DISASTER ROBOTICS

ROBIN R. MURPHY

Disaster Robotics

Intelligent Robotics and Autonomous Agents
Edited by Ronald C. Arkin

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To Kevin, Kate, and Allan

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Preface

The purpose of this book is to provide a comprehensive resource for researchers, practitioners, and the public on the use of robots for any type of disaster. The recent series of earthquakes, tsunamis, oil spills, and mine disasters has heightened the awareness of the value of robots for response and recovery as well as for prevention and preparedness. The book is intended to serve as an *introduction* for researchers and technologists who need to understand the domain and the state of the art to apply their research and development expertise to this emerging field; as a *reference manual* for agencies and emergency managers on the state of the practice; and as a *textbook* for students in field robotics and human–robot interaction. The book also acts as a *history* of disaster robotics for the public and science writers seeking to place current technologies in context with past innovations or deployments and to project future uses and challenges.

Motivation

The motivation for writing this book stems from my engagement with disaster robotics, now approaching 20 years. My primary goal is to pull together the objective data and published findings about disaster robotics from all sources in more detail than captured in the chapter on search and rescue robotics that I co-wrote with many colleagues for the *Handbook of Robotics*. My secondary goal is to share my "up close and personal" experiences from the field. As a field researcher, I have adopted many methods from anthropology and cognitive science, especially the technique of reporting case studies. Though my experiences do not support statistical inference, the case studies offer a narrative on the complex sociotechnical ecology within which robots must function. I also hope that the case studies impart at least some of the sense of excitement and discovery that has made my career so rewarding.

My involvement in disaster robotics started in 1995, when my research shifted from artificial intelligence for mobile robots in general to artificial intelligence specifically for disaster robots. The shift came in the aftermath of the twin disasters of that year: the bombing of the Alfred P. Murrah Federal Building in Oklahoma City in the United States and the Kobe earthquake in Japan. One of my graduate students at the Colorado School of Mines, John Blitch, then a U.S. Army major with search and rescue training, participated in the response at the Oklahoma City bombing. His experiences motivated his master's thesis that combined artificial intelligence and operations research to analyze the utility of rescue robots, and they were also responsible for my conversion to disaster robots.

My disaster robotics research shifted from the laboratory to the field in 1999 after my move to the University of South Florida. At the University of South Florida, my group began working with the Hillsborough County Fire Rescue Department and Florida Task Force 3. Under the tutelage of Chief Ron Rogers, we had to discard most of our laboratory-based research in artificial intelligence and marsupial platform designs where a mother robot would carry and deposit a daughter robot. The research was not addressing the needs or the realities of fire rescue operations. I drew on my fond memories of an anthropology course that I took as an undergraduate and started conducting ethnographies during exercises, creating the foundation for my work in human–robot interaction. We began routinely participating in exercises and even taking response classes to learn more about the realities of disaster response. The fieldwork changed not only our research but also the type of equipment we purchased with grants, how we packed and stored the gear for ease of transportation to field exercises, the tools and spare parts we brought along, and the data we learned to collect.

The shift from field research to actual deployments started in 2001. On September 11, 2001, my group joined the Center for Robot-Assisted Search and Rescue (CRASAR) for the response to the collapse of the World Trade Center, the first reported use of rescue robots. CRASAR had been formed 2 weeks earlier by John Blitch. He was in the process of stepping down as the manager of the Defense Advanced Research Projects Agency (DARPA) Tactical Mobile Robots program, which created the iRobot Packbot, QinetiQ Talon robots, invested in the Inuktun series of microrobots, and inspired the Dragonrunner and throwable robots. He wanted to use CRASAR to push for the use of small military robots in emergency response, which was eerily prescient. At the World Trade Center, the 2 years of fieldwork allowed my team to contribute to the response: Our small robots were the most heavily used, we set up the data collection and archiving processes, we provided tools, and we could speak the lingo.

In 2002, I became the director of CRASAR when John resigned to return to military service in Afghanistan. Under my direction, CRASAR has continued to lead the way in deploying robots, including the first deployment of unmanned surface vehicles, which was at Hurricane Wilma in 2004, and the first deployment of small unmanned vehicles at Hurricane Katrina in 2005. The CRASAR cache of tactical ground, aerial, and marine robots remains on call 24/7, and upon my move to Texas A&M University, we established the *Roboticists Without Borders* program to match robots from industry and agencies with disasters. CRASAR also trains emergency managers and responders all over the world about robots and how they can, and have, been used. Other agencies have adopted robotics, and the deployments have begun to accelerate.

Within the academic community, I have been active in establishing disaster robotics and human–robot interaction as a recognized discipline within robotics and automation, cofounding an annual scientific conference, the IEEE International Symposium on Safety, Security, and Rescue Robotics, and hosting numerous workshops and tutorials. I have continued to publish and conduct basic research in my field. These activities have exposed me to other perspectives on rescue robotics and allowed me to witness the growing interest in, and frequent questions about, disaster robotics.

Now, with more than a decade of deployments and research since the collapse of the Twin Towers of the World Trade Center, disaster robotics has matured, and the range of deployments is sufficiently broad to merit a comprehensive examination of the field. As of April 2013, I personally have the most experience with those deployments of robots (15 of 34) and in formally analyzing the performance of robots at those 15 deployments and at 8 other disasters. This gives me a unique position from which to synthesize the state of research and the state of the practice in disaster robotics.

Content and Convention

This book uses several features designed to promote learning and to stimulate further reading and discussion. Each chapter begins with a statement of objectives and ends with a summary to help the reader to find information of value. Chapters 2–5 include a section on common misperceptions about the topic for that chapter, the gaps between theory and practice, and what research directions are suggested by those gaps. Case studies are interspersed, and they illustrate particular technologies and the role of the robots in the larger emergency enterprise.

The book is divided into six chapters, as follows:

- Chapter 1 provides a broad overview of rescue robotics in the context of the larger emergency informatics enterprise, the specific missions, and the major applications of robotics by the type of disaster.
- Chapter 2 presents a summary of the 34 deployments of robots to disasters worldwide in chronological order and offers a formal analysis of how well they have performed their missions and where and why they have failed and the general trends.
- Chapters 3, 4, and 5 describe the typical disaster robot modalities: ground, aerial, and marine, respectively. Each of these chapters follows the same organization of content to enable the reader to compare and contrast the modalities. The chapters repeat and expand on the material from chapters 1 and 2, so that a reader interested only in one modality, say unmanned aerial vehicles, can go directly to the relevant chapter to find
    - the types of robots within that modality;
    - the environments they are expected to operate in, the missions and tasks, and where they have been used;
    - the selection heuristics for determining if that modality is appropriate for a disaster; and
    - the surprises, gaps, and open research questions.
- Chapter 6 describes the types of fieldwork and provides practical advice in planning and conducting fieldwork, what data to collect and how, and working with emergency professionals.

In addition, a list of acronyms and abbreviations and a glossary are found at the back of the book.

The book is written largely in third person but uses a first person point of view in two different situations. First person is used for the case studies in keeping with ethnographic reporting norms and because based on more than 20 keynote addresses and tutorials, I have found that first person storytelling encourages the reader to relate to the realities of disasters and think more closely about how to apply the principles that are distilled in this book. First person is also used to distinguish when material is from the corpus of studies that I as a scientist have contributed to or when the analysis is based on my personal experience. While this book is intended to be a distillation of the entire field and should neutrally reflect the state of the art, my biases most certainly appear, and first person alerts the reader to that possibility.

The book uses boldface and italic to help highlight material. Boldface is used for definitions and important concepts that an instructor may wish to emphasize or test over, and italic is used for emphasis.

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I have many people and organizations to thank for their help: funding agencies, the two universities I have worked at during the evolution of disaster robotics, the professional responders, team members, my students, the MIT Press, and above all, my family.

This book could not be possible without the research funded by the National Science Foundation (NSF), the Mine Safety and Health Administration (MSHA), the Defense Advanced Research Projects Agency, the Office of Naval Research (ONR), the Army Research Laboratory (ARL), Microsoft Research, the Global Center for Disaster Management and Humanitarian Assistance at the University of South Florida, and the Florida High Tech Corridor. Rita Rodriguez at NSF and Jeff Kravitz at MSHA have been especially supportive. The gifts from SAIC through Dr. Clint Kelly combined with my endowment from Raytheon and donations from SeaBotix to our Roboticists Without Borders program have helped cover the costs of deployments, exercises, and training for responders.

The University of South Florida and Texas A&M University have been wonderfully supportive. My colleagues at the University of South Florida covered my classes for fall 2001 to allow me to analyze the lessons learned from the World Trade Center and travel to promote rescue robotics. Everyone there encouraged me to “go for it,” giving me the freedom to help create a new scientific discipline. The faculty and students at Texas A&M remain an inspiration with their ideas, encouragement, and accommodation of my sudden disappearances. I am grateful to work with the Texas A&M Engineering Extension Service, learning from world leaders in all facets of public safety and using its excellent facilities such as Disaster City®.

Countless emergency response professionals have shared their insights and time, but I particularly want to thank the following individuals and groups: Ron Rogers, Hillsborough County Fire Rescue, and Florida Task Force 3 gave generously of their time and expertise, and Mike Gonzalez opened the doors to the Tampa Fire Training Academy and their experts. Bill Bracken actively involved us in structural forensics. Justin Reuter and Indiana Task Force 1 adopted CRASAR after September 11, 2001, and their technical search team manager, Sam Stover, remains an integral part of CRASAR and has organized several of our deployments. No greater love

has an Indianapolis urban search and rescue team than to give up going to the Brickyard 400 in order to host a comprehensive search and rescue exercise for 20 scientists for our first Summer Institute. Jim Bastan with New Jersey Task Force 1 became the first adopter of rescue robots in the United States and remains a source of great ideas. New Jersey's disaster training facilities remain my second favorite place on Earth, just second to Disaster City®. John Holgerson and Joe Sorrentino of Rescue Training Associates incorporated us into training events at major demolitions all over the country, often with a large cadre from Florida Task Forces 1 and 2 out of Miami; it is now difficult to conduct a response exercise without a shot of Cuban coffee. Geoff Williams from the United Kingdom, who remains an inspiration, and Jacques du Plessis at Rescue South Africa engaged us on an international scale. California Task Force 2 and California Task Force 1 hosted us for a rescue robotics awareness training exercise for the Los Angeles basin, followed by Los Angeles County Fire Rescue training us on their confined-space rescue techniques. The U.S. Marine Corps Chemical Biological Incident Response Force (CBIRF) continues to educate me on hazmat responses, and the 10 days I spent for their CBIRF boot camp has had a major impact on how I conceptualize the diversity of roles of robots for disaster response. Virginia Task Force 2 and Missouri Task Force 1 also have been great. The response experts at the Texas A&M Engineering Extension Service and Texas Task Force 1 have also been helpful, with Billy Parker offering insights into where and how robots could be deployed long before I moved to Texas A&M. Kem Bennett, who was the dean of engineering at Texas A&M, the founder of Texas Task Force 1, and the creator of Disaster City®, remains a role model. Clint Arnett is our go-to guy and has organized countless exercises, Summer Institutes, and experiments at Disaster City® and has deployed to Cologne, Germany, with me—how it all works is a mystery but a fun one. Bob McKee co-hosted several Summer Institutes at Disaster City® with me and served as a co-principal investigator on an NSF grant, and David Martin, Susan Brown, and Matt Minson have been highly supportive.

This book also benefits from the experiences of everyone who has participated in deployments, but Sam Stover and Eric Steimle deserve special thanks. They help me organize resources and responses, and they volunteer their time and talents in keeping up with the best systems that are emerging from industry and in promoting rescue robotics. I would like to thank all the people I've deployed with: Fred Alibozek, Mike Bruch, John Blitch, Jennifer Casper, Mike Ciholas, Bart Everett, Tom Frost, Jay Haglund, Robin Laird, Arnie Mangolds, Mark Micire, Brian Minten, Grinnell Moore, Gary Mouru, Chris Norman, Scott Pratt, Andy Shein, Chris Smith, (World Trade Center), Sam Stover (La Conchita mudslides), Mark Micire, Sam Stover (Hurricane Charley), John Dugan, Chandler Griffin, Mike Lotre (Hurricane Katrina), Chandler Griffin, Kevin Pratt, Sam Stover (post–Hurricane Katrina), Charlie Cullins, Chandler Griffin, Mark Hall, Kevin Pratt, Eric Steimle (Hurricane Wilma), Ron Gust, Jennifer McMullen, Sam Stover (Midas Gold Mine collapse), Jeff Kravitz, James Milward, Ken K. Peligren, Jeff Stanway (Crandall Canyon Mine collapse), Bill Bracken, Jenny Burke, Jeff Craighead, Chandler Griiffin, Noah Kuntz, Kevin Pratt, Toshihiko Nishimura, Sam Stover, Osachika Tanimoto, (Berkman Plaza II collapse), Stefan Hurlebaus, Michael Lindemuth, Daniel Mays, Zenon Medina-Cetina, Eric Steimle, David Trejo (Hurricane Ike), Clint Arnett, Sebastian Blumenthal, Thomas Christaller, Thorsten Linder, Peter Molitor, Hartmut Surmann, Satoshi Tadokoro (Cologne Historical Archives collapse), Daniel Nardi (L'Aquila earthquake), Karen L. Dreger, Michinori Hatayama, Osamu Kawase, Tetsuya Kimura, Kazuyuki Kon, Kenichi Makabe, Fumitoshi Matsuno, Hisashi Mizumoto, Sean Newsome, Jesse Rodocker, Brian Slaughter, Richard Smith, Satoshi Tadokoro (Tohoku tsunami), and Lindsey Ballard, Scott Bump, Jeff Lumpkin, and Bradley Welch (Fukushima Daiichi).

I want to thank my students and postdoctoral students for continuing to teach me as much as I teach them and for the great times we have exploring new ideas and insights. John Blitch, Jenny Burke, Jennifer Casper, Jeff Craighead, Mark Micire, Brian Minten, and Kevin Pratt have been extraordinary in the gifts of their time and hearts to the humanitarian use of robots and have deployed to disasters. Cindy Bethel, Brian Day, Brittany Duncan, Jennifer Carlson, Thomas Fincannon, Rachel Flores-Meath, Aaron Gage, Marco Garzo, Zack Henkel, Jeff Hyams, Elliot Kim, Mike Lindemuth, Matt Long, Josh Peschel, Tanner Perkins, Brandon Shrewsbury, Vasant Srinivasan, Jesus Suarez, and Rosemarie Yagoda have spent countless hours at exercises and in the field and helping to support teams at deployments. Marco Garza, Edgardo Calzado, and Tanner Perkins have served as student laboratory managers with the hidden but essential task of keeping CRASAR ready to go at a 4-hour notice.

Marie Lee, Ada Brunstein, and Bob Prior at the MIT Press have guided the publishing of this book and the anonymous reviewers provided excellent feedback. Christopher Curioli, who copy edited this volume for the MIT Press, was outstanding; he helped the book maintain a consistent pedagogical focus and counteracted my tendency to overuse italics for emphasis which had created a reading experience suitable for delivery by William

Shatner, where everything (pause) is (pause) important. I especially want to thank Brittany Duncan, Rachel Flores-Meath, Zachary Henkel, Elliot Kim, Tanner Perkins, Vasant Srinivasan, Brandon Shrewsbury, and Jesus Suarez for their critiques of early drafts and numerous contributions to the overall organization and figures.

I could not have written this book or conducted the work upon which it is based without the support of my family. After the deployment to the September 11 disaster, it was clear that there needed to be an active advocate of rescue robotics for adoption and for researchers and industry to recognize the special demands of emergency response. The other CRASAR participants were being re-absorbed into their day jobs, so either I was going to have to step up and be the advocate or no one would. However, that would entail a huge cost in time and travel; indeed I gave more than 50 talks on rescue robotics to agencies and at conferences in the first year alone. My husband, Kevin, our two children, Kate and Allan, and I made the decision together, and they have been totally supportive during my long hours away from them. I could not do any of this without Kevin.

Any errors herein are solely mine, and I fervently hope they are minor and do not distract or mislead anyone in the quest to make and use robots to assist in disaster prevention, preparedness, response, and recovery.

1 Introduction

Rescue robotics is devoted to enabling responders and other stakeholders *to sense and act at a distance from the site of a disaster or extreme incident*. Although the high public profile of search and rescue robots counters the weaponized-drone portrayals of robots, rescue robotics is a relatively small discipline within corporate and academic circles. However, as will be discussed later, the impact of earthquakes, hurricanes, flooding, and accidents is increasing, so the need for robots for all phases of a disaster, from **prevention** and **preparation** to **response** and **recovery**, will increase as well. This broader consideration of robots for all phases of a disaster and for disaster science in general is referred to as **disaster robotics**, though the terms *search and rescue robot*, *rescue robot*, and *disaster robot* will be used interchangeably. As robots evolve to handle extreme events, they will hopefully find their way from the military to local fire rescue departments and other stakeholders for use in "regular" emergencies.

This chapter addresses five basic questions to provide background for the material that will be covered by this book:

- *What is a rescue robot?* This is a broad question with a set of related questions to be addressed: What makes rescue robots different from "regular" mobile robots? Aren't military robots sufficient? How did rescue robotics get started?
- *Why rescue robotics?* While robots (or any mechanism to save lives and reduce suffering) have an emotional appeal, is there really an economic justification for rescue robots or are incidents too rare to justify the expense? Can't animals or insects be used; after all, they are much more mobile than any robot?
- *Who uses rescue robots?* This is a question about the nature of who is involved in disasters: Are robots used and owned by federal or state

authorities? Local authorities? Volunteer organizations? Can or do companies and private citizens use robots?

- *When can rescue robots be used?* This is another question about the nature of responses: Are robots just for use after a disaster or are they (or can they be) used before?
- *What are rescue robots used for?* The popular expectation is that robots are used for immediate lifesaving operations such as searching for survivors, but what are the other critical tasks that robots can help with?

This chapter begins with a brief history of the origins and development of the field, then proceeds to describe what a rescue robot is compared with other kinds of robots. Rescue robots are tactical, organic, unmanned systems that allow emergency professionals to perceive and act at a distance in real time, also known as having a remote presence at the disaster site. The chapter then describes why robots—and the remote presence they provide—are needed to assist in saving lives, reducing long-term health consequences, and accelerating economic and environmental recovery. Surprisingly few formal response organizations own rescue robots, which explains the average lag time of 6.5 days for a robot to be used at a disaster. The chapter then turns to an emergency management perspective on robotics, describing the phases of a disaster and then the types of disasters and associated missions.

1.1 Brief History

The general consensus is that the use of robots from the Defense Advanced Research Projects Agency (DARPA) Tactical Mobile Robots program by the newly established Center for Robot-Assisted Search and Rescue (CRASAR) at the World Trade Center disaster in New York in 2001 represents the first known use of rescue robots. Yet, speculation as to the utility of robots for search and rescue, firefighting, and other emergency missions began in the 1980s (Kobayashi and Nakamura, 1983). Academic research into rescue robotics started in 1995 (Davids, 2002), most notably led by two research groups. Prof. Satoshi Takokoro's group, then at Kobe University in Japan, was motivated by the tragic loss of life in the Hanshin-Awajii earthquake in Kobe, Japan, in 1995; his group became the foundation for the International Rescue System Institute (IRS). My laboratory, then at the Colorado School of Mines in the United States, was motivated by the 1995 bombing of the Alfred P. Murrah Federal Building in Oklahoma City, Oklahoma. Two mobile robot competitions, the Association for the Advancement of Artificial Intelligence (AAAI) Mobile Robot Competition in the United States and the RoboCup Rescue League internationally, were started shortly thereafter to engage the scientific community in rescue research. The RoboCup Rescue League continues, with its focus shifting from enabling research to providing students with a socially relevant set of tasks within which to build robots and explore artificial intelligence principles.

The site of the 2001 collapse of the World Trade Center buildings, however, was not the first site where robots were used at a disaster. Dr. Red Whitaker at Carnegie Mellon University constructed robots to enter and explore the Three Mile Island nuclear facility several months after the 1979 incident and also constructed robots for the 1986 Chernobyl disaster. These robots were thickly armored to protect against radiation, which made them heavy, large, and fairly slow. Fortunately, both nuclear disaster areas were **human scale** (i.e., a site large enough and still intact enough that a human outfitted in protective gear may walk through the site), and thus robot size was not an issue. Likewise, robot speed was not critical, as the robots were being used for postdisaster mitigation and not for time-critical lifesaving or injury stabilization. The robots required multiple operators for teleoperation. The success of these robots set the precedent for nuclear robots as radiation-hardened, large, heavy, and teleoperated systems. These designs began to migrate to the bomb squad community, where the heavy shielding protected the expensive robot from explosions, and speed was not a factor.

The tipping point in the evolution of current rescue robots came at the Oklahoma City bombing in 1995, where numerous bomb squad robots sat idle (Manzi, Powers, and Zetterlund, 2002), too big to navigate the narrow voids and too heavy to use without fear of causing a secondary collapse that might kill trapped survivors or rescue workers working in layers below the surface. The large, ponderous robots created for nuclear disasters and bomb squads eventually generated a backlash in the mobile robot community, which led to newer ground robots, including rescue robots, being conceived as small, agile, and autonomous with a small degree of supervision by a single human. The advances in robotics and artificial intelligence in the 1990s—especially the smaller platforms being developed for the NASA Mars missions and reactive behavioral software architectures—supported the moral imperative for roboticists to contribute to this societal need.

Advances in usable rescue robots have been partially enabled by investment by the U.S. military, especially through DARPA. The DARPA Tactical Mobile Robots (TMR) program under the program management of Lt. Col. John Blitch was highly influential in creating smaller robots that could be carried in backpacks and operated by one or two soldiers. The iRobot Packbot and QinetiQ mini-Talon are perhaps the best-known outcomes of this program. While the intended application was military operations in urban terrain, the potential for dual use of TMR robots with rescue operations was also a consideration (Krotkov and Blitch, 1999; Blitch, Murphy, and Durkin, 2002), leading Lieutenant Colonel Blitch to found CRASAR shortly before the September 11 attack on the World Trade Center. Developments in small unmanned aerial systems for Special Operations forces led to their use in the aftermath of Hurricane Katrina, and the National Guards of several states on the U.S. Gulf Coast use the larger Predator unmanned aerial vehicles for surveying large areas before and after a hurricane. With the use of small, agile (but not radiologically hardened) ground robots such as the iRobot Packbot and QinetiQ Talon and aerial vehicles such as the Honeywell T-Hawk during the Fukushima Daiichi nuclear emergency, rescue robots have returned to their nuclear origins.

However, commercially available ground and marine robots designed for civilian uses also have a dual use for disasters. One frequently used type of ground robot at disasters is the pipeline inspection robot, such as the Inuktun Micro-Tracks and Micro-VGTV series; these robots are typically much smaller than military systems and can penetrate into voids that people, dogs, and robots designed to dispose of improvised explosive devices cannot enter. The other frequently used ground robot is the U.S. Mine Safety and Health Administration's mine-permissible variant of a Remotec civilian bomb squad robot. Unmanned marine vehicle technology stems primarily from oceanographic research and the underwater inspection business.

1.2 What Is a Rescue Robot?

Rescue robots are **mobile robots**, or robots built to sense and act in an environment; in artificial intelligence terms, this type of robot is often called a **physically situated agent**. Mobile robots are distinct from factory robots and industrial manipulators that perform repetitive tasks. By moving about in the often unpredictable world, these robots have to be more aware of the environment, not just for navigation but also to make sure that they aren't causing secondary collapses, dislodging debris, or disturbing forensic evidence.

Rescue robots are a category of mobile robots that are generally small enough and portable enough to be transported, used, and operated on demand by the group needing the information; such a robot is called a tactical, organic system, compared to a strategic asset such as a Predator or a Global Hawk. A rescue robot may be designed differently than a military unmanned system because of the need to meet three design constraints:

1. *extreme terrains and operating conditions* that affect size, sensor performance, and pose general robot survivability constraints;
2. *ability to function in GPS- and wireless-denied environments*; and
3. provision of *appropriate human–robot interaction* for operators "behind the robot" and for victims "in front."

The history of rescue robots illustrates some of the interplay between robots developed for defense and space applications and rescue robotics.

1.2.1 It Is a Tactical, Organic, Unmanned System

Mobile robots are often referred to as **unmanned systems** to distinguish them from robots used for factory automation. Unmanned systems have three different **modalities** based on where they operate. If they operate

- *on the ground*, they are called **unmanned ground vehicles** (UGVs);
- *in the water*, they fall in the general category of **unmanned marine vehicles** (UMVs);
- *in the air*, they may be called by various names including **unmanned aerial vehicles** (UAVs), **unmanned aerial systems** (UASs), **remotely piloted aircraft** (RPA), or **remotely piloted vehicles** (RPVs).

The three different modalities of robots have been developed by independent communities, leading to somewhat contradictory marine and aerial terminologies and taxonomies. UMVs may operate on the surface of water, underwater, or, more rarely, in both environments. UMVs restricted to the water surface are often called **unmanned surface vehicles** (USVs). UMVs working underwater may be referred to as **unmanned underwater vehicles** (UUVs). UUVs fall into two main categories: tethered **remotely operated vehicles** (ROVs) and untethered, free-swimming vehicles called **autonomous underwater vehicles** (AUVs). The letters in AUV are sometimes rearranged to UAV for "underwater autonomous vehicle," leading to confusion with "unmanned aerial vehicle." Unmanned aerial vehicles are sometimes called UASs (to emphasize the sociotechnical system aspects) or RPVs (to emphasize that there still is a human in the loop). Regardless of nomenclature, UAVs fall into two categories: fixed wing (e.g., looks and acts like a plane or jet) and vertical takeoff and landing (VTOL; e.g., looks and acts like a helicopter).

Regardless of robot modality, this book restricts rescue robots to unmanned systems used as *tactical, organic assets* (figure 1.1). **Tactical** means the robot is directly controlled by stakeholders with "boots on the ground"—people who need to make fairly rapid decisions about the event. **Organic** means that the robot is deployed, maintained, transported, and tasked and directed by the stakeholder, though, of course, the information can be shared with other stakeholders, and via networks the stakeholders may be far removed from the site of operation. A **tactical, organic asset** travels with the stakeholder and thus is immediately available and used on demand (and also tends to be smaller and more portable). This is in contrast to a **strategic asset**, such as a satellite, a military or Coast Guard helicopter, or a high-altitude drone, which is deployed and tasked by an agency that then passes or filters information to the tactical teams as it becomes available. There are exceptions to every rule, and it is possible to have a strategic unmanned system used tactically: NASA's Ikhana high-altitude Global Hawk was directed in real time by the California wildfire incident commander on the ground at the 2006 California wildfires (Ambrosia et al., 2010). But, in general, Ikhana is not considered a rescue robot.

1.2.2 It Satisfies Three Design Constraints

Disaster robotics is similar to robotics for military applications and historically has leveraged defense and civilian inspection robots, but it is the need to satisfy three constraints simultaneously that makes disaster robots different from robots designed for other applications. Rescue robots must be small enough and environmentally hardened to function in extreme terrains and operating conditions, able to work in environments where GPS and wireless signals are blocked, and must interact with victims and other responders "in front" of the robot as well as with the operator and stakeholders "behind" the robot.

Disasters present **extreme terrains and operating conditions** that affect *size, sensor performance, and general robot survivability* (figure 1.2). As will be described in later chapters, UGVs must function in openings as small as 3 centimeters (e.g., Berkman Plaza II collapse) and must move horizontally and vertically through irregular voids and uneven mixtures of corrosive building materials and textured furnishings. UGVs are often exposed to large amounts of groundwater (e.g., Crandall Canyon Mine and Pike River Mine). The robots may have to navigate through mud or drilling foam, which fouls sensors (e.g., Crandall Canyon Mine) and interferes with effectors (e.g., La Conchita mudslides). UGVs may have to operate in extreme heat (e.g., World Trade Center) or explosive atmospheres (e.g., Sago Mine and Pike River Mine). UMVs may have to function in currents, avoid flotsam and debris, avoid complications from tides and flood crests, and peer through turbid waters. UAVs may have to overcome unpredictable buffeting and wind shears near urban structures. Any of these types of vehicles may need to function in smoke (e.g., World Trade Center) or be shielded to function while exposed to radiation (e.g., Fukushima Daiichi).

Figure 1.1
Typical rescue robots are small and easily portable: (top left) Inuktun VGTV Xtreme ground robot (Berkman Plaza II collapse); (top right) iSENSYS miniature helicopter (Hurricane Katrina); (bottom) YSI Echomapper and SeaBotix SARbot marine vehicles (Tohoku tsunami).

Rescue robots typically function in **GPS- and wireless-denied environments**. The material density of commercial buildings interferes with GPS and wireless networks for robots working in the interiors of commercial buildings. However, interference is not limited to interiors; urban structures such as buildings or bridges can create shadows or multiple paths that affect approaching UAVs and UMVs. Inertial navigation sensors are often large,

Figure 1.2
Example of the extreme terrain that a robot is expected to enter and travel *through*, not over (Historical Archive of Cologne building collapse).

expensive, and susceptible to sudden movements (such as the bump as a robot slides over a rock). Wireless communications can be boosted with more power, but that leads to a trade-off between making the robot larger to carry the power and it becoming too large to be of use.

Rescue robots also present **extreme human–robot interaction** challenges for operators and for victims. Stakeholders in the safe **warm** or **cold zones** use rescue robots to help them see and act in the **hot zone**, the restricted area of impact. This means the robots mediate between the operator and the distal environment. Mediation introduces cognitive challenges, such as trying to see and understand the world through the robot's "keyhole" view into the situation; this can lead to poor performance and errors. Teleoperation assumes the operator can overcome these cognitive challenges, though usually with the help of well-designed user interfaces. Artificial intelligence has focused on making the robot completely autonomous, though a middle ground of adding intelligence assistance seems more productive. NASA pioneered the field of teleoperation, which investigates remote presence primarily in terms of mitigation of time delays in transmission of data over long distances. In rescue robotics, the conditions for remote presence are more demanding than those for NASA space operations because missions do not have days or months of preplanning, the world may dynamically change due to a secondary collapse or a levee break, and the amount of training and rehearsal is much less. However, human–robot interaction challenges are not limited to operators interfacing with the robots; victims will also interact with rescue robots. A comprehensive study demonstrated that if robots operate without considering a victim's personal space, the simulated victim's biophysical measurements show increased stress and discomfort (Bethel and Murphy, 2010).

1.3 Why Rescue Robotics?

Disaster robots help stakeholders prevent, prepare for, respond to, and recover from the increasing number and complexity of urban disasters and extreme events by providing stakeholders with the ability to access an area of interest. If a disaster has occurred, it may be physically impossible, too dangerous, or too inefficient for a responder to enter the hot zone. Robots do not replace people or dogs but rather complement human and canine abilities and mitigate their risk. Disasters have a significant impact on lives, quality of life, the economy, and the environment, and if they cannot be prevented, rapid response means less loss of life and long-term injuries and faster economic and environmental recovery.

1.3.1 The Impact of Urban Disasters and Extreme Incidents Is Increasing

The U.S. Federal Emergency Management Agency (FEMA) *Guide to Emergency Management and Related Terms, Definitions, Concepts, Acronyms, Organizations, Programs, Guidance, Executive Orders & Legislation* gives multiple definitions of the term *disaster*; this book will use "An event that requires resources beyond the capability of a community and requires a multiple agency response" as the definition of **disaster** (Blanchard, 2007). Unlike a disaster, an **extreme incident** is handled internally within a fire rescue department, usually by a team with specialized training. As a result, extraction of workers trapped in a cave-in at a construction site may be addressed by the urban search and rescue (US&R) specialists in the local fire rescue department, while the collapse of a major building complex such as the World Trade Center in 2001 may require the aggregation of US&R specialists from all over the United States, as well as additional expertise.

Of all the types of disasters, events in urban settings are the most significant in terms of deaths and economic impact. The most recent *World Disasters Report* (McClean, 2010) prepared by the International Federation of Red Cross and Red Crescent Societies reports that between 2000 and 2009, 1,105,353 people were killed worldwide in 7,184 disasters with another 2,550,272 more directly affected, creating a cost of $986.7 billion. The number of disasters each year remained relatively constant, around

700. However, the impact of the disasters was a function of whether or not the event occurred in an urban area. The *World Disasters Report* argues that deaths and effects of disasters will dramatically increase, citing the increasing numbers of people living in concentrated urban environments, as well as the consequences of damage to urban structures where people live and work (e.g., office and apartment buildings) and to structures serving to mitigate a disaster (e.g., hospitals, transportation, and other critical infrastructure).

The statistics from the 1985 Mexico City earthquake and subsequent urban disasters (United States Fire Administration, 1996; National Fire Protection Association, 1999) established the conventional wisdom that *only a small fraction of trapped victims actually survive an urban incident*. Eighty percent of survivors of urban disasters are **surface victims**; that is, the people lying on the surface of the rubble or readily visible to a rescuer. Only 20% of survivors of urban disasters come from the interior of the rubble, yet the interior is often where the majority of victims are located. Those victims may be in (relatively) good health and **entombed** or **trapped** beneath rubble with urgent medical needs. Worse yet, the mortality rate increases and peaks after 48 hours, meaning that survivors who are not extricated in the first 48 hours after the event are unlikely to survive beyond a few weeks in the hospital. Others will be crippled or have persistent health issues. These statistics suggest that robots that can penetrate into the interior of rubble to speed search, rescue, and intervention would have a significant impact.

But the value of robots for economic and environmental recovery should not be ignored. For example, our use of ROVs at Minamisanriku in Japan 6 months after the Tohoku tsunami to assist in clearing Shizugawa Bay of debris had no lifesaving value. But consider that Minamisanriku is the second largest fishing area in Miyagi, a prefecture famous for its fishing industry and pure waters. The Shizugawa Fishing Cooperative was eager to remove submerged cars and the more than 800 fishing boats (about 85% of the fleet) known to be missing (Leitsinger, 2011) that might be leaking fuel and contaminating the water; to remove rubble that might snag nets; and to reopen navigation beyond a few major channels. The loss of fishing affected the availability and price of food for everyone in Japan, but it also affected the local community: fishermen who routinely made $86,000 to $124,000 a year were reduced to making $100 to $150 a day collecting wreckage (Leitsinger, 2011) until fishing was restored.

1.3.2 Robots Provide a Remote Presence at the Disaster

Stakeholders need the ability to “sense and act at a distance,” which can be more formally stated as they want to have a **remote presence** in the incident area (Murphy and Burke, 2008). Each disaster is different and cannot be accurately modeled. Thus, a robot can enable a stakeholder to see, in real time, deep into the interior of a collapsed building where there is no physical entry large enough for a human or dog or where the area is unsafe or does not support life (e.g., on fire, engulfed in hazardous materials or radiation). Robots can penetrate further than the 3 to 4 meters a camera on a wand can extend into densely packed debris. They can interact with the environment to mitigate a disaster; for instance, the use of robots to insert a containment cap at the 2010 Deepwater Horizon explosion (Newman, 2010) or to turn valves at the 2011 Fukushima Daiichi nuclear incident (Strickland, 2011).

1.3.3 Rescue Robots Work Where People and Animals Cannot

Rescue robots serve as smart tools that complement, not replace, people and animals. Robots can stay on task indefinitely (depending on power source) and do not tire. They can go into places and do combinations of things or host sensors that animals cannot. Robots can be turned off and stored indefinitely, unlike animals. Robots do not require special handling in the way that a swarm of wasps for smelling bodies (Science Daily, 2006) might, as they do not require food to be brought with them or create biowaste to be disposed of. Most importantly, they are not alive. Immediately after the World Trade Center disaster, rats with camera implants were posed as an alternative to expensive microrobots for navigating through densely packed rubble. But as noted in Murphy (2002), these “robo-rats” could not have survived the high temperatures from the smoldering fires in the interior of the World Trade Center rubble that the robots worked in. (Not to mention terrorizing trapped survivors, which was the subject of a segment of the *Daily Show* with Jon Stewart.)

Likewise in some missions, such as a chemical or nuclear emergency, the robot is expected to do tasks a person could normally do (e.g., turning a valve) and in environments that a person could normally work in. But the robot is not replacing a responder, because the responder could not have lived long enough, even with protective gear, to accomplish the task or would have died shortly afterward from the effects. *To be clear, responders expect to continue to risk their lives to save others; robots don’t replace their rapid actions or sacrifices but rather eliminate unnecessary risks.*

1.4 Who Uses Rescue Robots?

Rescue robots are or can be used by a wide variety of agencies, nongovernmental organizations (NGOs), and even industries and companies. The definition of rescue robotics points to "responders and other stakeholders" as the end users of rescue robotics, not robot operators. Emergency management is best described as a **polycentric** enterprise, where there are multiple ("poly") places or organizations ("centers") that integrate or share information and that can bring expertise or capability to the situation (Andersson and Ostrom, 2008). Regardless of the incident command hierarchy specified in documents such as the U.S. National Response Framework, emergencies always include some *surprising and unique demands*, because multiple organizations become involved in a response *each with a different mix of response expertise and capabilities* and because the time course of response and recovery brings a *changing mix of different organizations* together. To see one example of how even a straightforward incident is polycentric, consider the 2010 Deepwater Horizon explosion and oil leak. While BP retained authority for the disaster and the U.S. Coast Guard provided important expertise, there was nothing in prior planning that factored in the role of local fishing and tourism industry organizations as stakeholders. Robots are a means, not an end, to enabling each group to get the data they need to make effective decisions.

Only two agencies in the United States own rescue robots. New Jersey Task Force 1, a state team, not a FEMA team, is the only US&R team in the United States known directly to own and maintain a rescue robot. Federal US&R teams are not allowed to purchase rescue robots because they have not been approved. The U.S. Department of Homeland Security, which FEMA is part of, has been sponsoring the creation of standard test methods that would verify that a robot model meets the minimum qualifications for a rescue robot. No Japanese agency owns a robot, though British fire rescue departments have been actively acquiring all modalities of rescue robots. The U.S. Mine Safety and Health Administration (MSHA) owns the only robot in the world certified to work in explosive atmospheres.

While robots have become ubiquitous in U.S. military operations, they are still quite new to disaster response. This explains in part the average lag time of 6.5 days between a disaster and when a robot of any modality is used: If the incident command institution had a robot or an existing partnership with a group that had robots, there was an average lag time of 0.5 day before the robot was used, whereas if not, the average lag time went up to 7.5 days. The socio-organizational culture of response and adoption constraints will be discussed in chapter 6.

1.5 When Can Rescue Robots Be Used?

The short answer to "when can rescue robots be used?" is anytime, though researchers have focused on development of systems primarily for the immediate response phase rather than for before the event occurs or for mitigation and recovery. A related question is *when have they been used?* The short answer to that is late in the response or recovery. Robots are deployed on average 6.5 days after the event, reducing their immediate value for lifesaving and reconnaissance, but they are still useful for other missions. Chapter 6 will discuss more about the socio-organizational aspects of a disaster that lead to these delays.

Since the 1970s, the **disaster life cycle** has been thought of as having **four phases**: *prevention, preparation, response*, and *recovery* (Blanchard, 2007). Each phase conjures up expectations of different agencies; for example, the U.S. Forest Service created Smokey the Bear to encourage prevention of forest fires; response is associated with urban search and rescue and National Guard teams; and recovery is associated with insurance inspectors and business recovery loans. In reality, these entities are involved throughout the entire disaster life cycle.

These phases are not independent and sequential so that several stakeholders may each have robots or the data from a robot deployed by one agency may be of immediate use to another agency. Response and recovery operations start instantaneously, though the more visible and emotionally compelling lifesaving mission of rescuers often dominates media reports. Response operations rarely last beyond 10 days, though local officials may be reluctant to declare the response phase over. Initial recovery operations can go on for months and are generally marked by when roads, schools, and hospitals are reopened. Economic recovery often takes years beyond that.

With response and recovery occurring simultaneously, a single robot can provide information to many “consumers.” An unpublished study by the author and colleagues at Ohio State University on the role of robots for structural inspection identified that urban structures are likely to be manually inspected at least four times by different stakeholders from the response and recovery groups: search and rescue teams to determine safe entry for search, the American Red Cross to estimate how long a region will need assistance, insurance adjusters, and building inspectors.

Rescue robots are typically deployed fairly late, toward the middle of the response phase or later. My analysis of robot deployments worldwide in 2010 (Murphy, 2011b) showed that the average time between an incident and the actual use of a robot was 6.5 days. If the analysis considers only the five deployments where the mission was clearly to search for survivors (e.g., Upper Big Branch Mine; Wangjialing Coal Mine; Haiti earthquake; Prospect Towers; Pike River Mine), then the average was 4.2 days for a robot to arrive, well after the 48-hour peak in the mortality curve—too late to be of value. The biggest predictor of whether a robot would be deployed and how quickly was whether the agency in charge had a robot or a partner with robots. In four of the 2010 deployments, the agency or industry that held incident command responsibility either already used the robots in day-to-day operations (BP at Deepwater Horizon; Italian Coast Guard for a missing balloonist) or prior lines of authority were already in place [MSHA for Upper Big Branch Mine; New Jersey's regional Urban Area Security Initiative (UASI) teams at Prospect Towers]. In those four cases, robots arrived on the scene and were put to use in one-half day on average.

1.6 What Are Rescue Robots Used For?

The previous sections have provided a sense of what robots are and the phases of a disaster, which sets a foundation for understanding the specific missions that rescue robots can be used for. This section first describes the types of disasters followed by 13 proposed missions for rescue robots.

1.6.1 Types of Disasters

There is no comprehensive list of the types of disasters and incidents, perhaps because new events continually emerge. The Federal Emergency Management Agency (FEMA, 2013) offers examples of disasters that are traditionally managed by the fire rescue community, and the list continues to grow. Many are "natural disasters" stemming from **meteorological and geological events** such as *avalanches, earthquakes, floods, fires, heat waves, hurricanes, landslides, thunderstorms, tornadoes, tsunamis, volcanoes, wildfires*, and *winter storms*. Others are **accidents** or **terrorism involving man-made facilities** such as *building, bridge, or tunnel collapses, chemical emergencies, dam failures, hazardous materials, nuclear power plants*, and *train wrecks*. High-profile incidents include *wilderness search and rescue*, where a person(s) may be lost in the woods or trapped in a cave, and *swift-water rescue*. A commonplace urban incident is a *trench collapse*, when construction excavation collapses on workers. In general, management of events involving man-made facilities, with the exception of nuclear power plant emergencies, are collectively referred to as urban search and rescue.

In the United States, **mining- and mineral-related disasters**, either geological events or accidents, are managed by the owner, not the government. For example, the MSHA does not manage a mine collapse the way that a fire department assumes control of a fire, but the agency is present to provide support. While in theory MSHA or the Coast Guard could assume incident command or be appointed to do so, this is not the case for federal and state agencies. The tradition of assisting rather than assuming command most likely originated from the unique expertise associated with a mining or drilling incident: the companies were more likely to be knowledgeable on how to respond effectively. However, this has led to the notable opacity in recent private mining, drilling, and nuclear responses. There is a potential conflict of interest of a company to minimize response expenditures or to hide potential evidence that could be used against the company in lawsuits, which could retard adoption of rescue robots.

1.6.2 Missions

The entire set of tasks for rescue robotics is incomplete, as the field is new and evolving. It is hard to project all the tasks for a robot, as they do things that humans and animals cannot; instead, imagination and opportunity drive creation of novel uses. This makes most of rescue robotics a **formative work domain** (Vicente, 1999) as opposed to a **normative work domain**, in which robots perform existing tasks (though some missions such as hazardous material response has tasks currently performed by responders that could be done by robots). The *Handbook of Robotics* identifies 10 tasks for rescue robots for the rescue phase (Murphy et al., 2008b), while deployments to recent disasters such as the Tohoku earthquake and tsunami and the Fukushima Daiichi nuclear emergency suggest that robots designed for rescue can support a rich set of tasks for mitigation and recovery as well.

Robots have been used or proposed for the 13 activities in the list that follows, and more activities are expected to emerge as robots are put into use. Training manuals often describe response tasks as being executed serially where one activity follows another (e.g., search then extrication), but emergency workers multitask, performing activities concurrently (e.g., mapping and structural inspection while searching) (Casper and Murphy, 2002). As a result, robots will be expected to be reconfigurable and reused for serial tasks and be able to perform several of the tasks below in parallel.

Search is a concentrated activity in the interior of a structure, in caves or tunnels, or in the wilderness and aims at finding a victim to extricate and any potential hazards. The objective for using robots for the search task is to perform a search where people or existing tools cannot be used, to perform the search faster, and to ensure completeness without increasing risk to victims or rescuers.

Reconnaissance and mapping provides responders with general situation awareness and an understanding of the destroyed environment. The objective is speedy coverage of an area of interest at the appropriate resolution.

In meteorological and geological disasters, the primary focus is on the exterior and outdoors (Where is the damage? Where are people in distress? What is the wildfire doing?), while for hazardous material or nuclear events the focus may shift to what is going on inside of the facility.

Rubble removal, either for extrication of victims or for rebuilding, can be expedited by robotic machinery or exoskeletons. The objective is to move heavier rubble faster than could be done manually, but with a smaller, lighter footprint than required by a traditional construction crane. Robots and exoskeletons may be man-sized or smaller and easier to move to the site and begin working.

Structural inspection and **forensics** are related missions that can be facilitated through robots that deliver structural sensor payloads to more favorable viewing angles. The objective is to enable an engineering understanding of critical infrastructure that affects public services such as bridges, roads, utilities, aqueducts, or shipping channels and urban structures such as buildings or manufacturing inlets and outlets. Structural inspection may be conducted either from the interior (e.g., inserting a robot into rubble to help rescuers understand the nature of the collapse) or on the exterior (e.g., to determine whether a structure is safe to enter).

In situ medical assessment and intervention are needed to permit medical personnel to triage victims and provide life support functions such as transporting and administering fluids and medication. The inability to provide medical intervention was a major problem at the Oklahoma City bombing (Barbera, DeAtley, and Macintyre, 1995). The objective is to provide telepresence for medical personnel during the 4 to 10 hours that it usually takes to extricate a victim (United States Fire Administration, 1996; National Fire Protection Association, 1999).

Medically sensitive extrication and evacuation of casualties may be needed to help provide medical assistance while victims are still in the disaster area, also known as the hot zone. The objective is to ferry survivors rapidly and safely to a collection point. In the case of a chemical, biological, or radiological event, the number of victims is expected to exceed the number that can be carried out by human rescuers in their highly restrictive protective gear; this makes robot carriers attractive. Because medical doctors may not be permitted inside the hot zone, which can extend for kilometers, robot carriers that support telemedicine may be of huge benefit.

Acting as a mobile beacon or repeater in order to extend wireless communication coverage and bandwidth and to localize personnel based on their radio signal strength. The objective is to ensure reliable communications for both robots and the response and recovery operations in general.

Serving as a surrogate for a team member such as a safety officer or a logistics person, where team members outside the hot zone use telepresence to work with team members in the hot zone to monitor the state of progress and anticipate needs. The objective is to use robots to speed up the workflow and to help notice developing events that could pose a threat to workers concentrating on their immediate tasks.

Adaptive shoring of unstable rubble to expedite the extrication process. Rubble removal is often hindered by the need to take a conservative pace in order to prevent a secondary collapse that might further injure a trapped survivor or responder. The objective is to maintain the state of the collapse without being able to map out the structure fully.

Providing logistics support by automating the transportation of equipment and supplies from storage areas to teams or distribution points within the hot zone. The objective is to reduce the number of personnel in the hot zone devoted to routine tasks.

Victim recovery support is needed after the possibility of survivors remaining has dwindled and operations turn to extricating bodies already found or finding all the missing. The objective is to search exhaustively and help extricate all remaining victims.

Estimation of debris volume and types to speed cleanup and enable residents to reenter affected areas. Meteorological and geological events distribute trees, homes, cars, and other materials throughout the hot zone. This not only blocks roads but also can cause environmental and sanitation problems, preventing residents from returning until the area is cleaned up. Removal is not a straightforward process of just bulldozing and burning the debris (consider the amount of plastics and toxic lawn chemicals in a typical suburban home); it requires separation of materials. Cleanup is usually done by commercial companies based on bids, with significant delays due to the need of companies to obtain sufficient information to make and provide accurate estimates. The objective is to locate and analyze the debris (e.g., area A has x cubic meters of vegetation and y cubic meters of light construction and household materials).

Direct intervention, such as manipulating valves or emergency devices, to mitigate the consequences of the event. Recent examples of the need for robots to manipulate the environment include robot submersibles inserting a tube and regulators into the damaged drill pipes at the 2010 Deepwater Horizon spill in the Gulf of Mexico and the use of robots to attempt to turn valves in the 2011 Fukushima Daiichi nuclear emergency. The objective is to provide safe, reliable action at a site while situated at a distance from the site.

1.7 Summary

Disaster robotics covers the entire disaster life cycle of *prevention, preparation, response,* and *recovery*. Rescue robots are unmanned systems used as *tactical, organic, unmanned systems* that enable responders and other stakeholders *to sense and act at a distance from the site of a disaster or extreme incident*. Rescue robots are usually smaller than military robots and hardened for the extreme environments and must be capable of working without GPS or wireless. Most of the land and aerial vehicles used in rescue robotics can be traced back to DARPA programs, while marine vehicle development has largely stemmed from the undersea industry.

The economic justification for robots (and associated costs of training and maintenance) is based on four effects: *saving lives, improving the long-term health and recovery of survivors, mitigation of negative effects such as environmental pollution,* and *economic recovery*. Disasters and extreme incidents occur frequently, and their impact is increasing. Robots can make a difference if they are deployed in a timely fashion, though currently it takes almost a week for a robot to be used.

There are multiple stakeholders who can use robots, from federal agencies to municipalities and NGOs. In the United States, only one search and rescue team, New Jersey Task Force 1, and one agency, the MSHA, own rescue robots. As a result, the majority of robots used at disasters have been provided by CRASAR through CRASAR's Roboticists Without Borders program. Companies and universities who offer or bring robots risk being perceived as profiteers, too high risk, or too experimental if they do not have prior ties with the incident command structure.

Rescue robots are generally thought of for the immediate lifesaving response for meteorological, geological, man-made, and mining or mineral disasters. But these robots also can be used for the recovery operations and for prevention and preparation. They can perform immediately and directly engage missions such as search, reconnaissance, mapping, structural inspection, in situ medical assessment and intervention, and direct intervention for mitigation. Robots can also carry out important indirect tasks such as acting as a mobile beacon or repeater, removing rubble, providing logistics support, serving as a surrogate for a team member, and adaptively shoring a collapse to make it safer for responders. Recovery operations include all of the above tasks, but robots can also assist with victim recovery and estimation of debris volume and types.

Often, researchers and investors focus on or are only aware of immediate lifesaving activities in a disaster, neglecting the lower-profile but high-value missions for both rescue and recovery. There is also a tendency to think in terms of replacing a person or a canine, rather than extending and supplementing those capabilities. While incidents like hazardous materials responses could benefit from robots that could do what a human would do if a person were able to survive long enough, the majority of missions will use robots for novel tasks. These formative uses of robots pose design risks, as the developer has to project how the robot would fit into larger environmental and organizational constraints.

The remainder of the book is organized as follows. The next chapter summarizes the 34 deployments of rescue robots that have been identified as of April 2013 and analyzes their performance and the lessons learned. The following three chapters discuss each of three modalities (ground, air, marine) in more detail, including typical platforms and gaps in technology. Together, chapters 1–5 provide a broad overview of the state of the practice in rescue robots. The final chapter, chapter 6, offers recommendations for working in the field with stakeholders and provides more detail about the emergency response enterprise.

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