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LOCALIZATION OF IONIZING RADIATION SOURCES VIA AN AUTONOMOUS ROBOTIC SYSTEM

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The article discusses an autonomous and flexible robotic system for radiation monitoring. The detection part of the system comprises two NaI(Tl) scintillation detectors; one of these is collimated to allow directionally sensitive measurements, and the other is used to calculate the dose rate and provides sufficient sensitivity. Special algorithms for autonomous operation of an unmanned ground vehicle were developed, utilizing radiation characteristics acquired by the implemented detection system. The system was designed to operate in three modes: radiation mapping, localization of discrete sources, and inspection of a region of interest. All of the modes were verified experimentally. In the localization mode, the time required to localize ionizing radiation sources was reduced by a half compared to the field mapping mode exploiting parallel trajectories; the localization accuracy remained the same. In the inspection mode, the desired functionality was achieved, and the changes in the sources arrangement were detected reliably in the experiments.

INTRODUCTION

There are many reasons to be prepared for radiation situation reconnaissance of a region of interest (ROI). Accidents in transportation or handling a radioactive material pose a risk of losing control over the source of ionizing radiation (IR)(1),(2). A similar problem consists in the intentional misuse of an IR source as a radiological exposure device (RED); the worst case scenarios comprise potential threats arising from a radiological dispersal device (RDD) (3),(4) or nuclear power plant accidents (Chernobyl, Fukushima). The affected area can be of various sizes and different degrees of danger. To take proper radiation protection measures, we first need to identify the area contaminated with radioactive substances and to localize the 'hot spots' or radiation sources quickly and efficiently. To prevent people from entering a high risk area, remote sensing and manned or unmanned robotic systems are widely studied. The aim of our research is to satisfy the requirements for a modern, autonomous, and flexible robotic detection system that provides comprehensive data on the radiation situation at the deployment site. The monitoring of a radiation situation using unmanned aerial or ground vehicles is also a subject of research (5),(6),(7); however, the output of such a process is a map of ionizing radiation intensity that must be evaluated by a competent person.

The method to expand the capabilities of radiation situation reconnaissance consists in obtaining more information than solely the intensity of IR. The direction to the IR source can constitute such information. The novelty of the research lies in the development of a new, directionally sensitive detection system together with special algorithms to autonomously operate the unmanned ground vehicle (UGV) in dependence on the detected radiation characteristics. These new capabilities provide radiation mapping with new possibilities in localizing discrete IR sources, performing radiation inspection of objects, and surveying the radiation signature of regions of interest.

METHODS

Dosimetry System

A special detection system was developed within the research procedures. The system comprises two detectors, one omnidirectional and the other directionally sensitive. Both detectors are based on a scintillation crystal of sodium iodide doped with thallium (NaI(Tl)) in the size of $2'' \times 2''$ accompanied with photomultiplier tubes (Nuvia a.s., CZE). The counting electronics was specially developed to avoid data delay and distortion usual in data processing in commercial devices. The processed data comprise a 256-channel spectrum of gamma radiation measured every second. Thev detectors were calibrated for the energy range from 30 keV to 2 MeV. The quantity dose equivalent rate was approximately determined by summing the spectra from the omnidirectional detector. This conversion was calibrated for the energy of 662 keV (^{137}Cs). The dynamic range of the dose equivalent rate was up to 0.6 mSv h^{-1}.

The directionally sensitive detector was placed in a lead collimator. Shielding with the thickness of 2 cm enclosed the top and sides of the scintillating crystal.

Due to the weight and volume, it was not possible to shield the whole detector. The collimator had a vertical aperture of 11 mm on its side, corresponding to the viewing angle of 15°. The collimator exhibited the weight of 7 kg, and its capabilities included rotation around the vertical axis. The sum of the gamma spectra was measured in 24 sectors during 1 turn (24 sectors $\times$ $15^\circ = 360^\circ$). The obtained histogram was evaluated for a statistically significant increase in the detector response, which was interpolated by a triangle; subsequently, the direction to an IR source was estimated.

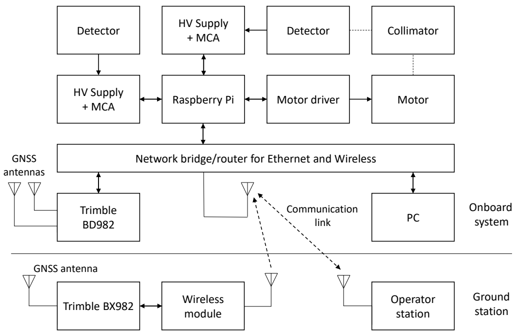

Figure 1. A block diagram of the system.

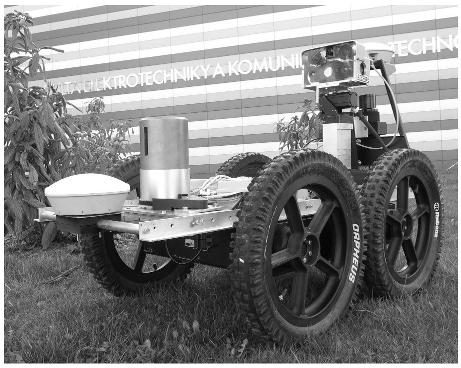

Figure 2. The Orpheus-X4 carrying the detection head.

Robotic System

The detection system can be integrated in any arbitrary robotic system mechanically capable of carrying its load and is equipped with reliable self-localization and navigation modules. Within the scope of this paper, the Orpheus-X4 robotic platform developed at the Faculty of Electrical Engineering and Communication and CEITEC institute, Brno University of Technology, is employed[8],[9]. The Orpheus-X4 is a mid-size, four-wheeled reconnaissance robot with a differential drive having the payload capacity of approximately 30 kg. Importantly, the vehicle utilizes an advanced module based on the Real Time Kinematic (RTK) Global Navigation Satellite System (GNSS), which ensures high-accuracy measurement of the robot's position, with the error in the order of centimeters[10]; consequently, the robot can automatically follow a pre-defined outdoor path.

The block diagram in Fig. 1 shows the manner in which the detection system was integrated in the robotic platform. The key on-board components are connected via Ethernet, and they are embodied by a Raspberry Pi (control of detectors), a GNSS receiver, and a computer running all the control algorithms. A wirelessly connected ground station provides the correction data for the position measurement and also the remote control. An image of the complete system, namely, the robot carrying the detection head, is shown in Fig. 2.

Operation Modes

For the autonomous detection system testing, three operation modes to facilitate radiation reconnaissance were designed: radiation mapping, localization of discrete sources, and inspection of objects or regions of interest.

The first operation mode uses standard ROI exploration along parallel lines by a robot carrying the radiation detector. There is no need of communication between the detector and the UGV. The results of this mode comprise a map of the ionizing radiation intensity. A subsequent evaluation is required to identify the hot spots, discrete sources, and other aspects.

The main benefit of the second mode is the ability to modify the robot trajectory in real time, exploiting the data measured by the detection system. The purpose of this mode is to reduce the time needed to accurately localize IR sources. The basic idea consists in reacting to an increased level of IR, executing the directional measurement and subsequently inspecting portions of the surveyed region where the sources have been detected. This approach causes strong sources to be reported quickly to the operator, along with their parameters. The method is described in more detail within the following subsection.

In the third operation mode, the robotic detection system performs autonomous inspection of the specified area in terms of the presence of gamma radiation. The system must be capable of indicating a possible change in the IR intensity and subsequently specifying the character of the change (e.g., a new or a missing source). Prior to the inspection, there must be a 'learning' pass of the inspection trajectory to identify and remember the radiation signature of the ROI. During the inspection, the current radiation signature is continuously compared with the learned one. This mode is able to inform the operator about new IR sources (accident, contamination) or 'lost' sources (stolen, moved) in the region of interest, including, for example, a nuclear power plant site or a radioactive waste repository.

Control Algorithms

The algorithm utilized for navigating the robot along the defined path is also described in other papers, such as 'Autonomous field measurement in outdoor areas using a mobile robot with RTK GNSS'[11]. This chapter emphasizes the algorithms necessary for operation in the modes described above.

The first mode is rather straightforward, with the data collected along a pre-defined trajectory composed of parallel lines; the trajectory is not changed during the measurement. Only one parameter, namely, the distance of parallel lines, significantly influences the result, and its choice corresponds to the desired minimum detectable activity (MDA). In order to produce a well-arranged map of the area distribution of the ionizing radiation, the scattered data are interpolated via the Delaunay triangulation[12] The resulting map is of importance to the human operator, as it offers a quick survey of the sources' layout and intensity; moreover, it can provide an additional item of information, such as that on isodoses. Directional measurement is not employed in this mode, which serves mainly as a reference for the localization performance of the second mode.

Regarding the utilized algorithms, the second mode is more appealing; its purpose is to localize the radiation sources in a shorter time but at the same (or similar) accuracy, exploiting the directional information provided by the detection system. To perform a directional measurement, the robot has to stop for 12 seconds; thus, it is desirable to minimize the number of directional measurements to maintain the algorithm's ability to compete with the first mode. A possible approach to achieving this objective is described below.

Let us assume that the sources are present in a region with delimited borders. The region of interest should be chosen based on a primary measurement; for example, its border can be constituted by an approximate isodose. A feasible solution is to employ aerial assets[13],[14].

The exploration of the region comprises two phases, namely, a rough and a detailed one. First, the region is decomposed into cells consisting of a 3×3 matrix of subcells. The size of a subcell should ensure that any source with an MDA present in it is detectable from its center. Then, to each cell and subcell, a priority number is assigned (the lower the number, the higher the priority), having the highest value by the border. A primary trajectory is built over the cell centers, following a set of rules which prefer:

- a lower priority number,
- unvisited cells,
- constant direction.

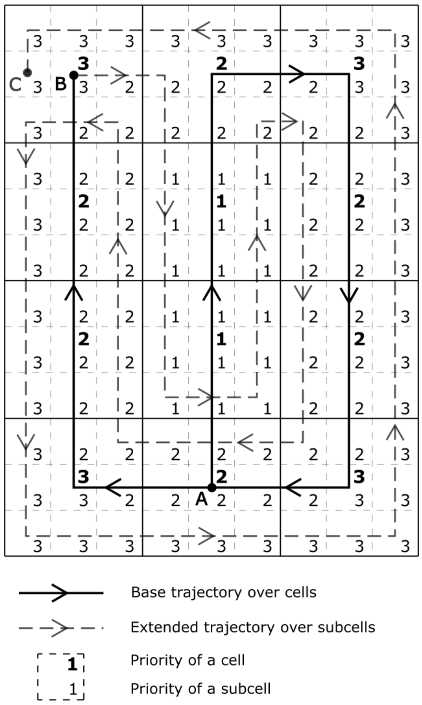

Figure 3. An example of the two-phase survey trajectory from point A to point C; point B is a dividing spot between the primary and the secondary trajectories.

The rules are obviously more complex; therefore, their detailed description is not discussed within this paper. A secondary trajectory over the subcell centers is built in a similar manner. An example of exploration trajectories is shown in Fig. 3 for a region of 3×4 cells.

During the localization, the robot follows these predefined trajectories until the presence of a source is indicated. The indication is based on the instantaneous measured radiation intensity (represented either by a count rate or a dose rate) if its value is significantly higher than expected. Before the first source is localized, the anticipated intensity is defined solely by the radiation background, which should be measured prior to the survey, outside the stricken area (if possible). Once the indication conditions are fulfilled, the robot stops operating, and the directional measurement using the detection head is performed. If a significant direction is found, the robot will alter its trajectory in order to follow that direction. After the source is provably passed (we need to consider the dead time effect), the trajectory changes again, with the objective to collect data along a perpendicular line. The purpose consists in supplying sufficient input data into the algorithm that estimates the parameters of the source (the position and 'emission'); such a trajectory is represented in Fig. 4. The estimation can be performed using, e.g., the Gauss-Newton

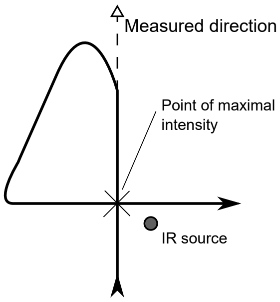

Figure 4. A trajectory example for a better estimation of the source parameters.

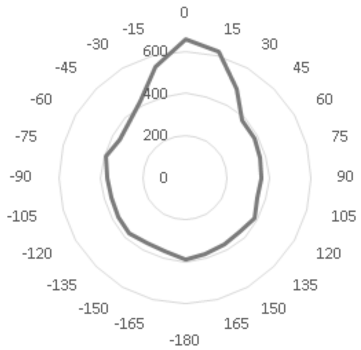

Figure 5. The angular dependency of the directionally sensitive detector in CPS; source of ^{137}Cs, 293.5 MBq, distance 3 m.

method, as described in 'Optimizing the localization of gamma radiation point sources using a UGV'[15]. If multiple significant directions are found, i.e., more than one source is within the detectable range, then each of them is handled in the described manner. Afterwards, the robot returns to the base trajectory to continue the survey. However, the expected radiation intensity value does not derive from the background only but also from the established sources' radiation field. The exploration is completed when the final point of the secondary trajectory is reached.

Finally, in the third operation mode the operator needs to manually define several checkpoints that exhibit a significant radiation signature. Directional measurements are conducted in these points to provide reference for a future inspection. The course of the first inspection sequence, which is driven manually, is logged in a configuration file containing the trajectory and the distribution of the radiation intensity along it; the results of the measurements are saved. During the following autonomous sequences, it is checked whether a change in some of the quantities oversteps the tolerance area; if such a condition is found, the anomaly is reported to the operator and can be verified by additional measurements.

Experimental Setup

For the experimental verification of the autonomous detection system, a rectangular region with the area of 330 m^2 was selected. Sealed radioactive sources of radionuclide ^{137}Cs with the activities of 293.5 MBq and 2.9 GBq were employed to test the first two modes of operation (the radiation mapping and localization of discrete sources). The location of sources was the same in both cases in order to compare the accuracy and time requirements of the different approaches; in the third mode, the setup included other two sources of radionuclide ^{137}Cs, whose activities equalled 14.2 MBq and 94.7 MBq. Here, the intention was to move the sources during the experiment.

RESULTS

The detection part of the system was properly tested and calibrated. In particular, the structure and properties of the collimator for the directionally sensitive detector (i.e., the thickness of the shielding or the shape and dimension of the aperture) were investigated and estimated on the basis of Monte Carlo simulations[16] (in Czech). The real angular dependency as the main property is represented in Fig. 5. The Figure indicates the output of the detector in counts per second (CPS) as the function of the angle between the aperture and the source of ^{137}Cs (293.5 MBq, distance 3 m). The ratio of the CPS for 0°to that for 180°is approximately 1.7. Naturally, the ratio depends on the gamma radiation energy. A low energy radiation with a higher attenuation coefficient constitutes a higher value of the ratio.

The directionally sensitive detector is able to estimate the direction to the source very reliably within 4 to 6 meters (source of ^{60}Co, 152.5 MBq). The angle measurement accuracy equals approximately 5°.

The field experiments were performed correspondingly to the setup characterized above. For the radiation mapping (the first mode), the distance of 1 m between the parallel lines was chosen in order to provide data for sufficiently smooth interpolation. The resulting map is shown in Fig. 6. The area exploration took 10.5 minutes, and the localization accuracy of 10.6 cm RMS was achieved.

The experimentation in the second mode (the localization of discrete sources) necessitated the control algorithm alteration, as some of the spurious attributes of the detection system had not been anticipated; basically, several effects caused by the measurement geometry and the robot movement were compensated. Eventually, the sources were localized with the accuracy of 12.4 cm RMS in 5.5 minutes. The results of the experiment are visualized in Fig. 7. The final part of the trajectory is missing due to the data integrity corruption caused by shading of the GNSS antennas. Note that the

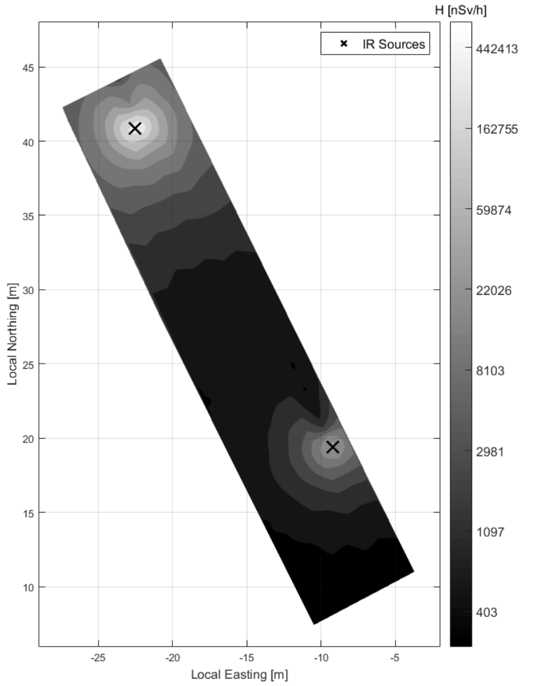

Figure 6. The radiation mapping result related to the ^{137}Cs sources; the upper left one has the activity of 2.9 GBq, while the other exhibits 293.5 MBq.

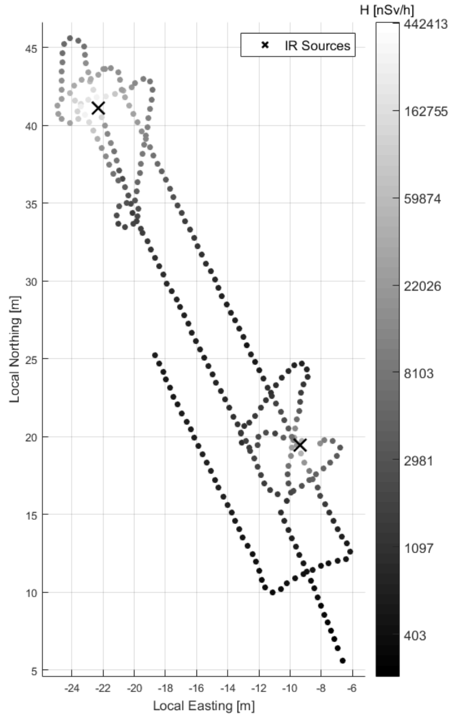

Figure 7. The source localization result related to the ^{137}Cs sources; the upper left one has the activity of 2.9 GBq, while the other exhibits 293.5 MBq.

region was decomposed to 1×4 cells; the straight line in the middle embodies the primary survey trajectory while straight lines along borders of the region represent the second one.

In the inspection mode, an approximately oval trajectory was defined manually, with two checkpoints near the IR sources where the directional measurements were carried out. The correct behavior of the system was verified by multiple passes of the inspection trajectory for each of the scenarios described below. First, the sources were kept in their initial locations; the algorithm indicated no change, as expected. Then, one of the sources was removed, and the event was correctly evaluated by the algorithm. Finally, the weaker source was placed in a new location; the system was able to report the presence of a new source on the basis of a radiation intensity higher (compared to the background) than that detected in the initial measurement.

The described experiments were run multiple times in the same configuration (due to logistic issues) to verify the algorithms.

DISCUSSION AND CONCLUSION

The paper presents a custom-made, two-detector system capable of measuring both the dosimetry quantities and the direction to sources of ionizing radiation. The system was integrated in the Orpheus-X4 robotic platform and successfully tested in field experiments with real radioactive sources.

The operation mode, which enables faster localization of discrete IR sources via a directionally sensitive sensor, is introduced. Compared to the localization approach based on conventional radiation mapping, the system should offer the same accuracy within a shorter time under certain circumstances. The duration of radiation mapping in a given area is constant, and the choice of the initial measurement point is relevant in terms of the time required for the first significant item of information to arrive. Conversely, once the assumption of the sources' presence near the center of the region is correct, primary information on the situation is provided earlier, eliminating the dependence on the initial conditions even with the long directional measurement time.

Another benefit of our research consists in the inspection mode, which embodies a rather innovative technique within radiation protection. Currently, the inspection is possible merely in an outdoor environment, as it depends on the self-localization provided by the

GNSS; such a scenario constitutes an apparent disadvantage. Prospectively, however, the system can be extended with an indoor self-localization module (e.g., by means of computer vision(17). Moreover, a variable inspection trajectory of the robot is envisaged to decrease the system's predictability (to make a malevolent attack on the system more difficult).

There are several major possibilities of improving the system within future research. First, the size of the directionally sensitive part of the detection system could be reduced by employing a one-inch detector and a photodiode instead of the photomultiplier. Although such adjustment will probably reduce the detection efficiency, it could still ensure a satisfactory trade-off between the mechanical ruggedness and the accuracy of the directional measurements. Then, the system can be equipped with a detector for high dose rates, e.g., a GM tube, as the scintillators become overloaded in the vicinity of high emission sources. Finally, more general and robust localization algorithms for the robot are planned to be developed and tested.

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