

Forum

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From environmental exploration to clearance measurement – developing mobile robot systems for decommissioning of nuclear power plants

Von der Umgebungsexploration bis zur Freimessung – Entwicklung mobiler Robotersysteme für den Rückbau kerntechnischer Anlagen

Realization of a robot based closed-chain for automation and digitalization of the dismantling process

Realisierung einer roboterbasierten, geschlossenen Kette für die Automatisierung und Digitalisierung des Rückbauprozesses

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Abstract: The number of decommissioning projects related to nuclear power plants is increasing and has been regarded as a challenging task for many nations. For example, Germany has decided to phase out nuclear power plants by the year 2022. To reduce the hazardous potential and the personal radiation exposure of the employees, robotic support in the decommissioning process is needed. In this contribution, a robot-based closed chain is presented as an important component for an

automation and digitalization of the dismantling process of a nuclear power plant. The focus of the chain is on the investigation and decontamination of flat wall areas in nuclear facilities. First, geometric and radiation data are collected autonomously with a mobile, agile robot. The collected data is processed by using Building Information Modelling (BIM) methods to support the following steps. A second, industrial platform is modified to enable the positioning of two developed tools, a milling tool, and a contamination array, which will be used for decontamination and clearance measurement of concrete surfaces.

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Keywords: automation; autonomous exploration; contamination measurement; decommissioning process; digitalization.

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Zusammenfassung: Die Zahl der Stilllegungsprojekte im Bereich kerntechnischer Anlagen nimmt zu und wird von vielen Ländern als eine Herausforderung betrachtet. Deutschland hat zum Beispiel beschlossen, bis zum Jahr 2022 aus der Kernenergie auszusteigen. Um das Gefährdungspotenzial und die persönliche Strahlenbelastung der Mitarbeiter zu reduzieren, ist eine Unterstützung durch Robotersysteme im Rückbauprozess erforderlich. In diesem Beitrag wird eine roboterbasierte geschlossene Kette als wichtiger Bestandteil für eine Automatisierung und Digitalisierung des Rückbauprozesses eines Kernkraftwerkes vorgestellt. Der Schwerpunkt der Kette liegt auf der Untersuchung und

Dekontamination von ebenen Wandbereichen in kern-technischen Anlagen. Zunächst werden Geometrie- und Strahlungsdaten autonom mit einem mobilen, agilen Roboter erfasst. Die gesammelten Daten werden mit Hilfe von Building Information Modeling (BIM) Methoden verarbeitet, um die folgenden Schritte zu unterstützen. Eine zweite, industrielle Plattform wird modifiziert, um die Positionierung von zwei entwickelten Werkzeugen zu ermöglichen, einem Fräswerkzeug und einem Kontaminationsarray, die für die Dekontaminierung und Freimessung von Betonoberflächen verwendet werden sollen.

Schlagwörter: Automatisierung; Autonome Exploration; Digitalisierung; Kontaminationsmessung; Rückbauprozess.

1 Introduction

The protection of people and the environment are central aspects on the part of policymakers in the dismantling of nuclear facilities [1]. To reduce the hazard potential from radioactively contaminated plant components, employees must wear radiation exposure measuring devices and personal protective equipment throughout their stay in the controlled area [2]. The execution of the process steps “room survey – preliminary investigation – decontamination – clearance measurement”, which are currently carried out manually and by personnel, are physically and mentally stressful with the protective equipment described above. Automation offers great potential for relieving the workload of employees in a targeted manner. The use of the employee on site is limited to hard-to-reach areas and personal radiation exposure is significantly reduced. Furthermore, operators can plan the deployment of their personnel more efficiently and the dismantling time can be reduced.

For this reason, an automatic robot-based closed chain is being developed that comprises four process steps and consists of two robot systems (see Figure 1). In the beginning, the environment is explored using the first robot system. The obtained information is used to create digital models of the building structures. These digital models can be used to determine the optimal path planning for the second robot system, the *decontamination system*, which consists of a mobile industrial platform and two end effectors that must be mounted on the mobile robotic system in sequence.

The first end effector, an automatic milling system, mills and decontaminates the walls, and the second end

effector, is used to measure the release of the walls after decontamination.

No previous work has investigated a closed chain for the dismantling process of nuclear power plants. Especially no system is on the market that supports employees in direct measurement of surface activity on flat wall surfaces in an automated way. The key purpose of this work is to establish an automated process for the dismantling of building structures with the help of robot systems and digitalization.

The paper consists of four chapters including this introductory chapter. A literature review of the development of related works in the field of decontamination of building structures is conducted. Each step of the closed chain (from environmental exploration to clearance measurement) is explained in detail in the third chapter, including completed steps and future ideas. The last chapter provides a summary and outlook, which contains the main contribution of this paper and areas for further research.

2 State of the art

For each nuclear power plant, about 100,000 m² of the surface area must be decontaminated [2] and then cleared. For the clearance of building structures from the Atomic Energy Act, walls and ceilings are currently being examined in a grid dimension of approximately 1 m [3]. The objectives for decontamination of building structures are to reduce the radioactive concrete waste and the release of the building.

According to [4] the large concrete surface can be decontaminated by mechanically removing the surface. In this process, the information on building geometry and the radioactive measurement can only be acquired manually, which is a monotonous and time-consuming work process. An all-in-one concept [5] has already been developed for machine-supported decontamination and clearance measurement, which consists of a milling tool in combination with a detector system. However, the overall system needs to be placed manually, as the system has neither an automation function nor a localization function [5].

With the rapid advancements in robotics, there is also increasing research for robotic applications in construction. However, the focus is still on conventional buildings. For example, a mobile robot unit is developed by Detert et al. [6] to remove asbestos contamination automatically. Compared with this contribution, the developed system from Detert et al. can only be operated in 2D planning

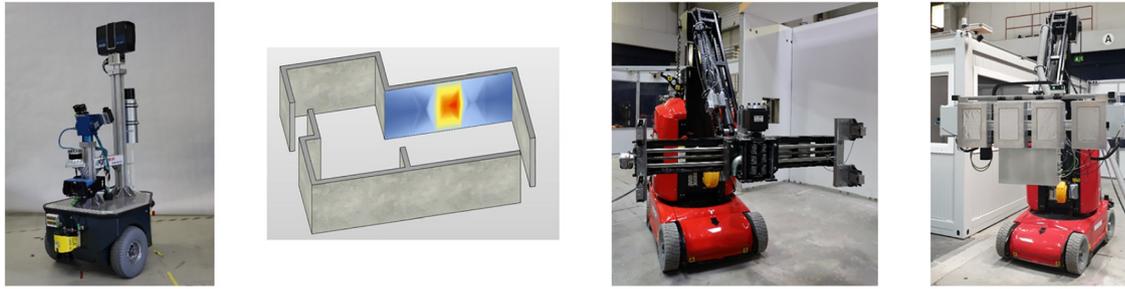


Figure 1: Automatic robot based closed chain, starting from the left side: environment exploration, digitalization, decontamination and clearance measurement.

and the developed method is not suitable for large room heights.

3 Implementation

In this chapter, the novel robot-based closed chain for the decontamination of building structures is introduced. As it was mentioned before, it consists of four process steps, which will be described in detail. For each step, the main ideas will be presented and explained. On this basis, the developed concept or approach with the used hardware and software will be described. With the help of the developed chain, the decontamination process of building structures can be operated automatically.

3.1 Autonomous exploration of nuclear power plants for decommissioning

This section describes the acquisition of geometry and radiation data from rooms in a nuclear power plant. For this purpose, an exploration platform with an algorithm for autonomous exploration is designed and built.

3.1.1 Design and construction of the autonomous exploration platform *GammaBot*

The first step in the robotic decommissioning chain is to create a complete geometric model of the nuclear power plant. The state of the art for creating this model is the manual placement of a 3D laser scanner at many locations within a room or building complex [7]. The laser scanner records a 360° point cloud at various points in the area under examination. With the help of developed software, the individual point clouds are combined algorithmically or manually to form an overall model. This point cloud model can then be used in a BIM context in the following steps of the chain.

This approach uses a mobile robotic platform (Neobotix MP-500) equipped with sensors and a 3D laser scanner to autonomously create the 3D point cloud model. The mobile robotic platform uses differential kinematics that allow rotations in place to increase maneuverability. It is equipped with a safety laser scanner (SICK S300) for collision avoidance and navigation.

Figure 2 shows the structure of the robot platform. The on-board computer was replaced with a powerful Intel NUC to be able to perform the necessary calculations. A 3D laser scanner (FARO Focus S 150) is mounted on a profile rail as the main sensor, which can capture 1 million points per second. For additional safety against collisions, a forward-facing 3D Time of Flight (ToF) sensor (SICK Visionary-T) can prevent collisions with overhanging installations. Above the ToF sensor is a lidar sensor (Ouster OS-0) for mapping and detecting impassable sections, such as holes in the ground. To enable teleoperation and monitoring, two RGB cameras and an infrared camera are mounted on a pan-tilt module (SCHUNK PW70). By mounting a scintillator probe (Automess 6150AD-b) on the side of the robot, it is possible to estimate which wall areas have hotspots or contamination. The scintillator probe has a detection range down to natural background radiation. The complete platform is named *GammaBot*.

3.1.2 Algorithm for autonomous exploration of nuclear power plants for decommissioning

A common method for autonomous exploration is the next best view approach [8]. In this approach, the currently available model is examined for potential new view points from which a new scan should be performed. A metric is defined to estimate the information gain from the potential vantage points, and a cost function is selected to estimate the cost of reaching the new view point. Finally, an optimization function is chosen to find the optimal next view point for the robot to move to and perform a new



Figure 2: The completed autonomous exploration platform *GammaBot*.

scan. The process is repeated until a termination condition occurs.

In this approach, an initial scan is taken, and the resulting point cloud is converted to an octree structure. This representation has the advantage of enabling efficient ray casting. Figure 3 shows the point cloud after an initial scan and the potential next viewpoints it could choose. The potential next viewpoints must be in free space, have a fixed height above ground and be reachable by *GammaBot*. To generate these potential viewpoints, a rapidly exploring random tree (RRT) is used. A check for collisions between nodes of the RRT is performed by casting rays within a motion corridor of the mobile robot. The motion corridor has the height and width of the robot plus a small buffer. At the end of the corridor, additional space for maneuvering is added. Nodes with collisions are removed from the tree. At each remaining potential new viewpoint, rays are cast in all directions of a sphere. The rays that end in a cell of the octree and the rays that go to infinity in free space are counted. The metric for estimating the information gain is the ratio of free space rays to all casted rays. As a cost function, the Euclidian distance along the RRT is used.

To choose the next viewpoint, all potential viewpoints are first compared with the viewpoint that has the highest information gain. All viewpoints that have less

information gain than 80% of the viewpoint with the highest information gain, are then removed. Out of the remaining potential viewpoints, the one with the least cost is chosen. This heuristic approach ensures that a significant gain in information is achieved while choosing a viewpoint that is close to the current location. This avoids unnatural “ping-ponging” of successive viewpoints. *GammaBot* then navigates to the chosen location, takes a new 3D scan, the point clouds are combined, and the algorithm is repeated. The process is stopped when every potential viewpoint has an extremely low information gain.

3.2 Digitalization and modeling with BIM

The point cloud model created by *GammaBot* can provide the information needed for the trajectory planning of the *decontamination system*. Especially the integration of radioactive measurement results, such as hotspots or contaminations in the structures, is crucial for the decontamination and further project planning steps. However, the ability to integrate and manage information, such as the material of the wall or the interference with the building structures as well, is currently lacking.

The first step to solving the problems mentioned above is to combine the point cloud with useful information. As the foundation of the digital transformation platform in the architecture, engineering, and construction (AEC) industry, Building Information Modelling (BIM) can overcome this problem. It can provide a useful platform for information management, which can be used for such tasks as energy analysis and project planning [9]. Compared with a simple point cloud model, a BIM model provides not only a 3D model but also a comprehensive set of semantic information, which can be used for logistic simulation and documentation in the decontamination workflow.

To use the BIM platform in decontamination projects, it is necessary to transform the point cloud data into a BIM model. The commonly used method is manual transformation. In this process, a BIM model can be created manually based on the imported point cloud data in Revit software.¹ However, manual transformation is time-consuming and error-prone. A semi-automated methodology to transform building structures from point cloud to an as-built BIM model for the dismantling of nuclear power plants will be introduced in the following chapter 3.2.1. Figure 4 shows the overview of the process. The input data is the registered point cloud data as well as the measured radiation results

¹ Revit is a commonly used BIM software.

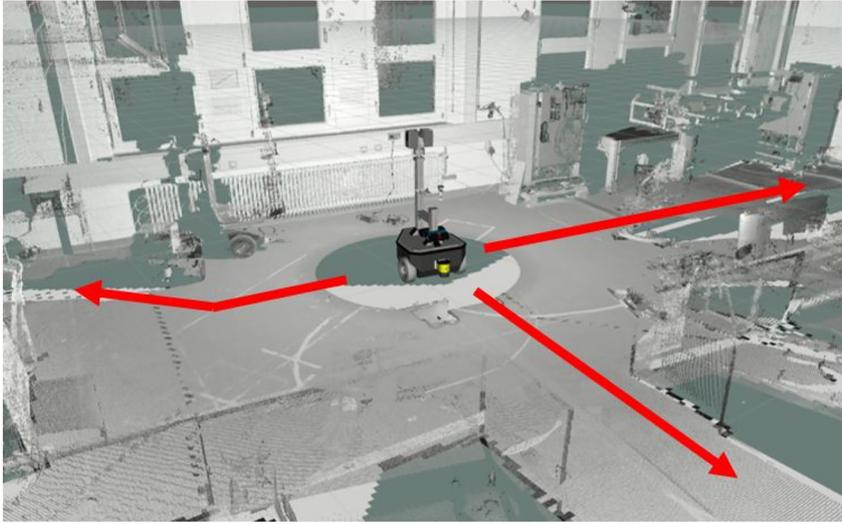


Figure 3: After an initial 3D scan the mobile robot must choose where to go next.

from *GammaBot* from Section 3.1. The developed process with four steps includes the reconstruction from the point cloud into a BIM model (steps 1–3) and the information management of radiation measurement results (step 4).

3.2.1 Reconstruction of building structures from point cloud to BIM

The structure of point cloud data can be divided into four main categories, floor, ceiling, walls, and the objects placed in rooms. The first step of reconstruction is to extract the information from the data set. The point cloud data can be regarded as a big multi-modal data set containing the position information in the cartesian coordinate system. The histogram method, which is the most common application of the nonparametric approach, is used to investigate the distribution of such data set. After getting an overview of the data distribution, the next step of the information extraction is to find the possible positions of the building structures. To determine the positions, the maximum likelihood estimation in the algorithm is implemented to determine the positions of structures. To make the process of extracting information the least complicated as possible, the building structure is segmented and then the information will be extracted separately. Since the point cloud data of the floor and ceiling have a significantly high probability on the z -axis, the histogram on z -axis is used for the floor and ceiling segmentation. Once the position of the floor and ceiling are determined using the maximum likelihood estimation, the points belonging to the ceiling and floor are removed. The histogram on x - and y -axis can be used for investigating the

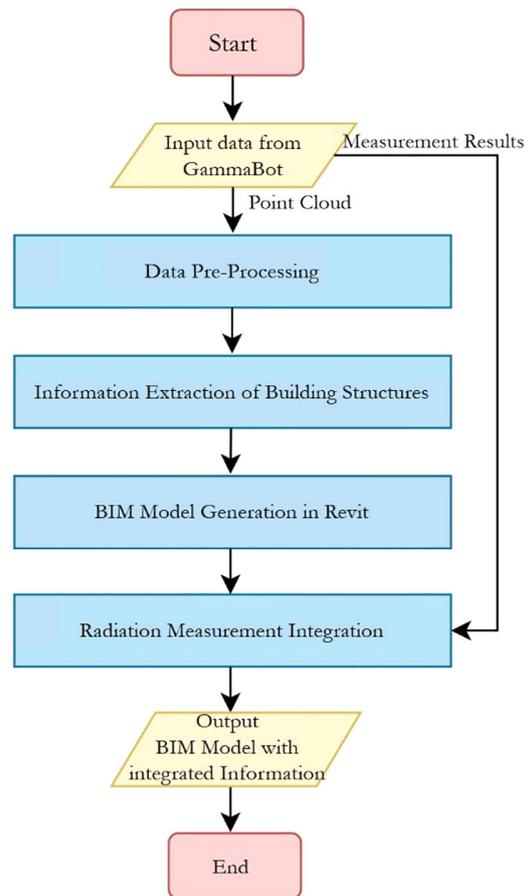


Figure 4: Overview of the digitalization process.

positions of wall structures. To get the start and end points of each wall structure, a middle point search algorithm is implemented. At the end of the information extraction process, the detected start and end points of each wall

will be stored in a text file, which will be used in the following step for BIM model generation. The software Revit is used for building the model.² Furthermore, the parametric design with the visual programming language Dynamo is used in this process to generate the BIM model semi-automatically.

3.2.2 Information management of radiation measurement results

As introduced before, a BIM model supplies a platform for information management and documentation. During the dismantling of the nuclear power plants, radiation measurement plays a key role in the decontamination of building structures. It is useful to integrate the measured results into the built Revit Model. With accurate information of contamination in the building structures, the material that needs to be processed will be reduced. Therefore, less hazardous waste during decontamination will be created as well as less operation time is required. One advantage of the information integration is that the distribution of contamination can be directly observed, which provides guiding information for the following *decontamination system* (which will be introduced in Section 3.3) to remove the contaminated part. In addition, the measured value will be integrated into the model, which is useful for information management. To achieve this, a component for the contamination is created. Figure 5 shows the included information in this component, which is a host-based 3D component. The component can be created and inserted into structures such as wall, floor and ceiling components. The measurement results, such as the size of the contaminated place and the measured value from *GammaBot* can be documented in the component. Besides, whether this place is a hotspot or whether it has been processed during the decontamination process can be stored in this component as well.

3.3 Modification of an industry platform for realizing an automatic *decontamination system*

A mobile robotic platform with a manipulator is required to automatically position the milling tool and the contamination array in the correct area point without human intervention. The mobile part of the robot, called the “vehicle”, must bring the manipulator to the surface area to be examined. Once the vehicle is in the right

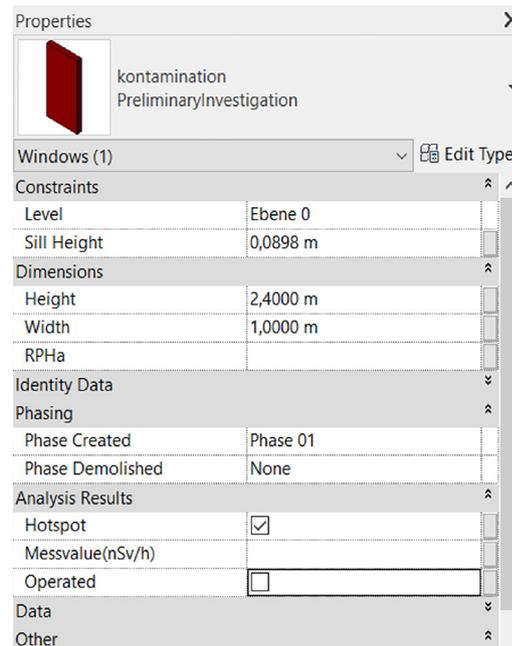


Figure 5: The created component for contamination.

position, the manipulator can start its work and place the end effectors in the right position on the wall surface. For this reason, the automation tasks are divided into two independent tasks: the automation of the vehicle and the automation of the manipulator.

An industrial mobile platform (Manitou 100VJR) is selected as a suitable *decontamination system*. The large working area and sufficient load capacity are the main reasons for this selection (see Figure 6).

3.3.1 Automation of the mobile platform

The automation of the mobile platform will be realized by implementing control loops on a mobile platform. Figure 7 shows the closed-loop controller that must be implemented on a mobile platform.

The first step in implementing a closed-loop *decontamination system* is to define the desired system behaviour of the mobile platform. This can be done using the map/information created by *GammaBot* and BIM-Model. The desired system behaviour, or in this case the desired trajectory, is the optimal path for the vehicle in a 2D space $[x(t)y(t)\theta(t)]$ with respect to a fixed frame coordinate system in the environment and the optimal joint trajectories $[\alpha(t)\beta(t)z(t)]$ with respect to a fixed frame attached to the robot (see Figure 6).

As can be seen in Figure 7, the difference between the actual positions (measured by the sensors) and the

² Revit is a commonly used BIM software.

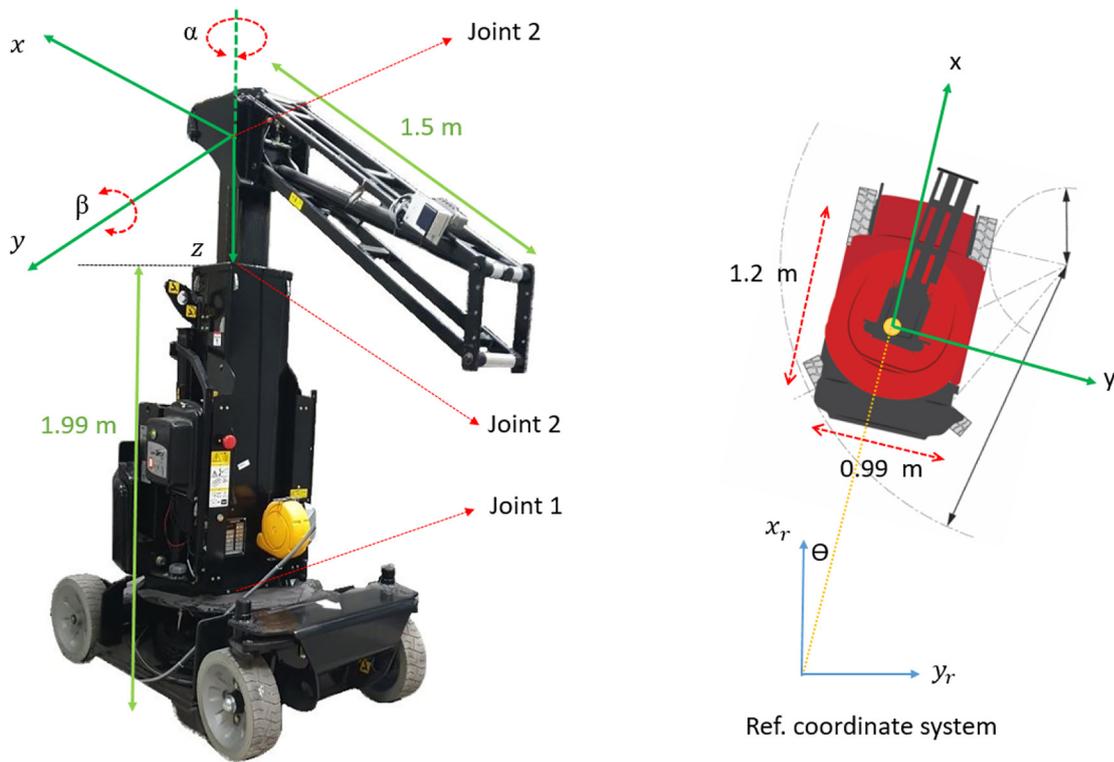


Figure 6: Joints, dimensions, and degree of freedoms of the decontamination system [10].

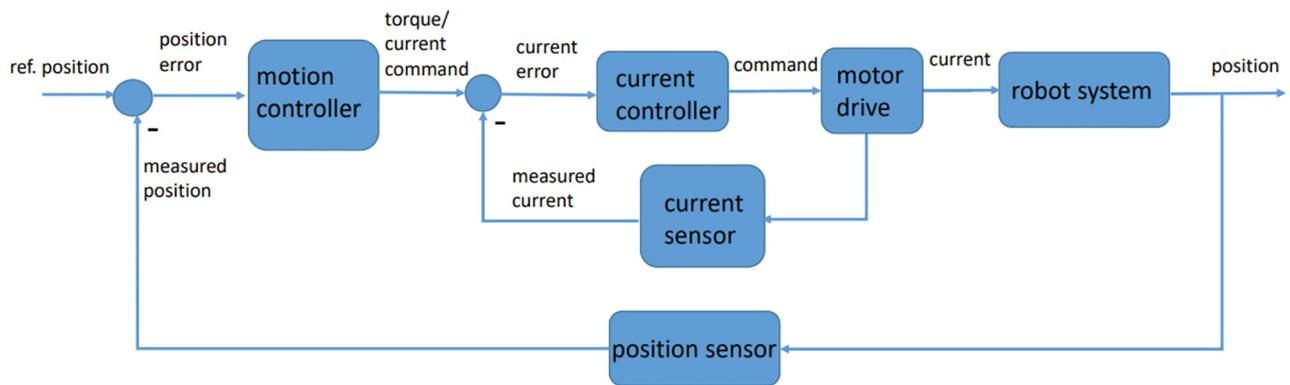


Figure 7: Closed loop motion controller of the decontamination system.

desired positions is defined as position error $e(t)$. The motion controller takes the position error and sends appropriate action messages (Torque-command) to the system to reject and reduce the position error. Since torque is proportional to current for DC motors, torque can be replaced by the current. The actual current tracks the desired current (commanded by the motion controller) using a current controller that sends a PWM command signal to the motor drive. Motor drive converts the current controller command to the high current input to the motor.

There are various forms of control algorithms that can be used in specific applications. A PID-controller is often used as a motion controller and a PI-controller as a current controller.

PID-controllers have been used for years and are known for their ease of implementation as well as their strong and robust performance.

The following equation describes the control-law of a PID-controller:

$$u(t) = K_p e(t) + K_d \frac{d}{dt} e(t) + K_i \int e(t) dt,$$

where $u(t)$ is the command signal of the controller.

In addition to the controller design, it is important to assign parameters to the PID/PI-controller, i.e., to calculate the optimal controller gains $[K_p, K_d, K_i]$. Otherwise, the system behaviour can be either unstable or stable but very slow and unsatisfying. For this purpose, in this work, a model of the entire robot platform will be created. Based on this model, the optimal gains using methods such as the “Root-Locus Method” or optimization functions [11] can be calculated through simulation. The control gains confirmed by simulation can be implemented on controllers of the real robot system.

Although the PID-controllers have robust and strong performance, the controller parameterization is a time-consuming procedure. Moreover, the measurement noise and external disturbances affect the system behaviour and lead to control errors. Adaptive controllers with self-tuning capabilities can update the control parameters in real-time based on the current state of the system, which leads to optimized controller performance and strong rejection of measurement noise and disturbances.

The control concepts implementations in this project will start with implementing the PID-controllers. Then based on the robot model, the optimal control parameters for PID-controllers will be calculated. After that, advanced controllers such as state controllers, adaptive controllers, neural networks, and fuzzy controllers will be implemented and tested. Finally, the tested control concepts will be compared and documented.

3.3.2 Implementation of sensors and controller

In order to realise the control loop described above, suitable components, such as controllers, motor drives and sensors, must be selected and mounted on the *decontamination system*.

Due to the compact design, a special controller (Bosch-Rexroth CtrlX Core) is selected as suitable.

For localization of the vehicle in the environment, also estimating $x(t)$ $y(t)$ $\theta(t)$, two 2D lidar sensors (microScan 3 Pro) and LidarLoc software from the German company (SICK) are selected.

The angle of joint 1 of the manipulator $\alpha(t)$ will be measured by a laser surface motion sensor (SICK Speotec 1D), whereas the linear movement of joint 2 of the manipulator $z(t)$ will be measured using a wire draw encoder (Sick BKS09).

The angle of joint 3 of the manipulator $\beta(t)$ will be measured by using two inclination sensors (SICK TMS88B), one located on the meeting point of joints 2 and 3 and the

other at any point on the pendulum, the angular difference between two sensors determines the angle of joint 3.

The connection between the controller and the sensors is made by a safety controller (SICK FX3), which provides all the necessary stop functions, such as the presence of a person on the vehicle path. Finally, the currents will be measured using 500A current sensors (Vaccumschmelze 4648-X053).

3.4 Automation of contamination measurements for release

The automation of contamination measurements is the last step in the process chain. On one hand, it offers a great potential to relieve employees and on the other hand, it fulfils the purpose of integrating automation and digitalisation for building decontamination and documentation. Currently, contamination measurements are carried out manually on the surface of the material and it is checked whether the threshold values for the surface activity per unit area are complied with [12]. This type of measurement is particularly suitable for solid materials with accessible surfaces such as concrete surfaces. The measurements are either carried out stationary or dynamically [13].

Due to the one-sided hand-arm strain, the examination of these surface areas is physically tiring for the employees in protective clothing, especially measurements in hard-to-reach places such as ceilings. The activity itself leads to monotony due to the uniform, low-communication work. Particularly when performing dynamic measurements, measurement errors occur due to the stresses described above. Keeping the specified distance between the measuring device and the wall surface is crucial for the quality of the measurement results [14].

The integration of automation and digitalization for building decontamination and documentation purposes is required. To achieve this, a *contamination array* as a second end effector for the *decontamination system* is developed. The requirements and development of the system are presented below.

3.4.1 Requirements for the automation the contamination measurements

When performing radioactive contamination measurements on wall surfaces, the activity and range of particle radiation require that the contamination measurement systems will be placed as close as possible to the wall surface. The final position of the measuring devices depends on the surface condition [14]. If the surface is even and smooth, the tool can be positioned directly in front of the surface. If

the surface has been broken up and roughened by various decontamination processes, reaching the final position depends on the homogeneity of the work. The transition between a smooth surface such as a decontamination layer and a machined surface (e.g., milled off) also influences the automated positioning of the tool. With increasing distance from the material surface, the entry of the particles into the detector is influenced and the quality of the measurement result decreases. Another important aspect is the presence of obstacles such as heavy-duty dowels on the surface of the material. These can damage the sensitive detector window foil on the underside of the measuring devices. Therefore, the obstacles must first be automatically detected on the upper side of the material.

For the reasons mentioned above, first, the tool must be slowly moved to the wall surface using the *decontamination system* until it reaches its final position. The compliance with a specified distance between the detector window foil and the concrete surface area should be verified in real-time. By maintaining this distance precisely, fluctuations in the scanning of the measurement surface and measurement errors are reduced.

Commercially available, hand-held contamination measuring devices should be used to measure radioactive contamination on concrete surfaces. This can significantly reduce development times and enables the tool to be used for validating requirements. Up to four systems should be attached to the *contamination array* to parallelize the measurement. The measurements should be started automatically from a control station and carried out stationary. Therefore, the probes should be arranged on the tool in such a way that the surface area to be examined can be divided into grids and can be scanned effectively. In summary, the planned movement of the

contamination array is comprised of horizontal and vertical displacements.

The measured values have to be automatically saved for documentation purposes and integrated into the previously created BIM model. The building model is supplemented with the information where the tool is located in the room or building complex and which wall area is currently being examined.

3.4.2 Specification of the sensor concept for the implementation of automation

In the following, a *contamination array* (see Figure 1, right side) as an end effector for the *decontamination system* introduced in Section 3.3 is presented as a technical solution for the previously described requirements and planned movement sequences. Figure 8 shows the *contamination array* which is based on two sensor concepts: measurement (blue) and localisation (green). An important aspect is to integrate all sensors into one central software (MATLAB, The MathWorks Inc.). This has the advantage that all components can be addressed and controlled via one user interface. In addition, being a stand-alone tool is another important advantage of the development of the *contamination array*, i.e., all sensors are mounted on the tool itself which makes it independent of the robot platform.

First, the sensors with a focus on the measurement techniques are presented. To avoid damaging the sensitive detector window foil of the contamination probes, the wall surface to be measured is first examined for obstacles using a laser scanner (Micro Epsilon scanCONTROL 30x0). The measuring range of the laser scanner corresponds to the outer dimensions of the detector window foil. This ensures

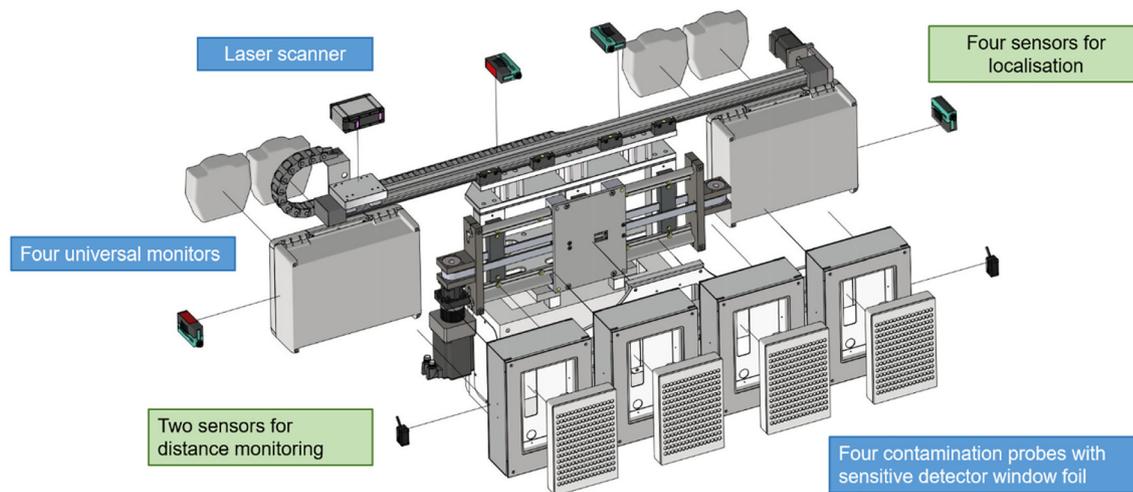


Figure 8: Sensor concepts of the *contamination array* for the automation of the clearance measurement.

that all obstacles are measured under the detector window foil. The laser scanner is moved over the wall surface utilizing a linear system (igus GmbH drylin) at a defined speed.

Four contamination measurement systems (Berthold Technologies GmbH & Co.KG LB 134 UMO II) are used for automation. Each of these contamination systems consists of a large contamination probe and a universal monitor as an evaluation unit. Both the probes and the universal monitors are protected by housing against damage or even dust from other ablations in the building complex. The detector window foil is uncovered. The contamination probes can be easily dismantled from their housing and decontaminated in the event of contamination. The universal monitors are mounted in a second housing. This allows the user to flexibly switch the monitors on and off for control purposes and also to charge the devices. With the central software, background measurements and contamination measurements are triggered automatically using the counter-timer principle. For example, the background measurement can start in the centre of the room and the *decontamination system* can then be positioned on the surface of the wall to be examined. The measurement results are automatically saved after each measurement in a table specific to the measurement method and are available for employees for documentation purposes at any time. Employees are also automatically informed via the software interface whether the thresholds for surface contamination are exceeded. The sequence of the overall program can be individually adapted. After completion of the first horizontal measurement, the contamination probes are moved horizontally by a second linear system (igus GmbH drylin) and a new stationary measurement can be started. This is the cycle for one horizontal process. Subsequently, the *contamination array* must be moved vertically with the help of the *decontamination system* to initiate the next measurement process. The goal of the development is to measure an examination area within the shortest possible time through a defined amount of vertical and horizontal displacements.

Afterwards, the sensors with a focus on the localization technology are presented. To measure the distance between the wall surface and the detector window foil, two laser sensors are mounted on the outer side walls of the housings. One sensor is mounted on the right, outer housing side and one sensor on the left, outer housing side. With assistance from two sensors (Micro-Epsilon optoNCDT 1320), a given distance is continuously monitored. The data are enquired in real-time by software and displayed graphically to the user. For this purpose, the *decontamination*

system moves the tool to the concrete surface via a linear unit on the manipulator. The target position corresponds to the maximum permissible distance between the concrete surface to be inspected and the detector window foil. In order to be able to localize the *contamination array*, up to four additional laser sensors (Micro-Epsilon optoNCDT ILR 103x/LC1) are used to measure in real-time the distance to the ceiling, floor and walls in a room or building complex. This measurement data are used to continuously determine the position of the *contamination array* on the wall and in the room. The localization information in combination with the measurement results will be integrated into the BIM Model.

4 Conclusion and outlook

In this paper, a robot-based closed chain for the automation of four steps for the dismantling process of nuclear facilities was presented. The process starts with autonomous exploration of the environment, which is followed by digitalization and modelling with BIM. The information flows to the automation of an industrial platform and contamination measurement. The described robotic systems represent solutions to the work sequence “room survey – preliminary investigation – decontamination – clearance measurement”, which is currently carried out manually and by personnel. In the future, this will be performed by machine in an automated way, without the need for personnel on site. For each process step, the state of the art was explained, and concepts, methods and the used sensor technology were presented. The focus of this paper was on the development of practical and process-safe robot platforms that optimally support the user in this process. This limits the field operation of employees to hard-to-reach areas and reduces personal radiation exposure. Furthermore, it allows operators to plan the deployment of their workforce more efficiently, and dismantling time can be reduced. In addition to use in the nuclear sector, the systems can also be used in the dismantling of conventional buildings. The automated milling machine for example is suitable for processing asbestos-containing filler on walls. In the future, development will focus on the application and practical suitability of the robot systems in a real environment.

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