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Robotics in Disaster Response: Enhancing Search and Rescue Operations

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ABSTRACT

Robotics has dramatically improved disaster response, allowing for more efficient and effective search and rescue (SAR) operations. This review investigates the role of robotics in disaster situations, with an emphasis on unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), and developing technologies that support SAR operations. The Global Robotics for Advanced Search (GRAS) system is presented as a case study, demonstrating its effective deployment in a simulated gas explosion situation. A historical review chronicles the history of robots in disaster response, followed by an examination of contemporary uses, problems, and new technology. The report finishes with predictions for the future of SAR robots, emphasising the need of ongoing innovation and integration to handle the issues that disasters provide.

Keywords: Robotics in disaster response, Search and rescue (SAR), Unmanned aerial vehicles (UAVs), Unmanned ground vehicles (UGVs), Global Robotics for Advanced Search (GRAS).

INTRODUCTION

Robotics revolutionized automation in real-world applications. Disaster response now utilizes automated systems. Robotics systems include mechanical bodies, computer systems, sensors, and AI for autonomous or semi-autonomous actions. They are categorized as UAV, UGV, and UWV based on design and medium [1]. Trained first responders and response team dispatched to handle incidents and save victims. Their main purpose is to secure the site, gather information, and make a plan. Chaotic and complex scenes include smoke, debris, and inaccessible areas. Robotics systems can be used as an alternative for search and rescue in dangerous environments [2]. The first responders and rescue team need vital on-site information to assess and conduct effective search and rescue operations. GRAS is a set of automated robotic systems that gather information using an aerial UAV, a ground UGV, and a fixed camera. The UAV takes real-time aerial photographs and the UGV captures normal and thermal video footage. Both operate simultaneously and can adapt to different situations. The command center receives information from all devices, builds a ground model of the area, and controls UGVs based on the model and acquired information [3]. The efficacy of the GRAS system was validated on a real-case scenario of a simulated gas explosion in a two-storied building conducted in the EMRS 2018 (Emergency Mission Robot System 2018) joint exercise. A robotic competition was also conducted under that exercise with a set of tasks to be completed by the teams as a means of evaluating the capacity and viability of the robotics systems in disaster response [4].

THE ROLE OF ROBOTICS IN DISASTER RESPONSE

With increasing disasters, effective ways to save more people in less time are needed. Robotics can enhance search and rescue operations in inaccessible, dangerous environments. Unmanned aerial vehicles (UAVs) collect aerial imagery and smaller UAVs are better for navigating collapsed structures. Unmanned ground vehicles (UGVs) can enter buildings. Legged robots provide additional mobility. Multi-robot systems utilize different strengths. Robotics in disaster response has evolved from small incidents to large disasters. The history and current state of robotics in disaster response are discussed [5].

HISTORICAL OVERVIEW

Robots have proved themselves eminently viable in the field of natural and man-made disaster mitigation, preparedness, response, and recovery; and there is great interest in the advent of affordable, easy to operate, portable robots to aid individual efforts in disaster situations. One of the first experiments of using a robot for hazardous rescues occurred after the AFM building fire incident in Tokyo, Japan, in 1972. An experimental robot called "Robo-Cane" was developed by the Tokyo Fire Department, which was tested in various settings including a building fire scenario. The experiment was followed by the development of the 3.5 m long, 1.2 m wide wheeled vehicle "Rosie" in 1981. In 1986, a trial was carried out using a wheeled rescue robot called "SRV-001" at the collapsed Meiji Yasuda-life building in Tokyo, which was to prove a turning point in the move to develop robotic systems for disaster environments. A joint team of rescuers including machine vision and control scientists successfully rescued three people from the rubble. "SRV-001" was a three-ton vehicle equipped with a high-definition camera, a robotic arm, and infrared vision system to search and rescue people. It could communicate contact to the rescue team through the coaxial cable, and its four operating videos were transmitted to the flat panel display in the control cabin located 80 m from the building. From this incident, several countries started projects to develop robotic systems for similar applications. Research proposals under the European Community's Fourth Framework Programme have focused on both rescue robots to be used by search and rescue teams and on autonomous robots for use in collapsed buildings. The US National Science Foundation has funded a number of research teams to investigate robot vision systems that could be mounted on aerial vehicles, as well as wheeled and tracked mobile central vision systems. Although the experiments with ground robots at the scene of the collapsed building in Japan have not been followed for several years, attempts are still made to develop various robot systems for disaster environments [6].

CURRENT APPLICATIONS

There is an increasing number of practical applications of robots in real disaster situations. This field has rapidly improved over the past two decades, and robots continue to play important roles in responding to disasters. The U.S. urban search-and-rescue (USAR) robots were first deployed in Manchester, New Hampshire after the collapse of a four-story mill building in 1991. The USAR task is to find survivors trapped under collapsed structures after earthquakes or terrorist actions. The building was large, with a total floor area of approximately 120,000 ft2. Emergency personnel searched for survivors using canines and listening devices. A truck-mounted articulated boom was also employed to search for humans in a location that was tough to access. The rescue operation took three days, and there were no survivors found. In 1994, five USAR robots were deployed for the first time in a real rescue operation after the Northridge earthquake in California. The robots provided eyes and ears for the rescue teams, relaying audio and video from inside a partially collapsed apartment complex. One of the robots was thrown off a balcony during an attempt to investigate an area. Only four of the five robots were ever recovered. In hindsight, these robots were still primitive. They were not designed for autonomously entering an unknown environment, did not understand languages, had no planning capabilities, and required constant interaction with human operators. However, despite these limitations, the robots saved lives. They provided rescuers with basic information that significantly sped up rescue efforts. The use of robots in this situation proved beneficial, even with a level of technology far below what is considered possible today [7]. In the past decade, reports of 20+ robot deployments in disaster situations have been made. Notable instances include the use of a PackBot robot in Mosul, Iraq to search a car bomb and provide live images to the Emergency Operations Center. PackBots were also deployed during the I-35 bridge collapse in Minneapolis. The New York Police Department used small military UAVs for surveillance. In the San Francisco Bay Area, bomb-spotting robots were employed to search for explosives after a freeway bridge collapse caused by a gas leak and fire [8].

CHALLENGES AND LIMITATIONS

Advancements in robotics are crucial for improving automation in disaster response. Robots can perform tasks too dangerous for humans, such as searching for victims, assessing damage, mapping affected areas, and transporting supplies. However, there are challenges in reliability, flexibility, situational awareness, and human interaction. Extensive research is still needed to develop robotic systems that seamlessly integrate into disaster response. This article addresses some areas of research to stimulate further discussion on enhancing the effectiveness of robots in such scenarios [9]. Natural and man-made disasters such as earthquakes, tsunamis, floods, building collapses, bombings, and industrial accidents often result in a large need for help but with humanitarian organizations impeded from acting by hazards to life, further damage possible to unstable buildings and dangers such as flames, toxic leakage, and radiation. Time is of the essence, and the first phase of a disaster response operation revolves around quickly gaining an understanding of the situation in order to assess what actions must be taken.

Additionally, there might be a need to search for victims and provide them with water and medical supplies. Unfortunately, the first hours are precisely those in which the most information is required, but also when it is most difficult to obtain. Using robots to survey the disaster site is an appealing solution, as they can go where humans cannot [10]. While there are examples of robots being used in military crisis zones, they are rarely used in civilian disaster response situations today. There is therefore a technology gap between what might be feasible and what is feasible today. Simply building better robots will not be enough; the total system must be improved, and now it is again up to man. The technology gap is nonetheless closing due to the rapid advancement of technology and lowering costs of both sensors and hardware. There are several other important hurdles that should be cleared before robots can play an important role in disaster response. Technology is never neutral, and the introduction of robots on disaster sites will change the most basic aspects of how the response is performed. There are several risks tied with using robots, such as communication breakdown and technical fault, that can lead to improper use of the robots and worsen the outcome of the response. To mitigate this, the introduction of robots must go hand in hand with measures that ensure proper usage [11].

EMERGING TECHNOLOGIES IN ROBOTICS FOR SEARCH AND RESCUE

Advancements in robotics are expected to provide significant benefits for search and rescue (SAR) operations in the years to come. SAR robotics will combine the latest advancements in the fields of robotic vehicles, sensor systems, and autonomous technologies. Although SAR robotics is a very broad topic, a few promising aerial and ground robotic platform concepts are presented here as examples of the development of potential SAR robotics capabilities [12]. The use of unmanned aerial vehicles (UAVs) in a variety of areas, including disaster response and search and rescue operations, is becoming increasingly common in both the civilian and military sectors. Drones have been equipped with advanced sensor technology, imaging capabilities, and wireless communication systems, allowing them to operate in previously inaccessible areas. The use of drones can increase the effectiveness of SAR operations and, at the same time, reduce operator workload and risk to human life [13]. Drones equipped with high-resolution visible light, infrared, multi-spectral, and thermal imagers and capable of using Fused Video Analysis (FVA) image enhancement technology have been developed. The image enhancement technology merges the strengths of several imaging sensors, allowing drones with low-light capabilities to operate in darkness, generating clear high-resolution imaging. A prototype drone was tested with two imagers: a high-resolution visible light imaging sensor and a thermal imager. After pilot operation, on-board processing of the FVA imaging resulted in combined still images with improved clarity and detail, allowing better interpretability and maximizing pilot effectiveness [14]. A low-cost UAV equipped with a visible light onboard ATM camera, a fluorescent light source, and enhanced still imaging capabilities for underwater SAR is introduced. Underwater SAR is especially challenging because GPS location, UAV support, and traditional sensors are limited or inoperable. The developed UAV utilizes source illumination and filtering techniques to enhance visibility of fluorescent markers on victims or debris, generating potential rescue leads. Close-range CTX underwater fluorescence imaging with GPU processing has achieved 10-100x improvements and demonstrated successful victim visualization in controlled underwater scenarios [15]. The development of autonomous ground vehicles intended for disaster response and search and rescue operation is explored. Autonomous vehicles can assist SAR personnel in the operating environment by transporting equipment and supplies to remote areas, augmenting operator capabilities by bringing sensors and imaging equipment to dangerous and inaccessible sites, and providing communication, navigation, and other essential support. Various ground vehicle concepts and capabilities will be briefly introduced, emphasizing the need for a combination of robotic functions rather than single functionality. The design of a prototype autonomous vehicle capable of performing remote navigation in unknown areas by fusing sensor input data and automatically evaluating its ability to follow mapped path is also discussed. An experimental study simulating the environment, operating conditions, and tasks of vehicles assistance in SAR is presented [16].

DRONES AND UAVS

Drones and UAVs (Unmanned Aerial Vehicles) have emerged as an essential component of robotics in recent years, revolutionizing various industries, including search and rescue operations. With their versatility, maneuverability, and ability to access hard-to-reach locations, drones are used to perform a wide range of tasks, such as mapping disaster areas, locating victims, and delivering supplies. They are equipped with various sensors and cameras, providing real-time images, videos, and data, allowing rescue teams to assess situations before deploying other resources [17]. The use of drones in disaster response and recovery is becoming the norm thanks to their ability to improve emergency response and resource management. With their significant use in non-military sectors, UAVs have become low-cost, off-the-shelf solutions available to everyone, including search and rescue teams. Various networks of programmable drones equipped with sensors improve the understanding of a disaster's area and assist rescue teams. Drones with GPS and camera equipment gather data such as temperature, humidity, and CO_2 concentration indices and provide real-time video images that are analyzed using image processing algorithms [18]. Fixed-wing drones can cover great distances and gather high-level images in large disaster-stricken areas. Since they fly at a higher altitude, their costs and range of action are very advantageous compared to quadrotor mini-drones. However, these drones can't provide a 360° investigation and have a secondary flight imaging. Due to difficulties in controlling their flight path, these drones only work on pre-programmed schemes. Quadrotor multicopters, on the other hand, can perform a 360° assessment with on-board cameras and can be remotely controlled by a rescue team through handheld consoles. Thanks to their embedded technology, drones are capable of controlling their own flight path and must be safely used even in places with none or bad GPS signals [19].

AUTONOMOUS GROUND VEHICLES

In addition to aerial vehicles, ground vehicles are also employed in scenarios where drone use is impeded by safety concerns, regulatory or communications policies, and/or the environment. The development of ground vehicles was pioneered mainly by military groups and allowed for the remote operation of vehicles in hostile environments, such as battlefields and scenarios involving chemical, biological, radiological, and nuclear (CBRN) events. More recently, research efforts focused on the deployment of such vehicles for civilian search and rescue (CSAR) operations [20]. Autonomous ground vehicles have various designs, including tracked, wheeled, and legged systems. They typically have a wheeled chassis with sensors such as cameras, LIDAR, GPS, and IMU. On-board processing involves a computer running an odometry algorithm using LIDAR and IMU data to map the environment. Some vehicles have a stereo camera for perception and object detection/control algorithms. A high-level path planning algorithm may also run on the computer, generating optional paths. Communication options include radio waves and satellite methods. Internet-based teleoperation is not suitable for compromised communication infrastructure, requiring line-of-sight for the operator [21].

CASE STUDIES AND SUCCESS STORIES

The increasing frequency and severity of natural disasters and accidents poses challenges for rescuers. Cooperative systems in SAR can include aerial drones, ground robots, and marine vehicles. This review presents investigation results on search strategies for robot teams in uncertain environments. The analysis aims to enhance the performance of mobile robotic systems [22]. The new scene classification algorithm based on Convolutional Neural Networks (CNNs) has been evaluated in the context of complex outdoor environments composed of urban and natural scenes. The proposed method incorporates a two-stage, hybrid framework for scene classification. In the first step, the eight deep CNN descriptors are extracted from the input images. The feature grids are then aggregated by the Spatial Pyramid Matching Kernel in order to obtain the final histogram descriptor. The baseline query-by-image dataset, which contains over 600 images from various outdoor environments, has been created by augmenting the Oxford Pets dataset with robot information captured by a mobility platform and a 360° field of view camera setup. Competitions have been held to assess the performance of scene classification techniques and recent advancements based on learning methods have outperformed traditional algorithms on this task [23]. Various mobile robotics systems, including wheeled robots and aerial vehicles, have been used in outdoor scenarios with different weather conditions and illumination. Deep learning detection systems have been evaluated for their impact on execution time and missed detections on mobile platforms. System detections corresponded accurately to geo-references obtained from GPS or odometric measurements, facilitating fusion with other information such as planar maps and laser-based SLAM point clouds. Multiple platforms with communication links enabled coordinated search and exploration tasks. Fixed radio communication between aerial drones and ground platforms demonstrated potential mobility for effective exploration missions [24]. The introduction of mobile robot platforms with the implementation of various visually based techniques for terrain classification has broadened the robotic system applicability and reduced the need for external infrastructure. The complexity of physical structures, environments, and situations is still a major challenge when it comes to designing robotic systems, choosing appropriate search strategies, or distinguishing useful attributes for the robots deployed on SAR missions. The innovative, tailored-to-sectors, robust, adjustable by manner of deployment, communication type, onboard capabilities, etc., solutions having a potential to fully understand complex environments and situations remain in a distant future [25].

CONCLUSION

The integration of robotics into disaster response operations represents a paradigm shift in how search and rescue missions are conducted. As demonstrated by the GRAS system and other emerging technologies, robotics can significantly enhance the safety, efficiency, and effectiveness of SAR efforts in complex and hazardous environments. Despite the challenges in reliability, situational awareness, and human-robot interaction, the continuous advancement of robotic technologies promises to bridge the gap between current capabilities and the future needs of disaster response. To fully realize this potential, ongoing research and development are essential, focusing on improving the autonomy, adaptability, and collaborative capabilities of robotic systems. As these technologies evolve, they will become indispensable tools in saving lives and mitigating the impacts of disasters worldwide.

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