PROCEEDINGS OF SPIE

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Potential of LiDAR sensors for the detection of UAVs

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ABSTRACT

The number of reported incidents caused by UAVs, intentional as well as accidental, is rising. To avoid such incidents in future, it is essential to be able to detect UAVs. LiDAR systems are well known to be adequate sensors for object detection and tracking. In contrast to the detection of pedestrians or cars in traffic scenarios, the challenges of UAV detection lie in the small size, the various shapes and materials, and in the high speed and volatility of their movement. Due to the small size of the object and the limited sensor resolution, a UAV can hardly be detected in a single frame. It rather has to be spotted by its motion in the scene.

In this paper, we present a fast approach for the tracking and detection of (low) flying small objects like commercial mini/micro UAVs. Unlike with the typical sequence -track-after-detect-, we start with looking for clues by finding minor 3D details in the 360° LiDAR scans of scene. If these clues are detectable in consecutive scans (possibly including a movement), the probability for the actual detection of a UAV is rising. For the algorithm development and a performance analysis, we collected data during a field trial with several different UAV types and several different sensor types (acoustic, radar, EO/IR, LiDAR). The results show that UAVs can be detected by the proposed methods, as long as the movements of the UAVs correspond to the LiDAR sensor's capabilities in scanning performance, range and resolution. Based on data collected during the field trial, the paper shows first results of this analysis.

Keywords: 3D object detection, 360° LiDAR scans, UAV detection, UAV tracking, scanline analysis

1. INTRODUCTION

The worldwide availability of low-cost UAVs that are easy to operate leads to rising problems, reaching from mislead toys up to abusive use of UAVs for spying or other hostile activities. Especially with regard to sensible areas like airports, company premises or military facilities, options for the detection, tracking and monitoring of undesired UAVs are needed.

Not only the small size of UAVs renders their detection and tracking a complicated task. Their high acceleration capacity, their high top speed and their great maneuverability in all three dimensions make it hard to track the UAVs or to predict their paths reliably. Nevertheless, most of the known standard surveillance techniques can be applied for UAV detection:

- There are various approaches with cameras in the visible [1] [2] and the SWIR [3] spectra. For all camera-based algorithms, the main challenge is the separation of the object from the background. Furthermore, the detection results are mainly dependent on the quality of the images, e.g., the resolution and the focus on the object.

- Another well-proven technique for the detection of (flying) objects is the use of radar sensors. Noetel et al. [4] describe two types of millimeter wave radars for the detection and tracking of small UAVs. The UAV detection with radar is limited mainly by the low radar cross-section of most UAVs.

- The detection of UAVs with acoustical sensors is described by Christnacher et al. in [5]. Based on acoustic antenna arrays, the acoustic signatures of flying UAVs are measured continuously. With this hardware setup, a wide range of UAV sounds (up to 6.8 kHz) can be detected and tracked.

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- The use of active imaging in the form of gated viewing for UAV detection and tracking is presented by Christnacher et al. in [5] as well. The main advantage of gated viewing in contrast to the imaging with CCD cameras is the option to set the gate around the object and to suppress the foreground and the background. For this purpose, the distance to the UAV has to be known initially.

3D point clouds acquired by LiDAR sensors (light detection and ranging) have proven to be a good basis for object detection, e.g., for persons [6], cars [7] or ships [8]. Today's available scanning LiDAR systems represent a compromise between acceptable resolution, realizable refresh rate and field of view (FOV). Since UAVs usually have a small laser radar cross-section (LRCS) [9], the sparse resolution of most LiDAR sensors seems to make them rather unsuitable for UAV detection. On the other hand, LiDAR-based detection methods show many advantages: the separation of the object from fore- or background is comparatively easy, the exact 3D position of the object is known instantaneously after its detection, and the sensor is not dependent on daylight conditions. In this paper, we assess the potential of LiDAR sensors for the detection of UAVs.

2. DATASET

For our experiments we used data which we acquired with the measurement vehicle MODISSA [10] during a joint field trial in cooperation with the Institute Franco-Allemand de Recherches de Saint-Louis (ISL) and the Fraunhofer Institute for High Frequency Physics and Radar Techniques FHR [11].

2.1 Sensor platform MODISSA

The vehicle shown in Figure 1 is equipped with several scanning LiDAR sensors, various cameras for omnidirectional monitoring, an EO- and a SWIR camera on a pan-tilt head and an inertial measurement unit (IMU) and two GNSS (GPS, GLONASS) receivers. We used the two LiDAR sensors Velodyne HDL-64E mounted on the roof in the front of the vehicle in combination with the two LiDAR sensors Velodyne VLP-16 PUCK mounted on the roof in the back of the car. Each HDL-64E is capable of performing 1.3 million measurements per second in a range up to 120 meters. Its vertical FOV is 26.9°, divided into 64 scanlines resulting in a vertical resolution of 0.4°. Due to the rotating sensor head, the horizontal field of view covers 360° with a resolution of about 0.17° at a typical rotation frequency of 10 Hz. This means that every point cloud could consist of approximately 130 000 measurements. However, since not every emitted laser pulse results in the detection of a returning echo (e.g., measurements directed to the sky or water surfaces), the resulting point clouds are usually smaller. The smaller VLP-16 has a vertical FOV of 30° generated by 16 scanlines, leading to a vertical resolution of 2°. At a rotation frequency of 10 Hz, the horizontal resolution is about 0.2° and a single 360° scan could consist of up to 30 000 measurements (3D points). The recording of the LiDAR measurements is time-synchronized and the geometric constellation of the four sensors is known, so the four individual point clouds can easily be merged together.
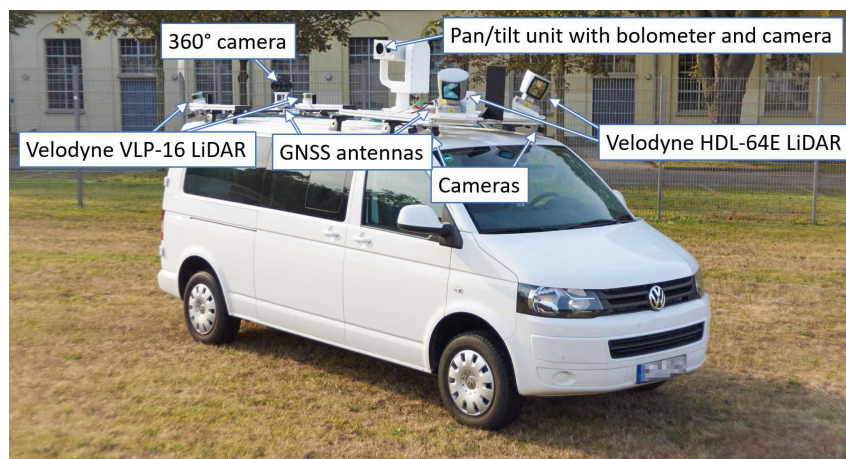

Figure 1: Sensor platform MODISSA equipped with several sensors including four 360° LiDAR scanners.

The two HDL-64E sensors are mounted to the sensor carrier with a tilt of 25° downwards and an angle of 45° outwards (cf. Figure 1), the VLP-16 are mounted to it with a tilt of 15° downwards and 45° outwards. This special configuration

leads to an enlarged FOV in upwards directions (e.g., towards the facades of buildings). Otherwise, if a HDL-64E is horizontally mounted as intended by the manufacturer for applications like autonomous driving, its FOV would cover +2° to -25° in elevation, which would be inappropriate for UAV detection. With our setup, elevation angles up to +27° are realized, at least in parts of the surrounding.

2.2 Field trial

A field trial took place on a testing ground near Baldersheim (France). Its main goal was the acquisition of realistic sensor data in order to assess the capabilities of different sensor technologies for the detection, tracking and identification of small unmanned aerial vehicles (mini/micro UAVs) flying at low altitude. An additional aspect of these activities was the investigation of a sensor network, comprising of a small radar system, distributed acoustic antennas, passive/active EO/IR imaging and static as well as vehicle-mounted LIDAR sensors [11]. The various sensors were distributed to different measurement locations within the structured environment. The sensor vehicle MODISSA was used both stationary and moving. Within this setup, different types of small UAVs (see Table 1) were used for different scenarios like an ascending/descending UAV, an approaching UAV, a UAV that flies attacks, UAV in high altitude patrol, UAV in fast flyby and multiple UAVs in various maneuvers. All the different sensor systems recorded the data of the scenarios. In the sensor fusion approach, it is investigated how the fusion of the individual detection results can enhance the overall detection rate. A more detailed description of the field trial and first results of the other sensors and the sensor fusion are given in [11]. In this paper, we focus on the analysis of the LiDAR data.

Table 1: UAVs used in the field trial

No.	Type	width	length	model
1	quadcopter	25 cm	25 cm	DJI Phantom 3
2	quadcopter	32 cm	32 cm	Parrot Bebop 2
3	flying wing	115 cm	58 cm	Parrot Disco
4	quadcopter	24 cm	24 cm	DJI MAVIC Pro

No. 1 No. 2 No. 3 No. 4

Figure 2: Different mini/micro UAVs that were used during the field trial (see Table 1 for the types).

3. METHODOLOGY

The proposed object detection and tracking algorithm takes advantage of the dense, ordered structure of the point clouds corresponding to single 360° rotations of the laser scanner (organized clouds). In the following, we call that a single *scan* or *frame*, consisting of n rows or scanlines ($n = 64$ for the HDL-64E, $n = 16$ for the VLP-16) and m columns (m depending on the pulse repetition rate and the rotation frequency of the scanner head). With the Velodyne sensors, single frames are generated such that for every emitted laser pulse a data value is recorded, even if it is NaN since no actual measurement was possible (too far, low reflectance etc.). Due to this ordered data structure, for each point the range value of its neighboring points within the same scanline can easily be determined, similar to a range image.

3.1 Segmentation of single 360° scans

As we have shown in an earlier work [12] and as it is known from literature [13], a fast geometric 3D segmentation is possible if the 3D data are given as organized point clouds like it is described above, i.e., if the range of neighboring pixels in rows of the range image is known. At first, this requires a 2D segmentation where neighboring points of a row are clustered as long as no changes in range exceeding a given threshold are found. All line segments (that means at least two neighboring points) with a width less than the maximum width of a target object (we assumed up to 1.2 m for the examined small UAVs, see Table 1) are further examined as possible target-related 2D clusters. Due to the high variety

(a 2D cluster could contain between two and over 200 points), a high number of 2D clusters is detected for each sensor, most of them being artefacts of rough ground in higher distance.

3.2 Merging of 3D point clouds and 3D clustering

The four time-synchronized LiDAR sensors of MODISSA are mounted to the sensor carrier with a fixed, known relative orientation, such that the individual point clouds can be transferred to a common coordinate system. Therefore, it is easy to merge the 2D cluster we get from the individual segmentation runs into one large 2D cluster set. All these 2D clusters are further merged to 3D clusters if they overlap horizontally and do not exceed a maximum vertical distance. 3D clusters with an overall width in x-y direction or a height (z dimension) wider than the maximum dimensions of a UAV are rejected. The number of 3D clusters typically varies between a few and more than several hundred potential objects per frame. Assuming that a UAV has to keep a minimum distance to the scene (walls, trees or the ground), we find 3D clusters that are isolated in the point cloud, i.e., 3D clusters that have no or only very few other points in their direct neighborhood. This detection of isolated clusters is done with an occupancy grid which is set up with all points of all four sensors and a grid size of 0.5 m. As a result, the number of potential UAV objects can typically be reduced from several hundred to less than twenty for each frame.

Because of the small size of a UAV and the limited resolution of the LiDAR scanner, the number of points per UAV is low, even on short distances. Due to this fact, a further geometric analysis of the point cloud objects (the remaining 3D clusters) is not very promising. A better approach for a further classification of the object (UAV/non-UAV) is the analysis of its movement. This requires a tracking of the 3D clusters.

3.3 Tracking of 3D clusters

We record the continuous data stream of each Velodyne LiDAR sensor in such a way that it is subdivided into single 360° scans which we call *frames*. An object detected in the last frame should occur in the current frame at a position near its last position or the extrapolated next position. In order to achieve that, a track list is set up with all detected objects of the first frame. For all subsequent frames, the coordinates of all detected 3D objects are compared with the objects in the track list. Each new object is assigned to the track list object with the minimum distance. If there is no track list object with a distance below a threshold, the new object is set as a new track list object. For each track list object, a prediction of its further movement is calculated using a Kalman filter. For each track list object, the current speed and the overall motion can be calculated and objects without any movement can be classified as non-UAV.

4. EXPERIMENTAL RESULTS

4.1 Field Trial

During the field trial, we recorded over 1 hour of data of eight different scenarios, of which 75 % are supplemented with ground truth data, provided by GPS-receivers attached or belonging to the UAVs. Due to the limited FOV of the LiDAR sensors, most scans do not contain a UAV object. A UAV was detected in 4704 of 39480 frames (12 %). For a quantitative evaluation of our methods (precision and recall), only the scenarios with ground truth information are considered. In 28 224 frames, 2961 UAVs should have been detectable, meaning that the UAV was in the FOV and in a range of less than 50 m. For the evaluation of the detection range and the resolution on the target all frames are taken into account.

4.2 Detection range

The maximum range in which a UAV can be detected is a crucial parameter for the use of a panoramic scanning LiDAR system. The Velodyne sensors are optimized for applications like autonomous driving, not for long-range UAV detection. The maximum range of the HDL-64E is specified with 120 m for a target with 80 % reflectivity. Due to the small LRCS of most UAV, it is to be expected that the maximum range for UAV detection is much shorter, even under good other circumstances. In the data sets we detected 4704 UAVs in ranges between 3.5 m and 50 m (preset maximum detection range). The histogram of the detection ranges is shown in Figure 3 (left side), the prominent maximum values result from UAVs hovering a longer time at the same point. Other than that, the distribution of the detection ranges is dependent on the scenario and the flight path of the UAV. But it can be assumed that the probability of a detection decreases with increasing distances over 30 m. In contrast to that, the false-positive rate (objects or parts of objects erroneously detected as UAVs) increases in distances over 40 m (Figure 3, right side).
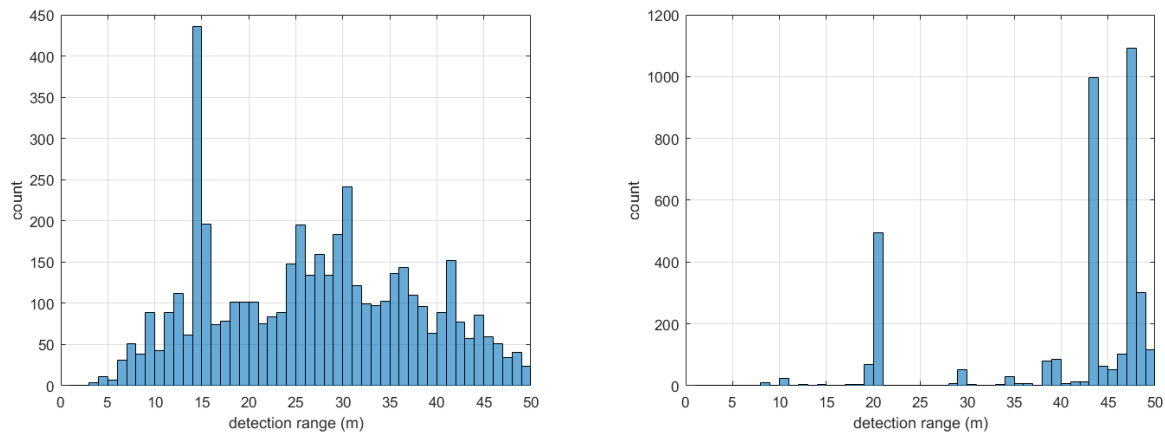
Figure 3: Left: histogram of the detection range of all UAVs, right: histogram of the detection range of all false positives.

4.3 Resolution on target

The detection range is not only limited by the LRCS, but by the resolution of the sensor and the size of the target to be detected. For the HDL-64E rotating at 10 Hz, the horizontal resolution is about 0.17°. This corresponds to a horizontal sampling resolution of 0.15 m on a target in 50 m distance. The vertical resolution of 0.4° leads to a gap of 0.35 m between two scanlines at that distance. Aiming at objects of the size of a mini/micro UAV (see Table 1), it seems doubtful to expect a detection range of more than 50 m. For the VLP-16 scanners, the values for the horizontal resolution are comparable to those of the HDL-64E, but due to the 2° angle between two scanlines, the vertical gap of 0.35 m is reached already at a distance of 10 m. When analyzing the number of points on a detected UAV (see Figure 4) it can be seen that only a small number of UAVs are represented by more than 20 points and most of the detections are performed with less than ten points on the object.
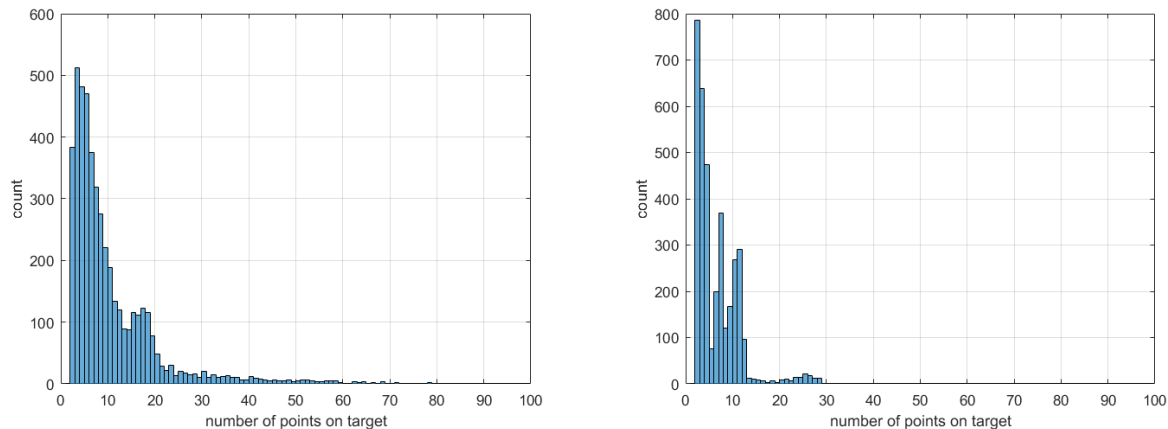

Figure 4: Left: histogram of the number of points on the object (correctly detected UAVs), right: histogram of the number of points on the object (false positives).

This sparse point density on the targets prevents a further classification of the 3D clusters by exact types of UAVs. Even if a UAV is scanned in low distance and therefore higher point density, it is hard to identify an individual type of UAV. The correlation between detection range and points on the target is also confirmed in Figure 5, where the number of points is plotted against the detection range. If the detection range is above 30 m, there are less than 10 points to be expected on the target. To explain the false positives: apparently single isolated objects in the scene like poles or trees are responsible for the high number of erroneously detected UAVs.
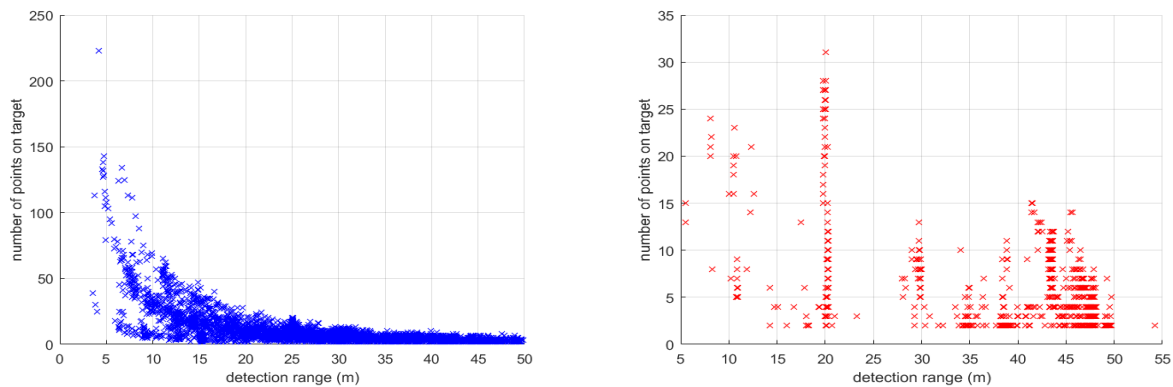
Figure 5: Number of points on the object vs. detection range, left: all UAVs, right: false positives.

4.4 Detection rate

It is hard to give precise numbers like precision and recall for the detection rate, because such calculations would require accurate ground truth information. The ground truth recorded for the UAV's trajectories is derived from their onboard GPS sensor, but the accuracy of that data is limited due to the low update rate of the GPS readings, given the high speed of the UAVs. On the other hand, the overall FOV of the LiDAR sensors in our system is quite complex, due to the different tilt angles of the sensors (see Section 2.1). In detail, the height of the UAV is crucial for its detectability. The height values measured by GPS are generally more blurred than the horizontal values and while scanning 360° horizontally, the vertical FOV of the LiDAR sensors is strictly limited. Furthermore, due to the number of sensors on our sensor platform MODISSA, the FOV of individual sensors can be restricted by other sensors in the line of sight. Therefore, it is hard to decide if a UAV (with blurred GPS height) should have been detectable by a LiDAR sensor.

Although the ground truth information may be imprecise that way, we calculated a detection rate or recall (true positives (TP) divided by the sum of true positives and false negatives (FN)) as well as the precision (TP divided by the sum of TP and false positives (FP)) for our system of four LiDAR sensors. In this analysis, we considered only those measurements that had supplementary ground truth data available. In four scenarios, 2961 UAVs should have been visible in the FOV of the sensors, 1489 of them were detected correctly (TP). 1472 UAVs were visible in the FOV but were not detected (FN) and 3556 objects were erroneously taken as UAVs (FP). Hence the precision can be estimated to 29.5 %. This result is quite poor, but it is linked to the high number of FP which has to be seen in connection with the number of measurements considered (28224 frames) and the trend to misdetections in ranges above 40 m mentioned above (see Section 4.2 and Figure 3). The recall is estimated to 50.3 %, which should be seen as a lower bound, given the imperfect ground truth information. More than 50 % of all FN are detected in a distance of more than 30 m (Figure 6). Hence 3 m to 30 m seems to be the reasonable range for a stable UAV detection with this kind of sensors.
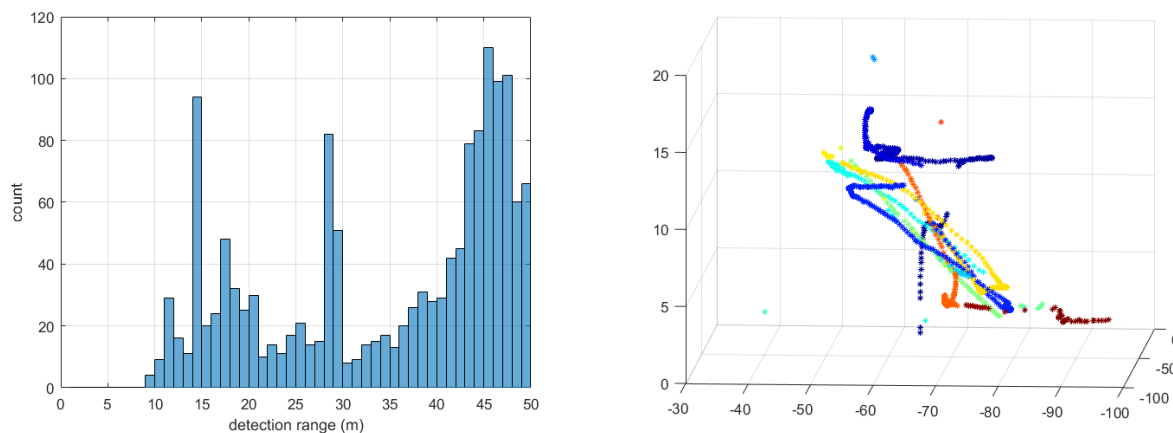

Figure 6: Left: histogram of the detection range of undetected UAVs (FN), right: detected UAVs in scenario 4

In a consideration of all measurements, the false positive rate can be estimated to 9.2 % (3651 FP in 39476 frames). That means there is less than one false positive in ten frames (one second). A UAV was detected and tracked precisely as long as it stayed within the FOV. On the right side of Figure 6, all detections of a single UAV in a single scenario are visualized. It can be seen that a new track (new color) is set up and followed every time the UAV enters the FOV.

5. CONCLUSIONS AND FUTURE WORK

In this paper, we investigated the potential of 360° LiDAR sensors for UAV detection. We have shown that it is possible to detect UAVs with a high probability, as long as the UAV is in the FOV of the sensor and the distance between sensor and UAV is not too big. A remarkable finding was the reduction of the detection rate for distances above 30 m, which can be traced back to the low point density on targets. In addition, the gap between scanlines allows UAVs to remain undetected in these distances.

The major advantage of LiDAR-based UAV detection is the automatically generated 3D coordinate of the UAV. Especially for applications like close-range facility protection and for countermeasures, an accurate trajectory of the UAV is needed. Besides that, LiDAR is robust against changes in illumination and environmental conditions. We participated in a field trial with various sensor technologies; the individual results will be analyzed and compared in the near future. We expect that a fusion of the results of the different sensors can further improve the detection rate. Although a set of different mini/micro UAVs was utilized in the field trial, the presented results do not pay attention to the differences between the UAV types. The impact of the shape, structure and material of different aircrafts should be further examined.

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