ROBDEKON: Robotic Systems for Decontamination in Hazardous Environments

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Abstract— **Contamination with radioactive or chemical substances can have serious consequences for humans and the environment. For this reason, thorough decontamination is of great importance in the decommissioning of nuclear power plants and the remediation of contaminated sites. People who have to carry out such tasks are working under physically demanding conditions and may be exposed to high health risks.**

To get humans out of those hazardous environments, the ROBDEKON project was launched with the aim of establishing a national competence center for "Robotic Systems for Decontamination in Hazardous Environments". In ROBDEKON, four research institutions work together with partners from industry to develop practical robot systems for decontamination tasks. The research activities include the development of mobile robots for rough terrain, autonomous construction machines, and robot manipulators as well as decontamination concepts, planning algorithms, multi-sensory 3D mapping of the environment and teleoperation using virtual reality. The focus is on three applications: the decommissioning of nuclear facilities, the decontamination of plant components and handling of waste, and the remediation of landfills and contaminated sites.

This paper gives a high-level overview of the goal and the ongoing research activities in ROBDEKON, provides an insight into the infrastructure of the involved laboratories, and presents first project results.

I. INTRODUCTION

Contamination caused by substances hazardous to the environment and health can have a wide variety of causes. For example, toxic substances leaking as a result of chemical incidents can render entire properties or their surroundings impassable to humans; in nuclear power plants, some parts of the building structure and plant components are contaminated due to adhesions and some are activated because of the neutron activation during operation; improper dumping of toxic substances can contaminate soil and groundwater, resulting in a considerable health risk for humans and the environment.

Decontamination is the removal of one or more hazardous substance from a carrier material. In any type of decontamination, self-protection is paramount: on the one hand to prevent further spread of contamination, and on the other to protect those involved in decontamination work from the dangers of toxic or radioactive substances. The protection of humans from contamination, the protection of the population and the environment, the efficient performance of decontamination work, and safe disposal are the top priorities. The considerable hazard potential during decontamination in a mostly inhuman working environment requires extensive protective measures, such as elaborate protective suits, which significantly increase the workload for humans and considerably limit the admissible duration of their working time. In addition, it is essential to keep human exposure to pollutants during decontamination work as low as possible. For example, during decontamination work in nuclear facilities, upper limits for the dose uptake of personnel must be observed. This is currently achieved by restricting the duration for which a person may stay in these environments; however, it is desirable to minimize the dose even below the specified maximum values. This principle is known as the ALARA principle ("as low as reasonably achievable"), which means that there is no specific lower bound but all reasonable and sensible measures must always be taken to keep the risk to humans as low as possible.

As long as people have to perform decontamination tasks manually, they are potentially exposed to chemical, biological, radiological and nuclear (CBRN) hazards. As effective protection measures for humans are common today, a further reduction according to the ALARA principle can only be achieved if humans no longer have to act directly on site in these environments.

The increased use of robotic systems in hazardous environments can decrease the exposure of humans to those health threats. In recent years, there have been considerable innovative advances in the field of robot technology, driven in particular by industrial applications. The innovations range from flexible multi-arm manipulator systems to (partially) autonomous mobile robot systems and robots that work cooperatively with humans. The manifold possibilities for the use of robots in hazardous environments are currently far from being exhausted.

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However, robots will only be able to prove themselves if they offer significant added value compared to the processes used today. This means that in addition to suitable hardware, the "intelligence" of the robot in particular will play a decisive role. In recent years, substantial progress has been made in the field of artificial intelligence, enabling robots to perform an assigned task semi-autonomously. The reasonable degree of autonomy can vary considerably and ranges from advanced teleoperated systems to semi-autonomous and fully autonomous systems. In particular, the synergetic cooperation of humans and robots ("shared autonomy") has increasingly come into the focus of research. This goes hand in hand with novel operating concepts that build on modern forms of telepresence using virtual and augmented reality.

II. STATE OF THE ART

Although advanced technologies are slowly gaining a foothold in robotic systems available on the market, they are currently only used to a minor extent in the area of robotic systems for environments that pose high health risks to humans. On the one hand, this is due to the fact that scientific research has generally been highly specialized, so that although robotic components are developed at a high level, due to the complex requirements of contaminated environments they must first be qualified for practical use. On the other hand, industry is currently still exploring the market for robots in the context of inspection and decontamination because the development of new technologies and concepts is associated with a high financial risk.

The remainder of this section provides some insights into the current state of the art regarding three robotic decontamination applications which form the thematic focus of the presented research project ROBDEKON.

A. Decommissioning of Nuclear Facilities

Worldwide, the need for decommissioning of nuclear facilities will increase significantly in the coming years and decades, as a large proportion of the plants currently in operation were built in the 1970s and 1980s. However, the great demand for decommissioning services is only met by a few specialist companies operating both nationally and internationally.

Research work on robotic systems for decontamination in this context covers tracked vehicles [1]–[3], single- and two-arm manipulators [4]–[6], and climbing robots based on vacuum suction technology or magnets [7]–[10]. Applications are the disassembly of components during the dismantling of nuclear facilities, e.g., the cutting up of pipes [4], as well as the milling of contaminated wall layers and the handling of radioactive substances and wastes [11].

Robots used today in the dismantling of nuclear facilities and for the handling of radioactively contaminated parts are predominantly specialized solutions for the respective facility [12]. For example, construction machines with crawler track and hydraulic excavator arm are adapted for teleoperated operation with high development costs. There are also electrically-driven systems and conventional industrial robots. The attached tools are used for cutting metal, crushing and milling concrete. But also in the rare case of accidents in nuclear facilities, robotic systems can provide people with important information on inaccessible areas and can remove contaminated material [13], [14].

Currently used robots are run almost exclusively teleoperated and have no significant autonomy [12], [15]. Therefore, extensive training and education measures for the operators are necessary, up to and including the replication of the plants under consideration for testing the teleoperated dismantling. The teleoperation is error-prone and a tedious activity for the operator [16]. The specialized robots used are far from as reliable as standard industrial robots [15].

B. Decontamination of Plant Components / Waste Handling

The ongoing dismantling of nuclear facilities and significantly increased regulatory requirements for the treatment of contaminated plant components are creating a strongly growing market for robot-assisted applications. In recent years, the EU has launched a number of research projects to advance the use of robotic systems for decommissioning of nuclear facilities. The research focuses on the transition from conventional teleoperated robots (like well-known master-slave concepts for manipulation systems for handling radioactive waste and for packaging contaminated material in barrels) to an increased level of autonomy for manipulation tasks (cf. project RoMaNS, [17]). Further, sorting tasks for unclassified nuclear waste have been the subject of robotics research (cf. project RadioRoSo, [18]). However, the proposed concepts share many ideas with classical production robotics and have not found their way into broad application yet.

In addition to radioactively contaminated components in nuclear plants, plant components from the chemical industry in particular are also often contaminated with hazardous substances. Pipes, pumps, valves, compensators and other plant components are contaminated by contact with chemicals and reaction products from various processes and thus cannot be disposed of in the usual manner. The requirements placed on the algorithmic capabilities of robotic systems for handling contaminated parts is very similar regardless of the source of contamination. This is even true for robotic systems used in municipal waste management [19] as well as for recycling of waste and electronic equipment or scrap in general [20]. Those materials also expose humans to considerable health risks during manually executed sorting and segregation work, which is why an increased use of robotic systems in this domain is very desirable.

C. Remediation of Landfills and Contaminated Sites

Today, modern remediation of landfills or contaminated sites is often carried out under an enclosure due to the high hazard potential. This ensures that no emissions can escape into the environment by means of a negative pressure inside the enclosure and exhaust air purification [21], [22]. Most of the time, the removed waste is discharged in closed gas- and dust-tight containers. Further transport is done by truck,

Fig. 1. DFKI's walking excavator (photo by Felix Bernhard).

rail or inland waterway to a recycling/disposal plant, in the majority of cases a hazardous waste incineration plant.

Until now, the actual retrieval of the waste is performed using manually operated construction equipment (mainly excavators and dumpers) having airtight cabins with external air supply. Protective suits, breathing masks and compressed air supply protect the operating personnel from toxic substances, for example, during manual sampling tasks [23].

Often neither the nature of the hazardous substances nor their location are sufficiently known. Thus, the possible dangers during excavation and sampling are not predictable. For example, the mixing of contaminated material and further physical actions can lead to chemical reactions that create new hazards for personnel and the environment. During the remediation work of the Bonfol landfill in Switzerland, explosions occurred which necessitated a long interruption of the remediation work [24]. Afterwards, teleoperated construction machines were used for recovery work, which were controlled from a control station relying on video streams and direct visual contact by the operating personnel. Beyond this individual case, the use of teleoperated let alone partially autonomous systems seems to be very limited in the area of landfill remediation. Only a few particular tasks in the field of remediation of contaminated sites have been considered in robotics research so far, e.g., the removal of asbestos layers on steel beams in buildings was investigated in a research project [25].

III. THE ROBDEKON APPROACH TO DECONTAMINATION

The competence center "ROBDEKON – Robotic Systems for Decontamination in Hazardous Environments" (German: "Robotersysteme für die Dekontamination in menschenfeindlichen Umgebungen") is dedicated to the research of autonomous or semi-autonomous robotic systems, which are to be used in environments where work for humans has so far been associated with a considerable health risk. The aim is to establish a network which will bundle and sharpen Germany's scientific and technological competencies in the field of robot-based decontamination. Since June 2018, ROBDEKON is funded by the Federal Ministry of Education and Research (BMBF) within the scope of the German Federal Government's "Research for Civil Security" program. The duration will initially be four years, but the aim is for the competence center to continue to exist in the long term.

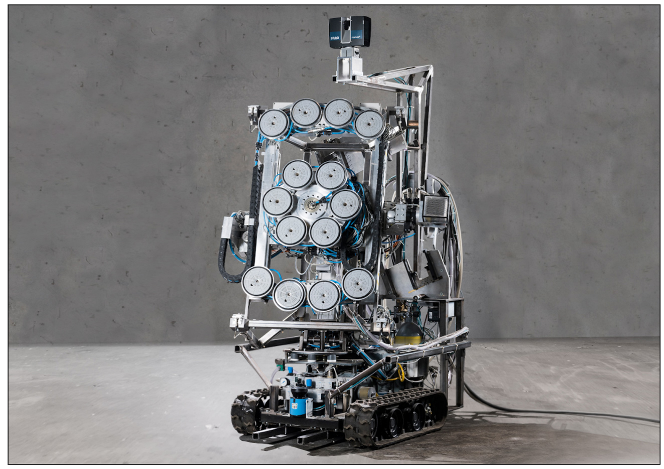

Fig. 2. KIT's climbing robot MANOLA [30] for the decontamination of conrete walls.

ROBDEKON focuses on research and development of novel robotic systems for decontamination tasks. For this purpose, ROBDEKON builds on the broad foundations of existing work, like algorithms for Simultaneous Localization and Mapping (SLAM) [26], motion planning in general [27] and for automated vehicles [28], as well as for grasp synthesis [29]. The goal of ROBDEKON is to refine these methods for decontamination applications and put them into practice.

Research topics include mobile robots for rough terrain, autonomous construction machines, highly specialized robot manipulators as well as robot-based decontamination concepts, planning algorithms, multi-sensory 3D mapping and teleoperation using virtual reality. In order to enable robots to perform their assigned tasks semi- or even fully autonomously, ROBDEKON heavily builds on and expedites methods of artificial intelligence for robotic decontamination systems.

A. Robotic Systems

Unstructured, hazardous environments place high demands on robots. Both locomotion in difficult terrain and complex manipulation tasks during decontamination pose great challenges. Therefore, there are two lines of action in ROBDEKON for hardware-related research and development work: on the one hand, mobile robot systems such as tracked and walking excavators addressing specific application requirements are being developed, and on the other hand, research focuses on manipulators, which will carry out decontamination work largely autonomously.

Mobile robots can be used in many different ways for decontamination tasks. Especially in the field of landfill and contaminated site remediation, but also in the decommissioning of nuclear facilities, robots can help to keep people out of the danger zone. In ROBDEKON, heavy machines are automated for this purpose. A walking excavator (see Fig. 1)

Fig. 3. KIT's humanoid robot ARMAR-6 [31] grasping test objects.

Fig. 4. FZI's mobile robot HUSKY.

is being enabled to move over landfills and salvage objects. In the course of the project, a large crawler excavator will be able to autonomously remove contaminated soil layers and load them onto a transport vehicle. But also smaller mobile robots with specialized kinematics are to be used in ROBDEKON, e.g., for sampling tasks on landfills. For this purpose, the machines are currently being converted so that they can be controlled via a computer, and sensors are being installed to collect information about the environment.

In addition to the carrier platforms, research on novel manipulators plays a major role in ROBDEKON, especially in the context of decommissioning of nuclear facilities. For example, a robot using suction cups to climb along a wall is being refined for milling off contaminated layers of concrete (see Fig. 2).

B. Robot-based Decontamination Techniques

In addition to the development of robotic platforms which are suitable for decontamination tasks, the robot-based decontamination techniques themselves are a major research topic within ROBDEKON. The main focus is on the treatment of building structures, the cleaning of contaminated objects and the removal of contaminated soil.

For the treatment of building structures, it is being investigated which technologies are most suitable for milling off wall layers. The development of the removal device is carried out in close coordination with the further development of the carrier platform similar to the climbing robot in Fig. 2. The goal is a system that can mill off the top layer of concrete as automatically as possible while at the same time ensuring a secure hold and contact pressure during climbing. The removal of the material all the way into the corners of the room is also a major challenge.

In ROBDEKON one- and two-arm manipulators are used for cleaning contaminated objects (Fig. 3). In the context of decontamination of plant components, methods for robust object recognition and segmentation in unstructured arrangements as well as for grasp, motion and manipulation planning for carrying out the actual decontamination are researched here.

The third example of decontamination techniques developed in ROBDEKON is the autonomous removal of soil layers. For this purpose, the automated construction machines are enabled to compute an optimal digging strategy on the basis of a given area to be excavated. Motion planning methods are then used to plan the actual motion of the machines. One important topic of the ongoing research are adaptive control systems which can react to unforeseen events such as a stone in the digging area.

C. Telepresence for Robotic Systems

Due to the variability of the environment, fully autonomous exploration and decontamination is not feasible in many cases. However, in order to prevent people from being exposed to hazards by entering the contaminated areas, at least teleoperated control of the robots is required.

In ROBDEKON, telepresence and virtual/augmented reality technologies are developed that offer the operator an immediate, immersive 3D impression of the robot's environment (see Fig. 4). On the one hand, classical control station concepts are being further developed in such a way that heterogeneous mobile robot systems can be integrated (see Fig. 5). The focus is in particular on concepts for the teleoperation of heavy machinery. On the other hand, novel immersion concepts are investigated in ROBDEKON, such as the construction of a holodeck, so that a large virtual motion space is available to the user through the use of methods for motion compression or through the use of an omnidirectional treadmill.

Intuitive control possibilities for the diverse robotic systems are also very important; here, the haptic feedback of occurring forces is considered in particular, which can be realized e.g. via an exoskeleton. Furthermore, the development of assistance functions for the semi-autonomous performance of decontamination work is an important aspect. For this reason, ROBDEKON investigates concepts for so-called shared autonomy, since the meaningful degree of

Fig. 5. Control station for teleoperated heavy machinery (Götting KG).

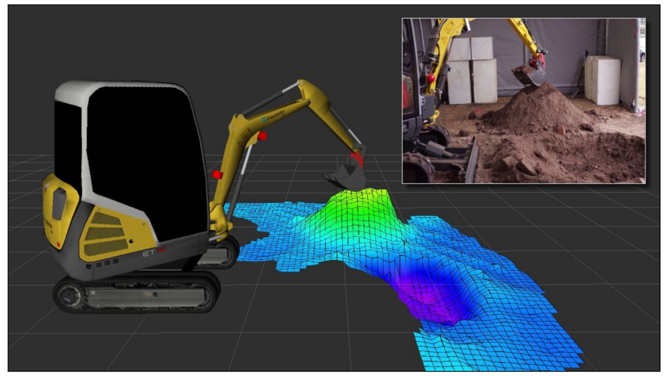

Fig. 6. 2.5D map built by the autonomous excavator *IOSB.BoB* [32].

autonomy is not always obvious in advance and it can make sense for a robotic system to selectively request help from an operator.

D. Multi-sensory Perception of the Environment

As the degree of autonomy of robots increases, accurately sensing the environment becomes increasingly important. The precise mapping of unstructured environments poses great challenges for sensors and algorithms. In addition to the geometric mapping of the environment, robot-based detection of hazardous substances and radiation measurement also play an important role.

The comprehensive perception of the environment is an important research topic within ROBDEKON. Methods are being developed that allow mobile robots to move safely in an unknown environment. For autonomous construction machines, this research is based on extensive prior work by the participating research institutes (see Fig. 6). On the basis of a precise environment map and localization, the robots are enabled to perform their actual tasks as autonomously as possible. ROBDEKON also addresses the precise geometric measurement of objects in order to ensure effective manipulation of the objects, whether when removing wall material or decontaminating plant components.

Moreover, the detection and measurement of hazardous substances using robotic systems is an important research topic in ROBDEKON. The robotic systems are enabled to autonomously generate a hazardous substance map of a given area or a radiation map of a building. For this purpose, probabilistic methods of estimating spatially distributed states are investigated.

E. Planning Algorithms for Decontamination Tasks

Besides sensing the environment, planning the next actions and the actual robot motion is an important prerequisite for autonomy. Therefore, research in ROBDEKON focuses on methods and algorithms for motion planning for robots in unstructured environments. This includes robot-independent planning algorithms for automated area-wide radiation mapping and exploration tasks as well as robot-specific path planning algorithms taking into account the vehicle kinematics for specialized robots such as construction machines or particular tasks such as the deployment of climbing robots.

To perform decontamination tasks efficiently and effectively, a 3D planning tool for logistics, simulation, evaluation and documentation of the decontamination task will be developed. On the basis of the 3D model of the environment, sequence and deployment plans are to be generated and transport routes optimized. In addition, methods for grasp and manipulation planning for decontamination tasks are being developed in ROBDEKON. Once again, the focus is on unstructured arrangements, which means that objects must be picked up from boxes or a moving conveyor belt, as is the case when sorting electronic scrap, for example.

IV. ROBDEKON LABS

The members of ROBDEKON contribute a total of seven existing test sites and laboratories to the competence center. These are continuously expanded during the course of the project and serve as a basis for the development and evaluation of technology demonstrators. In addition, the laboratories will be networked so that in the future it will also be possible to build cross-laboratory demonstrators. For example, it is planned to implement telepresence concepts for robotic systems across laboratories.

1) Test site for heavy machinery: KIT's Institute of Technology and Management in Construction has an outdoor area of approx. 6 ha where large-scale decontamination scenarios are simulated for controlled decommissioning as well as for incident situations. The site allows the testing of the decontamination systems developed in ROBDEKON as well as the construction of larger test rigs and 1:1 mock-ups for comprehensive feasibility studies. In addition, the outdoor area has a 50 m long, roofed ground channel in which ground movement tests are carried out. A construction machinery park is available at the test site, which can be used whenever required.

2) Test site for teleoperated robotic systems in nuclear facilities: On the premises of the Kerntechnische Hilfsdienst GmbH (KHG) there are training areas for the indoor and outdoor use of manipulator systems of all sizes. A crawler excavator of the 20 Mg class converted for remote-controlled operation, which is equipped with numerous sensors and

Fig. 7. KHG's robot capable of climbing stairs.

camera systems, serves as an operator-guided functional model for autonomous systems to be developed. The enclosed outdoor area for the crawler excavator has an area of approx. 2000 m^2. In addition to driving manoeuvers, sorting and earth moving work can also be carried out in this area. Several rooms with different exercise objects are available for indoor use, where complex handling tasks as well as the use of tools and additional sensors can be tested. In addition to the several teleoperated mobile manipulator vehicles (for an example see Fig. 7), a mobile control station, radiation measuring equipment and decontamination facilities are also available to support the research in ROBDEKON.

3) Lab for climbing and milling robots: Within the BMBF project MAFRO (Manipulator-controlled release measurement procedure for surfaces), a demo cell was set up to test the developed integrated system. In ROBDEKON the test facility of KIT's Institute of Technology and Management in Construction has been extended for future decontamination robots by construction of additional demo cells. This allows a realistic emulation of decommissioning scenarios. There are several climbing robots (see Fig. 2) as well as decontamination devices available which can mill off several square meters of wall surface per hour up to 5 mm deep or remove them by means of a laser working head.

4) Lab for mobile robots in unstructured environments: With its Living Labs, the DFKI Robotics Innovation Center (RIC) has a spacious infrastructure for testing and evaluating the newly developed robotic systems. Large indoor and outdoor test areas with different surfaces and obstacles allow the testing of mobile robotic systems as well as the investigation of topics regarding human-machine interaction, manipulation or sensor technology. The planning of a further hall, which offers large space for various robots and will also be available to ROBDEKON after completion, is currently in its final phase. A virtual reality environment serves as an immersive, interactive 3D test environment, which allows to test robots cost-effectively in realistic simulated environments on a total projection surface of 21.6 m^2. Furthermore, a spacious outdoor test site for large scale experiments with ROBDEKON's walking excavator (see Fig. 1) is available.

5) Teplepresence Lab / Holodeck: The telepresence laboratory of the KIT chair Intelligent Sensor-Actuator-Systems (ISAS) can be used directly as a user front end for teleoperation. The user receives visual, acoustic and haptic feedback while being able to move around freely. From the holodeck, the user can freely explore the target environment, whereby the user's movement is captured by a 3D tracking system, transferred to a robot located in the target environment, and finally replicated by the robot. Visual and acoustic sensor data of the robot is transmitted to the user and presented by a head-mounted display. In addition, the user can also carry out on-site handling operations with force feedback via a haptic interface. The size of the target environment is not limited by the holodeck's size of 5 m $\times$ 7 m, but is arbitrary thanks to motion compression, which is the process of compressing the robot's large-scale movement in the target environment to the user's movement.

6) Manipulation Lab: The FZI Living Lab "Service Robotics" features a large number of manipulators. With more than eight robot arms, multi-arm mobile manipulators, numerous grippers and human-like hands as well as mobile, autonomous robot systems such as the ROBDEKON demonstrator. With the four-wheeled mobile platform HUSKY, equipped with a lightweigt manipulator (UR5), a 3D laser scanner (Velodyne), a stereo camera, and a GPS module (see Fig. 4), the walking robot LAURON V, or the snake-like inspection robot KAIRO 3, all capable to perform locomotion and manipulation in hazardous, rough, uneven and narrow environments, the laboratory offers many possibilities for hardware-related developments, feasibility studies and real experiments on roughly 160 m^2 indoors and larger areas outdoors. At the Institute for Anthropomatics and Robotics at KIT, several humanoid robots and robot arms exist and will serve as platform for demonstrating and evaluating the developed methods in the project. These range from methods for object detection, grasping and manipulation of decontaminated parts to the autonomous and semi-autonomous execution of decontamination tasks. In addition, numerous 2D and 3D sensors as well as an extensive collection of software libraries for robot perception, navigation, and motion and action planning are available for use in ROBDEKON.

7) Autonomous Heavy Machinery Lab: The Fraunhofer IOSB has a large test site, which consists of both an outdoor area and a dedicated lab building. The outdoor area serves as a test area for environment perception and motion planning for mobile robots in unstructured environments. In addition, there is a partially covered area with an accompanying control station. In ROBDEKON, the test site is used to simulate the autonomous decontamination of contaminated soil layers by using automated heavy construction machines. In its new lab building, the Center for Autonomous Systems (CAS), Fraunhofer IOSB also operates a number of indoor robots for logistics applications. With its 250 m^2, the CAS serves mainly two purposes: First, it is a workshop for the development and constructions of new robots at varying scales; and secondly, the lab is used for testing and evaluation of these robots.

V. CONCLUSIONS

This paper provides a comprehensive insight into the ongoing research activities of the joint project ROBDEKON. Since initially the focus was on the development of novel robotic systems suitable for decontamination tasks, work in the future will increasingly concentrate on the development of the actual robot-supported decontamination techniques and on research into autonomy capabilities. The availability of a large number of well-equipped labs allows the solid evaluation of the practical suitability of the technology demonstrators developed in the project.

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