Current state of the art of unmanned systems with potential to be used for radiation measurements and sampling

ERNCIP thematic group
Radiological and nuclear threats to critical infrastructure
Task 3 deliverable 1

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Related ERNCIP documents:

1. List-mode data acquisition based on digital electronics (EUR 26715)
2. Critical parameters and performance tests for the evaluation of digital data acquisition hardware (EUR 26976)
3. Remote expert support of field teams — Reachback services for nuclear security (EUR 27099)
4. Possible scenarios for radiation measurements and sampling using unmanned systems. in preparation.

Executive Summary

There is a significant potential in the use of unmanned remote controlled vehicles in sampling and measuring radiological events. No attempts to standardise sampling and measurement methods using these types of vehicles have yet been made. Common standards would simplify the use of remote controlled vehicles in an emergency scenario and would thus be very valuable in critical infrastructure protection (CIP). The main advantage of using unmanned systems in radiological events is the protection of the human personnel involved.

This report is about current state-of-the-art of unmanned systems that have potential to be used for radiation measurements and sampling. It is believed that search and rescue robotics is the domain that is closest to the robots applicable to the radiation measurement scenarios. Therefore, a definition for search and rescue robots and outlines of their major subsystems are given. This is followed by a review of deployment scenarios for search and rescue robots outlining case studies of major emergencies at which robots have been deployed — with an assessment of their value to the emergency services. Additionally, research and development in search and rescue robotics, including current projects, testing environments and search and rescue robotics competitions, is outlined.

Furthermore, this report shows unmanned robots and concepts for sensor systems capable of radiation detection based on state-of-the-art radiation sampling using unmanned ground vehicles, unmanned aerial vehicles with rotary wings or unmanned aerial vehicles with fixed wings.

Contents

Acronyms

BfS	Bundesamt für Strahlenschutz – Federal Office for radiation protection (Germany)
BRD	backpack radiation detector
CBRNE (CBRN-E)	chemical, biological, radiological, nuclear and explosive
CEA	Commissariat à l'énergie atomique et aux énergies alternatives — French atomic and alternative energy commission
CEN	Comité européen de normalisation — European Committee for Standardisation
Cenelec	Comité européen de normalisation électrotechnique — European Committee for Electrotechnical Standardisation
CSIC	Institutional Repository of the Spanish National Research Council
DEMA	Danish Emergency Management Agency
EDA	European Defence Agency
ERNCIP	European Reference Network for Critical Infrastructure Protection (European Commission)
HASS	high-activity sealed sources
HC	Health Canada
IAEA	International Atomic Energy Agency
IND	improvised nuclear device
IRSN	Institut de Radioprotection et de Sûreté Nucléaire – French national public expert in nuclear and radiological risks
JRC	Joint Research Centre, the European Commission's in-house science service
LHC	Large Hadron Collider
LML	Linssi markup language (XML)
MORC	material out of regulatory control
NaI	sodium iodide, scintillator crystal used in gamma spectrometer
NATO	North Atlantic Treaty Organisation
NBC	nuclear, biological, chemical
NEN	Netherlands Standardisation Institute
NIST	National Institute of Standards and Technology (United States)
NORM	naturally occurring radioactive material
NPL	National Physical Laboratory (United Kingdom)
NSDA	nuclear security detection architecture
PRD	personal radiation detector
RDD	radiological dispersal device
RED	radiation exposure device
RID	radionuclide identification detector
RN	radioactive and nuclear materials
RPM	radiation portal monitor
SPRD	spectroscopy-based personal radiation detector
SRPM	spectroscopy-based radiation portal monitor
SQL	structured query language
SSTC-NRC	State Scientific and Technical Centre for Nuclear and Radiation Safety (Ukraine)
STUK	Säteilyturvakeskus — Radiation and Nuclear Safety Authority (Finland)
UAV	unmanned aerial vehicle
WLCG	worldwide LHC computing grid
XML	extensible markup language

1. Introduction

There are several measurement and sampling scenarios that are too risky for humans to carry out. For these scenarios, remote controlled radiation measurements and sampling, using robots needs to be developed. Note that the use of remote controlled devices, such as unmanned ground vehicles (UGVs) and small size unmanned planes (UAVs) may be more cost effective than the use of manned vehicles or planes. Decontamination of the measurement system and related costs should be taken into account. Situations envisaged for the use of remote controlled measurement and sampling devices are:

- reactor supervision and related accidents, such as Chernobyl and Fukushima;
- dirty bombs before or after an explosion;
- search of sources out of regulatory control;
- long-term measurements.

Incidents such as Fukushima and Chernobyl, as well as the decommissioning of old nuclear power plants, have taught us that robots have some advantages. Robots can operate in areas with high radiation or danger of explosives (e.g. boiling liquid expanding vapour explosions (BLEVEs), collapsing structures, improvised explosive devices (IEDs), booby traps and heat). Additionally, they have the ability to manipulate the environment and to take potentially heavy samples, as they usually have a high payload. Robots can also be used for long-time surveying in contaminated areas and monitoring the movements of a threat with real-time data from multiple mobile sensors.

Despite the huge potential presented by the use of remotely controlled robots, no standards for sampling or taking measurements have been developed for these systems. The development of such methods could prove to be very beneficial to critical infrastructure protection (CIP). For example, use of unmanned aerial vehicles to perform standardised measurements of the radioactive plume from a nuclear reactor incident or dirty bomb explosion is of tremendous importance to emergency response personnel. This type of information could be used in atmospheric transport modelling calculations that are important parts of the decision support systems. Thus, this topic contributes to CIP by enhancing the infield operation capability.

The European Reference Network for Critical Infrastructure Protection (Erncip) ([1]) has established a Thematic Group on the Protection of Critical Infrastructure from Radiological and Nuclear Threats (the 'RN thematic group'). The group looks at issues such as certification of radiation detectors, standardisation of deployment protocols, response procedures and communication to the public, for example in the event of criminal or unauthorised acts involving nuclear or other radioactive material out of regulatory control. In short, the focus of the RN Thematic Group is to advise CEN/Cenelec on standardising formats and protocols used in sending the collected data to enable further analysis. The issue is closely related to the opportunity, opened up by the current developments in technology, of utilising remote support of field teams (reachback) for radiation detection.

The RN thematic group works with the following three issues:

([1]) The Erncip office operates within the organisational framework of the Institute for the Protection and Security of the Citizen (IPSC) of the European Commission's Joint Research Centre. The institute provides scientific and technological support to European Union policies in different areas, including global stability and security, crisis management, maritime and fisheries policies and the protection of critical infrastructures. IPSC works in close collaboration with research centres, universities, private companies and international organisations in a concerted effort to develop research-based solutions for the security and protection of citizens. The Erncip mission is to foster the emergence of innovative, qualified, efficient and competitive security solutions, through the networking of European experimental capabilities. The Erncip office has been mandated by the Directorate-General for Migration and Home Affairs (DG HOME) of the European Commission.

1. **List-mode data acquisition based on digital electronics**. A time-stamped list-mode data format produces significant benefit compared to the more conventional spectrum data format. It improves source localisation and allows signal-to-noise optimisation and noise filtering, with some new gamma and neutron detectors actually requiring list-mode data to function. The list-mode approach also allows precise time synchronisation of multiple detectors enabling simultaneous singles and coincidence spectrometry such as singles gamma and ultra violet-gated gamma spectrometry.

2. **Expert support of field teams**, i.e. data moves instead of people and samples. A fast and high-quality response can be achieved with fewer people. Optimal formats and protocols are needed for efficient communication between frontline officers and the reachback centre.

3. **Remote-controlled radiation measurements and sampling using unmanned systems**. There are several measurement and sampling scenarios that are too risky for humans to carry out. Applications envisaged are reactor and other accidents, dirty bombs before and after explosion and the search of nuclear and other radioactive material out of regulatory control.

This report deals with the third item, remote-controlled radiation measurements and sampling using unmanned systems, and will present the current state of the art in robotics for this domain.

2. Deployment scenarios

The aim of this section is to provide a comprehensive review of the state of the art in search and rescue (SAR) robotics. This domain of robotics is believed to be the one that is closest to the robots applicable to the radiation measurement scenarios. This section first proposes a definition for search and rescue robots, and outlines their major subsystems. This is followed by a review of deployment scenarios for search and rescue robots, outlining case studies of major emergencies at which robots have been deployed — with an assessment of their value to the emergency services. The section outlines research and development in search and rescue robotics, including current projects, testing environments and search and rescue robotics competitions.

2.1. Definition of search and rescue robots and their major subsystems

A search and rescue robot is a mobile robot whose primary function is to support emergency workers in their efforts to search for survivors, or critical hazards, at the scene of an accident, emergency or disaster. Key characteristics of all search and rescue robots are:

- being able to operate in **challenging** and often unknown **environments**, which may be outdoors, or in enclosed structures (i.e. buildings or tunnels);
- being **mobile,** search and rescue robots must be sufficiently agile or versatile to cope with broken terrain and steps and stairs (if ground robots), etc.;
- search and rescue robots must be equipped with **sensors** for mapping and searching their environment as well as detecting environmental hazards, and video cameras for human monitoring and control;
- search and rescue robots need two **human interfaces**: one for any humans working in the field alongside the robot, and another for the remote teleoperator (although these might be the same person);
- optionally, search and rescue robots need to be equipped with multi-axis **manipulator**(s) and end effectors (**grippers**), to allow direct physical intervention by the robot — under human control.

The design of any search and rescue robot, whether operating alone or as part of a multi-robot team, will necessarily follow a similar basic pattern. The robot will require:

- one or more sensors, with which it can both sense its environment for safe navigation and detect the objects or people it is searching for;
- actuators for both locomotion through the environment and for physically effecting a rescue;
- a control system to provide the robot with — at the very least — a set of basic reflex behaviours.

Since robots are machines that perform work, which requires energy, power management is also very important.

Normally, a communication transceiver is also a requirement, either to allow remote teleoperation or monitoring or, in the case of multi-robot collective search and rescue, for robot–robot communications. A search and rescue robot is therefore a complex set of interconnected subsystems and, although its system-level structure may follow a standard pattern, the shape and form of the robot will vary significantly depending upon its intended environment and application.

2.2. Deployments of search and rescue robotics technology

2.2.1. Chernobyl

The first major catastrophe that gave an impetus for the use of robots is undoubtedly the nuclear accident in Chernobyl, Ukraine.
On 26 April 1986, a stress test of reactor No 4 at the Chernobyl nuclear power plant resulted in a power excursion, which caused the reactor to explode ([2]). This explosion left the core wide open, with over 13 tons of radioactive debris scattered over a large area. The radiation close to the reactor at that time exceeded 35 Gy per hour, which is enough to give a lethal dosage within a few minutes of exposure.
In the following immediate countermeasures, the debris had to be put back onto the core. The first obvious choice was to send in robots. A consortium of 13 different research facilities developed a total of 15 different types of robots. The equipment assembled included remote-controlled robots that could detect radioactivity and carry radioactive debris. The large majority of these robots were used to clear the roofs and machine rooms.
The use of these robots can be divided into two phases. In the first, immediate response phase in 1986–87, the robots were used as excavators and bulldozers to move the radioactive debris back onto the open core. In addition, the vehicles were used to detect, measure and map the radioactivity in all contaminated areas.
The second phase using robots was the building support and inspection of the 'sarcophagus,' i.e. the concrete shelter built around the broken reactor.
The robots used in these activities included:

- Wedge-1,
- Special transport robot (PP-1) — Wedge-2,
- Mobot-W-HV and Mobot-W-HV-2,
- MF-2 and MF-3,
- BAER ('Beloyarets'),
- Bauman-2,
- TR-B1,
- RTC 'Vanguard',
- PP-G1 (reconnaissance robot).

Most of these systems failed very quickly due to the high radiation. Valery Legasov, the first deputy director of the Kurchatov Institute of Atomic Energy in Moscow, said in 1987: 'But we learned that robots are not the great remedy for everything. Where there was very high radiation, the robot ceased to be a robot—the electronics quit working.' At that point, the human 'liquidators' had to do their heroic work. Using shovels and crowbars, they continued where the robots had failed, but were only allowed to work for approximately 40 seconds in the vicinity of the core because of the high radiation doses.
Probably the best-known robot is the STR-1 (Wedge) which is based on the moon rover 'Lunokhod'. It was made of titanium and had a weight of 1 100 kg. The vehicle's top speed was around 1 km/h, being propelled by wheel hub motors. The energy source was two silver zinc batteries. Available

([2]) http://www.oecd-nea.org/rp/reports/2003/nea3508-chernobyl.pdf

sources state that the robot was operated by radio and therefore had no problems of getting tied up in its own cables.
Also used was the Mobot-W-HV, a track-based chassis weighing about 450 kg and equipped with a sort of bucket shovel. The system was remote controlled, with power supplied through a cable. It is claimed that the system was operational for over 1 000 hours and that it cleared about 11 000 m^2. The first version was used on the rooftop while the second version was used on the sarcophagus in late 1987.
Sources differ on the usefulness of the robots: some claim that they were of some use, while other sources claim that they were of very little use. It is however clear from information, which has emerged during the past 25 years since the accident, that the robots must have been useful at least in the second phase and later on for inspecting and maintaining the sarcophagus and its entrails.
Most of the problems were caused by the high energetic radiation that affected not only the printed circuits, electronic components and radio links but also, quite seriously, the batteries. This led to the use of tethered robots for the communication and the power supply — which unfortunately induced the problem of them getting stuck by enlacing themselves.
The catastrophe gave a huge boost to research and development in this field of Russian robotics. A couple of research facilities specialised in ‘extreme robotics’, as it is now called. Focus areas at that time were new concepts of locomotion, energy supply, autonomy and teleoperation.
The robotics research and development that remains today, after many budget cuts, is coordinated by the Ministry of the Russian Federation for Civil Defence, Emergencies and Elimination of Consequence of Natural Disasters.

2.2.2. 9/11 — World Trade Centre — New York City

On 11 September 2001 two hijacked airplanes, American Airlines Flight 11 and United Airlines Flight 175 crashed into the World Trade Centre complex in New York City.
The buildings were flooded with approximately 58 tons of kerosene from the crashed aircraft. Within 2 hours, the resulting firestorm — which reached over 1 000 °C — and the damage done by the aircraft weakened the building structures severely.

Collapsed buildings	Height	Number of floors
WTC 1 (hit by plane)	415m	110
WTC 2 (hit by plane)	415m	110
WTC 3 (hit by debris)	85m	22
WTC 7 (hit by debris)	174m	47

Both towers (World Trade Centre 1 + 2) collapsed, in turn causing the partial or complete collapse of other buildings in the complex, as well as significant damage to 10 other large surrounding structures. Debris was scattered within a radius of about 500 m around the World Trade Centre complex.
Most of the nearby infrastructure was destroyed. In the initial hours, almost no stable electricity, water or means of communication was available. Even wireless communication (radio, mobile, etc.) was heavily affected. The access to the adjoining roads was blocked.
As one can deduce from the table above, the pile of rubble and debris was tremendous. The scene was flooded and later on covered with smoke, dust and concrete powder. Most of the buildings collapsed like houses of cards, some in a pancake manner, resulting in the formation of a huge number of caves and caverns.
These were the hours of the robots. Most probably, this incident led to the first serious attempts to use robots for search and rescue missions.

Several companies and the Centre for Robot-Assisted Search and Rescue[3] sped to the World Trade Centre with the intention of supporting the rescue forces. The robots were mainly used to do reconnaissance in areas and confined spaces that were inaccessible because of their small openings or the danger of collapse. None of the robots actually 'rescued' a victim in the sense that it pulled or dragged out a person.

The vast majority of the robots faced serious mobility problems when traversing the collapsed structures. Irregular structures and patterns of rubble, steel reinforcements, pipes, cables, glass, fine dust and even office furniture turned the scene into a obstacle course that was far from what had ever been tested before.

These problems were also closely enmeshed with the fact that the visibility and orientation (some would say 'situation awareness') was more than limited. On the video sensor side, the right combination of equipment was lacking. It transpired that the right kind of cameras like (day and night, thermal), searchlights (normal and infrared) and radar arrangement were not found. Additionally, the ability to pan/tilt the optical sensors was missing, and two-way audio communication on the robots was not available.

Since there was no global positioning system (GPS) inside the buildings, magnetic compasses were used for navigation but proved useless due to the concrete and steel environment. Therefore, if the operator made the robot turn a couple of times it was hard to imagine where the robot was actually heading.

Another aspect is the failure of communication. Radio communication is hard in this type of environment. In addition, the lack of radio communication systems resistant to interference led to the use of inappropriate radio links, while the obvious alternative of using a cable (copper, fibre or otherwise) was not used.

Using a tethered robot could instead have provided a system with power and an interference-free communication interface. A cable could also be used to pull the robot out of a building or to lower the robot through holes. However, a cable has a strong tendency to tangle and, additionally, can be damaged or even severed by the robot, especially if it is tracked. Still, the conclusion from the use of robots in real scenarios has been that using a cable is better than the currently available radio communication.

If your radio is bad, you usually go for autonomy. However, no autonomy was shown or used by any of these robots, which can hardly be a surprise to anyone in the robotics field.

Summing up all these hardware disabilities, it is of no surprise that none of the robots was able to penetrate more than 10–60 metres with the scene.

The disappointing conclusion of Robin Murphy is that the benefit of using robots was very limited (Casper and Murphy, 2003).

2.2.3. Fukushima Daiichi

On 11 March 2011, a series of earthquakes with the strength of M_W 6.4–9.0 close to Japan's Miyagi prefecture ([4]) initiated the meltdown of three nuclear reactors. The meltdowns caused the release of substantial amounts of radioactivity, which contaminated large areas of land around the power plant.

Japan's oldest and most powerful nuclear power plant, with its six reactors, Fukushima Daiichi is located not very far from the epicentre of the earthquakes on the coast. The shockwaves initiated an automatic shutdown of Fukushima's reactors 1 to 3. Reactors 4 to 6 were offline because of maintenance. Even so, the tremor of the shockwave exceeded the upper limiting value of reactors 2, 3 and 5 by over 20 %. This was just the beginning of the catastrophe.

Sea-based earthquakes are typically followed by tsunamis. A couple of tsunami waves with heights of up to 15–23 meters hit the site. The waves flooded the emergency generators and their fuel tanks and

([3]) http://crasar.org/

([4]) Also known as the Tōhoku or Sendai earthquake.

destroyed the seawater pumps that are part of the cooling system. This was the deathblow for the cooling system.
In the series of technical breakdowns that followed, the emergency cooling systems failed. As the cooling water in the reactors boiled off, large amounts of hydrogen gas were released. This exploded and seriously damaged the reactor buildings, as well as the efforts of the power plant personnel to cool the reactors. In the end reactor cores 1, 2 and 3 experienced partial or complete meltdowns. The incident is categorised at level 7, the highest level of the International Nuclear Event Scale.
Japan did not have any nuclear emergency response unit with appropriate robots (such as KHG in Germany or Emercom in Russia) to cope with a nuclear incident. The robots that had been developed for this purpose about 10 years previously had not been maintained and were therefore not functional. Because of their size and weight, they would probably have been of little use.
Therefore, the first robot on the scene came from abroad, and later Japan successfully developed systems of its own. The robots were first used for reconnaissance and to measure temperature, pressure and radioactivity, especially in the areas with a high risk to human life. Some of the robots were later also used to install nitrogen pipes in reactor 2.
Not only the radiation but also the hot steam and scrap metal (which risked ripping the protection suits) posed a serious threat for all human personnel. In some areas, the robots measured between 2–4 Sv/h. In addition to problems which were similar to the ones described for the World Trade Centre environment (rubble, pipes, cables, etc.), the robots had to contend with the special construction of nuclear facilities. There were a lot of stairs, closed and heavy containment doors, high temperatures and humidity (90 %). The later caused the camera lenses to be fogged. The high air temperature caused several electronics boards to overheat and the robots had to pause to cool down.
Surprisingly, the radiation did not affect the robots as much as expected. The Japanese robot withstood a dose of over 100 Gy for a couple of hours without any serious malfunctions. It looks like modern (commercial and consumer) hardware does not need as much shielding as formerly expected.
However, not surprisingly the radio communication did not work. Beside the problems induced by the radiation itself, the fact that the buildings were designed to withstand high pressures and act as a radiation shield meant that radio communication was also effectively blocked.
Switching to cable-based communication resulted in the same problems experienced by the World Trade Centre teams: tangled, damaged and severed tethers. Not only did the environment pose a threat to the cables but also the tracks of the robot itself. The Japanese team later used a combination of wireless local area network (WLAN) access points and tethered networks to enhance the cable-free locomotion of the robot in certain areas. The best solution proved to be a combination of wireless and wired communication.
The amount of ‘autonomy’ that was shown in Fukushima can probably better be classified as ‘assistance functions’ rather then what is understood as classical autonomy. The vast majority of operations were purely remotely operated. The background knowledge needed to operate in such a complex environment can hardly be expected from an ‘autonomous’ robot system.
Nevertheless, the robots could not cope with these scenarios, leading Tokyo Electric Power Company, Incorporated (TEPCO) official Takeshi Makigami to conclude that robots are limited in what they can do and eventually ‘people must enter the buildings’. The knowledge needed to operate robot systems in such a special and complex environment was not yet available.

2.3. Present and future scenarios for search and rescue robot deployment

2.3.1. Scenario definition

Before going into detail regarding present and future scenarios a clear outline should be given of what classical ‘search and rescue’ really means.

Search and rescue is defined internationally as the search for and provision of aid to people who are in distress or imminent danger.
Historically, the term comes from the sea domain and refers to all scenarios around ship wreckage. Of course, water landings of aircraft are also standard sea search and rescue missions today. The typical tools today are helicopters, aircraft and specialized ships. Also quite classical is mountain search and rescue, which is done with dogs and helicopters. Ground-based search and rescue emerged with air traffic. If an aircraft did not come down over the sea, the search and rescue mission had to be carried out in whatever environment it came down in, such as rain forest, desert, mountains, swamp or even the Arctic. Helicopters and planes are the natural choice to survey large areas quickly and to reach people in distress.
These search and rescue missions can be more or less seen as a sort of response to an SOS call. All of them have their focus on 'locate' and 'pickup'. In these scenarios, environmental factors such as weather, as well as injuries, have to be taken into account.

Figure 1: Hazardous operations and emergency response in the intersection between emergency services, (para-)military and law enforcement

The newer search and rescue (SAR) missions like the 'urban SAR', special medical evacuation and combat search and rescue deal additionally with threats made by humans.
The military version of search and rescue usually includes the risk of being threatened by enemy forces during a search and rescue mission. The threat might include snipers; mines; chemical, biological, radiological, nuclear and high-yield explosives (CBRNE) involvement; improvised explosive devices (IEDs) or artillery fire. Additionally, military search and rescue might also refer to the liberation of prisoners. However, this very important field of search and rescue is also a very special one regarding its overall circumstances.
Urban search and rescue is a relatively new field. It refers mostly to scenarios that involve damaged or collapsed (large) human-made structures. A collapsed building would be a classic example. Mines or tunnels also fall into this category. In most countries, the handling is associated with fire brigades. The 'tool' with the longest tradition in these scenarios is still the dog.

Both of these fields include missions that extend over the classic search and rescue scenarios. Tasks like reconnaissance and mapping, removing or shoring up rubble, delivery of supplies, medical treatment and evacuation were not part of the core activities within classical search and rescue.
The lines between search and rescue, civil protection/defence agencies, emergency services/management/relief/response and disaster management are fluid and a full disambiguation is far beyond this article.
In the rest of this section we will broaden the view from simple search and rescue to 'hazardous operations' and 'emergency response', known as Hazoper for short, missions. This will also allow the inclusion of fabricated and natural disasters, as well as terrorism and acts of war.

2.3.2. Current robot-supported scenarios

The real world scenario with the longest (non-military ([5])) history of robotic use is surely bomb disposal. It is also the most successful branch economically. The 'birth' of bomb disposal robots occurred during the height of the conflicts in Northern Ireland in the 1970s. Since then it has evolved to the strongest and biggest market for ground-based robots. These robots are often also used for hazardous operations and emergency response and similar missions. The reason for this is not that these robots are generally good for hazardous operations and emergency response missions but they are simply the only professional ones commercially available.
Another scenario that has recently seen strong growth (at least in Russia) is robots for firefighting. The application has been around for quite a while and there have been a number of individual attempts by fire brigades to use robots in fire extinction. Here robots are also used to measure toxic industrial chemicals (TICs) and do visual reconnaissance with video or thermal cameras. In most cases, the chassis used came from bomb disposal robots. Also new on the market are remotely operated water cannons combined with a sort of turbine.
Since the Ministry of the Russian Federation for Civil Defence, Emergencies and Elimination of Consequence of Natural Disasters (EMERCOM) had capacity for robotics increased it has come up with a complete fleet of 'emergency' robots.
A part of this taskforce consists of defence material like tanks but some are new developments. Most of the vehicles focus on firefighting but there are also strong efforts in the area of elimination of consequences of radiological and nuclear disasters. Emercom's field of responsibilities includes the whole hazardous operations and emergency response spectrum.
The later application is quite similar to that of Kerntechnischer Hilfsdienst (KHG) in Germany. The operators of nuclear power plants in the country have taken technical and personnel precautions to stabilise a plant following an accident or breakdown, to analyse the cause and to eliminate the resultant effects. Within this mandate, they maintain a fleet of remote-controlled manipulator vehicles to cope with such incidents.
The next best area of applications are underwater robots for (sub-)marine search and rescue and for post search and rescue in collecting information and black boxes after aircraft or ship accidents. While only a very small fraction of these systems is exclusively used for search and rescue and hazardous operations and emergency response scenarios, there is a big commercial market in the oil and gas industry.
There are some (small) air-based robots that are used for fire detection and reconnaissance. However, to the best of our knowledge there is no dedicated search and rescue robotic aerial system.
To be perfectly clear: all robots, except those for bomb disposal, can be categorised as unique specimens. Therefore, it is not surprising that there is no manufacture of dedicated search and rescue

([5]) The history of using robots in military conflicts is beyond the scope of the publication. If you are interested, please see the Wikipedia articles about the Goliath & TT-26 teletank (ground, https://en.wikipedia.org/wiki/Teletank (last accessed 2015, June 15th)) or Fieseler Fi 103 (air https://en.wikipedia.org/wiki/Fieseler_Fi_103R_Reichenberg (last accessed 2015, June 15th)) as a starter.

robots or any serial production. Only in the military and oil and gas domains do the numbers of units reach a level beyond prototypes or small batch series.

2.3.3. Future scenarios

The problems of robots in the field of hazardous operations and emergency response and especially in search and rescue are diverse. There are several technical challenges, such as communication, sensors, situational awareness, mobility/locomotion and robustness. Some of these just accrue from the fact that these systems have not been used enough to gather a solid treasure trove of experience. There are still a lot of lessons to be learned.

The EU/European Commission has also identified a huge gap between what the research and development community is able to deliver, the existing industry state of the art and the user requirements (if properly determined). This sets difficult conditions for mature search and rescue robotics to emerge.

One of the major problems is the unrealistic expectations of the potential user. There are many false expectations about robots, probably stimulated by Hollywood movies. Some of the requirements articulated in procurement documents are far beyond the state of the art. The robots that are currently in the theatre are mainly teleoperated cameras with some extras.

Naturally the research and development community does not have a focus on manageability, sustainability, robustness (of hard- and software) or reliability. A more constructive way ahead might be to first focus on simple assistance functions rather than 'full' autonomy that fails in too many cases.

3. Research and development in the search and rescue domain

3.1. Search and rescue research projects

The application area of search and rescue has been very popular in the academic field. The disaster scenarios are well known; the users range from police and fire brigade up to emergency services and all kinds of soft- and hardware problems can be mapped on the domain. The following section will describe the most prominent search and rescue projects. Undisputedly there are a lot more projects that touch on this field, but the section will concentrate on those that really cover the search and rescue core aspect.

3.1.1. Integrated components for assisted rescue and unmanned search

The international research project Icarus, an acronym for 'Integrated components for assisted rescue and unmanned search operations', was founded in early 2012 as a 4-year-coordination project, aiming at the development of usable robotic tools for supporting 'human' crisis intervention teams. After the disastrous earthquakes in Haiti and Tohoku (Japan), the European Commission launched this project to bridge the huge gap between the research community and the search and rescue end-users and, thus, to be better prepared for future catastrophes. The general project goal is the development of a toolbox-like set of integrated robotic components for detecting, locating and rescuing humans.

Apart from developing classic robotic components, such as a light infrared sensor capable of detecting human beings or a self-organising wireless communication network, this also includes the complete system design of cooperative unmanned ground vehicles, unmanned air vehicles and unmanned surface vehicle tools (Cubber et al., 2013a). To ensure effective human–robot collaboration, an important higher-level goal is the seamless integration of these robotic vehicles into the C4I ('Command, control, communications, computers and intelligence') systems of the human search and rescue forces.

The final demonstration and validation of the Icarus project will be done during two major exercises in Belgium and Portugal in late 2015. The real-life scenarios for these demonstrations have been designed by two of the potential end-users that belong to the project consortium: the Belgian First Aid and Support Team (B-FAST) and the Portuguese Navy (CINAV). The first scenario was inspired by the 2010 Haiti earthquake and will be simulated in Marche-en-Famenne, Belgium. An integrated team of Icarus unmanned air vehicles and unmanned ground vehicles is supposed to work in close collaboration with a B-FAST response team. A shipwreck similar to the *Costa Concordia* disaster in January 2012 will be simulated near Lisbon, Portugal. A team of unmanned surface vehicles and unmanned aerial vehicles will support the crisis managers in locating human survivors (Cubber et al., 2013b).

The Icarus consortium is led by the Royal Military Academy of Belgium and consists of 24 partners from 10 European countries; the overall budget is EUR 17.5 million.

3.1.2. Natural human–robot cooperation in dynamic environments/Long-term human–robot teaming for robot-assisted disaster response

Another important example for large international research projects in the search and rescue domain is NIFTi. Although generally dealing with 'Natural human–robot cooperation in dynamic environments', in fact NIFTi mainly addresses urban search and rescue (USAR) tasks. In fact, the problem of an efficient human–robot interaction in the search and rescue domain is often covered in the literature, in empirical and conceptual studies (e.g. Casper and Murphy, 2002) as well as in actual deployment descriptions (e.g. Murphy and Stover, 2008). Hence, by investigating how a rescue robot

can complement models of its own capabilities and situational awareness with cognitive user models of task load and workflow, NIFTi addresses an important and still open issue.

The ultimate application scenario that NIFTi tries to address is one in which human–robot teams work successfully together to explore a disaster site, assess the situation, locate victims and support the responders. In order to do so, one of the project goals was to maintain full 3D environment models, fusing laser data and camera input. These 3D models are then integrated into a multimodal user interface to increase human situational awareness and, at the same time, used to perform full 3D navigation for the robots. Additionally, a human–robot team consists not only of robots in the field and human personnel at the command post, but also of in-field rescuers making on-site observations and posting the information gathered back to the control station.

NIFTi performed extensive field experiments, studies and end-user evaluations. In 2013, for instance, a realistic train accident setting was taken as a demonstration scenario and was assessed by a human–robot team consisting of both unmanned air vehicles and unmanned ground vehicles. The same set-up was used during a real deployment in Mirandola, in the Emilia-Romagna region in northern Italy, where a series of earthquakes had structurally damaged a number of historical buildings. Robots had to be used because it was too dangerous for humans to enter the damaged buildings. First, an unmanned air vehicle was developed to build 3D models of the buildings. Afterwards, this map was used by the team to decide the path along which to drive an unmanned ground vehicle equipped with additional sensors (Kruijff et al., 2012).

NIFTi was funded by the European Union’s seventh framework programme for research and technological development (FP7) and ran from early 2010 until the end of 2013. The project was coordinated by the German Research Centre for Artificial Intelligence (DFKI) and the consortium consisted of nine partners from five different countries.

Based on the experiences and results of NIFTi, the TRADR project, an acronym for ‘Long-term human-robot teaming for robot-assisted disaster response’, started on 1 November 2013. The DFKI is also the coordinator of this 4-year project, which, again, is funded through FP7. The consortium has 12 partners from six countries, including three fire brigades from Germany, Italy and the Netherlands representing possible end-users (TRADR, 2014).

The goal of TRADR is to develop technology for human–robot teams to assist in disaster response efforts, persistently and consistently over multiple missions possibly lasting several days. The test cases involve a medium- to large-scale industrial accident and collaborating teams of human rescuers and several robots and unmanned and air vehicles, which explore the environment and gather physical samples. Throughout multiple, possibly long-lasting, missions the teams gradually develop an understanding of the disaster area, improve team members’ understanding of how to work within it and improve teamwork. These tasks correspond very well to TRADR’s main scientific objectives, i.e. to generate and maintain, during the whole disaster response mission:

- a persistent model of the environment;
- persistent models for multi-robot acting;
- persistent models for human–robot teaming.

3.2. Search and rescue development and deployment centres

Some countries — including, not surprisingly, those that have experienced large-scale disasters — have already established search and rescue development and deployment centres. These centres do not only perform research and development on the topic but also provide search and rescue robotic services to the public. Some of these institutions have a commercial interest whereas others are more or less government-funded non-profit organisations. However, it is important to highlight that all of these centres still have a very strong research and development section since none of the hard- and software is broadly available on the consumer market.

3.2.1. Centre for Robot-Assisted Search and Rescue

The Centre for Robot-Assisted Search and Rescue (Crasar) was officially established on 1 September 2001 by Lt Col. John Blitch as a United States National Institute for Urban Search and Rescue (NIUSR) centre of excellence. Today it is affiliated with the Texas A & M University, bringing together university researchers and professional first responders. Its current director, Dr Robin R. Murphy, is at the same time Raytheon Professor of Computer Science and Engineering at Texas A & M. The centre aims to improve disaster prevention, preparedness, response and recovery by developing and adopting robots and related technologies.

Only a few days after the centre's official foundation, its experts took part in the World Trade Centre disaster response mission (see Section 2.2.2) from 9 September until 2 October 2001 (Casper and Murphy, 2003). This was the first time that robots were actually used for technical search tasks in an urban search and rescue (Snyder, 2001). Since then the centre and its scientists have been deployed to search and rescue missions after many severe disasters worldwide, including Hurricane Katrina in 2005 and the huge tsunami responsible for the Fukushima Daiichi nuclear accident[6] in Japan in 2011. Additionally, the Centre for Robot-Assisted Search and Rescue has formally analysed and described other events (e.g. in Murphy and Stover, 2008) and formulated guidelines and typical problems for applications of robots in the search and rescue domain. As a result, the centre now provides an archive of data on rescue robots in use.

An important ambition of the Centre for Robot-Assisted Search and Rescue is to create a worldwide community for rescue robots that supports technology transfer, motivates fundamental research and provides information to professional rescue personnel as well as the general public. Thus, apart from appearing at disaster sites, the centre and its funding agencies and industry partners provide a number of small land, air and sea robots that can be used by interested first responders. Rescue organisations are offered readily deployable robot-assisted search and rescue teams. This both gives the centre's researchers further insights into current practices and demands in the search and rescue domain and helps to convince the response teams engaged in the work that search and rescue-specific robot systems are a useful and valuable addition to any search and rescue mission.

3.2.2. International Rescue System Institute

The International Rescue System Institute (IRS) may be considered as the Japanese counterpart to the Centre for Robot-Assisted Search and Rescue. Founded only a few months after the Centre for Robot-Assisted Search and Rescue on 18 April 2002 the IRS is a non-profit organisation (NPO) aiming at an improved cooperation between academia, government and industry. With its densely populated areas and very large cities that are mainly in the coastal regions, heavy earthquakes have been identified as a major risk factor for Japan and its people, especially after the disastrous Kobe earthquake in 1995. The government decided to establish the IRS as a result, as a nationwide effort to improve and spread advanced disaster response technology, closely collaborating with all relevant and affected parts of society.

In contrast to the Centre for Robot-Assisted Search and Rescue, which works with commercially available robots, the IRS plays an active role in the development of robot systems and platforms for disaster response. For instance, addressing a sub-task of the national 'Special project for earthquake disaster mitigation in urban areas', a 5-year project that started in 2002, the IRS developed the snake-like robot Soryu in cooperation with the Tokyo Institute of Technology. Due to its small dimensions and special kind of locomotion, the Soryu was able to enter very confined spaces like small holes typically found in rubble piles (Tadokoro, 2006). Other examples are the Kenaf robot, which originates from an IRS initiative and which now serves as a common development platform for the Tohoku University, the University of Tsukuba, Okayama University, and others. An active scope

(6) https://en.wikipedia.org/wiki/Fukushima_Daiichi_nuclear_disaster (last accessed 2015, June 15th)

camera (ASC) enhanced Soryu's idea of a snake-like appearance and completely abandoned classical locomotion approaches like wheels, tracks or artificial feet. Instead, the ASC looks like a slightly thicker fibrescope camera and uses an insect-like ciliary vibration drive mechanism (Hatazaki et al., 2007). The resulting robot has a diameter of only 24 mm, but is 8 m long, crawls at a maximum speed of 47 mm/s, climbs slopes of up to 20 degrees and is able to surmount obstacles 200 mm high.

To assess the operational readiness of its own robots as well as of other rescue and disaster response systems, in March 2006 the International Rescue System Institute established the so-called International Rescue System Unit (IRS-U) consisting of voluntary fire fighters and rescue workers. The role of the IRS-U is twofold: on the one hand, it tries to evaluate the usefulness and benefit of the various types of disaster response technology. On the other hand, since the members of the IRS-U actively work in all kinds of first response teams, it tries to increase acceptance for rescue robotics among first responders, on the decision-making level as well as for any actual personnel on a disaster site.

4. Ground (no legged systems)

This section will review approaches and techniques for sensing, actuation, communication and control, within the context of robot search and rescue and with reference to research that focuses on advancing specific capabilities within each of these domains of interest.

4.1. Platforms

The number of companies that manufacture commercially available robots for the domain under consideration in mentionable quantities is very limited. Most of the professional robotic systems that are deployed in the field come from the bomb disposal domain (EOD, UXO, etc.).
Due to this fact, most of these robots have a very similar appearance. Usually the platforms are propelled by tracks and run on batteries. Most of them are lead acid battery-based while some of the newer models use some form of lithium-based batteries. The vast majority of the systems have manipulators for handling the explosive device. The systems are usually not very fast and the stair-climbing capabilities require quite a bit of training for the operator.
The following three pictures show the most common and top-selling EOD robots.

Figure 2: PackBot Irobot; Cutlass Northrop Grumman; TeleMax and Teodor Cobham (former Telerob); Talon Qinetiq; Wheelbarrow Remotec; Defender MedEng (former Allen Vanguard) (all from top left to bottom right)

There are of course other types of robots but most of them are individual items produced in very low quantities. The vast majority do not exceed the state of a prototype.

Figure 3: GARM II and GARM I RUAG; FENRIR Fraunhofer FKIE (from left to right)

4.2. Sensing

4.2.1. Obstacle avoidance and path planning

There are many sensors available to designers of search and rescue robots and a comprehensive review can be found in Everett (1995). A search and rescue robot will typically require short- or medium-range proximity sensors for obstacle avoidance, such as infrared return-signal-intensity or ultrasonic- or laser-based time-of-flight systems. The most versatile and widely used device is the 2D or 3D scanning laser range finder, which can provide the robot with a set of radial distance measurements and hence allow the robot to plan a safe path through obstacles (Spero and Jarvis, 2002). For a comprehensive review of motion planning and obstacle avoidance in mobile robots see Minguez et al. (2008).

4.2.2. Localisation

All but the simplest search and rescue robots will also require sensors for localisation that are to enable the robot to estimate its own position in the environment. If external reference signals are available — such as fixed beacons so that a robot can use radio trilateration to fix its position relative to those beacons, or a satellite navigation system such as GPS — then localisation is relatively straightforward. If no external infrastructure is available, then a robot will typically make use of several sensors including odometry, an inertial measurement unit (IMU) and a magnetic compass, often combining the data from all of these sensors, including laser-scanning data, to form an estimate of its position. Simultaneous localisation and mapping (SLAM) is a well-known stochastic approach which typically employs Kalman filters to allow a robot (or a team of robots) to both fix their position relative to observed landmarks and map those landmarks with increasing confidence as the robot(s) move through the environment (Dissanayake et al., 2001; Thrun and Leonard, 2008).

4.2.3. Object detection

Vision is often the sensor of choice for object detection in laboratory experiments of search and rescue robots. If, for instance, the object of interest has a distinct colour that stands out in the environment then standard image processing techniques can be used to detect it and steer towards the object (Bryson and Sukkarieh, 2007). However, if the environment is visually cluttered, unknown or poorly illuminated then vision becomes problematical. Alternative approaches to object detection include, for instance, artificial odour sensors: Hayes et al. demonstrated a multi-robot approach to localisation of an odour source (Hayes et al., 2002). An artificial whisker modelled on the Rat mystical vibrissae has been demonstrated (Pearson et al., 2007); such a sensor could be of particular value in dusty or smoky environments.

4.3. Actuation

4.3.1. Locomotion

The means of physical locomotion for a search and rescue robot can take many forms and clearly depends on the environment in which the robot is intended to operate. Ground robots typically use wheels, tracks or legs, although wheels are predominantly employed in proof-of-concept or demonstrator search and rescue robots. An introduction to the technology of robot mobility can be found in Siegwart and Nourbakhsh (2004). Whatever the means of locomotion, important principles that apply to all search and rescue robots are that robot(s) must be able to:

- move with sufficient stability for the object detection sensors to be able to operate effectively;
- position themselves with sufficient precision and stability to allow the rescue to be effected.

These factors place high demands on a search and rescue robot's physical locomotion system, especially if the robot is required to operate in soft or unstable terrain.

4.3.2. Object manipulation

The manipulation required by a search and rescue robot is clearly dependent on the form of the search object of interest and the way the object presents itself to the robot as it approaches. The majority of search and rescue experiments or demonstrations have simplified the problem of object manipulation by using objects that are, for instance, always the right way up so that a simple gripper mounted on the front of the robot is able to grasp the objects with reasonable reliability. However, in general a search and rescue robot would require the versatility of a robot arm (multi-axis manipulator) and general-purpose gripper (hand) such that — with appropriate vision sensing — the robot can pick up the object regardless of its shape and orientation. These technologies are well developed for teleoperated robots used for remote inspection and handling of dangerous materials or devices (Vertut and Coiffet, 1986; Schilling, 1999).

4.4. Communication

Communication is of fundamental importance to robot search and rescue. Regardless of the degree of autonomy, a continuous communication link is required between the search and rescue robot (or robots) and their operators. This operator–robot communication link needs to be:

- **duplex**, in order to allow the operator to send command/control data while receiving video, sensor or status data from the robot;
- **continuous**, with low latency, in order to allow smooth uninterrupted control or supervision of the robot;
- **secure** and reliable, to avoid unintended interference or signal loss from other radio sources or as a result of environmental factors;
- normally **high-bandwidth**, to allow for streaming real-time video.

These are demanding requirements that are often tested to the limit in real-world emergency scenarios. Both wired and wireless communication links are employed in search and rescue robots; wireless communication is the preferred mode, although reliable wireless communication can be very problematical when search and rescue robots must be deployed in buildings, metal structures or under high levels of radiation. Wired (cable) connections suffer a different set of problems, because of the

problems of managing cable spooling and run-out and the need to avoid cable snagging in the environment, or on the robot itself.

Standardisation around network and Internet protocols has led to networked telerobots; for an introduction to communications and networking for teleoperation (Song et al., 2008). Wireless local area network (WLAN) technology is highly appropriate for terrestrial robot systems, and the advantages of the technology (including bandwidth and reliability) are sufficient to justify the proposed use of intermediate robots acting as wireless relays between the operator and the search and rescue robot (see for instance Çayırpunar et al., 2008).

Future multi-robot search and rescue systems can take advantage of the fact that a spatially distributed team of wireless networked robots naturally forms an ad hoc network, which — providing the team maintain sufficient connectivity — allows any robot to communicate with any other via multiple hops. Providing the operator maintains connection with one of the robots (the nearest perhaps), a multi-hop multi-path network connection is then maintained with all robots (Winfield and Holland, 2000; Hauert et al., 2011).

4.5. Autonomy and teleoperation

A robot's autonomy describes the degree to which it can make decisions about its next possible action without human intervention. Autonomy thus falls on a spectrum, from fully teleoperated robots — robots with zero autonomy — at one end, and fully autonomous robots — robots capable of completing their mission from start to end without human intervention — at the other. Search and rescue robots might, in principle, be found anywhere on this spectrum of autonomy, but in practice they are either teleoperated, or semi-autonomous.

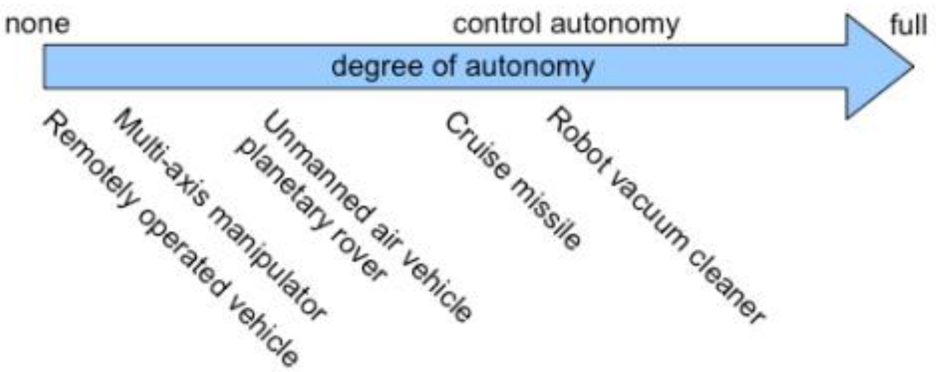

Figure 4: A spectrum of control or supervised autonomy

Figure 4 illustrates the notion of a spectrum of autonomy. In practice no search and rescue robot is likely to be 100 % autonomous, nor indeed very few robots of any kind; even a robot capable of completing its entire mission without human control will need to have mission parameters set by a human operator and will, presumably, need to report back when its mission is completed. In practice therefore, all robots on this spectrum will need some degree of human supervision; we refer to this as supervised autonomy.

A fully teleoperated robot is one in which a human operator controls every function of the robot directly, via a wireless data link (Winfield, 1999). The data link provides a continuous connection between the robot and its operator's control station. (Human–robot interfaces are outlined in a later

section.) Full teleoperation places a considerable burden on the robot's human operator(s), since the operator needs to continuously watch and interpret the video feed from its camera(s) and provide continuous control of motors while steering around obstacles, navigating the terrain, etc. Semi-autonomous operation, also referred to as supervisory control, reduces this burden. For an overview of telerobotics, see Niemeyer et al. (2008).

A semi-autonomous robot is one in which some (often low-level) functions can be left to the robot while high-level control remains with the human operator. A common approach to semi-autonomous operation — especially in unmanned air vehicles — is for the human pilot to set a target destination (waypoint) and then leave the low-level control required to reach the destination to the aircraft's autopilot. Just like pilots of commercial aircraft, the unmanned air vehicle operator(s) continue to monitor the robot's progress while it is proceeding autonomously to the waypoint. The same semi-autonomous approach is perfectly possible for ground search and rescue robots, although the autonomous control functions may need to be more complex to enable the robot to, for instance, safely navigate rough terrain or steer around obstacles. We could describe this as navigation autonomy.

Another, higher level of semi-autonomous operation would allow a robot to search some bounded area for objects of interest — and then perhaps halt and alert its human operator when an object is found; this mode would be most appropriate if the robot is searching for survivors or, say, some single critical object. Another mode might require a robot to autonomously search the entire area, find and localise each object of interest and then — once the area has been covered — halt and provide its operator with a map marking the positions of the found objects. We could call these modes search- or search-and-map-autonomy.

Clearly, there are many different possible modes for semi-autonomous operation; the intention here is not to provide a comprehensive list, but to outline the principle.

4.6. Control

Niemeyer at al. (2008) provide an overview of control architectures for telerobotic systems, and identify three main categories of control, which they call **direct** control, **shared** control and **supervisory** control. Direct control means that all robot functions are controlled by a human operator, i.e. full teleoperation in the spectrum of autonomy in Figure 1. Niemeyer et al. define shared control as a mode in which task execution is shared between direct control and local sensory feedback and autonomy for low-level functions; thus, the robot might have local low-level control for precise and stable motion while the operator sets the speed and direction of the robot.

Under supervisory control the operator gives high-level commands, which are executed by the robot autonomously until complete, at which point the robot alerts its operator. Figures 2, 3 and 4 show high-level finite state machine control architectures for the three examples outlined in the previous section.

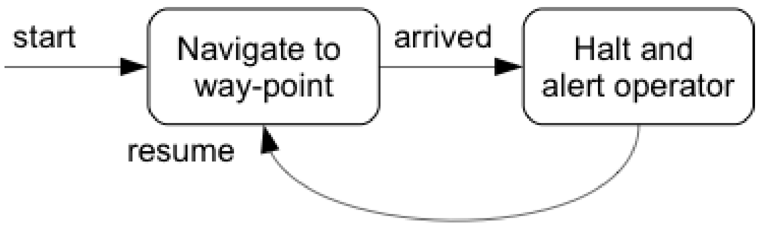

Figure 5: Finite state machine for 'Navigate autonomy' mode

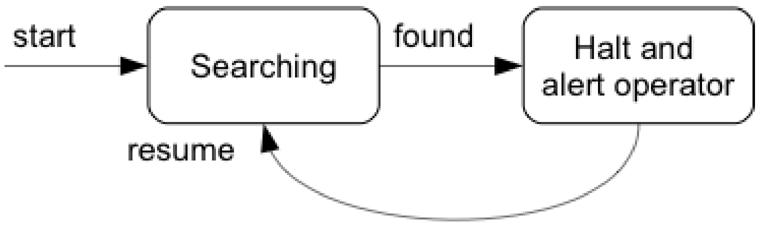

Figure 6: Finite state machine for 'Search autonomy' mode

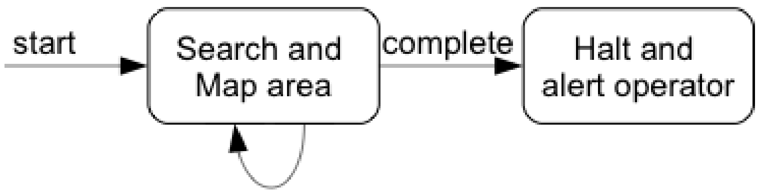

Figure 7: Finite state machine for 'Search and map autonomy' mode

In Figure 5, 'Navigate autonomy' mode, the robot navigates to a waypoint specified by the operator, and when it arrives at the waypoint the robot halts (or maintains station if it is a flying or underwater robot) and alerts its operator. In Figure 6, 'Search autonomy' mode, the robot autonomously searches for an object of interest until it finds it (or what its sensors and local sensor processing indicate is an object of interest) and then halts and alerts its operator; the robot would also have a 'time-out' function so that if nothing is found after a pre-set time period it would also halt and call its operator. In the third example, 'Search and map autonomy' in Figure 7, the robot would search and map a defined area, marking the position of any object of interest, continuing the search until the area has been covered before halting and alerting its operator.

4.7. Human–robot interfaces

Search and rescue robots by definition need to work as part of human rescue teams and therefore — whatever the level of autonomy — there will need to be a human–robot interface (HRI). The design of the human–robot interface is of great importance. A well-designed human–robot interface will significantly increase a search and rescue robot's usability and this, in turn, is likely to lead to greater deployment and value to the rescue team.

The essential ingredients in a search and rescue human–robot interface are:

- the means to control the robot's locomotion, i.e. joystick or equivalent;
- the means to control the robot's actuator(s), i.e. robot arm, gripper or equivalent device;
- video displays to see what the robot's camera(s) are seeing — and to control camera functions such as pan, tilt and zoom, etc.;
- video displays or readout devices, to allow monitoring of key environmental measurements, such as temperature, pressure, humidity, radiation level and hazardous gases, etc.;
- video displays or readout devices, to allow monitoring of a robot's status, including battery or fuel levels, the robot's attitude, altitude/depth, location (i.e. via GPS) and proximity to nearby objects, etc.

As Murphy at al. (2008) conclude in their definitive review of search and rescue robotics, human–robot interface is a major challenge in rescue robotics that 'has been declared to be an exemplar domain within human–robot interface'.

5. Future directions for search and rescue robotics

As Murphy et al. (2008) make clear, search and rescue robotics is an emerging field, which has a long way to go before it reaches its full potential. Almost every advance in intelligent autonomous robotics has the potential to benefit search and rescue robotics. In this section, we outline a number of directions that, either individually or jointly, could lead to significantly more capable search and rescue robots in the near- and medium-term future.

5.1. Heterogeneous multi-robot multi-domain SARs

Search and rescue is clearly a task that lends itself to multi-robot systems and, even if a single robot can accomplish the task, search and rescue should — with careful design of strategies for cooperation — benefit from multiple robots. The most significant advantage of multiple robots is the ability to cover a much larger area and hence reduce the time taken to find survivors or critical hazards. Another benefit is gained by combining the advantages of robots in different domains: for example, a flying robot providing a birds-eye view of the scene to guide a land robot's search.

At the time of writing, there are no known examples of multi-robot systems deployed alongside real-world search and rescue teams. The principle reason for this is the difficult problem of controlling and coordinating a multi-robot team. Teleoperating a single robot can be challenging — so teleoperating a whole team is probably beyond even the most skilled human operator.

The solution to this problem will be found in a combination of greater individual robot autonomy and advanced human–multi-robot interfaces. Consider autonomy; there are two paradigms for the control and coordination of multiple robots: multi-robot systems (MRSs) or swarm robotic systems. Multi-robot systems are characterised as centrally controlled, whereas in swarm robotic systems control is distributed and decentralised.

Swarm intelligence is the study of natural and artificial systems of multiple agents in which there is no centralised or hierarchical command or control. Instead, global swarm behaviours emerge because of local interactions between the agents and each other, and between agents and the environment (Bonabeau et al., 1999). Swarm robotics is concerned with the design of artificial robot swarms based upon the principles of swarm intelligence; thus control is distributed and robots, typically, must choose actions on the basis only of local sensing and communications, (Beni, 2005; Sahin, 2005).

Promising real-world proof-of-principle demonstrations of multiple flying robots, based on swarm robotic principles, have been given for fixed-wing flying robots (Hauert et al., 2011) and quadrotor flying robots (Vásárhelyi et al., 2014). The former work is motivated by the need to be able to create a wireless infrastructure in disaster scenarios (when the fixed communication system is damaged); the idea is that the flying robots form a flying ad hoc wireless network for rescue workers to use for wide-area communication.

The problem of how humans can naturally control and interact with a swarm of robots (called human swarm interfacing) has also received attention. For example Giusti et al. (2012) show how a swarm of ground robots can recognise and respond to gestural commands from a human. Pourmehr et al. (2013) show how both facial recognition and voice commands can be used to instruct a group of quadrotor (indoor) flying robots.

5.2. Dynamic autonomy in search and rescue

Consider the situation in which a semi-autonomous search and rescue robot is searching inside a structure in 'Search autonomy' mode. If the structure contains — as is likely — unknown hazards, then it is possible the robot will encounter a problem that is too difficult for its intelligent search capability to cope with. Ideally, we would like the robot to be able to detect when its semi-autonomous capability has been exceeded, halt (safely) and then 'ask' its human operators to resume

control. We describe this as dynamic autonomy. Baker and Yanco (2004) outline the potential for dynamic autonomy in an urban rescue scenario; Schermerhorn and Scheutz (2009) investigate dynamic autonomy in human robot teams. Dynamic autonomy would be a significant advance for search and rescue robots, but is not straightforward to implement, both because of the complex human factors and because it requires that the robot is able to assess the level of danger posed by any hazards it encounters **before** it becomes irrecoverably stuck or damaged.

5.3. Immersive telepresence

After more than 20 years in development, it now appears that virtual reality (VR) headsets are set to become a practical, workable proposition; the recently announced low-cost Oculus Rift VR headset integrates 3D gyros, accelerometers and a magnetometer — and claims to reduce latency (the time between head movement and image update in response) to very low levels (Oculus, 2014). Of course, the primary market for VR headsets is likely to be entertainment, including video games. VR could, however, revolutionise the human–robot interface for teleoperated robots.

Consider a teleoperated robot with a pan-tilt camera linked to the remote operator's VR headset, so that every time she moves her head to look in a new direction the robot's camera moves in sync; so the operator sees (and hears) what the robot sees and hears in immersive high-definition stereo. Of course, the reality experienced by the robot's operator is real, not virtual, but the head-mounted VR technology is the key to making this work. Reis and Ventura (2012) describe work at the Intelligent Robot and Systems Group, IST Lisbon, in which a stereo camera with pan-tilt mechanism mounted on a tracked mobile robot is coupled to a head-mounted display with a head tracker system.

With the addition of haptic gloves for control, the robot's operator would have a highly intuitive and immersive interface with the robot (assuming also a high-speed low-latency data link with the robot). The illusion of 'being in' the robot could well provide the operator with a much more natural sense of the robot's position and its immediate surroundings. The haptic gloves would provide the operator with the ability to, for instance, move the robot's arm and gripper simply by moving their own arm and hand — this control would be natural and responsive. With this kind of immersive telepresence, the robot almost becomes an 'avatar' for the human.

5.4. Bio-inspired search and rescue robots

The design of current search and rescue robots, and in particular their morphology and locomotion, has its origins in vehicle design. Ground search and rescue robots are generally wheeled or tracked vehicles following a conventional pattern; search and rescue unmanned air vehicles are — explicitly — aircraft without pilots. Conventional search and rescue robots do not in general, therefore, have any resemblance to animals.

The emergence, in the last decade, of bio-inspired and bio-mimetic robotics is leading to a new generation of animal-like mobile robots. For reviews of bio-inspired intelligent robots — including humanoid robots — see Bar-Cohen and Breazeal (2003) and Mayer and Guillot (2008). Although none have yet been deployed into search and rescue teams or emergency services it seems likely that they will be soon. In the following sections, we outline a sample of bio-inspired (including both zoomorphic and humanoid) robots that have either a potential or an intended application in search and rescue.

5.4.1. Snake robots

Using neither legs or wheels, snake-like robots have been proposed for navigating terrain, small enclosed spaces or pipes that would be impossible for conventional robots. Already mentioned in Section 3.2.2 are the Japanese Soryu and ACS snake-like robots (Tadokoro, 2006; Hatazaki et al.,

2007). Another example is the snake-like hyper-redundant robot (HRR) for urban search and rescue from the biorobotics and biomechanics laboratory of the Technion Israel Institute of Technology (Wolf et al., 2005); this robot has 14 serially chained actuated segments, each of which is capable of supporting the entire robot structure.

5.4.2. Legged robots

Although not designed for search and rescue, the Boston Dynamics BigDog robot is perhaps the best-known example of an advanced quadrupedal robot designed for rough terrain. Raibert et al. (2008) introduce BigDog by explaining that ‘less than half the Earth’s landmass is accessible to wheeled and tracked vehicles, yet people and animals can go almost anywhere on Earth’ — a statement that strongly implies future search and rescue robots will need to be legged, in order to achieve the same versatile motility as humans, horses or dogs.
With an explicit target of search and rescue applications are the legged quadrupedal robots HyQ and StarETH. HyQ is a hydraulically actuated quadruped developed at the IIT’s Department of Advanced Robotics, and StarETH is a quadruped based on series elastic actuation developed at ETH Zurich’s Agile and Dexterous Robotics Lab. These two labs, together with the Max-Planck-Institut für Intelligente Systeme, have launched a collaborative project named Agility, with the aim of developed robots with both (four) legs and (two) arms capable of autonomous dynamic full-body manipulation (i.e. jumping, or reaching with arms while standing on back legs) (Hutter et al., 2013).

5.4.3. Humanoid rescue robots

Although it is not clear if the robot was designed specifically for search and rescue tasks, the ATLAS humanoid robot has been provided to ‘track B’ contestants of the DARPA search and rescue robotics challenge (described in Section 3.4.3). Designed by Boston Dynamics, Atlas is a hydraulically actuated humanoid robot 1.88 m in height and 155 kg in weight. The robot has 28 actuated degrees of freedom, and required a tethered connection for three-phase power, cooling (water) and wired communications. Fallon et al. (2014) describe an affordance-based perception and planning architecture developed for the ATLAS robot by the Massachusetts Institute of Technology (MIT) team.
It is supposed that humanoid robots would, in search and rescue situations, have the advantage of being able to use tools and devices designed for humans, including vehicles, and move more readily through human environments. However, the question of whether a humanoid robot (even something smaller, lighter and more autonomous than ATLAS) would actually outperform a well-designed conventional search and rescue robot remains an open (and interesting) question.

6. Air (fixed wing)

Radiological and nuclear incidents where fixed-wing UAVs could be used as part of response are accidents, security threats and non-proliferation. In these incidents, radioactive materials or other hazards may pose a health risk to individuals near the site of the incident, leading to the need for robotics. Missions where fixed-wing unmanned air vehicles are superior compared to other unmanned platforms include radioactive plume tracking, sampling of airborne radioactive material, fallout mapping of large areas and searching of unshielded point sources (‘Material out of regulatory control’, MORC), both stationary and moving, from large areas. Legislation and procedures for operating the UAVs in open airspace should be developed. However, in the case of a reactor accident, for example, air space near the site would be closed anyway, allowing the straightforward use of UAVs.

6.1. Platforms

When choosing a UAV for a specific type of mission, several important requirements have to be taken into account. What is the weather sensitivity of the vehicle, i.e. for how many days of the year is the system unusable due to weather conditions? What is the payload of the UAV and how does the payload affect range as well as operational time? Can the system operate in darkness? Take-off and landing arrangements, payload capacity, price, ease of decontamination and operating modes (manual/programmed missions) are also important, as well as capacity for online transfer of measurement data from the unmanned air vehicle to the ground control station.

According to Kurvinen et al. ([7]), there were already more than 150 unmanned air vehicle manufacturers on the market in 2005, offering more than 400 different unmanned air vehicle models ranging from micro UAVs with a 15 cm wingspan and a payload capacity of a few grams to UAVs with a wingspan of 35 m and a payload of 2 000 kg. Notice that unmanned air vehicles with endurance, operational range and flight altitude comparable to, or even better than, conventional aircraft exist. Presently tactical UAVs are the most utilised type of unmanned air vehicles in military applications. Tactical UAVs are normally propeller-driven, single-engine aircraft with an operating range of 50–200 km, endurance of several hours and a payload capability of the order of 20 kg. Several UAV manufacturers offer payloads for nuclear, biological and chemical (NBC) reconnaissance. Publicly available information about these payloads is typically limited.

6.2. Sensors

Relevant questions for the payload are what needs to be measured (dose rate, counts per second, gamma-ray energy spectra) and whether air sampling is required. Since the detection requirements and boundary conditions are quite similar for both the rotary- and the fixed-wing UAVs, and since the detection technology part has already been described in the section on rotary wings (section 7), it will not be repeated here. (The main differences are that the rotary-wing UAVs can stay still in optimal measurement location and some fixed-wing UAVs have significantly larger maximum altitudes compared to rotary-wing UAVs.) Instead, here we just conclude that radiation surveillance instrumentation has been mounted to fixed-wing UAVs. Flight tests have been performed for the equipment and it has been proven to be viable. As a rule of thumb, even small detectors (cylindrical CsI detector of length of 38 mm and diameter of 13 mm) can easily locate unshielded ^{137}Cs and ^{60}Co

([7]) K. Kurvinen et al., J. Environ. Radioactivity 81 (2005) 1.

sources whose activities correspond to those mentioned in the high activity sealed sources (HASS) directive (20 GBq and 4 GBq, respectively) at an altitude of 100 m ([8]).

When discussing air sampling, what is being sampled needs to be defined first, i.e. whether it is a gaseous species or aerosol particles. This leads to the selection of the sampling approach. Here we concentrate on the sampling of aerosol particles. Due to air fluctuation, reliable particulate sampling is not as straightforward with the rotary-wing as with the fixed-wing unmanned air vehicle. Optimal sample volume depends on the activity concentration of air. Namely, difficulties arise if samples get so radioactive that they cannot be measured in normal configurations on the ground. Particulate sampling should be isokinetic (sampling efficiency does not depend on the aerosol particle size). This should be valid throughout the relevant air speed range. The selection of filter type in particulate sampling depends on the offline analysis that will be made. For example, high-resolution alpha spectrometry requires the use of membrane filters, while almost any filter type is good for gamma spectrometry. Note that different filter types have different fluid dynamical properties.

In many cases, online monitoring of the sampling would be useful. The capability to start and stop sampling during the flight is also important. In addition, the ability to link the results of the online spectrometry and the offline analysis of samples is important (for example, the analysis of gaseous versus particulate iodine ratio).

Figure 8: TIKKA air sampler mounted to the back of a mini unmanned air vehicle

The robust and cost effective TIKKA air sampler ([9]), which is a completely passive instrument, has been shown to collect airborne radioactive particles in a mini unmanned air vehicle (see Figure 8). Minimum detectable concentrations of several transuranium nuclides are ~ 0.3 Bq/m^3 using direct alpha spectrometry. This information can be obtained within 2 hours of the beginning of the sampling.

([8]) R. Pöllänen et al., J. Radioanal. Nucl. Chem. 282 (2009) 433.
([9]) Ibid. and K. Peräjärvi et al., Rad. Prot. Dos. 132 (2008) 328.

7. Air (rotary wing)

7.1. Platforms

Unmanned aircrafts are commonly referred to as 'drones' or 'remotely piloted aircraft systems' (RPAS). The term 'drone' is usually linked to armed, military systems while RPAS is mainly used in the hobbyist community. For systems with a higher range of autonomy, unmanned aircraft system (UAS) is the expression commonly used: this comprises the unmanned aerial vehicle itself and the ground control station (GCS) and any launch devices. An UAS may consist of many GCSs and launch systems.

Rotary-wing unmanned aircraft systems (RWUAS) have the advantages of hovering capability and independent movement in three dimensions. Due to these abilities, they are suitable for measurement of ionising radiation from radioactive sources. As these systems can be powered by electric motors, the noise level produced by the vehicle can be very low. These capabilities are useful in many aerial missions, especially in situations involving antagonists.

A rotary-wing UAS may have different configurations, including a single ducted rotor or main and tail rotors (conventional helicopter), coaxial rotors, tandem rotors or three or more rotors — so-called multi-rotors (tri-/quad-/hexa-/octocopters). Their motors can be powered by electricity or petrol. There are also hybrids that combine the vertical take-off and landing (VTOL) function of multirotors with the traditional plane design for speed and range.

A ducted or shrouded rotor, or rotors, is used for its aerodynamic efficiency (Hrishikeshavan, Black et al., 2012) and for the safety of vehicle and humans. The duct boards act as a shield from the sharp propellers as well as protection to the propeller itself when bumping into objects.

The conventional configuration is the most effective and can be used with petrol-driven engines. There are tests on quadcopters driven by one central, petrol engine using variable pitch rotors. The readiness level for this concept is still low.

Multirotor configurations are simpler since they can use fixed-pitch rotors, which are safer due to smaller rotors and are easier to control by software. They are however intrinsically unstable and vulnerable to damage to any propeller or motor.

The variety of innovative RWUAS platforms is infinite and opens the possibilities to find an ultimate RWUAS for any application. A power-saving configuration with a combination of a lifting main rotor and a quadcopter configuration for direction has been elaborated by Driessens and Pounds (2013) and Kawasaki, Zhao et al. (2013) have demonstrated the great manoeuvrability of a quadcopter with variable-pitch rotors. Recent developments have been summarised by Cai, Dias et al. (2014) and Kendoul (2012).

Since all air lifting force for rotary-wing systems relies on the rotors, they have a relatively shorter operating endurance/range and payload capacities. They are also relatively more sensitive to weather conditions than their fixed-wing equivalents.

RWUAS can be operated by a pilot through radio control, visual or camera guided or by autonomy or pre-planned routes when human interaction is not required. The UAS can in these cases be operated beyond the visual line of sight. In most European countries, the UAS needs type certification and authorisation (EASA, 2009).

The planning and logging of the flight is done in the GCS. The station typically is a computer installed with a set of modules for communication, data handling and planning of the autonomous route. The waypoints are uploaded to the vehicle before the mission or during flight. The GCS also displays and logs the telemetry and measurement data during the flight.

The most common technique for positioning is GPS, but for localisation in GPS-denied environments, such as indoors, there are systems based on laser or light (LADAR/LIDAR). Vision-aided inertial navigation systems (V-INS) use an on-board camera to identify obstacles and facilitate autonomous flights even indoors. This has been validated and reviewed by Chowdhary, Johnson et al. (2013).

The availability of RWUAS depends on the size of the system since it needs to be transported to the site of interest or a nearby launching position. The availability and redundancy of the system also depends on the competence needed from the operating personnel to operate the system.
Aviation authority regulations are under revision in many countries and will hopefully be harmonised and facilitate cross-border operations since we foresee a need for assistance between countries.

7.2. Measurements and sampling

Little has been published in the scientific literature on radiation measurement using RWUAS: either the systems are military or only feasibility studies have been made.
This application of mobile measurements is not mature; it is still in a research state. Hence it is driven by funded projects. The market for a commercial system is limited.
Radioactivity measurement missions for RWUAS could be repetitive measurements, measurements in areas of high dose rate, taking samples or in general operate in dangerous and uncooperative environments. Localisation and identification of possible radioactive sources and assessment of their activity are the desired results. It is important to identify the aim of the operation and identify when the result is good enough and meets the goal of the operation.
The measurement system could either be integrated in the unmanned air vehicle or it could be stand-alone, being self-supported. This would be dependent on the measurement systems power, communication and positioning requirements. An integrated system could be used for active sensing, where the measurement is used to direct the unmanned air vehicle. A stand-alone system is more versatile and can be used with any vehicle.

7.2.1. Detection

The payload weight is limited and can vary from single grams up to several kilograms. The weight of the detector is roughly proportional to the sensitivity, but RWUAS have the ability to descend closer to the source and reduce the distance and extend the measurement time and hence reduce the minimum detectable activity (MDA), hence reducing the demand for heavy detectors.
The measurement data need to comply with standard data format to facilitate reachback support and intercomparison. The XML-based N42.42 standard (ANSI 2012) is commonly used.
The detector system needs to be insensitive to shocks to withstand the impacts in rough landings and the vibrations during flights.
Since there is a risk of air contamination, the entire system needs to be easy to decontaminate. Either the surfaces should be easy to decontaminate or any cover material should be easy to replace.
There are several examples of feasibility studies on whether a light enough detector-acquisition system combination could be carried by a RWUAS and perform measurements. Many research groups have tested their localisation algorithms and contamination depth assessment models, etc. and have illustrated the usability of RWUAS as radiation measurement platform.
International Atomic Energy Agency (IAEA) Nuclear Science and Instrumentation Laboratory (NSIL) in Seibersdorf, Austria, performed a demonstration of its unmanned air vehicle (Kaiser 2013) at the IAEA 58th IAEA General Conference ([10]) in September 2014. This project was prompted by needs after the Fukushima Daiichi accident.
A commonly used conventional unmanned helicopter, the Yamaha RMAX, was used with a plastic scintillator (Okuyama, Torii et al., 2005; 2008) for use in a nuclear emergency. The system was tested by using it to detect fertiliser bags at low altitude and was able to distinguish between natural background dose rate over land and sea.

([10]) http://www-naweb.iaea.org/na/news-na/58GC_NA_activities.html

A similar platform with an NaI(Tl) scintillator has been suggested for mapping of radioactively contaminated areas (Towler, Krawiec et al., 2012) and illustrates search and localisation algorithms based on recursive Bayesian estimators or dose rate contour analysis.
Other commercially available off-the-shelf (COTS) quadcopters have been considered for carrying detector systems (Gårdestig and Pettersson 2011) and being integrated in the UAS communication systems (Bogatov, Mazny et al. 2013).
In recent years, several lightweight (50–500 g) spectrometers have been developed and are now commercially available. CZT (Gårdestig and Pettersson, 2012; MacFarlane, Payton et al., 2014) and CsI (Pöllänen, Toivonen et al., 2009) seem to be the detection materials of choice in this category.
If the payload capacity is over 1 kg, it is possible to use larger scintillation spectrometers (e.g. NaI(Tl) and LaBr:Ce). These detector systems would offer a different feature set, such as a higher sensitivity and list mode acquisition.

Table 1: A selection of lightweight spectrometers used or plausible for use with small RWUAS

Name	**Type**	**Detector size**	**FWHM %662 keV**	**Energy range**	**Power/ Signal**	**Unit size, weight**	**Price (EUR)**
FUIJapan Chappy	CsI (TI)	12.7x12.7x19 mm	8–8.5 %	65–3 000 keV	USB/ (USB/Audio)	38x94x31 mm 130 g	400
iMetry	CsI (TI)	10x10x20 mm	8–8.5 %	200–2000 keV	USB/ Audio	25x25x53 mm 43 g	200
Ritec Ltd and GBS Elektronik GmbH µSpec	CZT	60/500/1 500 mm^3	2.5–3.5 %	20–3 000 keV	USB/ USB	80 g	6 500
Kromek GR-1	CZT	500/1 000 mm^3	2–2.5 %	20–3 000 keV	USB/ (USB/MCX)	25x25x63mm 60 g	3 000–9 000
Kromek SIGMA	CsI	25x25x25 mm 25x25x50 mm 17x17x25 mm	6.5 %		USB/ USB	35x35x105 35x35x130 200/300 g	4 000–5 000

7.2.2. Sampling

As mentioned earlier, rotary-wing vehicles are more complicated to use for isokinetic aerosol particle sampling compared to fixed-wing vehicles since the airflow fluctuates more. Air fluctuation may not be as big problem if noble gases are sampled. Particulate sampling using rotary wings could be carried out with the use of manipulators (Kosmatka, Hong et al., 2011).

7.2.3. Data handling and communication

The precision in position determination, in particular for altitude, is crucial in the calculation of the source activities or surface activities. Therefore, any increase in the precision of the positioning system is welcome. Differential GPS or real time kinematics (RTK) are two techniques that can provide highly accurate positioning. Affordable positioning systems using these methods, which can provide accuracy down to the level of centimetres, have recently become available. The benefits of high-accuracy 3D positioning have been demonstrated by Lupashin, Hehn et al. (2014).

Wireless communication between the UAS and the ground station is crucial and the range could be increased by using other UASs as relays in a distributed network, as indicated by Hening, Baumgartner et al. (2013). Multiple UASs operating together have been demonstrated by Lupashin, Hehn et al. (2014) and Han, Xu et al. (2013).
Reliable communications are of the essence, and there is a demand for bandwidth if spectral data are to be transferred online, but there could be possibilities to have identification computations made on-

board the vehicle and only transmit the results if the algorithms are reliable enough. The communication requirements have to meet congested public communications in case of a public event and resilience against attempt to jam or manipulate the data link.
The GCS also assess the activities or activity concentrations of point sources or surface contamination. Point source calibration and infinite surface calibration can easily be made for unshielded sources and for different depth distributions.
The measured spectral data can be presented in waterfall display, spectrogram, and alert levels be set for different regions of interest according to the Windows methodology or by full spectrum data analysis (FSA).
The dose rate can be estimated from the spectrum by calculating the spectrum dose index (SDI).

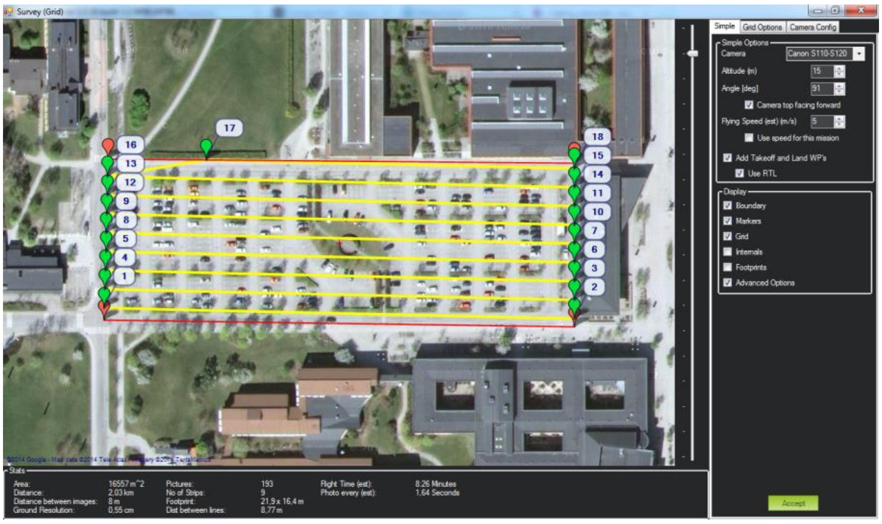

Figure 9: Planning of photographic mapping — given the desired area, the camera and altitude, the software Missionplanner calculates the route and the turning points

The screenshot in Figure 9 is from planning a photographic mapping of one of the parking lots at Linköping University, Sweden, with a Canon S110 camera at 15 m altitude, with 9 m between lines, covering over 16 000 m^2 in 8 minutes. The input in this case was the boundaries of the parking lot, the camera and the desired altitude. The software calculates the waypoints for the flight and the image quality. Analogue, it could be a plan for a full search for radioactive material. The input values in this case would be the desired MDA for an energy interval or a specific radionuclide, the detector and the search area. The pre-calculation would be the waypoints and the required time to perform the task. Alternatively, the input could be the time and area and the program calculates the resulting MDA for specific nuclides, elaborating with the altitude, speed and grid spacing.

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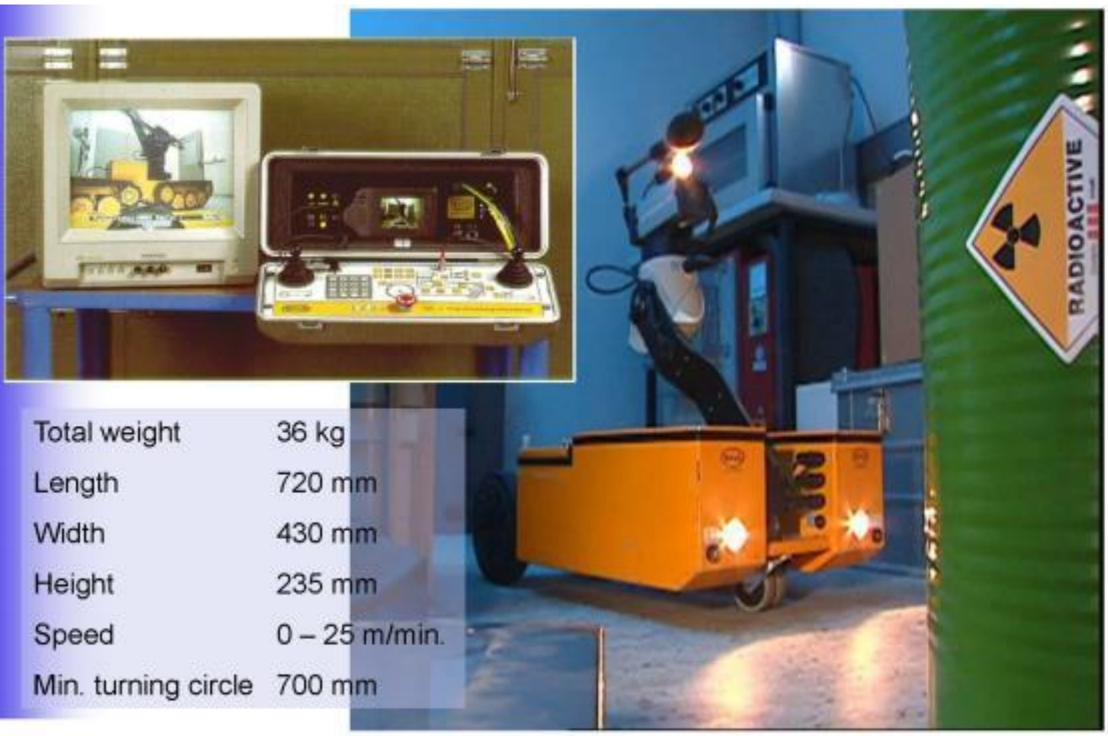
Appendix 1: Country-specific information

Germany

Small Inspection Vehicle



Total weight	36 kg
Length	720 mm
Width	430 mm
Height	235 mm
Speed	0 – 25 m/min.
Min. turning circle	700 mm

Remote controlled inspection vehicle MF 6

Length of cable	100 m	
Total weight	max. 400 kg	
Payload	250 kg	
Length	2.260/940 mm	
Width	745 mm	
Height	400/1.080 mm	
Velocity	0 – 10 m/min	
Stair climbing ability	45°	
Manipulators	KM 20, KM 80	
Degrees of freedom	6,	max. 8
Length of arms	1.600,	2000 mm
Capacity of tongs	20 kg,	80 kg

Manipulator vehicle MF 3

Total weight	350 kg
Payload	150 kg
Length	1.300 mm
Width	850 mm
Height	400 mm/1.080 mm
Velocity	0 – 30 m/min
Stair climbing ability	45°
Carriage units	2, rigid
Manipulator	KM 20
Degrees of freedom	6
Length of arm	1.600 mm
Capacity of tongs	20 kg

Manipulator vehicle MF 4

Length	980 mm / 1.570 mm
Width	440 mm
Height	1.150 mm
Total weight	300 kg
Manipulation arm	ROMAIN 125
Degrees of freedom	6
Horiz. manip. distance	1,25 m
Verti. manip. distance	2,22 m
Payload	12,5 daN

Manipulator vehicle EROS

KHG Kerntechnische Hilfsdienst GmbH

Length	min. 1350 mm
Width	850 mm
Height	1900 mm
Stair climbing ability	45 °
Step climbing	400 mm height
Ditch crossing	400 mm width
Velocity	max. 25 m/min.
Min. turning circle	1.200 mm
Payload of manipulators:	
MAESTRO (6 dof)	100 daN
MA23M (6 dof)	25 daN
LEFT ARM (4 dof)	27 daN

Light manipulator vehicle (LMF)

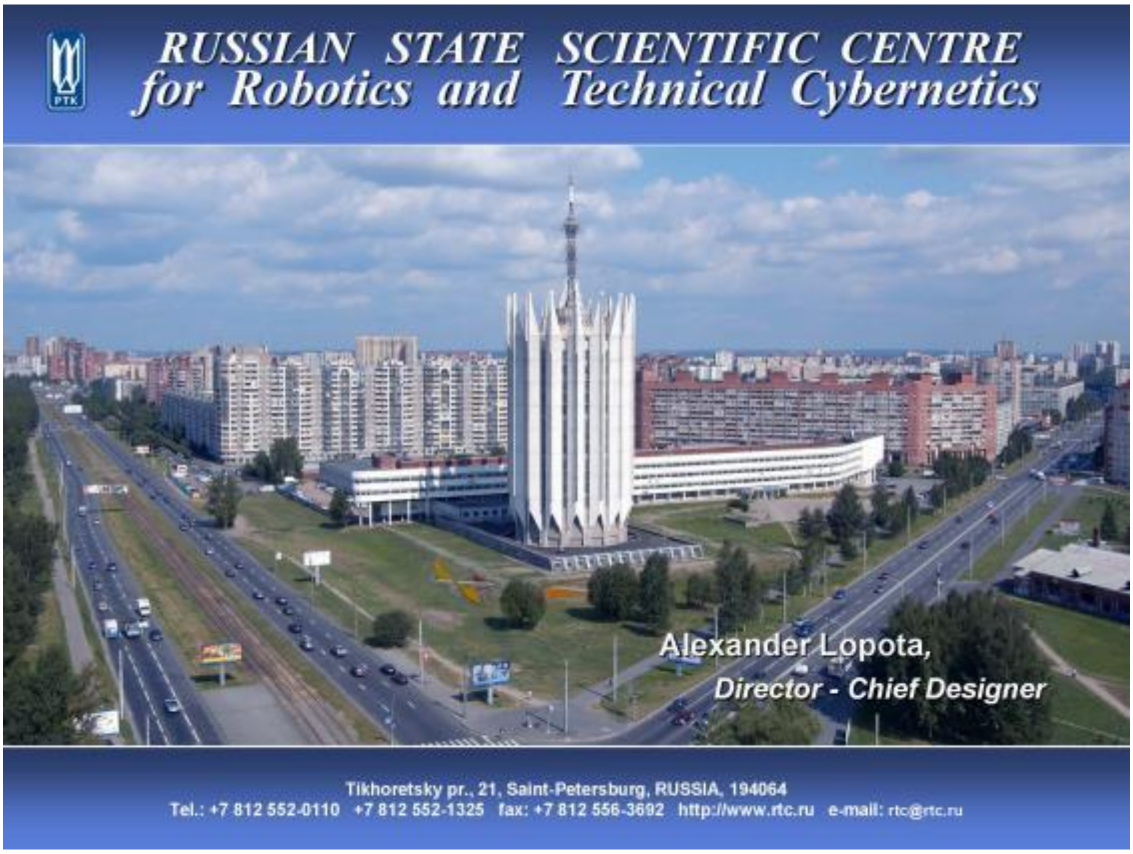
KHG Kerntechnische Hilfsdienst GmbH

Total weight	7.850 kg
Length	3.300 mm
Width	1.450 mm
Height	1.900 mm
Velocity	max. 10 km / h
Climbing abiltiy	60 % Step 400 mm
Carriage units	2
Diesel engine	90 kW
Manipulator	folding arm manip.
Degrees of freedom	6
Length of arm	3.000 mm
Payload	250 kg

Heavy duty manipulator vehicle
(SMF)

KHG Kerntechnische Hilfsdienst GmbH

Russia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Tel.: +7 812 552-0110 +7 812 552-1325 fax: +7 812 556-3692 http://www.rtc.ru e-mail: rtc@rtc.ru

Remote-controlled multifunctional mobile robot for radiation monitoring designed for the EMERCOM

Purpose

- Radiation and chemical reconnaissance
- Search of local gamma-ray sources in out-of-the-way places, industrial projects and living quarters

Robotic complex for radiation reconnaissance and visualization of local ionizing radiation sources RTC-10

Purpose

- The complex is designed for radiation reconnaissance, search and visualization of local ionizing radiation sources in out-of-the-way places, industrial projects and living quarters.

Configuration

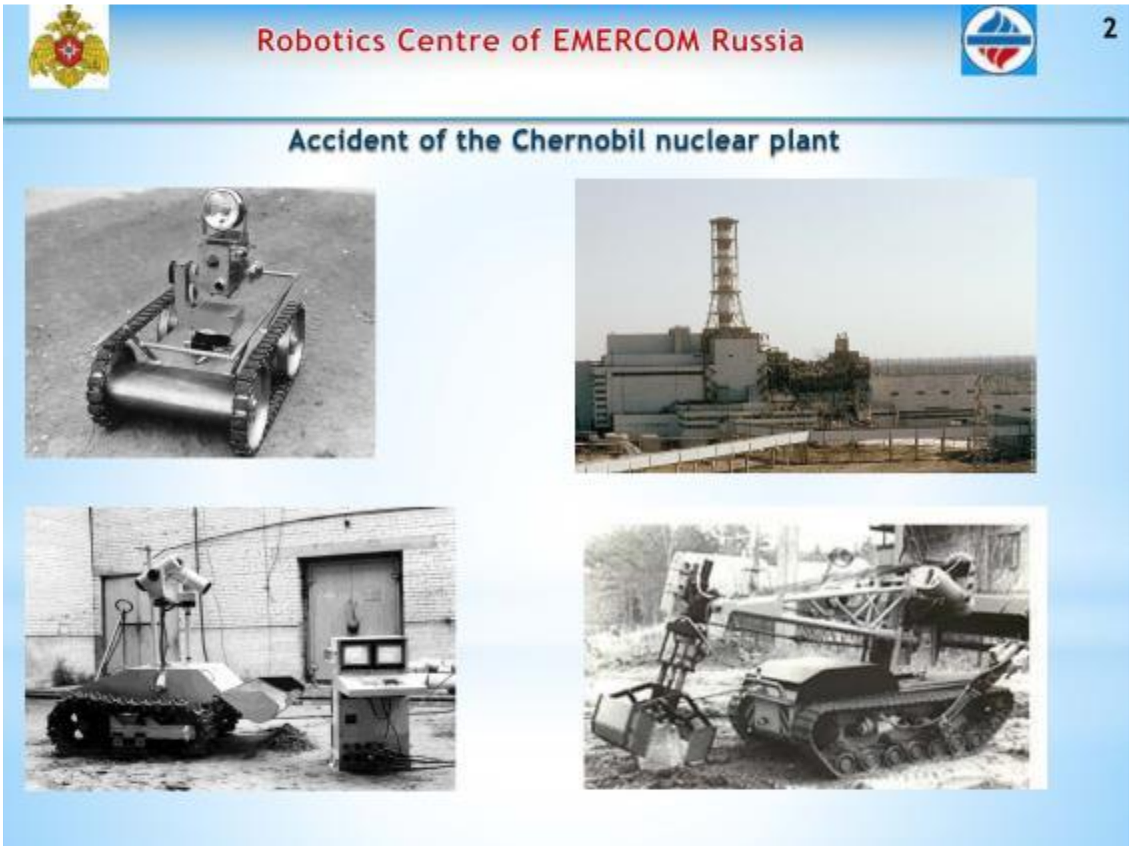
- Robotic mean for radiation reconnaissance
- Delivery and control vehicle on the base of Mercedes-Benz medium van

Tasks to be solved

- storage, processing and presentation of information about the radiation environment in the form of dose cartograms along the route of reconnaissance, and about location of radioactive sources;
- visualization of radioactive sources, including multiple;
- remote measurement of the radiation source spectral composition;
- transfer of the reconnaissance results to the data transmission channel
- recording of the RTC-10 burn-up life


Robotic mean for radiation reconnaissance with gamma-vision system as a part of EMERCOM complex RTC-10
Purpose
Search and identification of gamma-radiation sources in the out-of-the-way places, under conditions of increased gamma-radiation background
Radiation reconnaissance devices
1. Gamma camera RTC-03
2. Gamma locator RTC-02
3. Gamma spectrometer RTC-02
1
2
3


Robotics Centre of EMERCOM Russia
1
EXPERIENCE APPLICATION AND PERSPECNIVE DEVELOPMENT OF THE FIRE-RESCUE ROBOTICS IN RUSSIA
Professor Sergey Tsarichenko
Head of the Robotics Centre
Military Robotics 2014
21-22 May 2014
London


Robotics Centre of EMERCOM Russia
2
Accident of the Chernobil nuclear plant


Robotics Centre of EMERCOM Russia
4
Breakdown Nuclear elimination in Sarov Physical Centre at the 1997
MR-25 equipped neutron shielding and fire extinguisher (Bauman MSTU, Russia)
HOBO(Kentree,Ireland)
RASCAL Kentree, Ireland
MV-4 (Telerob, Germany)


Robotics Centre of EMERCOM Russia
14
Perspective fire-fighter mobile robots
SIBARS (Russia)
MVF-5 (Croatia)

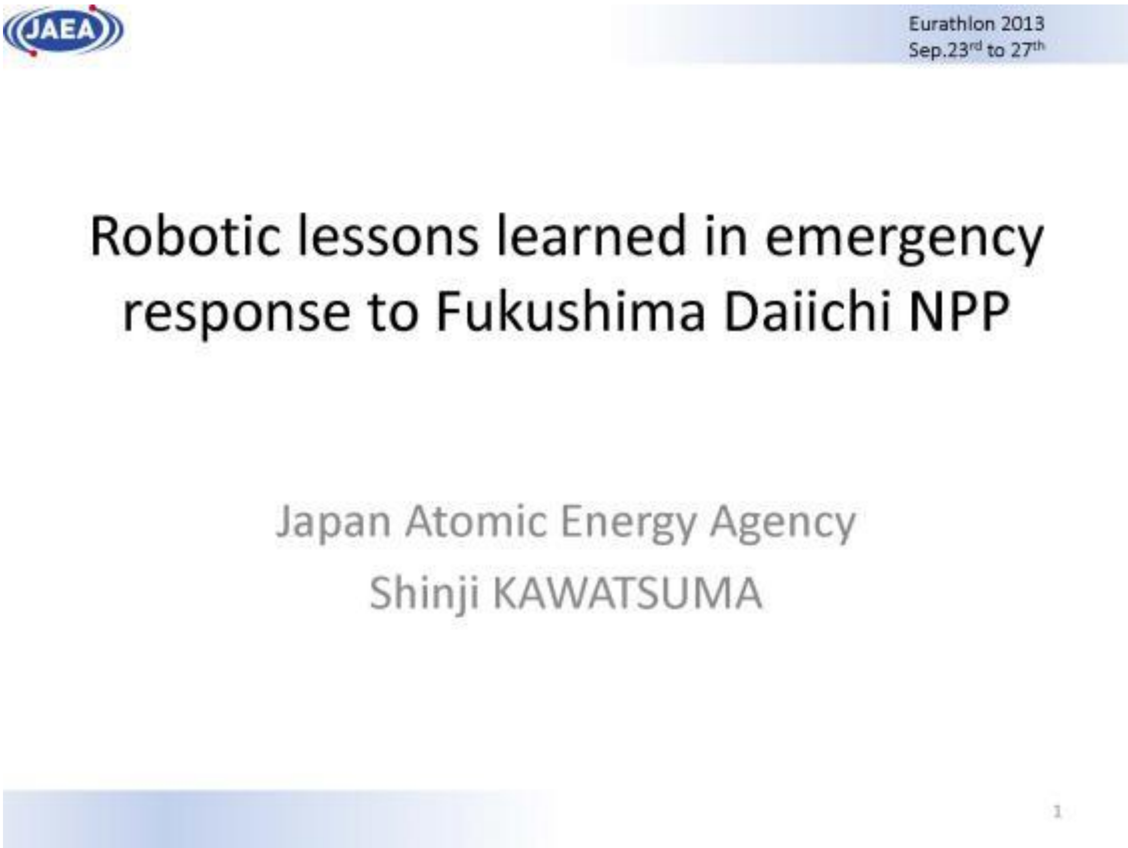

Robotics Centre of EMERCOM Russia
16
Engineering robot systems for radiation detection and wrecking (CR&DI RTC, Russia)


Robotics Centre of EMERCOM Russia
19
Robot crawler for rescue and engineering works


Robotics Centre of EMERCOM Russia
20
Design modularity for Fire-Rescue Robots
Universal crawler chassis for mounting different fire-fighter and engineering equipment


Robotics Centre of EMERCOM Russia
29
The manoeuvres Air-Ground Fire-Rescue Robotics Force on the training ground (October 2012)

Japan


Eurathlon 2013
Sep.23rd to 27th
Robotic lessons learned in emergency response to Fukushima Daiichi NPP
Japan Atomic Energy Agency
Shinji KAWATSUMA
1

Eurathlon 2013
Sep.23rd to 27th

1.Introduction

Nuclear robots developed before Fukushima accidents

MR-3

In-Service inspection Robot for Steam Generator of PWR

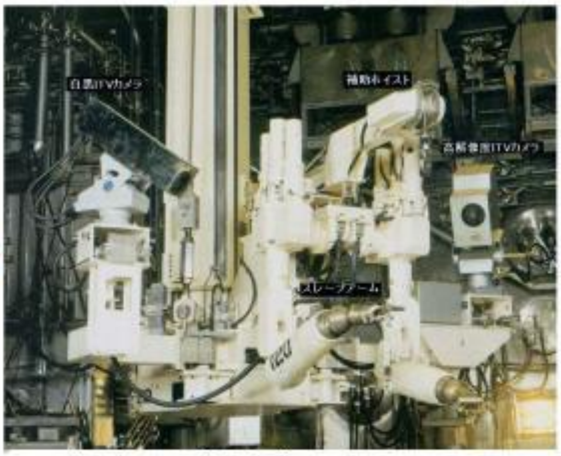
2011年～

11

Eurathlon 2013
Sep.23rd to 27th

1. Introduction

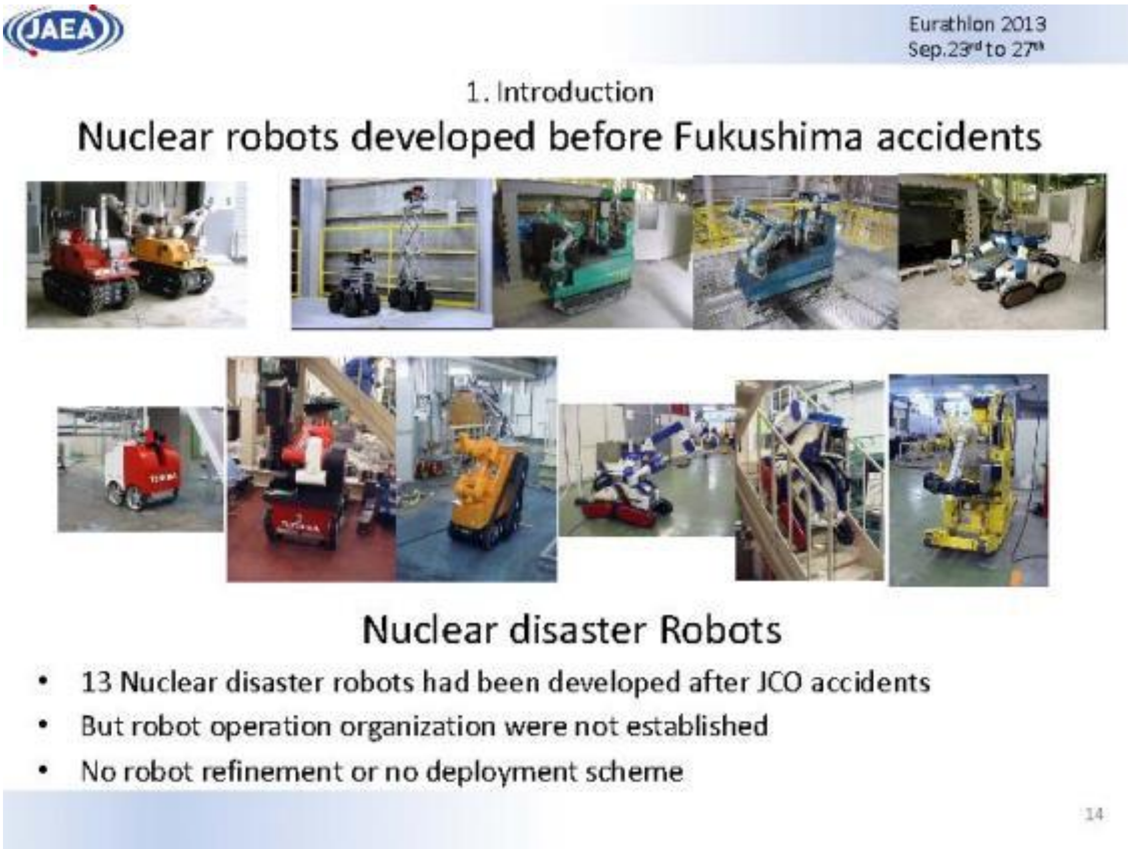
Nuclear robots developed before Fukushima accidents



Bilateral servo manipulator (BSM) system

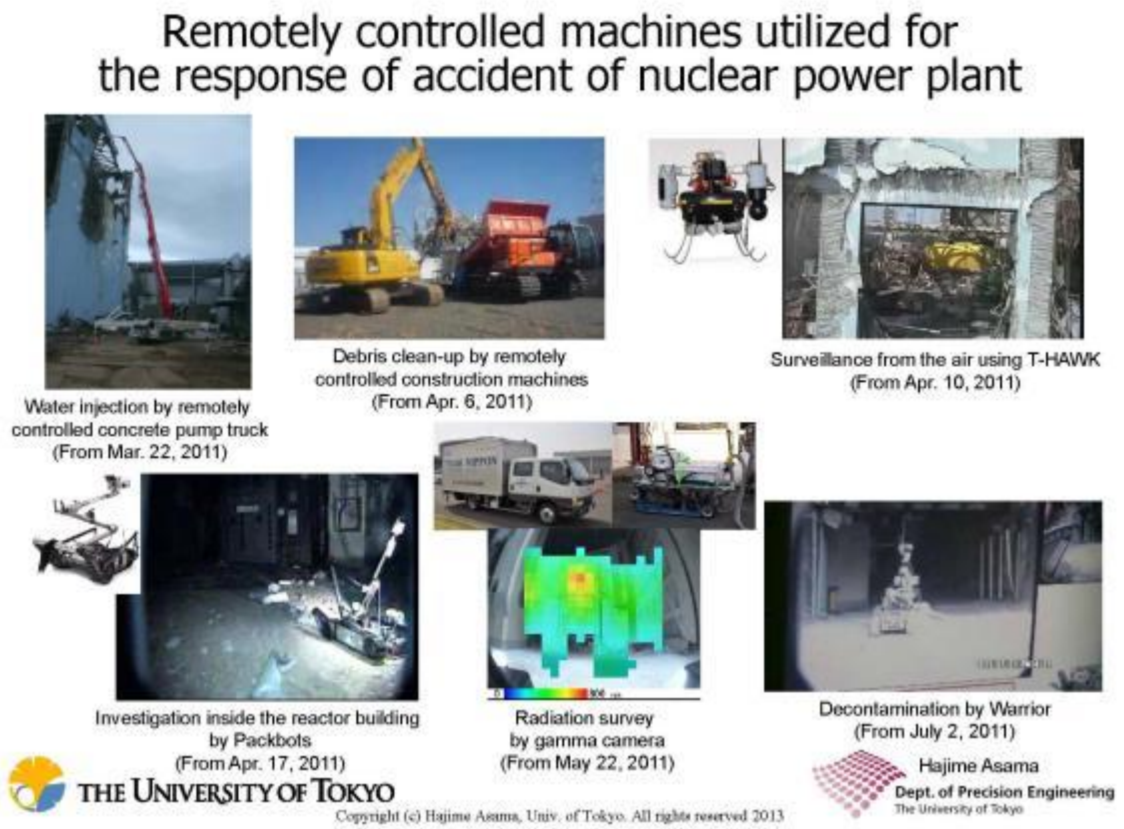
- BSM system for tasks under high radiation
- Development for more than 12 years, with users' deep contributions
- BSM has been use for more than 15 years.

13


Eurathlon 2013
Sep.23rd to 27th
1. Introduction
Nuclear robots developed before Fukushima accidents
Nuclear disaster Robots
• 13 Nuclear disaster robots had been developed after JCO accidents
• But robot operation organization were not established
• No robot refinement or no deployment scheme
14


Eurathlon 2013
Sep.23rd to 27th
2. Examples and lessons learned
2.1. Nuclear disaster robots
• 13 robots developed, but No Maintenance, No feedback, no refinement.
• Some discussion, but no deployment scheme, no operator training
• No immediate deployment to Fukushima daiichi.
16

GFJ Meeting on emergency response by remote operated equipment
Tokai, Nov. 6, 2013


Remotely controlled machines utilized for the response of accident of nuclear power plant
Water injection by remotely controlled concrete pump truck (From Mar. 22, 2011)
Debris clean-up by remotely controlled construction machines (From Apr. 6, 2011)
Surveillance from the air using T-HAWK (From Apr. 10, 2011)
Investigation inside the reactor building by Packbots (From Apr. 17, 2011)
Radiation survey by gamma camera (From May 22, 2011)
Decontamination by Warrior (From July 2, 2011)
THE UNIVERSITY OF TOKYO
Hajime Asama
Dept. of Precision Engineering
The University of Tokyo
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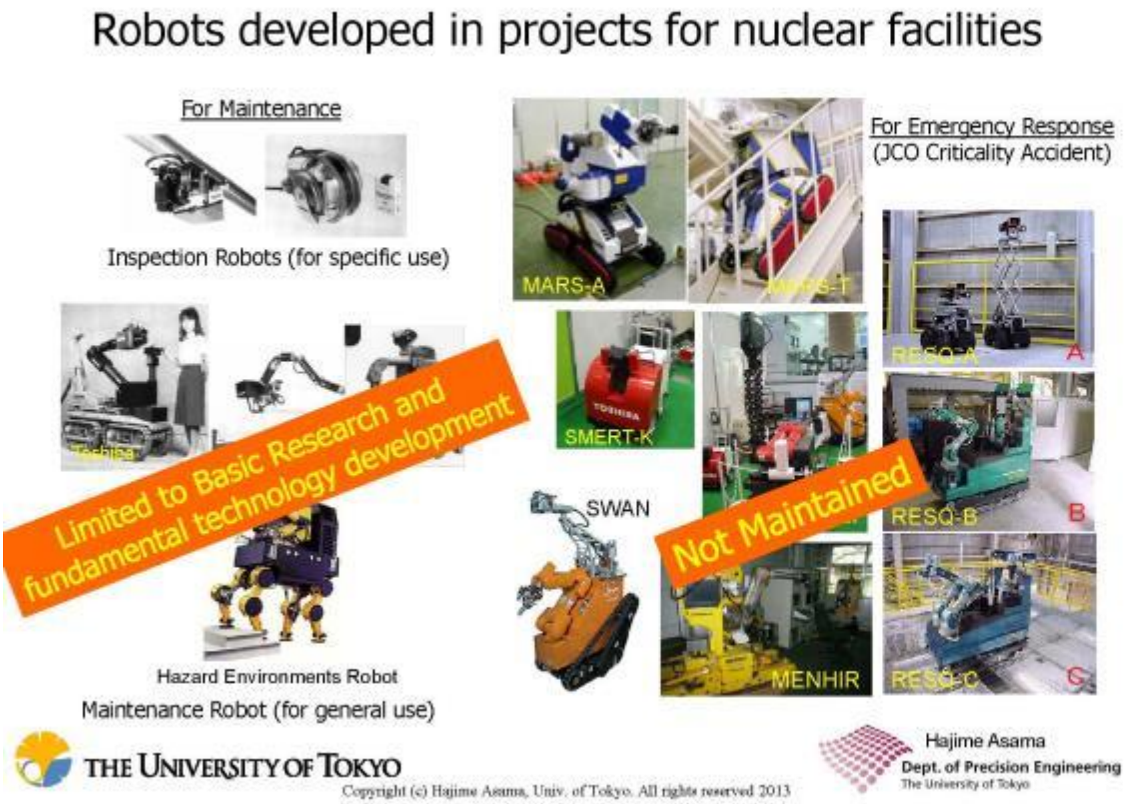
54
METI/NEDO
Anti-disaster unmanned system R&D project
Outcome
Sakura
Tsubaki
選択スイッチ
Common Human I/F
Super Giraffe
Super lifter
Hybrid inspection robot
Robust Radio Repeater
HAL for decommission



Expectation to Robot Technology

Gap

Reality

- There are few robots and remotely controlled machines which have sufficient function to be used in the real disaster sites.
- Most of the robots developed in Japan were just prototypes developed by researchers, and there are few products.

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Appendix 2: Definition of technology readiness levels for hardware/software

NB: Definition of technology readiness levels (TRLs) according to the 'Technology readiness assessment (TRA) guidance', United States Department of Defense, April 2011.

Technology readiness level for hardware	Description
1. Basic principles observed and reported in context of a relevant military capability shortfall	Lowest level of technology readiness. Scientific research begins to be evaluated for military applications and translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be postulated. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic paper studies.
3. Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Technology component and/or breadboard ([1]) (system/subsystem representation) validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively low fidelity ([2]) compared with the eventual system. Examples include integration of 'ad hoc' hardware in a laboratory.
5. Technology component and/or breadboard ([1]) (system/subsystem representation) validation in relevant environment ([3])	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so the technology can be tested in a simulated environment. Examples include high-fidelity ([6]) laboratory integration of components.
6. Technology system/subsystem model ([4]) or prototype ([5]) demonstration in a relevant environment ([3])	Representative model or prototype system, which is well beyond the breadboard ([1]) (representation) tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity ([6]) laboratory environment or in a simulated operational environment ([7]).
7. Technology system	Prototype near, or at, planned operational system. Represents a major step

([1]) Breadboard: Integrated components that provide a representation of a system/subsystem and that can be used to determine concept feasibility and to develop technical data. Typically configured for laboratory use to demonstrate the technical principles of immediate interest. May resemble final system/subsystem in function only.

([2]) Low fidelity: A representative of the component or system that has limited ability to provide anything but first order information about the end product. Low-fidelity assessments are used to provide trend analysis.

([3]) Relevant environment: Testing environment that simulates the key aspects of the operational environment.

([4]) Model: A functional form of a system generally reduced in scale, near or at operational specification. Models will be sufficiently hardened to allow demonstration of the technical and operational capabilities required of the final system.

([5]) Prototype: A physical or virtual model used to evaluate the technical or manufacturing feasibility or military utility of a particular technology or process, concept, end item or system.

([6]) High fidelity: Addresses form, fit and function. High-fidelity laboratory environment would involve testing with equipment that can simulate and validate all system specifications within a laboratory setting.

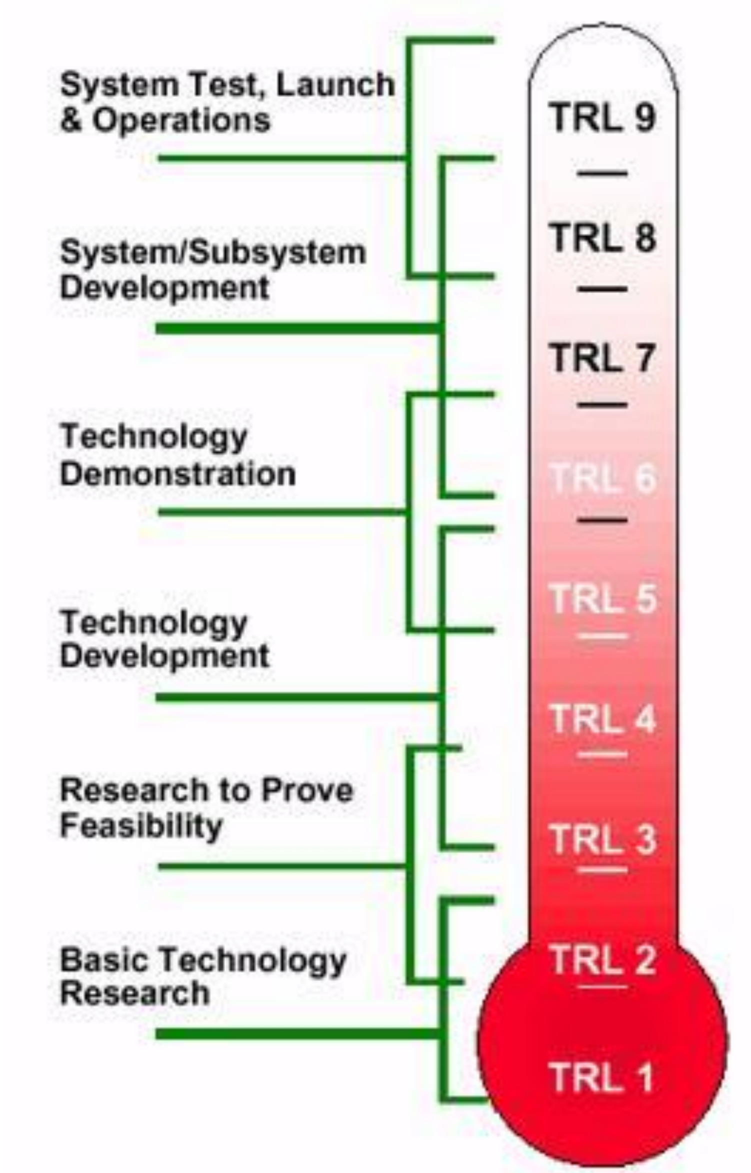
([7]) Simulated operational environment: Either (a) a real environment that can simulate all of the operational requirements and specifications required of the final system, or (b) a simulated environment that allows for testing of a virtual prototype. Used in either case to determine whether a developmental system meets the operational requirements and specifications of the final system.

prototype ([5]) demonstration in an operational environment ([8])	up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment (e.g. in an aircraft, in a vehicle, or in space). Information to allow supportability assessments is obtained. Examples include testing the prototype in a test bed aircraft.
8. Actual technology system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development and demonstration. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications, including those relating to supportability.
9. Actual technology system 'mission proven'/'qualified' through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test, evaluation, and reliability trials. In almost all cases, this is the end of the last 'bug fixing' aspects of true system development. Examples include using the system under operational mission conditions.

Technology readiness level for software	Description
1. Basic principles observed and reported	Lowest level of software technology readiness. A new software domain is being investigated by the basic research community. This level extends to the development of basic use, basic properties of software architecture, mathematical formulations, and general algorithms.
2. Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies using synthetic data.
3. Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. The level at which scientific feasibility is demonstrated through analytical and laboratory studies. This level extends to the development of limited functionality environments to validate critical properties and analytical predictions using non-integrated software components and partially representative data.
4. Module and/or subsystem validation in laboratory environment (i.e. software prototype ([5]) development environment)	Basic software components are integrated to establish that they will work together. They are relatively primitive with regard to efficiency and robustness compared with the eventual system. Architecture development initiated to include interoperability, reliability, maintainability, extensibility, scalability, and security issues. Emulation with current/legacy elements as appropriate. Prototypes developed to demonstrate different aspects of eventual system.
5. Module and/or subsystem validation in relevant environment ([3])	Level at which software technology is ready to start integration with existing systems. The prototype ([5]) implementations conform to target environment/interfaces. Experiments with realistic problems. Simulated interfaces to existing systems. System software architecture established. Algorithms run on a processor(s) with characteristics expected in the operational environment ([8]).
6. Module and/or subsystem validation in a relevant end-to-end environment ([5])	Level at which the engineering feasibility of a software technology is demonstrated. This level extends to laboratory prototype ([5]) implementations on full-scale realistic problems in which the software technology is partially integrated with existing hardware/software systems.
7. System prototype ([5]) demonstration in an	Level at which the program feasibility of a software technology is demonstrated. This level extends to operational environment prototype

([8]) Operational environment: Environment that addresses all of the operational requirements and specifications required of the final system, including platform/packaging.

operational ([8]) high-fidelity ([6]) environment	implementations where critical technical risk functionality is available for demonstration and a test in which the software technology is well integrated with operational hardware/software systems.
8. Actual system completed and mission qualified through test and demonstration in an operational environment ([8])	Level at which a software technology is fully integrated with operational hardware and software systems. Software development documentation is complete. All functionality tested in simulated and operational scenarios.
9. Actual system proven through successful mission-proven operational capabilities	Level at which a software technology is readily repeatable and reusable. The software based on the technology is fully integrated with operational hardware/software systems. All software documentation verified. Successful operational experience. Sustaining software engineering support in place. Actual system.


System Test, Launch & Operations
System/Subsystem Development
Technology Demonstration
Technology Development
Research to Prove Feasibility
Basic Technology Research
TRL 9
TRL 8
TRL 7
TRL 6
TRL 5
TRL 4
TRL 3
TRL 2
TRL 1

European Commission
EUR 27224 EN – Joint Research Centre – Institute for the Protection and Security of the Citizen

Title: Current state of the art of unmanned systems with potential to be used for radiation measurements and sampling
ERNCIP thematic group Radiological and nuclear threats to critical infrastructure - Task 3 deliverable 1

Authors: Frank E. Schneider, FKIE
Bastian Gaspers, FKIE
Kari Peräjärvi, STUK
Magnus Gårdestig, Linköping University

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Abstract

There is a significant potential in the use of unmanned remote controlled vehicles in sampling and measuring radiological events. No attempts to standardise sampling and measurement methods using these types of vehicles have yet been made. Common standards would simplify the use of remote controlled vehicles in an emergency scenario and would thus be very valuable in critical infrastructure protection (CIP). The main advantage of using unmanned systems in radiological events is the protection of the human personnel involved. This report is about current state-of-the-art of unmanned systems that have potential to be used for radiation measurements and sampling. It is believed that search and rescue robotics is the domain that is closest to the robots applicable to the radiation measurement scenarios. Therefore, a definition for search and rescue robots and outlines of their major subsystems are given. This is followed by a review of deployment scenarios for search and rescue robots outlining case studies of major emergencies at which robots have been deployed — with an assessment of their value to the emergency services. Additionally, research and development in search and rescue robotics, including current projects, testing environments and search and rescue robotics competitions, is outlined. Furthermore, this report shows unmanned robots and concepts for sensor systems capable of radiation detection based on state-of-the-art radiation sampling using unmanned ground vehicles, unmanned aerial vehicles with rotary wings or unmanned aerial vehicles with fixed wings.

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Stimulating innovation
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