



The GSD dependency of the eTOD photogrammetric survey

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Received: 16 October 2018 / Revised: 15 February 2019 / Accepted: 13 June 2019 / Published online: 1 July 2019
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Abstract

We have been looking for a safe and economical technique for making an Electronic Terrain and Obstacle Data collection (eTOD). We have developed a method and a quality assurance system which covers the complete process from making an aerial survey to data processing. In addition to presenting the method, the article focuses on the dependence of the aerial photogrammetric obstacle survey on spatial resolution. We have found that the most effective way of making an obstacle database is by making a passive aerial remote sensing, which is supported by a high-speed (200–600 km/h) fixed-wing aircraft. The high-speed aerial camera systems with vertical and oblique camera axis are more accurate and more aerial triangulation can be used with them than with classic single camera solutions. The carefully planned flights for fixed-wing platforms provide a stable camera position and the homogeneous shooting network more easily, and obstruct the air transport for less time. In most cases, a terrestrial survey in itself does not allow the creation of the eTOD within a reasonable time frame and with complete safety, because of hard-to-reach areas, subjectivity and slow traversal in the field.

Keywords Airport · Aerodrome · Obstacle detection · Aerial survey · Photogrammetry · Remote sensing

1 Introduction

Throughout the years, airport regions, by being the engines of economic growth, have become outstanding and prominent centers. The development of aerodromes, which is among the highlighted objectives of many countries, has the

advantage that by contributing to the free flow of services, it serves both local and global transport goals at the same time. The International Civil Aviation Organization (ICAO) member states that aerodromes nowadays are requiring more and more advanced infrastructure, and for the developments that contribute to this, the mapping of the airfield terrains is as indispensable as mapping the landscape, obstacles, and hazards in the environment. To maintain safety margins, accurate and detailed Terrain and Obstacle Data are essential.

The ICAO defines policies and Standards and Recommended Practices, or SARPs. These policies and SARPs are used by ICAO Member States. A Standard is a rule that sets the minimum requirements, so the included parameters will not be ignored or carried out with less obligation, but at the same time, it permits a stricter way during legislation. Standards are recognized tasks of the ICAO Member States. Recommended Practice is also a requirement for uniform application by the Member States; it is feasible and desirable, but not obligatory. In the case of Recommended Practices, there are optional choices given for the Member States by the ICAO, therefore the regulatory text contains alternatives, recommendations, and comments [1].

Taking the Standards into account is emphasized by the ICAO and other authorities. Electronic Terrain and Obstacle Data (eTOD) collection incorporates Standards as well,

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which are defined by coverage areas [2] and by electronic terrain [3] and obstacle data features [4].

In the case of an aerodrome survey, eTOD is required within a 45 km radius area or TMA (terminal maneuvering area) boundary (whichever is smaller)—and 10 km radius area from the extremity of runway strip (area 2a) of the aerodrome. Obstacle data elements are features that shall be represented in the data sets by points, lines, or polygons [5]. For example, the top of an antenna can be represented as a point as long as the bounding box sliding towards the ground does not exceed the footprint threshold [6].

The article presents an internationally accepted method of aerodrome surveys through Interspect's survey and designer and Erenfield's aviation juristic and implementer group. In addition to the development and implementation activities, the group provides assistance to airports in adjusting to the international and local regulations, and their work enables the whole process to be overviewed easily.

One of the alternatives of surveying aerodromes consists of the conventional terrestrial survey, but in applying this method exclusively, experts may face many difficulties. This method does not allow the survey of those spots which are difficult to access, and in addition it is time consuming and inefficient; overall, it is not recommended by itself for surveying larger areas. In addition, field geodetic surveys for areas of hundreds of square kilometers do not allow the execution of a survey with proper density.

Worldwide, the aerial survey is the solution. Unmanned aerial vehicles (UAVs) have become widely used and available, but the small size UAVs do not allow a cost-effective survey of larger areas. Among the reasons for this technique's inadequacy for surveying larger areas is that the mass of equipment that they are able to carry is limited, and that in some of the Member States there are some legal obstructions that can make the execution of an adequate survey impossible. Other limitations should also be mentioned, for example, UAVs could not be used in controlled traffic regions (CTRs).

Nowadays for aerodrome mapping, Terrain and Obstacle Data with the relevant ICAO numerical requirements can be most efficiently collected by the method of aerial photogrammetry. The TOD Working Group indicates that with a photogrammetric method, the required height accuracy of easily distinguishable objects with ± 30 cm is feasible [6]. This far beyond exceeds the accuracy required by ICAO. This accuracy was also achieved with a GSD of merely 15 cm with 55% and 60% overlap. In the case of higher spatial resolution, even higher accuracy is attainable.

Although there are other similarly accurate procedures (e.g., laser scanning), their higher cost often puts an unnecessary financial burden on the customer.

For many use cases such as narrow columns and complex obstacles mash inspections, LiDAR (light detection and

ranging) point clouds require additional classification which might be very laborious and often need expensive software. Depending on the application, photogrammetry services are typically cheaper than LiDAR, simply because the investment in the hardware has to be amortized.

The Eclips LiDAR, for example, can reach a density of 5 point per m^2 at 600 m altitude above ground level (AGL) with 60° field of view. In this case, the stripes are approximately 700 m wide. Meanwhile, its optical camera takes images with 9 cm spatial resolution.

Compared to this, with the photogrammetric process of the 5 cm GSD images of low cost (less than 10,000 €), moderate resolution, 50–80 MP aerial camera, at least a three times greater density point cloud can be made with similar or shorter flight duration.

In case of the Galaxy LiDAR, the width of the strips is 10–115% of the altitude AGL. From 500 m altitude, AGL 60 pts/ m^2 can be collected up to 210 km/h groundspeed. At the same time, the minimum target separation distance guarantees the detection of thin, tall objects only which are wider than 70 cm. For example, the small antennae on top of the buildings have to be captured, but they are hardly detectable in the aerial laser scanned point cloud. In contrast, in case of photogrammetry, the thin obstacles which are not represented by the point cloud are shown in the orthophotos, and they are measurable by manual stereo photogrammetric evaluation. To capture very thin objects (e.g., antennae, street lamps, etc.), the image scale has to be bigger than with traditional survey flights and this requires a lower flight height [7], but the latest technology allows the survey with high GSD from economical flight altitude and groundspeed. Table 4 of the Terrain and Obstacle Data Manual does not consider the latest modern, ultrahigh spatial resolution aerial photogrammetry when comparing the methods. In the 2011 case study, they used 15–50 cm ground pixel resolution [8], while we worked with 3, 5, 7.5 cm GSD images. The resulting spatial accuracy is much higher than requested.

Eurocontrol also advises the use of aerial photogrammetry for surveying aerodromes—among other reasons, for example, from an economical point of view. The image-based data can be richer than the LiDAR points, while the geometric accuracies are shown to be in the same range. With an aerial camera, a flying mission can be completed in 10% of the time that a LiDAR takes [9]. The accuracy of direct georeferenced photogrammetry which is also supported by ground control points (GCPs) is often near 1 pixel, whereas the LiDAR accuracies are defined by the direct georeferencing from GPS/IMU measurements. An unequivocal relationship can be detected between the Z-direction accuracy of the point cloud made by the photogrammetric method and the percentage of the forward and side overlaps between the flightlines [10]. The high overlap improves the internal accuracy [11].

The quality of these three-dimensional databases and maps is consistent, and the local distortions can be eliminated, so overall, we may state that it is a reliable and accurate method of data collection.

2 Methodology

Throughout the method, the area is captured by a precision device, which consists of a calibrated camera system mounted on an aircraft. An aerodrome survey using aerial photogrammetry can be divided into three main phases. The first stage of the process is a detailed aerial survey, which results in a three-dimensional cloud (digital surface model, DSM). Besides this step, a digital terrain model (DTM) is also determined. DTMs are created by the method of stereo photogrammetry and terrestrial survey. After the aerial survey, by processing the three-dimensional cloud (Fig. 1), we filter the obstacles according to the surfaces defined by international documents (Fig. 2).

When creating eTOD, the surfaces compared to the terrain and the predetermined collecting surfaces cooperatively determine which objects are considered to be obstacles and which are not (Fig. 3). The collection of Terrain and Obstacle Data and the requirements differ in designated areas in the case of investigating the obstacle collection surfaces, and besides this, they also differ in the case of applying obstacle limitation and obstacle protection surfaces (Fig. 4).

After this step, experts in terrestrial geodesy visit the obstacles on the site, and through the use of measuring stations, they can even more accurately measure the coordinates and the altitude of the base, the top points, and the high objects (e.g., lightning rods, antennas). The results of the terrestrial geodetic survey, through a comparison with the results of the previously made aerial photogrammetric survey (including the point cloud), contribute to even higher accuracy and greater reliability. Overall, with the help of terrestrial geodesy, we obtain a final insurance through the iteration of measurements, as we repeatedly measure some of the most outstanding obstacles. In Fig. 5, the measuring

Fig. 1 Detail of a three-dimensional high-density point cloud

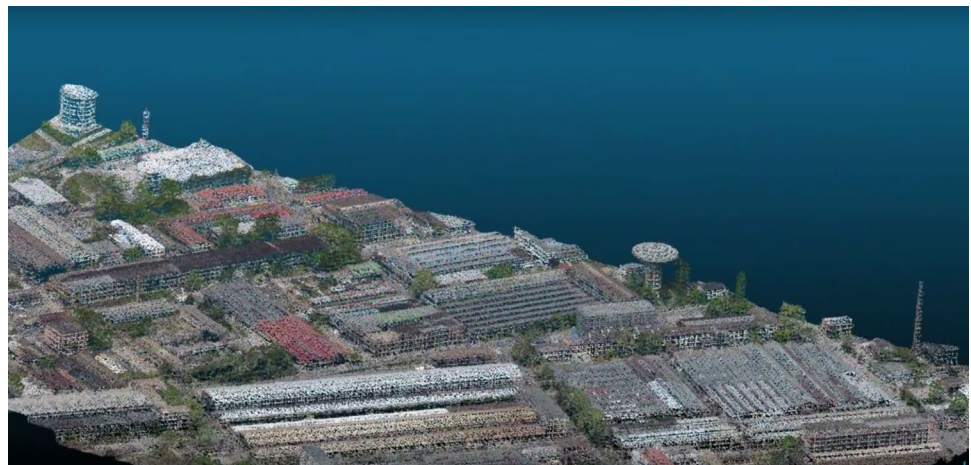
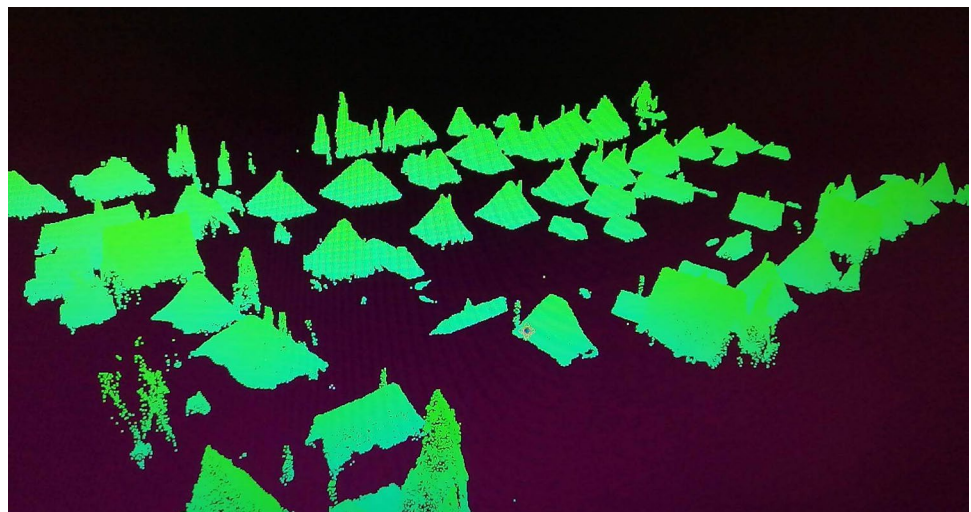


Fig. 2 Detail of a point cloud, which is cut by specified obstacle surfaces



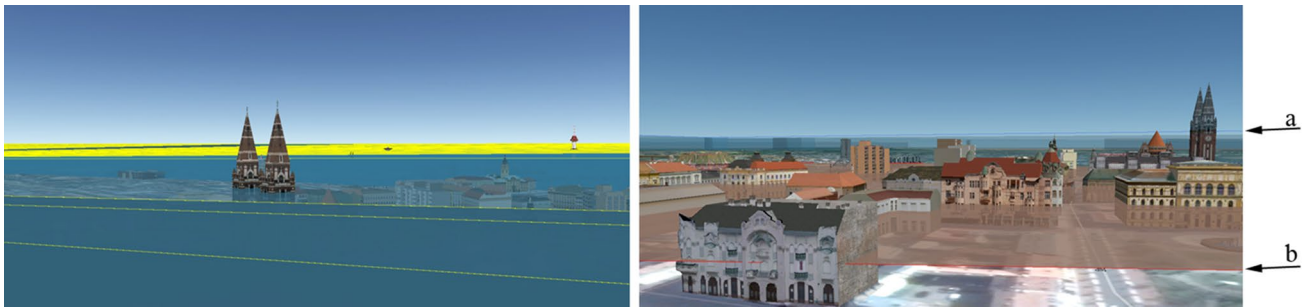


Fig. 3 The point cloud has to be cut by different surfaces. A report is made on the objects that exceed them

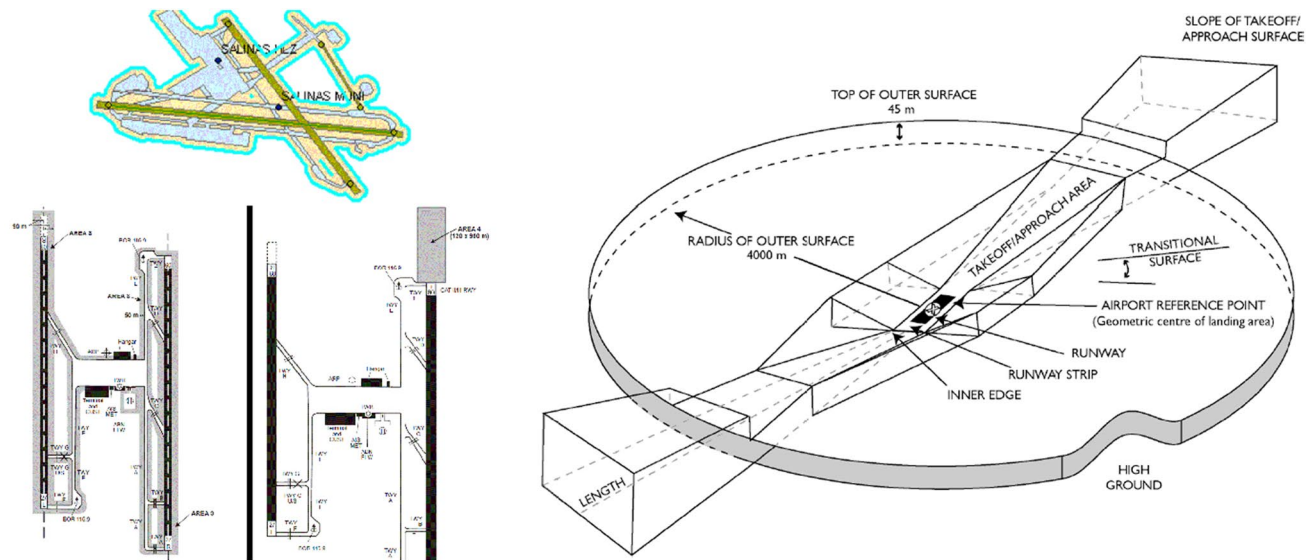


Fig. 4 The point clouds should be sorted by obstacle collection, limitation and protection surfaces. The figure illustrates only a few areas and the obstacle limitation surfaces [12]

difference of a given point between the aerial photogrammetry and the terrestrial survey was only half a centimeter.

The terrestrial survey is followed by the last phase, which consists of the processing of the obtained data. The data are processed electronically through the use of the so-called geographic information system (GIS), a tool that integrates spatial and descriptive information into a single scheme, providing a suitable framework for analyzing spatial data.

Obstacles can be described by several geometric methods. Polygons describe a closed surface of an area, while points describe a discrete geolocation with a small extension obstacle. The narrow and long obstacles (e.g., tree rows, high fences) are visualized through the use of line-type vectors. They include a variety of mandatory and optional attributes for Terrain and Obstacle Data. Following this step, the dataset goes through an independent check before being uploaded to the European AIS Database (EAD), uploaded and checked by the AIS (Aeronautical Information Service).

3 Results

The technique which is described in the methodology was tested with several parameters. Through the application of 70–90% forward overlap and 40% side overlap, we executed 3, 5, 7.5 and 10 cm spatial resolution aerial surveys on a 0.5 km² and on a 0.4 km² large sample area (Fig. 6). The flight speed varied from 220 to 340 km/h and the altitude was 640–860 m during the experiments. We reached the 3 cm spatial resolution using telephoto lens also from 640 m relative flight height. During the tests, we used field-adjusted flight lines.

With the increase in resolution, the point cloud displays smaller and smaller details. However, with the dense point cloud, we cannot detect as many potential obstacles as spotted through the use of aerial images and by measurement using a manual stereo photogrammetric evaluation

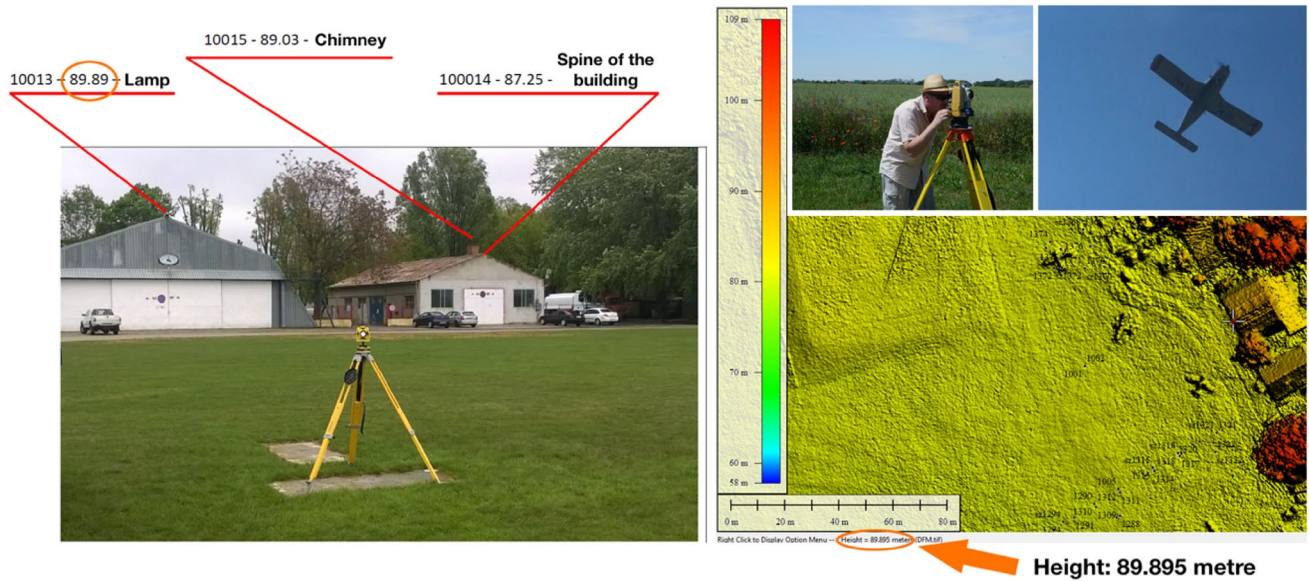


Fig. 5 An example of how to access the desired reliability of an aerodrome survey

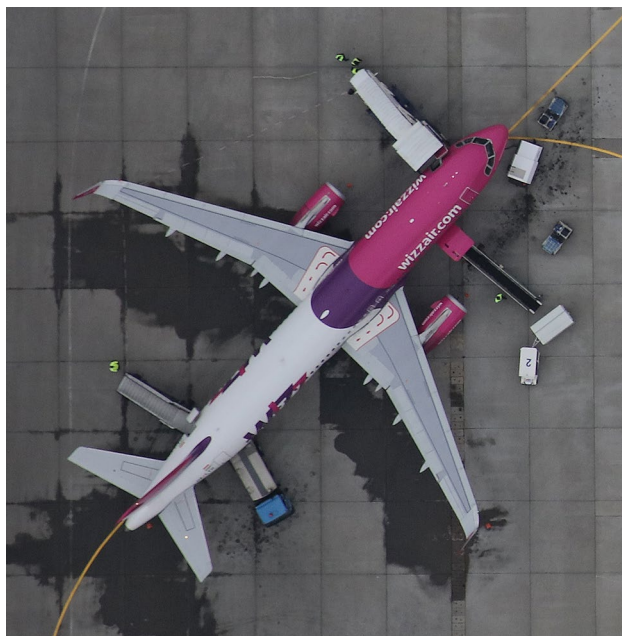


Fig. 6 Details of a 3 cm GSD ortho image mosaic of Debrecen International Airport

(Table 1). Besides comparing the GSD ranges, we also compared the reliability of the dense point cloud, the manual stereo photogrammetric evaluation, the terrestrial survey, and through the use of all of these data, the obstacle survey. The efficiency of each procedure was compared to the results of the combined method.

Due to the detail of the point cloud, the detectability of small obstacles with small footprints are deteriorated the

Table 1 The GSD dependency of the obstacle detection

| GSD of aerial images (cm) | Percent of the detected obstacles in the dense point cloud (%) | Percent of the detected obstacles by manual stereo photogrammetric evaluation (%) | Percent of the detected points by field geodetic survey without aerial survey (%) | Percent of the detected points by combined method (%) |
|---------------------------|--|---|---|---|
| 3 | 85 | 98 | 44 | 100 |
| 5 | 71 | 96 | 44 | 100 |
| 7.5 | 60 | 94 | 44 | 100 |
| 10 | 27 | 91 | 44 | 100 |

Table 2 The detectability of those obstacles whose diameter is smaller than 40 cm—examined by medium dense point clouds of surveys executed with different resolutions

| GSD of aerial images (cm) | Average point density (points/m ²) | Percent of the detected obstacles $\phi < 40$ cm obstacles (%) |
|---------------------------|--|--|
| 3 | 55.5 | 58 |
| 5 | 23.3 | 39 |
| 7.5 | 10.2 | 35 |
| 10 | 4.5 | 6 |

most by the decrease in the spatial resolution of the aerial survey. Therefore, Table 2 quantifies obstacles that are less than 40 cm in diameter.

As a result, it can be concluded that the high-resolution photogrammetric evaluation, and especially the combined method, can be considered to be the most reliable methods for a survey which is carried out at a given time and financial expense. However, the survey does not recommend abandoning the manual photogrammetric procedure. As seen in Tables 1 and 2, by increasing the resolution, the number of objects that have to be measured manually decreases radically, and the margin of error decreases as well.

4 Conclusions

On a day with suitable weather with an aircraft with ground speed below 500 km/h, we can carry out an aerial survey with 10 cm GSD of a 350 km² large area. With subsonic airplanes (500–1000 km/h, below Mach 1), an aerial survey of up to 1000 km² can be carried out in less than ideal weather conditions. Modern digital CMOS (complementary metal-oxide semiconductor) sensory frame aerial cameras are capable of producing sharp and well-overlapped captures at such high ground speeds as well.

The method of aerial photogrammetry, which is quick and accurate, can be rightfully considered as the most complete, the most documentable, and the safest existing survey form. Collecting obstacles is not restricted to the objects which are judged to be high by the geodetic team—the objects, trees, and terrain obstacles are filtered by a point cloud with unified density, while bearing in mind the legal criteria. Thus, we are talking about an objective method of obstacle survey. For 1 cm spatial resolution, reliability is between 1 and 3 cm, depending on the conditions. Under conditions, we refer to the degree of image overlap, the sharpness, the noise and dynamics of the images, the exposure and the accuracy of the direct orientation, or the accuracy of GCPs. Besides, with 10 cm or better spatial resolution aerial images, with at least 70% overlap inside the lines and at least 40% overlap between the lines, eTOD can be accelerated and facilitated, allowing the expenditures to be significantly reduced. Based on our experiments, we recommend the economical, but highly detailed 5 cm field resolution survey and the combined evaluation method (but note that the parameters depend on a number of determinants and variables) in case of area 2 c. Table 3 contains our recommendations for areas 1–4.

The described procedure is independent of the mandatory reporting of construction projects and changes at the airports. Thus, the biennial obstacle survey database is comparable to previous years' surveys, as well as to day-to-day maintenance data sets based on notification obligation at the installation. The comparison of independent source databases results in a controlled and secure obstacle database,

Table 3 Recommended GSD depending on the terrain and obstacle data requirements

| | Area 1 | Area 2 | Area 3 | Area 4 |
|---------------------------|--------|--------|--------|--------|
| GSD of aerial images (cm) | 20 | 5 | 1 | 1 |

therefore the method can be considered as a periodic review solution.

5 Limitations

We would like to emphasize that the survey is not recommending that the manual photogrammetric procedure should be abandoned. Besides, it would be advisable to examine whether by taking multispectral (MS) aerial images—which require only minimal additional costs—through the use of the MS orthophoto mosaics and the multispectrally colored point cloud, to what extent could the ecological and environmental surveys of airports be improved.

Acknowledgements Open access funding provided by Óbuda University (OE).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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