Directional Detection and Fissile Material Identification with the nFacet 3D detector

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Abstract

Source localisation is a critical point in nuclear safeguard and security, but it is currently an overlooked concept. Source search using counters is the standard method but is very time-consuming when the environment is complex or unknown. We introduce the nFacet 3D system, a portable gamma and neutron radiameter with directional capabilities, to fill the gap of directional detectors. We present here the results of the measurement campaign done at the STUK facility in Finland to assess the performance of the system in the field. In-field resolution below 5° for both ^{137}Cs and ^{60}Co at 5 and 10 meters away was demonstrated using machine learning techniques. High sensitivity to neutrons was shown, allowing long-range detection of a source at least 50 meters away, with possible detection up to 80 or 100 meters away. Gamma source separation capabilities were shown using energy window selection techniques, and good stability across variable environments in terms of count rates was demonstrated. The high angular resolution, with high detection range, gamma separation capabilities, and stability across the environment enables source localisation and detection on a large scale, making nFacet suitable for a wide range or security-related applications.

***Keywords* — neutron, gamma, direction, source localisation, machine learning, multimodal.**

I. Introduction

Source localisation in an unknown or critical environment, such as nuclear facilities, is a staple of nuclear safeguard and security. Checkpoints are set where flux control is essential, such as border crossings or restricted areas. Passive Radiation Portal Monitors (RPMs) are the historical technologies, prone to false alarms due to Naturally Occurring Radioactive Materials (NORMs) or tampering with high-activity sources nearby. After a trigger, localising the source is done by using handheld counters or droness but this procedure is time-consuming. Directional systems such as gamma cameras can be used to reduce the localisation time [2], but they have low efficiencies, especially for high energy gammas, limited field of view (FOV), and limited range. Due to the very nature of neutrons, very few systems like gamma cameras exist and suffer from the same limitations [6]. Some systems combine both radiation detection, achieving an integrated system [4]. Machine learning techniques are now used to increase the performance of reconstruction algorithms, improving the localisation capabilities of the system [7].

II. nFacet 3D

The detector technology introduced here, called nFacet3D, is a portable directional radiation monitor and dosimeter, capable of discriminating gamma rays, thermal and fast neutrons at the same time. The detector is composed of 4 modular detection units, each one composed of 16 active cells. Each detection cell is composed of a 5 cm PVT cube, for gamma detection and neutron moderation, and of a sheet of ^{6}LiF:ZnS(Ag) to capture thermal neutrons. Each detection unit reads the scintillation light through 8 silicon photomultipliers (SiPMs) with active temperature correction. The specifications of the system can be found in Table I, a mechanical drawing of the detector is shown in Fig. 1.

Table I
Specification of the nFacet3D system

nFacet 3D	Specifications
Modules	4
Channels per module	8 SiPMs
Scintillators per module	16 cubes
Gamma scintillator	PVT
Neutron scintillator	^{6}LiF:ZnS(Ag)
Field of View	4π
GARRn	1.019 at 10 mR/h
Autonomy	8 H
Weight	15 kg
Digitization rates	65 MHz
Acquisition mode	Waveform, Integration
Trigger	Amplitude, Time over threshold, Coincidence, Periodic
Saturation rates	10 kHz
Power draw	7 W
Connection	Ethernet
UI	Touchscreen

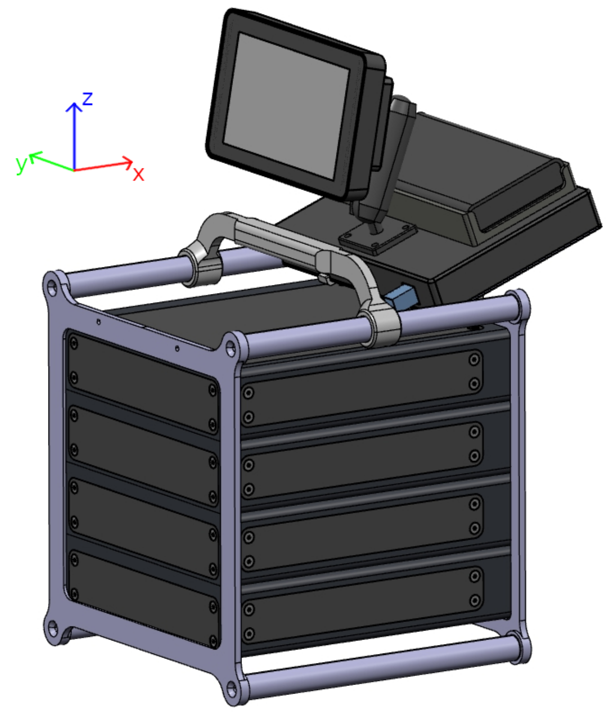


Fig. 1. nFacet 3D system CAD view.

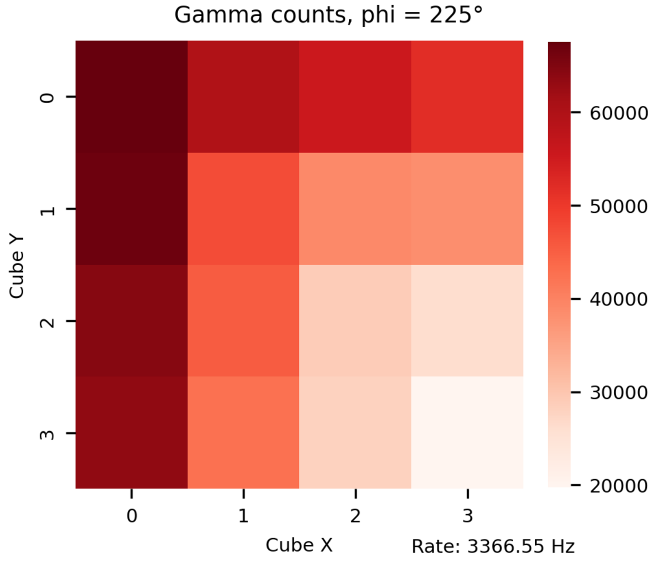


Fig. 2. Top view of the counts per cube, summed along the Z axis. A ^{60}Co source was placed in the direction of the detector's upper left corner of the figure.

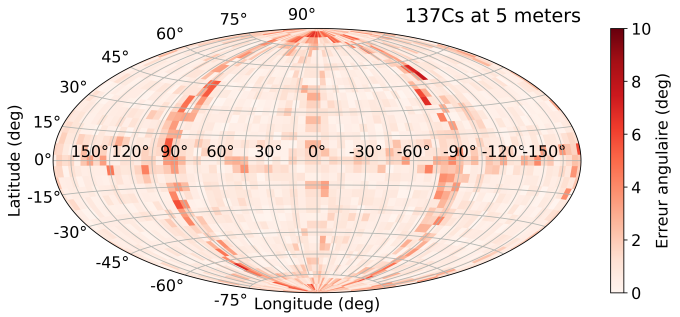


Fig. 3. Performance of a ^{137}Cs simulated source. The pattern comes from the symmetry planes of the cubic geometry of the nFacet system.

The segmentation of the system enables the reconstruction of the direction information during a measurement in all 4π angles. Fig. 2 shows the count rates in different cells of the detector summed along the Z axis with a ^{60}Co source located in the direction $\varphi = 225°$.

To infer the direction of the source, a fully connected neural net is used for its simplicity, lightweight design, and short inference time. The input of the model is the fraction of counts per cube and the output is the Cartesian direction vector. The task is a regression, using the AdamW [5] optimizer and the PReLU with a single parameter for the activation function.

The model was trained on a selection of 11 sources covering the energy range from 1 keV to 15 MeV. The isotopes ranged from ^{241}Am, ^{9}Be-based neutron sources to ^{252}Cf's fission gamma rays. The nuclear data were loaded from the International Atomic Energy Agency (IAEA) Livechart Data API [3]. The data includes both the gamma rays and the X-rays of the isotopes.

The positions of each source for the training set were homogeneously randomized in space, occupying the volume of a hollow sphere, with an internal radius of 1 meter and an external radius of 8 meters.

The position for the test set were generated at a distance of 5 meters and linearly disposed on ϑ and φ angles, with a step of 5°.

The performance of the pre-trained model is shown in Fig. 3 for a ^{137}Cs source. Each pixel represents the direction of a test source, and the color is the direct angle between the predicted direction and the true direction.

The patterns visible on the figure are from the planar symmetry of the cubic formation of the system. The worst-case scenario is perpendicular to a face, resulting in a 6° error. Along any X, Y, or Z plane, the performance is a little better but around the same 5° error value. The best-case scenario is around any corner of the system, which result in an error below 1° theoretically.

The model is then fine tuned with real data to improve the model's performance and learn the little variation of the detector real response.

III. Measurement

We participated in the SamLoc campaign held at the STUK facility, Finland. The objective of this campaign was to assess the capabilities of different technologies to localise a gamma source. Multiples measurements were made, with both neutrons and gamma rays, to assess different system capabilities, such as the angular resolution and the maximal detectable distance.

A. Angular resolution

For this, a 167.7 MBq ^{137}Cs and 77 MBq ^{60}Co gamma sources at 5 and 10 meters respectively were used in the

STUK's irradiation halls to determine the angular resolution of the system. The detector was manually turned around with a 22.5° step and the detector was vertically aligned with the source, fixing ϑ to 90°.

B. Maximal detectable distance

To determine the maximal detectable distance of a neutron source and assess the stability of the directional information over the distance, a 57 MBq ^{252}Cf, nominal activity of 500 MBq with a reference date of November 15 2016, was used outdoor on the STUK facility's parking lot. The distance was set from 3 to 50 meters away with a fixed approximate direction of $\vartheta = 90°$ and $\varphi = 180°$. The source was vertically aligned with the detector and the distance was measured with a ribbon tape of 50 meters length.

C. Spatial discrimination

During the outdoor measurement of the ^{252}Cf source, an unexpected ^{137}Cs source was inside the facility, waiting to be used, interfering with the gamma ray measurement of the neutron source. Exploiting that error, source separation in function of the energy and the relative intensity of each can be attempted. The ^{137}Cs source emit monoenergetic gamma rays of 662 keV, and the ^{252}Cf emits a continuous gamma ray spectrum from spontaneous fission, ranging from at least 100 keV to more than 20 MeV [8]. Using the source gamma signature, an energy selection can be done to isolate the higher source component.

D. Environmental stability

Finally, following the procedure in [1], done at the same facility, the effects of the environment on the count rate of nFacet were assessed in comparison to other technologies.

The objective was to assert the effect of the environment on the count rates for multiple technologies of passive neutron counters used in the nuclear weapon disarmament monitoring and verification process proposed by the International Partnership for Nuclear Disarmament Verification (IPNDV). The count rate as a function of the distance is modeled by (1).

$$R = \frac{A}{r^x} + B \tag{1}$$

Where R is the count rate, r the detector-source distance, and A, B, and x are the fitting parameters. Without scattering, the neutron count rates should follow an inverse square law, this model tries to take into account the neutron scattering from the environment, effectively reducing the power law of the equation. It's important to note that this model is non-physical, neutron scattering is nearly impossible to model and is one way to represent the scattering. The comparison will not be done on the value of the parameters but on the relative variation in different configurations.

Two indoor configurations and one outdoor were assessed. For the indoor configurations, one where the source is placed in the middle of the irradiation hall, limiting the backscattering and one where the source is placed 1 meter away from the back wall, increasing the scattering. The distance from the detector to the source was from 3 meters to 7 meters. The outdoor configuration result in little scattering, mostly from the air and the soil, the distance was set from 3 meters to 50 meters and reuse the same data acquired for the maximal detectable distance.

IV. Discussion and analysis

A. Angular resolution

The neural net model is used to predict the direction of the source for both ^{137}Cs and ^{60}Co, the background is scaled down to match the exact measurement time and removed from the counts of every cube. The latitude angle ϑ was every time very close to the correct value, 90°, the difference between the true φ angle and the predicted φ was computed.

The value and the error range are evaluated by resampling each cube count over a Poisson's law 100 times and computing the mean value and the dispersion of the φ angles of every prediction.

The result is shown in Fig. 4, in both cases, the uncertainty is below 5° with a confidence interval of 1, which is comparable or even better than typical gamma cameras at greater distances and with a 4π field of view [9].

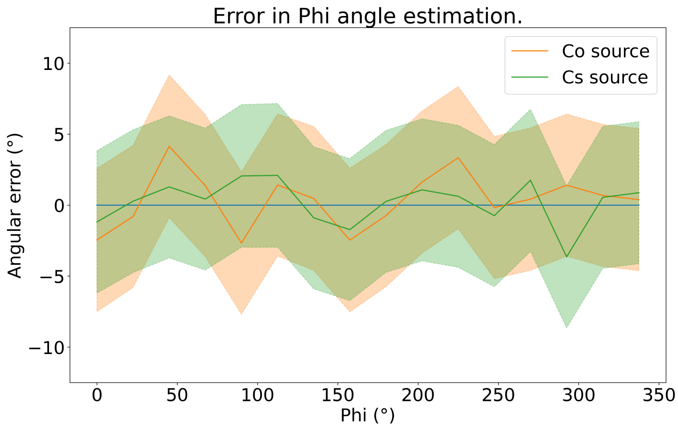


Fig. 4. Angular resolution for both ^{137}Cs and ^{60}Co sources.

B. Maximal detectable distance

The Signal over Background (SoB) is computed as (2), for no signals, the result will be 0. Following a similar equation as (1), (3) is used to fit the SoB over the distance, where A is the amplitude factor, r the distance, and x the power law. B is fixed to 0, forcing the equation to be null at infinity.

$$SoB = \frac{R_{measured} - R_{background}}{R_{background}} \tag{2}$$

$$SoB(r) = \frac{A}{r^x} \tag{3}$$

The SoB over the distance is shown in Fig. 5. At 50 meters, the SoB is still at 7, fitting with (3) and setting an

SoB threshold of 3, it appears the maximal detectable distance is 80 meters. Setting the SoB threshold to 2 increases the distance to 100 meters.

That high detectable distance can be explained by the skyshine effect, most of the neutrons are scattered in the air or the soil back to the detector, increasing the count rates. One other effect that can affect the count rates is the STUK's building. The detector was placed in the middle of the parking lot of the building at 11 and 16 meters from the walls, the configuration might have the effect of a satellite dish for neutrons, scattering back to the detector and thus increasing the count rates.

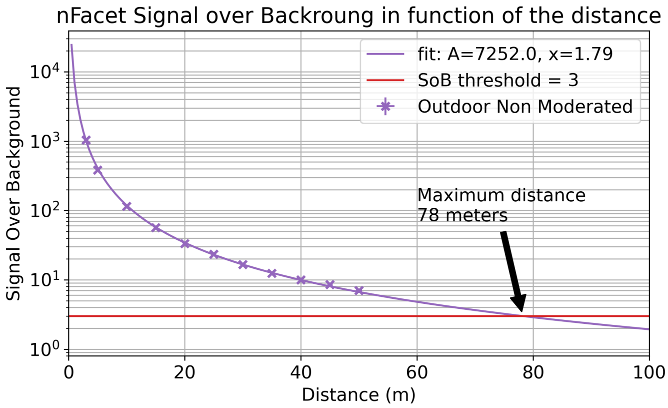


Fig. 5. Signal over background.

C. Spatial discrimination

Using the same data but looking at the gamma information instead of the neutron, the direction of the source was plotted as a function of the distance, in orange in Fig. 6. One should expect the prediction to be constant or worsen with the distance.

A shift of the direction from 180°, the correct value, to 320° can be observed after 10 meters. This shift represents the point the dominant gamma source swapped from the ^{252}Cf to the ^{137}Cs inside the facility.

A selection window in energy is applied to only keep the gamma rays that deposited more than 2 MeV in the detector. This selection has been done to select only the fission's gamma rays emitted by the ^{252}Cf source.

In Fig. 6, the green line shows the prediction of the direction for the fission's gamma rays only, the direction is close to the expected 180°, showing the effectiveness of the method. The variations and errors are due to the lower statistics of the measure, the intensity of these high-energy gamma rays decreases drastically the higher the energy is.

D. Environmental stability

The fits are done using (1) and the results are plotted in Fig. 7.

A few observations can be made across the 5 different configurations. The moderation of the source decreases the count rates, even if nFacet has a higher efficiency for thermal neutrons. This can be explained by the fact that

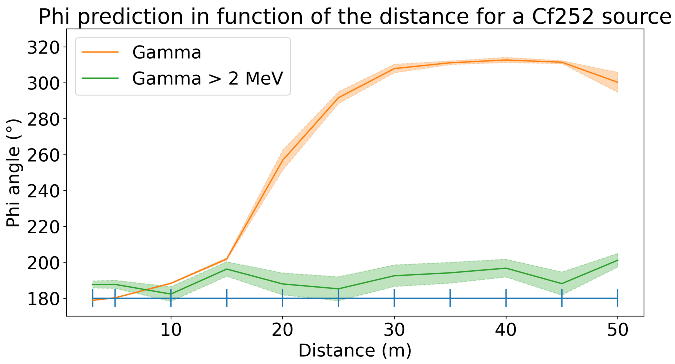


Fig. 6. Source direction in function of the distance. When applying an energy cut to only keep the fission's gamma from the ^{252}Cf source, a discrimination between the ^{137}Cs and the fission source is achieved.

thermal neutrons scattered are captured before reaching nFacet.

When the source is close to the wall, it increases the count rates. This is explained by the higher surface for the neutron to scatter back to nFacet, effectively increasing the neutron flux.

When in an outdoor configuration that approaches a low scattering factor, the count rate are at least a factor of 2 below the indoor configurations, which shows the impact of the environment when detecting neutrons.

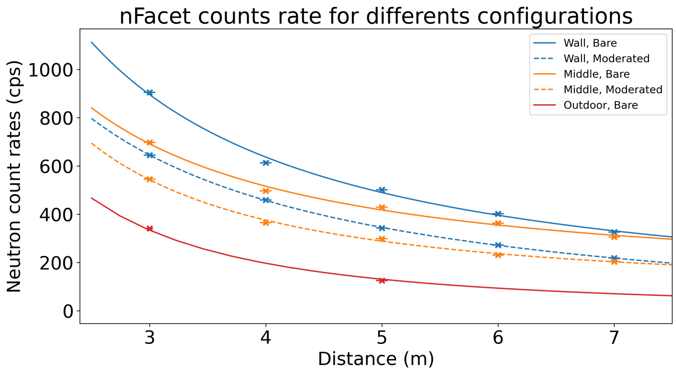
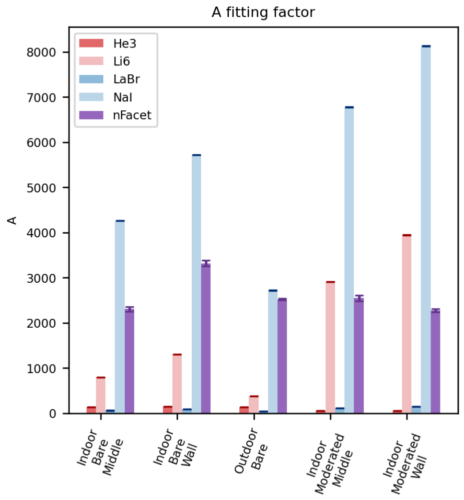


Fig. 7. Count rates as a function of the distance for all the configurations.

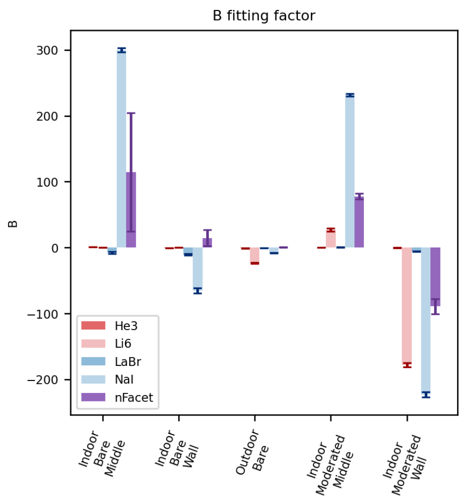
Looking at the fitting parameters, the variability can be compared to the ^{3}He counter, the reference. The A parameter, shown in Fig. 8a, representing the amplitude over a powered distance, is among the highest yet is the most stable in that category. The most stable is the reference ^{3}He but has a drastically lower efficiency. That's explained by the fact that nFacet is very sensitive to both thermal and fast neutrons.

In Fig. 8c, the x factor, the power law on the distance that represents the amount of neutron scattering, the closest to a value of 2 represents a detector little to not affected by neutrons backscattering. nFacet is the second best in stability, just behind the ^{3}He. It's notable to see that the x factor, in the case of the outdoor measurement, is very close to 2. It was unexpected to get such a high value in this configuration.

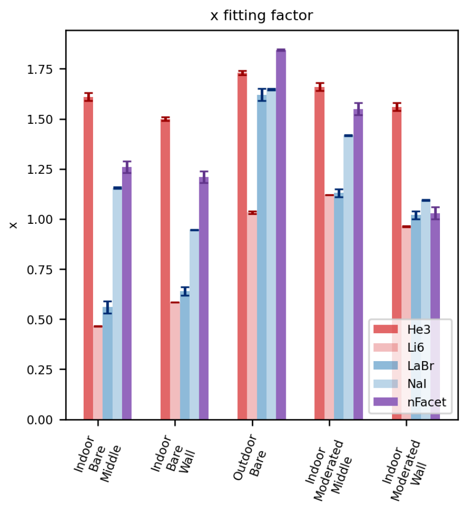
Finally, the B factor in Fig. 8b should be compatible with 0 if the model was realistic, since it's not the case it should be added to get better results.



(a) A parameter.



(b) B parameter.



(c) x parameter.

Fig. 8. Fitting parameters for different neutron counter technologies.

V. Conclusion

The in-field performances of the nFacet 3D system were shown across a wide range of parameters. Using the segmentation of the system with an IA model, the direction of a source can be accurately estimated, with an angular resolution below 5° for two standard gamma sources at greater distances than typical gamma cameras due to the system's high efficiency. Gamma source separation has been achieved using the energy window technique, separating a low-energy gamma ray source and a high-energy source. A great sensitivity for neutrons has been shown, detecting a neutron source at least 50 meters away and possibly reaching 80 or 100 meters. The stability of the system has been compared to reference ^{3}He proportional counter in the context of nuclear disarmament monitoring and verification processes, showing good stability across multiple configurations. All these parameter are needed for area monitoring and security, making the nFacet 3D system perfectly adapted to this field of applications.

VI. Acknowledgements

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