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# COMPARISON OF THE LASER SCANNING SOLUTIONS FOR THE UNMANNED AERIAL VEHICLES

# PORÓWNANIE KONCEPCJI SKANOWANIA LASEROWEGO Z BEZZAŁOGOWYCH STATKÓW LATAJĄCYCH

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SŁOWA KLUCZOWE: unmanned aerial vehicle, UAV, point clouds, LiDAR, resolution, comparison

STRESZCZENIE: This article provides description of new achievements in Unmanned Aerial Vehicles (UAVs) in the field of photogrammetry and remote sensing related to laser scanning technology. Platforms equipped with laser scanners are becoming a growing trend in UAV mapping. Two perspectives of development, which use laser sensors, as payload are described in this paper. The first solution is related to application of advanced LiDAR sensor, which collects data with simulated Beyond Visual Line Of Sight UAV (BVLOS UAV) platform from high altitude. The second development was less expensive UAV laser scanning system that acquires data from low-altitude Visual Line Of Sight (VLOS) platform. Additionally, state-of-art of LiDAR sensors, which can be mounted on UAVs, is presented, including categorization of ultralight laser scanners, legal restriction related to operating UAVs equipped with LiDAR system. In the experiment described in the article two datasets are introduced, one collected with Riegl VUX-1 UAV mounted on the first platform and the second with YellowScan Mapper that is a part of second UAV system. Captured datasets are evaluated concerning point density, spatial resolution, vegetation penetration and noise of laser beam assessment. The comparison indicates the differences between the platforms, what determines fields of their application. Therefore, conclusion related to the presented perspectives of development of UAV laser scanning can be drawn and possible future applications of both platforms are discussed.

## 1. INTRODUCTION

Unmanned aerial vehicles (UAVs), for more than decade (Eisenbeiss, 2004; Remondino *et al.*, 2012; Colomina, Molina, 2014) have played an instrumental role in the development of photogrammetry. They have created a new market for applications of remote sensing in areas that were too small for efficient application of standard aerial photogrammetry, such as insurance (Quaritsch *et al.*, 2010), criminalistics (Jurkofsky, 2015) or the redefinition and popularization of the use of photogrammetric tools, as in the case of archaeology (Sauerbier, *et al.*, 2010), real estate (Manyoky *et al.*, 2012) and civil engineering (Aicardi *et al.*, 2016) in which UAV photogrammetry has become more and more popular. UAVs are also competitive with manned platforms in the acquisition of standard photogrammetric products (orthoimages DSM) when the project covers a small area.

However, most of these developments are strictly related to the photogrammetry and acquisition of aerial images, when the second of the most popular aerial mapping technologies — airborne laser scanning — is still waiting for a breakthrough. The first applications of laser scanner on UAVs were connected to the use of a LiDAR sensors, which was mounted on a large unmanned helicopters (Nagai *et al.*, 2009; Lin *et al.*, 2011; Conte *et al.*, 2013). This situation has begun to change in recent years, first in the area of scientific experiments (Wallace *et al.*, 2011) and finally, smaller and lighter sensors have become commercially available (Esposito *et al.*, 2014) for wider groups of users and applications (Petrie, 2013), enabling them to obtain data from smaller multirotors (Tommaselli *et al.*, 2016; Bakuła, *et al.*, 2016).

Nowadays, we can distinguish two main categories of UAV laser scanning (ULS) capabilities, which are similar to those which were mentioned previously in terms of aerial images from UAV. The first one is strictly related to the fields in which UAV could be competitive for manned platforms, while the second one introduces a new quality of airborne laser scanning and brings it to new markets. Both these applications, because of the platforms, sensors and applications, could be seen as two completely different technologies of data acquisition.

In this paper, we describe state-of-art applications in the field of laser scanning from UAV (sec. 2) and then we introduce the experiment (sec 3). The experimental part was designed to be an in-the-field comparison of both mentioned ULS types of data acquisition. As the test field, we chose levees monitoring. This is because linear object monitoring seems to be an area in which ULS could find many applications. Finally, the results (sec. 4) and conclusions (sec. 5) will be presented.

## 2. STATE OF TECHNOLOGY

Recent developments in UAV laser scanning are impressive. There are various platforms and sensors available on the market, which can be used in different applications. The technical aspects of UAV laser scanning are clear and the sensors are being constantly developed. However, the legal aspects of using UAVs still need to be solved and standardized. In this part of the article, practical aspects of the use of UAVs and laser scanners that are available on the market will be presented.

### 2.1. Practical aspects of using UAV

Using unmanned platforms in the mapping industry is not only associated with strictly technical aspects of platform operating procedures and sensor configuration but also with legal issues related to flying. In the process of flight planning, it is important to take into account all the regulations and limitations concerning UAV operations. In fact, national regulations all over the world are becoming more and more precise and restrictive. Recent years have shown increasing legislation trends to adjust current aviation law so that it matches current technology and the common usage of UAV platforms (Rees, 2015). The main goal is to ensure safe cooperation of current aviation with new airspace users, namely UAV operators. Separation in the air and clear procedures are now the most important factors. UAV technology grows stronger each year and we are now fully able to fly unmanned platforms on long distances and at great heights, even with non-professional grade drones. Despite this fact, it is still impossible in most parts of the world to fly legally and safe in this way. For this reason, it is mostly necessary to reduce flight strip lengths while planning photogrammetric flights.

The most popular division of UAV missions is VLOS (visual line of sight) and BVLOS or BLOS (beyond visual line of sight) flights. In some countries (e.g. Australia), it is also possible to fly in EVLOS (extended visual line of sight). It extends the flying range, but remote observers are needed. However, it is not a popular way of flying UAVs, because additional staff, telecommunication devices and staff training are needed. Another important fact is that the airspace is generally zoned, according to ICAO (International Civil Aviation Organization) standards. These divisions clearly show zones where the operation of a UAV is strictly forbidden or permissions are needed to fly one. Those areas are mainly neighborhoods surrounding airports, important infrastructure objects, national parks or military areas.

There are different regulations related to UAV flying, which are restricted in different countries. We present an example from Poland to introduce the trend of using LiDAR sensors mounted on UAV platforms in the present and the future. In 2016, the law concerning UAV flights has been updated in Poland. New regulations are mainly focused on creating clear and consistent procedures for VLOS flights. BVLOS rating operations are very rare and still require complicated registration procedures, airspace reservation and tight cooperation with air navigation and safety services. Thus, VLOS flights are still the only way to fly in the country. Operating in non-controlled airspace (called G-class airspace, according to ICAO) needs no permission or any additional procedures. Despite the lack of legal restrictions about flying height in this kind of airspace, good practices say not to fly higher than 150 m AGL, as this is the lowest flying altitude for manned aircrafts. Flying higher can be extremely dangerous. The UAV operator is always responsible for the flight. Moreover, the manned aircraft always has priority in the air. This leads to a situation in which flying safely and responsibly is only possible in the line of sight and with the lowest possible range. This minimizes the risk of losing control by the operator and assures precise steering.

The way of flying will also depend on the platform type – whether it is a multirotor or a fixed-wing. Each of these two constructions has its own characteristics. It is not clear which type is better for mapping purposes, as it depends on what needs to be done. The main advantages of a multirotor is its agility and hovering capability. As it is a vertical takeoff and landing platform, it is generally safe for imaging sensors, especially when it comes to light and sensitive laser scanners. It is also relatively easy to navigate for the operator. It can fly in very hard terrain without much starting/landing space. Multirotors are also relatively cheaper than planes and are currently much more popular. The drawbacks mainly relate to batteries technology. The flight time is actually very limited. As a result of this, the maximum payload cannot be too high, because then much more power will be needed to fly. The mission range is, of course, also important and it is limited for the same purpose.

Unlike multirotor, fixed-wing is typically a high altitude and long-range platform. Its main advantage is the extended flight time. Planes are also able to fly with much higher speed. This results in much higher efficiency and the possibility of mapping large areas or long corridor objects. In a way that depend on laser scanner technology, the higher the speed and altitude, the lower the point cloud density that can be obtained. The drawbacks of plane platforms relate to difficulties with operating. It is a bit harder to safely operate the planes. They need much more space to land safely and it is operating problematic to land them in hard terrain conditions. Moreover, landing a plane is dangerous for the sensors mounted onboard, which means it needs additional work to design the platform in order to keep the sensors safe and clean. When plane UAVs have more payload, a launching catapult is often needed, otherwise it can take off directly from the hands.

Recently, some hybrid solutions have been presented that combine multirotor and fixed-wing in one platform. A good example of this type of UAV is TerraHawk V by Phoenix Aerial Systems. TerraHawk uses electric engines in its “multirotor mode” and typical gasoline engine while flying as a plane. This solution offers vertical landing and takeoff, platform agility, spot hovering, a flight time of 4-6 hours and the capability to mount an ultralight laser scanner with a light, compact camera. It is possible that this kind of UAV is suitable for mapping purposes with ultralight scanners and cameras.

### 2.1. Laser scanners for UAVs

Nowadays, many laser scanners that can be used on unmanned platforms are available on the market. As a result, various categorizations of UAV laser scanners are presented in literature. According to Petrie (Petrie, 2013), four groups can be distinguished: (1) simple scanners, (2) multilayer laser scanners, (3) multiple spinning laser scanners and (4) terrestrial 3D laser scanners (Starek, Jung, 2015) divide light laser scanners by considering the size and weight of the UAV platforms on which the scanners can be mounted.

In this paper, a slightly different categorization of UAV-dedicated laser scanners is proposed: (1) scanners based on airborne devices, which were recently adopted by manufacturers for use on unmanned platforms and (2) lightweight, UAV-dedicated scanning systems based on multi-layer and multiple spinning laser scanners (Glennie *et al.*, 2010; Mitteta *et al.* 2016).

Representative of group (1) are only the UAV-applicable airborne LiDAR systems produced by Riegl. In this group, the Riegl VUX-1 Series consists of three sensors. The first one is Riegl VUX-1HA, in which the HA stands for high accuracy. The weight of the scanner is approximately 3.5 kg and is easily mountable to any type of moving platform. The maximum measuring range for this sensor is up to 400 m. Riegl VUX-1HA is characterized by competitive accuracy and precision. VUX-1UAV is another example of a lightweight scanner offered by Riegl. The weight of this scanner is approximately 3.5 kg and the maximum operating flight altitude AGL is 350 m. The density of the dataset registered by VUX-1UAV varies from a few to up to several hundred points per square meter. This scanner is easily mountable to UAVs. The third laser in the VUX-1 Series is the Riegl VUX-1LG, in which LG stands for long range. This scanner is distinguished by a maximum measurement range of 800 m and a maximum operating flight altitude AGL equal to 530 m.

Besides the Riegl VUX-1 Series, another example of a lightweight ALS is the Riegl VQ-480-U, which can be mounted on ultra-light aircrafts and UAVs. The flight altitude for this scanner can reach 800 m AGL, capturing datasets with a density of 3 - 4 points per square meter. The weight of the scanner is approximately 7.5 kg.

The second group of UAV-applicable laser scanners is characterized by lightweight sensors (approximately 1 - 2 kg), for which the measurement range is up to 100 - 200 m. The representatives of this group are several commercially available solutions: YellowScan, Phoenix, LidarUSA and LidarPOD, which are based on Velodyne laser scanners (Velodyne VLP-16 and Velodyne HDL-32E). Also in this group, presented at the INTERGEO 2016 trade conference, is the Riegl miniVUX-1UAV.

Comparing Riegl VUX-1 Series scanners with lightweight UAV scanners, Riegl sensors operate at various altitudes; therefore, the point density differs significantly. Moreover, Riegl VUX-1 scanners are more accurate than lightweight sensors, which are able to provide high-density datasets because of the lower operating altitude. If the operating altitude for light UAV scanners grows, the measurement accuracy decreases (Pilarska *et al.*, 2016).

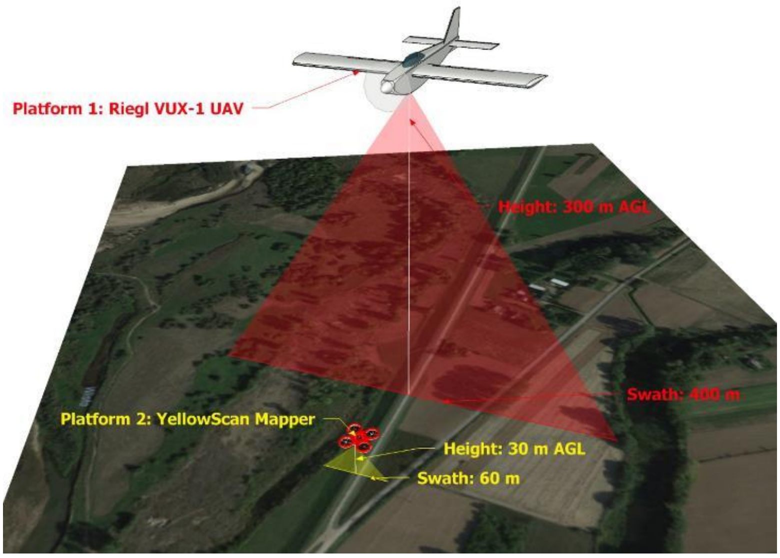


Fig. 1. Graphical comparison of swatch width provided with two types of LiDAR sensors from UAV platforms (Platform 1: Riegl VUX-1 UAV, Platform 2: YellowScan Mapper).

## 3. EXPERIMENT

As mentioned earlier, there are two basic groups of UAV laser scanners available on the market, i.e., long range but relatively heavy, Riegl VUX-1 Series scanners and light, low-altitude scanners delivered by multiple manufacturers. The aim of the experiment was to present datasets captured during two missions, which differ not only in the used laser scanners but also in the flight parameters.

A flight mission utilizing a light, ultra-light and low-altitude scanner was designed for high quality data acquisition over a relatively small area. Data captured with a large UAV, operating a BVLOS flight equipped with the Riegl VUX-1 scanner, was planned as an alternative for standard flood protection using ALS data. Hence, because of the different operating altitude, both data sets differ significantly, especially considering the swatch width (fig. 1) and the expected point density. The analyses focused on noise comparison, penetration of vegetation and spatial resolution of obtained data sets.

### 3.1. Flight missions and Platforms

Most of the information presented in section 2 relates to legal issues. However, there are also some technical limitations and research goals that were essential while planning the flights of both platforms. From a purely technical perspective, all the flights in the research were performed with respect to the possibilities and restrictions of platforms and scanners as well. The experiment data have been acquired by two different platforms (Tab. 1). Each has different LiDAR sensor on board and different flying and operation capabilities.

The ultralight aircraft (Platform 1) flew about 300 meters above the ground, which was appropriate for safe aircraft operation and almost reached the Riegl scanner range maximum. Such flying configuration ensures extremely high productivity of hundreds of kilometers using a UAV scanning device and a UAV autonomous, long-range platform.

The flying missions of small UAV (Platform 2) were limited by maximum flight time and legal issues but also by the effective range of YellowScan scanner. A consequence of the first limitation was a strip length of 300-400 meters. This range was safe and convenient for the UAV operator and platform batteries as well. As missions were performed along the levee back and forth on both sides of the operator’s base, the total distance of 1 mission could reach about 1.2-1.6 kilometers (4 × 300-400 m). The second limitation in this case resulted in a flying height of 30 m above ground level. Flying higher resulted in significantly lower accuracy and sparser point cloud density (Bakuła *et al.*, 2016), which is one of the disadvantage of this scanning platform.

Table 1. Review of platforms used in the research.

| **Scanning platform 1** | **Scanning platform 2** |
|---|---|
| Manned ultralight aircraft VL-3  | MSP Hawk Moth quadrocopter  |
| Riegl VUX-1 UAV scanner  | YellowScan Mapper scanner   |

**Scanning platform 1 (Riegl VUX-1 UAV)**

The first platform is based on an ultralight aircraft equipped with a UAV dedicated laser scanner. Technical data are presented in Tab. 2. The ultralight aircraft has been used as a simulation of a large, long-range UAV platform capable of accomplishing advanced autonomous flying missions. With regard to technological development, this kind of UAV is available right now. It could ensure enough flight time and payload, but current legislation and safety issues in most parts of the world do not permit it to be used easily. However, it is very possible that in the immediate future, the use of such unmanned platforms will be possible and safe. That is why the ultralight is regarded as a good approximation of the future high-range UAV.

Today there are already some ultralight planes that can be operated in manned or unmanned mode and these are called OPVs (optionally piloted vehicles). The Riegl VUX-1 UAV is a lightweight laser scanner dedicated to all kinds of UAV platforms, even those with higher flight and altitude range. The maximum flight altitude set to 350 m AGL is very high. This was an important factor in the research experiment, as mentioned before. Tab. 3. presents the Riegl scanner specification. Additionally, the aircraft was equipped with a Phase One Industrial camera, but the acquired images were not part of this research.

Table 2. VL-3 ultralight aircraft specification.

| **Parameter** | **Value** |
|---|---|
| Wing span | 8.44 m |
| Length | 6.24 m |
| Engine output (Rotax 912 ULS) | 2.05 m |
| Fuel consumption | 73.5 kW |
| Fuel tanks volume | 8-18 l/h |
| Cruising Speed | 90-120 l |
| Speed while scanning | 210-270 km/h |
| Gross weight | 472.5 kg |

Table 3. Riegl VUX-1 UAV specification.

| **Parameter** | **Value** |
|---|---|
| Accuracy / Precision | 10 mm / 5 mm |
| Max. Effective Measurement Rate | 500 000 meas./sec |
| Field of View (FOV) | max. 330° |
| Max. Scan Speed | 200 scans / sec |
| Max. Operating Flight Altitude | 350 m AGL |
| Weight | approx. 3.5 kg |
| Swath width @300 m AGL | approx. 400 m |
| Average point density @300 m AGL | 3 p./m2 |

**Scanning platform 2 (YellowScan Mapper)**

The second platform is a quadrocopter drone equipped with an ultralight laser scanner system. Like platform 1, it collects images using a Sony Alpha camera, but these images were not used in this experiment. The precise specifications are listed in Tab. 4. This platform is a traditional quadrotor capable of lifting payloads of about 4-5 kg. The platform has been equipped with two sensors: the YellowScan Mapper laser scanner (Tab. 5.) and the Sony α6000 digital camera with a 16 mm lens.

The YellowScan laser system is designed to be use with light UAVs. It is accessible to UAV users due to the relatively low price and small weight, which means the scanner is mountable even on smaller platforms. The maximum operational height is limited to about 100 m AGL, which can be a limitation for high altitude platforms, e.g., planes. YellowScan Mapper registers up to three echoes. The scanner is also equipped with a navigation GNSS/INS module with a double-frequency single-antenna GNSS receiver. The scanning data can also be post processed with kinematic precise point positioning – PPP (Rizos *et al.*, 2012). This process allows for an increase in data accuracy.

Table 4. MSP Hawk Moth quadrocopter specification.

| Parameter | Value |
|---|---|
| Engines | 4 (electric) |
| Hoovering time with 3 kg payload | ~15 min. |
| Max. cruising speed | 12 $ms^{-1}$ |
| Average speed | 5 $ms^{-1}$ |
| Weight | 5.9 kg |
| Max. gross weight | 11.5 kg |

Table 5. YellowScan Mapper specification.

| Parameter | Value |
|---|---|
| Accuracy / Precision | 100 mm / 40 mm |
| Max. Effective Measurement Rate | 18 500 meas./sec |
| Field of View (FOV) | 100° |
| Max. Operating Flight Altitude | 100 m AGL |
| Weight | 2.1 kg |
| Swath width @30 m AGL | approx. 60 m |
| Average point density @30 m AGL | 70 p./m2 |

### 3.2. Test area and data acquisition

The test field is located near Płock city in central Poland, next to Vistula River (Fig. 2). There are levees on the riverside that were investigated in the research. Levees are extremely important in this region because of frequent flooding. The condition of the levees is a critical factor and needs to be controlled as frequently as possible. It is needed as a preventive work but also as an essential process when flooding occurs. Ultralight laser scanning technology seems to be a very suitable tool to use in both of these cases.

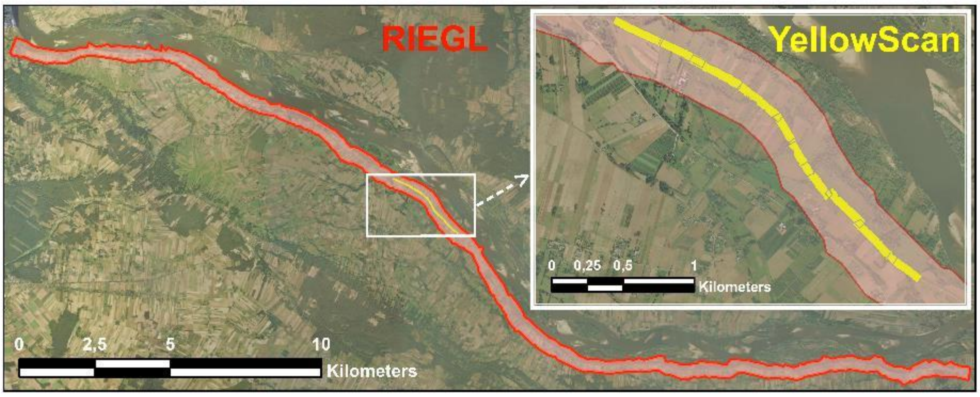


Fig. 2. Visualization of test areas for both type of data collected by platform with ULS.

Table 6. Flight parameters for both flights and basic statistic of acquired point cloud.

| | **Riegl VUX-1 UAV** | **YellowScan Mapper** |
|---|---|---|
| Flight height (AGL) | > 300 m | 30 m |
| Duration of data collection | ~ 30 minutes | ~ 3 hours |
| Number of flight lines (length of flight line) | 1<br>(~ 35 km) | 10<br>(300- 400 m per line) |
| Area of acquired points clouds | ~ 1547.4 ha | ~ 18.6 ha |
| Point cloud density | ~ 3 points/m$^2$ | ~ 70 points/m$^2$ |
| Number of registered echoes | I – 93.04%<br>II – 6.29%<br>III – 0.62%<br>IV – 0.04%<br>(as specified by the manufacturer ,the max number of echoes is practically unlimited) | I – 97.78 %<br>II – 1.85 %<br>III - 0.38 % |
| Recording of intensity | For each echo signal, 16 bit intensity information is provided | No recording of intensity of return signal; instead of if scanner provide information about echo width |

Flight parameters for both flights and the basic statistics of the acquired point cloud are summarized in Tab. 6. The data acquired by Platform 1 were processed in Riegl's dedicated RiPROCESS software, which is a standard workflow recommended by the manufacturer.

The final point cloud of this process was used in the research. The data from Platform 2 were processed using YellowScan plugin, operated in QGIS software. The trajectories were also post processed with the Kinematic Precise Point Positioning service. This kind of trajectory processing allows for an improvement in the final point cloud accuracy. A detailed description of the use of this methodology was presented in the work of Bakuła *et al.* (2016).

## 4. RESULTS

Data obtained during the missions were captured with platforms that differed considerably regarding the technical parameters of both the laser scanners and the platforms. In most cases, evaluation of primary product of LiDAR data processing: digital terrain model (DTM) is carried out using vertical error. In this case two presented data sets: Riegl VUX-1 UAV point cloud from AGL over 300 m and YellowScan Mapper point cloud from 30 m were compared using over 100 control points regularly located and measured with GNSS RTK technique. The results were quite comparable: RMS for Riegl VUX-1 UAV was 0.06 m and for YellowScan Mapper – 0.12 m. Comparing these values it can be said that they present centimeter-level accuracy. Referring to other issues related to analysis concerning the point density, spatial resolution and vegetation penetration these datasets differs very much which will be presented in this section.

### 4.1. Spatial resolution

The spatial resolution of the acquired point cloud is one of the most crucial parameters for describing the LiDAR data. It determines the details that will be noticed during the interpretation and analysis. The most popular indicator of spatial resolution, in the case of airborne laser scanning, is the point density, which is defined as the number of points per square meter. The density of the datasets registered by Riegl and YellowScan scanners differs significantly (tab.6 ). Therefore, more detailed analysis of this feature was conducted. Results were presented both as histograms and as raster files. According to the histograms (Fig. 3), which were generated using OPALS software (Mandlburger *et al.*, 2009), YellowScan delivers a much denser point cloud than Riegl.

Additionally, point cloud density distributions differ considerably. In the case of the dataset registered by Riegl scanner from the long-range Platform 1, points are distributed regularly. Higher density occurs only on trees, which is a normal phenomenon for a LiDAR dataset. Based on an examination of Figure 4, YellowScan's point cloud density from the low altitude Platform 2 is not constant across the scanned path, because the density decreases far more in the outer zones of the footprint. This makes the dataset nonuniform, an issue that may be problematic during the point cloud processing.

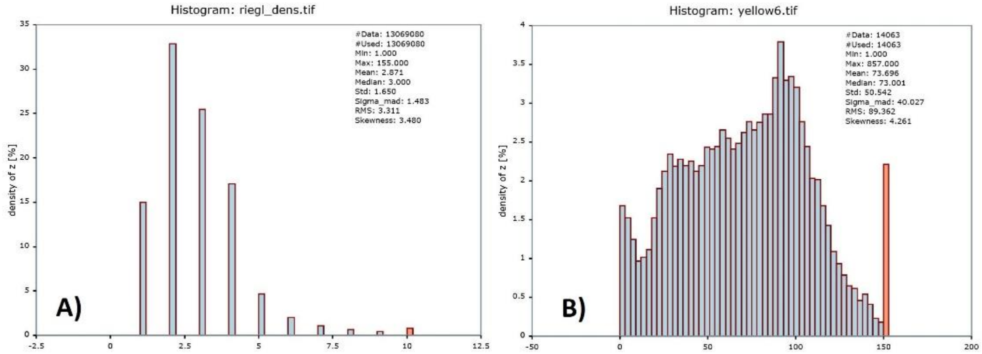


Fig. 3. Histograms presenting point density of datasets acquired with (a) Platform 1: Riegl VUX-1 UAV, (b) Platform 2: YellowScan Mapper.

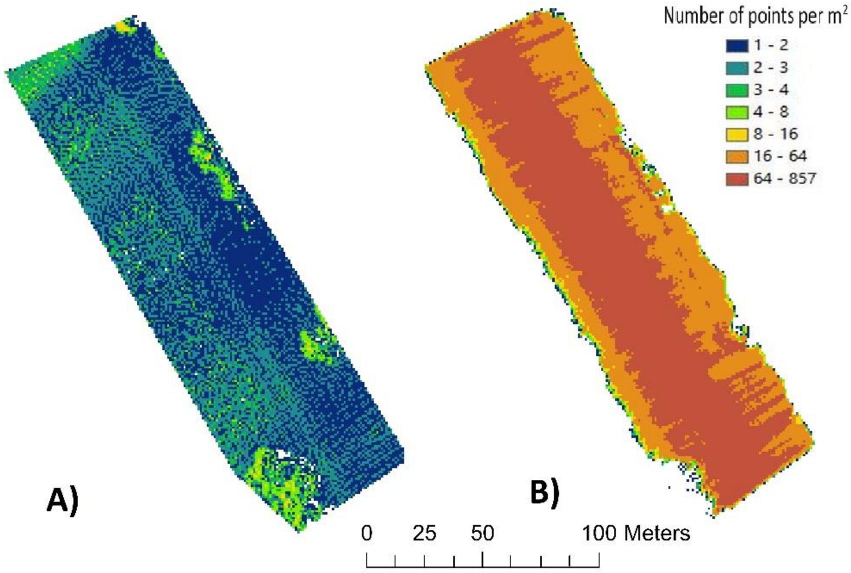


Fig. 4. Raster images presenting point densities: (a) Platform 1: Riegl VUX-1 UAV, (b) Platform 2: YellowScan Mapper.

Comparing mean densities, for the Riegl scanner it is about three points per square meter, whereas, for YellowScan, it is more than 73 points per square. This difference is a result of many factors connected to the flight mission (flight height above ground, speed) and the used scanner (measurements frequency). In this case, the factor that has the biggest influence on the point density is the operating altitude, which was already described and clearly explained (Tab. 6). Such a high difference in point density has an influence on further data processing, in particular on the possibilities of data usage.

Considering airborne laser scanning data sets, the most popular way of using them is to create digital elevation models. Generating a DTM or DSM, minimum grid size depends on point density. Figure 5 shows shaded presentation of DSM overlaid with color-coded elevation for both data sources obtained with UAV LiDAR sensors. Despite the comparable accuracy, it can be seen clearly that point cloud from the low-altitude sensor (YellowScan) provides more detailed information. For data obtained with the YellowScan scanner, the interpretation potential is higher, because the grid size of the raster file may be smaller when the point density is a few times higher. Using the provided digital elevation models, the levee can also be presented with more detail. The DSM generated from the Riegl dataset due to lower point cloud density is smoother compared to YellowScan's one. Additionally, the potential for more detailed interpretation is connected not only with grid resolution but also with the size of the smallest detail, which might certainly be registered during data acquisition. In Figure 6, parts of the two DSMs are provided; one is generated from a point cloud delivered by the Riegl scanner and the second one which is generated from the YellowScan dataset. Even though the grid size is the same for both models (1 m), smaller objects (fruit bushes) are registered more properly and numerously with the YellowScan dataset.

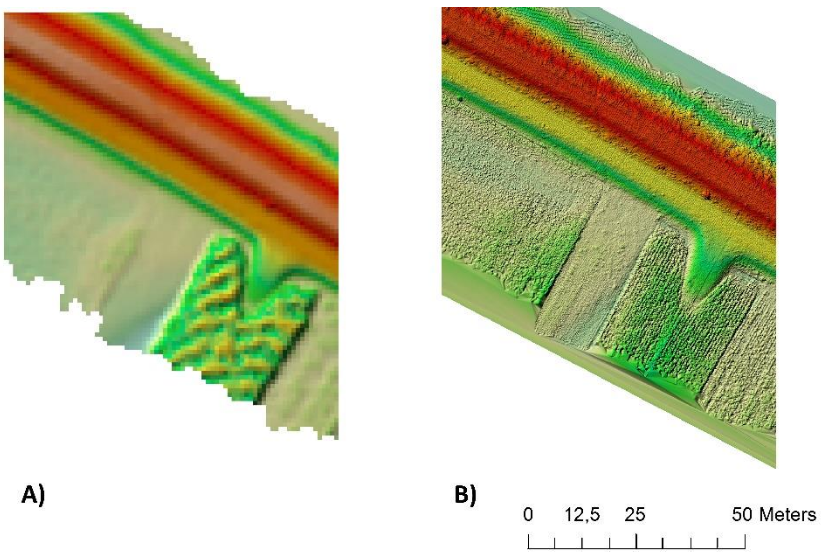


Fig. 5. Digital surface model created from (a) Platform 1: Riegl VUX-1 UAV data with grid resolution of 0.5 m, (b) Platform 2: YellowScan Mapper data with grid resolution of 0.1 m.

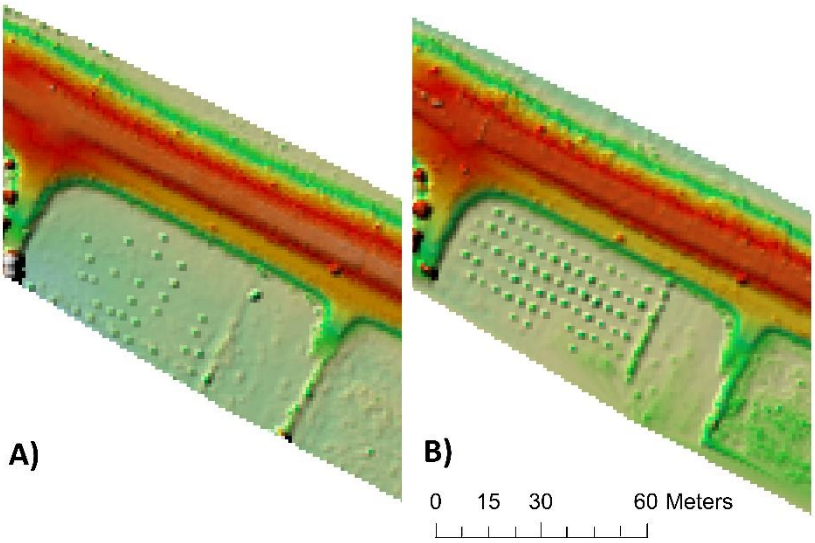


Fig. 6. Digital surface model in resolution of 1 m created from (a) Platform 1: Riegl VUX-1 UAV, (b) Platform 2: YellowScan Mapper.

Spatial resolution, besides digital surface models, can be compared directly on point clouds registered by both platforms. Point cloud densities are significantly different. However, apart from the total number of 3D points, the height above ground level (AGL) and scanning angle are factors determining point distribution. In the following example, two types of objects - an outbuilding and a medium-voltage power line, which were located in the immediate vicinity of the levee - were analyzed.

In the case of the outbuilding (Fig. 7), the density of the point cloud acquired with the Riegl VUX-1 UAV – scanner (Platform 1) is sufficient for automatic roof-plane detection or ground-floor vectorization processes. Thereby, this kind of data enables the generation of a LOD2 building models (as well as from the ALS data). Apart from the several-times-greater number of points per square meter for YellowScan's point cloud (Platform 2), lower altitude with a greater scan angle leads to the registering of the sidewall of the outbuilding. As a result, additional information about the elements of the sidewall, such as the door or windows, can be provided. Moreover, it is possible to obtain a more accurate contour of the ground floor by fitting a plane to the sidewall points in 3D rather than by projecting a roof edge (as in the case of ALS or ULS from the long-range platform).

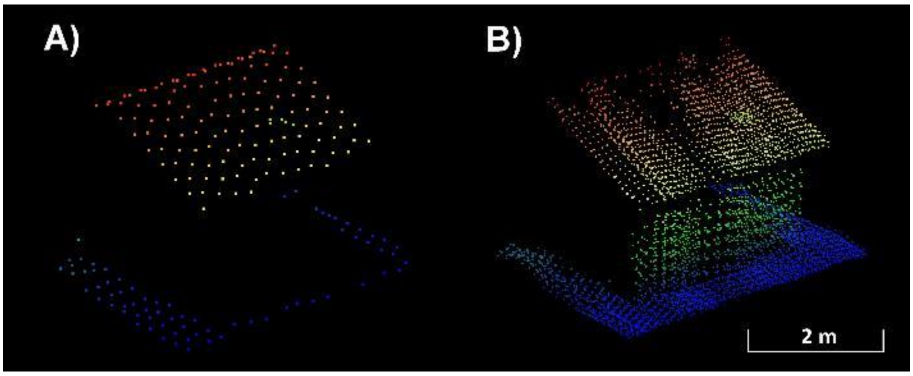


Fig. 7. Point cloud for outbuilding from (a) Platform 1: Riegl VUX-1 UAV, (b) Platform 2: YellowScan Mapper.

Another example of the performance quality of the point cloud is the linear objects (power lines), which were often inventoried based on ALS or ULS data. Power lines can be detected from point clouds with density of several points per square meter and as well as from a few points per square meter (Zhu, Hyyppä, 2014). Figure 8 presents an example of a medium-voltage power line recorded during both experimental missions.

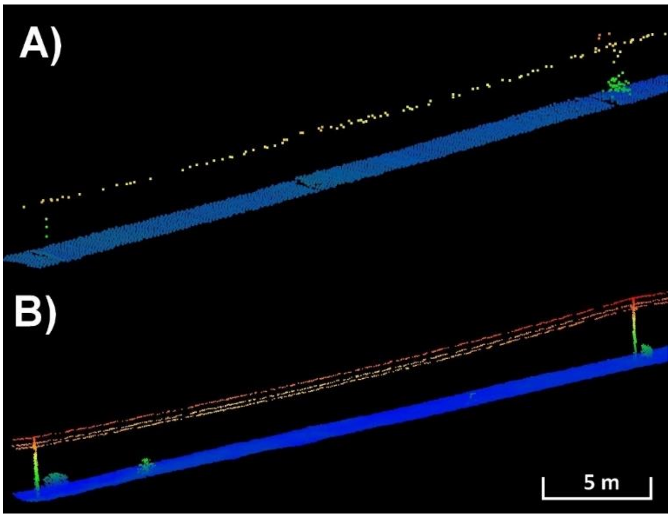


Fig. 8. Example of medium-voltage power line, registered by (a) Platform 1: Riegl VUX-1 UAV, (b) Platform 2: YellowScan Mapper.

Point cloud, registered by the Riegl scanner from the long-range Platform 1, allows for the fitting of a wire to the 3D points and for the determining of the approximate location of the next pylons along the power line corridor. Higher point cloud density, as in the case of the YellowScan on the low altitude UAV, offers the opportunity to build high-quality, professional 3D models of pylons and provides more accurate geometric information on wires.

### 4.2 Measurement noise

Point cloud quality is also strongly connected to the measurement noise. According to the technical specifications of the laser scanners, which were presented in Tab. 3 and 5, range measurement accuracy differs meaningfully. Riegl's scanner range accuracy is 1 cm, while for the YellowScan sensor, it is 10 cm. The influence of range accuracy can be easily checked using flat surfaces, e.g., a road. Therefore, to examine the influence of the range accuracy, the standard deviation of the interpolated grid height (sigma Z) and the standard deviation of the unit weight observation (sigma 0) for a roof surface were calculated and compared (Fig. 9). According to sigma Z values, the differences between sensors are relatively small. For both datasets, sigma Z values are up to 5 cm. For most of the roof surface, the sigma 0 values are lower than 5 cm, whereas, for the YellowScan dataset, there are more areas in which sigma 0 ranges from 5 to 10 cm.

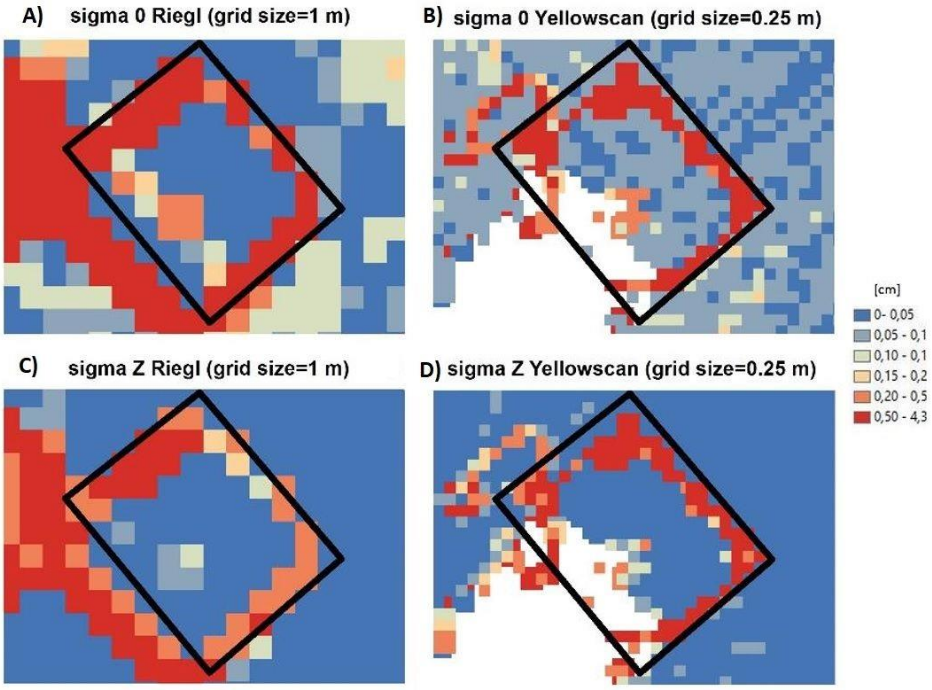


Fig. 9**.** Differences in distribution of sigma 0 (a) Platform 1: Riegl VUX-1 UAV, (b) Platform 2: YellowScan Mapper and sigma Z (c) Platform 1: Riegl VUX-1 UAV, (d) Platform 2: YellowScan Mapper values on the roof surfaces.

### 4.3 Penetration of vegetation

As has been shown in an earlier section, the Riegl and YellowScan Mapper are multiple-return LiDAR systems. Therefore, the sensors offer the opportunity to register points, define the canopy surface and penetrate into vegetation. The potential of both measuring systems may be set out through assessment of penetration effectiveness. A visualization of the multiple LiDAR returns for a single tree for point clouds registered using two variants of platforms is presented in Figure 10. In spite of the lower density, ground points under vegetation were registered regularly for Riegl's point cloud. Figure 10. shows that a lack of ground points is visible under a neighboring, dense bush. In the case of Platform 2, the scanning angle has a significant influence on the penetration efficiency. The power of the laser beam in the Riegl scanner is high enough to penetrate all the way down through the tree canopy during registration at 300 meters.

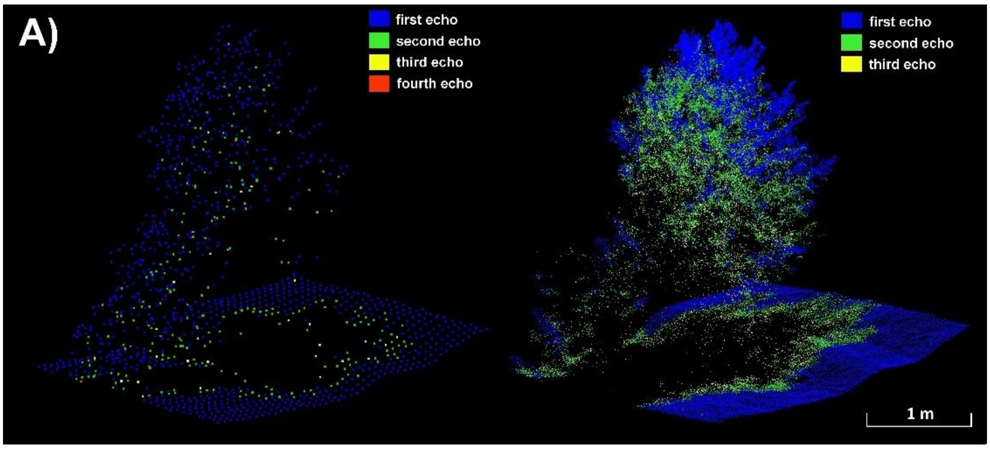


Fig. 10. Visualization of multiple LiDAR returns for a single tree for point cloud registered with: (a) Platform 1: Riegl VUX-1 UAV, (b) Platform 2: YellowScan Mapper.

In addition, histograms that present point counts that depend on the return number of the point clouds registered by both scanners, are presented in Figure 11. Despite the fact that the Riegl scanner registers more echoes than the YellowScan scanner, the distribution of the first three returns looks very similar. In both variants, the first return points represent the highest level of the tree crown. The second and third echoes were registered for the rest of the tree and mostly the ground points. The point cloud data acquired by Riegl contains a few fourth return points.

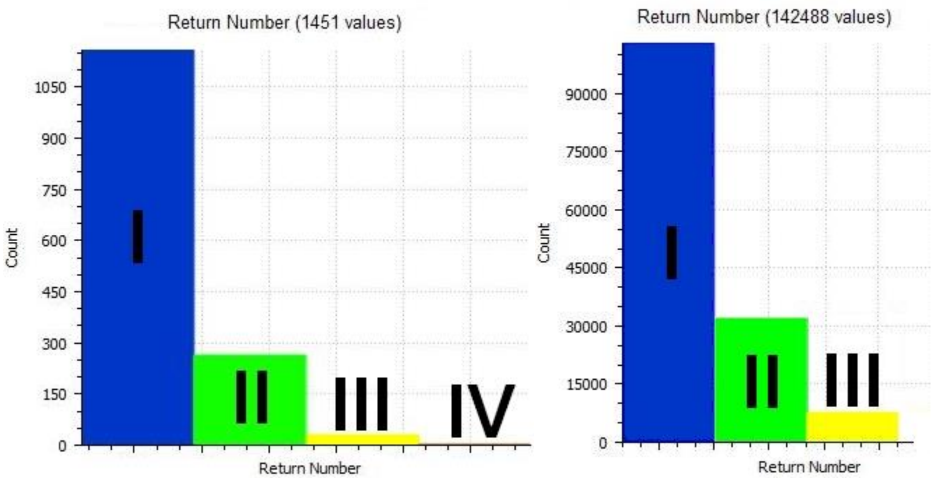


Fig. 11. Histograms presenting point count depending on return number for point cloud registered by: (a) Platform 1: Riegl VUX-1 UAV, (b) Platform 2: YellowScan Mapper.

In the next step, the efficiency of UAV – LiDAR penetration through low vegetation may be investigated on the basis of cross sections of point clouds in places where the grass reaches thirty centimeters or taller on the levee. The digital surface model, which was generated from digital photographs taken synchronously with laser scanning on the ultra-light scanning Platform 1, is used as the reference height of the low vegetation (DSM profile). The cross section, which was surveyed using RTK Technology, is treated as the reference for the elevation data (RTK profile). Cross sections in two variants of the point clouds, together with reference profiles, are presented in Figure 12. Both sensors can penetrate through low vegetation successfully. The point cloud from Riegl and from the YellowScan dataset contains many points that represent the ground level. The results are quite surprising, because it was expected that the difference between the power beams of both scanners will be more visible in the penetration of vegetation. Looking at Figure 12, the influence of the range accuracy, which was analyzed in section 3.2, is clearly visible in the YellowScan variant. Both scanners did not register any points, markedly located under the RTK profile, which could indicate the alarming measurement errors. The noticeable difference between both point clouds and the DSM profile, occurring on the right levee slope, does not mean that the top level of the grass was not registered by both scanners. The occurrence of a height interpolation error, during the DSM generating, is much more probable.

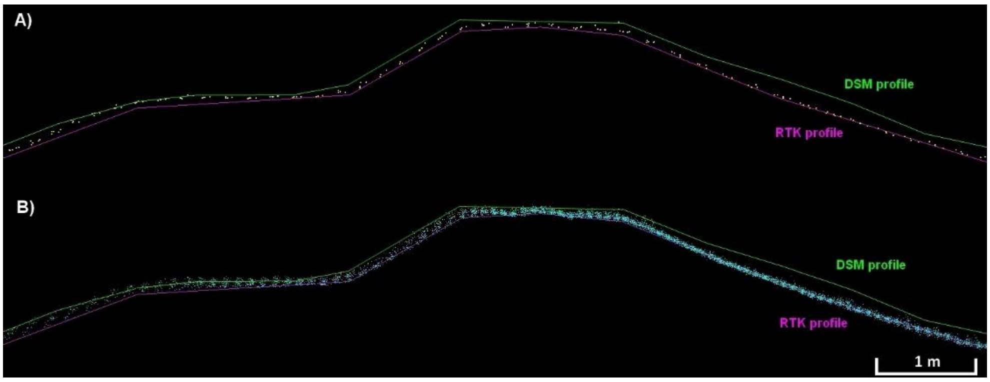


Fig. 12. Cross sections in two variants of the point clouds for (a) Platform 1: Riegl VUX-1 UAV, (b) Platform 2: YellowScan Mapper, together with reference profiles DTM (from RTK) and DSM (from UAV photogrammetry).

## 5. CONCLUSION

In this paper, two distinct UAV missions were presented, in which different laser scanners were used. These different approaches offer a perspective on the development of the market related to UAV LiDAR solutions and applications. In the experiment, a manned ultra-light aircraft was used instead of a heavy UAV platform, because the final platform is still being constructed in the SAFEDAM project (Kurczyński, Bakuła, 2016). The two solutions presented in the article are compared, although they are not competitive. Each of their application possibilities and flight parameters differ. YellowScan Mapper, mounted on a fixed-wing platform and flying at high speed at a higher altitude, would provide a less accurate point cloud. On the other hand, if Riegl VUX-1 UAV is mounted on quadrocopter and flies lower and slower, it will be ineffective and because of the high point density, this data could be dedicated to very detailed applications.

According to the experiment, two analyzed platforms deliver significantly different datasets. The first platform, equipped with the Riegl laser scanner, operates on 300 m AGL and delivers a low-density point cloud. On the other hand, the second platform, on which the YellowScan Mapper is mounted, flies 30 m AGL and provides users with a high-density dataset. As a result, differences between the spatial resolutions of the digital surface models generated by the given datasets can be noticed easily. Point density determines also the possibility of registering thinner linear objects such as power lines. According to penetration analysis, both sensors have registered points on the ground. The return number distribution for both payloads is similar; however, a greater number of fourth returns were expected for the Riegl scanner.

The results of the comparison prove the future possibility of creating a fixed-wing platform equipped with laser scanning, which could become an alternative to traditional airborne laser scanning. The biggest obstacle is the measurement platform, which needs to be efficient and fly beyond the visual line of sight, what is limited by law. Despite the requirements, this technique will certainly be improved in the near future. The second solution is based on light laser scanners, which can be competitive for low-altitude photogrammetry. In future developments, this scanner will become more accurate and cheaper compared to now. Along with the laser scanners, the efficiency of the UAV platforms will continue to grow.

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# PORÓWNANIE KONCEPCJI SKANOWANIA LASEROWEGO Z BEZZAŁOGOWYCH STATKÓW LATAJĄCYCH

SŁOWA KLUCZOWE: bezzałogowe statki latające, UAV, chmura punktów, LiDAR, rozdzielczość, porównanie

**Streszczenie**

Artykuł zawiera opis koncepcji rozwoju bezzałogowych statków latających (UAV) w dziedzinie fotogrametrii i teledetekcji związanych z technologią skanowania laserowego. Platformy wyposażone w skanery laserowe stają się coraz bardziej zauważalnym trendem w wykorzystaniu UAV w geodezji i kartografii. W niniejszym artykule opisano dwie perspektywy rozwoju tej branży, które wykorzystują sensory laserowe. Pierwsze rozwiązanie jest związane z zastosowaniem zaawansowanego skanera, który zbiera dane z symulowanej w doświadczeniu platformy poza zasięgiem wzroku (BVLOS UAV) z dużej wysokości. Drugą koncepcją rozwoju rynku jest pokazanie przykładu systemu skanowania laserowego UAV, który pozyskiwał dane z platformy w zasięgu wzroku (VLOS) na małej wysokości. Ponadto w artykule przedstawiono najnowocześniejsze skanery LiDAR, które mogą być montowane na UAV, w tym kategoryzację ultralekkich skanerów laserowych oraz prawne ograniczenia związane z eksploatacją UAV wyposażonych w system LiDAR. W opisanym eksperymencie w artykule analizowano dwa zestawy danych: jeden zebrano za pomocą UAV Riegl VUX-1 zamontowanego na platformie w postaci załogowego płatowca i drugiego za pomocą YellowScan Mappera, który jest częścią systemu UAV z platformą wielowirnikową. Przechwycone zestawy danych są oceniane pod względem gęstości punktów, rozdzielczości przestrzennej, możliwości penetracji roślinności i obserwowanego szumu wiązki laserowej. Porównanie wskazuje różnice między platformami, a tym samym koncepcjami i ich możliwymi zastosowaniami w perspektywie rozwoju skanowania laserowego UAV.

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