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Compton imaging to support a new robotic platform for mapping nuclear decommissioning sites

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I. INTRODUCTION

A nuclear decommissioning environment requires the characterisation of hotspots in a high dose rate environment. The current practice to identifying hotspots is for human operators to enter the facility and manually localise and characterise these hotspots. As a result, operators that carry out these measurements are exposed to dose uptake, which implies that special safety measures are necessary to protect the workers performing these measurements.

In these situations, where operators are exposed to high dose rates, the time available to perform the mapping measurements is limited to keep the dose uptake as low as reasonably achievable. This, however, introduces the risk of an incomplete characterisation, where sources are missed or inaccurately characterized. Instead of using human interventions, an alternative approach could be to use a robotic platform to automate the repetitive measurement procedures of localising hotspots [1]. Not only does the use of a robot minimise human radiation exposure by reducing the need for human presence and thus reducing unnecessary dose uptake. The use of robots also takes away the time limitation, leading to more accurate measurements.

In the ARCHER project (Autonomous Robotic platform for CHaractERization), a robotic system is being developed to perform mapping and characterisation measurements in a nuclear decommissioning environment. One of the applications of this platform is the localisation and characterisation of radioactive hotspots inside tanks or pipes larger than 60cm.

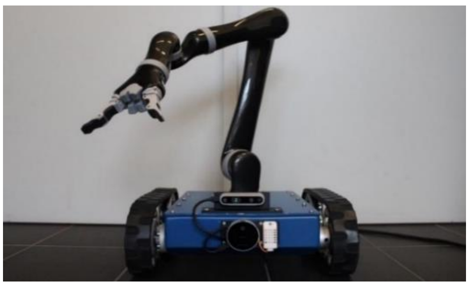

Figure 1. Picture of the ARCHER robotic platform

Figure 1 shows a picture of the robotic platform that is currently being developed in the ARCHER project. This platform is equipped with a robotic arm that is used to perform the necessary movements and manipulations of the detector. The measurements aim at identifying and characterizing hot spots.

In literature, different methods have been proposed to localise hotspots. Two categories of approaches that are frequently reported are i) [2] performing multiple measurements in a scanning approach and apply interpolations to determine the source location or, ii) [3]–[5] using a gamma or Compton camera that can directly give spatial information in a single measurement. Selivanova et al. [2] demonstrated the capabilities of a scanning approach by using a CloPema dual-arm robot in combination with a kromek-GR1-A+ CZT (Cadmium Zinc Telluride) spectrometer. By measuring spectrums with a detection time of one second per spectrum and scanning performed in a serpentine pattern with a scanning speed of 5 cm/s, heatmaps were created based on the measured total counts per spectrum. Selivanova et al. proved a scanning approach to be a feasible method for localising standard point sources with activities of hundreds of kBq. Selinova et al. achieved minimal detectable activities (MDA's) in the order of kBq to tens of GBq, depending on the amount of shielding between source and detector.

Due to the repetitive nature of a scanning pattern, measuring with a robotic arm remains a time-intensive method. As the measurements are performed in close proximity to the hot spots, every executed movement has a risk of contaminating the robotic platform or detector. The alternative approach, (approach ii) of using a gamma camera (with physical or electronic collimation) has the advantage that direct spatial information about the source location can be extracted. This minimizes the need for movements and manipulations of the robot and therefore reduces the risk of contaminating the robot. Carrel et al. [4] proposed the gampix gamma camera that performs spatial localisation of a source in a single measurement. This system utilises a Timepix readout chip in combination with a 1000 µm thick CdTe (Cadmium

Telluride) semiconductor crystal and a coded aperture or multi-pinhole collimator. By introducing a decoding step, sources with varying energy were successfully localised. However, at higher gamma energies, e.g. ^{60}Co, the efficiency significantly dropped for this system. Additionally, when a collimator would be used in a high background environment, also shielding needs to be added to limit incident radiation from outside the field of view of the collimator. This would significantly increase the weight and make it too heavy to use on a small robotic platform, such as ARCHER, which needs to be able to manoeuvre inside tanks or pipes.

Contrary to the approach of using a gamma camera equipped with a physical collimator and shielding, electronic collimation can be used. A Compton camera makes use of the kinematics of Compton scattering to calculate the possible directions of incident gamma radiation. Therefore, a Compton camera can directly extract geometric information about the location of hotspots. This limits the need for manipulations and movements of the robotic platform and arm while also limiting the needed weight for the detector. Also, the weight will be kept low as no physical collimator is needed. Sato et al. [3] proved this concept of using a Compton camera to localise sources. In his research, the Compton camera with a total weight of less than one kg was mounted on a drone. This camera consisted of two detectors, one scatterer and one absorber detector, both made from Ce-doped GAGG ($Gd_3Al_2Ga_3O_{12}$) scintillators with a distance of 23.5 mm between the two. Instead of using two detectors for the Compton camera, as was the case during the research of Sato et al., in this work only one detector was used. This was done using a method similar to the method proposed by Turecek [5] to operate an advapix TPX3 as a single layer Compton camera. This eliminates the need for multiple detectors, which reduces costs and simplifies the setup.

The ARCHER platform in the current state makes use of a lightweight spectrometer to map a nuclear environment by repeating multiple measurements in a scanning pattern. However, using a Compton camera or a combined approach including both a CZT spectrometer and a Compton camera could highly optimise the time needed for the measurement process to localise hotspots. This paper focuses on the comparison of both approaches individually as the hybrid approach of combining CZT spectrometer with Compton camera will be researched in a later stadium in the project. Using a Compton camera on the ARCHER robotic platform to localise sources is compared to the currently used method of repeating measurements in a scanning pattern. Lab-scale tests were performed to evaluate the time needed to localise the sources for both methods.

II. METHODS AND MATERIALS

In order to compare A) measuring in a scanning pattern with B) using a Compton camera to localise sources, an **Epson c3a601s robotic arm** with **RC6+ controller** was used. In the current setup, the arm has a reach of about 40 cm by 20 cm with a maximum payload of 3 kg for the detector and mounting hardware. The same sources were used during the tests of both methods, a ^{137}Cs source with an activity of 168 kBq and a ^{60}Co source with an activity of 23 kBq.

A. Scanning pattern measurements

The detector used in the scanning setup was a **25S25 BriLanCe 380 $LaBr_3$ scintillator** connected to an **osprey multi-channel analyser** with an integrated power supply was used with a bias voltage of 650V.

To measure the different spectra, the commercial software **Genie gamma analysis and acquisition** was used. Different measuring times were used, with varying grid sizes of 100 mm by 100 mm, 50 mm by 50 mm and 25 mm by 25 mm. Table 1 shows the different settings used to perform the scanning measurements with the spectrometer. The listed heights correspond to the distances between the table surface and detector. This was done in natural background.

Table 1. Different configurations of measured grids with corresponding height, source and measuring time for each spectrum.

Test case	Total area	Grid size	Height	Source	Source location	Measuring time
nr	cm	mm	mm		mm,mm	s
1	40 x 20	100 x 100	100	^{241}Am	200,100	60
2	40 x 20	100 x 100	100	^{241}Am	250,150	60
3	40 x 20	100 x 100	50	^{241}Am	200,100	60
4	40 x 20	100 x 100	50	^{241}Am	250,150	60
5	40 x 20	100 x 100	100	^{137}Cs	200,100	60
6	40 x 20	100 x 100	100	^{137}Cs	250,150	60
7	40 x 20	100 x 100	50	^{137}Cs	200,100	60
8	40 x 20	100 x 100	50	^{137}Cs	250,150	60
9	40 x 20	100 x 100	100	^{137}Cs	250,150	5
10	40 x 20	100 x 100	100	^{137}Cs	250,150	10
11	40 x 20	100 x 100	50	^{137}Cs	250,150	5
12	40 x 20	100 x 100	50	^{137}Cs	250,150	10
13	40 x 20	50 x 50	50	^{137}Cs	250,150	5
14	40 x 20	50 x 50	50	^{137}Cs	250,150	10

After measuring a spectrum at a certain coordinate, the total counts were calculated. Also, the number of counts within 3 regions of interest (ROI) in the spectrum was calculated. These ROI's correspond to the energies emitted by ^{137}Cs, ^{60}Co and ^{241}Am. Next, the background spectrum of $LaBr_3$ was subtracted from the data and heatmaps were created using **SAGA gis geostatistics** software [6]. This software was used to interpolate the values of total counts and counts per ROI for each measuring point with the use of a thin-plate spline interpolation method with a cell size set to 1 mm. The expected location of the source was defined by the location of the maximum value in these heatmaps. The different configurations of measured grids will be evaluated on the accuracy of the source location and measurement time.

B. Compton camera

A single **advapix TPX3 detector** with 1000 µm CdTe semiconductor crystal was mounted on the Epson robotic arm. This detector will be used as a lightweight Compton camera which makes use of the Timepix3 readout chip. This chip has an event-based readout for a total of 65k pixels and can simultaneously register the time of arrival and energy for each pixel [7].

From a Compton event that is in coincidence with a photoelectric absorption, it is possible to reconstruct a cone that contains possible locations of the source. To do this, the following information is needed: the coordinates of the

Compton interaction, the coordinates of the photoelectric absorption and the energy of the incident gamma.

Depth reconstruction of coincident pixels and events was used to determine the depth across the z-axis between two coincident interactions. This was done by reconstructing the height based on the small difference in time of arrival for pixels where interactions occur at a different height, according to the method described by Bergmann et al. [8].

To be able to reconstruct the depth difference between two interactions, a correction for time-walk is necessary. Time-walk is an effect that results in a slower detection of arrival time for, lower energy pixels in a gamma camera and if not corrected, it will result in a wrong calculation of the z coordinates. The correction was performed according to the method proposed by Turecek by making a calibration, using the 59 keV gamma peak of ^{241}Am [9].

After applying this correction, adjacent pixels are grouped into clusters and the mean x, y and z values of the interactions were calculated. From these coordinates, the axis of each cone is calculated. After this, the opening angle of each cone is calculated from the energy of the two coincident interactions, according to the Compton formula. This results in cones where the surface of a cone represents all possible locations of the source. The cones where the total energy corresponds to the 662 keV gamma of ^{137}Cs are then summed and expressed in spherical coordinates. The location of the source is then defined at the intersection of these cones. Figure 2 shows a simplified illustration of the used method.

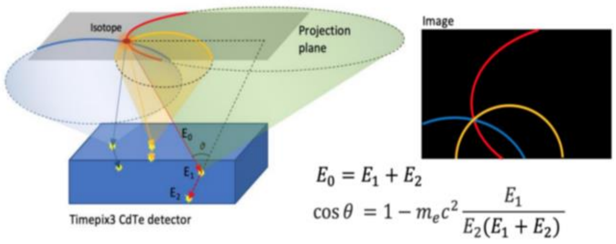

Figure 2. Illustration of the principle of reconstruction of a gamma source (left) with the reconstructed image of the Compton cones(right) [5]**.**

A ^{137}Cs source was used to simulate a hotspot and was placed on the table 10 cm below the detector and with a distance of 12 cm between the table surface and detector. Additionally, a ^{60}Co source was placed on the table to simulate an increased background.

III. RESULTS AND DISCUSSION

Measurements with point sources were performed with both discussed techniques and the same sources were used in both measurements.

A. Scanning pattern measurements

Table 2 shows the results of the errors made on the localisation of the measured test cases. When a grid size of 5 cm by 5 cm is used, ^{137}Cs sources can be localised with an accuracy up to 5.8 mm for the worst-case scenario, which is when a source is in the middle of four measuring points. It can be noted that when heatmaps are made based on the total number of counts in a spectrum, the achieved accuracy is generally higher. However, when the total number of counts is used, it is not possible to directly perform identification of the used sources, as is the case for heatmaps based on only the number of counts inside a ROI.

As expected, reducing the distance between measurements will improve the accuracy of retrieving the source, but this will also increase the time needed to scan the surface and manoeuvre the robot or robotic arm so a trade-off will be needed.

Table 2. Results of the localisation of point sources by using the scanning method with the $LaBr_3$ connected to osprey.

	nuclide energie thin-plate spline			Total counts thin-plate spline		
Test case	*Δx*	*Δy*	Δtotal	*Δx*	*Δy*	Δtotal
nr	mm	mm	mm	mm	mm	mm
1	0	0	0,0	1	0	1,0
2	0	3	3,0	1	3	3,2
3	0	0	0,0	0	0	0,0
4	6	-1	6,1	6	-1	6,1
5	1	0	1,0	1	0	1,0
6	9	-4	9,8	7	-4	8,1
7	0	0	0,0	0	0	0,0
8	9	-4	9,8	7	-4	8,1
9	2	16	16,1	3	7	7,6
10	-1	4	4,1	-1	4	4,1
11	9	-1	9,1	3	-5	5,8
12	6	-3	6,7	5	-2	5,4
13	1	-1	1,4	1	-1	1,4
14	1	-1	1,4	1	-1	1,4

Figure 3 shows the heatmap interpolated with the thin-plate spline method of test case number 8 where the source was located in the middle of 4 measuring points. The source was found on the green dot with an error of 8.1 mm compared to the actual source location. With a total of 15 measuring points of one minute and the movement of the robotic arm, it took about 25 minutes to complete this scan.

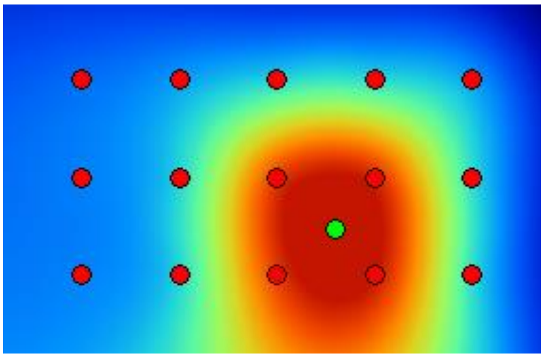

Figure 3. Interpolated heatmap based on the total counts of a ^{137}Cs source placed in the middle of four measuring points on a 10 cm by 10 cm scanning grid with a measuring time of 60 seconds. Red dots indicate the points where measurements are performed and the green dot indicates the estimated position of the source.

An additional measurement with two sources was performed to check the ability to distinguish multiple sources. This scan was performed with a grid size of 25 mm by 25 mm. The upper left source located on the table was a ^{60}Co source and the lower right source was a mixed source with ^{60}Co and ^{137}Cs. The measuring times for this grid were 60 seconds per measurement. This mixed source had an activity of 7.3 kBq for ^{60}Co and 9.1 kBq ^{137}Cs.

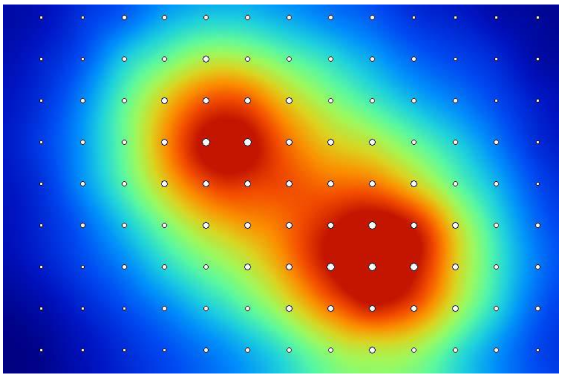

Figure 4. Measuring points and heatmap interpolated by thin-plate spline method of a 25 mm by 25 mm scanning grid with ^{60}Co and mixed ^{60}Co/ ^{137}Cs source.

Figure 4 shows the interpolated heatmap based on total counts for each measuring point. Two clear hotspots can be distinguished. However, it took several hours to complete this scan and map a surface of 40 cm by 20 cm.

B. Compton camera

The measurement with a measuring time of 15 minutes was performed to localise a ^{137}Cs source located at 10 cm below the detector with a detector to surface distance of 12 cm. A ^{60}Co source was used to simulate a background.

Figure 5 shows the reconstructed image where cones are accumulated in spherical coordinates. This reconstruction can then be used to localise the source. It can be seen that a hotspot is being identified at the location with a polar angle of 35 degrees.

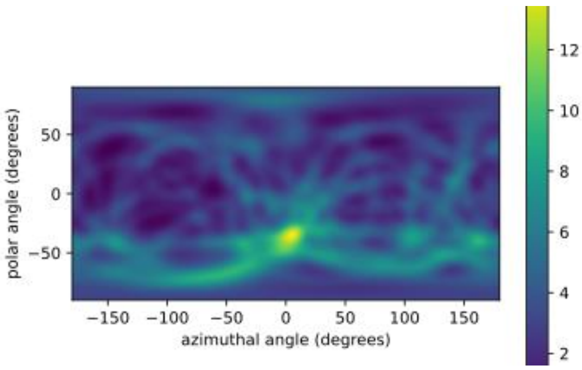

Figure 5. spherical back-projection of a 15-minute measurement with a detector to table distance of 12 cm. The colourmap represents an arbitrary unit that indicates the overlap between cones.

The algorithm in its current state was able to successfully localise ^{137}Cs without significant interference of ^{60}Co in the background. The Compton camera indicates the region where hotspots or sources are located without the need for movement of the robotic platform or manipulations of the robotic arm. However, one of the use cases of the ARCHER project is the characterisation of sources. Therefore, a combined approach where the Compton camera is used to indicate the region of the hotspots followed by a very local scanning pattern is suggested to optimise the time to localise hotspots and characterize this hotspot. The advantage of using a spectrometer for this local scanning is its better performance in the characterisation of the present radionuclides while limiting the time needed to localise sources by using the Compton camera.

IV. CONCLUSION AND FUTURE WORKS

Using a robotic arm to scan surfaces by performing measurements on multiple points proves to be a valuable approach to localise hotspots. However, it is time-consuming. Our experimental results demonstrated that a measurement of an area of 40 cm by 20 cm took 25 minutes (test case 8). In the current setup, when a 5 cm by 5 cm grid size is used, accuracy could be achieved of up to 5 mm to localise point sources.

The use of a Compton camera has been found to be an added value. The Compton camera reduces the time needed to localise hotspots compared to using the scanning approach with a spectrometer and limits the necessary movements of the robotic platform. It should, however, be noted that this paper only compares on measurement time. Future works will also include other factors such as sensitivity limits.

Both the methods for hotspot localisation will go into further development. For the approach of repeating spectrometric measurements in a scanning pattern, further research will focus on improving the necessary measurement times. For the Compton camera, developments will focus on improving its efficiency by optimising the used algorithm for reconstruction.

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