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RESEARCH OF DETECTION OF SMALL UNMANNED AERIAL VEHICLES USING A 3D LIDAR SENSOR

Abstract. Unmanned aerial vehicles (UAV) have been in the service of people, doing a variety of tasks in science, business, the military, and even for personal amusement. Additionally, they have been used increasingly frequently for bad intentions, such as targeting infrastructure, disturbing nearby residents, and interfering with air transport. A UAV's modest size presents an issue since it makes detecting it difficult. Numerous conventional methods and technology might not even be appropriate to solve this task. This work outlines a feasibility assessment for the use of a Light Detection and Ranging (LiDAR) sensor to identify a flying unmanned aerial vehicle. The VL53L0x laser rangefinder time-of-flight (ToF) sensor module was used for high-precision distance measurement. The results showed that the range of operation has a significant impact on the object detection rate when employing LiDAR sensors. Particularly, the detection rate drastically declines when the distance between the object and the sensor exceeds 30 m.

Keywords. Drone detection, 3D detection, deep learning, lidar, sensor.

Introduction.

The best UAV (or drone) manufacturing companies on the market, like DJI, 3DR Solo, Yuneec, and Parrot, offer a wide range of drones used in logistics, manufacturing, construction, and aerial photography. As a result, the size of the global drone market has been growing rapidly every year. The affordability and ongoing advancements in UAV technology, along with their capacity to transport hazardous cargo such as chemicals or poisonous substances, have become these devices a valuable instrument for terrorist organizations and criminal organizations to launch attacks or gather intelligence [1]. This has led to an increase in the frequency of events worldwide, including mass UAV assaults on civilian and military targets, military cargo transit, the crossing of illegal narcotics, and the spraying of poisonous chemicals. Consequently, there has been a significant surge in the development of autonomous drone detecting system research in recent years. Since most drones are tiny and fly at low speeds and altitudes, it makes UAV detection, identification and classification tasks challenhing. Based on the literature reviewed thus far, sensors for autonomous drone flight detection include radar, electro-optical cameras, thermal and infrared cameras, microphone arrays for detecting drone rotor sounds, RF sensors, and scanning lasers such as LiDAR and LADAR. Radar is one of these technologies that, despite its history of success in object identification and tracking, is thought to be very expensive and professional, requiring skilled individuals who can interpret the visual output of a radar system (Figure 1).

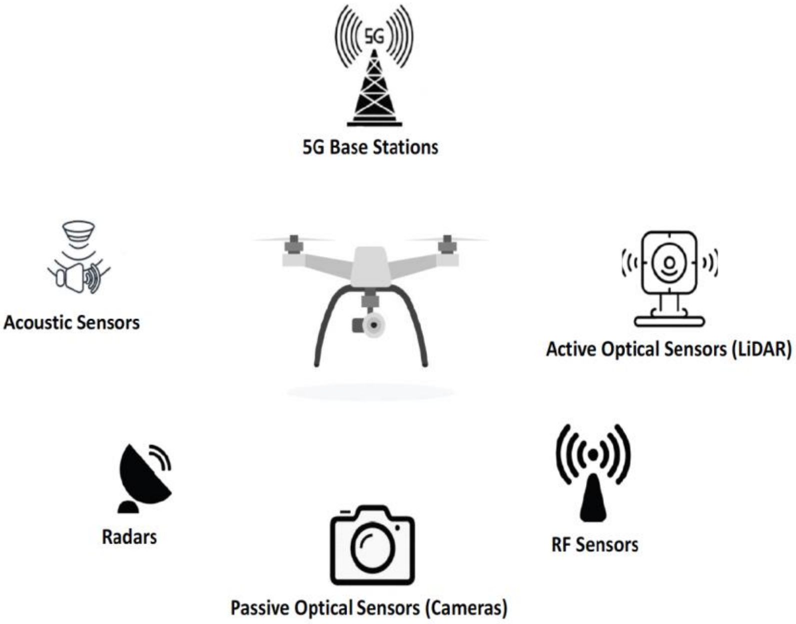


Figure 1 – Different drone detection technologies

It can be slightly less expensive to identify UAVs using acoustic signals (but the cost increases as accuracy needs climb). Its ability to perform regularly in low light and various weather situations, such rain, fog, dust, etc., is one of its advantages. Furthermore, LOS to the target is not necessary. Acoustic devices perform best in remote areas with little background noise. However, because of wind and temperature variations, it is susceptible to outside noise and weather, and the size of the microphone grid often dictates its operating distance. This approach is not accurate in noisy environments and makes it hard to determine whether a drone is utilizing a sound-suppression gear [14]. As a result, it is ineffective to use acoustic sensors as the primary detection method due to their decreased accuracy of detection in loud surroundings and their reliance on wind and noise. Radio frequency (RF) detection serves as the foundation for yet another efficient drone detection technique. Drones equipped with GPS receivers or radio transmitters can release energy that is detected by radio frequency sensors. Wireless signals may be captured using RF scanner technology, which can be used to determine whether UAVs are present in the target area [15]. However, at low signal-to-noise ratios, none of the current RF-based detection techniques function well [26]. Additionally, radio frequency (RF) technology has the potential to reduce the detecting range of drones, and RF sensors are vulnerable to interference from other electrical devices like televisions, radios, and mobile phones. As a result, drone identification may become challenging and result in false positives [15]. Despite being one of the most widely used techniques for object recognition based on camera sensor image data, computer vision is much less accurate in detecting objects in certain lighting and weather situations, such as fog and rain [16]. Sparse point clouds, which provide a distinct 3D location of the object's surfaces at each point, are used in LiDAR-based object detection models. LiDAR sensors function effectively in low light or even at night and may offer precise three-dimensional information about an item [17].

Utilizing radio frequencies, radio detection and ranging (radar) devices identify objects and determine their location. The obstacle’s distance is calculated using the time obtained for radio waves to reach an obstruction and then returned after being reflected by it [1]. The sole difference in how light detection and ranging (lidar) systems operate is that they employ laser light as opposed to radio frequencies. LiDAR has precise and high spatial dimension information and privacy-free data. It captures absolute scale of objects and is not restricted by light conditions [2]. These benefits make LiDAR best option at solving 3D object detection tasks. The range of operation has a significant impact on the UAV detection rate when employing LiDAR sensors. Particularly, the detection rate considerably declines over 30 m in distance between the target and sensor [3, 4]. Thus, by demonstrating the target detection rate under various conditions, the findings of these investigations demonstrated the effectiveness of deploying LiDAR sensors. The range appears to have the most influence on this efficiency, whereas other factors like the lighting, which have a significant impact on other types of sensors (like cameras), have very little effect on LiDAR sensors [5].

Materials and methods.

LiDAR is one of the sensors that works by light detection and ranging, which works based on three-dimensional laser scanning method. It measures the time-of-flight (ToF) of the emitted laser pulse and captures a set of 3D points called point clouds [6]. Unlike images taken by cameras, the point clouds produced by LiDAR provides 3D spatial information about objects in the form of coordinates (X, Y, Z) and intensity. As a result, distance estimate becomes less of a barrier, and 3D object tracking or detection becomes considerably more precise [7].

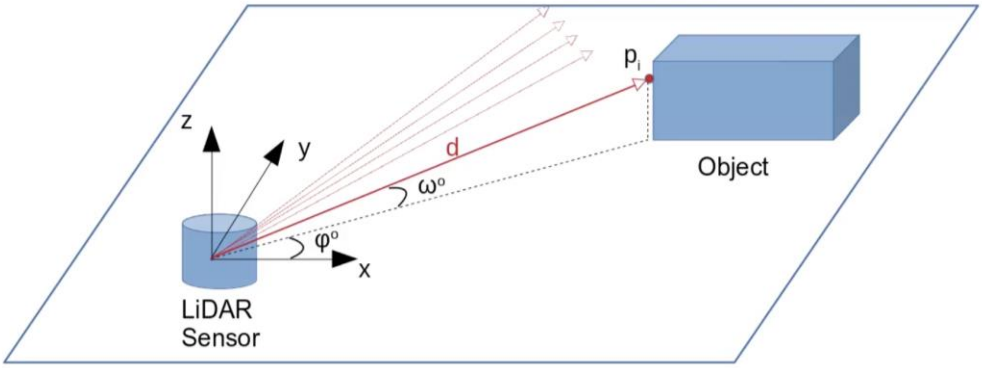


Figure 2 – Measuring the object’s distance with LiDAR sensor

A point cloud ℙ is a collection of 3D points $\{P_i$ = [x, y, z, r], $P_i \epsilon$ ℙ$\}$ obtained by lidar scanning. It provides information about the spatial distribution of environmental points and characteristics of the object surface. Each point has a three-dimensional coordinate vector (x, y, z) relative to the center of the sensor and an associated characteristic vector R, which is the intensity of the laser reflection. Taking the commonly used mechanical lidar as an example, the position vector of the point P_i is calculated as follows [8]:

$$d = \frac{c(t_2 - t_1)}{2} \tag{1}$$

$$\begin{gathered} x = dcos(w)\cos(\phi) \\ y = dcos(w)\sin(\phi) \\ z = dsin(w) \end{gathered} \tag{2}$$

LiDAR sensors create three-dimensional environmental scans as clusters of points in space called point clouds. Although point clouds are accurate and reliable, making them useful for robotics applications, the raw data of point clouds is large, contains high-density noise, and has a diffuse distribution. Point data forms objects. Thus a class of objects arises (Figure 2) [9, 10].

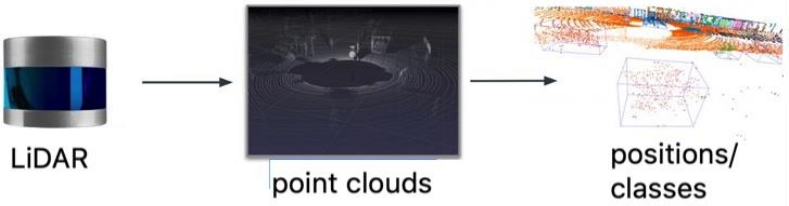


Figure 3 – Stages of 3D data preprocessing

The point-based method of LiDAR 3D object detection involves various mathematical formulas and operations. Although the exact formulas may vary by implementation and approach, here are the mathematical concepts and formulas commonly used in point methods [11]. The Euclidean distance between two points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ is determined by formula 3:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}\,. \tag{3}$$

The farthest point selection algorithm involves iteratively selecting the farthest point from the selected points. Calculation of the distance for each point of candidate P is given by formula 4:

$$distance(P) = \min\left(dist\,(P, P_{candidate})\right). \tag{4}$$

Results and Discussions.

The VL53L0x is a popular laser rangefinder time-of-flight (ToF) sensor module that can be used for high-precision distance measurement. It uses a laser diode to emit short pulses of light and measures the time it takes for the light to travel to the object and back to the sensor. The Vl53l0x module uses time-of-flight technology to measure distance. It emits a laser pulse and measures the time it takes for the pulse to reach the target and return to the sensor, and knowing the speed of light, the module calculates the distance based on the time-of-flight measurement [12].

Measuring range:

- The VL53L0x can accurately measure distances up to several meters depending on the specific model and environmental conditions.
- The typical measurement range for the VL53L0x module is 2 to 4 meters, some models are capable of measuring beyond this range.

Accuracy and resolution:

- The VL53L0x provides high accuracy distance measurements, typically to the millimeter.
- It provides a resolution of up to 1 mm, which allows accurate distance measurement, even at short distances.

Multi-region features:

- The VL53L0x module can measure distances in multiple areas or regions of interest within its field of view.
- This feature allows you to detect and monitor multiple objects at the same time or selectively measure specific areas.

Power consumption:

- The VL53L0x is designed to be energy efficient, making it suitable for battery-powered or low-power applications.

- It offers different power modes to optimize power consumption depending on the specific application requirements.

An OLED display (Organic Light-Emitting Diode) is a type of display technology that uses organic compounds to emit light when an electric current is applied. OLED displays are known for their high contrast, wide viewing angles and low power consumption. A servo motor is a type of motor commonly used in Arduino projects to control the position or movement of mechanical parts. It is designed to rotate within a certain range, usually from 0 to 180 degrees [13]. These tools are connected to each other electronically in Visuino.

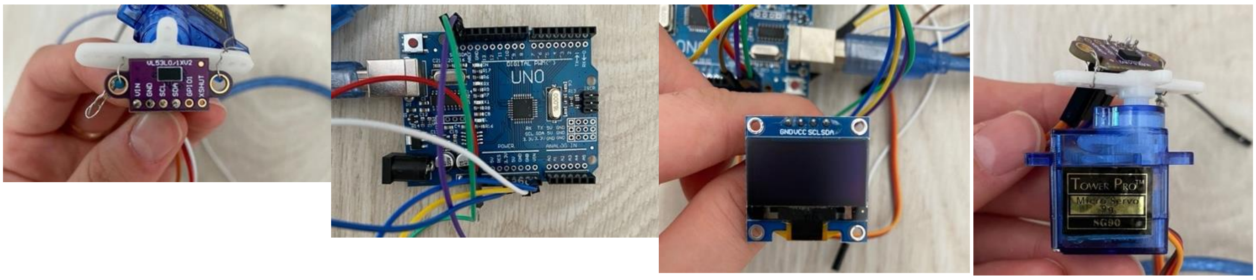
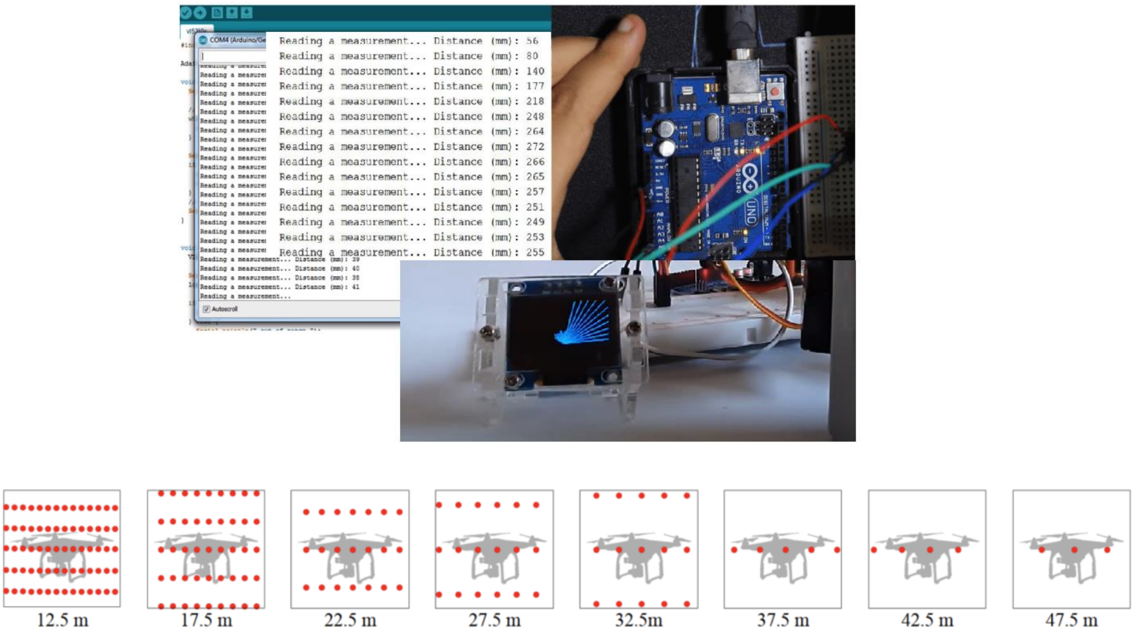


Figure 3 – Hardware set: VL53L0x laser rangefinder ToF module, Arduino microcontroller, OLED display, servo motor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Reading a measurement... Distance (mm): 56
Reading a measurement... Distance (mm): 80
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Reading a measurement... Distance (mm): 177
Reading a measurement... Distance (mm): 218
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Reading a measurement... Distance (mm): 257
Reading a measurement... Distance (mm): 251
Reading a measurement... Distance (mm): 249
Reading a measurement... Distance (mm): 253
Reading a measurement... Distance (mm): 255
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Figure 4 – Display of object detection by distance

As a result, after the device was activated, it is necessary to define the sensor library initially and the lidar sensor module detectobjects by distance. In the main portion of the program, the sensor's distance from the object is measured and its result is shown on the Serial Monitor. The result shows "outside of the range" if there is no data to measure. The Serial Monitor's output has shown below. The recorded range will grow in millimeters as sensor is moved. That is, when an object is placed in front of it, the part of the display where the object is located turns black.

Evaluation metrics. As a joint 3D model, the object detector produces multiple detection results, each containing a 3D box position and a class confidence estimate. Both classification and localization accuracy should be considered when evaluating a 3D detector. The most commonly used evaluation metrics in 2D detection competitions and 3D detection tests are mean accuracy (mAP) thresholds at pass-through fusion (IoU).

The average value of the average accuracy with a threshold value at the intersection by integration:

$$mAP = \frac{1}{|C|} \sum_{c \in C} AP_c \ . \tag{5}$$

Typically, ranked definitions are iteratively assigned to a ground truth value to determine whether a detection is a true positive (TP) - a correct detection or a false positive (FP) - a false detection. The 3D IoU calculated by the fusion between the 3D prediction block and the 3D confidence block of the ground data is used to measure the accuracy of object location, as well as to identify objects as TP and FP to evaluate the overall performance of the detection system. If the 3D IoU exceeds the threshold, this detection is TP, otherwise FP.

Precision is the proportion of all correct detections (TP) across all detections:

$$Precision = \frac{N_{TP}}{N_{all\ detections}} \ . \tag{6}$$

Intersection over Union (IoU) is a metric widely used in object detection tasks, including 3D object detection. It measures the overlap between the predicted bounding frame and the underlying true bounding frame of the object. IoU is particularly useful for estimating object localization accuracy.

$$IoU = \frac{TP}{(TP+FP+FN)} \ . \tag{7}$$

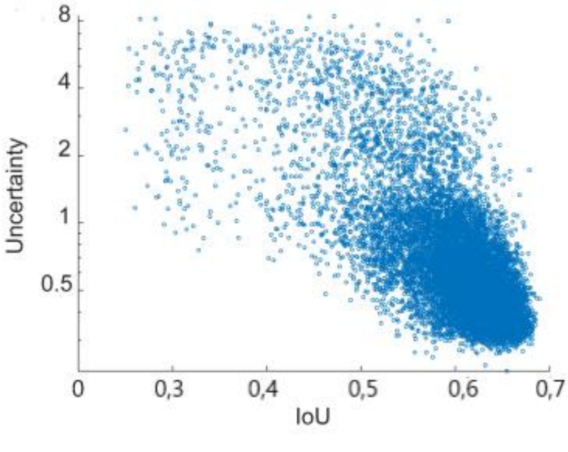

Figure 5 – IoU value depending the distance

Conclusion.

This research work considers the problem of object distance detection using sparse point clouds with the exact 3D position of object surfaces at each point and was carried out as the part of the Zhas Galym project for 2022-2024 on grant funding (Grant No. AP14971031) on the topic "Research and implementation of a bimodal system for real-time detection of Unmanned Aerial Vehicles". The object detection task was implemented using the VL53L0x lidar sensor switching board. This lidar module transmits laser pulses and uses the time of flight to determine the distance between an object and the sensor. It oscillates to locate any obstacles that are in its line of sight and then shows those obstacles on a graphic liquid crystal display (GLCD).

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3D LIDAR СЕНСОРЫНЫҢ КӨМЕГІМЕН ШАҒЫН ҰШҚЫШСЫЗ ҰШУ АППАРАТТАРЫН АНЫҚТАУДЫ ЗЕРТТЕУ

Аңдатпа. Ұшқышсыз ұшатын аппараттары ғылымда, бизнесте, әскери салада, тіпті жеке ойын-сауық үшін де әртүрлі тапсырмаларды орындап, адамдарға қарқынды қызмет етуде. Онымен қоса, олар инфрақұрылымды нысанаға алу, жақын маңдағы тұрғындарды мазалау және әуе көлігіне кедергі жасау сияқты зиянды мақсаттар үшін де жиі қолданылуда. Ұшқышсыз ұшу аппаратының шағын габаритті өлшемі оны анықтауды қиынға соқтырып, проблема туғызады. Көптеген дәстүрлі әдістер мен технологиялар бұл тапсырманы шешуге дұрыс сәйкес келмеуі мүмкін. Бұл жұмыс ұшқышсыз ұшу аппаратын анықтау үшін жарықты және қашықтықты анықтау (LiDAR) сенсорын пайдаланудың техникалық-экономикалық бағалауын сипаттайды. VL53L0x лазерлік қашықтық өлшегіштің ұшу уақыты (ToF) сенсорлық модулі жоғары дәлдіктегі қашықтықты өлшеу үшін пайдаланылды. Нәтижелер LiDAR сенсорларын пайдалану кезінде жұмыс ауқымы нысанды анықтау жылдамдығына айтарлықтай әсер ететінін көрсетті. Атап айтқанда, нысан мен сенсор арасындағы қашықтық 30 м-ден асқанда анықтау жылдамдығы күрт төмендейді.

Түйінді сөздер. Дронды анықтау, 3D анықтау, терең оқыту, лидар, сенсор.

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ИССЛЕДОВАНИЯ ПО ОБНАРУЖЕНИЮ МАЛЫХ БЕСПИЛОТНЫХ ЛЕТАТЕЛЬНЫХ СРЕДСТВ С ИСПОЛЬЗОВАНИЕМ 3D ЛИДАРНОГО СЕНСОРА

Аннотация. Беспилотные летательные аппараты служат людям, выполняя самые разнообразные задачи в науке, бизнесе, армии и даже для личного развлечения. Кроме того, их все чаще используют с плохими намерениями, например, для нападения на инфраструктуру, беспокойства близлежащих жителей и создания помех воздушному транспорту. Скромный размер БПЛА представляет собой проблему, поскольку затрудняет его обнаружение. Многочисленные традиционные методы и технологии могут даже оказаться непригодными для решения этой задачи. В этой работе представлена технико-экономическая оценка использования датчика обнаружения света и определения дальности (LiDAR) для идентификации летающего беспилотного летательного аппарата. Для высокоточного измерения расстояний использовался модуль датчика времени пролета (ToF) лазерного дальномера VL53L0x. Результаты показали, что дальность действия оказывает существенное влияние на скорость обнаружения объектов при использовании датчиков LiDAR. В частности, скорость обнаружения резко снижается, когда расстояние между объектом и датчиком превышает 30 м.

Ключевые слова. Обнаружение дрона, 3D обнаружение, глубокое обучение, лидар, датчик.

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