NENA 1.0: Novel Extended Nuclear Application for the Safekeeping of Contamination-free Environments

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Abstract: The accomplishment of inspection, safekeeping or cleaning tasks are essential daily routines in industrial facilities. These tasks are associated with time, personal expenses and physically demanding occupations. Various robotic systems have been introduced for the automation of these routines. The inspection and cleaning of severs or an automation of a biotechnology laboratory are successful examples for robotic systems and automation [1]. In this paper, we present a novel system for the autonomous 2D detection of radioactivity and contaminated areas. The importance of autonomous detection of radioactivity will increase in the upcoming years, due to stricter limits for contamination levels, when using radioactive materials in nuclear medicine, research or for nuclear power plants. The use of radioactive substances will also increase for diagnosis and therapy in nuclear medicine. Another area of application is the decommissioning of nuclear installations, concerning work time and personnel expenses savings. The mobile robot is able to scan the whole floor of a building, where radioactive contamination may occur, such as floors in nuclear power plants, hospitals with nuclear medicine departments or laboratories. It marks the contaminated areas in a generated map of the building for further evaluation. The paper discusses the main requirements of a navigation system for 2D detection of radioactivity and is based on [2]. It presents the hardware and software set-up and some real-world experiments with our mobile robot.

Key–Words: Industrial Application, Automation in Medicine, Automation, Robotics, SLAM, Path planning

1 Introduction

Generally, the challenging field of robotics has an enormous potential to support the industry in different fields. A robot is able to perceive and manipulate the physical world by means of different devices and can act in various working environments, for example planetary explorations, in the car industry or as a demonstrator in a theatre.

The market for service robots has an excellent chance for the future. An example for successful commercial systems are cleaning robots which have been studied and developed some years ago. Meanwhile, the market offers some cleaning robots for private purpose. The common enabling technology for a cleaning robot and our application is autonomous navigation in everyday indoor environments. In contrast, the main difference is the efficiency of our navigation system. An exploration task is an integral part of a robotic mission which provides a full coverage of the indoor environment. While a hoover robot usually cleans the floor randomly, our system aims to document all radioactivity measurements for every reachable position in the environment. The complete and efficient coverage of terrain is one of the elementary problems in reconnaissance [3][4], rescue [5], cleaning [6] and planetary exploration [7][8]. The handling of radioactivity in a nu-

Figure 1: Predecessor of NENA

clear power plant or any other nuclear installation as well as in nuclear medicine, is subject to many restrictions and relevant legislation, concerning the compliance of safety measures. One important safety task is the securing of a contamination-free working environment, typically needed for the personnel, working inside the controlled areas. Usually, the measurements are done by hand (see Figure 1), why a member of staff has to invest a lot of time for the safekeeping of a contamination-free building. It is necessary to prepare a documentation of every checked plane of the floor or walls. In the case of contamination, the exact position of the determined area has to be marked in a map of the building. The application of robots could be extremely timesaving, unforgeable and reduces physically demanding occupations. Our approach was driven by the idea for automation of the safekeeping of a contamination-free environment.

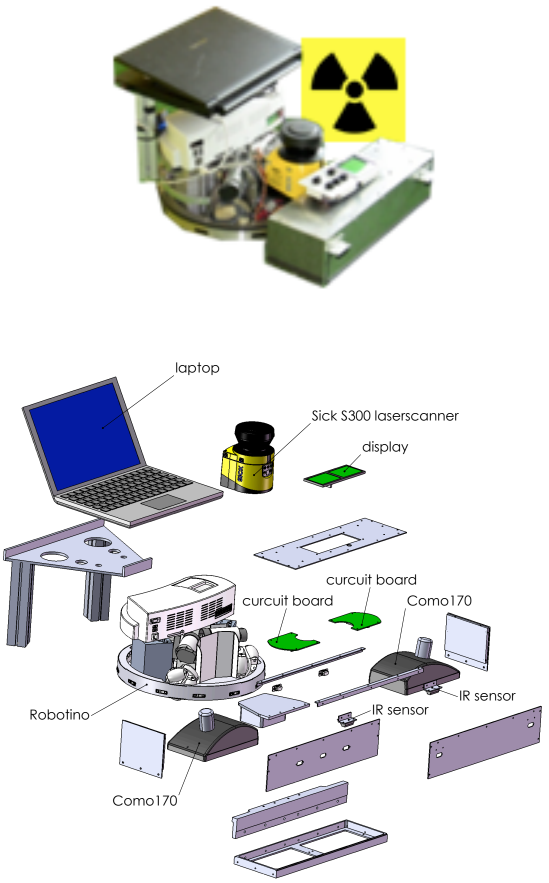

Figure 2: Mobile Robot Exploded View

We equipped a mobile robot with various devices which focuses on the detection of α, β/γ-radiation on planar surfaces. The complexity of our system is manageable because we focused on the floor of the areas. Thus, we did not need a robotic arm in order to reach walls and ceilings. The applied mobile robot, called *Robotino* (see Figure 2), is equipped with an omnidirectional drive, three wheels and multiple sensors. It is able to move in all directions, as well as to turn on the spot through its recent drive system. The control of the actuating elements and acquisition of sensor data results from the WLAN module. Alternatively, it is possible to use a network cable for the communication with Robotino. Festo Didactic offers a software named "Robotino View", which is an interactive graphic programming tool for Robotino. Furthermore, an open-source framework, called OpenRobotino[1], and the corresponding documentation are available for the development of applications. Robotino was additionally equipped with a laser rangefinder (SICK S300), two contamination monitors (S.E.A. CoMo 170, modified version) and an Intel Core Duo notebook for the developed navigation framework. The exploded view (see Figure 2) visualises the hardware set-up with its extensions. The contamination monitor serves for the detection of radioactive contaminated surfaces. The hardware was built into a new box, which is mounted in front of Robotino. This box contains two detectors to attain a complete cover. An additional hardware feature are two infrared sensors, vertically mounted in front of the box. Thus the detection of dangerous spots like stairways or bigger holes can be avoided during a mission in a nuclear power plant or other nuclear facilities. The standard PC of Robotino is not capable of fulfilling the computation power requirement, why we run the navigation framework on a mounted notebook. The power is supplied by two rechargeable 12V batteries with a rating of 4Ah. A full, in-depth presentation of all features of our system is beyond the scope of this paper. Rather, we will focus on the core functions of the software respectively mobile robot. In section 2, we will briefly describe some recently developed robotic and navigation systems, followed by the overall architecture of the system in section 3. To validate our approach we perform multiple experiments in section 4 to confirm the accuracy of our system. For this purpose, we received a permission for an experiment in a laboratory of the Max-Planck institute in Mainz. The Alpha Particle X-Ray Spectrometer (APXS), which determines the consistency of stones and dust on the mars surface, was originally developed in this laboratory.

[1] http://www.openrobotino.org

2 State of the Art

In the past, several efforts have been made, regarding the creation of autonomous mobile robot systems [9][10][11][12]. Since every creation had its specific requirements and involves the combination of several algorithms, we will try to give a review for our work below. The problem that we are trying to solve falls in the context of navigation systems. We therefore split the related work discussions into two distinct parts that correspond to the respective subjects covered in this paper, namely: SLAM and Exploration strategies for the full coverage of environments. A mobile robot for the automation of the complete sample management in a biotechnology laboratory is presented in [13]. The navigation of this mobile robot is based on a generated static map of the current working environment. Another example, presented in [14], is the service robot LISA (Life Science Assistant) which supports lab personnel in biological and pharmaceutical laboratories. It makes automated experiment cycles flexible and helps employees to prepare experiments, e.g. by collaboratively executing transportation tasks or filling microplates. A Hokuyo URG-04LX is used for the localization in an a-priori map and the collision detection. The map of the laboratory is handmade and is initially used for the localization. A generation of a static map of the buildings is time-consuming and presumes a new map for every domain. Our application needs a flexible adoption of the robot, which requires the ability to map and explore unknown environments right from the start. The main technology for this purpose is called Simultaneous Localization and Mapping (SLAM) and has been in the focus of many researchers for several years. SLAM deals with the problem of constructing an accurate map of an environment in real-time. Thereby, it has to handle imperfect information about the robot's trajectory through the environment. For example, a robot which was placed in an unknown environment, incrementally builds a consistent map of its surroundings, while simultaneously determining its location within this map. OpenSlam[2] offers some open-source SLAM implementations for 2D and 3D mapping. SLAM implementations are based on the type of input data. Some approaches are camera-based but we focused on the algorithms which uses distance measurements of a laser rangefinder and odometry, allowing our system a deployment by night. A Rao-Blackwellized particle filter based approach (GMapping) is presented in [15][16]. It is able to produce accurate maps of indoor and outdoor environments using occupancy grids. The open-source library requires some programming effort for the adoption and only runs under Linux systems. Another framework, called CARMEN [17], provides basic navigation primitives like path planning, mapping and localization. We used some generated log files for the evaluation of the mapping module. It works for small environments correctly, but it was not able to resolve the loop closing problem in large buildings. The commercial framework KARTO[3] is a very efficient solution for navigation tasks. It provides exploration strategies, mapping and trajectory planning. A free functional trial copy is available for download. The evaluation of the mapping, using our CARMEN log files, has been very promising.

[18][19] DP-SLAM needs odometry measurements and an accurate laser rangefinder, e.g. SICK S300, for localization and building a map. It uses a particle filter to maintain a joint probability distribution over maps and robot positions, as well as some efficient data structures, which allow an efficient mapping.

DP-SLAM does not need predetermined landmarks and is accurate enough to close loops without any special off-line techniques. The data association problem was also eliminated through the abandonment of landmarks. Moreover, it is not necessary to predetermine the environment. With almost no exception, none of the open-source distributions can be used without additional programming effort. The KARTO framework is an ideal solution for mobile robots, but we prefer an open-source software, due to the costs for the licence. GMapping is an efficient and accurate SLAM algorithm but it needs some additional adaptation for our application. In contrast, DP-SLAM was implemented and successfully tested during a past project of our faculty. It runs under Windows and Linux and can be easily configured for our mobile robot. Additionally, a successful strategy for the full coverage of terrain, usually aimed by cleaning applications or planetary explorations, needs to be discussed [20]. The trajectory needs to be planned in a way, which guarantees a path through the whole environment. [21] proposed an approach for partitioning the environment into polygons and co-operatively arrange multiple cleaning robots. An interesting system for autonomous cleaning of supermarkets was presented in [22]. A similar navigation system, developed for pool cleaning, is presented in [6].

The main difference to our system is an authentic and exact documentation of contaminated areas in a human understandable format. Thus a technical employee can verify the results, measured while driving through the terrain. An exact documentation demands excellent navigation frameworks with exact pose determinations.

[2] http://www.openslam.org

[3] http://www.kartorobotics.com

3 Software Architecture

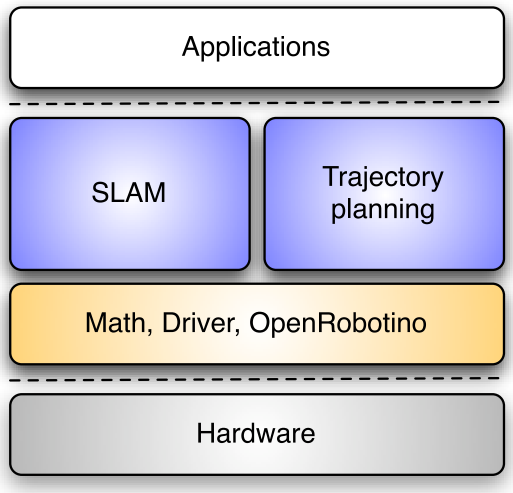

Figure 3: Software Architecture

Our navigation framework (see Figure 3) consists of a SLAM library, which interacts with a trajectory planning module. Thus, the robot is able to plan a path within known parts of the map. The radioactivity detectors log the results of the measurements, while driving through the building. The hardware is accessed via an API for Robotino and some additional drivers for the laser rangefinder and the contamination monitors. Based on the software architecture, it is possible to develop various applications for mobile robots. The topic of the paper is focused on radioactivity detection, and therefore we will address its main components (SLAM and Trajectory planing) below.
A **SLAM** library for our application needs to meet the following requirements:

- Accurate determination of the pose
- Correct map of the building
- Handling of dynamic objects
- Real-time ability
- Easy configuration for various scanners
- Usability for Windows and Linux

Our SLAM library is based on an algorithm, called DP-SLAM [23][19] and fulfills all listed requirements, except handling of dynamic objects. Generally, this requirement deals with state changes of objects in short time intervals. These dynamic objects addresses humans, chairs or doors for example. NENA avoids collisions with them by using the integrated bumpers and laser rangefinder measurements. Our group has long experience working with this SLAM library and the results were always promising for indoor buildings. The library works with various laser scanners and allows an easy configuration, for example particle amount or scanner resolution. It produces an occupancy grid map as output, which is the basis for the trajectory planning. This is why we preferred this algorithm instead of familiarise with a new framework. We briefly review the basics of the algorithm and refer the reader to the detailed description of the algorithm in [19]. This SLAM algorithm is based on a particle filter and an ancestry tree. A particle filter, also called Monte Carlo method (SMC), is one possible approach for localization. Like in a Hidden Markow Model, it is necessary to define a state transition, a hidden state and the observation. In this case, the robot's position is the hidden state that should be tracked. The state transitions represent the movements of the robot and the corresponding observations are extracted from the sensor readings. All sensor readings are noisy or ambiguous, because no scanner is adequate enough to resolve ambiguities. The state transitions are represented by a motion model, which acts as the proposal distribution in the sampling process of the particle filter.
The ancestry tree is the core data structure for an efficient maintenance of particles. It represents the elapsed time during the mapping process. The leaves represent the current particles and a corresponding occupancy grid.
Austin Eliazar and Ronald Parr proposed two different versions of DP-SLAM in the course of development. A hierarchical version of DP-SLAM, presented in [19], is able to recognise, represent and recover from drift which results from various small errors during the particle filtering process. Generally, these errors accumulate over time and result in the mentioned drift. Even if the local maps seem to be accurate, there could be a large total error at the end. These errors lead to a misaligned map after completing a loop in challenging domains. The small errors can be caused by an insufficient particle coverage, coarse precision or the resampling of the particles. On the one hand a finite number of particles causes that drift, on the other hand a high amount of particles increases the running time of the algorithm. Experiments with the hierarchical version have shown, that the running time has been dramatically increased, due to the two levels of DP-SLAM. The real-time ability is an important requirement for our application, why our library uses only one level of the algorithm. Our library works more efficient with dense sensor data, concerning localization accuracy and mapping results. A sufficient

amount of particles was experimentally determined. The next section describes our test scenarios and the great mapping performance. The **Trajectory Planning** is based on occupancy grid data, provided by the SLAM library. We differentiate between disturbances, dynamic stationary obstacles, free space and static obstacles by using probability values of the occupancy grid. For example, a high probability in a cell stands for a static obstacle. The trajectory planning is continuously updated with the current pose of the robot and the occupancy grid, which represents the environment. This information is used by the algorithm in order to place waypoints in free space. Each *waypoint* describes a possible position of the robot. The distance between the waypoints and the distance to walls can be set optional, but it has to be chosen carefully to avoid collisions with static objects. A bounding box (geometry of the robot) is placed on every possible position next to the robot and a validation outputs the usability of this position. If the box is located inside the explored area and no obstacle overlaps the box, the algorithm accepts that position as a possible waypoint. A road represents the way between two waypoints, and it also enables a collisions-free driving.

Road mapping is implemented by a graph data structure. It reduces the problem of negotiating a path through a complex shaped 2D representation of the world to finding a shortest path through a connected graph from node A to node B, for example.

The trajectory planning computes a path through the known part of the environment, starting from the robot's current position. The robot drives to every generated waypoint, as long as a waypoint exists in the map. The map of the environment is regularly updated with changes in the surrounding and registrations of unseen parts of the building. The trajectory module reacts accordingly to these changes and extends the path by new waypoints in these uncovered areas. Thus, we abandon a foregoing **Exploration phase** which would prolong the whole radioactivity search process. The only one constraint for this approach is the securing of a closed area. This is necessary to stop the trajectory planning from exploring new parts of the building.

There have been many research activities, which deal with the problem of an optimal autonomous exploration in unknown environments. A mobile robot must be able to control its movement and its perception system so that it collects the highest amount of information possible, allowing it to localise itself in its environment and to create a representation of this environment at the same time. Usually, the exploration strategy tries to cover unknown parts of the environment as fast as possible without re-localising itself in known areas. This naive approach is sub-optimal because a good pose estimate is necessary to enable a good data association, i.e. to determine if the current measurements fit into the map built so far. The revisiting of seen places in necessary for an accurate position estimation in the map [27]. Our application areas are bounded in the size and we use a S300 laser rangefinder which provides up to 540 measurements. These dense data improve the localization and mapping. The position estimation is always very accurate because the robot revisits known parts of the environment. This is an advantage of the full coverage strategy. The **Documentation** of the radioactivity measurements is done by logging all measurements for every reachable position in the map. For this purpose, the geometry of the box with its detectors, as well as the deviation from the centre of the robot has to be defined. Additionally, all results are marked in the corresponding map. For example, the detection of radioactivity is marked as a radioactivity sign and clean areas are repainted in the map in green colour. The position of detected radiation has a deviation of +/- 3 cm, due to uncertainties in the localization process. The representation of the distance measurements, in form of a corresponding map of the terrain, allows the technical employee to verify the documentation results.

4 Results

Before this assignment, the sensitivity of the radiation detectors was tested, using an old gas mantle from a gas-powered camping light, which contains natural radioactive Thorium (So called NORM = Naturally Occuring Radioactive Matter). The contamination monitors need to drive slowly in order to get a statistical assured measurement result and to achieve a detection limit, which is considerably below the regular limits. The detection limit can be calculated according to the appropriate nuclear regulations. Since the detection limit is depending on the radionuclide mixture or nuclide vector, it is necessary to adapt the speed of the robot to the specific measurement task.

To validate the SLAM library, we performed some experiments in the computer science department in Munich. The evaluations were done online and offline, in order to experiment with different parameters. The offline results are more accurate, due to the higher amount of particles, but also need a lot of computation time. The online tests were done with optimized parameters in order to enable a real-time mapping while exploring a building. The first experiment deals with the closing loop problem and is one of the difficulties in the mapping process (see Figure 4a). The map has to be accurate after completing a loop. Concerning this goal, the robot travelled approximately 130 m

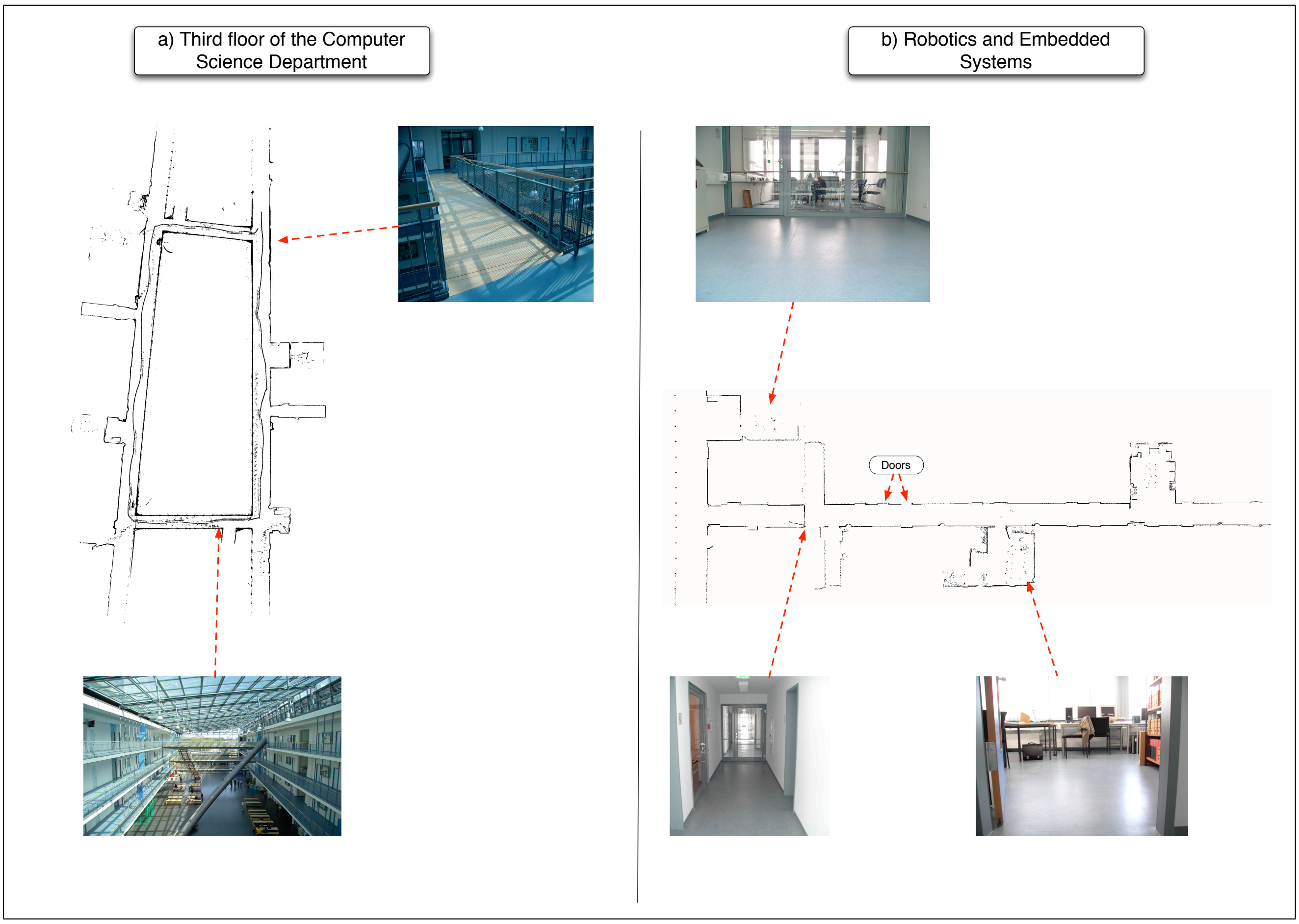

Figure 4: Mapping Results

with a speed of 10 m per minute at the third floor of the computer science department. The size of the environment is roughly 39 m x 16 m. It is a challenging domain because of its asymmetric characteristics. The experiment illustrates, that is was possible to complete the loop, applying 100 particles for the localization and a grid resolution of 35 grids per meter. This figure was generated in an online modus while driving through the corridor. So far, it was not possible to map a bigger area. It leads to bad performance and the probability of losing its own position dramatically arises.

Another experiment (see Figure 4b) generated an accurate map of the faculty for Robotics and Embedded Systems, using the same SLAM configuration. Robotino travelled through the faculty with a speed of 10m per minute. The collected measurements were saved in a log file, which could be used for off-line experiments. The railing with its balusters was accurately mapped, while moving along the hallway. Slight changes in the robot orientation affects, which balusters are hit by the laser, and which are missed. Robotino also passes an office at the left side. The glass wall in front of the office produced an inaccurate mapping of the office because glass is a semi-opaque surface to the laser. Glas stops the laser beams occasionally, due to dirt and angle of incidence. The result would get more accurate, if the robot revisits this part of the hallway a second time. The entrance door of the faculty is also shown, as well as the passage with some doors. The door was opened while the robot moved forward. Thus, it is possible to see the door in a closed and an opened state in the figure. This is illustrated as a slightly grey colored line. The SLAM library is even accurate enough to map the columns and closed office doors which were passed. The several small grey points in the rooms are the table-legs and chairs. This exploration was stopped at the end of the passage and all saved measurements were used to generate the illustrated map of the faculty.

Our approach is designed for laboratories, which usually have a smaller geometry. Thus, we focused on the overall performance of our system in the next experiment. The third scenario (see Figure 5 and 6) illustrates the operation in a laboratory of the former Max-Planck Institute in Mainz, while interpreting the

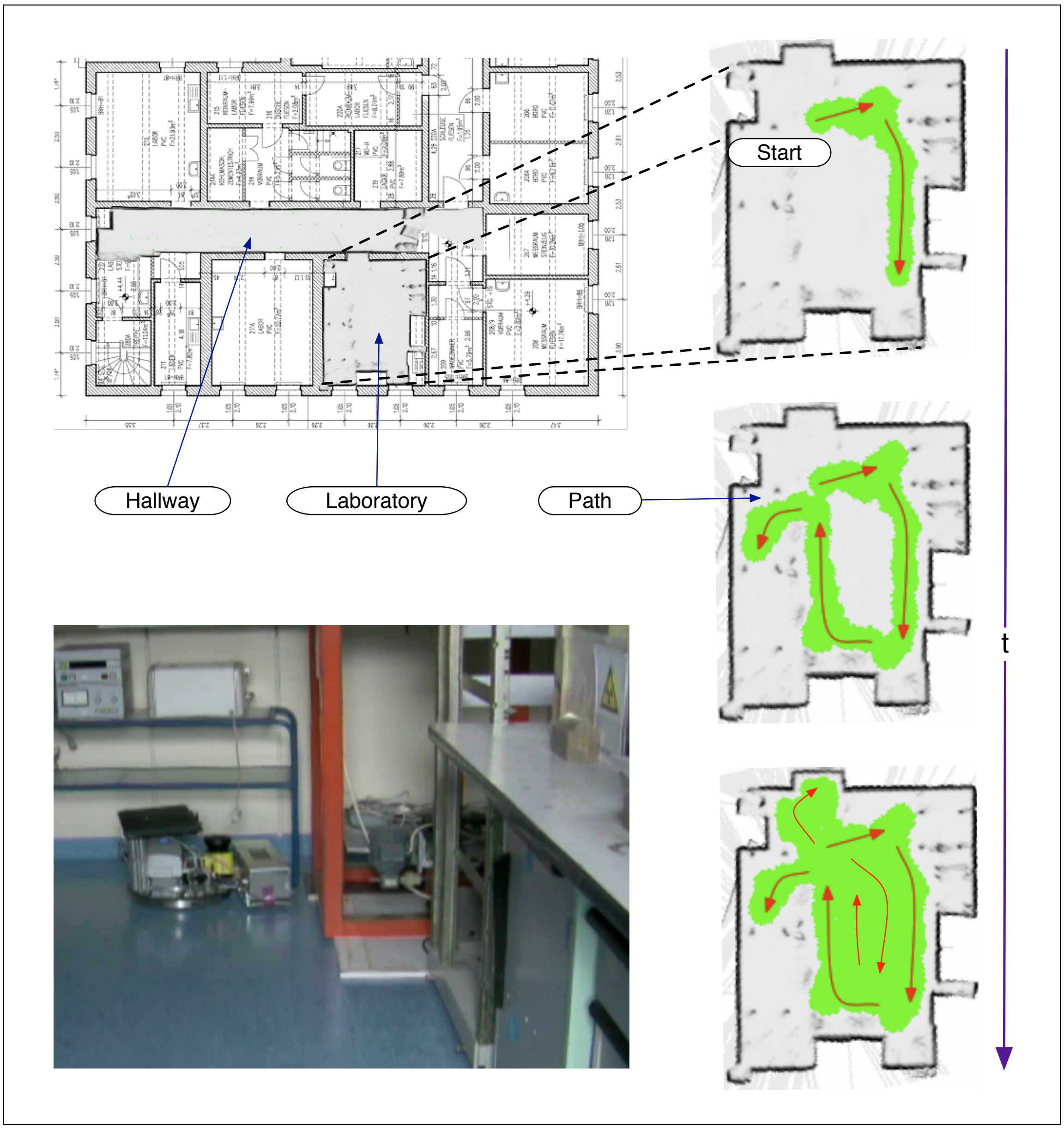

Figure 5: Search for Radioactivity

measurements of the radioactivity detectors. An architectural drawing of the controlled area of the former Max-Planck Institute was additionally added for the allocation of the corresponding room in the complex of buildings. The exploration progress is visualised by three points in time on the right side in figure 5. The robot is randomly placed and starts its exploration. Immediately after the first mapping of the subarea, the trajectory planning starts setting the waypoints in the map. We used the same configuration for the SLAM algorithm as in the last described experiment. The maximal accepted distance of the S300 is 8 m with $0.5°$ angle resolution over a $270°$ area. The waypoints keep a distance of 0.2 m to the wall and to each other. We decided for a small distance between the waypoints because it enables an approximated continuous path around obstacles. We aim a floor coverage, providing radioactivity measurements for every location. After reaching a waypoint, using its omnidirectional drive, it marks this position as completed and takes the next waypoint as target position. Finally, it traverses the seen section of the environment by itself until every possible location in the map was reached. The mapping process of the complete room was achieved after some minutes, due to the small size of the test terrain. We closed the door in order to avoid a further exploration down the hallway. The architectural drawing, combined with the resulting mapping results, demonstrates the accuracy of the mapping process. The map of the hallway was created in an additional run after finishing the experiment in the laboratory. A critical situation (see Figure 6) is

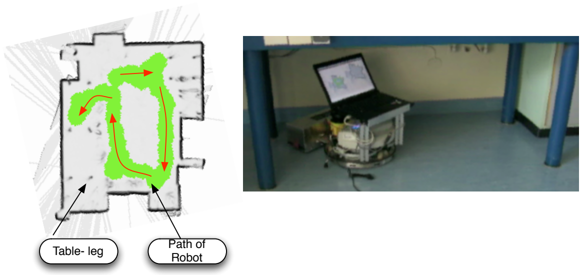

Figure 6: Allocation: Map Position - Real World

the exploration under tables. The trajectory planning module checks the distances between the table-legs, concerning its own geometry, in order to verify the potentiality of a collision-free path. Generally, the exploration of these regions is only possible, if the robot has enough space to move. Some areas in the map are not covered because of too narrow passages. The red arrows show the direction of the robot's movement. It starts to drive with a speed of 40mm per second along the wall and continues its search in the middle of the room until every reachable position was completed. The uncovered areas next to the walls resulted from a safe distance to the walls. Figure 5 also shows that the robot did not cover some areas under the tables because of the inapplicable geometry of the robot. The search for radioactivity was accomplished without any collisions. The green area stands for the clean floor. In the case of detected radiation a radioactivity sign would mark the corresponding position in the map. The robot drove with a speed of 40 mm/s and needed around 1 hour for the laboratory. Approximately 70% of the laboratory can be covered at the moment. We work on some extensions, which should solve that problem and guarantee a 100% coverage of the floor.

5 Conclusion

In this paper, we have presented a completely new application for securing of a contamination-free environment. So far, a comparable approach has never been deployed for this purpose. We extended a SLAM approach with the ability to plan a path and drive autonomously through an indoor environment. Inspired by the Open Source community, we released the SLAM library of our mobile robot on the Internet [3]. By providing this service to the international robotic community, we hope to attract other research groups to do the same and help to enlarge the existing knowledge base in this field of research. The DP-SLAM re-implementation with its extensions enables an adoption for various robots or laser rangefinders. There are some disadvantages, which have to be solved in future works. The SLAM algorithm is not able to map outdoor environments in real-time. We suggest to implement a Rao-Blackwellized particle filter which is able to compute an accurate proposal distribution taking into account not only the movement of the robot but also the most recent observation [15]. This approach reduces the uncertainty about the robot's position and allows to track its own position in large-scale and outdoor domains. Another improvement is the implementation of an efficient occupancy grid through a Quadtree, for example. Both proposals could drastically speed up the performance of the SLAM algorithm.
The strategy for an optimal coverage of the floor needs to be adapted in order to guarantee a 100% coverage for all possible environments. Another important factor for a successful mission is the power supply in order to guarantee preferable long operation times. We will resolve this claim by adding additional and more powerful batteries. The current prototype uses two 12V lead-gel rechargeable non-spillable electric storage batteries, permitting a limited running time of maximal 2 hours. We want to extend NENA by Automotive Class Lithium Ion Cells in order to triple the current running time. The experiments within this framework have been promising. That is why we want to extend the progress in near future. We aim for using our approach for a real industrial application.

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