Defense Systems Information Analysis Center

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LiDAR Use for Unmanned Aerial Vehicles (UAVs)

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The Defense Systems Information Analysis Center (DSIAC) was asked to identify the latest research and development of light detection and ranging (LiDAR) for use in detecting Unmanned Aerial Vehicles (UAVs). Advantages and disadvantages of using LiDAR compared to radar are explained, Department of Defense (DoD) applications and research are listed, and sample commercial-off-the-shelf products are introduced. LiDAR uses lasers with a lower wavelength compared to radio waves used by radar, which allows LiDAR to be more accurate and precise in detecting smaller objects with greater detail. Three dimensional (3D) images are easier to create based on the high-resolution image the LiDAR creates. Current research is trying to develop and lower costs of solid-state LiDAR technology for commercial and DoD use.

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A chief service of the DoD IACs is free technical inquiry (TI) research, limited to 4 research hours per inquiry. This TI response report summarizes the research findings of one such inquiry jointly conducted by DSIAC.

ABSTRACT

The Defense Systems Information Analysis Center (DSIAC) was asked to identify the latest research and development of light detection and ranging (LiDAR) for use in detecting unmanned aerial vehicles. Advantages and disadvantages of using LiDAR compared to radar are explained, U.S. Department of Defense (DoD) applications and research are listed, and sample commercial-off-the-shelf products are introduced. LiDAR uses lasers with a lower wavelength compared to radio waves used by radar, which allows LiDAR to be more accurate and precise in detecting smaller objects with greater detail. Three-dimensional images are easier to create based on the high-resolution image LiDAR creates. Current research is trying to develop and lower costs of solid-state LiDAR technology for commercial and DoD use.

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1.0 TI Request

1.1 INQUIRY

What is the latest research and development of light detection and ranging (LiDAR) technology used for unmanned aerial vehicle (UAV) detection?

1.2 DESCRIPTION

The inquirer wanted to compare LiDAR detection of UAVs with traditional radar methods of detecting UAVs. To do so, understanding the advantages and disadvantages of using a LiDAR platform to detect UAVs was critical. Current research in the U.S. Department of Defense (DoD) and public sectors and commercial-off-the-shelf solutions were also requested.

2.0 TI Response

The Defense Systems Information Analysis Center (DSIAC) staff searched open-source documents, the Defense Technical Information Center's repository, and the Institute of Electrical and Electronics Engineers (IEEE) database for current research using LiDAR to detect UAVs.

Detecting UAVs with high accuracy is critical to DoD operations and strategy to detect, identify, and classify foreign and enemy UAVs. Because LiDAR is more accurate than traditional radar, it is ideal for detecting objects in more detail by creating three-dimensional (3-D) images based on a high-resolution image created by the LiDAR sensor [1].

LiDAR uses light in the form of a pulsed laser to measure ranges by targeting an object, or surface, and measuring the time for the reflected light to return to the receiver. These light pulses help to generate precise, detailed, and accurate 3-D information about the target. It can be used to generate high-resolution maps from the air to locate enemy weaponry for air defense, air traffic control, ground surveillance, navigation, search and rescue, fire control radars, and identifying moving targets. This report will focus on LiDAR applications for detecting UAVs.

2.1 LIDAR VS. RADAR

LiDAR is more accurate than radar and can see through masking items, such as trees, leaves, and camouflage netting. Its high accuracy is due to the high spatial resolution from the beam's small focus diameter and a higher pulse repetition rate. The light pulses are ~100,000× smaller than radio waves used by radar, thus explaining the higher resolution of LiDAR. This helps with detecting and identifying objects.

LiDAR uses lasers with a much lower wavelength than the radio waves used by traditional radar and therefore has better accuracy and precision, which allows it to detect smaller objects in more detail and create 3-D images based on the high-resolution image created [1]. On the other hand, radar is more robust than LiDAR and has a lower starting price. While not as detailed, it works in worse operating conditions and has a wider range than LiDAR. Radar tends to be more affordable—but developing solid-state LiDAR is aiming for a lower price point. Alternatively, radar and LiDAR can be combined with other sensors using data fusion algorithms to create a system with better capabilities.

Current technology is using active optical sensors (e.g., LiDAR) to leverage an optical signal used to illuminate an area or a target of interest [2]. Detection occurs by processing the reflected optical signals from the target. This is advantageous for drone detection since the visual processing of the image from a target can show additional information for its classification. Image and video processing can be used to distinguish friendly and enemy drones and other flying objects, such as birds. Visual sensing can go beyond mere object detection to object classification with high accuracy.

2.2 CURRENT LIDAR RESEARCH

Detecting UAVs is critical to DoD missions to prevent malicious uses by foreign entities toward the United States. A variety of research is being done to develop LiDAR technology to detect, identify, and classify UAVs.

2.2.1 LiDAR Systems

A ground-based aerial target detection system using LiDAR has been developed which relies on sparse detections rather than dense point clouds [3]. The aim is to not only detect but estimate the motion of the UAV being actively tracked. Field experiments used LiDAR and several drones of various sizes to show the effectiveness in detection and tracking using sparse measurements. Using a way to ensure more unified distribution of laser pings ensured a higher probability of detection compared to a lay implementation of a LiDAR-turret system. This approach was validated for short-range LiDAR but can also apply to longer range LiDARs. Daytime use allowed the LiDAR system to work with optic systems to send the UAV quickly to recognize the intruding UAVs, or targets. Nighttime use was successful when daytime optic tracking systems were unable to operate.

Researchers from the Fraunhoft Institute of Optronics, System Technologies and Image Exploitation in Germany, have developed a 360° scanning LiDAR system to be deployed for the detection and tracking of (micro) UAVs in ranges up to 50 m. Researchers have proposed the automatic alignment of an additional sensor (mounted on a pan-tilt head) for identifying the detected objects [4]. The classification sensor is directed by the tracking results of the panoramic LiDAR sensor. If the sensor is an infrared camera, identifying the objects can be done by image processing algorithms. If a higher-resolution LiDAR sensor is used for this task, algorithms must be developed and implemented. After the handoff of the object position from the 360º LiDAR to the verification sensor, the second system can be used for further tracking the object.

A multiarray LiDAR system to detect UAVs using visible light communication was proposed and researched in 2020 by Tunisian researchers from Carthage University [5]. The system is composed of laser sources and laser concentrators arranged through arrays along a spherical form, including a photodiode at its center. The reflected optical energy reaching the concentrators is transmitted to the central photodiode and assesses the distance of the UAV from the system.

Many times, LiDAR changes its position with the movement of a targeted UAV, resulting in an offset in the detected point cloud and scattering laser light from the center to the surroundings. This can cause the detected point cloud to be externally sparse and dense inside. To combat this, a velocity estimation method based on the polynomial fit was used to estimate the position of a LiDAR as it scanned each point in a detected point cloud; research showed it corrected the twisted point cloud [6]. Based on relative distance and density, the clustering algorithm was used to cluster the point cloud with uneven density. Simulations and real-time experiments were carried out and showed the method had a good effect on obstacle detection.

Other LiDAR UAV detection methods have been researched, including using Euclidean distance clustering and particle filtering to track and detect UAVs and using sparse LiDAR detections rather than point clouds. When using Euclidean distance clustering, the particle filter algorithm was used to track the target [7]. In an experiment, the Livox Mid 40 LiDAR developed by the Livox company was used as the front-end sensor to detect the UAV. Experimental results showed that the proposed method could realize the detection and tracking of a UAV. Research in 2020 used ground-based aerial target detection systems that relied on sparse detections to not only detect but estimate their motion and active tracking [3]. Analysis of the performance of such a LiDAR-based detection system showed effectiveness in detecting and tracking UAVs of multiple sizes.

Obstacle Detection and Avoidance System for Small UAVs (sUAVs)

A 2020 research team used a LiDAR that generated a 360° view of the environment around a multicopter UAV to navigate it around any obstacle in any direction [8]. The LiDAR weighed 590 g, with a 10-m range, and had a power requirement of only 8 W, thus making it suitable for use with sUAVs for obstacle detection and avoidance. The developed obstacle avoidance system used the 360° image generated by the LiDAR to calculate an optimal path using a Python script on the flight computer before translating that into a velocity vector for the UAV to follow. The LiDAR settings could be accessed directly by connecting to the user interface. A three-cell battery was required for power, giving the LiDAR a battery life of ~30 min. An Intel NUC processor was used as an onboard flight computer, which processed the LiDAR data and obstacle avoidance algorithm. The flight computer communicates with the flight controller (Pixhawk2 autopilot) using a Python library called DroneKit to send the obstacle avoidance commands.

Ground testing and simulation examined the angle displacement and edge detection methods by communicating the avoidance commands through the DroneKit to the flight controller that orders the UAV to navigate the obstacle-free trajectory. This confirmed that obstacles can be detected and avoided. Future work will involve developing 3-D maps of the environment using the LiDAR and inertial measurement units data so that the obstacle avoidance algorithm can be tested in 3-D space. This addition will help further improve the avoidance algorithm by creating more efficient paths.

2.2.2 Frequency Modulated Continuous Wave (FMCW) Sensors

FMCW radar sensors are a key technology due to their low costs and capability to work at long distances while also allowing a strong robustness to illuminate in weather conditions [9]. LiDAR is being considered for UAV detection in environments where radar cannot be used, using FMCW sensors as a complementary technology.

2.2.3 Massachusetts Institute of Technology Research

Depth Maps

Obstacle avoidance is a key feature for safe drone navigation. However, systems enabling avoidance of dynamic objects like drones are much harder to develop due to the efficient perception and required planning and control capabilities, particularly in small drones with constrained takeoff weights [10]. Obstacle detection systems should be capable of running in real-time, with sufficient field-of-view (FOV) and detection range, ideally providing relative position estimates of potential obstacles. Researchers from Massachusetts Institute of Technology (MIT) have proposed a strategy to perform onboard drone detection and localization using depth maps. It was integrated on a small quadrotor, evaluated through several flight experiments, and demonstrated its capability to simultaneously detect and localize drones of different sizes and shapes. The stereo-based approach runs onboard a small drone at 16 Hz, detecting drones at a maximum distance of 8 m, with a maximum error of 10% of the distance and at relative speeds up to 2.3 m/s. This approach directly applies to other 3-D sensing technologies with higher range and accuracy, such as 3-D LiDAR.

Single-Chip LiDAR Sensors

Most LiDAR systems use discrete free-space optical components like lasers, lenses, and external receivers. To have a useful FOV, this module is mechanically spun around, often while oscillating up and down. This limits the scan rate of the LiDAR while increasing size and complexity, leading to concerns about long-term reliability, especially in harsh environments [11]. Commercially available, high-end LiDAR systems can range from $1,000 to $70,000, which can limit their applications where cost must be minimized.

An expensive LiDAR module is a major obstacle for use in commercial products. Work at MIT's Photonic Microsystems Group is trying to take these large, expensive, mechanical LiDAR systems and integrate them on a microchip that can be mass produced in commercial foundries. The LiDAR chips are produced on 300-mm wafers, with a potential cost of $10 each. The nonmechanical beam steering the device is 1,000× faster than the many current LiDAR systems in use. It can be used to accurately track small high-speed objects only in the FOV for a short time, which is important for obstacle avoidance for UAVs.

2.2.4 Small Form-Factor LiDAR

Developments in small form-factor LiDAR and radar sensors aim to be vital components in overall detect-and-avoid (DAA) solutions for UAVs, particularly sUAVs [12]. Developing sensors primarily for the autonomous ground vehicle market can also be adapted for UAV applications. In 2016, researchers from Ohio University completed a series of ground and flight tests to evaluate the performance of a small form-factor LiDAR and radar sensors in DAA situations. The obstacle detection range vs. obstacle detection size was determined for both sensors in static and dynamic flight modes.

Tests evaluated the detection performance of the LiDAR sensor while operating in a low-altitude environment with clutter present in the form of buildings, people, cars, tree, and brushes [12]. The performance of the LiDAR sensor was assessed with the LiDAR sensor being both stationary and mobile. Within the FOV and ranges up to 15 m, the LiDAR proved successful in detecting other sUAV platforms. Its high update rate (up to 20 Hz) and high ranging accuracy make it more possible to determine the target's position and average velocity when motion compensation and target tracking techniques are applied. An additional benefit of the LiDAR sensor is its ability to detect and map the environment in real-time. This map can then be used for obstacle-avoidance or path-planning purposes.

2.2.5 You Only Look Once v3 (YOLOv3) UAV Detection Method

In 2021, a team of Chinese researchers combined the 3-D range profiled collected by Geiger mode Avalanche Photo Diode (Gm-APD) LiDAR with a deep-learning method to develop a UAV detection method based on the improved YOLOv3 network [13]. The data of UAVs in low altitude were first collected by Gm-APD LiDAR to generate range profile information. Next, the YOLOv3 network was added to combine the local features of the target with the global features to improve the UAV detection accuracy. The UAV trajectory could then be drawn based on the distance information generated. Experimental results showed that the method effectively detected UAV targets and up to 238 mm in real time.

2.3 DOD APPLICATIONS

2.3.1 DARPA

The Defense Advanced Research Projects Agency (DARPA) developed the High-Altitude LiDAR Operations Experiment (HALOE), a laser-based version of radar, to provide high-resolution, 3-D geospatial data. HALOE was first used in Afghanistan in 2010 for tactical missions [14]. The HALOE sensor pod can collect data at high-speed rates, allowing it to map 50% of Afghanistan in 90 days. The U.S. Navy plans to use this LiDAR sensor on a Firescout, a robotic helicopter, to detect pirates. Research is ongoing to provide miniature LiDAR for UAV systems to provide 3-D images from the air.

DARPA's anti-submarine warfare (ASW) continuous trail unmanned vessel (ACTUV) aims to develop unmanned surface vessels that use LiDAR to detect and track nearby surface vessels and potential navigation hazards. While the ACTUV program focuses on demonstrating the ASW tracking capability in this configuration, the core platform and autonomy technologies are broadly extendable to underpin a wide range of missions and configurations for future unmanned vehicles.

2.3.2 U.S. Navy

The U.S. Navy gave a $15.4 million contract to Areté for the Pushbroom Imaging LiDAR for Littoral Surveillance (PILLS) system. PILLS is a compact, lightweight LiDAR system for precision bathymetry and topography that operates from a small tactical, uncrewed, aerial vehicle [15]. The system integrates a dedicated real-time kinematic Global Positioning System for precise mapping, independent of aircraft systems. PILLS requires a fraction of the power of current LiDAR systems on manned aircraft and delivers comparable mapping performance from a small UAV. Schiebel Aircraft GmbH in Vienna and Areté demonstrated PILLS aboard the Schiebel CAMCOPTER S-100 UAV for the Office of Naval Research in the summer of 2021.

The Navy is using PILLS to detect mines, unmanned underwater vehicles, and other target detection. This technology could also be applied and adapted for use in UAV detection.

2.3.3 U.S. Army

Officials of the Army Contracting Command have issued a source-sought notice for the LiDAR Payload for Manned and Unmanned Airborne Platforms project, which aims to determine the state of the art in LiDAR systems for a variety of missions, including object detection [15].

2.4 INDUSTRY SOLUTIONS

In keeping up with DoD demands for LiDAR systems for UAV detection, industry offers a variety of solutions. Some are not fully realized, while others directly apply to detecting UAVs using LiDAR.

2.4.1 Mobileye

Mobileye has developed a LiDAR-on-a-chip prototype the size of a Triscuit cracker that integrates lasers onto the chip through a process called silicon photonics [16]. It uses FMCW technology that sends out a constant stream of light to detect hazards or objects from 200 m away. FCMW systems can calculate the range and velocity of objects, making it more effective than the time of flight that sends out bursts of discreet pulses of light. Although Mobileye's chief executive officer does not expect the LiDAR system to be fully backed until 2025, it has potential DoD applications for UAV detection.

2.4.2 Aeva

Aeva offers the Aeries II, a four-dimensional (4-D) LiDAR with camera-level resolution using FMCW [17]. It is low size, weight, and power and can be used for object detection and classification. The software delivers real-time, camera-level resolution that gives up to 20× the resolution of legacy LiDAR sensors. Users can toggle between ultraresolution views of reflectivity, velocity, and distance for 4-D LiDAR data.

2.4.3 Voyant Photonics

Voyant Photonics produces ultrasmall, chip-scale, FMCW LiDAR sensors for machine perception that offer performance comparable to larger, more expensive LiDAR solutions on the market today. The targeted markets include drone and automation sectors. Voyant intends to leverage semiconductor fabrication processes to incorporate thousands of optical and electrical components onto a single chip [18]. This will harden and further decrease the size of the LiDAR solution, lowering production costs. Voyant's LiDAR operates at a 1550-nm wavelength, allowing for a larger operational range and reducing the risk of interference from extraneous sources.

2.4.4 LumiBird

LumiBird offers the OPAL LiDAR, which creates detailed scans of its environment by tracking objects that enter the FOV [19]. It can detect small drones out to several hundred meters and in urban and cluttered environments by removing a background sense. It can operate in all weather conditions and scans for detecting and identifying intrusion, including ground vehicles and UAVs.

2.4.5 Kyber Photonics

Kyber Photonics, an MIT spinoff, is developing a LiDAR-on-a-chip to enable next-generation autonomous robots and vehicles. The automotive industry needs LiDAR systems that are around the size of a wallet, cost $100, and can see targets at long distances with high resolution. With the support of DARPA, Kyber Photonics is working on a solid-state, LiDAR-on-a-chip architecture that was demonstrated at MIT in 2020 [20]. It has a wide field of view and a simplified control approach.

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BIOGRAPHY

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