Journal of civil engineering and transport **transEngin**

2024, Volume **6** Number **4** **ISSN 2658-1698, e-ISSN 2658-2120**

DOI: 10.24136/tren.2024.015

Overview of the use of Light Detection and Ranging and Ground Penetrating Radar implemented on an Unmanned Aerial Vehicle

Mateusz **Nowak** [1,*], Bartłomiej **Flis** [2], Maciej **Andrzejewski** [3]

[1] Poznan University of Technology, Faculty of Civil and Transport Engineering, Piotrowo 3, 60-965 Poznań, Poland, mateusz.s.nowak@put.poznan.pl, https://orcid.org/0000-0003-1966-0423

[2] Poznan University of Technology, Faculty of Civil and Transport Engineering, Piotrowo 3, 60-965 Poznań, Poland, bartlomiej.flis@student.put.poznan.pl, https://orcid.org/0009-0001-5891-1806

[3] Association of rail transport experts and managers, Trębacka 4, 00-074 Warszawa, Poland, m.andrzejewski@seim-tsz.pl, https://orcid.org/0000-0003-2400-4017

* Corresponding author

Reviewed positively: 12.12.2024

Information about quoting an article:
Nowak M., Flis B., Andrzejewski M. (2024). Overview of the use of Light Detection and Ranging and Ground Penetrating Radar implemented on an Unmanned Aerial Vehicle. Journal of civil engineering and transport. 6(4), 27-37, ISSN 2658-1698, e-ISSN 2658-2120, DOI: 10.24136/tren.2024.015

Abstract – Currently, there is a rapid increase in interest in unmanned aerial vehicles (UAVs). These devices can be used as platform for carrying various sensors, often enabling access to hard-to-reach areas using traditional, ground-based methods. Very popular sensors used in non-invasive search work include Light Detection and Ranging (LiDAR) and Ground Penetrating Radar (GPR). The combination of the above sensors with UAVs is becoming increasingly common, which provides many benefits in many areas, such as archaeology, forensics, agriculture, rescue, terrain mapping, or landmine detection. This article is a synthetic review of the principle of operation and the use of technologies such as LiDAR and GPR, as well as their use on unmanned flying platforms. Issues related to the use of these sensors on various UAV configurations and the resulting conditions of work are discussed. The differences between LiDAR and GPR are also discussed, as well as the possible analysis of the examined area using both technologies to obtain the best effect. The implementation of these non-invasive search methods is not a threat to traditional searches in the form of excavations, but only a method preceding invasive research. Thanks to such an innovative approach, the effectiveness of such work is increased by narrowing the excavations area.

Key words – Ground Penetrating Radar (GPR), Light Detection and Ranging (LiDAR), unmanned aerial vehicle (UAV)

JEL Classification – R14, Q19, Q54

Introduction

With the development of unmanned aerial vehicles (UAVs), their wide range of applications for various missions has been appreciated. Currently, these vehicles are used in civil and military applications. In a fixed-wing configuration, they can be used over long distances (e.g. monitoring borders or monitoring high-voltage lines), and in the form of multi-rotor aircraft, they can operate over shorter distances (e.g. monitoring a limited area, performing geodetic measurements) and use the possibility of hovering to collect specific measurement data.

Nowadays, unmanned aerial vehicles carry not only video cameras, but also thermal, night vision, multispectral cameras, as well as LiDAR (Light Detection and Ranging) or GPR (Ground Penetrating Radar) sensors. In addition, it is possible to carry warfare agents in military applications or plant protection products in agricultural applications. In the latter case, unmanned aerial vehicles are particularly useful, performing work in the field known as precision agriculture, thus enabling the return of aircraft to modern agriculture [1], which is supported by modern requirements in the field of environmental protection [2].

The growth in interest in unmanned aerial vehicles is very large. According to a report prepared by The Insight Partners, the value of the global drone market in 2022 was USD 22.91 billion, while in the years 2022-2028 it is forecasted to increase to USD 73.91 billion. This means an average annual growth of

21.6% [3]. As presented in this short introduction, the range of applications of unmanned aerial vehicles is very wide and it would be difficult to analyze in this work all areas of activity of unmanned aerial vehicles. For this reason, the authors will focus on the use of sensors such as LiDAR or GPR in unmanned aerial vehicle missions, which are used very often in practice. Of the above sensors, LiDAR in particular has a very wide civil and military application. In the civilian scope, LiDAR is used in agricultural work [4-5], search and rescue operations [6], environmental mapping [7-8], disaster response [9], autonomous vehicles [10-11], law enforcement [12], powerline inspection [13-14], archeological surveys [15-16], meteorological research [17-18], wildlife conservation [19-20], while in the military applications these may include: military reconnaissance [21-22], anti-terrorism [23], electronic warfare [24-25], mine detection [26-27]. As for GPR, it also has many applications, in particular it is suitable for searching for elements located under the surface of the ground, pavement, wall, such as mine detection or archaeological research [26, 28-29].

Often, work carried out using modern non-invasive methods is supplemented by research conducted using other sensors. Sometimes, work using LiDAR is supplemented by use of the data obtained with GPR. This aspect is also cited in this work.

The aim of the study was to present these two techniques of non-invasive search techniques, like LiDAR and GPR, point their application area, the advantages and disadvantages in different tasks, when the sensors are used on the UAV platforms.

1. LiDAR

LiDAR is a device consisting of two basic components – a laser and a scanner. The laser sends very short, precisely measured and strong pulses of light with a given wavelength. These pulses are dispersed along the way. The scanner, which is part of the device, records the reflected beams as well as the differences in time and wavelength of the received beam. At the same time, the time of return of the reflected beam from the device is measured, which, combined with information on the time of sending the beam and after making the necessary calculations, allows for the precise calculation of the distance of the device from the tested object. The detector also allows the recording of the laser light in the entire field of view, which allows for the creation of point clouds. As a result, LiDAR can create a spatial (3D) image of the tested object.

Typically, the LiDAR module is equipped with a GPS module (cheaper solutions can use data borrowed from the object on which the LiDAR module is mounted), allowing its position in space to be determined, which increases the accuracy of measurements. Such a solution, used in e.g. robotics and automation, allows for precise control of vehicle or robot movements.

The sensor discussed in this paragraph is currently produced in two versions of the available field of view: omnidirectional sensors and sensors with a set constant field of observation. The omnidirectional version is often used in, for example, autonomous vehicles, in order to ensure the safety of the passage or to create a spatial scan of the surroundings. LiDAR modules are available in a wide price range, which starts from about 30 EUR [30-31]. An example of a LiDAR system module is shown in Figure 1.

The creation of point clouds by LiDAR sensor is preceded by the analysis of return data provided in three formats [33-34]:

- discrete return - the most popular format, recording the first object that the laser pulse encounters, suitable for terrain mapping tasks and creating 3D models of examined objects,
- multiple return - the scanner records all possible points that reflect the laser pulse, this mode offers precise information on vegetation layers and complex structures being examined,
- full waveform - records the complete shape of the reflected laser pulse, enabling advanced analysis of shape properties and even allowing analysis of the material composition.

An example point cloud obtained using the LiDAR module is shown in Figure 2. Using the appropriate measurement technique, it is possible to map the surface of a forested area, despite partial obscuration by tree crowns. Sometimes, however, this requires scanning the area twice with different settings of the scanning head in relation to the surface being examined. This type of situation can be observed in Figure 2, where, apart from the tree outlines, all the unevenness of the terrain is visible.

LiDAR mounted on a UAV (usually a multirotor) is used in many research and industrial fields, e.g. in the energy sector, it allows for the assessment of the distance from power lines of nearby vegetation and facilitates the decision on its possible removal [14]. In forestry, the mentioned device can be used to calculate the number of trees, their height and location in space [35]. In combination with multi- or hyperspectral cameras, LiDAR allows for the assessment of the condition of plants in agriculture, e.g. in the health of cultivated olive trees [36] or for estimating the harvest of a given crop [37]. Of course, not all applications of LiDAR have been listed, because this aspect is beyond the scope of this article.

Fig. 1. Example of a LiDAR module with a range of up to 40 m [32]

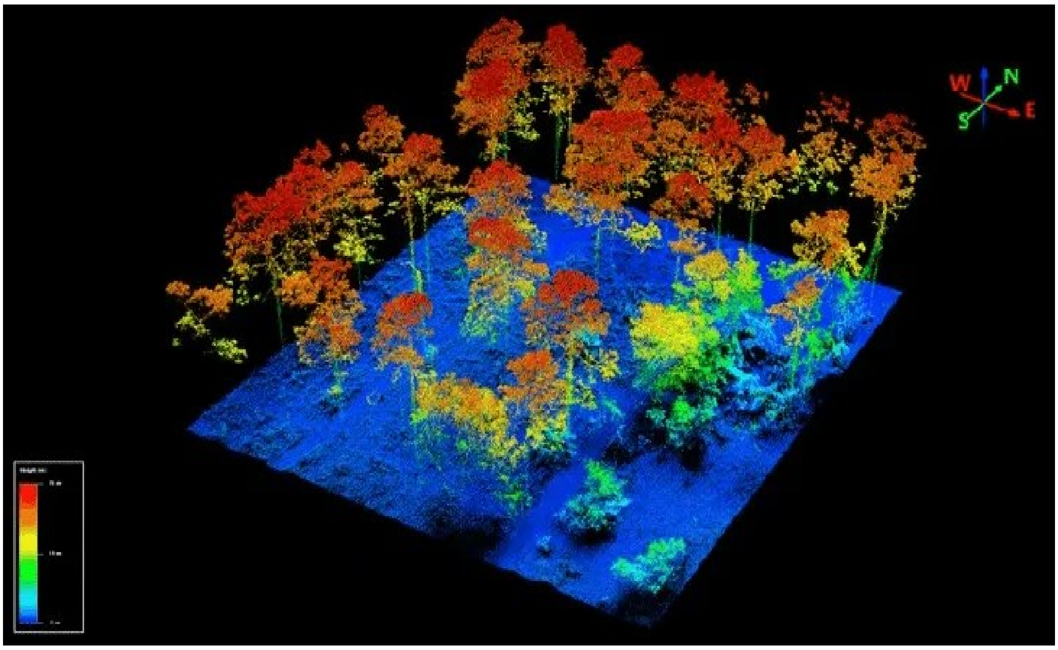

Fig. 2. An example of the LiDAR point cloud for use in forestry [33]

An interesting fact is that the entire area of Poland is scanned using a LiDAR system mounted on an aircraft. This data is available through the geoportal.gov.pl website. The density of the available point cloud ranges from 4 points/m^2 to 20 points/m^2 [38]. The aforementioned website provides a preview of the material and simple analyses (Fig. 3). While for hobby purposes the density of the point cloud in cities seems sufficient, an attempt to undertake archaeological analyses at a density of 4 points/m^2 is impossible. In such a case, it will be necessary to conduct dedicated research – e.g. using an UAV equipped with LiDAR sensor.

The LiDAR sensor is widely used in many fields. Every task has its own specific requirements, which should be taken into account during measurements. In Table 1, there are advantages and disadvantages for the use of LiDAR sensor on UAV platforms in selected applications.

Fig. 3. An example LiDAR data preview, available on the geoportal.pl website [38]

Table 1. Advantages and disadvantages of using LiDAR on UAV for selected applications [4, 9, 14, 16, 19, 20, 26]

Application	Advantage	Disadvantage
Agriculture	- Wide range of application of this solution in agriculture (leaf area, canopy volume, crop growth, crop damage, soil properties, etc.) - Collecting data from the air does not destroy the crops - Enables day and night operation	- Need some experience to choose the parameters (higher accuracy declines the field of view, which leads to lower efficiency of data collection) - Limited operation in fog conditions
Archeology	- Enables to scan large areas - Can detect small changes in the ground structure and potentially covered objects	- Require high density digital terrain models - Does not scan below the ground surface
Disaster response	- Enables to prepare accurate terrain surface map of a large area in high resolution - Provide 3D information to analyze the damage of different objects (trees, buildings, etc.) - Can analyze areas, which are difficult to reach or dangerous	- Does not enable do look under the surface
Landmine detection	- Can detect landmines in metallic and nonmetallic cases - Easy to scan large areas - Enables the work in wide range of weather conditions during the day or night	- Limited operation in fog or on in highly vegetated area - Not possible to scan the area below the ground surface
Military reconnaissance	- Enables to prepare accurate 3D map of terrain and location of enemy forces and equipment - Using an UAV it possible to map the terrain periodically	- Difficult to use, when the enemy has effective anti-UAV system
Wildlife conservation	- 3D landscape information (canopy height, canopy cover, woody debris, tree density) - Surface maps can be incorporated into species-specific habitat models	- Sometimes to build accurate predictive species habitat models, the LiDAR data needs to be combined with multispectral image data

2. GPR

GPR is a special example of a radar, the antenna of which is directed towards the ground or other surface. Its antenna transmits a regular sequence of pulses of low-power electromagnetic energy towards the ground and then reads the weak signal that has been reflected from a ground object. The transmitted electromagnetic energy takes one of the following forms: a very short period pulse, a scan over a certain frequency range, noise radiation in a given band, or a pseudo-random coded sequence of many pulses. Most GPR systems operate in a given frequency range from 10 MHz to 10 GHz and have a bandwidth of several GHz [39]. Example characteristics of GPR systems in relation to soil are presented in Table 2. If analysis needs to be performed deeper below the surface of the ground, a lower frequency GPR system will need to be selected, but at the same time the resolution will be increased, so it will not be possible to search for small objects.

Table 2. Characteristics of GPR systems in relation to soil with relative electrical permittivity at the level of 9 [39]

Pulse duration [ns]	**Main frequency** [MHz]	**Range** [m]	**Resolution**[1] [m]
0.5	2000	<0,25	0,025
1	1000	<0,5	0,05
2	500	<1	0,1
4	250	<2	0,2
8	125	<4	0,4
16	63	<8	0,8
32	31	<16	1,6

[1] Resolution is characterized as the detection of a square-shaped object with the edge length given in the table row

GPR devices are mainly divided into two types. Systems that transmit a pulse and receive a signal reflected from an object in the ground using a sampling receiver are classified as time domain radars. On the other hand, GPRs that transmit a signal on a single frequency, but in a sequential manner (changing between a given frequency range) and receive the reflected signal using a frequency conversion receiver are included to the group operating in the frequency domain.

GPR can probe the subsurface for elements made of not only conductive materials but also dielectrics. This phenomenon was implemented in 1926 by Richard Hulsenbeck. A buried object can therefore be a conductor, a dielectric or a combination of both. The material surrounding the subsurface object can be earth/soil, wood, rocks, water or ice, as well as man-made materials such as concrete [39-40].

GPRs are installed in a significant number of cases (we are talking about aviation applications as a general concept; GPRs are often installed on special carts-platforms) on multirotor UAV platforms (Fig. 4). Their physical dimensions are not too large, and the weight of such a device does not exceed 1 kg (often the device weighs 300-500 g), so it fits the payload characteristics of many commercial, readily available multirotor platforms [40]. An example image of an UAV during flight with a GPR module is shown in Figure 5.

The GPR device, installed on a multirotor UAV, is used for example to detect objects that lie on the surface or just under a thin layer of the substrate. In addition, they are used to detect water pipes, sewage pipes or gas transmission lines, e.g. during construction or operational works [41]. An example of the signal obtained from the GPR module during the location of pipes made of metal and non-metal materials is shown in Figure 6. It can be easily noticed that the signal when detecting metal pipes is higher than in the case of non-metal materials. This requires appropriate experience in the analysis of images obtained using GPR.

Another application is snowpack analysis; it provides information on depth, density and layering, which translates into information crucial for the safety of equipment and people in the mountains or on ski slopes. Until now, an expert was needed to manually dig out a sample of individual snow layers [43].

The research has shown that the GPR system implemented on a multirotor platform can successfully perform the soil moisture mapping mission. Additionally, it does not damage vegetation and leaves no traces on the ground; it also allows for the examination of hard-to-reach areas, which further increases the time-cost effectiveness of such research.

Due to the characteristics of this particular type of radar, it is used to search for military mines. It allows for the detection of mines made of metal and non-metallic materials. Additionally, there is a very low probability of detonating such a mine, while the probability of its detection is high. Studies have shown that if the total composition of the landmine contains 30% of conductive material, the probability of detecting the mine is about 80% if it is buried up to 20 cm below the ground surface [40].

Fig. 4. An example of the GPR system installed on a multirotor UAV platform [40]

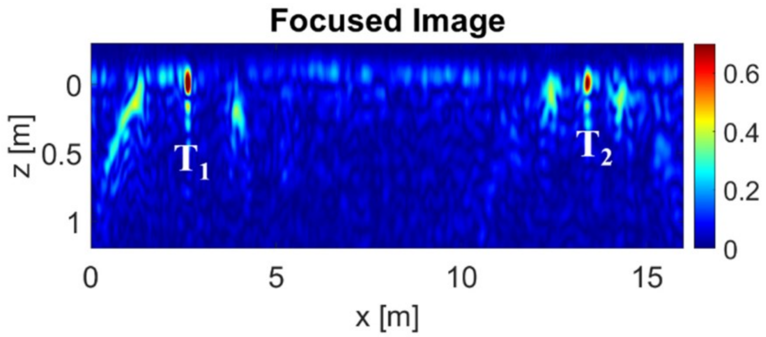

Fig. 5. An example of GPR output result with two detected objects – T_1 and T_2, z – depth, x – distance traveled in horizontal line [40]

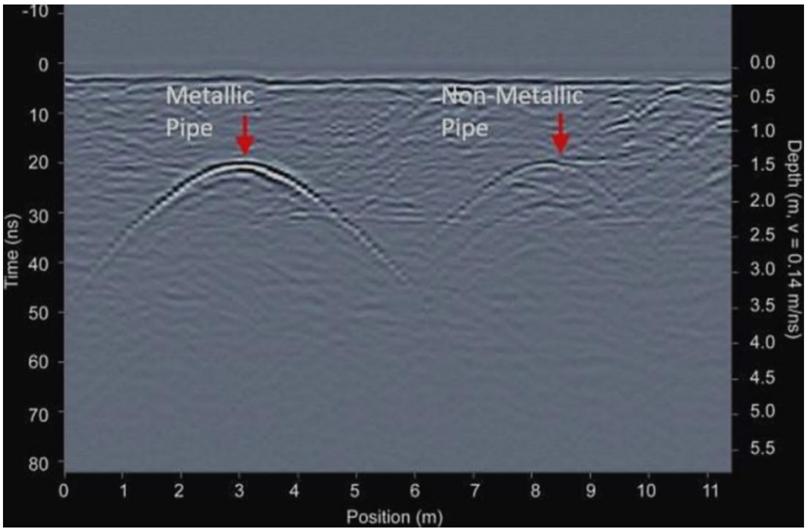

Fig. 6. An example of GPR scan result for metallic and non-metallic pipes [42]

The GPR sensor is used there, where it is needed to look under the surface (ground, wall, etc.), so it is very helpful in some research, especially when it is used complementary with LiDAR. However, there are some limitations to this device, which are listed along with the advantages of using GPR on UAV platforms in Table 3.

Table 3. Advantages and disadvantages of using LiDAR on UAV for selected applications [26, 28, 42]

Application	Advantage	Disadvantage
Archeological research	- Allow to make underground subsurface image or horizontal cross sections - Enables to estimate location, depth and geometry of buried objects - Saves time by narrowing the excavation area	- Needs some experience to choose accurate parameters of scanning - The GPR scanning with UAV is short, but it needs also postprocessing to analyze the obtained data
Underground pipe and cable detection	- No need to make excavation and/or narrows the area of excavation - No need to switch off the current in the cables - Detects different materials	- GPR signals are absorbed by the ground and in some types of soils (clays, saline), the exploration depth is limited
Landmine detection	- Suitable for detecting landmines in cases made of various materials Information about target depth - The signal is rather not interrupted by small metallic particles	- Difficult to detect mines in some types of soils (especially wet clay) - Problematic to detect plastic cased landmines, when the soil is very dry

3. APPLICATION ISSUES OF LIDAR AND GPR ON UAV PLATFORMS

It can be seen from the above information about the two devices that examining areas with both devices simultaneously (or in parallel) can bring positive results and contribute to the development of certain industries, but also science. From the point of view of ground research or inspection, whether for agricultural aviation or forestry, LiDAR works above the surface, providing detailed data on the visible aspects of the examined object, while GPR can look into its depths, allowing for obtaining information on, for example, its surroundings - in this particular case, this concerns, for example, the state of soil hydration. The first potential application after the above-mentioned advantages is therefore precision farming.

Using LiDAR, we can determine with a high degree of approximation the number of crops in a given area, which, combined with information on soil moisture, can provide estimated yield values that can be used to more effectively manage available material or land resources.

LiDAR implemented in aviation is not only installed on UAVs, but also on manned aircraft. Such application of LiDAR allows for scanning, for example, the depth of ravines or examining the riverbank condition. They are installed mainly on small single- and twin-engine fixed-wing aircraft. This means that the installed system must be able to scan the area at high speed (fixed-wing aircraft fly at an average speed in the range of 100 - 300 kts) and with the expected precision; this therefore implies high costs of purchasing and operating a device with the characteristics desired by researchers.

Like LiDAR, GPR is not just seen as research equipment on UAVs. Several such radar systems have been mounted on aircraft and satellites. The former have been used to image geological artifacts beneath the Saharan deserts; the latter have allowed for measuring the depth of the Moon, as well as scanning beneath the surface of Mars and some comets.

It should be noted that with the increase in depth at which we want to detect an object (using GPR), the image resolution decreases, as well as the probability of detecting smaller objects. The latter is influenced by the applied wavelength; if the object is significantly smaller than the wavelength (usually $<0.1\lambda$), the probability of detection is very low.

In the case of both devices, the results are not obtained immediately, and the necessary filtering and processing of data must be performed, and then appropriate calculations and/or transformations must be made. Finally, it is necessary to take care of a researcher-friendly, or further analysis, graphic interpretation or to prepare the data for further processing.

Combining both of these solutions into one is possible, but further steps must be taken to demonstrate the cost-effectiveness of the proposed product. Not only economic aspects should be taken into account, but also design aspects, such as the final mass, which has restrictive limits and must ultimately be as small as possible, while maintaining all the desired characteristics. However, the described devices can be used separately during research (there is no need to buy two UAV systems).

It should be emphasized that the implementation of these systems does not cause major problems in the case of installation on a multi-rotor UAV, so a case study of the use of such solutions on a fixed-wing aircraft should be performed. It should be noted that in today's times it is rare to see an unmanned fixed-wing aircraft performing missions. This state of affairs, according to the author, is caused by several factors:

- higher threshold for learning to fly a fixed-wing aircraft - the flight characteristics are different; you need to practice landings, take-offs, orientation in space, and a series of maneuvers related to, for example, recovering the aircraft from a spin and not stalling it (loss of lift by the wing/wings), lack of many easy accessible commercial solutions for the platform itself; greater requirements for knowledge and experience in the case of designing your own structure,
- currently, multi-rotor aircraft manage the energy available on board more and more effectively, which translates into longer flight times, thus matching fixed-wing aircraft. You should also pay attention to the capabilities of the LiDAR systems (e.g. measurement frequency, range) and GPR (e.g. range, resolution, measurement frequency), whether they are able to conduct reliable research at the cruising speed of a fixed-wing aircraft; it may turn out that there will be a need, for example, to purchase a GPR module with higher power.

CONCLUSIONS

The materials presented in this article confirm the validity of using GPR and LiDAR devices simultaneously in research. They complement each other in terms of applications, provide new data, and can be used not only in science, but also in real applications, whether in industry or other sectors of the economy. The sensors discussed have a very wide range of applications, but it is worth emphasizing the possibility of using them for criminal, archaeological or mine detection searches, which has a real impact on the protection of human life and health. The use of both of these systems can show a full picture of the area or object being examined, which may allow for taking actions appropriate to the current state.

Analysis of data obtained using this type of sensors often allows to analyze some data collected from a different perspective than the ground perspective, which makes it possible to increase the efficiency of some works, e.g. by narrowing the area of field research carried out in the traditional form of excavations or search operations, which must involve a large number of people at the same time. Similar effects can be obtained in other areas of application, such as precision agriculture, where using LiDAR sensors, it is possible to analyze soil moisture, estimate crop growth or analyze the health of plants [4-5]. This type of approach allows for increased yields and reduced costs through the precise use of plant protection products.

The researchers firstly should take into account the use of ready LiDAR maps, which are available on different internet sites, like: geoportla.gov.pl. For some applications the density of the available point cloud (4 points/m2 to 20 points/m2) will be enough. For more accurate applications, like archeology or landmine detection, the points density should be much greater (in some archeology research, there are used the LiDAR images with 800 points/m2. In some applications there should be used current images, like in the areas of landmine detection or in disaster response. In that cases it is not possible to analyze photos, which were taken a few weeks or months ago. In some applications the GPR images can be used complementary to the LiDAR images, to make sure that there is something under the ground. However, the limitations of LiDAR and GPR modules should be taken into account. For LiDAR the main limitations are: foggy weather and areas with extensive vegetation. Underground search capabilities with GPR are limited when the analyzed area is covered with wet clay and also when the ground is too dry, there can occur problem to detect plastic items.

The use of above discussed sensors on an unmanned platform results in a significant simplification of work compared to, for example, mounting this type of sensor on a manned aircraft. In particular, when choosing a multi-rotor configuration, it is possible to operate in nearly any conditions. There is only need of a small area of flat terrain that can be used as a landing strip. Additional advantage of using that sensors on UAV platforms is that most of modern UAV's can scan the area autonomous.

In the near future, we can expect an increasingly widespread use of LiDAR and GPR modules mounted on unmanned aerial vehicles. In addition to the forecasted growth of the unmanned aerial vehicle market mentioned in the introduction, this is indicated by both the number of scientific works conducted using both unmanned aerial vehicles [44] and LiDAR and GPR modules [45].

Przegląd wykorzystania skaningu laserowego oraz georadaru stosowanych na bezzałogowych statkach powietrznych

Obecnie obserwuje się szybki wzrost zainteresowania bezzałogowymi statkami powietrznymi (UAV). Urządzenia te mogą być wykorzystywane jako platformy do przenoszenia różnych czujników, często umożliwiając dostęp do trudno dostępnych obszarów dla tradycyjnych metod naziemnych. Do bardzo popularne czujników, stosowanych w nieinwazyjnych pracach poszukiwawczych zalicza się skaning laserowy (LiDAR) oraz georadar (GPR). Połączenie powyższych czujników z platformami UAV staje się coraz powszechniejsze, co zapewnia wiele korzyści w wielu dziedzinach, takich jak archeologia, kryminalistyka, rolnictwo, ratownictwo, mapowanie terenu czy wykrywanie min lądowych. Niniejszy artykuł stanowi syntetyczny przegląd zasady działania i wykorzystania technologii takich jak LiDAR i GPR, a także ich zastosowania na bezzałogowych platformach latających. Omówiono zagadnienia związane z wykorzystaniem tych czujników na różnych konfiguracjach UAV i wynikającymi z tego warunkami pracy. Omówiono również różnice między LiDAR i GPR, a także ewentualną analizę badanego obszaru przy użyciu obu technologii w celu uzyskania najlepszego efektu. Wdrożenie tych nieinwazyjnych metod poszukiwawczych nie stanowi zagrożenia dla tradycyjnych poszukiwań w formie wykopalisk, a jedynie metodę poprzedzającą te badania. Dzięki tak nowatorskiemu podejściu zwiększa się efektywność prac poszukiwawczych poprzez zawężenie obszaru wykopalisk.

Słowa kluczowe: georadar (GPR), skaning laserowy (LiDAR), bezzałogowy statek powietrzny (BSP).

References

[1] Ekielski A., Wesołowski K. (2019). *Agrotronic systems* (in polish). Polish Chamber of Commerce of Agricultural Machines and Equipment, ISBN 978-83-955096-0-5.

[2] Directive 2009/128/EC of The European Parliament and of The Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides (Text with EEA relevance). https://eur-lex.europa.eu/eli/dir/2009/128/oj (access date: 03/10/2024).

[3] https://www.globenewswire.com/en/news-release. Unmanned Aerial Vehicle (UAV) Market Share Worth US$ 73.91 Bn, Globally, by 2028 at 21.6% CAGR - Exclusive Report by The Insight Partners (access date: 02/10/2024).

[4] Debnath S., et al. (2023). Applications of LiDAR in Agriculture and Future Research Directions. *Journal of Imaging*. 9(3), 57. https://doi.org/10.3390/jimaging9030057.

[5] Rivera G., et al. (2023). LiDAR applications in precision agriculture for cultivating crops: A review of recent advances. *Computers and Electronics in Agriculture*, Volume 207, 2023, 107737. https://doi.org/10.1016/j.compag.2023.107737.

[6] Ding Y., Ye F. (2024). A search and rescue robot design based on LiDAR technology. *Applied and Computational Engineering*, 30(1):238-254. doi:10.54254/2755-2721/30/20230108.

[7] Jozkow G., Toth C., Grejner-Brzezinska D. (2016). UAS Topographic mapping with velodyne LiDAR sensor. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume III-1, 2016, *XXIII ISPRS Congress*, 12–19 July 2016, Prague, Czech Republic. doi:10.5194/isprsannals-III-1-201-2016.

[8] Giannoccaro N. I., Nishida T. (2020). Analysis of the Surrounding environment Using an Innovative Algorithm Based on Lidar Data on a Modular Mobile Robot. Jpurnal of Automation, *Mobile Robotics and Intelligent Systems*, 14(4), 25-34. https://doi.org/10.14313/JAMRIS/4-2020/41.

[9] Clasen C. C., Kruse F. A., Kim A. M. (2012). Analysis of LiDAR Data for Emergency Management and Disaster Response. *Conference: Optical Remote Sensing of the Environment*. doi:10.1364/ORSE.2012.RTu2E.2.

[10] Wang P. (2021). Comparison Review on LiDAR vs Camera in Autonomous Vehicle. *Journal of Physics*: Conference Series 2093 012032. doi:10.1088/1742-6596/2093/1/012032.

[11] Kumar G. A., et al. (2020). LiDAR and Camera Fusion Approach for Object Distance Estimation in Self-Driving Vehicles. *Symmetry*, 12, 324. doi:10.3390/sym12020324.

[12] Lidar Technology in Traffic Law. https://mcaleerlaw.net/lidar-technology-in-traffic-law/ (access date: 03/10/2024).

[13] Guan H., et al. (2021). UAV-lidar aids automatic intelligent powerline inspection. *Electrical Power and Energy Systems*, 130 (2021) 106987. https://doi.org/10.1016/j.ijepes.2021.106987.

[14] Li P., et al. (2022). Online Monitoring of Overhead Power Lines Against Tree Intrusion via a Low-cost Camera and Mobile Edge Computing Approach. *Journal of Physics*: Conf. Series 2422 (2023) 012018. doi:10.1088/1742-6596/2422/1/012018.

[15] Vinci G., et al. (2024). LiDAR Applications in Archaeology: A Systematic Review. Archaeological Prospection, Special issue: Under-canopy Airborne LiDAR for Archaeological Prospections in the Wooded Mediterranean Environment: Challenges, Best Practices and Future Prospects. https://doi.org/10.1002/arp.1931.

[16] Górecki A. (2017). Metody wykorzystywane przez polskich kryminalistów I archeologów przy eksploaracji mogił – różnice I zbieżności. Acta Universitatis Lodziensis. *Folia Archaeologica*, 32. http://dx.doi.org/10.18778/0208-6034.32.03.

[17] Behrendt A., et al. (2006). The benefits of lidar for meteorological research: The Convective and Orographically-Induced Precipitation Study (COPS). https://www.researchgate.net/publication/228638107_The_benefits_of_lidar_for_meteorological_research_The_Convective_and_Orographically-Induced_Precipitation_Study_COPS (access date: 03/10/2024).

[18] Vorobyeva O., Nechaj P., Gaál L. (2019). Lidar-Based Detection of Dangerous Meteorological Phenomena at the Bratislava Airport. *Transportation Research Procedia*, 43(2019), 199–208. https://doi.org/10.1016/j.trpro.2019.12.034.

[19] Cosgrove C. F., Coops N. C., Martin T. G. (2024) Using the full potential of Airborne Laser Scanning (aerial LiDAR) in wildlife research. *Wildlife Society Bulletin*, 48:e1532. https://doi.org/10.1002/wsb.1532.

[20] Merrick M. J., Koprowski J. L., Wilcox C. (2013). Into the Third Dimension: Benefits of Incorporating LiDAR Data in Wildlife Habitat Models. *USDA Forest Service Proceedings RMRS-P-67*. 389-395.

[21] Wang X., et al. (2008). The evolution of LiDAR and its application in high precision measurement. *IOP Conf. Series*: *Earth and Environmental Science* 502 (2020) 012008. doi:10.1088/1755-1315/502/1/012008.

[22] Webster S., et al. (2019). Simulation of LIDAR Systems for Aerial Intelligence, Surveillance, and Reconnaissance. NATO Science & Technology Organization (STO) – Meeting Proceedings Paper, STO-MP-MSG-149. doi: 10.14339/STO-MP-MSG-149-17-pdf.

[23] Łukasiewicz J. (2022).Unmanned aerial vehicles as a source of threats to the state's electricity supply infrastructure and the proposed methods of protecting this infrastructure. *Terroryzm - studia, analizy, prewencja*. 2022, 1 (1), 320–349. https://doi.org/10.4467/27204383TER.22.012.15428.

[24] Freestone P. (2021). LIDAR and Laser - how vulnerable is the RAN to the emergence of light spectrum weapons and sensors? *Royal Australian Navy – Tac Talks*. Issue: 52.

[25] Ostrowski R., Cywiński A., Strzelec M. (2021). Electronic warfare in the optical band: Main features, examples and selected measurement data. *Defence Technology*, 17(5), 1636-1649. https://doi.org/10.1016/j.dt.2020.09.007.

[26] Kasban H., et al. (2010). A Comparative Study of Landmine Detection Techniques. *Sensing and Imaging*. 11, 89–112. doi: 10.1007/s11220-010-0054-x.

[27] Riemersma G., James K., Pacheco P. (2023). How UAV Lidar improves landmine clearance planning. A project in Angola. www.gim-international.com/content/article/how-uav-lidar-improves-landmine-clearance-planning access date: 09/10/2024).

[28] Ristić A., et al. (2020). Using Ground Penetrating Radar to Reveal Hidden Archaeology: The Case Study of the Württemberg-Stambol Gate in Belgrade (Serbia). *Sensors*, 20(3), 607. https://doi.org/10.3390/s20030607.

[29] Doolittle J., W. F. Miller. (1991). Use of ground-penetrating radar techniques in archaeological investigations. NASA. Stennis Space Center, Applications of Space-Age Technology in Anthropology

[30] https://botland.com.pl/blog/czujniki-lidar/ (access date: 30/07/2024).

[31] https://edu4industry.com/systemy-lidarowe/ (access date: 30/07/2024).

[32] https://botland.store/time-of-flight-sensor/12036-laser-distance-sensor-lidar-lite-v3hp-i2cpwm-40m-sparkfun-sen-14599-753759180164.html (access date: 30/07/2024).

[33] https://medium.com/@matt-sharon/lidar-point-cloud-data-guide-62c126101c08 (access date: 01/08/2024).

[34] www.neonscience.org/resources/learning-hub/tutorials/lidar-basics (access date: 01/08/2024).

[35] www.bluemarblegeo.com/blog/calculating-tree-inventory-from-aerial-lidar/ (access date: 31/07/2024).

[36] Marques P., et al. (2024). Advancements in Remote Sensing Imagery Applications for Precision Management in Olive Growing: A Systematic Review. *Remote Sensing*, 16(8), 1324. https://doi.org/10.3390/rs16081324.

[37] https://www.agrotechnomarket.com/2019/01/lidar-usage-for-agriculture.html (access date: 31/07/2024).

[38] https://www.geoportal.gov.pl/pl/dane/dane-pomiarowe-lidar-lidar/ (access date: 10/10/2024).

[39] Skolnik M. (2008). *Radar Handbook - Third Edition*. McGraw-Hill Education - Europe, ISBN 10: 0071485473 / ISBN 13: 9780071485470.

[40] Noviello C., et al. (2022). *An Overview on Down-Looking UAV-Based GPR Systems*.

[41] Liang X., et al. (2022). Application of GPR Underground Pipeline Detection Technology in Urban Complex Geological Environments. Geofluids, Vol. 2022, Article ID 7465919. https://doi.org/10.1155/2022/7465919.

[42] www.sensoft.ca/gpr-for-underground-utility-pipe-line-locating/ (access date: 09/10/2024).

[43] Vergnano A., Franco D., Godio A. (2022). Drone-Borne Ground-Penetrating Radar for Snow Cover Mapping. *Remote Sensing*, 14, 1763., https://doi.org/10.3390/rs14071763.
[44] Zink R., et al. (2023). Assessing the potential disturbance effects on the use of Unmanned Aircraft Systems (UASs) for European vultures research: a review and conservation recommend-dations. Bird Conservation International. 33, e45, 1–12. https://doi.org/10.1017/S095927092300010.
[45] Soilán M., et al. (2019). Review of Laser Scanning Technologies and Their Applications for Road and Railway Infrastructure Monitoring. Infrastructures. 4, 58. https://doi.org/10.3390/infrastructures4040058.