental characteristics category explored in Section 3.1.

The shift in characteristics is in an effort to condense multiple similar elements into single classifications and expand elements that may contain multiple combinations of observable features. This overall decrease in granularity will make the feature selection space smaller and more intuitive for the commanding officer at the disaster scene. The condensed relationships can be seen in Figure 3.4.

Figure 6. Relationship of the environmental characteristics to void characteristics



The specific equivalencies and reasons for the condensed elements are as follows. The *size of void* and *entry dimensions* elements are grouped into the *void size* classification since they are very closely related to the robot's size. This grouping is important since the robot's size will ultimately be decided by the minima of these two elements. The *void moisture* characteristic in this section is equivalent to the previous environmental *wetness* element. *Void Orientation* helps to more carefully define the types and combinations of *grade* that the void may contain. It is important to expand this feature since a void may contain more than one grade through the robot's path.

Crumbling rubble size and *non-crumbling rubble size* helps to more usefully correlate the *size of debris* and *debris material type* elements into rock or non-rock based construction material. This cross-correlation is important to the ground clearance of the robot and the consistency of the materials to be navigated. Rock based debris typically breaks into material that is hard for low-ground clearance robots to travel over. Finally, *rubble weight* emphasizes specifically the weight characteristic of the *size of debris* and *debris material type* elements. This extraction of a single element helps to emphasize the robot's weight in relation to the debris in the void. The remaining elements of *temperature*, *electrical hazards*, and *regularity* are left as specific hazards to the robot platform that must be dealt with on an individual platform basis. These elements are left unchanged in this section as individual hazards, but are not required for classification of the void.

- *Void Size* has been broken into three categories describing the access and size characteristics of the void. *Sub-Human searchable confined spaces* are those that would be physically too small for a human or search dog to enter. This includes, but is not limited to, structural support elements, pipes, and extremely compressed rubble voids. This search domain has been accessed by Search-cam equipment in the past. *Human searchable confined spaces* are spaces that could be searched by trained confined space rescuers. Confined space is defined as "a space that is large enough and so configured that an employee can bodily enter and perform assigned work, has limited or restricted means for entry or exit, and is not designed for continuous employee occupancy" [29]. This includes culvert pipes, container access openings, roof and floor openings, and compressed semi-structured voids. These semi-structured voids might include traditional limited access voids such as pancake, lean-to, and "V" shaped collapses. Although these confined spaces can be searched by a human being, the setup time and risk involved would make a robot more efficient for the search task. Finally, *structured searchable areas* are areas that are large enough for a human to search without the need for confined space precautions. This does not indicate that the structured area is safe for search, only that the void size is considerably larger than the previous two categories. This might be a partially collapsed building, open basement, or parking garage.

- The *Void Moisture* classification is an indication of the amount of water in the environment. It is divided into three categories. *Dry and Dusty* environments are those that contain very little moisture and as a result have loose dirt and dust. Robots operating in this class of environment must be tolerant of the dust interacting with and collecting on its sensors. *Wet and Muddy* environments are those that have a marginal amount of water in the void, but no standing water or puddles. This water typically causes the dirt and dust in the environment to form a mud or paste that can attach to surfaces such as tracks and camera lenses. This might be from leaking water lines or fire suppression systems. Finally, a void containing *Standing Water* is an environment that has puddles or large pools of water in the void. This requires the robot to be waterproofed and have traction that can grip in this environment.

- *Void Orientation* describes the angle of the void's tractional surface relative to gravity. Four classes of orientation define the configurations that may be encountered. *Vertical* orientation is a search area that is completely perpendicular to gravity. In this case, the robot is typically suspended by a tag line or is physically adapted specifically for this type of vertical movement. Sewer access, elevator shafts, and multi-floor access are examples of vertical terrain that the robot may need to travel through. *Horizontal* orientation is a terrain that is parallel to gravity or normal to the earth's surface. This is the standard terrain for terrestrial structures and is the one for which most robots are designed.

Diagonal orientation is terrain that falls outside of the previous two categories. Fallen debris rarely lands flat, so this classification can be used to describe most unstructured search terrain. A specialized, but common orientation combination is the *"L"* category of orientation. This is a specific combination of the horizontal and vertical that is commonly observed in structural breaching and floor access. This orientation begins with a vertical descent into a lower floor or horizontal search area. Upon reaching the bottom of the lower terrain, the robot or rescuer must proceed in a relatively horizontal orientation to perform the desired search.

- *Crumbling Rubble Size* describes the size of the loose rock-based rubble that the robot will need to transverse to perform the desired search operation. This may include concrete, drywall, tiles, and plaster. The size of the debris will effect traction and the robot's ability to climb over the terrain given its ground clearance. *Dust and Dirt* is the first category and describes debris that is pulverized and is no larger than 1/16th of an inch. This typically does not provide a problem for climbing, but can reduce the traction of the traction surface. *Pebbles* are classified as debris no larger than one half of an inch in diameter. Pebbles may cause the robot to lose traction, thus impeding its travel. *Stones* are any debris greater than one half inch in diameter. This classification is the most detrimental to the robot's travel since the rocks may begin to approach the robot's ground clearance. Exceeding the ground clearance of the robot will most likely cause it to place its weight away from the traction plane, or high-center and lose its traction. Finally, concrete that is still in solid beams is categorized into the *Reinforced Beams* category.

- *Non-Crumbling Rubble* includes all rubble that does not fit into the crumbling rubble classification. Essentially, any material in a home or workplace that does not crumble into smaller components when compressed under high loads is considered non-crushing debris. This includes, but is not limited to ,*steel support beams, redbar, furniture, paper, etc.* This category of debris can be difficult for the robot if the debris is larger than the robot.

- *Rubble Weight* describes the weight of the debris compared to the weight of the robot. It should be noted that the numerical relationships in this category are only relative to a specific robot or robot class. *Heavier than robot* debris is material that has a greater weight than that of the robot. The importance of this category is that this material may be difficult or impossible for the robot to move through or manipulate if the material is blocking the search passageway. Conversely, this material can provide good traction material if it happens to have fallen in a structured manner. Large cinder blocks, steel beams, and concrete supports are examples of this type of material. *Lighter than robot* debris is material that is lighter than the robot platform. This type of material can be troublesome if there is a large amount of it trapped in a void. If the robot is dropped on top of the collection of materials, it will most likely sink into the debris and become immobilized. A benefit of this material type is that it can be easily moved within the environment if it is in sufficiently small quantities. Examples of this material are paper, cloth, fiberglass insulation, and ceiling tile fragments.

3.5 Record of Deployments

Eight deployments took place from September 11 through September 20. Robots were used on five of these deployments. Four of these deployments were on the rubble pile aiding in the rescue process, and one deployment was in the damaged buildings on the periphery of the World Trade Center site. A *deployment* is, defined for this work, *when a team is sent into the warm zone (a designated and restricted area around the* *hot zone) [30] for a defined period of time (called a shift) in order to work in the hot zone (immediate area encompassing the disaster) [30] or stand by until needed.* During the four on-pile deployments, the operators performed eight robot *drops*. A *drop* is defined for this work as *an individual void or space that robots are inserted into*. Table 8 lists the deployment during which that the insertion occurred, the drop number, the number of operators running the robot, the types of robot/s used during the insertion, and a brief description of the drop including motivation for the insertion and the outcome [28].

3.5.1 Deployment 1

The first deployment by CRASAR started on September 12 at 09:00 and continued until 19:00 . The first drop occurred directly across from World Trade Tower Two on Cedar Street. The team was asked to inspect a sewer access pipe for potential access to below-grade entrances into the World Trade Center structure. The Inuktun MicroTrac robot successfully navigated the vertical access to the sewer line, but the search did not reveal openings into other search areas. The robot showed, via video, that the sewer was partially collapsed on one side.

Shortly after completing the first drop, a second drop was requested by FDNY and NYPD. This drop was into a below-grade boiler room that had sustained great structural damage due to debris from World Trade Tower Two. The operators deployed the MicroTracs robot into this near vertical void and lowered the robot several feet into the confined space. Although the robot became caught on a ladder-like metal structure before reaching the bottom of the void, the operator was able to use the robot's tilt mechanism on the camera unit to give the rescue workers an idea of how the environment was configured below their sight. Also, the two-way audio feature of the robot was used to call out to potential victims that may have been trapped

Table 2. Description of drops that occurred on the World Trade Center rubble pile during the eight deployments. Included are the number of operators needed to control the robots, robots used, drop motivation and outcome. Deployments 3 through 6 are omitted due to no drops occurring during these times.

Deployment #	Drop #	# Operators	Robot/s	Details
1	1	2	MicroTracs	Task: inspect void, search Outcome: dead end void, no victims
	2	2	MicroTracs	Task: inspect void, search Outcome: robot became stuck
2	3	3	MicroTracs	Task: inspect void, search Outcome: void led to opening where rescuers were actively working; attempted drop twice
	4	2	MicroTracs	Task: inspect void, search Outcome: void end packed with material, found remains of 1-2 victims
	5	2	MicroTracs	Task: inspect void, search Outcome: void end packed with material beneath water
	6	2	MicroTracs	Task: inspect void Outcome: robot made no progress due to getting lodged on a metal rod during first attempt and sunk in paper debris during second attempt
7	7	2	Solem	Task: inspect void Outcome: void deemed unsafe before Solem was abandoned due to lost comms
8	8	2	MicroTracs VGTV	Task: inspect void Outcome: void packed with material and small opening sited toward the end, found remains of 2-3 victims; MicroTracs blew halogens on first attempt, VGTV dropped soft track during second

below the void opening. A rescue worker eventually entered this void and retrieved the robot from its trapped position.

Classification of these voids is shown in Table 3.

Table 3. Classification of drops 1 and 2

Drop	Void Size	Void Moisture	Void Orientation	Crumbling Rubble	Static Rubble	Rubble Weight
1	Sub-Human Searchable	Dry and Dusty	Vertical	None	None	None
2	Human Searchable	Dry and Dusty	Vertical	Dust and Dirt	Rebar	Heavier than robot

3.5.2 Deployment 2

Deployment 2 began at 23:00 on September 13 and ended at 07:00 on September 14. This operation was performed on the rubble pile located at World Trade Tower One using two Inuktun MicroTrac systems. In the first drop of this deployment, the CRASAR operators attempted to enter a void opening that was adjacent to a rescue operation which was already in progress. The robot's task was to maneuver underneath a large pile of debris to determine if alternate access to the victim was attainable. The drop was attempted twice and was successful in traveling underneath the pile of debris. Unfortunately, the confined space did not open into the area in which the potential victim was thought to be. Instead, it opened into the location where the rescue workers were already removing debris.

Shortly thereafter, the operators and robot were tasked to inspect the various tubular-steel support structures exposed at the top of the rubble pile. In addition to supporting the surface search effort, it was hoped that this would lead to void spaces in the fallen structure below. This task accounted for Drops 4 and 5. Both resulted in the discoveries that the bottoms of these conduit structures were highly packed with building material and were inaccessible to the robots. In Drop 4, the operators were able to identify remains fragments from approximately one to two victims.

The final drop on this deployment was requested by FDNY and required the inspection of an otherwise inaccessible void. The void had an extremely confined opening and was highly littered with paper and office debris. The operators inserted the robot into the void, only to have the robot almost immediately become stuck on a metal rod that speared between the track mechanism and the robot body. After removing the robot from the void, removing the metal object from the robot, and reinserting the robot into the void, the search was terminated due to mobility problems caused by the loose paper and debris.

Classification of this void is shown in Table 4.

Table 4. Classification of drop 3 through 6

Drop	Void Size	Void Moisture	Void Orientation	Crumbling Rubble	Static Rubble	Rubble Weight
3	Sub-Human Searchable	Dry and Dusty	Horizontal	Stones	Paper	Lighter than robot
4	Sub-Human Searchable	Dry and Dusty	Diagonal	Pebbles	Paper, furniture	Heavier than robot
5	Sub-Human Searchable	Standing Water	Diagonal	Dust and Dirt	None	None
6	Sub-Human Searchable	Dry and Dusty	"L"	Dust and Dirt	Paper, furniture	Lighter than robot

3.5.3 Deployment 6

On September 15 the CRASAR personnel and equipment were partitioned into two groups. The first team of four people and three robots was attached to Indiana Task Force One for directed search operations on the World Trade Center site. The second team was escorted by John Blitch to the buildings surrounding Ground Zero for the purposes of testing the larger robot platforms in potentially structurally unsafe buildings. Six operators and three robots operated continuously for more than one hour inspecting multiple structures and a parking garage. This deployment did not receive any “drop” association because it did not actually occur on the pile. Regardless, its classification is shown in Table 5.

Table 5. Classification of building inspection

Drop	Void Size	Void Moisture	Void Orientation	Crumbling Rubble	Static Rubble	Rubble Weight
*	Structured Searchable	Dry and Dusty	Horizontal	None	Furniture	Heavier than robot

3.5.4 Deployment 7

Indiana Task Force One (INTF-1) requested the assistance of CRASAR on the night shift of September 16. Four operators and three robots from CRASAR were deployed to assist the FEMA task force in their directed search efforts. The three robots on this operation were the two Inuktun MicroTracs and the Foster-Miller SOLEM. Late in the deployment, INTF-1 called the SOLEM platform and operators to the forward station. The robot operators were asked to have the robot quickly enter a void that had opened up after heavy debris removal at this location. In Drop 7, the robot needed to provide reconnaissance to the task force leader as to the safety and structure of the void before rescue personnel attempted entry. The SOLEM entered the void successfully and provided the task force with information confirming that this void was unsafe for human entry. As a result, no rescue personnel entered the void for further search on this shift. Unfortunately, the SOLEM platform lost radio contact with the operator control unit and could not be recovered after its tag line broke. It remained at the site for potential recovery later.

Table 6. Classification of drop 7

Drop	Void Size	Void Moisture	Void Orientation	Crumbling Rubble	Static Rubble	Rubble Weight
7	Human Searchable	Dry and Dusty	Diagonal	Stones	Rebar, Steel beams	Heavier than robot

3.5.5 Deployment 8

Virginia Task Force Two (VATF-2) utilized personnel and equipment from CRASAR on the night of September 18. Two CRASAR operators were deployed with an Inuktun MicroTrac and VGTV robot into the demolished underground parking garage immediately adjacent to World Trade Tower Two. The task was to enter a structural steel conduit much like the ones encountered on Deployment 2. The hope was that this conduit had "speared" into lower void pockets deep within the base of World Trade Tower Two that might contain victims. The Microtrac unit was sent into the conduit first, only to have its halogen lights fail upon reaching the bottom of the 30+ foot column. The Microtrac robot was removed, and the VGTV was inserted in its place. The VGTV navigated to the bottom of the void and identified that the void lead to a potential opening. Unfortunately, the robot was unable to navigate the terrain and proceed further. Additionally, the robot's track mechanism became disengaged from the drive wheel, and the platform had to be pulled from the void by the tether. Post-analysis of this drop showed that 2 to 3 victim remains could be identified at the bottom of this void.

Table 7. Classification of drop 8

Drop	Void Size	Void Moisture	Void Orientation	Crumbling Rubble	Static Rubble	Rubble Weight
8	Sub-Human Searchable	Dry and Dusty	Diagonal	Stones	paper, furniture	Heavier than robot

3.6 Deployment / Robot Observations

In the study of the robot response at the World Trade Center Disaster, several issues were found to be critical to the success of the robot in exploring void spaces. These issues fall into several broad categories that should be considered by incident commanders, task force leaders, and command personnel who might consider using robots as part of their search and rescue operations. Also, a robot designer, programmer, or systems integrator must take these factors into account when evaluating the design or expected performance of future robot technologies. The most important observations critical to mission success have been identified and are summarized by the following points:

- *Size of both the robot and the void* must be taken into careful account before deployment. The World Trade Center disaster was unique because all but one of the eight drops on the towers were sub-human searchable. Due to limitations in CRASAR's robot cache, this mandated the use of the *Micro* Inuktun robot platforms on all of these drops. Also, at the World Trade Center disaster, the size of the void stayed constant throughout the length of the voids searched. The size of the void creates an upper bound on the size of the robot that can be used. The commander must take into account that when the size of the void increases past initial size estimates, the search might be best served by a robot that is larger in an effort to gain speed and agility over the terrain. Conversely, if the void decreases in size as the search progresses, it may be best to remove the larger robot early in the search and use a smaller one so that there is less risk of the larger robot becoming lodged. For example, if Drop 7 would have been able to continue after the radio failure on the SOLEM, a larger robot may have been used in larger void areas below.

- *Orientation of the void* plays an important role in robot selection. If the void is diagonal or vertical, a light and agile robot is likely to be advantageous over a heavy one. The drops at the World Trade Center benefited greatly from the use of the Micro robots' tether. It provided a solid tag line from which the robot could suspend itself and be manipulated in the environment. The SOLEM was also used in this manner, but its increased size and weight, putting it high in the Micro-robot category, make it one of the largest robot types that should be considered safe for this type of assisted deployment.

- *Size and weight of debris* is a characteristic that must be taken into consideration. In the drops performed, the robot was not required to operate in an environment that contained anything larger than the *Stone* classification for debris. During the deployments of the Micro robots, The operator circumnavigated these rather than attempting to crawl over the debris. This may not be possible in a different disaster where the voids contain a high density of debris. The emphasis here is to make sure that the ground clearance of the robot is high enough to adequately cope with the debris size and density that it will encounter.

- *Moisture of the void and waterproofing on the robot* must be in the mind of the operator throughout the search operation to protect equipment health. If the robot being used is not rated for aquatic operations, then traveling through a void with a *Standing Water* classification will ensure platform failure. Drop 5 is an example of a drop that could have ended in a damaged platform if the operator or commander was not aware of the limitations of the robot.

It may be that these observations should be considered for all future deployments, but the unique nature of the World Trade Center Disaster mandates that additional studies are conducted before these observation can be considered representative of all building and structural collapses.

CHAPTER 4

ANALYSIS OF FAILURES

This chapter documents the robot failures that occurred at the World Trade Center disaster. The observations and classification of failures presented in this chapter will be relative to the robot and void classifications in the previous chapter. These are important in understanding the findings addressed in the next chapter on research findings. The analysis of these failures is important to the advancement of robot platforms in USAR because it exposes shortcomings in current platform designs. An analysis of these failures helps to identify future research objectives. The importance of this failure analysis is further enhanced due to the nature of the event. This set provides "live" data that was not produced under laboratory or artificially configured conditions. This event also provided the first data set of robots used in an actual urban search and rescue response. These unique features allow the failure analysis to provide a foundation for realistic findings and observations.

The coverage in this chapter is limited to the failures and robots that were used at the World Trade Center rescue operation. CRASAR was involved in the rescue effort from September 12 through September 20. As a result, failures are taken from the first two weeks of the response. Unfortunately, the first deployment, which involved sewer inspection, did not have a complete video record of the event, so it was not analyzed in this failure set. Also, the video recorded by the SOLEM unit on the drop involving World Trade Tower Two was so poor in quality that no information extraction was possible other than measuring the communication failure. Additional documentation from September 21 to October 1 was available, but was not used in this analysis since CRASAR was assisting in a recovery mode throughout these dates. This failure analysis is concerned solely with the results of responding in a rescue mode.

This chapter presents a classification of the errors observed during the rescue and provides a context for the findings. This classification segregates the failures into small, coherent partitions so that relationships between the robot and the environment can be exposed. Also included in this analysis are the underlying causes of the failures and any temporary solutions used on site.

The remaining portions of this chapter are organized as follows. First, the data set and collection method are discussed. Then the failure classifications are enumerated and defined to provide a framework for the analysis. This is followed by the analysis method used to generate the failure data. Failures common across multiple runs are explored next, followed by unique failures.

4.1 Data Collection

The data source for the failure analysis consists of five and a half hours of MiniDV video tape recorded at the time of the rescue deployment. This analysis excludes the additional 5 hours of tape that was recorded during the recovery effort after September 21. The collection of tapes is now stored at CRASAR and several other remote locations for backup redundancy.

The operators collected this data by connecting a Sony digital video camera to the video-out of the operator control unit and enabling the VCR-record feature of the camera. Each operator carried multiple tapes and batteries to the deployments so that a multi-hour rescue operation could be sequentially captured on standard 60-minute digital video tape. In addition to digitally documenting the events of the deployment from the viewpoint of the robot, the digital video camera was also used to record external views of the robot and equipment when the robot became damaged or failed. The resulting video data set captures important elements from the robot view, equipment view, and environmental aspects of the deployments.

Table 8 shows the deployments that are included in this failure analysis. It shows each drop relative to the void type classification and robot classification explored in the previous chapter. The relevance to the classification is important since the failures are indicative of elements in the environment or the robot's design.

The video is an important documentation of the activities that were performed throughout the rescue effort because it gives a real-time record of everything that the operator may have seen through the robot's eye view at that point in the rescue. More importantly, it has facilitated post-analysis that is vital to exploring the operator and robot failures during deployment.

4.2 Failure Classes

There were five classes of failures that are common to all of the deployments involving the Inuktun Micro platforms. These were termed *gravity assists, stuck assists, track slippage, occluded camera* and *lighting incorrect*. Each one of these failures indicates a deficiency in one of the relationships illustrated in Section 3.1. These categories are defined along with the relationship as follows:

- *Gravity assists* occur when the tether manager is required to provide support for the robot through the tether. In these cases, the tether manager prevents the robot from falling freely into the hole. Typically this action is used to keep the robot from tumbling forward or to reposition the robot in the conduit. This is considered a failure because the robot is not able to perform the search without manual intervention by the operator or tether manager. The criteria for deciding that this assist occurred was developed from the observation of the operator's inability to control the robot's movements. This event was determined in the analysis of the video when the camera bounced due to a failure in traction.

Table 8. Description of the six analyzed drops relative to the void and robot classification explored in the previous chapter. This includes deployment number, drop number, void type, operators, robots, robot type, and run duration.

Deployment	Drop	Void Type	Operators	Robot/s	Robot Type	Duration
2	3	*Size:* Sub-Human Searchable *Moisture:* Dry and Dusty *Orientation:* Horizontal *Crumb. Rubble:* Stones *Non-Crmb Rub:* Paper *Rub Weight:* Lighter then robot	Blitch, Mangolds	MicroTrac	Micro	05:41
	4	*Size:* Sub-Human Searchable *Moisture:* Dry and Dusty *Orientation:* Diagonal *Crumb. Rubble:* Pebbles *Non-Crmb Rub:* Paper, furniture *Rub Weight:* Heavier than robot	Micire, Blitch	MicroTrac	Micro	24:40
	5	*Size:* Sub-Human Searchable *Moisture:* Standing Water *Orientation:* Diagonal *Crumb. Rubble:* Dust and Dirt *Non-Crmb Rub:* None *Rub Weight:* None	Micire, Mangolds	MicroTrac	Micro	03:58
	6	*Size:* Sub-Human Searchable *Moisture:* Dry and Dusty *Orientation:* "L" *Crumb. Rubble:* Dust and Dirt *Non-Crmb Rub:* Paper, furniture *Rub Weight:* Lighter than robot	Micire	MicroTrac	Micro	06:59
7	7	*Size:* Human Searchable *Moisture:* Dry and Dusty *Orientation:* Diagonal *Crumb. Rubble:* Stones *Non-Crmb Rub:* Rebar, Steel Beams *Rub Weight:* Heavier than robot	Haglund, Morin	SOLEM	Mini	06:55
8	8	*Size:* Sub-Human Searchable *Moisture:* Dry and Dusty *Orientation:* Diagonal *Crumb. Rubble:* Stones *Non-Crmb Rub:* Paper, furniture *Rub Weight:* Heavier than robot	Micire, Blitch	MicroTrac, VGTV	Micro	13:31

Notes gathered at the response also helped quantify the void orientation under which this event occurred. It is directly tied to the *grade* element and the *void orientation* classification defined in Section 3.1.

- *Stuck assists* describe cases in which the tether manager needs to free the robot from some obstacle or terrain that does not permit the robot to move. In these situations the tether manager is required to pull back on the micro-robot's tether to disentangle the robot. This is considered a failure because the robot is not able to perform the search without manual intervention by the operator or tether manager. The criteria for deciding that this assist occurred was developed from the observation of the operator's inability to move the robot through the environment. Such an occurrence was identified during the video analysis when the camera bounced due to a failure in traction. The lack of visible movement in the video also helped to support an occurrence of this event. This is the result of the environment's *size of debris* becoming larger than the *ground clearance* of the robot.

- *Track slippage* is the amount of time that the track mechanisms are not sufficiently making contact with the travel surface. This characteristic is determined by two factors - the robot's track material characteristics and the surface on which the robot is traveling. The friction between the tracks and the ground plane determines if the robot is going to successfully travel forward, or stand in place while its tracks slip. This is considered a failure because the robot does not progress in the search of the void during the time that the robot is slipping. *Size of debris*, *wetness*, and *debris type* are the environmental characteristic factors that decrease the robot's *traction*.

- *Occluded camera* defines the time that the camera on the robot is completely occluded by objects and debris. This failure is considered since no useful search is performed while the camera view is blocked. The failure is caused by the environment's *size of debris* being large and reducing the robot's *sensing capability.*

- *Lighting incorrect* is the amount of time that the lights are either completely off or in a transition period between light intensities. This is a failure because no search is performed while the operator is adjusting the brightness of the camera view. In this case the task's *sensing requirement* indicates that lighting is needed in the void, but the robot is not able to dynamically adjust its *sensing capability* to compensate.

4.3 Failure Analysis Method

The classes of robot failures were determined by reviewing the tapes of the deployments repeatedly over a four month period following the disaster. This analysis was an attempt to assess the operational difficulties and failures due to problems in robot design. It was also used to explore how these problems were overcome in the field, and how these new methods can be used in future missions. From this tape analysis, common repetitive failures were observed, and a local consensus among the operators was formed as to their classification and importance. This local consensus included four members of the CRASAR staff that were considered expert operators and were present at the World Trade Center response. These categories do not reflect a universally accepted set of teleoperation errors, but rather those errors that most affected the rescue operations in this unique environment.

Once the classifications were generated, numerical data from the video archive was gathered over a two-day period. The 10 hour procedure for manually parsing the video footage provided the foundation for the numerical analysis. The data was collected by a single observer watching the tape and looking for each failure classification feature individually. When collecting enumerated data, the feature was counted for each drop and entered into a chart. For time relevant data, the feature was measured using a handheld stop watch. This overall time was then also entered into the chart. The procedure is repeated for all of the recorded drops creating a fifty-six data point table.

The criteria for determining an event was determined in three ways. First, the observer used occurrences in the video to trigger an event record. For example, if the observer witnessed the camera "bouncing up and down" but no forward movement could be observed, then this was recorded as a track slippage event. Second, the observer referred to the recollection of the operators. This was accomplished via telephone conversations and email correspondence. A final source for event determination was the fact that the author of this work was the operator for half of the 8 drops that occurred at this response. Detailed notes generated post-response by the author provided background and environmental constraints. These helped to determine the cause for the event observed during the data recording process.

4.4 Failures Common to Inuktun Platforms

In order to make any observations on the failure data, the basis and units for comparison must be established. The raw failure data is shown in Table 9. The metric used to describe the first two columns of failures is a count of the discrete occurrences of each event. In Table 10 discrete counts are converted into occurrences per minute to reflect a normalized frequency over the entire feature set. In Table 9, the last three columns show the total time the robot spent in that failure state. This time is converted into a percentage of the overall time in Table 10, allowing for an objective comparison with the other drops in the same column.

The nature of this disaster made the video data collection difficult and incomplete in many cases, so several considerations must be taken into account when observing the data set. In Table 9, the total times shown do not reflect total drop time, but reflect total time for which tape data was recorded. Also, Drop 3 was not completely recorded, so the analysis of this drop only includes available tape data.

Table 9. Count and duration of failures common to Inuktun deployments.

Deployment	Drop	Attempt	Total Time	Gravity Assists (Count)	Stuck Assists (Count)	Track Slippage (Time)	Occluded Camera (Time)	Lighting Incorrect (Time)
2	3	a	02:49	3	7	0:15	0:14	0:00
	3	b	02:52	1	6	1:03	0:25	0:05
	4		24:40	65	0	2:11	2:29	2:03
	5		03:58	2	0	0:11	0:00	0:00
	6	a	04:10	1	38	0:11	2:18	0:13
	6	b	02:49	1	6	1:01	1:41	0:16
8	8	a	06:39	0	0	0:00	0:00	2:37
	8	b	06:55	1	5	0:24	0:15	0:07
Average			06:52	9	8	0:40	0:55	0:40

This data was not procedurally recorded, is not reproducible, and is not statistically significant. It is an unstructured "live" data set that is extracted from archival video recorded in a highly disorganized environment. This numerical analysis and the conclusions herein should only be considered the conjectures and opinions of the operators in an effort to produce improved guidance for future robot design and performance evaluation tools.

Table 10. Frequency of failures common to Inuktun deployments.

Deployment	Drop	Attempt	Total Time	Gravity Assists (freq/min)	Stuck Assists (freq/min)	Track Slippage (% of time)	Occluded Camera (% of time)	Lighting Incorrect (% of time)
2	3	a	02:49	1.1	2.5	1%	1%	0%
	3	b	02:52	0.4	2.1	36%	14%	0%
	4		24:40	2.6	0.0	1%	10%	1%
	5		03:58	0.5	0.0	5%	0%	0%
	6	a	04:10	0.2	9.1	4%	55%	5%
	6	b	02:49	0.4	2.1	36%	60%	1%
8	8	a	06:39	0.0	0.0	0%	0%	40%
	8	b	06:55	0.1	0.1	1%	1%	0%
Average			06:52	0.7	2.1	11%	18%	6%

4.4.1 Gravity Assists

Gravity assists impacted all of the drops. The drop with the greatest number of gravity assists was Drop 4 with 2.6 assists per minute. This number is greater than the other drops because the void had a diagonal orientation and was filled with loose non-crumbling debris. This near-vertical environment required the tether operator to assist the robot throughout the entire drop. The second most assisted drop was Drop 3 with 1.1 assists per minute. This horizontal void's entrance was such that the tether operator was required to lower the robot several feet into stone-sized debris.

This proved problematic to the robot's movement and therefore required assistance 3 times.

Each of the 5 drops involved at least one gravity assist since the robot was lowered by the tether to the entrance point of the void regardless of the orientation. However, the data shows no gravity assists on the first attempt of Drop 8 into the conduit void under Tower Two. This is because the robot was placed into the void and removed from the void under its own power.

The use of gravity assists was both a hindrance and a help to the rescue operations. It was a hindrance because in 5 out of 6 drops it required direct and constant communication between the robot operator and the tether manager. This increases the ratio of operators to robots. Conversely, in the remaining drop, it hindered the situation by requiring a single person to act as both operator and tether manager at the same time, therefore increasing the number of tasks that the operator needed to perform. This is not to say that gravity assists did not help in the search. Gravity assists enabled a successful completion of 7 out of the 8 drop attempts.

4.4.2 Stuck Assists

Stuck assists greatly affected 2 of the 5 drops. The worst hole in this category was Drop 6, because it had a vertical orientation and was filled with paper, which is lighter than the robot. The number of stick assists in Drop 6 was greater than the other drops for two reasons. First, the robot was trapped by a metal bar lodged in the track mechanism and the robot could not be easily removed from the void. Secondly, once the robot was reinserted in the second attempt of Drop 6, the amount of paper prevented the robot's unassisted movement. The second drop which required stuck assists was the horizontal Drop 3. The large stone debris proved too difficult for the robot to navigate 13 times, forcing the tether manager to assist the robot. This failure in all of the other cases is attributed to rocks and debris caught up under the chassis of the robot. Overall, the robot was assisted two times per minute on average.

Stuck assists impacted the platform mobility. The state of the platforms resulted in the robots' inability to move through the environment unassisted. In cases other than the first attempt of Drop 6, these failures are caused by an object caught under the chassis. This environmental characteristic elevated the platform tracks above the traction surface and rendered the platform immobile unless assisted. The low ground clearance on the chassis was the main contributor to this failure. This decreased deployment mobility and search efficiency during the operation.

4.4.3 Track Slippage

The average percentage of time the robot slipped was eleven percent over all of the drops. Although Drops 3 and 6 are both tied for the greatest value, the reason for these numbers is different. The first attempt of Drop 3 had a high failure rate due to the large amount of paper and debris that got caught under the chassis decreasing the friction level. Drop 6 also had slippage due to the large amount of paper that was in the bottom of this void. However, in this case, the track friction was sufficient, but the ground plane was moving underneath the track.

Track slippage impacted the search by reducing the robot's ability to maneuver efficiently in the environment. As a result, this decreased the amount of area the robot could explore.

4.4.4 Occluded Camera

Camera occlusion impacted the search by preventing useful visual information from being sent to the operator. Drop 6 is significant in this category because the camera was occluded more than fifty-seven percent of the time that it was in the void. This was due to the paper material in the hole. As the operator moved the tracks, the paper was pushed to the side of the robot opposing the track direction. The movement of paper caused the robot's camera to be buried repeatedly. All other data points in this category are related to the camera passing within inches of a rock or object in the environment, temporarily occluding the view. Although the robot was typically not hitting the object, it was often the case that debris would pile up in front of the robot. This was true for the Inuktun MicroTrac, as the platform's ground clearance and blunt front made for an efficient pushing surface.

4.4.5 Lighting Incorrect

Incorrect lighting impacted the search by consuming six percent of the operator's time on average. This required the operator to suspend navigation techniques and manually adjust the image brightness and quality. In the case of Drop 4, the robot crawled up on the remains of a victim. The light intensities were adjusted for a total time of over two minutes to increase the brightness and enhance the image displayed on the OCU. This was futile because the auto-gain on the camera would then compensate for this increased lighting. In the case of Drop 8, the increase in this time is primarily related to the time required to diagnose the blown halogen lights, rather than the operator's need for image enhancement.

4.4.6 Analysis of Deployments

A correlation between drops is needed to evaluate the effectiveness of each individual drop. An analysis of the success of each drop is shown in Table 11. This is determined by averaging occurrences that contained the same metric of measurement. Two combinations result from this grouping. Gravity assists and stuck assists are measured in the frequency of occurrences per minute. These are also significant in their relation to assistance from the tether. For each deployment, their values are averaged. The second combined category uses the percent time metric for comparison.

Table 11. Analysis of failures common to Inuktun deployments.

Deployment	Drop	Attempt	Average Frequency per Minute	Average % of time
2	3	a	1.8	0.7
	3	b	1.3	16.67
	4		1.3	4.0
	5		0.3	1.7
	6	a	4.7	21.3
	6	b	1.3	32.3
8	8	a	0.0	13.3
	8	b	0.1	0.7
Avgerage			1.4	11.7

The best and worst drops can be determined from this analysis. Drop 6 is the worst drop in all respects compared to the other deployments. This was the paper-filled void in which virtually no search area was covered and no victim remains were identified. Drop 8 is one of the best since it is comparatively lower in the frequency comparison and only slightly above average with respect to the time percentage comparison. In addition, this is one of the platform's most successful runs in terms of distance searched and victim remains identified.

4.5 Single Instance Inuktun Failures

There were four failures that were not common throughout the deployments detailed above. These included an *impaled track mechanism, a thermally-induced failure, a lighting failure*, and a *radio failure*. Although these failures were not as repeatedly degrading to the success and speed of the deployment, they did have a large impact on the performance of the platforms.

4.5.1 Impalement of Track Mechanism Failure

During Drop 6, an aluminum rod was lodged into the track mechanism. The space tolerance between the track and the platform is less than one-eighth of an inch, making it highly unlikely that a failure of this type could occur. As the robot was facing downward, the aluminum rod rested against the front of the track mechanism. Then as the operator moved the track forward, the aluminum was pulled inside the upper track housing. This permanently lodged the rod into the track and would have prevented track movement if the robot had been able to gain traction on the bottom of the void. The robot needed to be fully removed from the void to fix this failure. This impacted the search due to the time lost while diagnosing the failure and removing the robot from the difficult void.

4.5.2 Thermally-Induced Failure

High levels of heat induced a mechanical failure in the VGTV platform during an inspection task on World Trade Tower Two. The loss of the track on the VGTV platform disabled the platform for three minutes in the second attempt of Drop 8. In this case the robot was placed in a void with a temperature estimated above 200 degrees Fahrenheit. The purpose of this drop was to see if the robot could climb down past the tightly compressed rubble and enter the remains of the parking garage below.

Although no direct measurements were taken at the time of deployment, the operators noticed that the heat coming from the access hole was considerable. After insertion into this hot void, the robot proceeded to the bottom of the hole. The robot lost its track while trying to climb over a small pile of debris. After unsuccessfully trying to assess the problem for more than three minutes, the robot was removed from the conduit.

It was realized that the heat was a primary contributor to the track problem. The track had become heated and loosened itself on the drive wheel mechanism. The VGTV platform is only rated to a maximum of 122 degrees Fahrenheit, so this void search fell outside of the recommended safety limits. The loss of the track was important because it was one of the contributors ending the robot's usefulness in this deployment, and shows how this design is poor for a potentially high temperature environment.

4.5.3 Artificial Lighting Failure

During Drop 8, the MicroTrac's halogen lights failed when the tether was disconnected and then reconnected to the OCU, thus disabling the platform's ability to visually search the void. It was not immediately clear if there was a malfunction on the robot camera or the halogen lights because the ambient lighting in the void was so low. After removing the robot and inspecting the platform, it was found to be the halogen lights. Initially, it was thought that heat may have been the reason for disabling the lights, but instead it was found that a design consideration caused the problem. When the operator reconnected the tether to the vehicle while the OCU controller was powered, the microprocessor momentarily hung and provided one-hundred percent to the light driver. The lights were rated at twelve volts, and the driver typically outputs thirty to forty percent of the voltage from a thirty-six volt source. The robot's lights received thirty-six volts when the microprocessor hung, subsequently causing them to blow. This was clearly a design failure that could have been avoided by a simple "power good" latch off the microprocessor controlling the voltage. The loss of the lights was significant because it was the contributor ending the robot's usefulness in this deployment.

4.6 SOLEM: RF Failure

In the approximately seven-minute run that the wireless SOLEM performed in Drop 7, over one minute and forty seconds resulted in completely unusable video. The reason for this failure was the structural steel of the World Trade Center making it difficult to transmit radio signals. This was because of the material's conductivity and thickness. The SOLEM carries a two watt transmitter that can nominally reach over a mile in range. The robot lost communication with the OCU after less than a twenty feet in this case. The platform finally lost video and control completely. It had to be abandoned after the rope attached to it snapped. The platform was never recovered by CRASAR.

The RF interference impacted the effectiveness of this drop in one major respect. The robot's video was not contributing to the search in any way during the time that the transmission was unusable. Since nothing in the video could be seen during these dropout periods, no potential victims or void characteristics could be identified.

4.7 Summary

The examined failures experienced by the Inuktun platforms at the World Trade Center disaster are significant and numerous. Each deployment points to a failure that impacted the effectiveness of the search. In the case of gravity assists and stuck assists, the operator was required to use the tether to artificially move the robot through the environment 2.8 times per minute. During track slippage, the robot's effectiveness in navigating through the search area was decreased by eleven percent over the time of the deployment. Occluded cameras and lighting adjustments reduced the ability of the operator to see the environment that the robot was operating in, and therefore decreased the ability to detect victims. The significance of the latter two failures is reflected in their causing the loss of twenty-four percent of the effective deployment time. Although many of these failures may never be reduced to zero, their significance in this data set clearly shows that the robot-assisted rescue effort suffered from these occurrences.

CHAPTER 5

RESEARCH FINDINGS

Seven findings resulted from the analysis of the data collected during the response to the World Trade Center disaster. These findings are based on the characteristics of the robots and equipment categorized in chapter 3, the analysis of failures detailed in chapter 4, and additional observations made by the CRASAR operators after the disaster.

Previous research in artificial intelligence, image processing, and mechanical engineering have helped to lay a foundation for the current work in USAR related robotics. Unfortunately, the World Trade Center disaster and previous work by USF has shown that there are some gaps in current robot technology that have not been explored in the context of USAR. These gaps are partially attributed to the fact that much of the classical planning, mapping, and localization techniques used in robotics rely on a highly accurate knowledge representation of the world in which the robot is working. The task of modeling the complex surroundings encountered in search and rescue is difficult due to limitations and application problems in sensing. This chapter will describe these issues and how the previously explored failures reinforce these findings.

As a result of the post-hoc analysis of the data gathered at the World Trade Center disaster, seven findings have been identified that point to technologies that were lacking in robot-assisted search and rescue. These provide the framework for the remainder of this chapter. First, *advanced image processing systems* were not available to aid the rescuer in identifying victims in this visually complex application. *Tether* *management systems* were not available to deal with the difficult task of ensuring the robot's tether was optimally placed to progress the search. *Wireless relay systems* were also needed, but not available to allow the robot to probe deeper and more reliably into the void spaces without the loss of communications. Enhanced robot awareness for *size adjustment and polymorphism* were needed, but not available at this disaster. *Localization and mapping* would have significantly improved the robot's ability to relay information about the structure to the rescue workers outside the void, but could not be used. *Size and Distance Estimation* methods were needed to aid the operator in determining the size and range of objects while using monocular based camera systems. Finally, *assisted navigation* was needed to assist the operator by limiting the number of pose and robot state errors.

5.1 Image Processing

High speed and high accuracy victim detection in adverse lighting and recognition conditions was not available on the robot systems deployed at the World Trade Center disaster. A computer-enhanced victim detection system would have augmented the operator's ability to positively identify victims in the environment. This is important since the operators were already cognitively saturated with navigation tasks. [14]

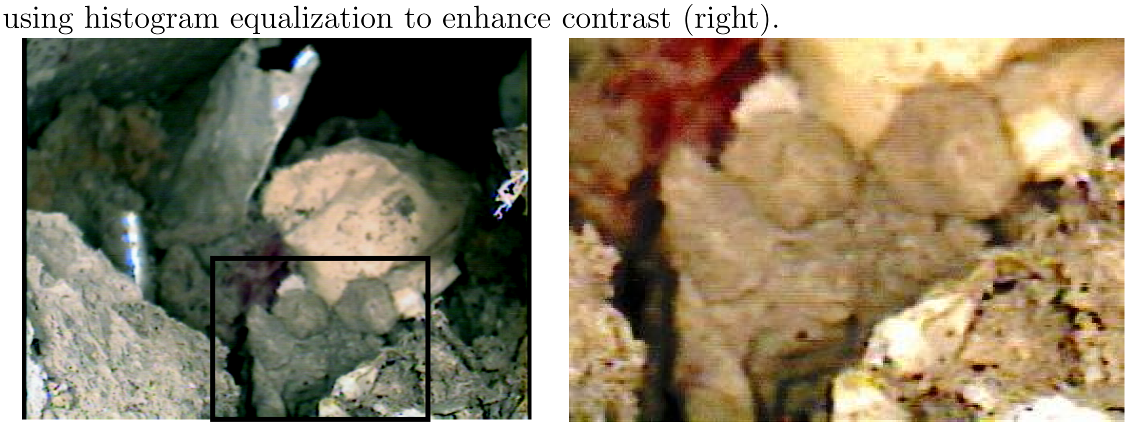
At the World Trade Center disaster site, the debris and victims were covered in a layer of dust. This dust originated from the drywall, ceiling tiles, insulation, and other pulverized building material. Unfortunately for the CRASAR operators, this dust removed most of the visible color from the environment. As a result, potential victim remains were camouflaged within the environment. Minimally, computers could have been used to quickly performed simple color and contrast enhancement to aid in the recognition process.

Quantitative support for the need for visual enhancement was seen on two of the drops preformed by CRASAR at the World Trade Center disaster. The operator was required to use a raw video signal and, as a result, only accurately identified two human remain fragments at the time of deployment. Post-analysis of the video later showed 7 victim fragments were visible to the operator, and one victim remain identified at the time of deployment was determined to be a false positive.

Additional support for image enhancement was shown through the operators' repeated adjustment of the lighting on the robot platform. Figure 7 shows some examples of victim remains that were identified at the time of the deployment. In this case, a simple histogram equalization of the picture is shown beside it. This enhanced picture is an illustration of how computationally efficient and established image enhancement methods can improve the quality of an image.

In cases involving attempted remains recognition, this adjustment was mostly in vain because the camera contained automatic gain features. The auto-gain negated the effects of the brighter lighting by lowering the light sensitivity on the camera. This shows that the operator was not aware that the camera was already operating at close to optimal brightness levels. Table 12 shows the percent of time that was spent in this activity over all of the deployments. Unfortunately, this activity accounted for six percent of the operator's search time on average, and forty percent in the worst case.

Figure 7. The remains of a hand in the lower part of the photo (left) are enhanced using histogram equalization to enhance contrast (right).



5.2 Tether Management

Robust and adaptive tether management systems for robot and mobility assistance were not available for the robot operators at the site. No mechanized tether system was available to manage the robot's cable in this difficult environment and adapt to the robot's changing navigational needs. All tether management actions were performed manually by an operator manning the tether throughout the drop. This technology would have helped considering two out of the three robot models used during the World Trade Center rubble pile search were tethered robots. These two micro-robot models were the Inuktun VGTV and MicroTrac platforms. The tether benefited the micro robots by providing required power, communication, and acting as a line for manual position adjustment. This allowed the tether manager to manuver the robot into desired positions within the void. Unfortunately this added an additional aspect of the robot control management because another operator was needed to handle the tether and ensure tangle-free operation.

The first support for advanced tether management was the requirement for assistance from the tether manager on every drop involving a tethered robot. This assistance was encapsulated in two forms in the former analysis chapter. *Gravity assists* were times in which the tether was used to keep the robot from falling forward into the void. These gravity assists also enabled the robot to gain access to parts of the void that would have been inaccessible under the robot's own power. On average, there was at least one gravity assist 0.7 times per minute as seen in the fifth column of Table 12. The second form of assistance was through *stuck assists*, or pulling on the tether to free the robot from a position in which it was stuck. The situations in which the robot got stuck included ground clearance problems and loss of traction. This operation was more frequent than the gravity assist, accounting for 2.1 assists per minute, as seen in the sixth column of Table 12.

Table 12. Frequency of failures common to Inuktun deployments.

Deployment	Drop	Attempt	Total Time	Gravity Assists (freq/min)	Stuck Assists (freq/min)	Track Slippage (% of time)	Occluded Camera (% of time)	Lighting Incorrect (% of time)
2	3	a	02:49	1.1	2.5	1%	1%	0%
	3	b	02:52	0.4	2.1	36%	14%	0%
	4		24:40	2.6	0.0	1%	10%	1%
	5		03:58	0.5	0.0	5%	0%	0%
	6	a	04:10	0.2	9.1	4%	55%	5%
	6	b	02:49	0.4	2.1	36%	60%	1%
8	8	a	06:39	0.0	0.0	0%	0%	40%
	8	b	06:55	0.1	0.1	1%	1%	0%
Average			06:52	0.7	2.1	11%	18%	6%

A second source of support for automated tether management was the need for a 2:1 man:robot ratio on 5 out of the 6 drops. This ratio would have been minimized to 1:1 if the tether management could have been autonomously maintained by the robotic platform or some additional apparatus. This would have afforded two benefits to the robotic rescue team. First, the manpower requirement of the system could have been lessened. This would have allowed twice as many independent searches to operate at the same time given the same number of personnel as a 2:1 search system. Second, safety of the operator would have been increased because the tether operator would not have been put in a potentially harmful situation. In all of the deployments, the tether operator was placed near the opening or ledge of the void where the robot was searching. This is illustrated in Figure 8. Along with the danger of the tether manager falling into the opening, flash-overs and exploding debris exiting the void threaten the safety of the rescue personnel. There would have been no need for this risk if the tether management had been automated.

Figure 8. CRASAR operator extended over void acting as a tether manager for robot.

A final source of support for tether management was seen when one of the second drops on September 12th caused the tether to get tangled on some bent metal. The operator tried to remove the robot, but because of his sub-optimal viewpoint he was unable to free the robot from its trapped position. This impacted the search because the robot could not proceed on its assigned inspection task. The robot was eventually freed from its position when a rescue worker proceeded into the questionable void. On the way out of the void, the worker released the robot and gave it back to the operator. If some mechanism to manage the tether was in place, the tangle might have been resolved without manual intervention.

5.3 Wireless Relay

The lack of wireless relays decreased the reliability and reception quality of the robots' wireless communications at the World Trade Center disaster. The reason for this finding lies in the nature of building construction. Large building structures are typically made of reinforced concrete and steel. These heavy material are used for their strength characteristics, but these characteristics also make them troublesome for radio communications. The propagation characteristics and attenuation due to material shielding pushes the signal loss past the receiver's low-decibel threshold. This loss of signal to the robot is always detrimental to the operator's control.

The need for a wireless relay methodology was supported by the eventual loss of the SOLEM wireless robot at the World Trade Center rescue effort. The robot lost one minute, forty seconds of a seven minute run due to RF shielding and interference from the structure. The run was ended due to the loss of the robot's communication signal even though the robot was no more than 30 feet away from the operator console. Extreme compaction of the World Trade Center's steel structure created a large RF shield that overcame a radio system which normally can transmit a mile within line-of-site. Unfortunately this robot did not have any software available which would allow it to autonomously reestablish communications. Further, the movement of the operator around the opening of the void was limited, so no manual adjustment could be made. As a result, the robot was abandoned.

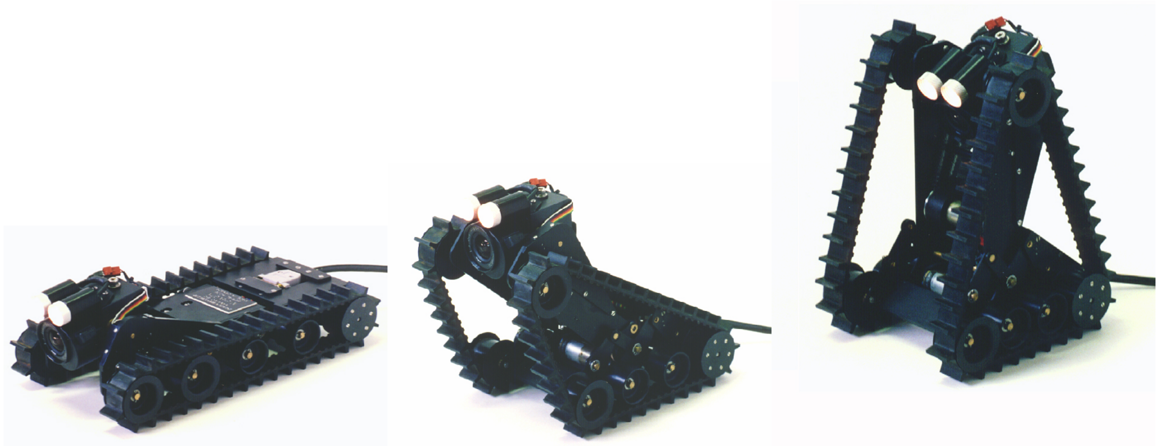
5.4 Size and Polymorphism

Small, agile robots that can change their shape relative to the changing environmental constraints were needed, but not available at this operation. Due to the extremely unstructured nature of the World Trade Center disaster site, it was impossible to accurately predict the optimal robot shape for transversing the rubble pile in search of victims. As a result, the robot needed to be able to adapt to the environment by adjusting its shape and traction for maximum utility. Unfortunately, the robots deployed during the response did not possess this capability.

Only one of the robot platforms used for rescue at the World Trade Center was able to change its shape. Unfortunately this needed to be done manually by the operator and no feedback was provided indicating the orientation of the platform. The three primary shapes that this robot can assume had three very distinct advantages in the environment. In a fully lateral position, the robot maximized its forward traction surface. This was useful when pulling long segments of tether behind the vehicle or maneuvering in slippery environments. Unfortunately, the robot's camera was only one and a half inches above the ground in this position, so the operator had a very limited view of the environment. This position can be seen in the first example in Figure 9. The second shape involved placing the robot half way through its possible shape transition. In this position the robot gained positive traction on obstacles that were larger than two inches. The forward traction was lessened slightly, but the forward view was improved due to the increased camera height, as seen in the center example of Figure 9. Finally, a full upward shape allowed the robot to gain its highest observation angle. While it gave the highest visual vantage point, this shape suffered from low ground traction and high instability in uneven terrain. This high position can be viewed in the last frame of Figure 9.

The ability to change the shape of the robot proved its usefulness in Drop 8 performed on World Trade Tower Two on the 18th of September. The robot could not see over a ridge in the pile of rubble at the bottom of one of the support conduits. It was thought that the opening might lead to a lower area which might contain victims. In its lowered stance, the operator could not see anything beyond the ridge of dirt and debris. Moving the robot's shape to the higher position allowed the operator to

Figure 9. VGTV in shape-shifting positions



confirm that the conduit did open up beyond the obstructing pile. An example of these two views can be seen in Figure 10.

Unfortunately, the robot's mobility did not allow it to climb over the pile and further investigate this void. This was partially due to the fact that the operator could not establish the orientation of the robot and optimize the traction surface. Even though the VGTV could not proceed into the void space, this discovery was important in later searches when it was decided to allow a SOLEM platform to further investigate the conduit.

Figure 10. VGTV in lowered, obstructed view (left), and higher non-obstructed view (right).

5.5 Localization and Mapping

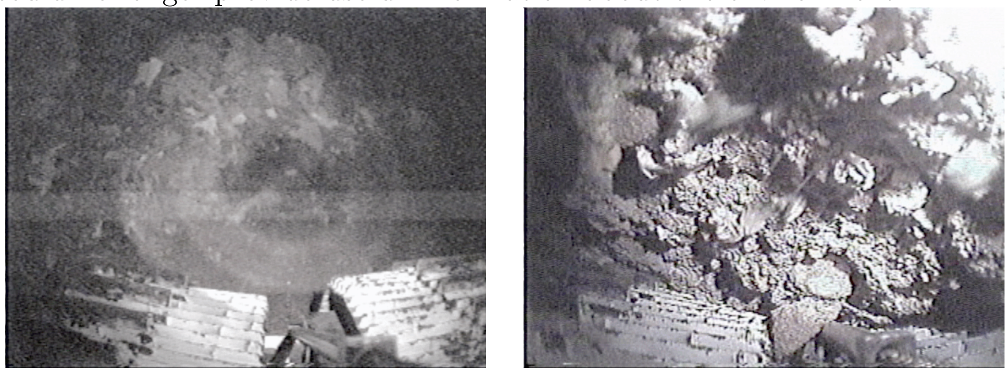
Localization and mapping in this complex environment was not available to the operators during this response. The ability to map the environment and relay that information to the operator and commanders would have been extremely beneficial to the search process. Detailed maps of the inner structure of the collapsed buildings would have provided information to guide search tasks and ensure the safety of the rescue personnel entering the voids. Only pre-disaster maps were used to coordinate the search process. Given the severity of this disaster, these were limited in usefulness and prone to error.

Support for this need was shown in Drop 7 when the SOLEM platform was used to investigate a void near World Trade Tower Two. From the opening to the pile, the rescue workers could see that there were two potential tunnels the robot could investigate. The mission of the robot was to quickly search the void and determine the safety and viability of these openings. When the SOLEM was lowered into the void, it was flipped upside down and fell into a third opening that had not been seen from the top of the void. A view from the robot in this situation can be seen in Figure 11. Unfortunately for the operator and rescue workers, the SOLEM did not contribute to the knowledge about the structure or size of the void, nor could it provide any information about where it had traveled. The inconclusive results of this search deployment suggests that had the robot been able to map the environment, the incident commander would have had a better idea of the void's characteristics and structure.

5.6 Size Estimation

The monocular camera provided very little depth or size information to the operator while navigating the robots within the pile. The operator could not use stereo vision

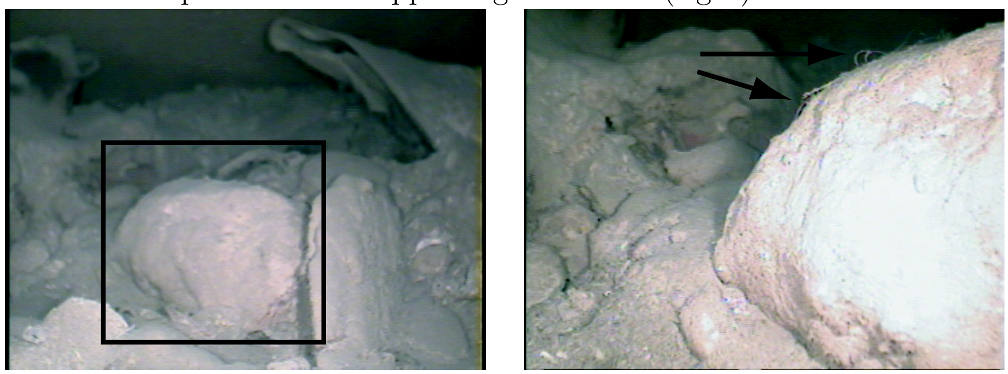
Figure 11. View from SOLEM when the robot flipped over into a third void opening and could no longer provide useful information about the environment.



with the available robotic platforms, so depth perception was extremely limited. The lack of depth perception had two main impacts on the response. First, the operator could not judge how far away an object was from the robot. This information would have been important when attempting to describe to the search personnel how far away a victim or remain was from the robot's position. The second impact was in estimating the size of objects in the environment. Without something else in the robot's view with which to make a size comparison, there was no way to determine if an object was close and small, or large and far away.

Size estimation was very important to the operator's ability to search a void area effectively. An example of failed size estimation occurred on Drop 8 when the robot was teleoperated to the bottom of a structural support member. During the inspection of the bottom of the void, the operator did not realize that there was a human head directly within the camera's view. At the time of deployment the dust covered "rock" appeared to the operator too be to large to be the remains of a human. This is shown in the left photo of Figure 12 After careful post-analysis it was later found to have small pieces of hair still attached, as seen in the right photo of Figure 12. Using the size of a wrist watch as a known object for size comparison, it becomes clear that this could be the head of a victim. If some size estimation had been available to the operator, the relevance of this debris may have been realized earlier during the deployment. Although the victim in this case was deceased, this type of identification would have been very important to the discovery of a live victim.

Figure 12. View from VGTV showing a pile of debris with a human head in the center (left) and a closeup of the hair supporting this claim (right).



5.7 Assisted Navigation

Navigational aides in confined space environments were not available to the operators at the World Trade Center disaster. Robots have been shown in the past to be useful in relatively tight and unstructured spaces [31] and navigation techniques have an extensive base in the robotics literature. Unfortunately no research has been done to evaluate the usefulness of these navigation techniques in USAR tasks. The usefulness of the navigation algorithms comes into question in this domain due to the systematic problems that many sensors have in tight spaces. Sonars, for example, are widely used on robots as range sensing devices for navigation tasks. In confined spaces these sensors suffer from specular reflection and noisy range readings. Fundamental techniques such as guarded motion and waypoint navigation could have potentially been used in this disaster response, but they were not available at the time and had not proven their effectiveness in prior testing.

The need for assisted navigation was supported by two elements in the analysis of failures. First, the *stuck assist* failures shown in Table 12 indicate that the operator had navigated the robot into a position that was undesirable for continuing the search through the void 2.1 times per minute on average. The robot blindly obeyed the operator and provided no feedback through any of the operator's sensing channels. Additionally, because the robots used had very limited environmental sensing ability and virtually no computational power, they could not autonomously guide the operator out of the problematic areas. A second source of support can be found in the *camera occlusion* failure also shown in Table 12. The operator maneuvered the platform into undesirable viewing positions eighteen percent of the time on average. Again, because the robot did not have the proper sensing and computational resources, it was unable to assist the operator.

5.8 Summary

Seven findings have been presented that point to areas that are currently lacking in robot-assisted search and rescue. First, the operator was required to expend six percent of the search time adjusting image brightness due to the lack of image enhancement. The operator also did not identify over seventy percent of the victim remains because there was no assistance related to victim detection. Secondly, tether management systems were not available to assist the robot operator and this required a second person be placed at the entry-point to the void. The tether manager was then required to provide manual assistance to the robot 2.8 times per minute on average. The third finding relates to the loss of the SOLEM platform after one minute and forty seconds of unusable video. This failure was because advanced wireless relay systems were not available to the rescue operators. In the fourth finding, only one small agile robot was available and it proved its effectiveness by enabling the operator to view an otherwise occluded portion of the void space. Unfortunately, this robot had limited sensing and could not adaptively adjust its shape to the environment. Localization and mapping, in the fifth finding, was not available to the operators. This is supported by the SOLEM not contributing to the knowledge of the surroundings while lost in a previously unknown void. The sixth finding was the lack of size estimation and this contributed to the operator completely missing a victim's remains in a void. Finally, assisted navigation was not available to the operators in any respect at this operation. This was confirmed by the need for assistance 2.1 times per minute on average and the camera being occluded eighteen percent of the search time on average. Overall, these findings greatly impacted the search and decreased the effectiveness of the robot-assisted search effort.

CHAPTER 6

RESEARCH RECOMMENDATIONS

In examining the failures in Chapter 4, this work has identified research topics for the the robotics community. Seven recommendation categories were derived from the findings explored in the previous chapter. As a result, the recommendations suggested in this chapter will closely mirror the findings. These recommendations focus on research work to minimize the failures similar to those experienced at the World Trade Center disaster. These categories are important because they identify gaps in current technology that need to be filled by both basic and applied research groups.

Seven research areas have been identified that point to technologies that should be researched for future robot systems used in urban search and rescue. These provide the framework for the remainder of this chapter. (1) Research in image processing is needed for *fast and accurate victim detection*. (2) *Automated tether management* is needed for robot mobility assistance. (3) *Methodologies to increase the quality of wireless communication* is required for robots traveling deep into void structures. (4) Research must continue for *small robots that can adaptively optimize their shape* in difficult void structures. (5) *Localization and mapping* must be expanded to include highly unstructured domains. (6) Operator assistance through *size and depth extimation techniques* should be researched. (7) Finally, *assisted navigation techniques* in highly irregular confined spaces must be explored to limit the number of pose and robot state errors.

6.1 Image Processing

Research is needed in high speed and high accuracy victim detection to augment the operator's ability to positively identify victims in the environment. As discussed in Section 5.1, the victim remains at the rubble site were covered in a layer of dust that camouflaged their existence. This caused the operator to adjust the lights 6% of the search time and prevented the user from identifying five of the seven victim remains. Given the state of the art in computer vision, it is believed that operators would have benefited from image enhancement techniques in three main areas:

- *High level algorithms such as perceptual organizational techniques are needed in this domain.* Perceptual organization techniques attempt to expose regularity and structure in otherwise noisy and unstructured sensor readings [32]. These algorithms would help in the identification of structured elements in the video. Any organization or structure that could be automatically recognized might indicate a potential victim or void space. Research should also be directed at decreasing the computational complexity of existing algorithms in this domain. It is currently impossible to run these high level algorithms in real time.

- *Robust color segmentation techniques are needed in this low-contrast environment.* As stated above, the environment in and around the site was covered in dust and this removed the visible color from the surroundings. It is important for the color segmentation algorithms in this domain to be robust and compensate for the lack of color information and inconsistent lighting conditions.

- *Future research must identify useful combinations of image processing algorithms, cooperatively beneficial techniques, and order of application of the these algorithms.* Prior to the disaster, research in image enhancement had indicated that heat, color, motion, and color differencing are accurate affordances in the victim identification process [11]. In this disaster the operator did not identify over seventy percent of the victim remains because there was no assistance related to victim detection. Research must continue to explore other algorithms and ensure that the techniques are useful in lowering the operator's cognitive load and enhancing technical search.

6.2 Tether Management

Research in the area of automated tether management is needed to provide robust and adaptive assistance for tethered robot mobility. Given the small size of micro-robots, it is unlikely that the use of tethered operation will diminish. The inability for these robots to carry their own battery and computational power is the primary limiting factor in this respect. Additionally, the tether was advantageous to the deployments in which they were used. This was directly supported by the finding that every deployment at the World Trade Center required assistance via the robot's tether. Gravity and stuck assists, as discussed in Section 5.2, accounted for the operator manually helping the robot 2.8 times on average per minute. Future research could focus on intelligent mechanized solutions or cooperative multi-robot teams in the following areas:

- *Research needs to expose the techniques that are currently used by operators to assist robot mobility.* The tether assistance methods of expert operators must be cataloged and analyzed to expose the fundamental elements of their actions.

- *It must be determined which of the operator's techniques can be automated behaviorally.* The known tether assistance methods described above must be investigated to see which ones can be mapped into behaviors. Techniques like "pull to one side and let the robot fall" and "pull back on the tether when the robot can't move" can be broken down into behaviors that allow the stimulus to drive the automated tether manager's response mechanisms. This technique of observing the operator and then encapsulating the techniques into behaviors was shown effective in autonomous docking software previously researched [33].

- *Researchers must analyze the benefit of involving another robot or mechanism in the deployment.* A successful tether management system is robust and can adapt to unstructured environments. If the added complexity of having a second robot or mechanism still requires a second person for management, then the gains achieved must be re-evaluated.

6.3 Wireless Relay

Methodologies to increase the reliability and reception quality of wireless communication channels must be further researched. The importance of this research is vital to the usefulness of wireless communication in heavy building rubble as described in Section 5.3. The need for this research is supported by the eventual loss of the SOLEM platform in Drop 7 after 23% of the video transmission was lost. Research areas that could help the wireless dropout problem fall into four categories:

- *Research must continue in radio relay "chains of robots" that can relay the communication information from one robot to the next.* In this possible solution, when the furthest robot reached its RF limit, another robot would step in to extend the this virtual chain deeper into the void [34]. The SPAWAR Urbot platform had software that would allow multiple robots to act as relays in this fashion, but the Urbot platform was too large for the World Trade Center voids and the software was unavailable at the time of deployment. An example of the this relay methodology is shown in Figure 13.

- *Hardware solutions such as dropping radio relays need to be investigated for their effectiveness.* Dropped relays along the traveled path would have extended the reach of the SOLEM platform. These relays would act much like a "chain

Figure 13. Example of a wireless relay system with the SPAWAR Urbot in the lead. Photo courtesy of SPAWAR.

of robots", but static. As the SOLEM reached the maximum radio distance from the previous relay, another relay would be dropped and the search would continue.

- *Persistent and opportunistic maintenance of line of sight must be researched for wireless communications.* In this arrangement, a second pursuing robot actively minimizes communication dropout. If a pursuing robot can obtain a direct line of sight to the wireless robot, a relatively optimal path for transmission could be established. A robot pursuing the wireless robot would then act as a persistent follower, subsequently keeping an optimal radio position relative to the pursued robot.

- *The investigation of a "hybrid tether" could provide a solution to many of the wireless problems.* In this system, the robot could extend the tether as much as possible. When the tether becomes tangled or fully extended, the robot could drop the tether. The disconnected tether would then act as a radio system to the robot. This would give the robot the “best of both worlds” as it can adapt to the benefits of both tethered and wireless communications.

6.4 Size and Polymorphism

Research must continue in small, agile robots that can reactively change their shape relative to changing environmental constraints. The robot adapting to the terrain is important because no fixed robot design can compensate for every void space configuration. This was supported in Section 5.4 when the VGTV was not able to optimally adapt its traction to climb over debris for further void inspection. Future research in this area should concentrate in three recommended areas:

- *Self-optimizing, shape shifting robots require research into their sensing needs and capabilities.* Sensory information is needed to allow the robot to realize its position and orientation relative to the environment. Animals typically achieve this ability through a highly redundant sensory network that provides them with their state relative to the environment. The ability to equip the platform with large numbers of sensors is currently extremely difficult given the size and mounting constraints of micro and mini-sized vehicles.

- *The robot will need to be able to determine a relatively optimal shape and sensor position in the environment.* Computationally sub-optimal shapes might be a consideration since a polymorphic robot in an unstructured environment may have a large configuration space. The computational complexity of the shape-shifting algorithm must be carefully analyzed to ensure the movements of the robot can be calculated in real time. Another interface research issue is whether these changes should occur autonomously, without the operator’s direct intervention. For example, if the robot is experiencing insufficient traction, the operator can't see what is wrong. This, therefore, makes direct intervention difficult.

- *Additional non-wheel based mobility techniques should be explored.* Tracks and wheels may not be optimal for the unstructured USAR environment. Biologically inspired models of high mobility such as snake movement [6] may provide insight into potential solutions to the mobility difficulties for robots in this domain. Since this area of research falls outside of traditional wheel and track based mobility, new models of movement through unstructured environments will also need to be developed.

6.5 Localization and Mapping

Research must be expanded in robust localization and mapping. This is important in search and rescue because classical localization and mapping problems are magnified in this unstructured environment. Support was seen in Section 5.5 when the SOLEM had no capability to localize itself or map the below-grade void it had fallen into. Research in this area would benefit in two areas:

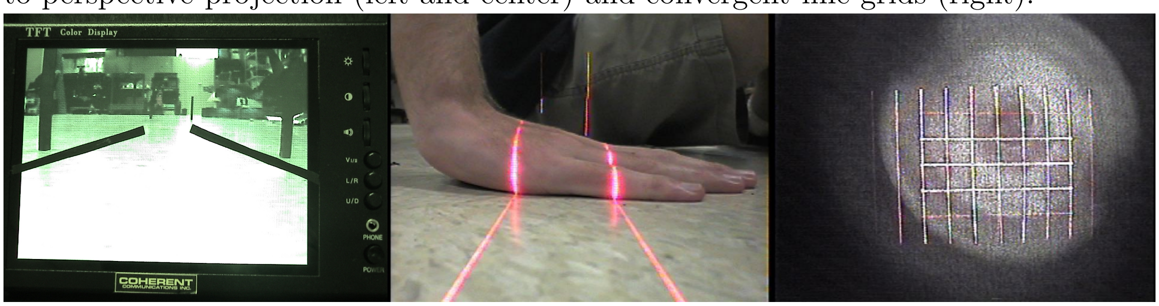
- *Localization research must explore problems specific to dynamic and unstructured environments.* Current sensing and mapping models are insufficient [35] [36]. Classical drive-based odometery in such unstructured terrain is error-prone. The localization and mapping must compensate for high-angle grades that may cause severe slippage. Classification of materials for range sensing is extremely difficult and must also be explored. Research must expose alternative localization methods.

- *The unstructured 3D worlds of USAR rubble piles will require currently unavailable robust 3D mapping techniques.* Mapping in robotics has traditionally focused on 2D representations. Disaster sites are 3D and complex in structure. Future research must address the spatial models required to make 3D mapping in this domain possible. Past work in 3D mapping has shown preliminary success [36], but this work has been in the domain of indoor structured environments.

6.6 Size and Distance Estimation

Methods for determining the relative sizes of objects in the environment must be researched. This need was supported in Section 5.6 when the operator was unable to determine the size of and object and therefore was unable to identify it as a victim's remains. Three methods are used by CRASAR robots, but these are highly subject to error. The methods are shown in Figure 14. Future research in this area should concentrate in the following areas:

Figure 14. Methods of size estimation used by CRASAR include vanishing point due to perspective projection (left and center) and convergent line grids (right).



- *Methods for improving the ability to detect size and depth in monocular vision systems must be explored.* Current robot implementations provide the viewpoint from a monocular camera that does not provide size and depth cues. This is typically due to size and weight constraints along with a lack of stereo implementations from robot manufacturers. Low complexity algorithms exist to present size and depth information the operator [37], but these must be expanded to unconstrained environments.

- *Stereo vision techniques must be further explored regarding their application in this domain.* Currently stereo techniques require detailed calibration of two cameras at fixed positions and have not been shown effective in unstructured domains such as search and rescue [38]. The depth information is also not easily conveyed to the operator without cognitive fatigue. It should be determined if the use of stereoscopic vision can be applied in this difficult domain.

- *Artificially introduced laser striping techniques are simple, but further research must extend their effectiveness and usability.* Currently available size estimation methods mandate that the user manually interpret the size of the object. These could alternatively be provided via computer vision mechanisms, but these methods have not been proven in search and rescue. Automated generation of the size and distance to an object should be explored.

6.7 Assisted Navigation

Advanced navigational aides must be researched for improving the operator's ability to guide the robot. This is important because confined space navigation is a difficult task that may provide little structure and numerous sensing deficiencies. Due to the operator's preference to manually control the robot movements, mobility assistance must be provided [11]. This need was supported in Section 5.7 when the robot required assistance 2.1 times per minute and lost 18% of the search time due to camera occlusions. This research should focus in four areas:

- *Techniques for assisting the robot's movements while navigating the void space must be further explored.* Current guarded motion and waypoint navigation techniques minimally require a semi-structured environment for navigation.

Debris piles are highly unstructured. This assistance issue must be resolved through increased environmental sensing and robust algorithms.

- *Methods to avoid camera occlusion and optimally calculate camera observation angles are needed.* There has been no research in this area for highly unstructured environments. Only industrial robot applications have been explored in this area [39]. Relevant research in industrial applications is difficult to adapt to search and rescue because the industrial robotics domain provides a highly structured and controlled environment.

- *Extend the research in collaborative teleoperation.* In the application of multiple robots, third-person viewpoints from assisting robots could be used to help ascertain the location and state of the pursued robot relative to its environment. The need for a third-person view was seen in Drop 8 when the robot lost its track mechanism. Another robot following the damaged robot would have been able to quickly diagnose the lost track rather than the operator spending over three minutes diagnosing the problem.

6.8 Summary

The seven recommendations in this chapter identify shortcomings that could be addressed by expanding or focusing current active research topics in the robotics community. Without progress in these areas, the failures experienced at the World Trade Center disaster could be repeated for future deployments.

First, image processing techniques are important to the victim identification process. The operators at the World Trade Center would have benefited from this, as 5 out of the 7 victim remains were not recognized as such at the time of deployment. This caused information to the incident commander to be incomplete and flawed for the recovery process. Although the victim was deceased in this case, there is a greater concern that under the same circumstances the operator may miss unconscious victims. Second, tether management systems can help to reduce the 2.8 robot assists per minute that were experienced during deployments. Third, research in improved wireless systems will allow the robots to probe deeper and ensure that robots do not loose communication, as was the case with the SOLEM platform. The fourth recommendation for active shape changing would help to allow the robot to adapt its shape to the environment and optimize its traction. The VGTV suffered in this respect when it could not gain sufficient traction in a difficult void. Research in localization and mapping is the fifth recommendation and is vital to the robot's ability to provide information to the rescue operators regarding the robot's position and environment. Sixth, size estimation is a recommended research area since the CRASAR operators were not able to identify relative sizes through the robot's monocular vision system. Finally, assisted navigation techniques must be explored that enable the robot to move through an unstructured environment without needing assistance from the tether manager or occluding the robot's camera.

These recommendations are important to the success of future robot-assisted operations. Their implementation will improve the effectiveness and search capability of robots given the findings and failures discussed throughout this work.

CHAPTER 7
SUMMARY

The World Trade Center disaster is the largest building collapse in the history of the United States. The disaster tested the endurance and expertise of first responders and rescue personnel throughout the entire rescue operation. For the first time, these rescuers had robot-assisted search capabilities and these tools were accepted by members of these teams. The robots were successful in searching confined space voids more safely and deeply than previously achievable. This was a large step for the field of search and rescue robotics, since the usefulness of the robots had never been directly validated in this respect. The success of the overall robot-assisted operation did not come without mistakes and failures. To this end, an analysis was performed to generate findings related to why these problems occurred, and how they impacted the search process.

The purpose of this work was to take this data set and analyze it in an effort to expose all the failures. Through the process of gathering data and analysis, four contributions resulted and a narrative for historical documentation. First, a detailed account of the events provided a context under which the failures occurred. Second, a taxonomy of the failures and environment was created to provide a framework and and vernacular for the remaining analysis. Third, an analysis of the data exposed significant and catastrophic failures. These failures were related to hardware, software, and operator error. Finally, seven findings presented significant failures that detracted from the effectiveness of the robots at this response.

The taxonomy relies on a novel classification of the robots used at the World Trade Center disaster. The robots fell into four categories based on the size and weight of the platforms. These two features were chosen because they were found to be the most influential to the robot's effectiveness in the environment. The first class was *micro* robots and these units were highly effective at the World Trade Center for confined space entry. These units are small enough to be safely man-packable (able to be carried by one or more people) by one person [2] These small units use a tether to provide power and communication. The second class was the *mini* robots. These platforms are larger than the micro robots and were shown effective for building inspection and in one case, void space inspection. Additionally, these platforms can be both wireless or tethered. These robots provide the partition between man-packable, and the man-portable (requiring special equipment for movement) [2]. *Macro* robots were the next largest size. These platforms were not shown effective for search tasks at the Trade Center, but their established usefulness in medium range reconnaissance and explosive ordnance removal makes them a potential platform for future deployments requiring larger payloads. They are typically wireless and not considered safely man-packable. Finally, the *maxi* robot category is the largest group of robots cached by CRASAR for rescue operations. These units have much larger power and sensing resources than their smaller counterparts, so they are useful for carrying equipment and robot payloads. They are wireless and are man-portable.

The taxonomy also relies on a classification of the voids. This work identified seven main categories. *Void size* represents the size of the void relative to entry and volume of the search space. *Void moisture* classified the degree of wetness in the void. This variable determines the robot's traction and safety in the void space. *Void orientation* is the angle of void's traction surface. This greatly influences the robot's ability to move through the environment. *Crubbling rubble size* classifies the rock based rubble that can interfere with the robot's traction due to ground clearance problems. *Non-Crumbling rubble* describes materials that do not break into smaller components when crushed. These include paper, furniture, and rebar. *Rubble weight* describes the weight of the rubble relative to the robot.

The analysis of the failures of the robots at the disaster exposed five failures that were repetitively detracting from the search process. *Gravity assists* required the tether manager to assist the robot 0.7 times per minute on average. *Stuck assists* accounted for 2.1 assists per minute. These required the tether operator to assist in the robot's movement in the void after it could not move on its own. *Track slippage* was the amount of time that the robot's traction was ineffective, and this accounted for eleven percent of the runtime on average. The robot's camera became *occluded* eighteen percent of the time on average. Finally, the robot searched the void with its *lighting incorrect* an average of six percent of the time. All of these failure modes had not been observed or codified prior to the World Trade Center response.

In addition to the repeating failures, there were four single instance catastrophic failures that detracted from the search. First, the MicroTrac robot lodged a metal rod into its track mechanism. Second, the VGTV lost one of its tracks due to heat loosening it from the drive wheels. Third, the lights on the MicroTrac platform failed due to a design consideration. Finally, the SOLEM platform was lost due to the structure of the debris pile shielding the wireless communication link. Each of these four failures were significant since they terminated the use of the robot for that drop.

Finally, from the analysis of the failures, seven shortcomings were identified. The first finding was the existence, but lack of interoperability of *image processing* on the platforms. This would have assisted in the victim identification process [11]. *Tether management* was done manually by the tether operator on all of the deployments. No automated tether assistance existed to eliminate the need for a second person. Third, improved *wireless relay* systems were available, but not brought for the radio communication based robots [34]. This could have saved the SOLEM platform from becoming lost in the pile. Fourth, *small and polymorphic* robots were available at this disaster, but they were unable to automatically adjust their pose to optimally configure their traction [4]. A Lack of *localization and mapping* techniques was the fifth shortcoming. This feature exists, but was completely unavailable on the platforms at the disaster, and therefore provided no assistance to the operator regarding the environment's configuration [36]. *Size estimation* was the sixth, but this was not available on the VGTV platform, and as a result victim remains were not classified correctly by the operator. The seventh finding was the complete lack of *assisted navigation* on all of the robots used. This assistance in navigating through the terrain exists for structured domains, but has not been applied to search and rescue.

This detailed failure analysis has been created to provide insight and structure to research and engineering professionals pursuing research in robot-assisted search and rescue. In addition it is hoped that the taxonomy can help to develop and formalize observations and procedures that will improve future emergency responses.

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