LOCALIZATION OF GAMMA RADIATION SOURCES

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Abstract: The paper describes a method for acquiring and processing data concerned with a radiation situation in a pre-defined region of interest with a goal of localizing point sources present in the region. The acquisition underlies the robotic platform Orpheus-X4 equipped with a precise navigation module and gamma radiation detectors, a path planning involves Boustrophedon decomposition. The processing is based on the Gauss-Newton method, a contribution of the paper consists in a way to provide the method correct input data. Introduced algorithms were verified experimentally. Although not all sources can be found using the chosen equipment, in case of successful localization the accuracy is not worse than 0.1 m.

Keywords: gamma radiation, robot, localization, parameter estimation

1 INTRODUCTION

The paper deals with the processing of data acquired posterior to a simulated accident involving discrete (point) radiation sources. As the ionizing radiation produced by those sources is unfavourable for a human health, it is desirable to localize them using unmanned systems in order to minimize a time spent by human personnel in the stricken area. Our team of robotics at the Faculty of Electrical Engineering and Communication, BUT, has already made a partial progress in the described field; previous results are presented, e.g., in paper [1].

A following scenario was assumed: Terrorists stole portions of a radioactive material and during their transport were stopped by safety enforcement bodies. Unfortunately, the action resolved in a loss of the radiation sources in an unknown area. It is desired to find parameters of the sources, especially their coordinates and some expression of the intensity, utilizing a multi-robot system. Necessary data should be acquired during a single operation in order to resemble a real scenario.

First, a model of the unknown area is measured applying a technique of the photogrammetry using an unmanned aerial system (UAS); details of the approach may be found in an article [2]. The resulting model called a digital elevation model (DEM) is utilized for a following motion planning of both the UAS and an unmanned ground vehicle (UGV). Then, an approximate radiation map is acquired by the UAS. Regions of interest (ROIs) with a significant radiation signature are selected within the map. Finally, these regions are explored in more detail by the UGV; a characterization of this survey is the main focus of the paper therefore, the UAS part is omitted.

The paper is organized as follows. In Section 2, devises used for the data acquisition are introduced, as well as its key component – a path planning algorithm. Section 3 deals with a description of algorithms used for processing the data in order to localize lost sources accurately. Results of performed experiments are summarized in Section 4. Consequently they are discussed and evaluated in Section 5.

2 DATA ACQUISITION

Essentially, any robotic platform possessing a capacity of carrying a radiation measurement system and is also equipped with a self-localization and navigation module, can be used for getting an appropriate dataset. In this case, the robot Orpheus-X4 developed at the Faculty of Electrical Engineering and Communication, BUT, was selected for the implementation of presented methods. Orpheus-X4 is as mid-size four-wheeled reconnaissance robot with payload capacity of approximately 30 kg. It is suitable for an outdoor environment, typical operation time is close to one hour. A key component of the system is a navigation module based on a GNSS (Global Navigation Satellite System) technology. As a Real Time Kinematic (RTK) GNSS provided by the receiver Trimble BD982 is utilized, the outdoor self-localization constitutes the accuracy better than 1 cm. The module is also capable of navigating the robot accurately through a series of waypoints. Details behind the navigation are available in an article [3].

A radiation detection system embodies a necessary component as well. The system is composed of two two-inch NaI(Tl) (sodium iodide doped with thallium) detectors. The utilization of two independent detectors provides better statistical parameters of the measurement as well as higher sensitivity. Each detector is encapsulated with a photomultiplier tube and ended with a standard 12-pin base. The detectors are mounted on the robot in a height of approximately 0.5 m. Both a source of high voltage and counting electronics are delivered by a compact NuNA MCB3 module. Detectors were calibrated for the energy range of 0 to 3 MeV using a Ceasium-137 source; the energy range is divided into 1024 channels. The device is controlled and data read via the Ethernet, the integration period is set to 1 second.

As the radiation spectra are measured periodically, the result depends mostly on a trajectory of the robot. It is assumed that an area in which a single source or multiple sources are present can be approximated by a polygon. Most likely, the polygon intersects with parts of the configuration space which can be denoted as obstacles, e.g., trees or steep slopes. Consequently, the primary polygon needs to be altered by a map of obstacles resulting in a set of polygons: the largest one is called the *envelope* and the whole region of interest lies inside it; the other ones, denoted as *holes*, embody forbidden areas for the robot. A path of the robot has to be planned in order to cover the envelope avoiding the holes with emphasis on low time and/or energy requirements. Following a survey of coverage path planning algorithms [4], a Boustrophedon decomposition was chosen.

The Boustrophedon algorithm is similar to a trapezoidal decomposition which divides the area into a set of disjoint trapezoids using a *sweep line* while their edges follow a shape of obstacles. In the case of Boustrophedon, the trapezoids are joined in generic nonconvex polygon. This kind of decomposition is not suitable for finding a shortest path between two points, however, it is beneficial for the coverage planning. In each polygon a “zig-zag” kind of path is easily computed while important portions of the trajectory are parallel to the original sweep line. Individual polygons are connected as nodes of a graph in which edges represent an adjacency of the polygons. If an optimal solution is not required, the sequence of nodes can be determined, for example, applying a depth-first search algorithm [5].

A speed of the robot and a distance between parallel trajectory lines belong among important parameters that influence a result of the measurement. It is necessary to take a minimal detectable activity into account. That is already partially defined by the height of detectors (0.5 m), therefore, for both the distance travelled by the robot during 1 second (sampling period) and the spacing of measurement lines, it is meaningful to choose them in the same order. Previous experiments proofed that the forward speed of 0.6 m/s and the spacing of 1 m provide useful datasets for localization of sources of activity greater than hundreds of keVs. As weaker sources are not assumed (they do not pose a significant health risk), these values were used for the purposes of this paper as well.

3 DATA PROCESSING

Following previous achievements, a Gauss-Newton gradient method is used for finding parameters of sources present in a measured area, namely, their Cartesian coordinates and intensity. The method is rather reliable, however, the dataset needs to follow certain requirements in order to receive meaningful results. First, it is necessary to determine a number of sources and find an initial guess of their parameters. Then, the dataset should be reduced in a manner that keeps most of valuable samples and omits those that do not provide helpful information and can be considered as a noise. A procedure to do so is introduced in this paper.

First, let us remind the Gauss-Newton method applied to the localization of radiation sources. The sources are described by a matrix $\boldsymbol{\theta}$ composed of parameter vectors:

$$\theta_i = (\alpha_i, x_i, y_i) \tag{1}$$

The matrix $\boldsymbol{\theta}$ is incrementally updated using a Jacobian and a vector of residuals:

$$\boldsymbol{\theta}_{k+1} = \boldsymbol{\theta}_k - \left(\boldsymbol{J}^{\mathrm{T}}\boldsymbol{J}\right)^{-1}\boldsymbol{J}^{\mathrm{T}}\boldsymbol{r}(\boldsymbol{\theta}_k) \tag{2}$$

where

$$r_m = c_m - \sum_{r=1}^{R} \frac{\alpha_r}{(x_m - x_r)^2 + (y_m - y_r)^2 + h^2} \tag{3}$$

where α stands for the intensity expressed as counts measured in a distance of 1 m, c stands for actually measured counts, x, y are Cartesian coordinates and h is a height of detectors.

The process continues until the sum of residuals is lower than an allowed error ε. Note that it is important to normalize values of measured counts per second (CPS) to a range 0 to 1 in order to ensure a numerical stability. The major problem of different localization methods, such as [6], consists in determining the number of sources. A possible solution is offered below.

Since the region of interest is covered evenly by the measurement points, it is possible to build a map of the radiation distribution inside the region by interpolating samples; typically a Delaunay triangulation is used as a method of the interpolation. Each source well-separated from the others should invoke a local maximum in the radiation map. Therefore, number of local maxima corresponds with a number of separate radiation sources. As the real data usually do not follow an ideal course in a vicinity of sources due to the dead-time and measurement inaccuracy, is it difficult to identify local maxima by a simple peak detector.

Accordingly, a method of adaptive thresholding is adopted to distinguish significant maxima. All values under certain threshold corresponding to a background are cut off leaving discrete areas of a number equal to a number of differentiable sources (peaks). A value of the threshold was derived from simulation results [7] and is equal to:

$$threshold = \mu_{background} + 3\sigma_{background} \tag{4}$$

where the background set is composed of samples with a value lower than $\mu_{all} + \frac{\sigma_{all}}{2}$. The μ stands for the mean value of a dataset and the σ represents its standard deviation.

The parameter matrix for the Gauss-Newton method is initialized with a CPS value and coordinates of a maximal point in each separated area created by the thresholding.

4 RESULTS

The described algorithms were experimentally tested using seven radioactive sources of Cobalt-60 and Caesium-137 isotopes with the activity ranging from 3 MBq to 80 MBq. A measurement trajectory planned using the Boustrophedon decomposition is shown in Figure 1 (left); note that there were three obstacles in the region. The interpolated radiation map with the cut background can be found in Figure 1 (right) – there were merely three local maxima (of seven sources) found. The complete result in a form of both the true and the estimated locations of sources put in the radiation map is illustrated in Figure 2. The average localization error was equal to 8.9 cm RMS.

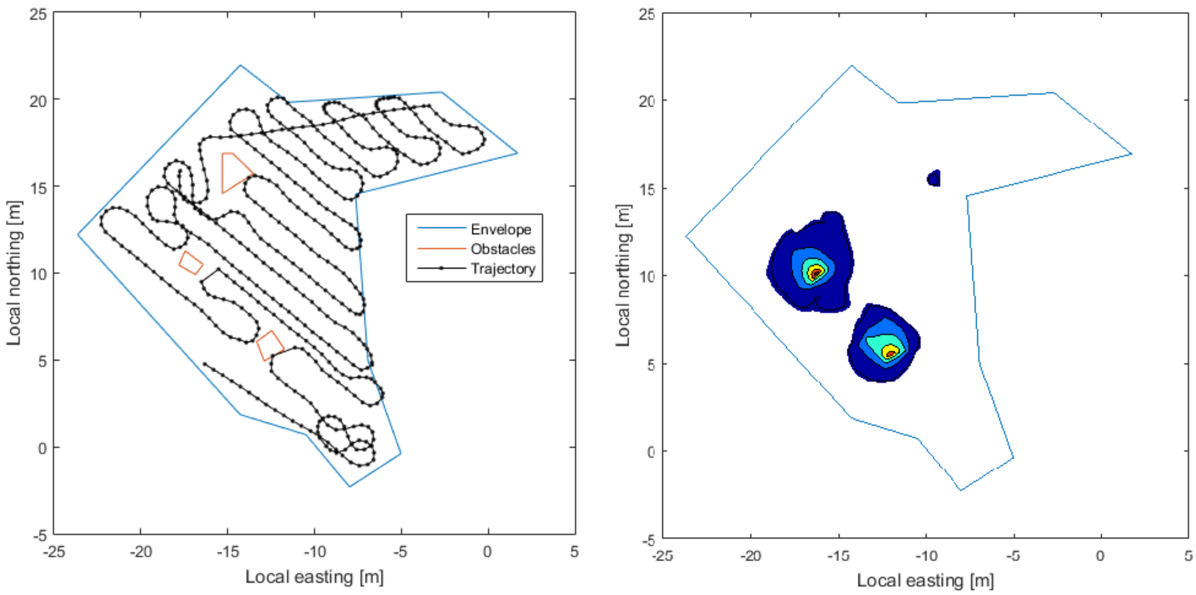

Figure 1: Left: The measurement trajectory. Right: Separated local maxima.

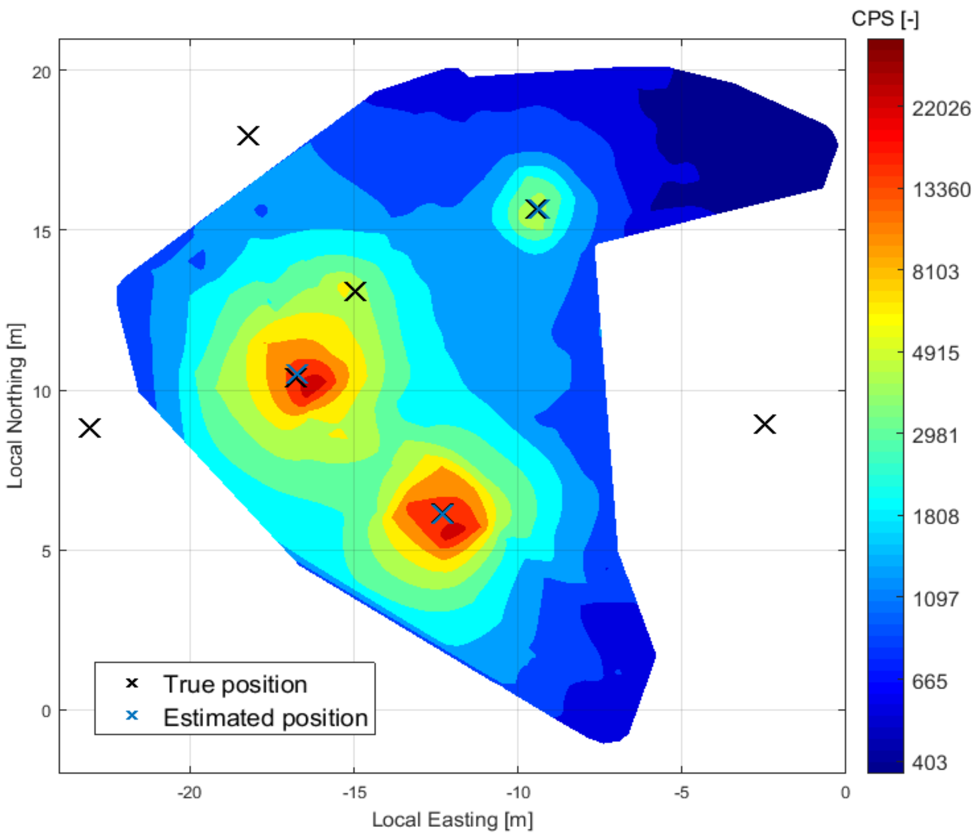

Figure 2: The result of localization.

5 CONCLUSION

A method for accurate localization of radiation sources lost in a pre-defined region of interest was introduced in this paper. The robotic platform Orpheus-X4 equipped with RTK-GNSS receiver and gamma radiation detectors was used for the data acquisition. Generally, within the region of interest, obstacles may appear; thus, a Boustrophedon decomposition along with depth-first search are utilized for planning safe "zig-zag" trajectories for complete coverage of the ROI. The measured data are pre-processed by interpolating them and cutting the radiation background applying an adaptive threshold. Remaining areas that exceeds background values are used to initialize the parameter matrix which is then processed by the Gauss-Newton method.

Algorithms were tested during a wider experiment where the region of interest was selected and a map of obstacles was acquired on a basis of previous measurements performed by a UAS. Borders of the region were defined using the same adaptive thresholding method exploiting its generality. In practice, the map of obstacles needs to be extended with a clearance to avoid collisions since the robot cannot turn on spot in an outdoor terrain and consequently an additional manoeuvring space is required. A value of the clearance should be greater than a minimal turning radius of the robot which is typically equal to 0.6 m for the Orpheus-X4.

As was presented in results, sources were localized with the accuracy better than 0.1 m; however, merely three of total seven sources were successfully found which points to a disability to be functional in any general scenario. One of the fail-to-locate sources was overshadowed by an adjacent stronger radionuclide and one collided with an obstacle (steep slope), the other two were just outside borders of the region. While the former two cases reflect drawbacks of the selected method, the latter two would be localized if the region was extended. In the future, further development of localization algorithms is planned with an emphasis on the cooperation with other robotic systems such as the aerial ones. A maximal autonomy of the system with a minimal intervention is desired.

ACKNOWLEDGEMENT

The completion of this paper was made possible by the grant No. FEKT-S-17-4234 - „Industry 4.0 in automation and cybernetics" financially supported by the Internal science fund of Brno University of Technology.

REFERENCES

[1] Lazna, T., Gabrlik, P., Jilek, T. and Zalud, L. Cooperation between an unmanned aerial vehicle and an unmanned ground vehicle in highly accurate localization of gamma radiation hotspots. *International Journal of Advanced Robotic Systems*, **15**(1). SAGE Publishing, 2018.

[2] Gabrlik, P., Cour-Harbo, A. la, Kalvodova, P., Zalud, L. and Janata, P. Calibration and accuracy assessment in a direct georeferencing system for UAS photogrammetry. *International Journal of Remote Sensing*, **39**(15–16). Taylor & Francis, 2018, pp. 4931–4959.

[3] Jilek, T. Autonomous field measurement in outdoor areas using a mobile robot with RTK GNSS. *IFAC-PapersOnLine*, **48**(4). Elsevier, 2015, pp. 480–485.

[4] Choset, H. Coverage of Known Spaces: The Boustrophedon Cellular Decomposition. *Autonomous Robots*, **9**(3). Springer, 2000, pp. 247–253.

[5] LaValle, S. M. *Planning Algorithms*. Cambridge: Cambridge University Press, 2006.

[6] Gunatilaka, A., Ristic, B. and Morelande, M. Experimental verification of algorithms for detection and estimation of radioactive sources. In: 2010 13th International Conference on Information Fusion. Edinburgh: Institute of Electrical and Electronics Engineers, 2010.

[7] Gabrlik, P. and Lazna, T. Simulation of Gamma Radiation Mapping Using an Unmanned Aerial System. *IFAC-PapersOnLine*, **51**(6). Elsevier, 2018, pp. 256–262.