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A MAPPING PLATFORM FOR GYROCOPTERS - THE INFLUENCE OF THE STABILIZATION ON DATA GEOMETRY

SYSTEM POMIAROWY DLA WIATRAKOWCÓW - WPŁYW STABILIZACJI NA GEOMETRIĘ DANYCH POMIAROWYCH

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KEY WORDS: LiDAR, autogyro, stabilization, point cloud, flight plan, Stewart platform

SUMMARY: The paper presents the experiments on the ultralight, stabilized mapping system designed for the gyrocopters (autogyros). It attempts to answer the following question: in what extent the applied stabilization solution (based on the Stewart platform) improves the quality of acquired LiDAR and photogrammetric data? The number of simulations resulting in measures of the influence of the stabilization on the point cloud density, point pattern and image overlaps has been carried out. As the input data the angular parameters of the trajectories recorded within the first test flight were utilized. Using the data, the artificial points clouds were generated. The clouds ware free of the geometric disturbances caused by such a factors as height differences of the terrain and instable flight speed. The only disturbances observed were to be caused by angular deflections that were not stabilized. Obtained results confirm that the stabilization system helps to keep the planned cloud density and overlaps of the images. However the disturbances in point pattern are caused mainly by vibrations and cannot by properly suppressed by the stabilization system. In the summary the ways of further system improvements were suggested.

1. INTRODUCTION

1.1. The use of autogyros in mapping missions

An autogyro is a type of rotorcraft that uses autorotation to develop lift. It is classified as an ultra-light aircraft and it is similar to a helicopter. It has some features which are interesting in terms of the acquisition of photogrammetric data. The start procedure may be performed within a smaller space than can be achieved in an aeroplane, resulting in higher flexibility when it comes to selecting a mission starting point. The autogyro permits travel at lower, safe velocities than an aeroplane, while simultaneously ensuring higher flexibility in the selection of photograph exposure parameters. This is important when applying medium format cameras (for which popularity has been recently growing) that are not equipped with FMC. In the context of measurements performed using an aerial laser scanner, the lower flight velocity results in the possibility of obtaining higher density point clouds. The autogyro's turning radius is smaller than an aeroplane's, resulting in shorter reverse times when strips of photographs are planned; when measuring for linear investments, reverses may be completely eliminated. Compared to a UAV, an autogyro may perform much longer flights, which allows them to acquire measuring data across bigger areas. It should be added that the flight and maintenance costs (including repairs and technical inspections) of an autogyro are much lower than for an aeroplane.

1.2. The ADRAM AMS mapping system

As an ultra-light and relatively small aircraft, the autogyro is characterized by some limitations in terms of the assembly of its on-board measuring systems. Those limitations are not only connected with the loading capacity; first and foremost, they are a result of its limited space. The majority of autogyro cockpits are small; this, combined with limited possibilities to change the autogyro's construction, may mean that it is not possible to attach it to some devices, such as large-format photogrammetric cameras, power supply systems, controlling electronic devices or *gimbal* type stabilizing systems.ADRAM has developed a dedicated mapping system for autogyros; its key component is a mapping platform equipped with the Riegl VQ-580 laser scanner, the Phase One iXA 180 medium-format camera and the GNSS/INS system developed by Applanix. The system is assembled in the place of the passenger's seat and it is fully controlled by the pilot; it is a one man mission system (Fig. 1). The flight plan recorded in the memory is read by the system software and displayed on a tablet screen. The pilot must select the planned flight strip and control the current position and flight altitude with the planned flight trajectory.

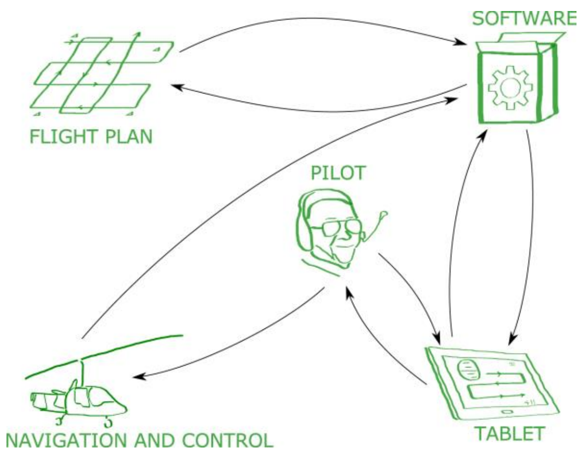

Fig. 1. The one man mission in the AMS system

1.3. Stabilization of mappingsensors

The acquisition of mapping data according to a developed plan does not guarantee its geometric correctness. The decree of the Minister of the Interior and Administration of 3rd November 2011 on databases concerning aerial and satellite images, orthophotomaps and the digital elevation models (MSWiA, 2011) defines geometric requirements which must be met by photogrammetric data and LiDAR data if they are to be approved by the Geodetic and Cartographic Documentation Centre.

Additional requirements may be specified in tender specifications (the so-called Terms of Reference) developed by contracting authorities. For example, the ToR for the ISOK Project (the IT system of the Country's Protection Against Extreme Hazards) (Kurczyński and Bakuła, 2013) required that the resulting point cloud density was equal to at least 4 points/m^2 and 12 points/m^2 for non-urban and urban areas, respectively, and that strips were carried out with a 20% overlap and points were regularly distributed. The criterion of regularity was defined by the quotient of the distance between scan lines and the distance between the points in a scan line, which had to fall into an interval of between 2/3 ÷ 3/2.

As an ultra-light aircraft, when flying, an autogyro experiences deflections caused by air currents. The influence of particular components of deflections (*roll*, *pitch*, *yaw*) on LiDAR data parameters, such as the overlap between strips, density and regularity, has been widely presented in former works (Kolecki *et al*., 2015). In order to compensate for deflections, the mapping system was equipped with a stabilizing system using a Stewart platform, i.e., with a set of six linear servo-motors with the ability to operate independently (Fig. 2). This solution is smaller than a *gimbal* stabilizer. One of its advantages lies in its ability to arbitrarily deflect the sensor system, within the limits specified by the constructor, in order to acquire oblique photographs. The stabilization system's operations were tested during the flight (Kolecki *et al*., 2016). The current data on deflections were collected from the AHRS MEMS unit (XsensMTi), which was rigidly connected to the carrying frame. The applied AHRS unit does not produce accurate information on the *yaw* component; therefore the tests performed were limited to *pitch* and *roll* angles. During the flight with the stabilization turned on, deflection values of below 2˚ were achieved for about 90% of flight lines. For the flight without stabilization, this index varied between 35% and 85%, depending on the flight line (Kolecki *et al*., 2016). Deflections exceeding 5˚ were also noted during flights without stabilization.

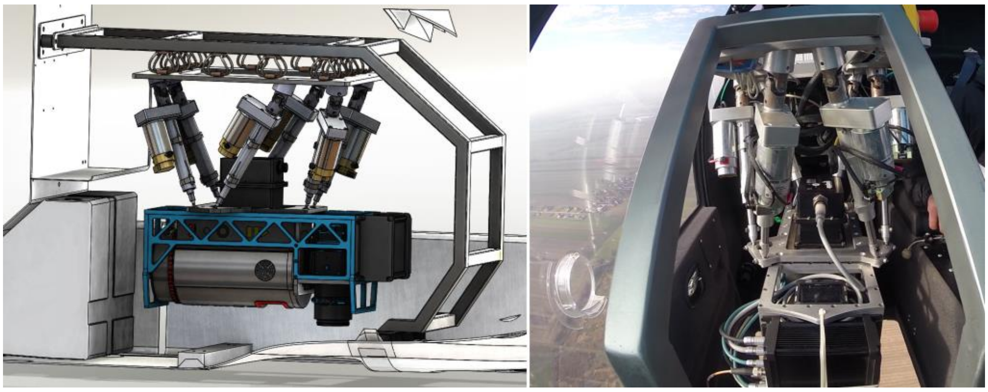

Fig. 2. The system prototype CAD model (to the left); the system photographed in flight (to the right) (Kolecki *et al*., 2016)

In the context of works presented in further sections, a simulation of the influence of stabilization on selected LiDAR geometric parameters and photogrammetric data was discussed. Then, a comparative analysis of the results was performed and possible directions for improvements to stabilization quality were suggested.

2. SIMULATION OF THE INFLUENCE OF DEFLECTIONS ON THE DATA GEOMETRY

The possibility of maintaining the correct data measurement geometry, as discussed in the previous section - apart from the efficiency of the stabilization system - depends on such components as the linear deflection of an aircraft from the planned flight trajectory or variations in flight velocity. The distribution of points on the point cloud, and the so-called footprints of photographs, also depend on differences in terrain elevation and on land-cover. Vibrations transferred by the mechanical elements of the autogyro onto the mapping sensors also have a negative influence on the regularity of point cloud density (Miraliakbari *et al*., 2012) . Vibrations should be suppressed using appropriate vibroinsulation, since their frequency is too high to compensate for them through stabilization. In order to analyse the influence of stabilization on improvements to the geometric characteristics of the acquired data, a series of tests were carried out in simulated conditions, using the real data acquired during the flight. As a result, it was possible to exclude factors other than angular deflections and to consider the influence of the stabilizing system on the analysed geometric parameters.

Through knowing the trajectory parameters (coordinates and angles over time) and assuming the parameters of the scanner operations (pulse frequency - PRR, scanning frequency – SR and field of view - FOV), it is possible to simulate the location of particular points of the cloud (Kolecki *et al*., 2015). The point position is determined as the section of a laser beam presenting the terrain. A horizontal plane was used for the tests. It was also assumed that the flight was horizontal and travelling at a constant velocity. For such conditions, the positions of particular points will depend on the scanner's operating parameters and on the angular parameters of the flight trajectory. If it were to be assumed that the angular deflection values are equal to zero for the entire trajectory, it could be possible to determine the scanner's operating parameters, which would guarantee the generation of the point cloud of the pattern and its regularity and density. Any angular deflections will result in disturbances to point cloud positions. Therefore, it is possible to generate point clouds for the trajectory which represent the flight with and without stabilization, and then to perform a further comparative analysis.

The extent to which the tested stabilization system can improve the possibility of maintaining the required density and uniformity of the point cloud was also analysed (Fig.3). Additionally, a simulation of photograph acquisition was carried out in order to test to the extent to which, with or without stabilization, the outlines of the acquired photographs will correspond to the planned footprints. In summary, the influence of stabilization on the following parameters, which describe the geometry of the mapping data, was analysed during tests:

- the point cloud density;
- the point cloud uniformity;

- the coverage of the planned areas by photographs.

Figure 3 illustrates the above parameters. All calculations were performed using scripts of Python 3.3.

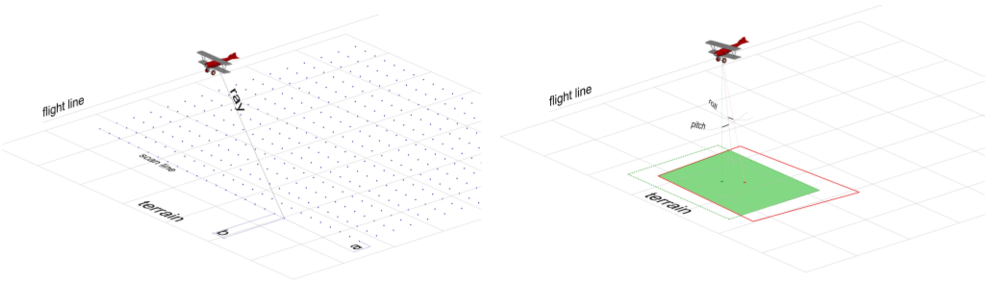

Fig. 3. Analysed geometric parameters. To the left: the point cloud uniformity determined for a sample as a quotient of *a* and *b* measures and the density as the number of points within the unit area (1 m^2). To the right: the planned outline of a photograph (the green line), the outline of an oblique photograph by *roll* and *pitch* angles (the red line) and the area covered by the planned outline (the green area). The figure was created using the services of Free3D (Free3D, 2017).

3. TESTS

During the first tests of the mapping system, a data series was acquired covering, among others, two test flights; each of them consisted of four flight strips (Kolecki *et al.*, 2016). Two lines of flight were carried out with the stabilization system turned on, and two lines were carried out with the system turned off. Figure 4 presents diagrams of changes to the *roll* and *pitch* angles for a selected part of the trajectory.

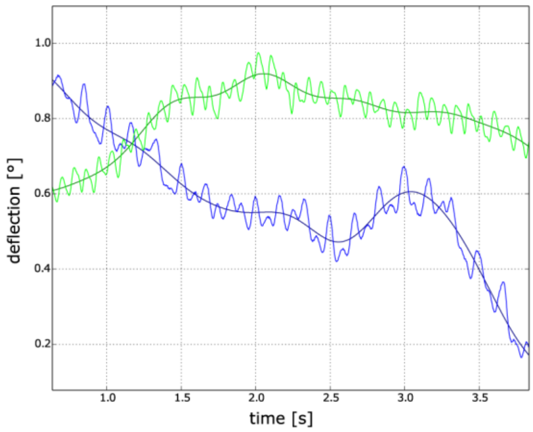

Fig. 4. Deflections of the *roll* (blue) and *pitch* (green) components over time - an example. Raw and filtered data are presented.

The mechanical solutions offered by the stabilization system are not sufficient to suppress vibrations, i.e., deflections of the high frequency of changes. A separate, vibroinsulation system is responsible for eliminating vibrations. Since the performed tests only aim to test the efficiency of the stabilization system, it was decided to eliminate disturbances of the angular parameters of the flight trajectory resulting from vibrations. For that purpose, the angular data were processed by the low pass filter. The "raw" trajectories were used only for the purpose of uniformity analysis, i.e., the parameter with the potential to be highly influenced by vibrations.

Point clouds were generated assuming the following data acquisition parameters (Riegl VQ-580 laser scanner) For analyses of the density:FOV = 50˚, SR = 89 Hz, PRR = 200KHz; flight velocity: 100 km/h; and flight altitude: 300 m. This resulted in a density of about 11.5 points/m^2. For analyses of the density regularity (the uniformity): FOV = 50˚; SR = 59 H PRR = 100 KHz; flight velocity: 100 km/h; and flight altitude: 340 m. This resulted in a density of about 5 points/m^2 for the *a* and *b* parameters (Fig. 3), equal to approximately 44 cm. When analysing the coverage, it was assumed that the photographs were acquired from an altitude of 400 m with the use of the Phase One iXA 180 camera (physical dimensions of the array: 53.7 × 40. 4 mm). Tests were performed for three different focal lengths: 35, 50 and 80 mm corresponding to 6, 4 and 2.5 cm GSD.

From a simulation, "artificial" point clouds and footprints of photographs were generated. Then, normalized, cumulative histograms were calculated (empirical cumulative distribution functions) for the analysed geometric parameters. When the density was analysed, the results were cross-referenced with the planned density and they were expressed as a percentage.

4. RESULTS

4.1. Scanning density

Figure 5 presents the empirical cumulative density distribution functions (*d*) of points in clouds generated from angular (*roll*, *pitch*) data acquired from flights with the stabilizing system turned on and off. The density which was to characterize the pattern cloud (100% of the planned density), generated for the zero deflection values at the edges of strips (i.e., about 11 points/m^2), was assumed to be the pattern density. Due to the fact that when using a scanner with a rotating mirror, the cloud density increases closer to the strip axis, more than 90% of the area had a density higher than the planned values, both with the stabilizing system turned on and off. The cloud acquired with the stabilizing system turned on had a lower than planned density for about 3% of the area, due to the fact that deflections were not fully compensated for. When the stabilizing system was turned off, this value was approximately 7.5%. At the same time, places where the cloud density is more than 15% lower than the planned value may also be noticed.

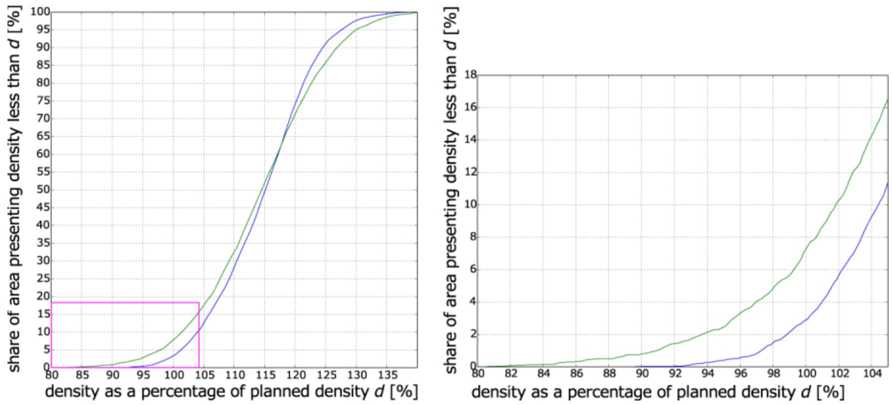

Fig. 5. Empirical cumulative density distribution functions of points in a cloud, expressed as a percentage of the planned density. In green: the stabilizing system turned off. In blue: the stabilizing system turned on. To the right: the zoomed area of the diagram, marked by a rectangle.

4.2. Uniformity of the point pattern

The uniformity values were calculated for 21 evenly distributed points on each of the scan lines. Following the ISOK project, j=2/3was assumed as the threshold value. In order to generate histograms (Fig. 6), the uniformity value was calculated as the quotient of a and b measures (Fig. 3), provided that if the value exceeded 1, its inverse was calculated. Histograms were calculated both for a filtered trajectory (i.e., one that eliminated vibrations) and for a raw trajectory (see Fig.4). If the stabilizing system was turned on, the condition $j>2/3$ was maintained for the entire area of the strip (the blue dashed line), although only in the case of filtered data. Vibrations definitely disturb the uniformity of the cloud density; the positive influence of stabilization is relatively low and the assumed requirement is met by only approximately 65% of the samples.

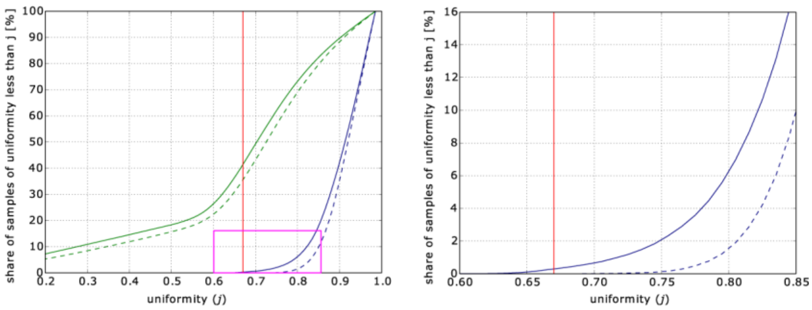

Fig. 6. Empirical cumulative uniformity distribution functions. The dashed line: the stabilizing system turned on. The continuous line: the stabilizing system turned off. In blue: filtered data. In green: raw data. To the right: the zoomed fragment, marked by a rectangle. The red vertical line marks the threshold value for the ISOK project, equal to 2/3.

4.3. Coverage of photographs

The performed test proved that the use of the developed stabilization system permits the acquisition of photographs with a coverage better corresponding to the planned value than when this system is turned off. For example, if we assume that a correctly acquired photograph covers 90% of the planned area, for a "stabilized" flight using a *f* = 55 mm lens, 2% of the photographs would be incorrect (Fig. 7). If the stabilizing system were turned off, the number of incorrect photographs would increase to almost 60%. For a*f* = 85 mm lens, those values would equal to 13% and 78%, respectively. However, it should be noted that this is an arbitrary criterion and that the resulting coverage would also be influenced by differences in terrain elevation and differences between the shutter release position and the planned position of the projection centre, which depends on the precise implementation of the planned trajectory and the accuracy of the autogyro navigation. Besides, the *yaw* (*kappa*) deflections were not considered in the performed tests; they may be of considerable importance for autogyros (for so-called *crabbing*).

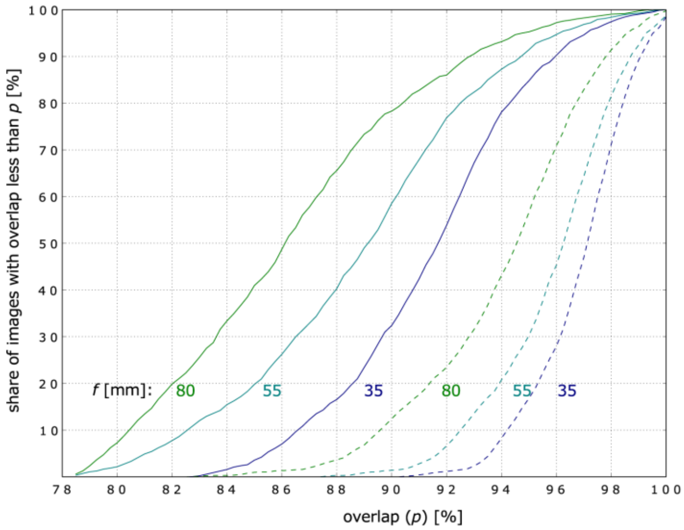

Fig. 7. Empirical cumulative distribution functions of the percentage of the planned area covered by photographs. The continuous lines: the stabilizing system turned off. The dashed lines: the stabilizing system turned on. The simulation was performed for three different focal length values and used the medium-format camera Phase One iXA 180.

5. FINAL REMARKS

The developed prototype of an ultra-light mapping platform for autogyros was equipped with a deflection stabilizing system using the Stewart platform, i.e., a system of six linear servo-motors which operate independently. In order to test the system's operations, experimental works were performed which covered two test flights, among other things. Each of them consisted of four strips, two of which were performed with the stabilizing system turned on, and the remaining two with the stabilizing system turned off.

The angular parameters of the flight trajectory, recorded during the flight together with the assumed scanner operations parameters, were used to simulate the positions of points in clouds (generating so-called, "artificial point clouds"). Only the *roll* and *pitch* components were considered. The influence of the *yaw* angle was not considered due to the impossibility of measure this value with sufficient accuracy at this stage in the work. The geometry of the acquired "artificial point clouds" was influenced angular deflections which were not compensated for; this lack of compensation was a result of turning off the stabilizing system or - when the system was turned on (every two flight strips) - from limited possibilities for stabilization.

For the generated point clouds, measures of such local geometric parameters as the density and regularity of the points pattern (the uniformity) were acquired. In a further step, a simulation of photograph acquisition and their coverage as a percentage of the planned area was also performed (Fig. 3). Empirical cumulative distribution functions were calculated for the obtained values (the density, the uniformity and the coverage) and presented in the form of diagrams (Fig. 5, Fig. 6 and Fig. 7).

Presented studies together with previously conducted experiments (Kolecki *et al*., 2016) provide the evaluation of the platform performance in the context of national law (Decree) (MSWiA, 2011) and tender specifications (e. g. ISOK specifications). Previous works (Kolecki *et al*., 2016) proved that the stabilizing system significantly helps to keep the axes of the sensors (camera, scanner) vertical – about 98% of samples provide *roll* and *pitch* within the limit of 3˚, which is the cut-off value provided in Decree in the context of vertical image acquisition. Not using the stabilization results in only about 60% of samples within this limit. What is of crucial importance, the developed stabilizing system would undoubtedly allow to significantly help to keep image and LiDAR strip coverage values, specified in the Decree. Analysing point cloud density (Fig. 5), which is the another important parameter also provided in theDecree, we observe that,if the stabilization is not applied, some single "worst" samples represent the density that is about 18% lower than the planned value. On the same time turning the stabilization on reduces the "worst" densities to be 8% below the limit. Consequently this allows us to significantly reduce the excess we should take into account when planning the acquisition (about 50% reduction) and conduct the mission more efficiently. However dealing with density limits provided in Decree (2 pts/m^2, 4 pts/m^2 respectively for non-built up areas and urban areas) should not be a challenge for current scanning systems providing data acquisition rate of 300 KHz and much more. Another LiDAR data parameter, i.e. the uniformity, which is not specified by national law but can be demanded by other specification, is much more challenging to be kept within the limits under the presence of considerable vibrations. As can be seen in the resultant plots (Fig. 6), using the stabilization helps only a little. The best way to cope the problem would certainly be improving the vibroinsulation system but at the same time one may think of other approaches like scanning the area with very high density and then eliminating excessive points.

The performed tests contribute to determining the direction that further works on mapping systems should take. First of all, it is important to develop and implement methods to determine the *yaw* angle. This will enable similar tests to be performed in a wider context. This system could use, for example, a two-antenna GNSS receiver, which operates independently or which is integrated with inertial MEMS sensors. For maintaining the required uniformity of a point cloud, it seems reasonable to initiate works concerning the improvement of the vibroinsulation system.

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SYSTEM POMIAROWY DLA WIATRAKOWCÓW - WPŁYW STABILIZACJI NA GEOMETRIĘ DANYCH POMIAROWYCH

SŁOWA KLUCZOWE: LiDAR, wiatrakowiec, stabilizacja, chmura punktów, plan lotu, platforma Stewarta

Streszczenie

Artykuł jest efektem prac nad ultralekką stabilizowaną platformą pomiarową dla wiatrakowców. Podjęto w nim próbę odpowiedzi na pytanie: w jakim stopniu opracowany system stabilizacji wpływa na poprawę parametrów geometrycznych danych LiDAR oraz danych fotogrametrycznych? W tym celu wykonano szereg symulacji obrazujących wpływ stabilizacji na zachowanie planowanej gęstości chmury punków, jej jednorodność a także wpływ na pokrycie zdjęć. Jako dane wejściowe wykorzystano kątowe parametry trajektorii rejestrowane podczas pierwszych lotów testowych. Dane te pozwoliły na generowanie w sposób „sztuczny" chmur punktów, których geometria jest wolna od zakłóceń wywołanych przez inne czynniki (np. niestabilna prędkość lotu), i zniekształcona jedynie z powodu niekompensowanych wychyleń kątowych. Uzyskane wyniki potwierdzają wyraźny, i korzystny wpływ stabilizacji na zachowanie wymaganej gęstości chmury punktów a w szczególności na zachowanie pokrycia zdjęć. Zakłócenia równomierności struktury punktów są natomiast powodowane głównie drganiami i kompensowane przez system stabilizacji tylko w niewielkim stopniu. W podsumowaniu zawarto między innymi propozycje dalszych prac badawczych zmierzających do udoskonalenia systemu pomiarowego.

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