TEDUSAR White Book - State of the Art in Search and Rescue Robots

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Abstract. The aim of this paper is to document the state of the art in disaster robotics and provide an overview of technology already available or currently under development. Over the last years, robotics technologies for disaster response continued to develop and a wide range of robotics solutions for first responders are available or in development. The idea is to provide first responder with information about technology that can be immediately applied as well as to provide information on ongoing research to allow responder to identify future promising application areas.

1 Motivation

The aim of this paper is to document the state of the art in disaster robotics and provide an overview of technology already available or currently under development. Over the last years, robotics technologies for disaster response continued to develop and a wide range of robotics solutions for first responders are available or in development.

First responder frequently face critical situations whose reconnaissance and handling is significantly afflicted with personal risks. Moreover, due to critical weather situations and increased use of technology in daily life there are situation in which even response experts do not have access to disaster sites anymore (e.g. mudslides, hazard materials). Modern robotics technology can help to reduce these risks and restrictions.

Ground or aerial robots equipped with advanced sensing technologies such as 3D laser scanners and advanced mapping algorithms are deemed useful as a

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supporting technology for first responders. Although, a lot of excellent research in the field exists, practical applications at real disaster sites are scarce. The reasons are manifold. One reason is that most systems and algorithms are neither suitable nor robust enough for the harsh and dynamic environments typically found in disaster relief. Another reason is that the systems are difficult to operate and a deployment in a real disaster needs specially skilled and trained personnel. Such personnel is usually found at research institutions but can hardly be found in emergency response units. In order to gain acceptance for such technologies by first responders, these two issues have to be solved.

A lot of research is conducted to equip robots with advanced capabilities such as autonomous exploration or object manipulation. In spite of this, realistic application areas for such robots are *teleoperated reconnaissance* or *search*. There is a good chance that new technologies in these particular fields will find their ways into regular operations in the next years as progress is made with ground and areal vehicles, sensors and algorithms.

In this paper we will give a brief overview on the state of the art in robotics technology for responders. Despite the rich corpus of literature the overview will not be exhaustive. We will present mature and commercially available systems as well as innovative ideas still under research and development. The idea is to provide first responders with information about technology that can be immediately applied as well as to provide information on ongoing research to allow responders to identify future promising application areas.

The paper is organized as following. In the next chapter we will discuss potential application areas for the individual types of robots as well as the development of applications during the next years. In Chapter 3 we will introduce common robot components and systems. In the following chapter we will present software used to control robots as well as to interpret and analyze sensor information. Chapter 5 gives an overview on national and international exercises and real missions conducted using robotics technology. We will conclude the paper with a brief discussion about the situation and the potential of robots in disaster mitigation.

2 Potential Application Scenarios

Robotics technology has the potential to contribute to the mitigation of natural and man-made disasters. In particular robotics technology can be used to extend the capabilities of the human responders or allow them to stay away from potential threats during the mission. The former allows for instance to increase the situation awareness in a disaster by quickly collecting data from large (e.g. flooded areas) or unaccessible (e.g. collapsed buildings) regions and to combine these data into an integrated representation. The latter allows for instance to manipulate dangerous objects (e.g. hazard materials) safely from the distance. During the last decades a number of technologies and systems for the support of disaster mitigation activities have been developed. Some of them are visionary and innovative like autonomous robots that integrate themselves into the responder team, interpret the intentions of the team members and act accordingly. Others are more focused on the concrete solution to a practical problem like new sensor systems e.g. ground penetration radar. A number of systems already reached a mature level and are available as commercial systems (in particular sensor systems and drones). But still many systems are research prototypes. Therefore, it is not completely clear for what application scenarios appropriate technology is available. In this section we will sketch some application scenarios where robotics technology can help. Moreover, we will discuss what application scenarios will be realistic in 5 years considering actual developments. Furthermore, in Chapter 5 we will discuss actual examples of deployments of robotics technology in disaster mitigation.

2.1 Reconnaissance with UAVs

Due to the recent impressive developments of unmanned aerial vehicles (UAVs, drones) and mapping technology (2D an 3D large scale maps) reconnaissance is one of the most promising application scenarios with a good chance of a broad deployment. UAVs are easy to deploy and can be equipped with different sensors like thermal imaging or 3D mapping. The collected information are usually georeferenced using GPS and can be used to augment for instance satellite imaging that suffers from limited resolution. Due to their limited payload and endurance UAVs are suitable for limited areas. Moreover, legal problems still hinder a broad deployment. In order to extend the payload to more advanced sensors and to allow longer endurance medium-sized fixed-wing vehicles can be used. Although, they offer also the advantage to observe the area from a higher altitude they ask for more skilled operators and pose further legal problems like necessary flight permits. Modern analysis software allows to pre-evaluate the obtained data in order to augment the situation representation with valuable information, e.g. detection of flooded areas, identification of different vegetation or soil types. This kind of reconnaissance can also be applied to situations where responders have limited access such as heavy mudslides and avalanches.

2.2 Incidents in large infrastructures like tunnels

Other scenarios are incidents in tunnels or mines. Any operation of first responders is afflicted with significant risk due to the insufficient knowledge of the situation inside the tunnel or the mine. The responders often have to proceed without prior information about the dimension of the incidents or the surroundings. The gathering of information and the handling of the mission is associated with a high risk. In addition such infrastructures become more extensive and events inside such infrastructures become more difficult to handle. Several large tunnel projects are currently under construction in Austria. Two of the construction sites (Semmering, Koralpe) are located in the Si-At project region. Such tunnels represent a major challenge for responders, both during construction and during operation. In the former case the situation in the tunnel changes rapidly and frequently due to the progress of the construction and the number of people and machines involved. In the latter case many potential victims are affected in a large environment. Here the deployment of ground robots equipped with advanced sensors for mapping (e.g. 3D laser scanners and high-resolution cameras) can be used to quickly obtain high-quality representations of the site. This mapping can be done in the case of an emergency as well as continuously beforehand to enhance preparedness.

2.3 Operation with hazardousous materials

Another field of application is safe operating with hazardous materials and hazardous situations from the distance. Such applications are already known from bomb disposal operations. One example related to such situations is the handling of gas cylinder (e.g. acetylene) in fires. Currently such scenarios are resolved by a targeted shot with tracer ammunition by the police (controlled burning). In such application suitably equipped robots could support the operation. A serious limitation here is the weight a robot can handle. There is always a tradeoff between the size and weight of the robot and the environment it is able to master. In general the smaller and lighter the robot the easier is its deployment and operation. But even if an active handling of the material is not possible or appropriate the robot can be used to bring sensors like CBR measurements close to the situation without endangering a responder. This kind of operation and in particular the handling of dangerous goods needs a well trained operator as well as robots that can be easily decontaminated.

2.4 Search missions

Search missions are common in Austria. In particular in the Alpine regions a significant number of searches for missed hikers, mountaineers or skiers affected by avalanches are conducted. Although, there exists technology to assist first responders (e.g. helicopters, locating mobile phones), due to weather conditions, time/night or local terrain many search missions are conducted manually. Here again UAVs can be helpful because of two major advantages. First they can be deployed easily, might not be affected by flight limitation of a commercial helicopter and can easily cover a larger area than a responder by foot in particular in Alpine terrain. Second the UAVs can easily be equipped with modern sensors like thermal imagining to increase the chance to find the missing person faster. Although, there are techniques to carry out such search missions with autonomous robots for now there will still be a human operator involved. In the future it might also be possible to use a team of UAVs to search a larger area much faster.

Table 1 at the end of this paper gives an overview of the chance of realization of all above discussed application scenarios now and in a timespan of 3 to 10 years.

3 Hardware

In the following section we will give an overview of robotics hardware. From a top view the robotics hardware can be broken down into the following individual modules:

1. Robot Platforms
2. Manipulators
3. Sensors
4. Operator Stations

3.1 Robot Platforms

This section will focus on mobile robotics platforms. The mobile platform is the major component of any unmanned vehicle on which additional payloads like sensors and manipulators are mounted. The main focus of mobile bases is to be able to operate and navigate in the given environment. The described mobile platforms are roughly divided into the following four environment of operation: (1) ground/land, (2) air, (3) water-surface and (4) underwater. We will categorize mobile robots generally in those four classes. Although, there are possibilities of various combinations of mobile robot locomotion systems.

Unmanned Ground Vehicles (UGV)

Ground mobile robots have capability to navigate on ground. Most common locomotion systems are wheels, tracks, legs or snake like. Two legged mobile robots are known as humanoid robots and become more and more interesting for research. Most of common affordable rescue robots use wheels or tracks to overcome complex ground structures in rescue environments. Rescue environments are that kinds of environments found after earthquake, tsunami, tornado or other natural or man-made disasters in urban areas. Mobile robots are also found in industrial, military, security and service areas. Domestic robots are consumer products, including entertainment robots and those that perform certain household tasks such as vacuuming or lawn mowing.

In the following we will outline some examples of commercially available UGVs.

The **Cobham NBC MAX**, as seen in Figure 1, was developed to deal with the wide and varied range of dangerous situations rescue forces and first responders are exposed. The platform is based on the bomb disposal robot Telemax and adapted to operations that involve hazardous materials and a high level of personal risk. The mobile base allows the robot to overcome obstacles and the manipulator allows the robot to handle hazardous materials and collect samples. The robot is teleoperated using a control panel. The platform can be equipped with a broad range of sensors to detect hazardous materials. All measurements are shown on the operator interface. Communication to the robot is usually done using a radio link.

Fig. 1. Cobham NBC MAX (Photo credit: IST - TU Graz)

The **Taurob Tracker** is another example for a commercially available ground robot platform. The robot can be seen in Figure 2. The Taurob Tracker was specially developed for firefighting applications. The platform is designed to operate in explosive environments (ATEX certification), is exceedingly resistant and waterproof (IP67). The adjustable track chassis allows the robot to overcome obstacles and a manipulator allows the robot to handle hazardous materials. The robot is equipped with different cameras for reconnaissance tasks and can be equipped with additional sensors. The platform is teleoperated with a tablet interface showing the current robot state and all sensor data.

An example for a low-cost research platform is **Wowbagger**. The robot as seen in Figure 3 was developed as part of the Technology and Education for Search and Rescue Robots (TEDUSAR) project. Wowbagger is based on the mobile platform Mesa Element, which allows the robot to overcome small obstacles. It is equipped with different sensors for victim detection in collapsed buildings. The robot was tested at international RoboCup Rescue competitions [1].

Unmanned Aerial Vehicles (UAV)

Unmanned Air Vehicles are able to fly in the free air space. They have one more degree of freedom than ground robots. Aerial robots are similar to known flying machines like helicopters. The usual propulsion systems comprises four (quadrocopters) or more (hexacopter, octocopter) propellers and motors. Flying robots still have problem of payload capabilities because the robot needs to oppose the earth gravity, carrying its own weight and most important its batteries. The weight of the batteries usually limits the air robot operational time.

Fig. 2. Taurob Tracker (Photo credit: Taurob GmbH - Taurob Tracker)

Fig. 3. Research platform Wowbagger

Flying robots are very useful for inspections from above like taking pictures or environment reconstruction. The vertical distance from the ground allows aerial robots to have larger overview over areas and they are able to assist first responders as well as ground robots in tasks like search and rescue. Aerial robots recently become very stable and are able to deal with strong wind in the open areas. Moreover, they are able to fly several kilometers from the base station. The latter is subject to national aviation regulations.

In the following we will present some examples of commercially available UAVs.

The **Schiebel CAMCOPTER©S-100** is a helicopter-like unmanned aerial vehicle. The system has a maximum weight of 200 kg and a maximum payload capacity of 50 kg. The vehicle has a maximum airspeed of 240 km/h, is powered by a 50 HP rotary engine and has an operation endurance of over 6 hours. A ground control station allows to operate the vehicle in a range of up to 200 km. Two separated operator interfaces allow the control of the helicopter and the sensor payload. The operation modes range from operator control to fully autonomous takeoff, way-point navigation and landing. The system can be equipped with different cameras (regular and thermal), different radar systems including ground penetrating radar, and laser range finders. In addition the CAMCOPTER©S-100 can be operated as communication relay.

Fig. 4. Schiebel CAMCOPTER©S-100 (Photo credit: Schiebel CAMCOPTER©S-100)

The **AscTec Falcon 8** is a light-weighted octocopter designed for remote imaging. The UAV as shown in Figure 5 has a flight time of 12-22 minutes. Redundant flight control electronics and flight components guarantee high reliability even in challenging conditions. The platform can be equipped with different imaging sensors for high-resolution imaging, thermal imaging, and recording of videos. The AscTec Falcon 8 provides automated waypoint navigation and automated imaging functionalities.

Honeywell's T-Hawk$^{\mathrm{TM}}$ as shown in Figure 6 is an unmanned micro aerial vehicle that can be operated in rain, maritime environments, fog, sand, and dust. The UAV allows vertical takeoff and landing. It provides an operation endurance of 45 minutes. The platform is gasoline powered, weighs under 8 kg and fits in a backpack. The T-Hawk$^{\mathrm{TM}}$can be quickly deployed and provides advanced features for disaster surveillance and damage assessment operations. The platform

Fig. 5. AscTec Falcon 8 (Photo credit: Ascending Technologies Falcon 8)

can be equipped with different imaging sensors and allows autonomous way-point flights with dynamic re-tasking and manual intervention.

Fig. 6. Honeywell's Aerospace T-Hawk$^{\mathrm{TM}}$MAV (Photo credit: Honeywell Aerospace - T-Hawk$^{\mathrm{TM}}$MAV)

The **Survey Copter Tracker 120** is a fixed wings UAV that can be launched by hand in less than 10 minutes. The vehicle is equipped with two electric motors that allows the UAV to operate up to 90 minutes and fly a distance of 25 km. The

Tracker 120 is equipped with different imaging sensors and allows autonomous way-point navigation.

Fig. 7. Survey Copter Tracker 120 (Photo credit: Survey Copter Tracker 120)

Unmanned Surface Vehicles (USV)

Unmanned Surface Vehicles are robots that can operate on the water surface. The robots have locomotion like boats or life-raft. With respect to navigation this type of robots can be compared to ground robots. USVs are used for oceanography, military, and research. Equipped with solar cells this type of robots could reach months of operations time.

In the following we will show an example of a commercially available USV.

The **Clearpath Robotics' Kingfisher** is a portable and agile surface vehicle. A picture of the platform can be seen in Figure 8. The robot is designed as a scalable and open carrier platform for research, surveillance and field studies. The robot can be teleoperated or follow a predefined path of GPS way-points. The platform can be equipped with different sensors.

Unmanned Underwater Vehicles (UUV)

Unmanned Underwater Vehicles are designed to operate underwater. UUVs are usually used for deep-see explorations where it is too dangerous for humans. Moreover, they are used for search and rescue operations underwater, ground monitoring, or recording data. Due to the fact, that wireless connections to underwater vehicles are hardly possible, robots for underwater applications have

Fig. 8. Clearpath Robotics KINGFISHER (Photo credit: Clearpath Robotics, Inc.)

to run the predefined mission autonomously or need an wired connection to the operator station.

In the following we will discuss some examples of commercially available UUVs.

The **Sparus II AUV** is a torpedo-shape unmanned underwater vehicle designed for long-term autonomy underwater. The platform can be equipped with different sensors depending on the mission. The vehicle has no wired connection to an operator terminal. Therefore, diving missions have to be executed autonomously. The Sparus II AUV is a low cost, flexible, easy to deploy and to operate platform that can be used for multi-purpose underwater missions. Figure 9 shows the diving Sparus II AUV.

The **Seabotix SARbot MiniROV** is another example for an unmanned underwater vehicle. It is specially designed for search and rescue missions underwater and to be teleoperated over a wired interface from a distance. The platform is equipped with imaging sonar sensor for zero visibility operation and a high-resolution camera for real time imaging. In addition the robot is equipped with a robotic arm that can be used to sample or manipulate objects.

3.2 Manipulators

In robotics mechanical manipulators are used to handle real-world objects. Manipulators have been designed to assist or replace human operation in hazard environments, to handle hazardous, hot or heavy materials, and operate in demanding fields like space and underwater. In addition robotics manipulators are used in precise manipulation like in surgery applications. In rescue robotics the use of manipulators is common practice. The robots are able to interact with the environment, search in inaccessible areas, move obstacles on the way, opening

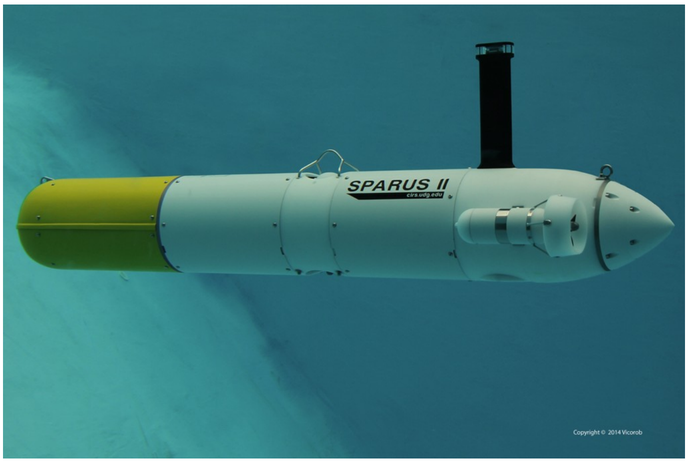

Fig. 9. Sparus II AUV (Photo credit: CIRS - University of Girona - Sparus II AUV)

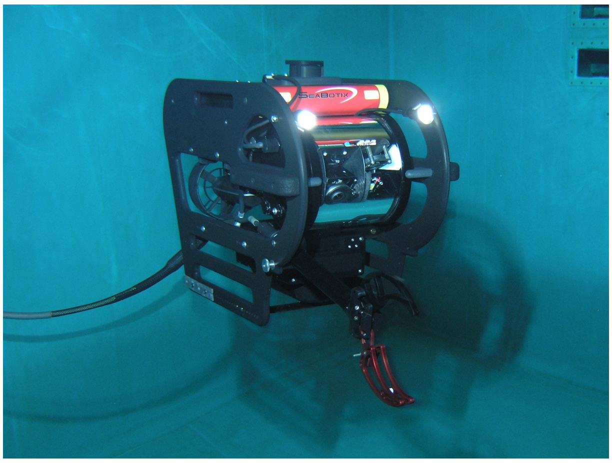

Fig. 10. SeaBotix SARbot MiniROV (Photo credit: SeaBotix Inc. - SARbot MiniROV)

doors, close/open valves, deliver supplies to trapped victims and perform hole inspections.

Attaching a manipulator to a robot base means adding additional degrees of freedom (DOF) to the manipulator. The manipulator becomes mobile. Robotic manipulators are usually build by light but strong material and electrical actuators. There can be other power sources for manipulators but in general the electricity is most common power source. Manipulators usually are equipped with some sensors or a gripper. Sensors are used to inspect the environment, e.g. cameras, gas sensors, laser rage finders to scan given environment. Grip-

Fig. 11. 2-Finger and 3-Finger Adaptive Robot Gripper from Robotiq (Photo credit: Robotiq - Adaptive Robot Gripper)

pers can be simple two-finger gripper or more complex hand-like configurations. More fingers allow for more reliable grasping and object manipulation. Figure 11 shows two example grippers from Robotiq that are compatible with all major industrial robot manufacturers.

In the robot platform section (see Section 3.1) we described three different mobile platforms with manipulator attached.

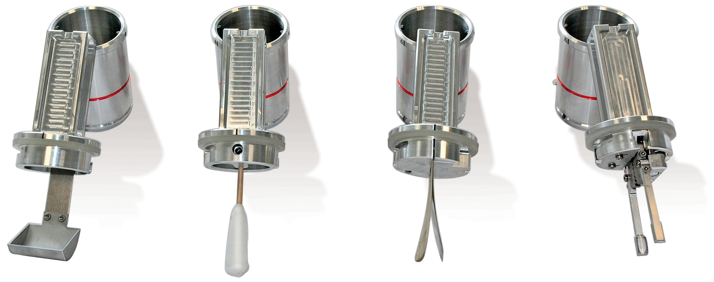

Fig. 12. Cobham NBC MAX sample-taking system (Photo credit: Cobham - NBC MAX)

The **Cobham NBC MAX** (Figure 1) is equipped with a 7-DOF manipulator that provides the operator a large workspace. The robotic arm has multiple mounting points for additional sensors. The arm is equipped with a two finger parallel gripper. The gripper allows to grasp different sensors stored in a holder to collect remote measurements. A specially developed sample-tacking system allows to collect samples of materials from a safe distance (see Figure 12). The arm can be commanded to special predefined configurations in order to make the operation in different tasks easier.

The **Taurob Tracker** as shown in Figure 2 is equipped with an 5-DOF robotic arm. The arm is equipped with different cameras and a parallel gripper. In addition, different measurements units can be mounted to the end-effector. Special predefined arm positions optimize the driving behavior of the robot platform for different undergrounds.

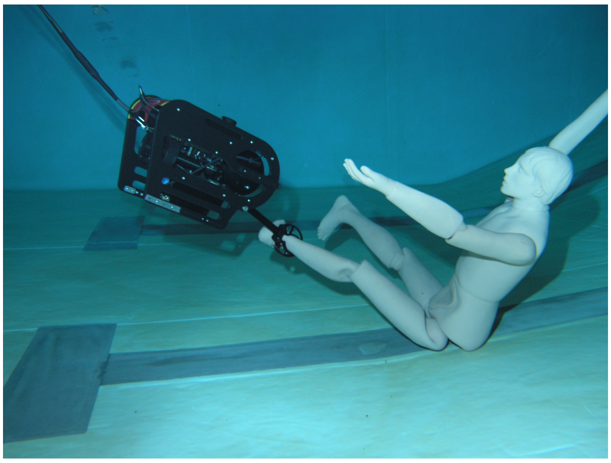

Fig. 13. SeaBotix SARbot MiniROV recovering a person in water (Photo credit: SeaBotix Inc. - SARbot MiniROV)

The **Seabotix SARbot MiniROV** (Figures 10) can be equipped with a limp grabber. The grabber is not movable as the robotic arms described above. Due to the great freedom of movement of an underwater platform this is not a major drawback. It is specially designed to recover a person in the water (see Fig. 13.

3.3 Sensors

This section will give an overview on different sensors for robotics applications. Sensors provide the robot and the operator the ability to observe the environment. This is an essential task during a mission. In the following we will describe different types of sensors useful for search and rescue missions.

Thermal Cameras

Thermal cameras are widespread in the area of mobile robots, especially for search and rescue. They can support search strategies where information of the environment temperature is essential. Thermal cameras are used to detect heat sources or measure temperature of the environment. An example can be seen in Figure 14. Advanced calibrated thermal cameras can provide thermal image with precise temperatures. Low-cost thermal cameras usually provide gray scale image of temperature differences. This kind of cameras need to be calibrated and properly scaled to provide absolute temperatures. Hand-held thermal cameras or wearable thermal cameras mounted on shoulders or helmets of the firefighters are already in use. First responders generally use the thermal cameras to locate hot spots in fires and to locate humans in different scenarios. First responders with professional thermal cameras can find humans in dusty or dark environments.

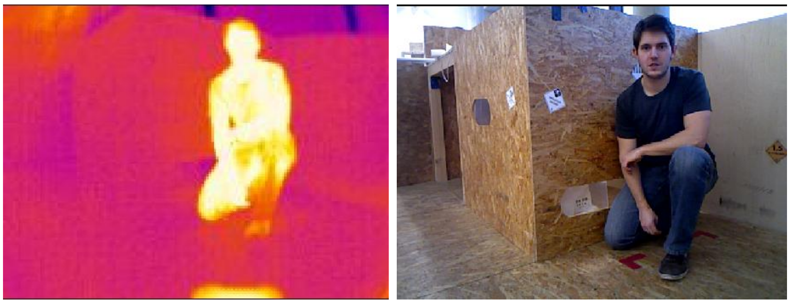

Fig. 14. Example for a thermal image (left) and a regular image (right) of the same scene. (Photo credit: IST - TU Graz)

Gas Sensors

Gas measurements are needed in a broad range of applications like in building automation and medical applications. These applications use several methods to measure the concentration of gases. Gas measurement methods can be divided into chemical and physical techniques. Chemical gas measurement techniques are based on chemical reactions and are often used to indicate if there is any high concentration of gases in the environment. They are not designed to measure continuous values or changes of a concentration. The sensors get easily influenced by environmental conditions (e.g. dust, humidity, etc.) and have a short lifetime. Physical methods to measure gases are mostly based on spectrography. The most common types are Molecular Correlation Spectrography [2], Quartz Enhanced Photoacoustic Spectrography [3] and Infra-Red Spectrography [4].

Laser Range Finders (LRF)

Laser range finders are time-of-flight depth sensor which can be found in various versions. For mobile robots mostly affordable 2D LRFs are used. They conduct measurements in one plane. Individual distance measurements are made at discrete angles. LRFs can provide two-dimensional floor plans in afew milliseconds. An example of a 2D scan can be seen in Figure 16. 3D LFRs can provide almost full scan of the environment and are much more expensive. 3D LRFs are usually limited in their vertical range of measuring environments mostly because of their mechanical constraints. 3D LRF provide millions of points in space in just few seconds. An example 3D scan can be seen in Figure 15. Processing these data requires a lot of computational power. To aquire 3D scans 2D LRFs are commonly used on mobile robots. Sometimes they are mounted on a pan-tilt unit. The pan-tilt unit provides two dimensional degree of freedom, which together with LRF one plane dimensions covers the entire 3D space. The pan and tilt mechanisms usually have similar mechanical constraints as 3D LRFs. The data provided by LRFs are used to build a map of the environment and localize the robot in the environment. This makes LRFs to one of the main environment sensors in robotics.

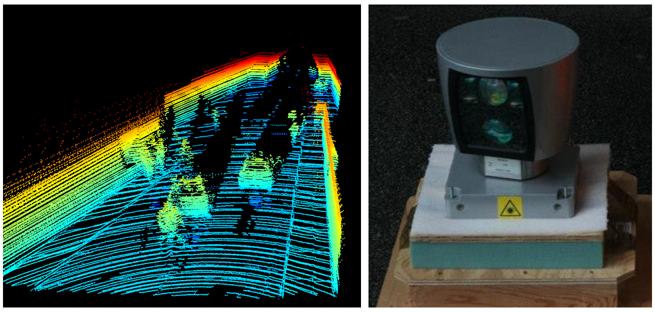

Fig. 15. 3D laser scan (left) taken with a HDL-64E LiDAR from Velodyne (right) (Photo credit: IST - TU Graz)

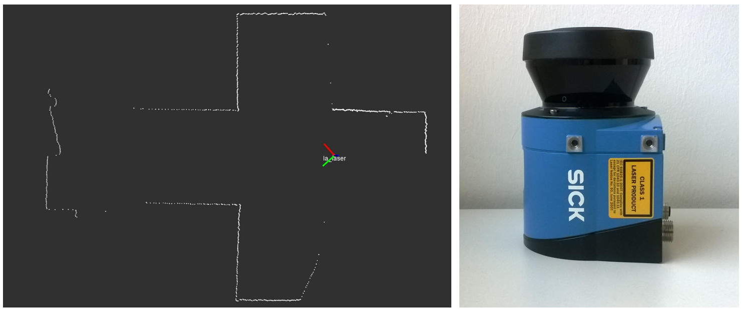

Fig. 16. 2D laser scan (left) taken with a Sick LMS 100 (Photo credit: IST - TU Graz)

Depth Sensors

Depth sensors are similar to LRFs. The depth sensors use different technologies to provide 2D depth images. The sensor returns distance measurements to points in the environment. Figure 17 shows an example of a depth image. The depth cameras usually use pattern projectors, a camera, pattern recognition, and triangulation to evaluate distances. Sensors can also be build up using laser measuring units. In the former case the measurements are limited based on camera resolution. For mobile robots the most popular and affordable sensors are Microsoft Kinect, Asus Xtion, and Intel RealSense. Depth sensors are used to detect ground structures and to digitally reconstruct a given environment. They can also provide depth and color information for each point of the environments which is useful for identifying objects using a combination of RGB and depth information.

Fig. 17. Example for a depth image (left) and an regular image (right) of the same scene. (Photo credit: IST - TU Graz)

Regular Cameras

Visual cameras or color cameras provide information in form of a colored 2D image. Images can hold a lot of information regarding colors and color spectra. The image can also present the relations and sizes based on camera parameters and used lenses. In robotics it is common to use cameras to localize the robot and to detect objects.

Inertial Measurements Unit (IMU)

Inertial measurements units are electro-mechanical devices that measure velocity, orientation, and gravitational forces. They use a combination of accelerometers, gyroscopes, and magnetometers. IMUs are typically used to control aircrafts, including unmanned aerial vehicles (UAVs), and to estimate the position of mobile robots. An IMU can assist a GPS receiver to estimate the robot's pose if GPS-signals are unavailable, e.g. in tunnels, inside buildings, or when electronic interferences are present. IMUs allow a computer to track a robot position using a method known as dead reckoning. For mobile robots IMUs can be used to monitor the attitude of the robot (roll, pitch and yaw) to allow safely maneuvering in an environment.

Global Positioning System (GPS)

The global positioning system is a satellite-based navigation system that provides location and time information in almost all weather conditions anywhere on or near the Earth if there is an unobstructed line of sight to four or more GPS satellites. The system provides critical capabilities to military, civil and commercial users around the world. It is maintained by the United States government and is freely accessible to anyone with a GPS receiver. Mobile robots usually use GPS to locate themselves in open environments or streets in urban environments.

Ground Penetrating Radar (GPR)

Ground Penetrating Radar is a nondestructive measurement method to capture the subsurface. It is based on electromagnetic signals which are reflected from the subsurface structures. It can be used to detect objects and voids in the subsurface. An example for the development of a specialized ground penetrating radar sensor is the BioRadar of the national German I-LOV project, a sensor that is able to detect the human heartbeat of trapped persons [5].

3.4 Operator Stations

The operator station is the main interface for the operator to control the robot, visualize the current robot state and inspect the sensor measurements. The connection from the operator station to the robot is usually established over a radio link. Specialized antennas allow the control of unmanned vehicles up to a distance of several hundreds of kilometers. In special areas like UUV control a wired connection is used because establishing a radio communication to underwater vehicles is hardly possible.

Outdoor laptops are frequently used as operator interface (Figure 18). They provide the robustness to work properly in harsh environments during search and rescue missions. For a reliable operation during a mission it is good practice to split up the task of robot control and sensor analysis to two operator computers. This allows the optimization of the interfaces to improve the visualization with respect to the requirements of the task.

Besides commercially available outdoor laptops specially designed operator interfaces are used. An example can be seen in Figure 19.

Fig. 18. Honeywell T-Hawk^{TM}Operator Station (Photo credit: Honeywell Aerospace - T-Hawk^{TM}MAV)

Fig. 19. Cobham NBC MAX control station (Photo credit: IST - TU Graz)

4 Software

Besides the hardware the control software is an important component of a robot. From a top view the robotics software can be broken down into the following individual modules:

1. Levels of Autonomy
2. Navigation and Control

3. Sensor Data Processing and Environment Representation
4. Human Robot Interaction (HRI) and Cooperation

4.1 Levels of Autonomy

One of the major characteristics of a robot system is its level of autonomy. The level of autonomy defines to what extent a robot system is allowed to decide about actions and to perform these actions without human supervision. There is always the tradeoff between the needs of responders (i.e. having complete control about the equipment) and the interests of researchers in developing intelligent systems.

Teleoperation This is currently the dominant mode of operation of robots in disaster response. Here the operator always has full control over the activities of the robot. The robot only executes the commands from the operator such as driving or grasping commands. The advantage is that the robot only executes commands issued by the responders. For instance this is an important issue in bomb disposal where unintended moves of the robot can be fatal. The drawback of this mode of operation is that the operator and the robot have to be connected all the time (e.g. radio link or tether), the operator has to be well trained in particular for complex robots and that the operation is demanding and exhaustive. Moreover, the operation of such a robot is far from trivial in particular if it is out of sight and only remote sensing (e.g. cameras) is used. A lot of research has been conducted to increase the usability of operator interfaces, the presentation of information and the controller haptics.

Full Autonomy In contrast to teleoperation in fully autonomous operation the robot acts by itself. It only receives a mission goal from the operator (e.g. go to a particular place, observe a given area) and pursuit that goal while reacting to the environment. This is the most complicated setup. But it is the most interesting scenario in terms of research. Moreover, the fully autonomous scenario offers a number of advantages. In particular it frees the operator from the mental load to control the robot all the time and allows the operator to focus on other activities. Although, there exists a number of advantages the usefulness of this mode of operation is still under discussion as responders needs to have control over their equipment, trust in such systems is not yet established and the use of such systems is not foreseen in the operational procedures.

Adjustable Autonomy A promising compromise seems to be adjustable autonomy. Here the robot can be used in both modes, remote controlled and autonomous. This gives the operator the freedom to decide which activities the robot is able to perform safely and reliably on its own (e.g. fly to a given location) and which activities are better performed under human supervision (e.g. open a suspicious box). Moreover, tasks that are cumbersome to perform remotely like open a door can be better performed by the robot itself using the local sensors directly. Therefore, a responders can decide to drive over a problematic terrain manually but then open a door using an autonomous behavior. Adjustable autonomy can also be used as a support to operators. For instance a robot my automatically stop when controlled by a operator and it reaches a attitude where it is likely that the robot fall over. It can be foreseen that this kind of operation will be more and more available and also accepted by the responders in the near future.

4.2 Navigation and Control

The main task of the robot software is the control of actuators to move the robot. The commonly used control technique is teleoperation, where an operator uses an interface to control the robot and complete the tasks. The robot is the tool that allows the human operator to perform the mission from a safe distance.

Fig. 20. Fire fighter testing teleoperation mode.

Besides teleoperation current research and development is done on algorithms that allow robots to perform missions autonomously, without interactions from a human operator. Autonomous applications that are currently developed are exploring a partially collapsed building or fly over a large area to locate missing persons or create a map of the environment. Autonomous algorithms promise benefits over pure manual control in real-world emergency response missions although there is still much development to be done.

The most promising approach is currently the semi-autonomous operation. The incorporation of autonomous task performance and human control has the potential to be much faster. It is expected to be more reliable because failures due to an insufficient situation awareness of the operator, who has to cope with severe bandwidth constraints, are eliminated, and autonomous manipulation requires less operator training than full teleoperation. Promising applications include for example opening doors to continue exploration, open or close valves, and building a temporary wooden structure to support a partially collapsed building.

4.3 Sensor Data Processing and Environment Representation

Robots are equipped with a number of sensors to measure different properties of the environment. The processing of this measurements is an essential step to detect objects of interest in the operational area of the robot. This data processing is also called object recognition. During the robot mission different algorithms are analyzing the sensor measurements to search for trapped and harmed victims, identify sources of danger for the rescue forces and create a map of the traversed environment.

Object recognition is based on the detection of different feature in the environment. The output of different sensors is analyzed to detect different signs of life and other interesting properties of objects, called features. The different features are combined and assigned to objects. This allows the system to detect objects of interest in the environment, mark them in a map, decide to examine objects in detail and report trapped victims to the operator.

Maps are the common representation of the environment. There exist different types of map representations: metric maps, occupancy grid maps and topological map. In robotics applications occupancy grid maps are the most frequently used representation of the environment. Grid maps can either represent two dimensional (2D) floor plan maps, 2.5D elevation maps or full 3D maps of the environment. Grid maps are usually generated using simultaneous localization and mapping (SLAM) algorithms.

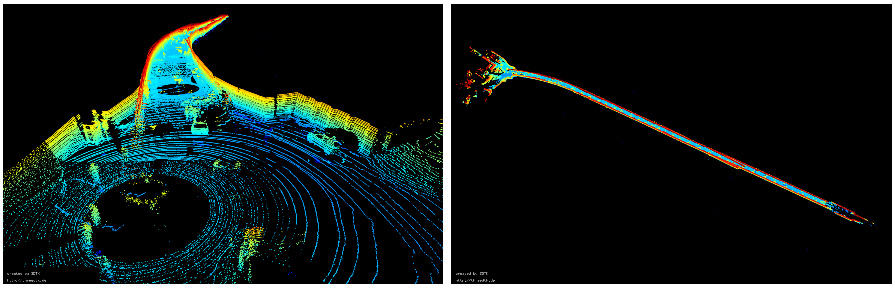

Fig. 21. Reconnaissance Using a Robot in a Tunnel Disaster Exercise: 3D Map of the Entrance (left) and 3D Map of the tunnel (right).

One work dealing with the SLAM problem is presented in [6]. A. Nüchter et al. explored abandoned mines with a tilting laser scanner deploying a 6D simultaneous localization and mapping (SLAM) algorithm. They acquire 3D scans in a stop and go fashion and register these scans with a variant of the Iterative Closest Points (ICP) [7] algorithm which takes roughly 9 seconds per scan. Figure 21 shows a map of a street tunnel generated using this algorithm. A real-time 3D mapping algorithm was presented by J. Pellenz et al. in [8]. Unlike Nüchter et al., their approach does not make use of loop closing (recognizing places already visited before) in their algorithm for performance reasons. Therefore, the algorithm works in real-time using just an ICP approach without loop closing. This comes, however, at the cost of a lower map quality. Other work deploying different sensors for mapping tasks are presented in [9–11]. They combined radar data with thermal sensing technologies.

A common algorithm to construct 2D maps from 2D LRF data is presented in [12]. Figure 22 depicts a map generated during a RoboCup Rescue competition.

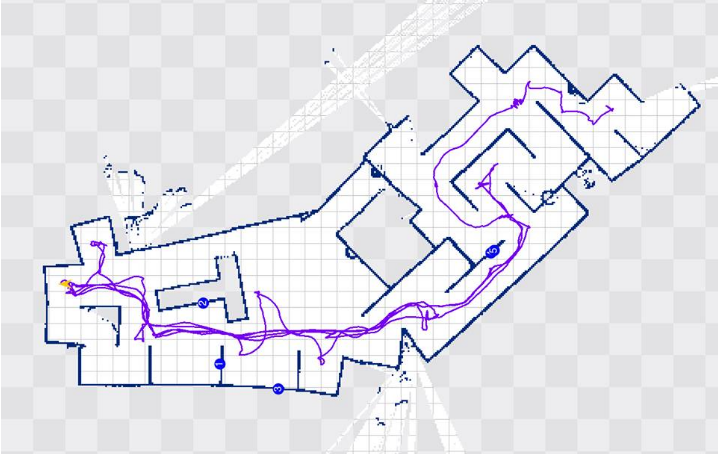

Fig. 22. 2D map showing the floor plan of the arena from the RoboCup Rescue competition in Brazil 2014. The map includes blue labels for objects of interest detected by the robot.

4.4 Human Robot Interaction (HRI) and Cooperation

The cooperation between first responders and robots or the collaboration between different robots is another important aspect in robot control software.

The EU FP7 project NIFTI deals with the problem of cooperation between first responders and rescue robots [13]. The focus of the project is the development of sensors, the advancement of driving and flying robots, as well as the development of methods to allow an autonomous robot to act and react as a member of a team and fulfill a mission together with first responders. To fulfill this purpose it is essential to improve of the robot's understanding of the environment and the activities of other team members, and to develop innovative possibilities of interactions between humans and robots.

5 Application Example

5.1 Domestic Missions

Within the TEDUSAR project the deployment of robot technology was tested in several domestic disaster response exercises. The exercises were mainly conducted together with first responders (e.g. fire brigade, ambulance, police, mountain rescue) within the GOAL project. These missions were great opportunities to test the technical readiness of the robot systems and their potential contribution to future disaster response missions and to obtain serious and objective feedback on the technology by first responders.

In [14] the results of the deployment of robots able to perform mapping in a large exercise were reported. The assumption of the exercise was a collision of a coach and a transporter with dangerous goods in a long street tunnel. The exercise was conducted in the Loiblpass tunnel at the border between Slovenia and Austria. The goal of the deployment of a robot in this mission was to show what off-the-shelf available sensors and public available mapping software can be used to obtain maps of a tunnel (see Figure 23). In particular it was tested how cheap sensors perform in comparison to advanced sensors, how easy the available software can be used, how critical environmental condition such as darkness or smoke affects the sensors, and how the results are accepted by the responders.

Fig. 23. Robot entering the Loiblpass tunnel during exercise. (Photo credit: IST - TU Graz)

During the experiments different 2D and 3D maps of the tunnel were created using different sensors and mapping algorithms. Following the discussion with the responders only detailed 3D maps are useful. Concerning the technical readiness only an advanced 3D laser scanner together with a pointcloud-based mapping algorithm was able to provide satisfying results (see Chapter 4.3) in terms of readiness of the robot. The robot was an research prototype. Therefore, the technical stability of the robot, its sensors and its software system was not satisfying. Moreover, the setup time was too long. Finally, the integration of the robot team into the overall team structure was not optimal leading to delays in providing useful information to the responders. Positive results of the exercise showed that remote operation of a robot via a radio link is possible also in a long tunnel and basically useful 3D maps can be obtained.

In [15] the results of a deployment of a robot for reconnaissance in a disaster response exercise were reported. Using the experience of the previous exercises the focus was laid on easier to use hardware and software (commercially available robot and robust cloud services for data) and an optimized team structure (clear roles within the robot team and a dedicated flight director for the sole interaction with the first responders).

The scenario for the emergency response exercise comprised a burning truck located within a large gas storage facility. There was a high chance for a serious explosions cased by this fire. Moreover, as the type of stored substance was not known in advance there was also a significant risk for the responders and the neighborhood. Prior to the exercise the robot expert team was located at the headquarter of the local fire brigade. The team used a Cobham NBCmax robot which was equipped with several gas sensors and sampling tools for substances. Moreover, the robot was integrated in a special vehicle that allowed for autonomous operation by the robot team and a quick deployment of the robot.

After the alarm went a special team of the fire brigade was ordered to the emergency. Immediately after arriving at the scene the team started to rescue the injured driver of the truck, to close down the area and to start assessing and attacking the fire. Because of the severity of the situation a staff headquarter was setted up and an evacuation of the neighborhood was ordered. At that point the responsible incident command decided to request a robot to help to inspect the facility. Then the robot team got the call and the core of the team moved to the site while the fourth communication member moved to the staff headquarter.

Once arrived at the site the flight director signed in at the incident commander and stayed with him for the rest of the mission as communication relay. Meanwhile, the pilot and the mission specialist set up the robot at the perimeter of the disaster. Here quick deployment was important. The requirement was less than 5 minutes which was met. Than the robot was commanded to accompanying the responders while checking the site (see Figure 24(a)). The pilot drove the robot according the commands of the incident commander while the mission specialist recorded images and measurements. It has to be noted that both acted remotely from outside the facility. In order to minimize the mental load in handling the data and to deal with problems in the communication all data

(a) Robot accompanying responders during reconnaissance.
(b) Robot camera showing leakage..

Fig. 24. Gas storage mission.

from the robot where stored in a dropbox folder. The robot and the mobile devices of the flight director and the communication person where connected via a GSM connection. Using such a cloud service allows to easily tolerate interruptions in the data connection as well as easy distribution of the data. In order to be able to most utilize the data all recorded data are augmented by their GPS location and additional comments from the mission specialist. Here again a standard extended image format was used for simplicity. Therefore, there is no need to install additional software on the mobile devices. Using this approach the flight commander/incident commander and the communication officer/staff where able to see data and images collected by the robot in nearly real-time.

Another highlight of the deployment was that using the robot it was quickly possible to identify a gas leakage at one storage tank. The leakage was introduced to give a surprising aspect to the responders. Using the on-board gas sensors of the robot, the on-board camera, a distance sensor on the robot arm and the user-interface it was possible to locate and also mark the leakage (see Figure 24(b)). Immediately after the marking by the mission specialist the data were available to the incident commander and the staff. Thus, they were timely able to command a special team with protective suits to seal the leakage. Moreover, the staff nearly in real-time were able to monitor the development of the situation in order to make higher level decisions such as ordering evacuation.

Focusing on robust commercially available hardware, a software solution that can deal with interruptions of data links and a rigorous team structure the deployment was eased and the acceptance by the responders was increased.

5.2 International Missions

There are a few examples of robot operations in disaster situations or crises.

Some interesting examples of robot applications originate from Prof. Robin Murphy from Center for Robot-Assisted Search and Rescue (CRASAR) of Texas A&M University in the USA. This research group makes robots and experts available for operations in disaster situations. Two use cases of the group dealt with the examination of consequences of hurricanes.

In 2005 after the hurricane Wilma flying robots equipped with cameras and swimming robots equipped with sonar were used examine inaccessible houses and inspect damage of bridges, piers and dams [16]. The operations shown that robot technologies can provide additional information about the situation after a catastrophe. In addition it was shown that for an efficient operation of robots in such applications a team consisting of flight director, mission specialist and pilot is required. The flight director is responsible for the safe execution of the overall mission, the pilot is the only person that operates the robot and the mission specialist is responsible to collect and process sensor information [17]. This team structure established nowadays as standard for robot operations in disaster situation.

Further successful robot applications of the group from Texas is the inspection of a bridge after the hurricane Ike in 2008 [18] and the examination of a collapsed public garage in 2007 [19].

A less successful example for the application of robots is the collapse of the Cologne City Archive in 2009 [20]. Due to the special dense structure of the rubble and changeover to rain it was not possible to use robots to search for trapped victims. One the reasons for that was the inappropriate shape of the robot (large concrete lumps in front of the building and small voids inside the ruin). Another reason were security concerns of the operation control (slippery rubble). Even if robots were not directly used new findings were made.

A very interesting application of robot technologies (reconnaissance drones) was carried out after destruction of a power plant through the explosion of a ammunition depot in Cyprus [21]. This use case is interesting due to three factors. First, the robots were requested via the European Civil Protection Mechanism (EUCP), an European project that allow to request external expertise in case of disaster situations. Second, the organization "Deutschen Zentrum fr Luft- und Raumfahrt (DLR)" provided satellite-based images of the destroyed region and in addition flying robots equipped with cameras to generated images and a 3D map of the destroyed power plant. Third, the team structure for the operation were refined to satisfy increased security requirements on site (scattered ammunition, oil leaks) and to allow the integration of additional experts (structural and electrical engineers) into the mission.

A further successful example for the use of flying and driving robots in an real situation is the inspection of damages cultural monuments after an earthquake in 2012 in the Italian region Emilia-Romagna [22]. The robots for the operation were developed as part of the EU FP7 project NIFTI. The robots were used to record videos and generate 3D maps of inaccessible parts of a collapsed church to allow first responders an assessment of the damage and assist further planning. The results from this assignment demonstrated the technical progress (precise 3D mapping) and enabled to improve the cooperation between first responders and the robotics team.

All this examples show that the developed is mature to assist and help first responders during their missions. However, the complexity of robot technologies require the presence of expert teams at the site.

In [23] a report was given on two missions where robots were deployed after the great earthquake in Japan in 2011. Expert teams from the Japanese International Rescue Institute (IRS) and the Center for Robot-Assisted Search and Rescue (CRASAR) from the U.S. were activated to join mitigation activities. The mission was to inspect harbors for damages of underwater structures, debris that may endanger ship traffic, and sunken cars. The primary goal was to direct removal activities efficiently in order to restore the harbor activities quickly, e.g. local fishing industry. The activities did not take place immediately during the direct disaster response. Mission one was conducted a couple of weeks after the disaster while mission two took place several month later. In both missions professional underwater vehicles were deployed. Due to the short preparation time and missing experience in the first mission the robot were mainly equipped with simple sensors like sensors and sonars. This setup allowed for inspecting a bay area for debris and to map the important pieces in a simple Google map using their GPS position. In the second mission robots equipped with sensors capable to map areas and advanced GIS software were used. This improved setup was based on the experiences collected in the first mission and allowed for a much more systematic and planned reconnaissance process and a better representation of the results in an integrated graphical representation. This detailed information were used by the local authorities to guide removal activities and the ship traffic. Although, the activities were not conducted in the immediate response actions they contributed to a faster recovery of the local fishing industry and provided invaluable lesses for the systematic and quick deployment of robot systems.

For large occurrences there already exist satellite-based and airborne services to gather a situation picture for security-related mission scenarios. The European program Copernicus (European Earth Observation Program) provides satellite-based pictures to improve the management of natural disaster. An example of how the service can improve the disaster response are predictions made during the extensive flooding in Germany in the summer of 2013 and the monitoring of storms and the estimation of damage during the typhoon over the Philippines in November 2013.

6 Conclusion

Robotics technology made a tremendous development during the last decades. The development of powerful ground and aerial vehicles, light-weight and powerful sensors and advanced control- and analyzing algorithms made this technology also very interesting for first responders and disaster response. But the application to disaster mitigation is difficult and can only be achieved in a close cooperation among responders, developers and researchers. Many different advanced methods and robotics systems had been proposed to responders. But there are only a few successful cases where robotics technology has been deployed in real missions.

In order to foster a deeper understanding of the technology and close discussion with the responders we presented in this paper a brief overview of the state of the art in robotics in connection with disaster response. We discussed potential application scenarios, hardware, software and field reports. So far only a few robot systems made it into a real mission. The reasons for that are manifold. Mainly we see a lack of technical maturity of the systems but also a lack of understanding of the real needs of responders as well as a lack of communication of the potential to the responders. We see this paper as a first step to overcome these limitations and to stimulate an open and cooperative discussion about the use of this technology. There is clearly a potential for the use of robotics technology in disaster mitigation. But the useful and reasonable application scenarios will be rather simple for the next years mainly focusing on reconnaissance with UAVs. We are convinced that a continuous exchange between responders and researchers will break the ground for more interesting missions in the future.

But besides the technical problems there are also a number of other issues that hinder the broad application of robotics technology. First, there are legal issues. There is a lack of regulations for the use of robots in public, in particular for UAVs. Second, the issue of liability has to be discussed. Third, useful use-cases have to be identified and integrated in the operational procedures of the responders. Finally, the quality of service has to be ensured. Here the question is how the robot operators are trained and certified as well as how the robot systems have to be maintained in order to ensure proper operation.

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	Actually					3-10 Years				
	Ground	Air	Underwater	Surface	Combined	Ground	Air	Underwater	Surface	Combined
Reconnaissance	0	+	-	-	-	0	+	0	0	0
Reconnaissance - autonomous	-	-	-	-	-	0	+	0	0	-
Reconnaissance - team -	0	-	-	-	0	+	0	0	0	0
Hazard Material Handling	0	-	-	-	-	+	-	0	0	0
Search for Missing Persons	-	0	-	-	-	0	+	-	0	0
Search for Missing Persons - autonomous -	-	-	-	-	-	0	+	-	-	-
Search for Missing Persons - team	-	-	-	-	-	0	+	-	-	0

Table 1. Overview Application Scenarios for Robotics Technology. + represents a high change for realization. - represents a very low chance. 0 is neutral.