Timepix Radiation Detector for Autonomous Radiation Localization and Mapping by Micro Unmanned Vehicles

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Abstract—A system for measuring radiation intensity and for radiation mapping by a micro unmanned robot using the Timepix detector is presented in this paper. Timepix detectors are extremely small, but powerful 14×14 mm, 256×256 px CMOS hybrid pixel detectors, capable of measuring ionizing alpha, beta, gamma radiation, and heating ions. The detectors, developed at CERN, produce an image free of any digital noise thanks to per-pixel calibration and signal digitization. Traces of individual ionizing particles passing through the sensors can be resolved in the detector images. Particle type and energy estimates can be extracted automatically using machine learning algorithms. This opens unique possibilities in the task of flexible radiation detection by very small unmanned robotic platforms. The detectors are well suited for the use of mobile robots thanks to their small size, lightweight, and minimal power consumption. This sensor is especially appealing for micro aerial vehicles due to their high maneuverability, which can increase the range and resolution of such novel sensory system. We present a ROS-based readout software and real-time image processing pipeline and review options for 3-D localization of radiation sources using pixel detectors. The provided software supports off-the-shelf FITPix, USB Lite readout electronics with Timepix detectors.

I. INTRODUCTION

Before remotely controlled and autonomous mobile robots become available, human presence was required for any in situ measurement. Be it at the bottom of a sea or outside of the Earth’s atmosphere, sensing in unreachable places was impossible. Nowadays, terrestrial sensing is not short on utilizing robotic platforms in hazardous environments. Since the widespread of Unmanned Aerial Vehicles (UAVs), often called drones, much effort was directed towards creating flying platforms capable of sensing the environment [1]. Aircraft can traverse ground obstacles and move quickly to the desired location when compared to ground robots. Although, the presented system is designed for use with any mobile platform, including even satellites, where it was successfully deployed [2], [3], let us put this paper into the context of MAVs, with their highest applicability.

Micro Aerial Vehicles (MAVs) are small UAVs which can be handled by a single person. Multicopter helicopters are popular MAVs due to their simple construction and low maintenance. As the technology of small and intelligent aircraft became available, many fields started to utilize new options for carrying sensor equipment. Security and rescue forces utilize camera equipment and often thermal imaging cameras to assist ground forces during environmental disasters, such as earthquakes and floods [4], [5]. In research and science, unmanned aircraft have various roles, from testbeds for control algorithms to autonomous sensor carriers. This paper will focus on a novel sensor setups for autonomous ionizing radiation mapping and localization by UAVs.

Demand for UAV platforms capable of localizing an unknown radiation source is increasing. Early attempts to design a radiation detection module for a UAV was presented in [7]. Fixed-wing aircraft, equipped with Kromek 1 cm\textsuperscript{3} gamma-ray spectrometer, was used to scan legacy mines in England [6]. Area of the size of 300 m × 400 m was covered during the total of 5 hours of flight, and a radiation map was created ex-post. A solution suited for a search for compact sources of radiation was presented in [2], [7]. The system utilizes 5 cm\textsuperscript{3} scintillator with an air sampler, which takes measurement of counts per second in 1 s intervals. Authors tested that the aircraft can detect presence of \( ^{137} \text{Cs} \) (activity 2.3 GBq) and \( ^{60} \text{Co} \) (activity 1.1 GBq) from a distance up to 50 m, while flying at 70 km/h. The plane followed a path designed by a human operator. Another remotely controlled aircraft system is proposed in [8].

Since Fukushima Daiichi nuclear power plant (FDNPP) incident, research groups aim to prepare aircraft, that would remotely scan the affected area without endangering human workers [9], [10], [6], [11], [12], [13], [14]. Authors of [12] present an aerial solution equipped with two gamma-ray spectrometers. Data would be transmitted to a ground station over a data link during the flight. In [14] a multi-UAV approach was taken to enhance the potential yield of information gain from onboard sensors. Three formation types and trajectory schemes for three fixed-wing aircraft are proposed in a scenario with simulated sensor scanning. A multicopter MAV was used in [9] to carry lightweight CdZnTe Kromek spectrometer with 1 cm\textsuperscript{3} of detection material. Real-world experiments, situated in 20 m\textsuperscript{2} area, showed a process of creating a radiation map where several uranium samples were located. During the flight, the unmanned vehicle followed a flight plan with a set of waypoints. Scanning of 1 km\textsuperscript{2} area was also conducted using the Kromek detector, near FDNPP [10], [6]. The fixed-wing plane carried a laser rangefinder, which was later used to create a 3-D map of the radiation above the affected area. The plane was controlled remotely or flew according to a pre-fabricated flight plan.

A multitude of published work relies on Kromek spec-
trometer, which measures the counts per second, i.e., the number of ionizing particles that interacted with the detector [14], [9], [10], [6]. Others use scintillating detectors [11], [13]. Scintillators are large and heavy, compared to other sensors, and require a large aircraft. A 94 kg UAV conducted flights around FDNPP [11] and a radiation map of the area was estimated. The UAV was flying a preprogrammed path through waypoints. The only exhibit of an algorithmic approach to locating an unknown radiation source in real-time was presented in [13].

A. Detection of ionizing radiation

Ionizing radiation is imperceivable by the human senses. However, the effects of interaction of the radiation with matter can be measured. Processing of electrical and optical signals is common since the results can be obtained in real time in contrast to measuring the chemical effects of radiation.

1) Scintillating detectors: Scintillation is an effect of visible light production (luminescence) in transparent materials by the passage of an ionizing particle. The radiation excites electrons in the material that releases light in the visible/UV line spectrum. The light is gathered and measured using a photo-multiplier. Scintillating detectors were used on UAVs [2], [7], [11], [13]. However, due to their size and weight, their use is limited to large vehicles, e.g., unmanned airplanes.

2) Semiconductor pixel detectors: Ionizing radiation interacts in many ways with materials. Depending on the energy, X-ray photons can cause photoelectric effect, Compton scattering and electron-positron pair and triplet production. Charged particles interact directly by the Coulomb force. A piece of semiconductor material (a diode) is used directly as a sensor by convert newly produced electron-hole pairs to electric current. A single pin-diode is often made of Si, CdTe and GaAs and can be as large as 1 cm³.

A special class of a semiconductor detector is a pixel detector which is composed of a matrix of detectors. The Timepix detectors (figure [1], developed at CERN (European Organization for Nuclear Research) by the Medipix collaboration [15], [18] are low-powered pixel detectors, commonly used for medical imaging and radiography. Timepix uses a single piece of a semiconductor sensor material, which is bump-bonded to an ASIC (Application Specific Integrated Circuit) CMOS (Complementary Metal-Oxide Semiconductor) readout electronics. Each pixel is individually configured and calibrated to produce a signal only when the measured energy exceeds a pre-set threshold, which can be as low as 3 keV. The detector does not require cooling. Each pixel of the Timepix detector is an individual dosimeter, capable of measuring in one of three modes. In Time-over-Threshold (ToT) mode, the pixel integrates energy deposited in the pixel during the acquisition time. Time-of-Arrival (ToA) mode measures the time of the first over-the-threshold event to the CMOS ASIC chip.

Recently, a newer version of the Timepix detector was introduced, the Timepix3 [18]. In contrast with Timepix, which reads out complete frames regardless of the recorded information, Timepix3 is an event-driven camera. Event-driven cameras output a continuous stream of data that is generated by the active (hit) pixels. A similar trend emerged in the visible-light camera field [19]. Similarly, as in the case of event-based cameras that indicated a new research stream mainly related to micro aerial vehicles, Timepix3 promises a similar impact in the field of aerial radiation detection, as its key properties are perfectly suited for dynamically flying MAVs.

The power of Pixel detectors resides in the capability to show the type and direction of the incoming radiation. Similarly to a bubble chamber, particles leave different traces in the image depending on their type, energy, and direction. The information can be obtained onboard and in real time from the recorded data by methods of computer vision and machine learning. This requires completely new approaches to radiation mapping and source of radiation detection. The ability to estimate position and matter of the source of radiation in real-time enables to control MAVs and even groups of MAVs based on the obtained information. Agile movement towards the estimated source increases the gain of the sensors and enables to exploit the potential of Timepix sensor fully.
B. Contributions

We present a novel system for acquisition flexible online radiation mapping and dynamic localization of a radiation source using Timepix radiation detectors on Robot Operating System. We present a ROS-based interface to the detectors, which allows direct integration to various robotic platforms. We provide an open source package for interfacing common Timepix electronic boards. Moreover, we include a particle track classification pipeline, for estimating the observed type of radiation in real time. The proposed system is novel in its applicability onboard mobile robotics, which could not be done so far due to the lab-focused nature of the current control software for Timepix pixel detectors. The proposed unique combination of Timepix detector and mobile robots, especially flexible MAVs, significantly improves measuring capabilities of this novel sensor and enlarges application potential on mobile robots in radiation detection scenarios. The main objective of the paper is to offer this unique and fully functional tool for real-time onboard radiation measurement to the robotics community and to motivate consequent research in the fields of homeland security and nuclear disaster mitigation. To facilitate the initial steps of the research, we provide a model of the Timepix sensor for Gazebo simulator under ROS, which enables verification of robotic algorithms.

II. LOCALIZATION OF IONIZING RADIATION SOURCES

Localizing a radiation source can utilize several physical principles, that can yield information on the direction to the source. Unlike with visible light, ionizing radiation cannot be redirected by an optical lens. Heavy electrons and ions do not change their heading in matter as visible light does in glass. X-Ray photons exhibit reflective properties, which can be exploited in X-Ray reflective optics. However, the use of optics in the atmosphere is limited; the reflectance decreases with the increase in photon energy; however, only high energy photons can penetrate large portions of the atmosphere. Following paragraphs will provide an overview of different options of estimating direction to the radiation source with the use of Timepix detectors.

A. Intensity mapping and estimation

As with the event-counting detectors, Timepix can also be used to estimate the intensity of a source by measuring the particle flux. When the spectrum of the source is known or estimated on the fly, the event originating from the natural radiation background can be filtered by an image processing algorithm, e.g., the one presented in section III-A.

B. Pinhole camera aperture

As with the visible light camera, a pinhole aperture (figure 3a) is used to restrict the direction of an incoming particle to a specific point on the detector. This method works for both photons and charged particles and is especially useful for an environment with significant particle flux since the aperture shield blocks most of the incoming radiation [20]. An extension of the pinhole aperture is a coded mask. A deconvolution is then used to re-project the image using the mask’s point-spread function.

C. Multi-detector stack

Multiple Timepix detectors are combined in multi-detector setup by stacking them on top of each other (figure 3b) [21]. Coincidences in all detectors are extracted by synchronizing the ToA mode of the detector. Charged particles that intersect multiple detectors will leave tracks, which are matched and the path of the particle is reconstructed. Stacked detectors are useful for observing heavy ions and electrons that give a portion of their energy to each of the detectors while maintaining the original path.

D. X-Ray collimator

A collimator (figure 3c) performs similarly to the pinhole camera. Each place on a detector is dedicated to capturing information on particles in a particular direction. Collimators can have better angular resolution than pinhole apertures; however, their use on flying platforms is limited due to their significant mass. When the collimator has reflective surfaces in its inner tubes, an increase in gathering gain can be observed. Such collimators are called X-Ray optics, and they are often used in laboratory or space cameras [22], [23].

E. Compton effect camera

Compton camera [24] utilizes the Compton scattering effect, during which a photon is scattered in a scattering detector while producing a new electron. Both the scattered photon and the new electron are measured using two
where \( \theta \) is the speed of light in vacuum. A cone

\[
E_r (\theta, E_0) = \frac{E_\theta (\theta, E_0)}{E_0} = \frac{1}{1 + \frac{E_0}{m_e c^2} (1 - \cos \theta)},
\]

where \( E_\theta \) and \( E_0 \) are the energies of the scattered and incoming photon, \( \theta \in [-\pi, \pi] \) is the scattering angle, \( m_e \approx 9.10 \cdot 10^{-31} \) kg is the invariant mass of the electron, \( c \approx 2.99 \cdot 10^8 \) m s\(^{-1}\) is the speed of light in vacuum. A cone of possible directions to the source is constructed using the known coordinates of the events in the two detectors.

The intensity mapping approach using a single Timepix detector was simulated in Gazebo simulator as well as deployed given the currently available detectors and interfaces, see section V. The Compton effect camera is part of the prepared simulation plugin for the Gazebo simulator. However, the experimental hardware, which requires two Timepix3 detectors and powerful onboard processing of the data-driven detectors, is still in development. The approaches relying on detection of heavy ions were not simulated, due to their low applicability due to the high particle attenuation by the atmosphere. Nevertheless, the simulation model can be extended to include those types of radiation.

III. DETECTOR READOUT AND PROCESSING PIPELINE

Reading out data from Timepix requires providing power and low-level communication to the detector. Readout interfaces are electronics boards, which allow connecting the detector to a computer via USB or Ethernet. Interfaces such as the USB Lite [16] and FITPix [17] were developed for laboratory use, however, they can be utilized on a mobile robot as well. See figure 2 for showcase of the interfaces. The software Pixelman [25], which is licensed with the interfaces, is a graphical program that does not support work on a mobile robot or an MAV. For that reason, we proposed the Rospix software, which allows connecting USB Lite, FITPix and in the future Katherine interfaces to Robot Operating System.

The complete pipeline (figure 5) consists of the Timepix detector, which is mounted on or connected to a readout interface. The readout interface communicates with the onboard computer of the MAV via the Rospix [3] software. Unprocessed image frames are published to the ROS ecosystem, where they are picked up by the track classifier and acquisition time controller. Lastly, a radiation source state estimator uses the processed data and provides feedback for the MAV controller.

A. Particle track segmentation and classification

Connecting a detector interface into the ROS ecosystem is facilitated by the proposed Rospix software. Rospix configures the Timepix detectors and handles the measurement parameters such as exposure time, bias voltage, pixel equalization, and low-level analog signals. Controls of the connected detectors are provided using ROS services, and the measured data are presented via ROS topics. Rospix is designed to provide a robust connection to the hardware, even when the communication may be corrupted, which is a common theme on mobile robots. The commercial programs such as Pixelman or Pixet tend to work poorly in such conditions. The robustness was well tested during a suborbital rocket flight, where two FITPix devices were continuously measuring while connected to Odroid XU4 microcomputer [3].

Ionizing particles create characteristic tracks in the detector images. By classifying the tracks into geometric classes, we can estimate the type of radiation that caused them. Particle tracks classification can be done using the proprietary Pixelman software [25], however, only offline. Also, the solution [26] is too slow for dynamical and real-time use, and it requires a dedicated CUDA capable graphics card since it uses a neural network. Thus we propose and provide a particle track classification pipeline, which is capable of running in real time onboard a mobile robot.

The tracks are classified into the following basic classes (see figure 4), which are based on track geometry and morphology:

- **dot**: 1–2 active pixels (photons or fast electrons),
- **blob**: small-to-large clusters of pixels with higher energy pixels in the center (ions),
- **straight track**: straight or curly lines (electrons, high-energy ions under shallow angle),
- **drop**: elongated blobs with deltoid (drop-like) shape (low energy ions, protons).

The shape and size of the track is closely related to the form of interaction of the ionizing particle with the matter of the detector is influenced by the particle energy, the material of the detector and the measurement parameters, such as the voltage applied to the detection diode. The proposed classifier and classes were learned on data from Low-Earth orbiting dataset http://github.com/rospix/rospix.
orbit [2], recorded with 300 μm Si sensor, which provides very rich family of particle tracks. Thus the full list of classes contains also minor class variants: blob branched, blob small, blob big, track straight, track curly and track lowres. Further labeling into the actual physical particle types is very challenging and often requires additional information, e.g., prior knowledge of the radiation spectrum or the angle of incidence with the detector [27], [28].

The track classification is very challenging and often requires additional information, e.g., prior knowledge of the radiation spectrum or the angle of incidence with the detector [27], [28].

First, the image is segmented into the individual clusters (particle tracks). This process is straightforward if the amount of particles is low. The lack of any digital noise in the Timepix images implies that the tracks can be separated cleanly. However, the particle tracks can overlap during high event pileup. Rather than to solve this issue algorithmically which is challenging, we set the acquisition time in real-time to minimize this effect. Following features are extracted for the track classification:

1) Area and occupancy of a convex hull: occupancy is \( \alpha_{hull} = n_{active}/n_{hull} \), where \( n_{active} \) is the number of nonzero pixels of the track and \( n_{hull} \) is the number of pixels forming its convex hull.

2) Linearity: given the eigenvalues \( e_1, e_2 \) of the point cloud formed by the active pixels in the track, the linearity is defined as \( \text{linearity} = \max (e_1, e_2) / (e_1 + e_2) \).

3) Number of crossings: after skeletonization of the binarized particle cluster, the skeleton is converted to a graph, where each node represents a pixel, edges are created between 8-connected pixels. Cycles in the graph are removed, its edges are weighted (diagonal ones are penalized) and a minimum spanning tree (MST) is found. The sum of node degrees of the MST larger than 2 is the number of crossing in the trace.

4) Skeleton to hull area ratio (SKHR): The feature is calculated as \( SKHR = n_{skeleton}/n_{hull} \), where \( n_{skeleton} \) is the number of pixels of the cluster skeleton and \( n_{hull} \) is the number of pixels in its convex hull.

5) Tortuosity: the ratio \( t = l_{curve}/l_{ends} \) is a measure of a cureliness of a curve, where \( l_{curve} \) is the length of the curve and \( l_{ends} \) is the distance between its start and end. In our case, the longest path in the skeleton of the cluster is used to calculate tortuosity.

6) Distance transform measures: the mean and std. deviation of distances from each pixel to the edge of the cluster was used as features.

7) Boxiness: blob branched class often contains isolated clusters of pixels, which are connected with a thin line. Morphological erosion is applied to disconnect the clusters and the number of connected components in the pixel graph is the boxiness feature.

8) Foreground connectivity with background: three features, which represent the number of pixels that are facing the background with 1, 2 and three edges.

9) Diagonality and straightness: an image \( I_1 \) is created from the original image \( I_0 \) as \( I_1 = (I_0 - (I_0 \circ s_1)) \circ s_2 \). \( s_1 \) is structuring element for morphological opening, \( s_2 \) is structuring element with two horizontally and two diagonally placed pixels for straightness and diagonality respectively. \( s_2 \) is applied two times with different orientation to obtain features in arbitrary direction. The features are calculated by summing the pixels in the resulting images for both operations.

10) Basic features: area: number of nonzero pixels in the cluster, energy: sum of values of pixels in the cluster, energy per pixel: ratio of area and energy, energetic quartiles: lower decile, upper decile and median of energies of pixels in the cluster, width and height of the rectangular hull of the cluster.

Support Vector Machines (SVM), logistic regression and random forest classifiers were trained on human-labeled data using the previously defined features. Implementation of the classifiers relied on the Python scikit-learn library. After hyperparameter search (see table I) and evaluation, the random forest classifier was chosen after having the best Mathews Correlation Coefficient (MCC) on testing data set. The random forest performed with test MCC = 0.7905. It was followed by the support vector machine with MCC = 0.7689 and the logistic regression with MCC = 0.7438. The confusion matrix in figure 6 shows that the classifier performance is very good for particles of types Dot (0), Track small (1) and Blob big (2). The classifier often confuses classes Blob branched (3) and Track curly (5). However, Blob branched is not very common in terrestrial measurements, since it is caused by very high energy ions such as cosmic rays. The branching is caused by a complex interaction of the ion with the sensor while producing additional particles – delta electrons. The classes Drop and Track lowres are problematic since the training data set did not contain enough data. The particle classification pipeline is available in ROS as a Python scikit implementation.

Fig. 5: The diagram of the data pipeline with the FITPix USB interface, which can be used onboard a mobile robot.
IV. DETECTOR SIMULATION MODEL

Together with the Rospix driver, we provide a simulation package for the Gazebo-ROS simulator to facilitate research of MAV control and planning algorithms with this new sensory system in feedback. Ray tracing method was developed to simulate gamma rays and their interaction with simulated Pixel detectors. Our focus is in localizing weak radiation sources, located in greater distance (>50 m). It has an important implication on the expected incoming radiation since most of any potential ions and beta radiation would be blocked by the atmosphere. High energy gamma photons (>500 keV) still have a high chance to penetrate even hundreds of meters of air. Such radiation can originate from materials that are commonly used in proton therapy: $^{60}$Co, $^{137}$Cs and $^{90}$Sr, which can be possible lost and misused. Search for those sources is the main interest of homeland security departments and therefore motivates our research the most. We aim to develop the Compton camera specifically for MAVs. Photo-electric effect and the Compton scattering are the key effects in the Compton camera. Following sections present the simulation model used to model these effects in the detectors.

1) Differential cross section: The properties of non-elastic scattering from scattering center and particle collisions are described by a differential cross section. A total cross section characterizes an effective area of an event (collision, scattering). Let us have a particle on an incident trajectory with the scattering object. The impact parameter $b$ is the displacement of the particle from the path to the scattering center; the radial angle of scattering is denoted by $\theta$. The total area of the impact parameter is the impact cross section $\sigma$, which is obtained by integrating the impact parameter $b$ over all possible azimuthal angles $\phi$. In a case where the scattering is not a function of $\phi$ (axially symmetrical case), the impact cross section takes the form

$$\sigma (b) = \int_0^\phi b d\phi = \frac{b^2}{2} 2\pi = \pi b^2. \quad (2)$$

Such relaxation is viable for Compton scattering, since the scattering bodies (electrons) are spherically symmetrical objects. The differential of the impact cross section is

$$d\sigma (b) = \frac{\partial \sigma}{\partial b} db = 2\pi b db. \quad (3)$$

The solid angle on a unit sphere under the angle $\theta < \Theta$ is obtained by the integration:

$$\Omega (r, \Theta) = \int_0^\Theta 2\pi r^2 \cos \theta (r d\theta = 2\pi r^2 - 2\pi r^2 \cos \Theta. \quad (4)$$

The differential of the solid angle is

$$d\Omega (\theta) = -4\pi r \cos \theta dr + 4\pi r \sin \theta d\theta. \quad (5)$$

In the case of a unit sphere, the differential of the area is simplified to

$$d\Omega (\theta) = 2\pi r^2 \sin \theta d\theta. \quad (6)$$

The total cross section $\sigma$ is obtained by integrating the differential cross section over the area of a unit sphere:

$$\sigma = \int_\phi \frac{d\sigma}{d\Omega} d\Omega = \int_0^\phi \int_0^{2\pi} \frac{d\sigma}{d\Omega} \sin \theta d\theta d\phi. \quad (7)$$

The decrease of the intensity $d\Phi$ of an incident beam with original flux $\Phi \text{[s}^{-1}]$ is described as

$$\frac{d\Phi}{dz} = -n\sigma \Phi, \quad (8)$$

where $dz \text{[m]}$ is the thickness of the material, $n \text{[m}^{-3}]$ is the particle density of the material and $\sigma \text{[m}^2]$ is the total cross section of the interaction. By solving the differential equation, we obtain a relationship between the initial flux $\Phi$ and the remaining flux $\Phi_{out}$ behind the object with the thickness $z$:

$$\Phi_{out} = \Phi e^{-n\sigma z}. \quad (9)$$

**TABLE I:** Optimized parameters of random forest.

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<th>Part of the pipeline</th>
<th>Variants</th>
<th>Parameters</th>
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**Fig. 6:** Confusion matrix of the random forest classifier, generated with the use of 10-fold cross validation from testing part (25%) of the dataset.

**Fig. 7:** (a) Showcase of solid angle $d\Omega$ and the differential size of the impact plane $d\sigma$ for $\theta = 60$ deg and (b) the plots of likelihood $P(\theta | E_0)$, integrated over azimuthal angle $\phi$ for various energies.
The probability of an event \( (E) \) is modeled as

\[
P( E ) = 1 - e^{-n \sigma z}.
\] (10)

2) **Photoelectric effect**: Photoelectric effect describes a total absorption of a photon by an electron. A portion of the energy is responsible for releasing the electron from the atomic orbital; the rest is converted to kinetic energy of the electron. Photon energy can be expressed using its wavelength \( \lambda \) [m] or frequency \( \nu \) [Hz] as

\[
E_\gamma = \frac{hc}{\lambda} = h\nu,
\] (11)

where \( h \approx 6.62 \cdot 10^{-34} \text{ m}^2 \text{kg s}^{-1} \) is the Planck constant and \( c \approx 2.99 \cdot 10^8 \text{ m s}^{-1} \) is the speed of light in a vacuum. \( k = E_\gamma/E_c \) is the ratio between the photon energy \( E_\gamma = h\nu \text{[eV]} \) and the electron rest mass energy \( E_c = m_e c^2 \approx 5.11 \cdot 10^{-8} \text{ eV} \). According to [29], the simplified Gavrila-Pratt [30] cross section for the photoelectric effect is

\[
\sigma_{ph} = \frac{16}{3} \sqrt{2 \pi r_e^6 \alpha^4} Z^5 \frac{1}{k^5},
\] (12)

where \( r_e \approx 2.81 \cdot 10^{-15} \text{ m} \) is the classical electron radius, \( \alpha \approx 1/137.04 \) is the fine structure constant and \( Z \) is the atomic number of the element. The accuracy of (12) is relatively low even in the energy range, where it should be valid \((\approx 1 \text{ to } 1000 \text{ keV})\), since (12) expresses the cross section for a free electron, not an electron bound in an orbital. Attenuation coefficients from NASA NIST [31] can be interpolated and resampled to achieve better accuracy.

3) **Compton scattering**: Compton scattering occurs when a photon transfers a portion of its energy to an electron. During this interaction, the photon is deflected from its original path by the radial angle \( \theta \) and azimuthal angle \( \phi \). The Klein-Nishina formula [31] describes the differential cross section \( d\sigma/d\Omega \) [m\(^2\)/sr] for the incident and scattered beam:

\[
\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 E_r^2 \left( E_r + \frac{1}{E_r} - \sin^2 \theta \right),
\] (13)

where \( E_r \) is the Compton ratio \([1]\), \( r_e \approx 2.81 \cdot 10^{-15} \text{ m} \) is the classical electron radius. The prior probability of the scattering in a material with thickness \( z \) is computed as:

\[
P(E_{cs}) = 1 - e^{-n \sigma_{cs} z}.
\] (14)

However, as well as with the photoelectric effect, the accuracy of the prior is low, since the Klein-Nishina formula describes the cross section for a free electron. Empirical-based probability distributions should be used to obtain more precise results. The value of likelihood probability density for the event \( E_{cs} \) of a single photon with initial energy \( E_\alpha \) [eV] being scattered by the angle \( \theta \) is calculated as

\[
P(\theta \mid E_{cs}) = \int_{\Omega} \frac{2\pi}{\pi} \frac{d\sigma}{d\Omega} \sin \theta \, d\phi, \quad \frac{d\sigma}{d\Omega} = \frac{\sigma_{cs}}{\Omega},
\] (15)

where \( \sigma_{cs} \) is the total cross section for Compton scattering obtained from [12]. Figure 9 depicts an illustration of \( d\sigma/d\Omega \) and the likelihood of scattering by the angle \( \theta \) calculated for 1 mm of silicon for various energies.

V. EXPERIMENTS

Proof of concept experiments that showcase the Timepix detector on an MAV was conducted with \( ^{241}\text{Am} \) source with activity \( \approx 500 \text{ MBq} \). This radiation source produces gamma radiation with energy 59.5 keV. A small MAV was equipped with FITPix interface and Timepix detector with 300 \( \mu m \) Si sensor. The MAV was built upon the DJI F450 frame and equipped with Intel NUC i7 computer, and the FITPix was connected via USB. Robot Operating System control pipeline [32] was used to guide the MAV along a pre-planned trajectory while being localized by GPS and optic flow. Figure 9 shows the resulting radiation maps for photon events and for the radiation background, which was separated using the classifier. Data gathered during the experiment and the classification pipeline can be accessed at [http://mrs.felk.cvut.cz/iros2019timepix](http://mrs.felk.cvut.cz/iros2019timepix).

Fig. 9: Simulation of Compton camera which consists of two Timepix detectors. Possible directions to the radiation source are shown by semi-transparent cones originating from the pixels in the scattering detector.

![Compton camera simulation](http://physics.nist.gov/PhysRefData/FFast/html/form.html)

(a) 2-D map of X-Ray photon event count measured with the MAV. (b) 2-D map of natural background radiation event count.

Fig. 10: Photo of the autonomous MAV while mapping the radiation environment using the Timepix detector.
VI. CONCLUSIONS AND FUTURE WORK

We present a system based on Timepix detectors for real-time localization of radiation sources by a mobile robot. The proposed solution consists of the Rospix software interface for Robot Operating System. The solution includes a fast particle track classifier, which is a feature that was up to now part of proprietary laboratory software only. Mobile robots can use our system to perceive and interpret the measured data in real time including estimating the position of a source and the type of incoming radiation. We demonstrate the system in an experiment with a Micro Aerial Vehicle and 241Am radiation source. The Timepix sensor and the Compton effect camera assembly is provided in the form of a plugin for Gazebo-ROS simulator. Thanks to the onboard radiation data processing, the proposed pipeline will enable automatic control of MAVs with the radiation sensor in control feedback. This will allow fully autonomous localization of radiation sources thanks to the high mobility of the MAVs. Currently, our group focuses on the Compton camera principle for localizing weak gamma-ray sources using Timepix3 detectors. With this physical principle the concept should be sufficient for localization of faint compact gamma sources (tens of GBq) at a distance of approx 100 m.

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REFERENCES