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PERCEPTION TECHNOLOGY FOR CONVERSION OF OFF-ROAD VEHICLES FOR THE PURPOSES OF UNMANNED MISSIONS

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Abstract – Autonomous ground vehicles (AGV) have great potential for a wide range of applications, both in the civilian and military fields. Nowadays there is an interest in converting existing off-road vehicles into remotely controlled platforms with autonomous mode due to several benefits, including reducing the risk to human life, increasing efficiency and accuracy, and allowing the vehicles to operate in hazardous zones. Environmental perception technology plays a critical role in enabling the safe and effective operation during unmanned missions. This technology involves sensors, cameras, and other devices to gather information about the environment and provide the unmanned ground platform (UGV) with a perception of its surroundings. In recent years, there has been significant progress in the development of environmental perception systems, including the use of advanced sensors, machine learning algorithms, and other innovations have become a focus of research and development for many countries.

This paper describes a combination of commercially available vision sensors, laser scanners and navigation modules for comprehensive understanding of operational environment, orientation, objects recognition during autonomous mode. Typical methods for vision and lidar-based obstacle detection and object classification for unmanned vehicles are described. The aim of the work was to examine in real environment the performance of a perception system that was configured using a daylight-thermal observation and stereo cameras, lidar sensor, GNSS module, radio links along with computing units. This system was evaluated in terms of performance of different sensors considering implementation for all terrain vehicle as subsystem for unmanned mode.

Key words – lidar, navigation, unmanned vehicles, perception system, obstacle detection

JEL Classification – R41, R42, 031, 032

INTRODUCTION

The development of autonomous vehicles is a rapidly growing field, and there are many companies and organizations working on these projects including military, industrial, and civilian sectors [1-4]. There are two different approaches to develop unmanned ground vehicles: designing new UGVs from scratch or converting existing vehicles into unmanned platforms by integrating the necessary hardware and software systems. The conversion process can be complex and requires specialized knowledge and expertise in areas such as robotics, autonomous systems, and vehicle engineering [5].

One of the example is ATV (All-terrain Vehicle) platform designed to help ease the transition from manned to unmanned mode [6-7]. There are also several other projects that aim to convert manned vehicles into unmanned ones like Robotic Vehicle Conversion (RVC) introduced by the US military to retrofit its existing fleet of vehicles with autonomous technologies. The size of the vehicle being used for conversion to unmanned mode can vary depending on the intended application and the requirements of the mission. The unmanned ground vehicles (UGVs) ranging from small, lightweight vehicles for reconnaissance missions to larger, heavy-duty vehicles for carrying cargo and supplies. Some popular platforms for converting to unmanned mode include all-terrain vehicles (ATVs), utility vehicles, and off-road vehicles [8-11].

The conversion of an off-road vehicle to an unmanned mode involves the installation of various sensors, cameras, navigation systems, and control systems that allow the vehicle to operate autonomously, without a human being presence. This process typically requires the integration of software, hardware, and communication systems that allow the vehicle to perceive its environment, make decisions, and execute actions based on its programming.

To convert an off-road vehicle to an unmanned mode we can distinguish the following steps [12]:

- Installing sensors, such as cameras, lidar and GPS systems, to allow the vehicle to perceive its environment and navigate.
- Design the control system that will manage the vehicle's movements and decision-making processes.
- Developing software to interpret the sensor data, make decisions, and execute actions.
- Conducting tests and validations to ensure that the vehicle operates safely and effectively in its intended environment.

Perception system must take into account factors such as reliability, accuracy, and computational efficiency [13]. Combining different vision sensors and laser scanners, GNSS modules with computing units allows comprehensive understanding of the environment and efficient operation of unmanned vehicles. Vision sensors, such as cameras, can provide high-resolution images and video of the surroundings, allowing the system to identify and detect obstacles [14]. However, cameras can be affected by lighting conditions and can have limited range, making it necessary to combine them with other sensors. LIDAR can complement the vision system for recognition by providing accurate, high-resolution 3D data of the environment. Lidar works by emitting laser beams and measuring the time of reflected waves to determine the distance of objects in the environment. This information can be used to create a 3D point cloud of the environment, which can then be processed to identify objects, detect obstacles, and perform semantic segmentation [15].

System architecture used for testing included also the computing unit and radio links enabling data transmission and processing sensor information for remote monitoring and control of the vehicle. The main aim of this study was to determine if these sensors and systems can effectively support unmanned missions of all train vehicle and provide the necessary data and information for safe and efficient operation.

1. Description of the developed Light Terrain Vehicle LST

The unmanned platforms can be used for a wide range of applications, including mining, agriculture as well as military operations like rescue and recovery missions, delivery and transportation. The demand for UGVs as well as manned-unmanned vehicles is expected to grow in the coming years due enhancing operational efficiency and reducing human intervention and technology advances [16].

There are many projects aimed at converting off-road vehicles into UGVs, both in the military and civilian fields. The base of converting an off-road vehicle to an unmanned vehicle is to utilize the existing structure and capabilities of the off-road vehicle, while adding the necessary components to enable autonomous operation. This approach has the potential to be more cost-effective and less time-consuming than developing a new UGV from scratch.

We have evaluated conversion of Light Terrain Vehicle (LST) designed and built as a response to market demand by consortium Military Institute of Armour and Automotive Technology (WITPIS), Military University of Technology (WAT) and company Szczesniak Pojazdy Specjalne [17].

The concept of Light Terrain Vehicle is to provide excellent drivability characteristics, high capacity and modularity in rough. LST vehicle is based on the 4x4 chassis, with dimensions of Land Rover Defender 110.

The vehicle is suitable to operate in all terrain and different weather conditions (temperature range from -30°C to +50°C). The LST is equipped with gearbox reducer integrated with differentials to achieve optimal performance in off-road environment. The high ground clearance ensures that the LST vehicle's undercarriage is kept clear of any obstacles that may be encountered on rough terrain (Fig. 1).

The Light Terrain Vehicle is also equipped with a powerful engine and durable suspension system, making it suitable for various applications, such as military operations and rescue missions. The strength and lightness of LST was obtained by selection of appropriate materials. Sheathing and load bearing structure of the vehicle are made of aluminium. The body is attached to the main frame by vibration absorbing rubber components.

Light Terrain Vehicle is equipped with high-quality off-road tires, which provide good traction and stability on rough terrain, and a powerful engine that delivers ample torque and power to handle tough off-road conditions. The LST is also designed to be easily reconfigured and equipped with various payloads and equipment, making it well-suited for a wide range of applications, including military, humanitarian, and civilian uses. Overall, the LST is a versatile, rugged and reliable vehicle that provides excellent performance in off-road environments, making it an ideal candidate for conversion to an unmanned ground vehicle.

Fig. 1. View of developed Light Terrain Vehicle

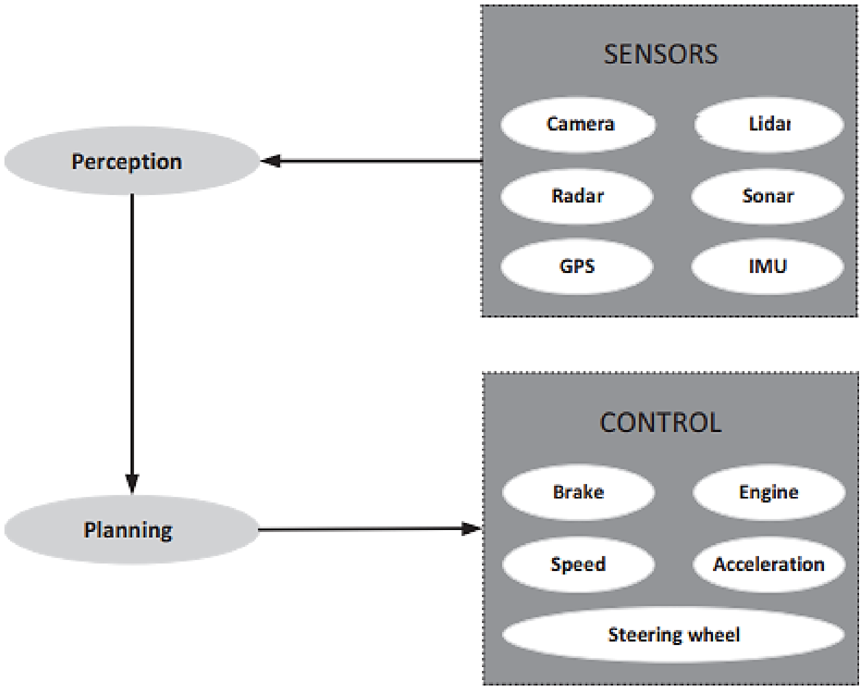

Fig. 2. Block diagram of autonomous system [19]

2. Technologies enabling remote control and vehicle autonomy

Remote control technologies with autonomous options can be divided into several categories, including perception, navigation, communication, and control systems.

Information about the environment is obtained by unmanned ground platforms from installed sensors: visible and infrared light cameras, laser scanners or radars [18]. The data obtained from various sources are process by the vehicle's on-board computer system to makes decisions on the next actions to be taken.

2.1. Autonomy architecture

Designing an effective control system for unmanned vehicles is a challenging task, as it involves integration of multiple sensors and algorithms to analyze the data and make decisions about vehicle behaviour in operational environment.

The control system for an unmanned vehicle is typically based on two subsystems: perception and planning [19]. The perception component of the system is responsible for collecting and processing data from the sensors, such as cameras, lidar, GNSS/IMU, and other sensors, to generate a comprehensive understanding of the vehicle's environment (Fig. 2). It is related with detecting and classifying objects in the environment, estimating the vehicle's position and orientation, and generating a 3D model of the environment.

The path planning component is responsible for generating safe and efficient paths for the vehicle based on the information received from the perception system. Implemented algorithms are related to avoiding obstacles, optimizing the vehicle's trajectory, and considering other factors, such as energy efficiency and mission constraints.

The control system must be able to operate in real-time, processing information from the sensors and generating control signals for the vehicle to carry out its mission. The system must also be designed with a high degree of modularity and flexibility with the ability to detect and respond to potential obstacles. Due to unknown operational environment advanced machine learning and computer vision algorithms are required to improve the accuracy and robustness of the control system.

2.2. Description of used sensors

There are many different types of sensors that can be used in autonomous systems that use different physical properties of the environment perception. Infrared cameras can provide information about the radiated heat of objects, which can be used to detect objects even in low-light or dark conditions. On the other hand, laser scanners and radars can provide a 3D representation of the environment, which can be used for obstacle detection and mapping of the environment. Sensors used in UGV applications have different requirements depending on the platform operational requirements.

2.2.1. Vision systems

Vision systems refer to the integration of cameras, algorithms, and hardware used to capture and process visual data regarding objects environment, such as the location and appearance of obstacles, other vehicles, pedestrians, buildings, etc. There are several types of vision systems that can be used on unmanned vehicles, including monocular cameras, stereo cameras, and RGB-D cameras. Each type of vision system has its own advantages and disadvantages, and the choice of system will depend on the specific requirements of the unmanned vehicle and the operating environment. Typical cameras provide a single view of the environment, and can be useful for basic obstacle detection and avoidance. Stereo cameras are able to capture two slightly different images of the same scene, similar to how our eyes perceive depth. RGB-D cameras provide both colour and depth information, making them well-suited for applications that require a more detailed understanding of the environment.

The LST vehicle was equipped with a stereo camera ZED 2 (Fig. 3) and the daylight-thermal observation system (Fig. 4). The ZED 2 camera is a stereo camera developed by Stereolabs, which can be used for 3D perception and mapping applications. The camera provides two 4K resolution sensors, which are used to capture images of the environment from slightly different perspectives. This allows the camera to estimate the depth of objects in the scene and generate a 3D point cloud of the environment.

Key parameters of ZED 2 camera [20]:

- Maximum resolution of 3840x2160 pixels for colour images and 2560x720 pixels for depth maps;
- Horizontal field of view of 95 degrees and vertical field of view of 71 degrees;
- Depth range of the camera is 0.2 to 20 meters.

The daylight-thermal observation system combines both daylight and thermal cameras to provide a comprehensive view of the environment.

The daylight camera captures visible light and provides a color image of the environment, while the thermal imaging camera captures the heat that is emitted by objects and provides a grayscale image that represents the temperature of the objects in the scene.

Fig. 3. View of ZED 2 camera [**20**]

Fig. 4. View of daylight-thermal camera [**21**]

Table 1. Parameters of dayligth-thermal camera [**21**]

Daylight Camera	Thermal Camera
Sensor: 1/2.8" CMOS	Uncooled VOx Microbolometer sensor
Resolution: 1920x1080 (Full HD)	Resolution: 640x480 (VGA)
Field of View: 60° (horizontal)	Field of View: 28° (horizontal)
Zoom: 30x optical, 12x digital	Spectral Range: 8-14 µm
Minimum Illumination: 0.1 lx	Thermal Sensitivity: < 50 mK

The thermal imaging camera can detect objects that are not visible in the visible light image, and the system can be used to estimate the temperature of objects in the environment, providing additional information about in both low-light and total darkness conditions.

2.2.2. VISION SYSTEMS

Lidar (Light Detection and Ranging) is a type of sensor that uses laser light to measure distances and gather information about the surrounding objects. Laser sensor emit a short pulse of light and then measure reflected waves to calculate the distance to an obstacle. Lidar sensor can generate a 3D point cloud which provides a detailed representation of the environment. It is often used in combination with other sensors, such as cameras and radar, to provide a more comprehensive view of the environment. The main advantage is its ability to accurately and quickly measure distances, even in challenging environments with poor lighting or complex surfaces. This makes Lidar a valuable tool for unmanned vehicle developers, who need to ensure the accuracy and reliability of their obstacle detection and avoidance systems.

The LST vehicle was equipped with Ouster OS0-1 that uses 32 laser beams to generate a high-resolution 3D point cloud of the environment (Fig. 5). It has a range of up to 120 meters and a field of view of 360 degrees horizontally and 24.9 degrees vertically.

Key parameters of Ouster lidar [22]:

- Range: up to 120 meters;
- Field of View (FoV): 45° vertical x 360° horizontal;
- Angular Resolution: 0.1°;
- Data Output: 128 vertical lines x 1024 points per line (131,072 points per frame);
- Data Rate: up to 1.33 million points per second.

Fig. 5. View of used Ouster lidar [**22**]

2.3. COMMON OBSTACLE DETECTION METHODS

There are different approaches to analyze data from vision systems and lidars. Data collected from cameras are usually in the form of images or videos, which can be processed using computer vision techniques to detect and classify objects. Common techniques include image segmentation, object recognition, and feature extraction. In case of lidar based systems, the data collected is usually in the form of point clouds, which can be processed using techniques such as segmentation, clustering, and registration. Mentioned techniques are used to identify objects in the environment and determine their position and shape.

Obstacle recognition from a vision system can be achieved through several methods like [23]:

- Image segmentation;
- Object detection;
- Deep learning-based semantic segmentation;
- Stereo vision.

Image segmentation is the process of dividing an image into multiple segments, each of which corresponds to a different object in the scene. This can be done using various techniques, such as thresholding, edge detection, or region growing. The resulting segments can then be classified as obstacles or other objects of interest.

Object detection is a method of detecting instances of objects within an image, such as vehicles, pedestrians, or buildings. This can be done using deep learning-based object detection algorithms, such as Faster R-CNN or YOLO, which can learn to detect objects of interest by training on large datasets.

Semantic segmentation is the process of assigning a label to each pixel in an image, such as "car", "building", or "obstacle". This can be done using deep learning-based semantic segmentation algorithms, such as U-Net or SegNet, which can learn to segment an image into different classes of objects.

Stereo vision is a method of using two cameras to estimate the depth of objects in a scene. This can be done by computing the disparities between the two images and using them to estimate the depth of each pixel. Stereo vision can be used to detect obstacles by identifying regions in the depth image that correspond to objects in front of the camera.

Lidar - based obstacle recognition can be more challenging due to analysis of the point cloud data generated by the sensor. It can be achieved through several methods like [24]:

- Point cloud segmentation;
- Ground segmentation;
- SLAM (Simultaneous Localization and Mapping);
- Depth image-based obstacle detection.

Point cloud segmentation is a method of separating the Lidar data into distinct groups of points that correspond to different objects in the environment. This can be done using clustering algorithms, such as the k-means algorithm or the Euclidean clustering algorithm, to group together points that are close to each other in space. The resulting clusters can then be classified as obstacles or other objects of interest, such as vehicles, pedestrians, or buildings.

Ground segmentation is a method that allows for the removal of ground points and the extraction of non-ground objects. One commonly used method is RANSAC (Random Sample Consensus), which fits a plane to the ground points and separates them from the rest of the data. The remaining points can then be classified as obstacles.

SLAM is a method that combines Lidar data with other sensory information, such as wheel odometry or IMU data, to build a map of the environment in real-time [25]. SLAM algorithms can be used to detect obstacles in the environment by analyzing the differences between the current and previous maps and identifying changes that correspond to the presence of obstacles.

Depth images can be generated from the Lidar data, which can be processed using computer vision techniques, such as edge detection or blob detection, to identify obstacles. This method can be useful for detecting small or partially occluded objects, as it can make use of the full 2D information available in the depth image.

Combination of vision and lidar systems can provide a more robust and comprehensive solution for object detection in unmanned vehicles. Data fusion allows higher level of accuracy and reliability in object detection, as well as the ability to detect a wider range of objects in a wider range of environments [26].

3. VALIDATION OF THE PERCEPTION SYSTEM IN OPERATIONAL ENVIRONMENT

Perception technology enables unmanned systems to understand and interpret the environment for navigation, obstacle detection and avoidance. The performance of environmental perception sensors was evaluated using testing system architecture based on different type of sensors like lidar and camera, navigation as well as computational units with additional wireless communication module. Developed perception system was tested mainly in terms of the functionality in an operational environment that represents the conditions in which the sensors will be used.

3.1. ARCHITECTURE OF VEHICLE PERCEPTION SYSTEM

Based on selected sensors for environmental analysis perception system was configured as shown in Fig. 6. The data from these sensors are processed by the computational units, that were configured using software packages and libraries for data acquisition, processing, and analysis. Capturing data required sensor calibration before using processing techniques to extract relevant information such as details about object parameters and classification.

The LST vehicle was used to as testing mobile platform to install environment perception sensors with on-board computer and radio modem, as shown in Fig. 7 The components were mounted on the roof of the vehicle in order to obtain better view of the environment and enable the sensors to capture data from a wider area.

Configured perception system was used for performance evaluation in off-road environment. The implemented wireless communication systems allowed for wireless data transfer between the perception system on the vehicle and a control station, enabling the recorded data to be analyzed later for further analysis and improvement of the system.

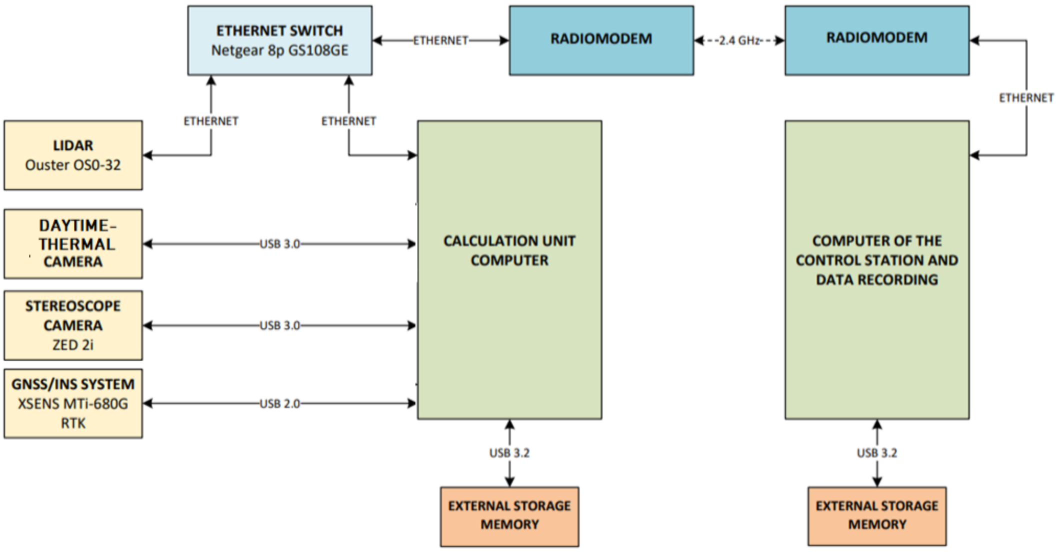

Fig. 6. Block diagram of examined perception system

(a)

(b)

Fig. 7. View of the LST vehicle with the installed sensor module(a) **perception system** (b)

3.2 VISUALIZATION OF ACQUIRED DATA FROM SENSORS

We conducted tests in unstructured environment in the area of military training grounds. The examination was carried out in the different day time as well as weather conditions.

Perception system was tested using configured visualization software that allowed the display of point clouds generated by the lidar sensor and images captured by the camera. The raw data could provide analysis regarding representation of the surrounding environment and detection of obstacles and other relevant objects.

Acquired data from sensors such as lidar can be represented as an array of measured distances, where each point corresponds to a specific angle or direction from the sensor. This data can be visualized in 3D using software that allows display of a point cloud (Fig. 8), which represents the surfaces and objects in the environment. The software can also display the data in a 2D map, which are related to the distribution of spatial data in a flat plane.

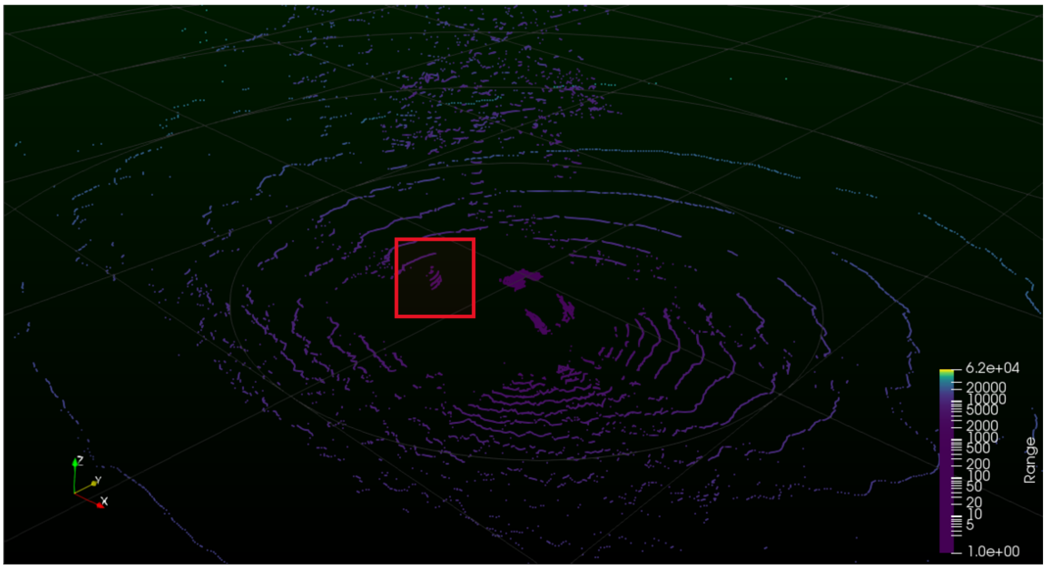

Fig. 8. 3D environment representation according to the distance from the sensor's center (**The observed object is marked in red**)

In addition, laser scanner allows to measure the intensity of the light returning to the receiver (reflectivity) and the energy that reaches the sensor, which is the sum of the energy radiated by the laser and the light coming from outside the sensor (signal photons).

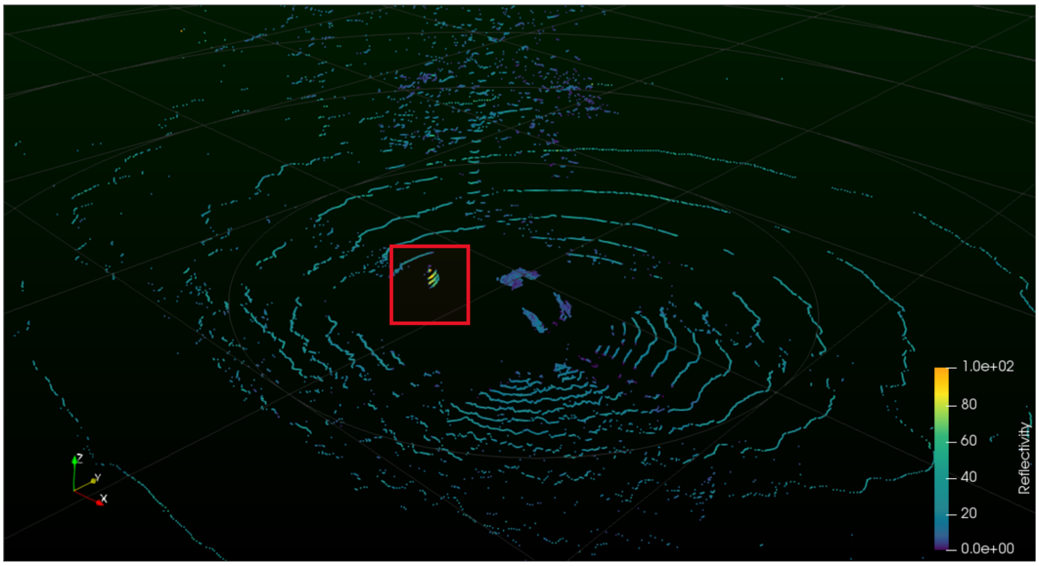

Fig. 9. 3D environment representation measured reflection coefficient (**The observed object is marked in red**)

The implemented function related to the energy reaching the sensor is useful to detect objects that radiate energy within the measuring range of the sensor (Fig. 9). Objects with low reflectivity, such as those with rough or matte surfaces, tend to scatter the laser light in various directions, leading to a weaker reflected signal. On the other hand, objects with high reflectivity, such as those with smooth or glossy surfaces, tend to reflect the laser light in a single direction, leading to a stronger reflected signal.

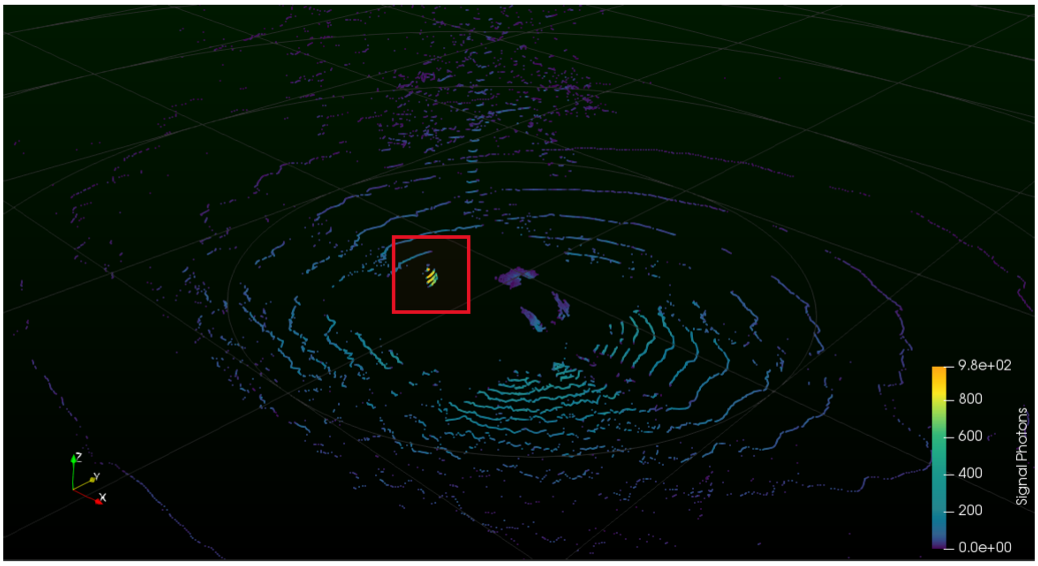

Fig. 10. 3D environment representation of reflected energy as signal photons (**The observed object is marked in red**)

Taking into account the Signal Photons parameter, the object as human in front of the vehicle is clearly visible (Fig. 10) due to the background (ground, tree, roof and part of the vehicle's body remain at a similar level). This allows the perception system to detect the presence of the person and use this information for obstacle avoidance or other autonomous vehicle functions.

The software enables the visualization of spatial data in two-dimensional distribution (Fig. 11) which can be useful for certain applications, such as analyzing the distribution of obstacles or other objects on a flat surface.

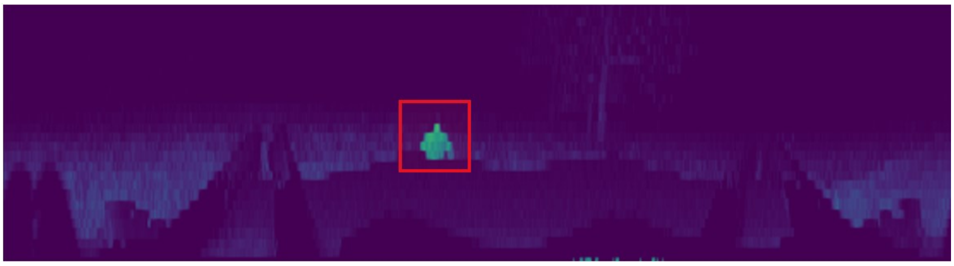

Fig. 11. Visualization of spatial data in two dimensions (**The observed object is marked in red**)

The two-dimensional plane can be used as a projection of the three-dimensional data onto a flat surface. It allows to compare the data from a 3D sensor (such as lidar) with the image from a 2D sensor like a camera.

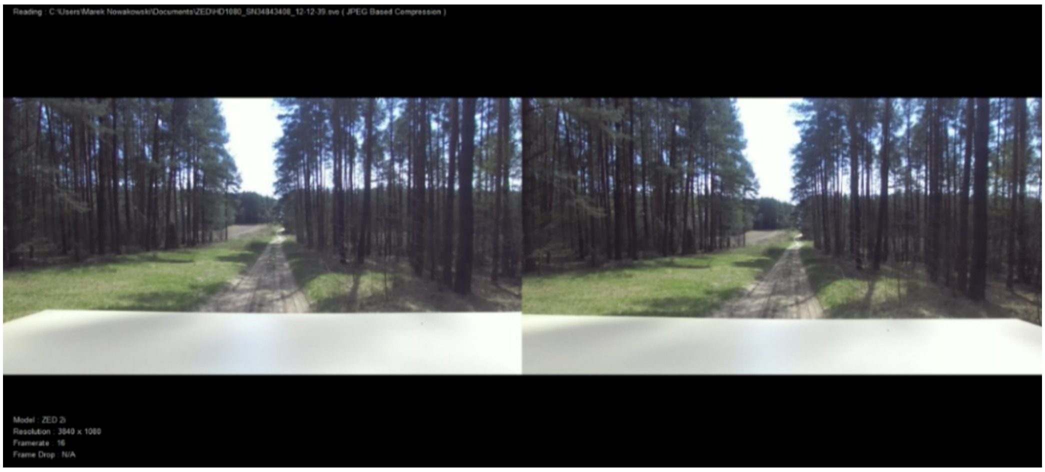

Fig. 12. Image from the ZED2i camera during daytime

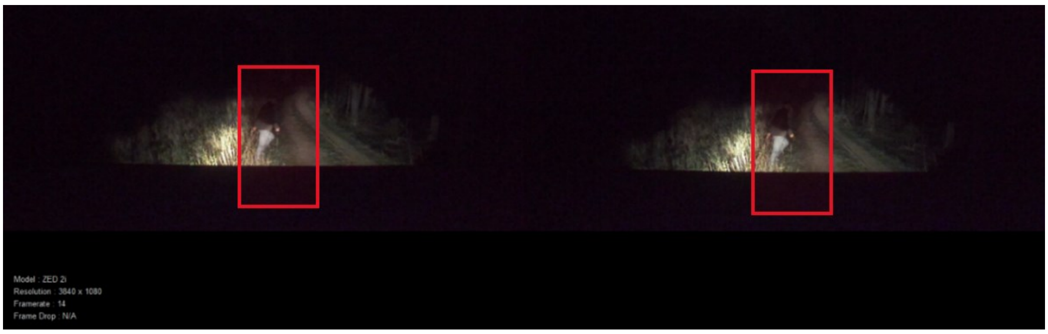

Fig. 13. Image from the ZED2i camera - night view - vehicle lighting on (**The observed object is marked in red**)

(**a**) (**b**)

Fig. 14. The image recorded by the RGB (a) and thermal (b) camera during night mode. The observed object is marked in red

The shown images in Figure 12 present the performance of ZED 2i camera with built-in two independent image sensors. The vision structure enables spatial estimation at the post-processing stage. Spatial imaging from camera is less accurate approach comparing to data received from a laser scanner.

Coloring spatial points with the image from RGB cameras can help in creating a more realistic represent-tation of the operating space. This technique is often used in fusion algorithms where the data from different sensors, such as lidar and RGB cameras, are combined to create a more comprehensive and accurate representation of the environment.

The built-in image sensors are not adapted to work in night conditions, as shown in Figures 13. The same environment was observed using a daylight -thermal camera equipped with two image sensors (Fig. 14).

The obtained results are base for further more advanced research and development of obstacle detection technology and thus autonomy in the field of unmanned vehicles.

CONCLUSIONS

The UGV control system requires obtaining reliable information from sensors in order to detect obstacles, their direction or estimate the distance. According to carried out performance tests installed sensors enable the detection of typical obstacles in the operational environment.

Spatial imaging of the operating environment with the ZED 2i camera is possible only during daylight conditions. The conducted experiments have shown that better recognition of the obstacle is possible using thermal camera. It should be highlighted that human detection was possible at a considerable distance from the vehicle, but the image did not provide additional spatial information.

The software of an effective perception system requires the implementation of spatial analysis algorithms with significant computational complexity. Obstacle recognition based on 3D laser scanner allows precise development of a spatial model of the operational environment.

Additionally, perception system was tested in various weather conditions, it was found out that performance of each sensors depends on day and night time or weather conditions. Thermal sensors detect the infrared radiation emitted by objects and can therefore work in complete darkness. However, their effectiveness can be affected by factors such as ambient temperature and the presence of other heat sources. In addition, the accuracy of object recognition using infrared sensors can be subject to distortion due to the variation of thermal signatures of different objects and the background. Furthermore, lidars can be susceptible to heavy rain, as water droplets can scatter the laser beams and cause interference. Inaccurate or incomplete data significantly impact the performance of the perception system. Therefore, it is necessary to expand the system with additional sensors that are less sensitive to weather conditions as well as providing additional parameters related to the properties of detected obstacles.

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TECHNOLOGIA PERCEPCJI UMOŻLIWIAJĄCA KONWERSJĘ POJAZDÓW TERENOWYCH NA POTRZEBY MISJI BEZZAŁOGOWYCH

Pojazdy (AGV) mają ogromny potencjał pod kątem szerokiego spektrum zastosowań, zarówno na rynku cywilnym, jak i wojskowym. Konwersja pojazdów terenowych w zdalnie sterowane platformy z trybem autonomicznym wzbudza duże zainteresowanie ze względu na szereg korzyści takich jak: zmniejszenie zagrożenia życia ludzkiego, zwiększenie wydajności i dokładności oraz umożliwienie poruszania się pojazdów w strefach niebezpiecznych. Systemy analizy otoczenia odgrywa kluczową rolę pod kątem bezpiecznego i efektywnej realizacji misji bezzałogowych. Układy percepcji obejmują: czujniki, kamery i inne urządzenia umożliwiające pozyskanie informacji o otoczeniu i dostarczenie danych o środowisku operacyjnym bezzałogowej platformie naziemnej (UGV). W ostatnich latach obserwuje się znaczny postęp technologiczny w dziedzinie systemów percepcji otoczenia, a w szczególności zaawansowanych czujników, algorytmów uczenia maszynowego i innych innowacyjnych rozwiązań, które stały się przedmiotem badań i rozwoju wielu krajów.

W artykule opisano wykorzystanie dostępnych na rynku czujników wizyjnych, skanerów laserowych i modułów nawigacyjnych w celu pełnego zobrazowania środowiska operacyjnego, lokalizacji oraz rozpoznawania obiektów w trybie autonomicznego przejazdu. Opisano typowe metody wykrywania przeszkód i klasyfikacji obiektów na podstawie systemów wizyjnych oraz skanerów laserowych instalowanych w pojazdach bezzałogowych. Celem pracy było zbadanie, w warunkach rzeczywistych, działania systemu percepcyjnego skonfigurowanego z wykorzystaniem kamery termowizyjnej i stereoskopowej, lidaru, modułu GNSS, modułów radiowych wraz z jednostkami obliczeniowymi. System ten został zweryfikowany pod kątem użyteczności informacji pozyskiwanych z poszczególnych typów sensorów na potrzebny realizacji trybu bezzałogowego przez pojazdy terenowe.

Słowa kluczowe: detekcja przeszkód, lidar nawigacja, pojazdy bezzałogowe, systemy percepcji

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