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Directionally-Sensitive Personal Wearable Radiation Dosimeter

Hai Huu Le, Paul Junor, Moshi Geso, Graeme O'Keefe

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Abstract**—**In this paper, the authors propose a personal wearable directionally-sensitive radiation dosimeter using multiple semiconductor CdZnTe detectors. The proposed dosimeter not only measures the real-time dose rate but also provide the direction of the radioactive source. A linear relationship between radioactive source direction and the radiation intensity measured by each detectors is established and an equation to determine the source direction is derived by the authors. The efficiency and accuracy of the proposed dosimeter is verified by simulation using Geant4 package. Results have indicated that in a measurement duration of about 7 seconds, the proposed dosimeter was able to estimate the direction of a 10μCi $^{137}_{55}Cs$ radioactive source to within 2 degrees.

Keywords**—**Dose rate, Geant4 package, radiation detectors, radioactive source direction.

I. INTRODUCTION

THE increasing worldwide use of radioactive sources has necessitates a dosemeter which not only detect their presence but also indicate their direction. An example of these attempts is a self-collimating BGO detector system [1] which is able to determine the direction of a 1mCi source placed 5m away from the detectors, with 10 degrees angular resolution using a 300 second measurement duration. Another approach was proposed in [2], using pixelated CZT arrays and coded mask apertures to detect and provide orientation information of radioactive sources. The result showed that a 2mCi source at 5m can be detected and localized with the accuracy of less than 3 degrees. In [3], a directional radiation detector based on an array of semiconductor detectors was presented, which can derive the source direction with the precision of 9 degrees by comparing the count rates measured at different detectors. Other systems using four scintillation detectors placed in a four-quadrant formation to localized radioactive source was proposed by Willis et al [4]. A fuzzy logic algorithm has been constructed to calculate the source position based on the relative measured signal intensity in the arrays of detectors. Simulation results have shown that the position of a radioactive source, placed 50cm away, can be determined with accuracy of less than 1 degree. In this work we aim at designing and fabricating a personal wearable directionally-sensitive radiation dosimeter using multiple semiconductor detectors which not only measure the dose rate but also indicate direction of the radioactive source based on the radiation intensity measured by each detector in the dosimeter. The configuration of proposed dosimeter, which includes 8 detectors (*D1* to *D8*) placed in a circle at the angle of 45 degrees, can be seen on Fig. 1.

The process of radioactive source direction estimation in our proposed dosimeter includes two steps:

- Determining the four detectors closest to the radioactive source in the detectors array.
- Calculating the direction of the radioactive source as the angle between source and the centre of the dosimeter.

In the proposed system, radioactive source direction is calculated directly from the measurement results using a simple and compact computational algorithm, easy to implement on small micro-controller which is best suited for personal wearable real-time dosimeter. Simulation has suggested that over a measurement duration of about 7 seconds, the proposed dosimeter can estimate the direction of a 10μCi $^{137}_{55}Cs$ radioactive source to within 2 degrees.

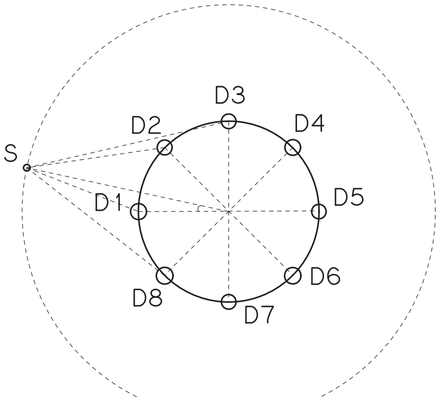

Fig. 1 Layout of the proposed dosimeter

II. DETERMINING FOUR CLOSEST DETECTORS TO THE SOURCE IN THE DETECTORS ARRAY

The four detectors closest to the source can be identified based on the number of interacting photons recorded in each detector in the array. After completing the measurement, the recorded number of interacting particles in each detector will be compared and the four detectors of highest reading are selected to be the closest detectors to the source. This can be explained further by an illustrative example shown in Fig. 1, with eight detectors from *D1* to *D8* of the array, the number of interacted particles from the sources S will be different. In this example detector *D1*, *D2*, *D3* and *D8* will record the highest number of interacted particles due to the closer distance from

H. H.Le and P. Junor are with the Department of Electronic Engineering, La Trobe University, Bundoora, VIC 3083, Australia (e-mail: h10le@students.latrobe.edu.au).

M. Geso is with School of Health and Biomedical Sciences, RMIT University, Bundoora, VIC 3083, Australia.

G. O'Keefe is with Centre for PET, Austin Health, Heidelberg, VIC 3084, Australia.

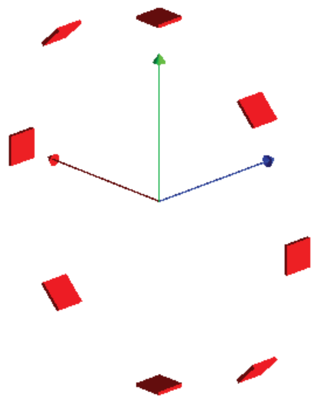

Fig. 2 Layout of the proposed dosimeter in Geant4

the source S to them in compare to other detectors. Therefore, *D1*, *D2*, *D3* and *D8* can be considered as four closest detectors.

III. ESTIMATING THE DIRECTION OF THE SOURCE

The source direction will be determined as the angle α which is created by the line from the source to the centre of the dosimeter with the horizontal axis of the dosimeter as show in Fig. 1.

Simulation using the Geant4 (**GE**ometry **AN**d **T**racking) package [5] have helped establish the relationship between radioactive source direction and radiation intensity measured by each detector. The detectors modelled were of 4cm x 4cm x 5mm size and made of CdZnTe. A detailed view of the dosimeter in simulation can be seen in Fig. 2.

CdZnTe compound semiconductors have been chosen due to their advantages over other traditional semiconductor material such as wider band gap (low background density), larger atomic numbers (high detection efficiency) [6] and battery power supply operation which satisfy a critical requirements of a wearable device.

Simulation was run with an isotropic point source emission of 2.5 million particles, equivalent to the dosimeter being irradiated by a 10μCi of $^{137}_{55}Cs$ source for about 7 seconds. This provided the closest detectors an adequate number of recorded particles between 2000 to 2500 counts. The source is placed 50cm away from the centre of the dosimeter (30cm away from each detector). Under simulation, the source was then moved from 0 to 45 degrees and measurements were taken at every 5 degrees in between. The results are displayed in Fig. 3.

As can be seen from Fig. 3, the number of collected hits in detectors 1(*D1*) and 8(*D8*) are decreased and increased in detectors 2 (*D2*) and 3 (*D3*) when the source angle α is increased from 0 to 45 degrees. It is due to the effect of changing in distant and angle of incident from the radioactive source to detectors. As the source move from 0 to 45 degrees we see that the distant and angle of incident from the source to detectors 1 and 8 are increased which lead to an decreasing in the number of the hits collected in those detectors and vice versa in detectors 2 and 3. If we take the average number of hits in two pairs of detector 1, 8 (*D18*) and 2, 3 (*D23*), we can see a linear relationship between source angle α and the number of collected hits in these pairs of detector as in Fig. 3. Based on that relationship, we can derive an equation to calculate the source angle α from the radiation intensity measured in four closest detectors as a linear function as show in (1).

$$\alpha = A(I_{18\_\alpha} - I_{23\_\alpha}) + B \tag{1}$$

Where:

$$I_{18\_\alpha} = \frac{I_{1\_\alpha} + I_{8\_\alpha}}{2} and I_{23\_\alpha} = \frac{I_{2\_\alpha} + I_{3\_\alpha}}{2} \tag{2}$$

And $I_{1\_\alpha}, I_{8\_\alpha}, I_{2\_\alpha}, I_{3\_\alpha}$ are the number of hits (radiation intensity) collected at detector 1,8,2,3 respectively when the source was at α degrees.

We know that, when source angle $\alpha = 22.5$ the average radiation intensity measured by two pairs of detector 1,8($I_{18\_22.5}$) and 2,3($I_{23\_22.5}$) should be equal. Apply that in to (1) we have:

$$22.5 = A(I_{18\_22.5} - I_{23\_22.5}) + B \tag{3}$$

Hence we got: B = 22.5 The constant A can be determined by calibration with the source angle α are 0, and 45 degrees.

$$0 = A_0(I_{18\_0} - I_{23\_0}) + 22.5 \tag{4}$$

$$A_0 = \frac{22.5}{I_{23\_0} - I_{18\_0}} \tag{5}$$

And:

$$45 = A_{45}(I_{18\_45} - I_{23\_45}) + 22.5 \tag{6}$$

$$A_{45} = \frac{22.5}{I_{18\_45} - I_{23\_45}} \tag{7}$$

Then:

$$A = \frac{A_0 + A_{45}}{2} \tag{8}$$

where $I_{18\_0}, I_{23\_0}, I_{18\_45}, I_{23\_45}$ are the average radiation intensity measured by two detector pairs 1,8 and 2,3 when the source angle α is 0 and 45 degrees respectively. Table I and Fig. 4 show a comparison between the real and estimation angle of the source achieve using proposed equation (1) when the radioactive source to detectors distant (STD) is 30cm.

In order to evaluate the efficiency and accuracy of the proposed dosimeter and algorithm, simulations were performed again with the STD is increased to 5m and 10m. To compensate for the longer STD distant, the dimension of the each detector is increased to 10cm x 5cm x 10mm with the number of emission particle are 555 million and 3.7 billion respectively which allow the closest detector to record between 1000 to 1500 particle hits. The results are consistent which can be seen on Fig. 5 and Table II. In both case, the radioactive source was estimated accurately within 2 degrees which have proved the efficiency, accuracy and robustness of the proposed dosimeter and algorithm.

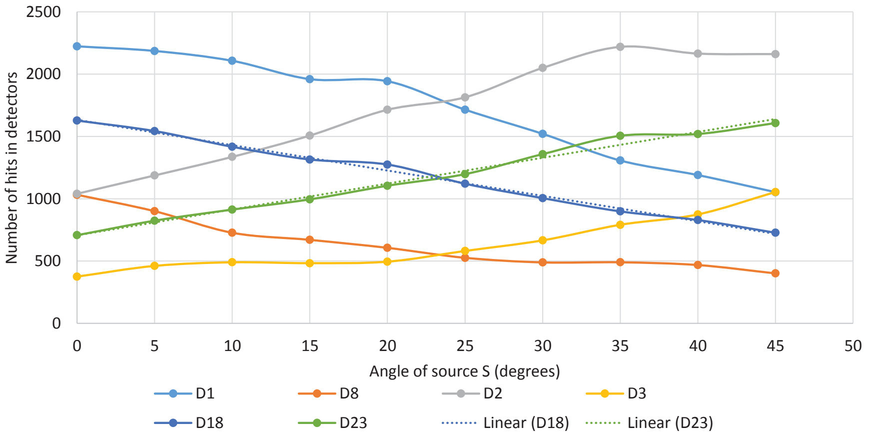

Fig. 3 Number of recorded interacted particles in detector 1, 2, 3 and 8 (STD = 30cm)

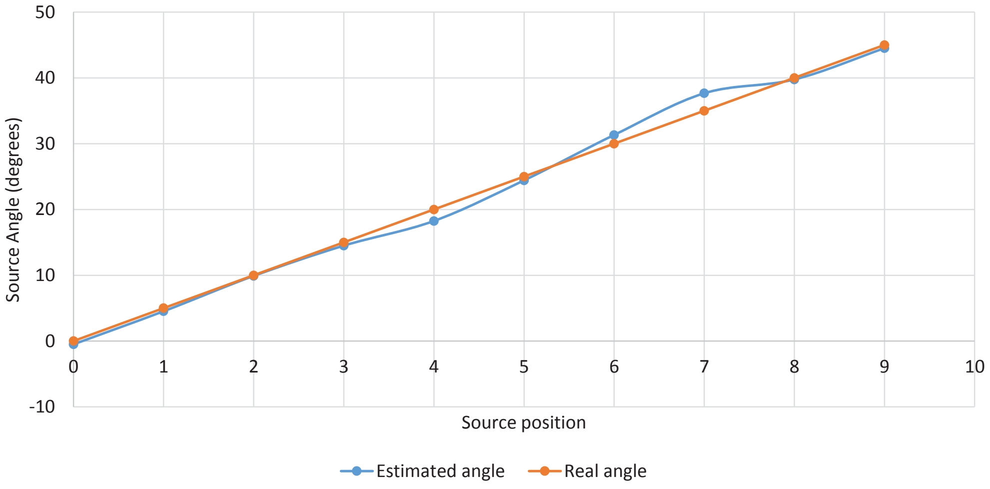

Fig. 4 Comparison between real and estimated source angle (STD = 30cm)

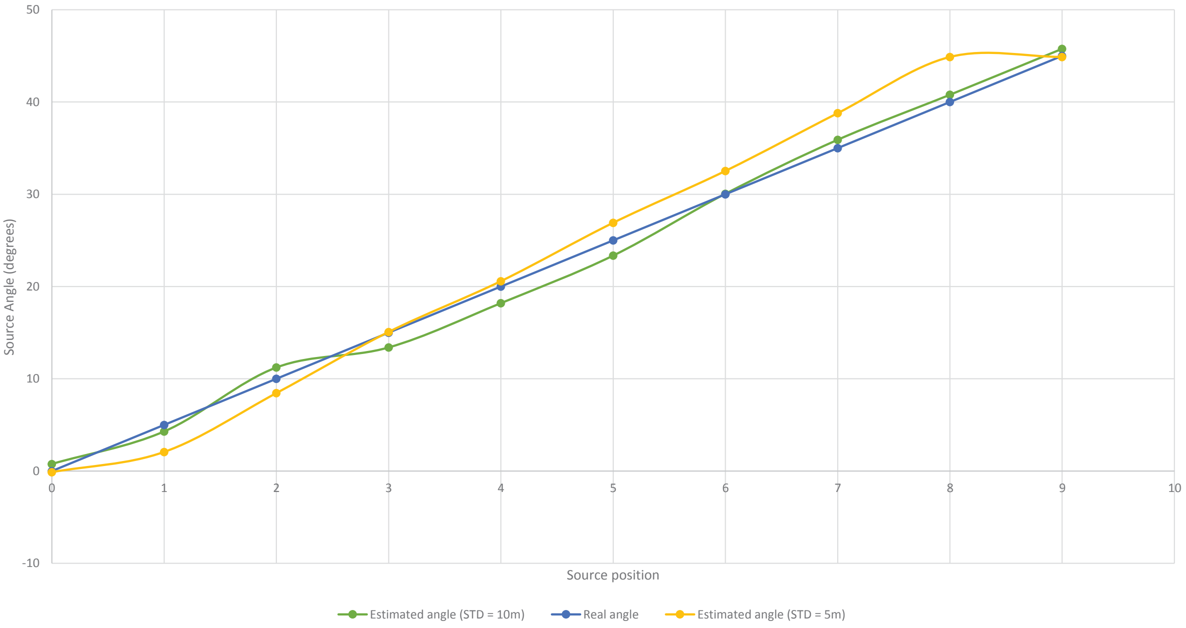

Fig. 5 Comparison between real and estimated source angle (STD = 5m and 10m)

TABLE I
REAL AND ESTIMATED ANGLE OF RADIOACTIVE SOURCE S (STD = 30CM)

Source position	Real angle (degrees)	Estimated angle (degrees)
0	0	-0.49
1	5	4.53
2	10	9.9
3	15	14.5
4	20	18.25
5	25	24.42
6	30	31.32
7	35	37.66
8	40	39.76
9	45	44.51

TABLE II
REAL AND ESTIMATED ANGLE OF RADIOACTIVE SOURCE S (STD = 5M AND 10M)

Source position	Real angle (degrees)	Estimated angle (STD=5m) (degrees)	Estimated angle (STD=10m) (degrees)
0	0	-0.12	0.77
1	5	2.07	4.29
2	10	8.45	11.23
3	15	15.08	13.4
4	20	20.58	18.2
5	25	26.91	23.35
6	30	32.53	30.05
7	35	38.79	35.9
8	40	44.08	40.79
9	45	44.83	45.77

IV. CONCLUSION

The proposed personal wearable dosimeter has shown some advantages over current directionally-sensitive dosimeters by providing a small, light-weight and mobile dosimeter satisfying both source direction estimation accuracy and short measurement duration requirements. Simulation results have indicated that the proposed dosimeter can estimate direction of a 10μCi $^{137}_{55}Cs$ radioactive source within 2 degrees.

In the proposed dosimeter, source direction is calculated directly from real-time measurement results which reduce the number of calibrations compare to other systems which use pre-determined data for source direction estimation. The algorithm, which is proposed to estimate source direction is simple, compact in computational, easy to implement on any available small micro-controller which is best suited for a real-time personal wearable dosimeter.

V. FUTURE WORK

The shielding effect of other objects (such as human body and other electronic parts of the dosimeter) when the dosimeter is worn under real-world operating conditions will be evaluated both by simulation and experimental test.

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