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Remote Radio Isotope Identification Using Unmanned Aerial Vehicle

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Abstract. Remote radioisotope identification over terrains with suspected gamma radioactive contamination using unmanned aerial vehicles (UAV) has been explored. Selection of gamma detectors suitable for embedding in UAV have been discussed. Described are the approaches to creating a flight plan for a line and point model for data collection from the terrain and the techniques of gamma-radioactive contamination mapping. Test data from artificially generated radioactive contamination are presented and data collection techniques are described. Finally, a concrete example has been given for data processing and mapping of the supposed radioactive contamination. With a software tool analyzing generated spectrum, the radio isotopes have been recognized.

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1 Introduction

For exploring wide areas from the ground surface and the lower atmosphere – mapping, agriculture, natural disasters, accidents, wild life, population observation, vehicle traffic, water and air quality, local contaminations and many others, one of the most convenient method is airborne observation. To this wide range of activities, we can also add the evaluation of the radioactive on-ground contamination from the board of an aircraft.

If we know the location of a radioactive contamination on the ground, we can approach it with the proper measurement tools in order to evaluate it qualitatively and quantitatively. For the safety of the personal that will perform the measurement (on foot or from the board of a ground vehicle) the information of the type and the strength of the radiation is critical. This information can be predicted if we know the radionuclide composition of the contamination. Another useful information would be, even rough, quantitative evaluation of the activity and its distribution over the ground surface. In other words, if all the activity is concentrated in a point or spread wide in the area. In order to gather such information in advance for relatively large territories, the most convenient way is to fly-over with an aircraft (manned or unmanned), carrying spectrometric radiation detectors.

Gamma radiation is a deep penetrating ionizing radiation from wide range of natural or artificial sources and knowing its photon energy spectrum is a powerful method for monitoring and evaluation of the surrounding radiation. Exploration of the gamma radiation is performed from aircrafts, ground vehicles, on foot, in drillings, on the seabed and in samples taken to labs. The widest areas are covered from aircrafts and ground vehicles. A lot of national and regional organizations have been created and published detailed gamma-maps generated this way. Such standardized ground maps of the concentration of radiation and radioactive material, could be compared and united showing regional tendencies in radioactivity deviation and used for environmental radiation monitoring. This process is being driven by the International Atomic Agency (IAEA) [1–4].

Gamma mapping from airborne flight systems dates back decades. The most active in this mapping are the countries and organizations that explore wide and difficult to access territories (for example in Australia [5]). There is a lot of experience gained in Bulgaria, as well [6–9].

The idea of using UAV for gamma-mapping dates back shorter period of time – about 10–11 years. In the overview a detailed picture of this method is being created.

Actually, the fastest development of the idea was after the nuclear accident in Fukushima Daiichi Nuclear Power Plant in March 2011, and after that year the idea of measuring radiation in accidents from a distance using remote-control robots is being followed much more serious [10]. One kind of such robots is the UAV. They are being implemented successfully in gathering urgent information without life risk for the working specialists and at the same time can be used for regular measurements and mapping of local contaminations (as for the anomalies in the uranium mining in Czech Republic [11]). Gamma-radiation surveys with UAV can be provisionally divided into two categories: using airplane type and quadcopter type [12]. First type is being used for quick and rough measurements from 30–50 m height, and the second for more precise measurements from the height of up to 10 m, including for interior of buildings and other closed spaces.

In order to build gamma-map with a good resolution and at the same time, our method to be economically effective, we should find the balance between the required sensitivity and the parameters speed and height of the flight. Higher speed and higher height give us faster covering of the area, which saves flying time and we get the result sooner. To achieve this, we need detectors with higher sensitivity, which from other side increases their size and price. The balance could be achieved by solving a number of physics problems.

With the development of the UAVs the possibilities for airborne mapping are increased. To the UAVs group we can also add the small satellites, which could be used for monitoring the radiation situation through their orbit in the lower space (space-born remote sensing) [13, 14]. UAVs make it possible to observe territories hiding different risks and dangers, not only the radiation one, but also from any other type, without imperiling the aircraft crew, which is working from the ground. This advantage opens new perspectives as for the dosimetry as for the authorities handling emergencies.

In the current work we have shared our experience from the last year, related to the UAV application in remote gamma-spectrometry mapping. This includes analysis of the different gamma detectors, planning lab and field experiment with artificial radioactive contamination, creating flight plan, processing and analyzing the data and creating the map – gamma-spectrometry mapping. At the end, conclusions have been made, which can lead us to our future work in remote gamma-mapping with UAVs.

2 Second Joint Project between St. Kliment Ohridski University of Sofia, Faculty of Physics and Theta-Consult Ltd. for Gamma-Mapping Using UAV

In the beginning of 2017, a team of PhD students from Sofia University's Faculty of Physics, under the guidance of Assoc. Plamen Dankov from the department of Radio-physics and electronics started a new for its time project, focused in analyzing the possibilities for development of the distance methods for evaluation of the radiation environment over the ground surface – in open and closed spaces. This is the method for airborne gamma-mapping, which was relatively new subject for the project team. The members of the team have been participating in the first and still the only airborne gamma-mapping on relatively wide open area in Bulgarian territory with the use of pilotable flying vehicle [9, 15]. It was implemented by the Bulgarian company Theta-Consult Ltd. This was one very successful experiment, in which the achieved result is meaningful and useful in practice. This gives us hope that the development of the mentioned method could be continued in future.

The new in the project from 2017 was the use of quadcopter UAV, which required complete rethinking of the measurement setting, detectors that have been used, electronic schemes allowing remote measurements, gaining experience in creating effective flight plans. This is almost completely new approach in the implementation of the method of gamma-mapping.

As the first project for the team in this area, it is important with in solving several problems that can help the further research. On the first place this is the comparative analysis and selection of the proper gamma-detector and electronic scheme for measurement. This includes research, selection, laboratory (on- ground) experiments and analysis of the present and the available on the market equipment in relation to three important parameters – sensitivity of the detector, weight of the complete measurement system and electric power consumption efficiency. The next completed task is the investigation of the feasibility of the method for remote gamma-mapping with UAV for different terrains – on the filed in open area, in the mountains, in urban environment, in dense urban environment and inside buildings. This requires a new approach and a new technology in creating flight plan for the used UAV. Very important task was completing experiment for gamma-mapping on a small open area with a view to prove the method efficiency. This is experiment is relatively complicated and external experts have been involved as consultants about UAVs. At the end, the result from the research and the experimental work, has been summarized and the method was accepted as recommended for its relative inexpensiveness for small areas. The result also gave information about the method sensitivity and the experimental uncertainty. Some recommendations have been made for the future implementation of the method in practice.

In 2018, as a second project, started the work on completing an additional task. This is gamma spectrometry mapping. It includes execution of all the tasks from the previous project, but with spectrometry measurement equipment and with reading and analyzing of gained spectrums. The goal is building maps of the distribution of different radionuclides in the investigated area.

3 Comparison between Detectors Suitable for Integrating in UAV

This is the first important problem to be solved: comparison of the different gamma-detectors on three of their characteristics. In the comparison participates, not only the material from which the sensitive part is produced, but the fully operational measurement system. This includes the sensitive material (scintillator or another type), converter from light photons to electrical pulses (photomultiplier tube (PMT) or another type of light sensor), preamplifier, amplifier, pulse forming scheme, counting sorting and saving electronics and power supply unit including batteries.

The three parameters that are the most important for implementation of the detector system in UAV are: weight, sensitivity and power consumption. By its structure gas discharge detectors are relatively light weighted, but their sensitivity is pretty low and cannot provide energy discrimination. The sensitivity of the scintillating detectors depends on the size, density and the effective atomic number Z_{eff} of the scintillating material (the efficiency in the photo peak is proportional to Z^5). The classical PMT can provide high amplification, but it is made of glass, which is heavy and fragile. Before designing the detector system, a comparison between already manufactured systems assembled for handheld dosimetry devices, has been made, where the parameters like weight, efficiency

Table 1. Comparative table of the studied detectors

	Size, [mm]	Weight, [cps/μS/h]	Sensitivity, [g]	Type/Material
1.	1000 mm^3	60	1000	CZT
2.	$19 \times \phi 13$	40	210	CsI
3.	$25 \times \phi 25$	120	290	NaI
4.	$38 \times \phi 50$	550	1500	CsI+Li
5.	$63 \times \phi 63$	1400	4600	NaI(Tl)

and power consumption are also taken to a count.

According catalogue data, a scintillating (CsI(Tl)) detector has been chosen. For the first test flights we chose detector #2 (Table 1). Because of its good sensitivity, small size and relatively low price, its use would be profitable as long as spectrometry is not the main goal. For spectrometry measurements more appropriate would be detector #5, made of the same material (CsI(Tl)), but in bigger size, which makes it more sensitive. A small part of the detector is a crystal (^{6}Li), sensitive for neutrons. Its price is higher but it would worth with giving the ability to create gamma-spectrometry map and find neutron sources in just one flight.

Tight to each scintilating detector a PMT is attached, which requires mechanical protection of its glass body and stable high-voltage power supply (1 kV). As the power consumption of all the used PMT are pretty similar and the counting electronics is the same for all the detectors, the parameter "power consumption" is not included in the comparison. Another important parameter of a spectrometric system is its energy resolution. The CZT and CsI(Tl) detectors have better resolution than the recommended by IAEA NaI(Tl) crystals, which means that any choice from the compared detectors will not lack of resolution.

As seen from the curve in Figure 1, detector #1 is the best choice and it was used for the "total counts" experiment. For the "spectrometric" experiment it is better to use a detector with higher count rate in order to compensate the spreading of the pulses trough different channels [16]. The other three detectors (#3, #4, #5) show nearly linear regression and there is no best choice considering the weight efficiency. We exclude detector #1 for one main reason – its higher price exceeds the project budget and except from this, it is costly more effective to increase the UAV payload than using semiconductor spectrometer. Increasing the payload affects the price nearly exponentially and using the more expensive detector #5 and bigger UAV also overleaps the budget.

For the previous experiment just a counter was integrating the pulses in the full energy range, but in the current experiment a multichannel analyzer will store the pulses with different amplitude in separate channels creating the histogram called spectrum. The spectrum gathered in every second is stored in a SD card. To each record two other parameters are attached. One is GPS data and the other is the distance to the ground (measured with ultrasound device). In the remote radiation measurement, distance is very important for the calculation of the measured activity, because the CPS coming from certain activity are inverse proportional to the square of the distance.

Before it is mounted to the UAV, the system is tested in conditions similar to the real flight, with two sources ^{57}Co and ^{137}Cs. These radionuclides are two of the most commonly seen industrial nuclear sources. The on-ground tests proved the abilities of the system. It also gave us results for the optimal measurement distance and flight speed for certain MDA (minimum detectable activity).

In the next step, software simulator is used to calculate the scattering, attenuation and shielding by different obstacles on the radiation path between the contamination and the detector. The main software tool used is MicroShield, and RadPro is used for proving the results. The input parameters are three different flight heights, as for the shield it is considered the air at 50% humidity, pressure 950 hPa, and temperature 20°C. The most important calculation is the shielding by four different materials expected in the ground surface covering the contamination. There are four most commonly seen surfaces: grass, bushes, soil and sand. In order to input the density for the four materials to the software another experiment is accomplished. It includes measurement of the weight and volume of the samples in order to calculate their densities. The result from the software simulation showed that the shielding of each material is significant. This information is very important and it said that no shield should be used for the real flight, otherwise much bigger detector or much stronger source will be needed.

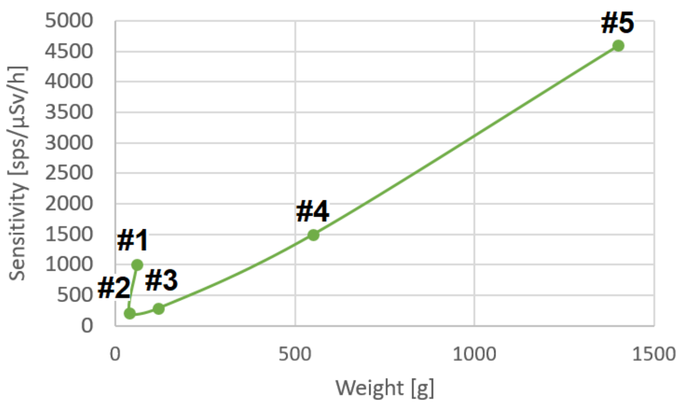

Figure 1. Graphical comparison between different detectors.

4 Accomplishing of the Test Flight with the Certain Gamma-Spectrometric System

For the current experiment UAF with four rotating wings is used (quadcopter). Its total lifting force of the four rotors is about 100 N. Its battery voltage is 22.2 VDC and 10 Ah capacity, which allows 10 min flight with the detector system on board.

Figure 2. UAV during calibration flight.

The explored terrain is the same as in the first experiment – 10×5 meters area from the car parking in front of the Physics Faculty building A. There is no vegetation and no obstacles higher than 15 cm, so it is easy to keep the flight height at 2 m. Anyway, the distance between the ground surface and the detector is precisely measured with the ultrasonic distance meter, because the GPS altitude and the geoid map of the earth do not provide good enough accuracy. As long as we do not have information about the contamination, we initially choose continuous distribution model. The flight plan should cover the whole area [17]. The profiles are parallel lines with distance of 2 m (the same as the flight height) between them. Typically, more than 60% of the signal comes from a circle on the ground with radius equal to the flight height [18]. We choose the distance to be reduced from 4 m (double the height) to 2 m as one of the methods providing higher resolution, caused by the overlapping between profiles. The horizontal speed of the flight is calculated on the base of the detector system integration time and the area to be observed. When the detector system is moving the observation area is an oval with shorter diameter equal to the profile distance and longer diameter equal to the sum of the shorter diameter and the distance traveled for one integration time. When we do not want the longer diameter to exceed the theoretically "seen" circle radius (2 m), the speed should not exceed 2 m/s.

Table 2. Measurement Raw-Data

Way-point	Latitude	Longitude	Count rate, [cps]	Distance, [m]
1	42.6736268	23.3302206	178	2.078
2	42.6736268	23.3302206	185	2.101
3	42.6736589	23.3301986	182	1.952
4	42.6736911	23.3301765	213	2.133
5	42.6737014	23.3301694	182	2.101
6	42.6737053	23.3301804	185	2.068
7	42.6737053	23.3301804	179	2.071
8	42.6736731	23.3302025	183	2.056
9	42.6736410	23.3302245	176	1.983
10	42.6736311	23.3302314	177	1.941
11	42.6736353	23.3302421	180	1.975
12	42.6736353	23.3302421	181	1.912
13	42.6736674	23.3302201	179	1.908
14	42.6736995	23.3301980	184	2.062
15	42.6737092	23.3301914	181	2.081
16	42.6737131	23.3302024	182	2.054
17	42.6737131	23.3302024	179	2.201
18	42.6736809	23.3302245	180	2.253
19	42.6736488	23.3302465	204	2.223
20	42.6736395	23.3302529	183	2.183
21	42.6736438	23.3302637	179	2.230
22	42.6736438	23.3302637	183	2.169
23	42.6736759	23.3302416	182	1.982
24	42.6737080	23.3302196	179	2.109
25	42.6737170	23.3302134	181	2.002

The average measured background on the site is 0.079 μSv/h. On the first look such a background would cause:

$$0.079\ \mu\text{Sv/h} \times 1500\ \text{cps/}(\mu\text{Sv/h}) = 118.5\ \text{cps} \tag{1}$$

using the equation:

$$I = eD\,, \tag{2}$$

where I is the counting speed in cps (counts per second); e – efficiency of the detector in cps/(μSv/h) for ^{137}Cs; D – dose rate in μSv/h. in the chosen detector (detector 5, Table 1). The real background gamma photons are with energies different from the energy spectrum of ^{137}Cs and that is why in the real measurement the counts are slightly different. The average count rate is 181 cps and the statistical uncertainty would be 13.45 cps using the equation

$$\text{MDA} = \sqrt{\text{BKG}}\,, \tag{3}$$

where MDA is the minimum detectable activity (MDA) in cps; BKG – background counting speed in cps.

In this manner we cannot achieve MDA less than 13.45 cps, which is equal to $\sim$ 0.009 μSv/h. In other words, in order to be able to detect the test source it should generate dose rate equal to at least 0.009 μSv/h at the distance of 2 m (the height of the flight).

As seen from Table 2 and Figure 3(b), (waypoints 4 and 19), the counts in the detector, when flying above the sources, are around 209 cps total and around 28 cps net value. This is around two times the MDA, which means it is sure enough that the detector is able to find the source with a good certainty. On the spectrum histogram with integration time of 1 second the 28 count are not only in one peak but also spread wide on the left of the Compton edge. This makes nuclide recognition not a very easy task. Most of the software tools might not do the job and will need more statistics, especially if the source is not a mono-nuclide with one single photo-peak. That is why in any case if a ground contamination is found, it is worth to waste a little more flying time on radionuclide recognition.

In our experiment we chose to perform a second flight directly to the places with the contamination in order to hang the UAV there for a longer integration time. The criteria for a longer time is on the basis of the certainty that is required for the source recognition on the number and type of radionuclides found. If there are many peaks from different radionuclides covering each other, then much longer integration time is needed. In general, it is not possible to completely predict the radio-nuclide contents, but in practice there are many cases in which this is partially possible. The criteria that we choose is 10000 counts totally in the spectrum. With our test source the time will be $10000/209 = 48$ s. We are also able to lower the UAV more near the contamination, but there is a risk of literally blowing out the source and even contaminate the UAV if the radioactivity is on a bulk material. For the second flight after we have initial information it is possible to avoid that problem using different techniques as hanging the detector on a rope under the UAV, increasing the distance between the propellers and the ground surface.

Before the second flight we insert the recorded data from the first flight into Microsoft Excel or similar software for quick analysis. The result is a graph showing the points with highest contamination. From a certain waypoint we can also open one-second spectrum to roughly define the energy of the radionuclide on the ground if the counts are enough.

5 Generating the Gamma-Map

For generating the map, we used two different software tools. First one is 3D Maps from Microsoft Office (Figure 3(a,b)) and the second one is ArcGis (Figure 4). The first one is very easy to use but lacks the variety of useful tools the second one offers [19]. In order to create a map giving more accurate information it is important to choose the model that fits best the contamination.

For the first flight we usually do not have much information and best model is continuous model in which we assume that the contamination is continuously distributed. After we have some basic information about the distribution of the radioactivity we can choose the best model. The three most common models are continuous, point source and linear model (for contaminated rivers, open or pipe channels). The difference of the other models is the shape of the contaminated object.

In our experiment we use two point sources and point source model.

(a)

(b)

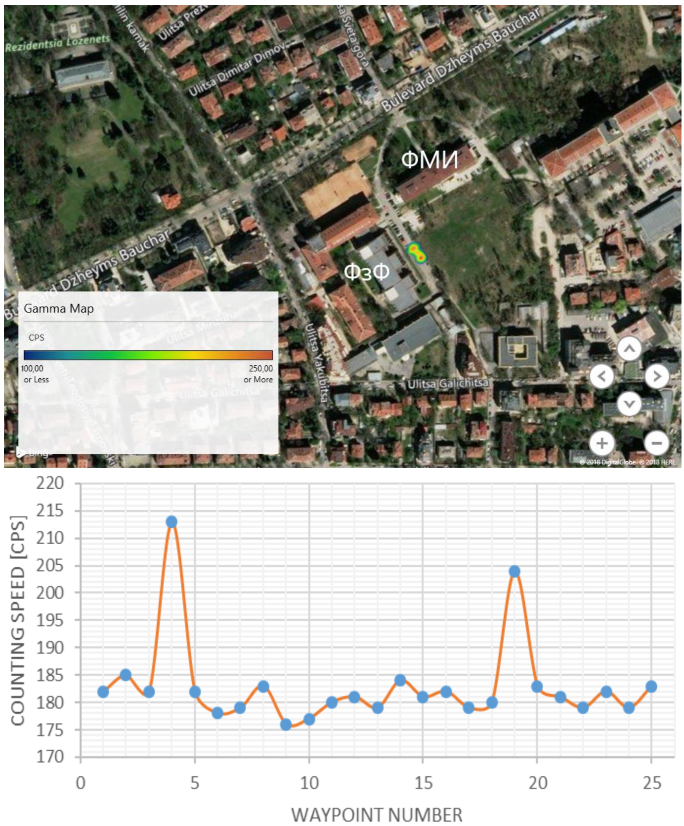

Figure 3. Initial determining of the contamination distribution: (a) using Microsoft 3D Map; and (b) a simple Excel graph.

6 Conclusion and Future Plans

As a second research in the series the current project confirms that using UAV in gamma-mapping gives almost all the functionality of the mapping with pilotable

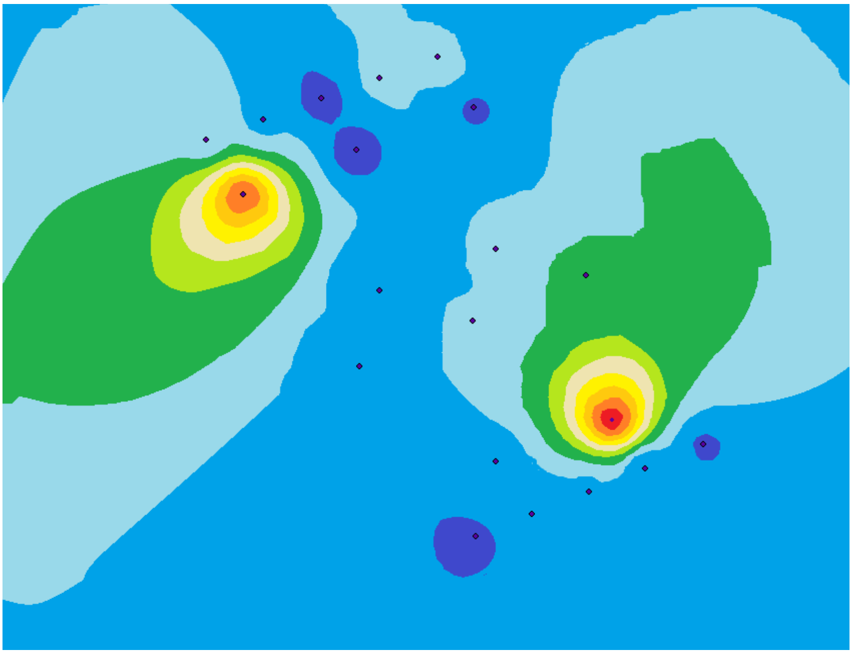

Figure 4. Gamma-map generated using ArcGis software.

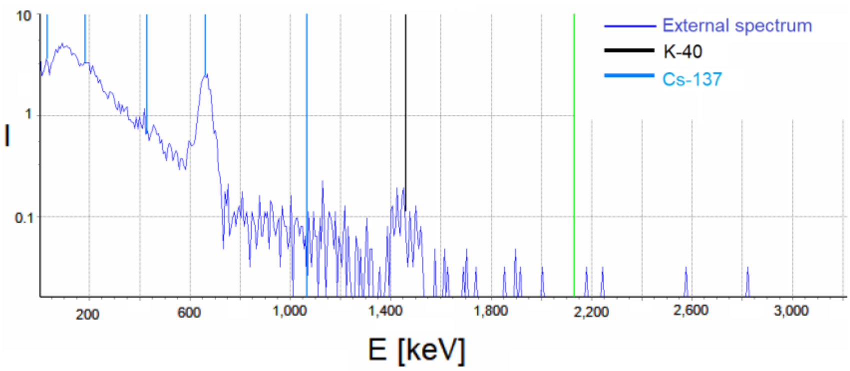

Figure 5. Spectrum integrated for 1 minute hanging over the most significant contamination spot. The SMI software recognizes presence of NORM and Cs-137.

aircraft and adds additional flexibility. It includes precise and close hanging, good speed control and cheap air-time. The best benefit of the UAV would be met in closed space and in areas with a lot of objects that need to be measured from different sides. The most important benefit is that no human is exposed to risk during the measurement, especially in nuclear accidents.

During the experiment we found, that most of the software tools for mapping are not adapted to such a small scale. Also, the maps created from satellite pictures does not give enough details on the terrain and are not created at the real time of the measurement. For the future research it is better to use different software and pictures taken from the board of the UAV at the time of the measurement. The pictures will also help in choosing the proper distribution model visually determining the radioactive source shape. The height of the flight or the distance between the object and the detector is also critical for activity calculations. In our experiment the ultrasound method for measuring the distance gave usable results only for distance up to about 4 m. such a distance is enough for searching but might not be enough for measuring very high activity when the distance to the source should be longer to prevent overloading the counting electronics. The better option is to use LIDAR which could be also used for creating a 3D map of the terrain and could also be used for navigation in closed spaces.

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