Issues in Intelligent Robots for Search and Rescue

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ABSTRACT

Since the 1995 Oklahoma City bombing and Kobe, Japan, earthquake, robotics researchers have been considering search and rescue as a humanitarian research domain. The recent devastation in Turkey and Taiwan, compounded with the new Robocup Rescue and AAAI Urban Search and Rescue robot competition, may encourage more research. However, roboticists generally do not have access to domain experts: the emergency workers or "first providers". This paper shares our understanding of urban search and rescue, based on our active research in this area and training sessions with rescue workers from the Hillsborough County (Florida) Fire Departments. The paper is intended to be a stepping stone for roboticists entering the field.

Keywords: Urban Search and Rescue, robotic platform, sensor suites, design issues

1. INTRODUCTION

Recent and past devastations have brought much attention to the area of Urban Search and Rescue(USAR). Technological advances within the USAR field in terms of sensors and equipment have greatly advanced the searching operations and have inadvertently saved lives. However, greater devastations and losses are calling for better solutions. The field of robotics has been turned to for providing a solution: an intelligent assistant for rescuers in an emergency situation. The USAR area is by no means an easy environment for people or dogs, much less robots.

This paper serves as an informative source of current USAR operation practices (specifically in terms of a collapsed building situation), victim issues, and what USAR demands of robots. The paper begins by describing the motivation for use of robots in USAR. Victim welfare is of the primary concern during the rescue operation, and is discussed. The USAR domain provides four main areas for robotics to participate. Applications for robotics in each area, specifically collapsed buildings, are discussed. Next, the general rescue response to a USAR incident is presented for the purpose of understanding the current system and to envision how robotics would collaborate. The common types of a collapsed structure are discussed because the information is utilized for victim and hazard location. The first section of the paper concludes with the five phases of a structural collapse rescue. The second section concentrates on how robotics is affected by the USAR environment in terms of hardware, software, and sensors, and how artificial intelligence is needed for resolution of USAR task conflicts. The paper concludes by posing questions and discussing lessons learned.

2. USAR AND MOBILE ROBOTS

Intelligent mobile robots are needed to help rescuers. They can assist in the dirty, dull and dangerous tasks of USAR. Currently, manpower is utilized in performing tasks that could potentially be automated, such as air monitoring. This task, and others, are time consuming and under-utilizing the rescuer. Other tasks, such as reconnaissance, victim locating, confined space searching, environment monitoring, and communication or biomedical monitor delivery, also hold a high potential for robots to perform. Trained rescue dogs are the most highly utilized assistants today. They are however, a limited resource due to their short attention span. Dogs are also threatened by the same hazards as people. In the case of the Oklahoma City bombing, the dogs needed booties to protect their paws from getting cut by shattered glass. A loss of a trained dog is difficult because of the relationship developed with the dogs and time and effort invested in training them.

Intelligent robots are also needed for the humanitarian reason of saving the lives of victims and rescuers. In the 1985 Mexico City earthquake, 135 rescuers died. 65 of these deaths were due to drowning when ground water flooded the confined space area where they were searching for earthquake victims.

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3. VICTIM WELFARE

The victim welfare is of up most importance. Robotic technology could potentially reduce the amount of time a victim is entrapped. For instance, a team of heterogeneous robots could survey the incident site while the officials organize rescue. Intelligent robots could potentially become the an important entity of a rescue operation.

The victims in an USAR situation are the center of attention. Rescuers will do everything within their power to save lives. Time, environment conditions, and situation determine the survival rate of a victim. Table 1 displays results of research conducted after the 1988 Armenian Earthquake.[1] The percentage of survivors is directly related to the entrapment time.

Table 1. Trapped victim survival rate.

30 minutes	91 survive
1 day	81 survive
2 days	36.7 survive
3 days	33.7 survive
4 days	19 survive
5 days	7.4 survive

The condition of the victim is determined by the situation and the weather. Hypothermia, hypovolemia, and dehydration are just a small sampling of the serious threats to a victim. Cold weather and/or rain allows for hypothermia to set in. Hypovolemia is a loss in blood volume. This leaves the victim in shock, is a very serious condition when not treated correctly. Inhalation injuries may also occur from dust, fiber glass, or insulation. Suffocation results from severe inhalation injuries. Nutrition is a serious problem when the rescue begins to take over a day. Compartment syndrome affects a trapped limb after only four hours. Toxins are released from the crushed tissue thus causing the limb to swell. This is a very serious condition that needs major medical treatment to save the limb. When the body is crushed or massive pressure placed upon it, blood flow is absent and the tissue dies. The tissue releases toxins that do not circulate until the victim is extricated. The toxins quickly flow throughout the body with the potential to cause severe damage or even death. The victim needs to be treated before being removed in order to minimize ill effects. Crush syndrome commonly occurs during trench and structure collapses.

4. USAR DOMAIN

The USAR domain is interesting from a theoretical viewpoint in terms of navigation and perception. The main task in USAR is *search*: searching for survivors, gas leaks, signs of failing structural integrity, etc. An individual robot may need to operate with a high degree of autonomy and perform many activities concurrently (e.g., navigation, mapping, perception), without observations from external cameras to help with localization. The domain lends itself to the use of multiple robots with multiple capabilities. The robots will have to interact with a great variety of users, often inexperienced with respect to robot and technology usage. And finally, the robots' activities must be optimized as the problems are absolutely time critical, frequently involving life and death situations.

The four main areas of Urban Search and Rescue are HAZMAT, bomb threats, collapsed buildings, and trench rescue. Every scenario involves a certain amount of risk to the rescuers and trapped victims, which is determined by the structural integrity of the collapsed structure, leakage of hazardous materials, potential for triggering another bomb, etc. Rescue dogs are highly utilized in USAR situations to assist humans. However, dogs are easily fatigued, can search only limited areas, and are a sparse resource. Given the need for rapid response, the risk to rescue workers, and terrain challenges, mobile robots appear to be a promising tool for USAR. The robot tasks for a HAZMAT situation includes reconnaissance, material removal and cleanup. In a bomb threat situation, robots may monitor the environment, perform reconnaissance, determine location of bomb and remove the bomb. A trench collapse requires intelligent robots to be capable of environment monitoring, reconnaissance, and locating the position of the buried victim or limbs. Figure 1 includes an image taken from the Hillsborough County Trench Rescue training session. Manpower is used to constantly monitor the air conditions around the trench site. Robots could be used

Figure 1. The image on the left shows the complex shoring required when performing a trench rescue. The image on the right is a worms' eye perspective of the destruction caused by the Oklahoma City bombing.

to perform this task thus freeing up manpower. In the case of trench rescue, a victim is buried to a certain degree. Most often the victim cannot accurately describe where his/her limbs are located due to disorientation, stress, etc. In the case of a completely buried victim, rescuers depend upon witnesses for victim location information. Thermal imaging is also used to localize victims. An intelligent equipped robot may be used to more quickly localize the victim. Robot tasks for a collapsed building incident include reconnaissance, determining victim location, confined space traversal, and environment monitoring. Much like a trench rescue, environment monitoring and reconnaissance are crucial to the rescue operation. A collapsed structure, as seen in Figure 1, is a more demanding incident in terms of searching, time constraints, and number of victims.

5. GENERAL RESPONSE

Each USAR incident is original and requires adjustment in the rescue operation to tailor to that specific incident. However, there is an accepted form of response that is utilized in every USAR situation. A common response method is crucial in major USAR situations which involve national and local rescue teams. The organization time of an emergency situation must be minimized for the sake of the victims. Intelligent robots are potentially useful entities that must fit into an already existing and accepted USAR response system; this section outlines the general response and how robots might fit in.

5.1. Incident Command System

The incident command system is a "combination of facilities, equipment, personnel, procedures, and communications operating within a common organizational structure with responsibility for the management of assigned resources to effectively accomplish stated objectives pertaining to an incident".[3] This is primarily a management tool for an emergency incident. The fundamental idea of the ICS is that it is flexible and scalable, thus it is applicable to every USAR incident. An incident commander is assigned and the incident management system is developed. The incident command system structure is shown in Figure 2. Figure 3 is a detail of the technical rescue branch which is included under the operations officer in a large scale rescue.

The incident commander is responsible for the incident as a whole. However, the incident commander may not be not an expert in all rescue operation aspects. The safety, liaison, and public information officers and technical advisors serve to assist the incident commander in specific areas. The operations officer is in charge of the fire suppression, rescue and medical branches. This is an overwhelming responsibility, thus the technical rescue branch has a branch officer who coordinates the ongoing rescue operations, and is responsible for implementing the objectives

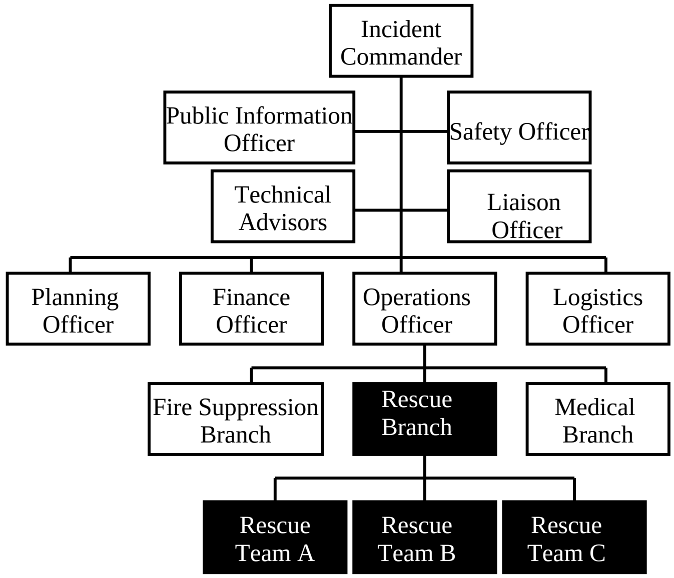


Figure 2. The incident command system structure, including the technical rescue branch.[2]

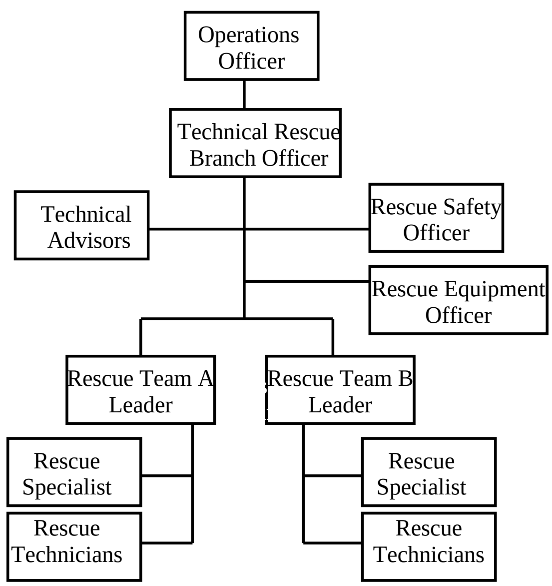


Figure 3. Detail of technical rescue branch structure.[2]

communicated by the operations officer. Like the incident commander, the technical rescue branch officer also has assistants; technical advisors, rescue safety officer, and rescue equipment officer. The safety officer is responsible for monitoring the activities of the rescue team for safe operations. The rescue safety officer may consult with the incident command safety officer and has the authority to halt a procedure for safety reasons. The branch officer is also in charge of the rescue team leaders. The rescue equipment officer manages the equipment, coordinates the collection of needed equipment, and accounts for equipment. The technical rescue branch officer is also in charge of multiple rescue team leaders.

5.2. Area Assessment

Part of the general response of an USAR incident is area assessment. It is crucial to prohibit site entrance to any personnel before a proper preparation has taken place. Heroic approaches may create further problems or situations than what was intended. Robots have the potential to assist with this task by monitoring the incident area. An outer circle check is performed by the rescuers. This involves collecting site information from a foreman, gathering witness accounts, and contact the public utilities for shutdown of electricity, water, etc. Area vibrations must also be terminated in order to prevent a secondary collapse. Position rescue units are limited to a 250 feet minimum distance from the incident site. An important step in the outer circle check is the collection of site information. This includes blueprints of the building, land mapping of the area, etc. In the case of a collapsed building, it is also advantageous to determine what kind of collapse has occurred. The blueprints will provide information of where the offices or cafeteria were, for instance. The time of the incident occurrence may provide clues as to where most of the people were at that time of the day. For example, if the incident occurred at noon, many people would likely be found in the cafeteria area. The type of building collapse provides information of the part of rubble the victims would most likely be found.An inner circle check is a reconnaissance of the immediate incident area. Tasks include opportunistically searching for victims, number and condition, record the environment condition, and hazard location and elimination. Robots could potentially perform an inner circle check, which would remove the rescuers from dangerous environment.

5.3. Hazard Control

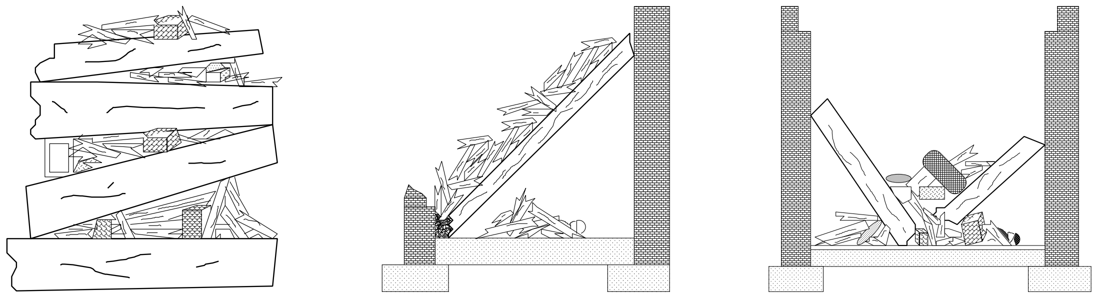
A USAR environment is hazardous to the people working within it. In order to minimize potential injuries and problems, hazards need to be recognized and eliminated. A robot could potentially be provided the capability to recognize hazards. There are seven major hazard categories: structural instability, overhead, surface, below-grad, utilities, hazardous materials, and incident. A structural instability hazard could be a weakened floor. Ceiling wires threaten entanglement and are an example of overhead hazards. Surface hazards include debris laying on the ground, such as glass or nails. This threatens the rescuers as well as the rescue dogs. An example of a below-grade hazard is a broken gas pipe in a basement. Rescuers could potentially fall into the basement which might lack oxygen. Utilities running to the site could cause an explosion. Incident hazards include fire and smoke.

5.4. Establish Hot, Warm, Cold Zones

The three zones establish perimiters for the rescue personnel, media, officials, etc. The hot zone is the immediate incident area. The personnel allowed in the hot zone include the rescue sector officer, rescue safety officer, rescue advisor, and medical personnel. Only highly qualified and trained personnel are allowed in this area. The warm area serves as the equipment and medical staging area. There is a lot of coordinated activity that occurs between the hot and warm zones. Although equipment hauling between the hot and cold zones initially appeared to be a worth while task for a robot to perform, it isn't ideal due to the high activity level and potential for a robot to get in the way. The incident command and equipment sector officer are two of the officials that stay within the warm zone. The cold zone serves as an area for rehabilitation and holding of the manpower pool, family and media.

6. COMMON TYPES OF COLLAPSED BUILDINGS

Commanding officers must make well informed decisions of where the personnel and equipment, including robots, should be used. This involves the consideration of victim survivability factors when making decisions concerning resource assignments. The type of collapse will influence the choice of robotic platform, sensors, and search algorithms. Victims are most likely to be found in collapse voids, access corridors, basements, and underground parking garages. The type of voids created by different building collapses will be discussed here.



a. b. c.

Figure 4. Three types of collapsed building structures - a. pancake, b. lean-to, c. v-shape

1. A *pancake collapse* is prevalent with multi-story buildings and results in a cement slab stack. The walls of each floor are essentially disintegrated, leaving the floors and ceilings to fall upon each other. Voids are created by the debris and rubble separating the cement slabs and holding them apart. Entire building floors are reduced to inches in most cases. Often these voids are large enough to server as a survivable space for victims, but are confined and difficult to access. In a pancake structure, as show in Figure 4a, the spaces between the cement slabs needs to be searched for victims.

2. A *lean-to collapse* is typically the result of a wall failure causing the floor or ceiling to fall on one end while being supported at the other end by the standing wall. The structure is very unstable as the supporting wall has a greater amount of pressure placed on it. The area may require shoring for additional support. This collapse leaves a triangular shaped void, as seen in Figure 4b. The triangular shaped void serves as a survivable void for victims. People may have been walking across the floor at the time of collapse so the top of the structure is also an option for searching.

3. A *v shape collapse* occurs when the center weight of a floor or ceiling is too much that the floor collapses in the middle. This could also be a result of a lack of center support. Two triangular shaped survivable voids remain on each side of the collapse, as seen in FIgure 4c. Victims will most likely be found in this voids and possibly on top as well if they happened to be walking across the floor at the time.

7. FIVE PHASES OF STRUCTURAL COLLAPSE RESCUE

The general response steps discussed above are applicable to all USAR incidents. In the case of a collapsed building, the steps are modified and refined specifically for a collapsed building incident. The applicability of robots will be considered and discussed in the description of each phase.

7.1. Phase 1: Establish ICS, Reconnaissance

The incident is the start Phase one. Reconnaissance teams are deployed to analyze the situation and size up the incident. This is normally accomplished be walking around the site, recording observations, and monitoring the area. Air monitoring sensors, for carbon monoxide and oxygen for instance, are used. The reconnaissance results should inform the incident commander of what resources are needed, what needs to be called in, is additional manpower necessary, etc. The incident command system is also being developed during this time. An incident commander is placed and the flow of information is determined through the management structure. The time spent in phase one directly depends on the magnitude of the incident. Average time completing phase one is three hours.

A use for robots in phase one is reconnaissance. For instance, a team of robots could be deployed to survey the immediate incident area, gather information, and opportunistically locate victims while the rescuers are organizing the incident command system. Robots could potentially reduce the time spent completing phase one of the structural collapse response.

7.2. Phase 2: Rescue and Recover of Surface Victims

This phase may occur concurrently or immediately after phase one. Surface victims are people who have been hit with flying debris, or injured during during a fall. They are the victims that have the best chance of surviving because they are easily reached and removed from further harm. Often surface victims are assisted by other witnesses or civilians before the rescue teams arrive on the scene. *Surface victims account for about 50% of the total number of victims recovered.* This step will do the most good for the most people. It is also necessary not to approach the incident area too soon as secondary collapses and aftershocks immediately threaten impatient rescuers.

7.3. Phase 3: Location of Lightly Trapped Victims

The reconnaissance results obtained in phase one should inform the rescuers of lightly trapped victims that were found while surveying the area. Lightly trapped victims are people who are trapped by items light enough to be removed by one or two rescuers, such as a piece of furniture or panel. These victims are extricated quickly and often easily. *Lightly trapped victims account for approximately 30% of the total number of victims recovered.* Victims are currently located using search dogs, listening devices, thermal cameras, etc.

Intelligent robots have the potential to be used for locating the lightly trapped victims and releasing them. Robots would assist the rescuers in the search and reduce fatigue of the rescue dogs.

7.4. Phase 4: Search Void Spaces

After the hazard have been removed from the area, void spaces are searched for victims. Trained and equipped rescuers are needed to search the void spaces of a collapsed structure. This is the most dangerous step of a structural collapse rescue. Structural engineers are needed to assist the rescuers in victim extrication and determine the safety of debris removal. Approximately *15% of the total number of victims are found in void spaces.* These victims are trapped in a void and are unable to move. The average removal time is 4 hours with 10 highly trained and equipped rescuers. Approximately *5% of the total number of victims are entombed.* Entombed means to be trapped by main building components, such as a wall or support beam. The delicacy with which a support beam or wall needs to be removed results in an approximate victim rescue time of 10 hours. Sensors currently used to locate victims in void spaces include thermal imaging cameras, directional listening devices, fiber optic cameras (borescopes), etc.

Robots need to be utilized in a confined space search and rescue because of the danger imposed on rescuers and search dogs. Time is crucial in a USAR situation, and robots may be able to assist the rescuers and reduce the time taken to locate victims. An average of 4 hours to remove a victim plus the 3 hours taken to complete a reconnaissance and ICS organization, the victim would already be trapped for 7 hours. This means that crush and compartment syndrome would already have set in. These victims need to be located quickly, at least to be treated while they are trapped. Robots could be utilized for victim location and delivering medical equipment to the victims.

7.5. Phase 5: Clean-up, Debris Removal

The final phase is cleaning up the incident area. Heavy equipment is used to move remove rubble. There is a small chance that a live victim may be found, so removal teams must be cautious. Human remains are removed and identified as well.

8. USAR CONSTRAINTS ON ROBOTS

The USAR domain presents extremely difficult environmental constraints on both the robot designer and programmer. This section examines the constraints imposed in terms of hardware and software issues. When designing a robot for the purpose of USAR, these aspects must be strongly considered and implemented.

8.1. Hardware

The robot and sensor packages must be weather proof and intrinsically safe in order to be considered useful for USAR. Disasters are not guaranteed to happen in fair weather, and are very rarely clean environments. Water, mud, dust, and fire retardant must not cause mechanical or electrical problems with the robot. This therefore requires the platform to be water-resistant and sensor packages to not be hampered by contamination. Unfortunately current sensors like sonar and laser range finders suffer greatly when exposed to water and other contaminates that can block their line of sight. In addition to water encountered due to rain and rescue operations, the robot must be able to be washed down thoroughly if any hazardous materials or body fluids are encountered. A sealed and intrinsically safe robot will protect it from environment conditions and protect a sensitive robot from affecting the environment. The robot should not threaten to cause an explosion in a gas filled area being searched for victims with sparks caused by one of its mechanical parts, for instance.

The robot's mobility in the USAR domain must be of very high concern. The distance of travel can in many ways determine the usefulness of the robot. Current technical rescue operations can mechanically penetrate 18 feet into a collapsed structure that is un-enterable by humans. This is accomplished using a borescope to provide a video feed to the rescuers. Although this distance might seem trivial for robots in laboratory conditions, it makes for a very good benchmark for truly useful robotic platforms in disaster situations. One implication of this requirement is the robot's agility over difficult and uneven terrain. It must be very sure footed throughout its travels for several reasons. First, it is know that the robot is already in a hazardous situation. It must be very careful not to worsen the situation by bumping into supporting structures and possibly causing further damage to the building. Precise movement must also be taken while maneuvering around victims, since the exact orientation of a partially buried victim's limbs might not be extremely obvious to the robot.

Another aspect of the environment to consider is the terrain that the robot is required to transverse. In the case of building collapse, it is very difficult to characterize what types of obstacles and structural problems that the robot might encounter during its rescue mission. Building debris, support beams, and water pipes are sure to plague the robot's attempts to travel the building. To account for this, the robot designer must first make the robot highly mobile over extremely dynamic and changing environments. The designer must also make the robot rugged, as it might fall or become trapped in such a way that a weaker robot would be crushed or damaged. The robot must also be self-rightable in that it will not be immobilized by being turned over. It is likely to encounter ground which will dramatically alter the robot's orientation and this must be accounted for.

It is extremely difficult to describe the most ideal size and shape for a robotic USAR platform. Size, shape, and weight all have different performance tradeoffs for the robot designer. There appears to be no "perfect" model for a USAR robot. Rather, the robotic designer must decide the robot's niche in the USAR domain and attempt to optimize the features that best suit that particular problem. One of the first considerations is the size of the robot. A designer might first insist that the robot be small, to accommodate even the smallest access spaces. Miniaturization can also afford speed and agility compared to larger, heavier robots. Unfortunately the designer will pay a hefty price in the way of battery runtime, sensor availability, and on-board computational power. Larger robots, on the other hand, can carry a much larger payload, including robust sensor packages, large battery reserves, and computational horsepower. The penalty here is of course the robot's ability to reach the victims due to the robots size and weight. In USAR, weight plays a special role since the stability of the supporting floors is not guaranteed. In essence, the lighter the better, but a balance must be made with payload requirements.

8.2. Hardware/Software

With all rescue operations, communication is vital among team members. Radio becomes a valuable tool for the coordination of the incident command system hierarchy, but limited channel allocation and building structure interference can quickly degrade the usefulness of this medium. Because the robot will be incorporated into this response system, careful considerations must be made to ensure that all communication links between the command center and the robot are maintained. This includes and is not limited to video and audio feeds, analog data transmission, and wireless Ethernet implementations. While the frequencies around 450Mhz are the preferred channels for structure penetration, in a large rescue operation these channels may quickly be taken up by voice traffic for rescuers. Also, because the FCC commercially licenses these frequencies according to region, the radio equipment on the robot must be adjustable to the frequencies available in the disaster area. Systems depending on cellular transmission must also account for the saturation of available local cells due to off-site communications. Even in the best of situations, radio problems may exist including drop-outs, interference, and frequency collisions. This implies that the platform's control software must be able to gracefully and autonomously deal with sensor allocation, quality, and failure issues. Without communication, there is no way to alert the rescuers as to the location of the survivors. This should be an important aspect of any AI system written for this domain.

The lighting within USAR environments can vary from completely black to sunlight. In addition, this variance is not guaranteed to be consistent for any given scenario. Flashing artificial indoor lighting, emergency vehicle lights, or high power floodlights can vary greatly over the course of a rescue. From a hardware standpoint, it is easy to see why the robot must carry its own lighting to augment and stabilize the external lighting conditions. The software must also be able to take this into account by adjusting and adapting its vision algorithms to minimize the impact of the changing light.

8.3. Software

Rescuers use their hearing during the rescue operation to locate victims. It would be expected that with directional listening sensors that the robot would also attempt to utilize this as a victim-identifying sensor. Because of the high sensitivity of most listening devices, silence at the rescue site is normally needed to obtain the direction of the sound in question. If robots are to use this type of a sensor, it must be able to take into account that the site will not always be in a silent state due to air and electric power tools, rescuer and victim calls, and air horns. The robot must not inadvertently think it has found a victim when in fact it is detecting other rescue operations. Because there is currently no hardware solution to this problem, the intelligence of these devices must be placed on the software designer for the system. Some type of sanity checks with regard to the probable location of the victims relative to the rescuers might be a possible solution, but this would need to be researched further.

9. USAR CONSTRAINTS ON SENSORS

USAR has specific sensor requirements unlike other robotic domains. Software developed for most previously explored domains makes general assumptions about the environment that will have to be discarded. Walls will be vertical, floors will be even and continuous, and random sensor obstructions can be solved by manually arranging the environment or sensor modality. All of these assumptions have to be thrown out before robots can help in an unstructured world like USAR. Unfortunately, not only environmental assumptions, but also sensory assumptions must be limited for the designer. Current "laboratory grade" sensor packages such as sonar and fast image processing must be re-vamped and strengthened if they are to be applied reliably.

The three main tasks of an USAR robot, victim detection, navigation, and environmental monitoring, provide an organization of sensors into three individual sensor suites that are used only for the one purpose of which they are designed for.

1. The first sensory suite is that of victim detection. There are several ways of detecting victims used by rescuers today. First, human rescuers most commonly use vision. While this might seem intuitively obvious, there are several facets that make this particularly difficult for robotics. First, traditional color segmentation and region detection will most likely fail because when victims are trapped within a collapsed building, they are typically covered with dust and dirt, camouflaging them within their environment. Movement would be another good visual detector to augment the color deficiencies, but because the victims are very often unconscious, this does not completely resolve the vision issues. Texture recognition may be another possible solution, but clearly much more research must be made in the area of visual victim recognition if it is to be feasible in this domain.

   Moving outside of the visible light spectrum might prove advantageous to USAR robotics, as has been found by rescuers in the field. Thermal imaging cameras have recently increased in accuracy and decreased in price as to make this an extremely useful tool for locating victims. In smoke or dust filled rooms, these temperature sensitive cameras can provide almost x-ray vision for a robot completely blind within the visible spectrum. Even lightly buried victims have a heat signature that stands out from the environment. Using adapted versions of classical image processing algorithms, false color pictures can quickly be analyzed for victim identification.

2. The second sensor suite deals only with the navigation of the robot into and through the structure. 2D navigation might be supplied through laser range finders or some type of improved sonar. Current sonar implementations cannot easily deal with the structural inconsistencies of building collapse. 3D structural mapping would most likely be handled best currently with 3D scanning laser equipment. Although ideal, power requirements of these specialized laser sensors must be realized by the robot designer. Also, laser equipment utilizes line of sight to approximate distances. With dust, smoke, and other air borne contaminates, the effectiveness of these sensors is not guaranteed and must be explored and tested.

   Another navigational tool for global mapping that might be used to augment the localized mapping of the above sensors is the use of GPS. Unfortunately because GPS uses the frequency bands around 1500Mhz, it is not very adept at penetrating large structures. In the best conditions, GPS relies on line of sight reception

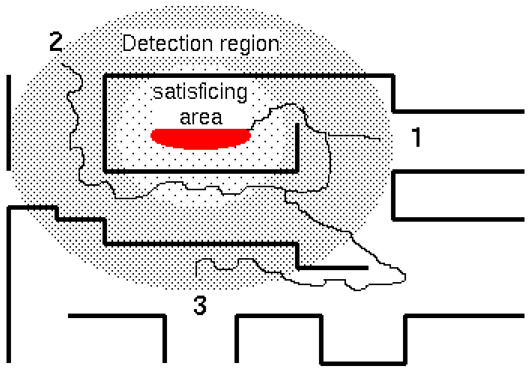


Figure 5. There exist conflicts between two main USAR robot tasks, navigation and detection, that AI must resolve.

of the satellite constellation, so its usefulness is currently limited to outdoor operation. Its limited usefulness should not be completely discounted though. In cases such as HAZMAT and perimeter surveillance, this can be an extremely useful tool for accurate identification of critical locations around the site.

3. The third and final grouping of the sensor suite is the need for environmental monitoring. This extremely important task is currently done manually by human rescuers and can easily be overlooked by robotic designers not specifically trained in this domain. The monitoring and ability to alert rescue staff about dangerous gases in the structure can save the lives of rescuers attempting to enter the structure. This can include, but is not limited to flammable gases, harmful gases, and oxygen richness, and general air quality. Because explosions from leaky gas lines can be an extreme hazard for all involved in the rescue efforts, the ability for the robot to alert the incident commander to these conditions would be extremely important. If the robot has sensors to detect these conditions, the utility companies associated with the lines can be told to shut off these lines and the robot could then let rescuers know when it is safe to proceed.

10. AI FOR NAVIGATION AND DETECTION

Two main tasks of an USAR robot are navigation and victim detection. These two tasks are difficult problems and have been extensively researched individually. However, these behaviors must co-exist in a USAR robot. The co-existence of navigation and detection causes great conflicts that must be resolved by AI. For example, Figure 5 shows three cases in which an intelligent system of the USAR robot must determine how the robot behaves when presented with a satisficing or optimal situation. A satisficing state occurs when the robot is close enough to the victim to drop off a communication device. Ideally, the robot should traverse into the optimal region (banana shaped region) which is close enough to the victim to deliver a biomonitor device. In the first case, the robot can easily navigate around and into the optimal area. In the second case, the robot navigates into the satisficing region. This is sufficient to deliver a two way communication device, but as can be seen, the robot could traverse into the optimal region. In the third case, the robot abandon detecting the victim in hopes to even reach the satisficing region. And if it got to this point, it would again have to decide whether this is sufficient or should it try to reach the optimal area. Questions arise in thinking of how a robot could handle the conflicts between navigation and detection, such has how long to persist, or when to give up. This is an unexplored topic that is needed for efficient victim detection while navigating.

11. SUMMARY

Five main lessons were obtained throughout this work and research. First of all, mobile robots are needed to assist the current rescue response system by providing reconnaissance, confined space traversal, victim location, and rescuer protection. By performing a reconnaissance of an unexplored incident area, the rescuers are removed from unknown and possibly deadly hazards awaiting them. Robots will inadvertently decrease the response time by allowing a great degree of multitasking. Second, USAR is an extremely unstructured and technically difficult arena for mobile robotics. Developing an intelligent mobile robot to server work in this field is not an easy problem that can be be solved overnight. The environmental and physical constraints require USAR mobile robots to be rugged, robust, and reliable. Next, the environment constraints do not allow for a single robotic platform solution. As previously discussed, there isn't an optimal size or capability set. A team of people with varying capabilities are needed in USAR. The USAR environment imposes constraints on hardware, software, and sensors. Also, it appears as though sensors are the weakest link in the system. Current available sensors are not sufficient for sensing aspects of the environment. There is a lot of information to be utilized, and there are not adequate sensors for this. Finally, artificial intelligence is needed to fill the gap between the hard problems of navigation and detection.

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