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## SOME DYNAMIC ASPECTS OF PHOTOGRAMMETRY MISSIONS PERFORMED BY “PW-ZOOM” – THE UAV OF WARSAW UNIVERSITY OF TECHNOLOGY

The article presents the analyses of the flights carried out the by the Unmanned Aerial Vehicle (UAV) named PW-ZOOM used to perform a photogrammetric mission and monitoring of fauna in Antarctic areas. The analyses focus on the deviations of the optical axis of the photo-camera which occurred during photogrammetric flights carried out on the same route but during several Antarctic expeditions performed in subsequent years (2014 and 2015). The results were subjected to correlation tests with weather conditions (wind speed and variability). The basis for these analyses are the data from the onboard signal recorder integrated with an autopilot.

### 1. Introduction

MONICA is the acronym for the Polish-Norwegian project funded by the Norway Grants programme entitled „Monitoring the impact of climate change on Antarctic ecosystems”. The project is carried out under the patronage of the National Centre for Research and Development and involves three partner institutions: the Polish Academy of Sciences, the Warsaw University of Technology, and the Norwegian Northern Research Institute. The objective of the project was to study the impact of climate change on the Antarctic ecosystem and biodiversity by monitoring penguin populations, which are the bio-indicator of the abundance of marine waters in the Antarctic region [1] (Fig. 1), and performing photogrammetric work on the selected areas called the ASPA (Antarctic Special Protected Areas ASPA 128 and ASPA 151) on King George Island, the largest of the South Shetland Islands (Fig. 2).

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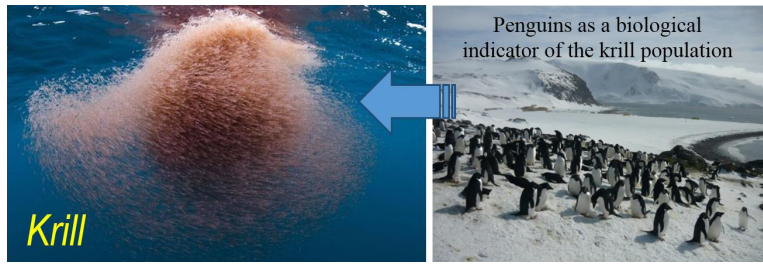


Fig. 1. Population of penguins as an indicator of krill abundance in waters

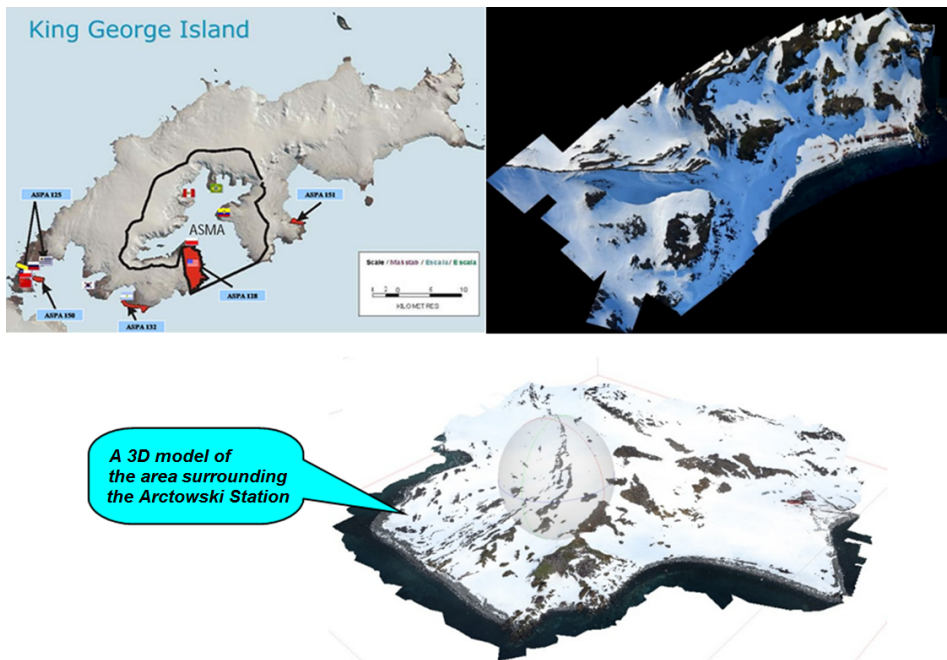


Fig. 2. Photogrammetry of the selected parts of the Antarctic Special Protected Areas on King George Island in the South Shetland Islands

Under the grants programme, two Antarctic missions were completed with the participation of the Polish and Norwegian UAV teams. The Polish team was equipped with PW-ZOOMs – an unmanned aircrafts (Fig. 3) and photogrammetric system, which were designed and constructed at the Faculty of Power and Aeronautical Engineering of the Warsaw University of Technology (PW).

The planes did well in Antarctica's harsh weather conditions flying, in total, 1204 km over the monitored areas (excluding from this summary all test and training flights) (Fig. 4). As a result, rich photographic material was collected (approx. 20 thousand aerial photographs) and detailed flight data was recorded, such as: speed, altitude, acceleration, controls movement, etc. One example of a



Fig. 3. The Polish UAV team with the PW-ZOOM plane during the 2014/15 Antarctic mission

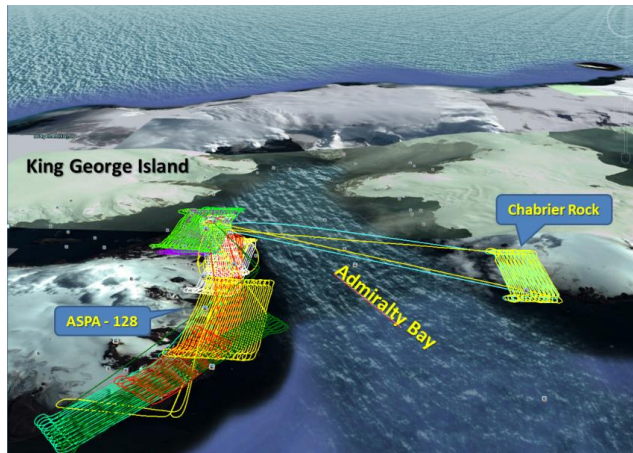


Fig. 4. Comparison of PW-ZOOM flights during the 2014 and 2015 expeditions

photogrammetric mission, reconstructed from the memory of the onboard signal recorder, is presented in Fig. 5. Depending on the duration of a mission, the plane would bring from one mission between 400 and 1000 images (orthophotos) with 18 MP resolution. In total, during two expeditions (including all types of flights) more than 2000 km were flown over Antarctica in the total time of approx. 18 hours.

Based on the photographs taken, the high-resolution stitches and orthophotomaps of the studied areas (Fig. 6) were developed and the populations of 3 penguin species (around 20 thousand nests in total) were calculated.

The results of the calculations made on the basis of aerial photos were positively verified with the traditional method (consisting in field expeditions organized by groups of biologists who collected field data by taking photos of penguin colonies at close range using small natural elevations) [2–4].

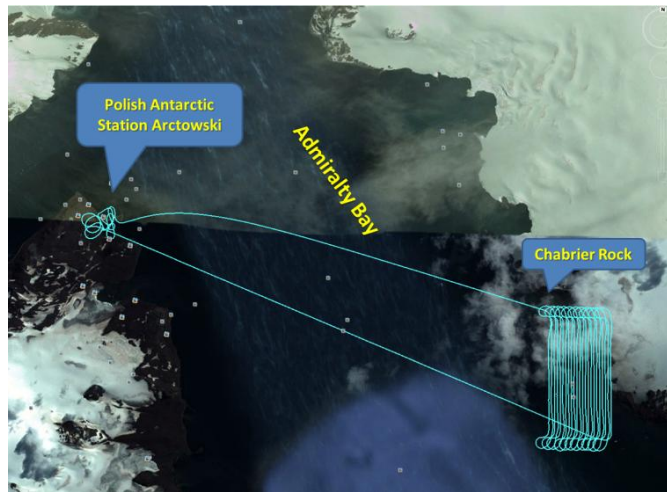


Fig. 5. Photogrammetric mission over the Chabrier Rock island in the eastern part of the Admiralty Bay of the King George Island (flight duration 55 min, distance flown 99 km)



Fig. 6. The compilation (stitch) of several hundreds of high-resolution aerial images

## 2. Requirements concerning aerial photogrammetry

The success of a photogrammetric mission depends on the quality of the photographic material obtained, which in turn depends on the stability of the flight of the plane and its ability to maintain the planned flight altitude and flight route. The route is planned specifically for the subsequent frames of aerial photographs to overlap (Fig. 7) both in longitudinal and transverse direction (60%), which is a condition indispensable for computer generation of orthophotomaps. It is therefore important that the flight trajectory deviations from the planned flight route do not cause these overlaps to shrink.

In addition, one must ensure that the optical axis of the photo-camera during the flight is oriented in a vertically downward direction, and the tolerance for deviations from the vertical axis is small (less than  $5^\circ$ ); (see Fig. 8) [5–7].

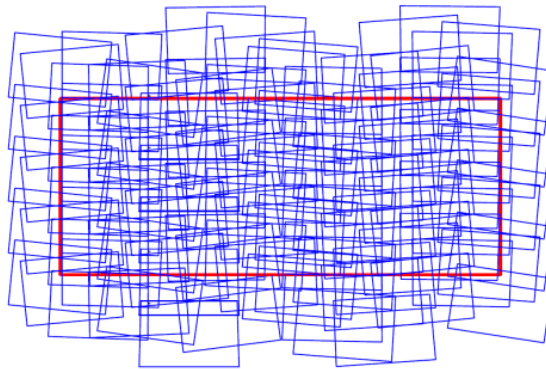


Fig. 7. Overlaps of photo frames necessary to make an orthophotomosaic

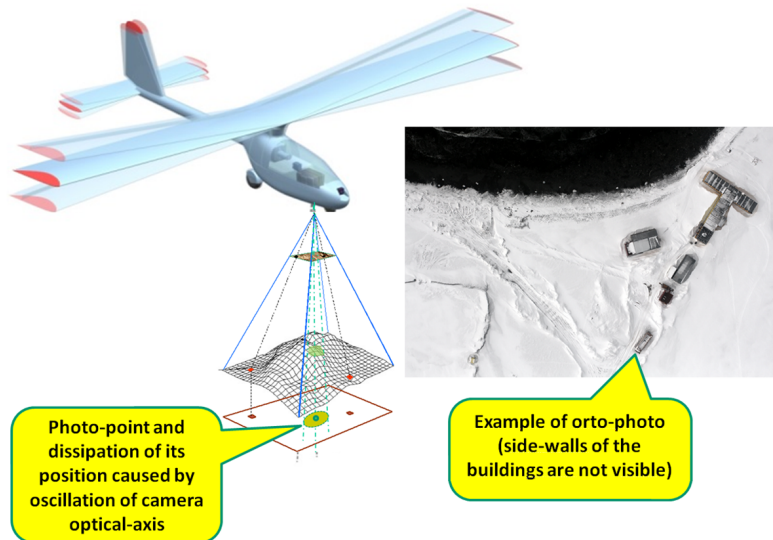


Fig. 8. The essence of orthophotography – small tolerance of roll and pitch angles of the optical axis of the camera

### 3. Desirable characteristics of a photogrammetric plane

The basic characteristics that an unmanned photogrammetric plane should have are:

- suitability for environmental conditions occurring in the planned operating area,
- sufficient loading capacity to accommodate onboard all the systems necessary for performing an autonomous photogrammetric mission, as well as the fuel reserve for covering the route of at least 100 km,



- stability of flight. This is a crucial feature because of the above-mentioned requirement of a small tolerance of the angles of deviation of the optical axis of the photo-camera from the vertical position. It must be noted here that in small photogrammetric planes (with mass smaller than 25 kg) the photo-camera suspension stabilizing system is not usually applied so as not to increase the mass of the photogrammetric system which often makes as much as 25% of the take-off mass. Adding the photo-camera suspension stabilizing system could have a negative effect on plane performance and could shorten the flight duration.

This is why when designing the PW-ZOOM plane a special attention was paid to its static and dynamic stability (especially its dumping abilities of oscillations generated by turbulence) to compensate with this feature for the lack of the photo-camera suspension stabilizing system [8].

The basic data of the PW-ZOOM photogrammetric Unmanned Aerial Vehicle (UAV) are presented in Fig. 9. Its take-off mass with a full fuel tank is approx. 23 kg. The plane was equipped with Canon 700D camera linked with the GPS, automatic control was supported by the MicroPilot 2128g. There were also applied anti-icing systems for the engine-carburetor and for the Pitot tube.

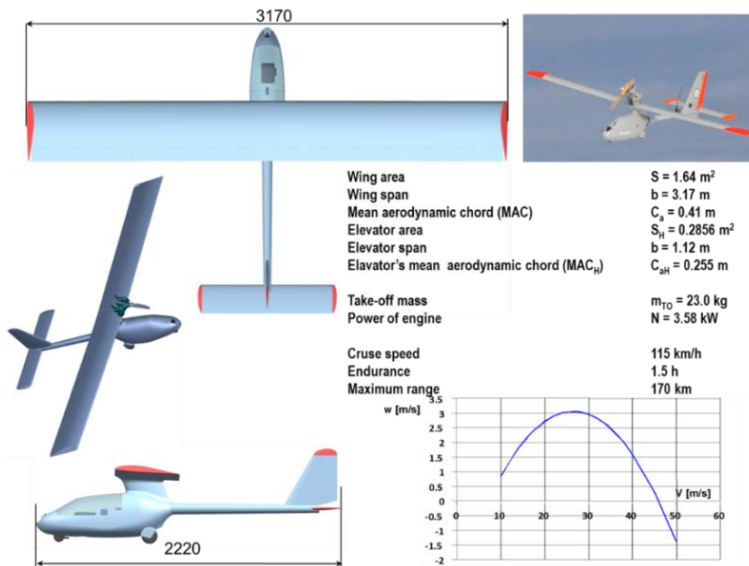


Fig. 9. The PW-ZOOM Unmanned Aerial Vehicle (UAV)

The suitability of a plane for photogrammetric missions depends not only on its dynamic properties but also on the correct integration with an autopilot in terms of the adaptation of its dynamic characteristics in such way that the plane-autopilot system (that is object-regulator) is stable and quickly dumps any oscillations caused by wind gusts.

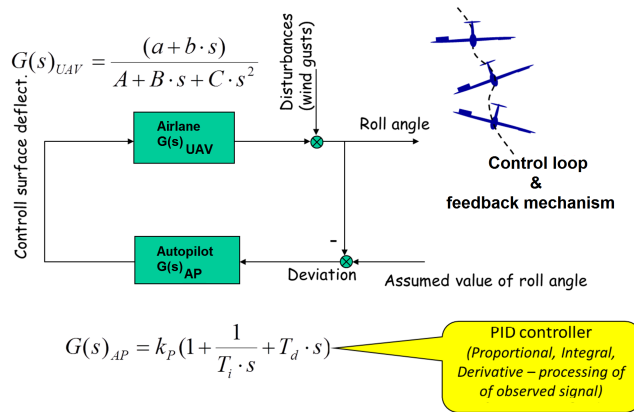


Fig. 10. Integration of the plane with the autopilot

In the autopilot system, a number of PID-type regulators occur, which support both the function of stabilizing the plane and the navigation function. The task of integration consists in entering – into the memory of the control unit of the autopilot – correct parameters of PID regulators in different control channels for both of the above-mentioned functionalities. As an example, Fig. 10 presents, in the form of a diagram, the regulatory function of the autopilot in the aileron control channel. The regulatory function supports the stabilizing function.

In order to integrate the plane-autopilot system, several flights are performed in light atmospheric conditions, during which the plane’s response to disturbances, caused by a violent movement of each control (Fig. 11), is studied. Then, from

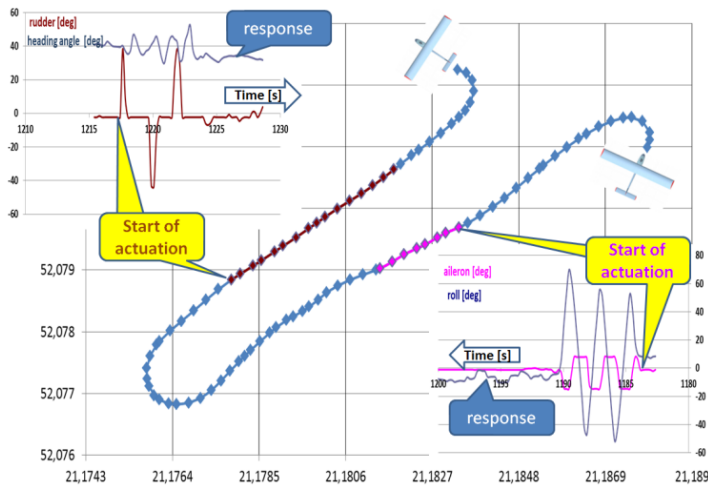


Fig. 11. Examination of the dynamic responses of the plane to the force-increments produced by control surface deflections

analyzing the input signal (controls movement) and the output signal (the response of the plane expressed e.g. by the angle change of the position) a transfer function can be derived, which represents a mathematical model of dynamic behavior of the plane for a given control channel [9, 10]. On this basis, the values of the P, I and D parameters are selected.

#### 4. The software supporting photogrammetric missions

Each flight of an unmanned aerial vehicle is preceded by terrestrial preparation. This preparation concerns many aspects such as the verification of automatic control systems, the functioning of photogrammetric systems, etc. The performance of a photogrammetric mission consists in the plane scanning a chosen area while flying over that area along a route that resembles a snake-shaped trail. The flight route is based on the points of the so-called photogrammetric grid and consists of several (or even several dozen) straight segments (called the lines of the photogrammetric rides) and turns which are supported by software in the form of an additional grid of the so-called guiding-points. It would have been very inconvenient to manually enter the geographic coordinates of all the points into the flight programme. Therefore, a special tool has been developed for the needs of the MONICA project. The tool makes it possible to quickly and effectively generate the geographic coordinates of the points of the planned photogrammetric grid. The programme by Głowacki, was written in the LabVIEW environment. The geographic coordinates of the start point, the length and width of the work area, the number of consecutive rides over the scanned area, the angle orientation, and the turn parameters are entered into the programme as input data. The programme generates a visualization of the route and produces files containing geographic coordinates of the points of the photogrammetric grid, which are formatted appropriately for two types of autopilots used in the MONICA project (Micropilot and Ardupilot). Fig. 12 shows the front panel of the developed file generator with the coordinates of the photogrammetric grid.

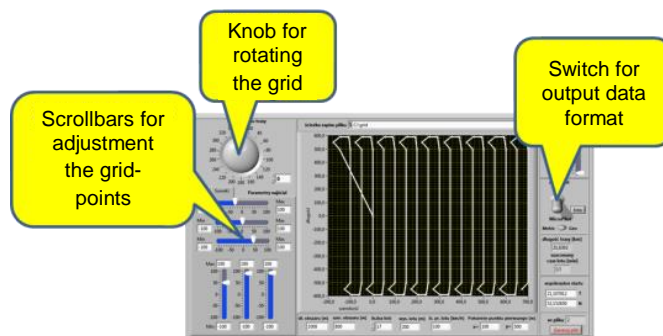


Fig. 12. The programme for generating the photogrammetric grid



A separate matter is the analysis of the flights data recorded in the memory of the onboard signal recorder integrated with the autopilot. The LogViewer programme of the MicroPilot company can be used for this purpose. It enables a simple visualization of all the registered data in the form of charts. However, the LogViewer programme is not a tool that is developed enough to conduct complex analyses. Therefore, a computer programme with the working title LogsReader has been created in the LabVIEW environment for the purpose of the MONICA project. The programme has a modular construction which contains tools that make it possible to create a quick visualization of the totality or of a fragment of the flight route covered, as well as to calculate the time in which the route was covered and its length. The programme makes it possible to generate charts of time courses of the flight parameters registered, for example: speed, (GPS and aerodynamic speed), altitude, acceleration, control surfaces deflection, and so on. It also makes it possible to study the correlation between the time courses of different registered signals and to perform statistical operations on signals. Moreover, the programme can attach tool modules which make use of original algorithms that enable the calculation of a number of values of signal functions based on the flight data registered. In particular, it is about determining wind speed and direction at different flight altitudes, as well as determining position deviations of the so-called photo-points (that is places where the optical axis of a photo-camera intersects the surface corresponding to the sea level) from the planned flight route. It creates enormous opportunities to conduct a detailed analysis of the course of the flights and to assess the influence of wind gusts on the plane. Fig. 13 shows selected screenshots of the LogsReader.

The algorithm for determining the speed and direction of the wind that occurs on the flight route of the plane together with the determination of the level of

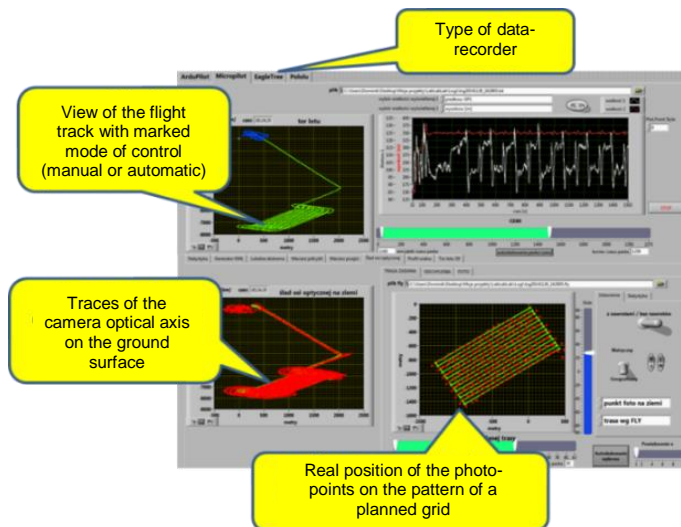


Fig. 13. The LogsReader screenshot

turbulence of the atmosphere are shown in the form of a block diagram in Fig. 14. The differences in the aerodynamic speed and the speed as provided by the GPS for a given course over-ground constitute input data in this algorithm. The method used in the selection of the function approximating these differences was the minimization of the metric entropy of the points representing the above mentioned speed differences (calculated on the basis of the data recorded in the memory of the recorder) with regard to the theoretical curve (a quasi sinusoid). The amplitude and phase shifting of this curve make it possible to determine wind speed and direction. On the other hand, the dissipation of the points with regard to the theoretical curve is the measure of the turbulence of the atmosphere. The method of minimization of metric entropy is more effective than the traditional method of least-squares.

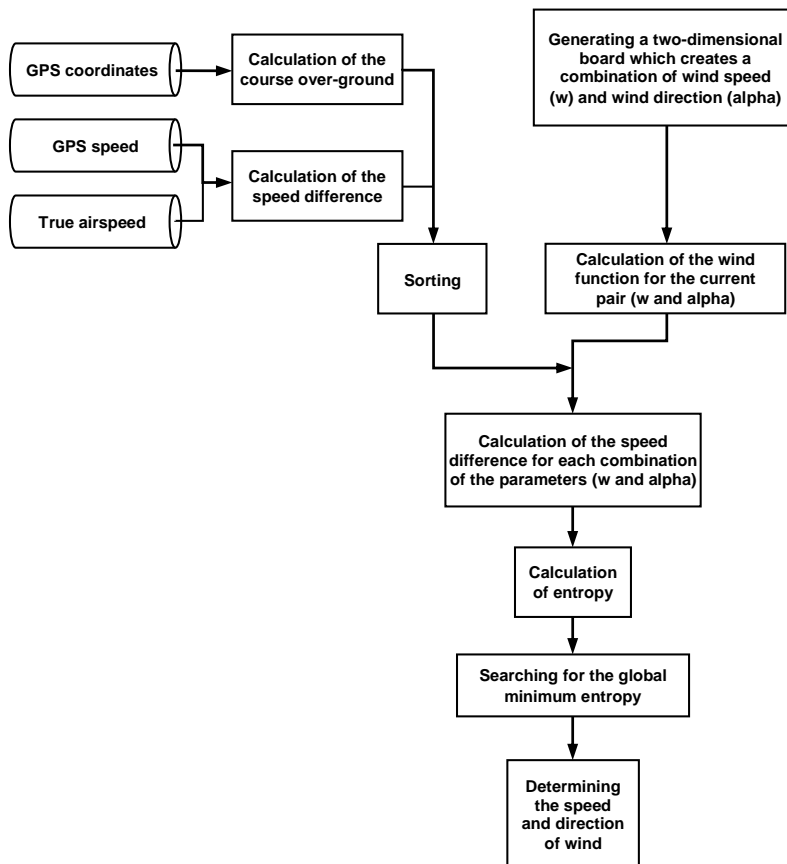


Fig. 14. Block diagram of the process of calculation of wind speed and direction

Fig. 15 presents, in the form of a diagram, the core of the module for determining wind speed and direction with an implemented algorithm for calculating metric entropy.

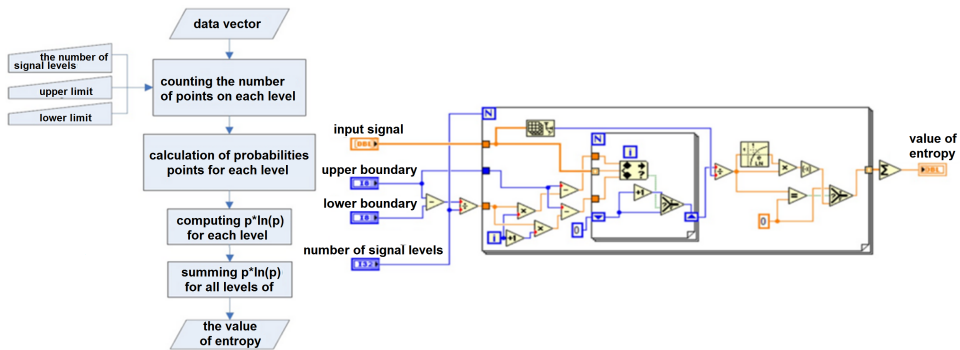


Fig. 15. LabVIEW structural diagram for calculating entropy in the G programming language

Fig. 16 presents a screenshot of the module for determining wind speed and direction. The window in the middle presents the spatial graph of entropy on which the global minimum is searched for.

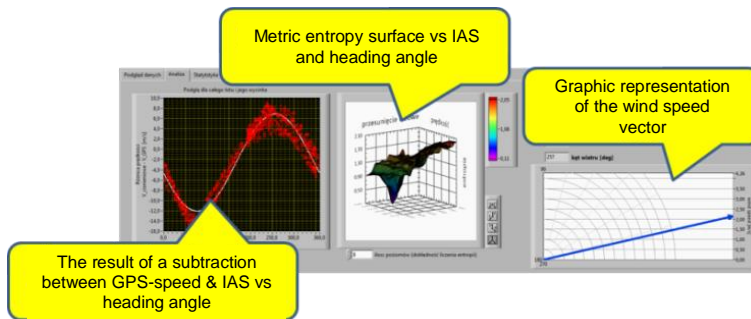


Fig. 16. The front panel of the module for determining wind speed and direction

To assess the quality of the performance of a photogrammetric mission another module was developed which allows one to track the angles of the optical axis of the photo-camera at each point of the flight path and to determine the photo-points. The smaller the deviation of the photo-points from the planned flight route, the better data are obtained for the creation of orthophotomaps. The programme allows us to calculate the deviations from the actual flight trajectory (projected on the surface corresponding to the sea level) and from the planned flight route, as well as to make statistical analyses of these deviations, both along the direction of the flight route and transversally to the route (Fig. 17a). In addition, when the \*.fly file with the coordinates of the planned route is uploaded (used for the MicroPilot software), it is possible to calculate the deviations of the photo-points from the planned flight route (Fig. 17b). The programme makes it possible to track the position of the photo-points during the entire flight or only on the straight segments of the photogrammetric grid. Because of the specific format of \*.fly files, it was necessary

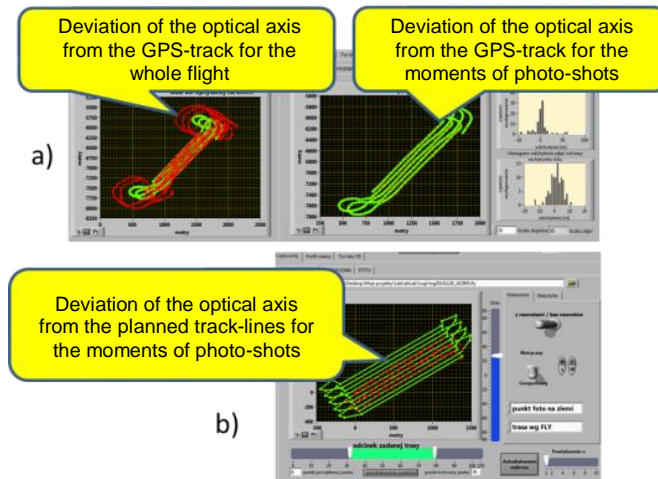


Fig. 17. The front panel of the module for tracking the optical axis. a) deviation of photos from the projection of the flight trajectory on the ground surface; b) deviation of photos from the projection of the planned route on the ground surface

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climb 350
waitClimb 50
flyTo (58.489506 W, 62.150631 S)
flyTo (58.488447 W, 62.151036 S)
fromTo (58.487069 W, 62.152834 S)
[scratch3]=1
fromTo (58.487069 W, 62.175310 S)
[scratch3]=0
flyTo (58.488994 W, 62.175759 S)
flyTo (58.488513 W, 62.177512 S)
flyTo (58.487454 W, 62.177108 S)
fromTo (58.486077 W, 62.175310 S)
[scratch3]=1
fromTo (58.486077 W, 62.152834 S)
[scratch3]=0
flyTo (58.488002 W, 62.152384 S)
flyTo (58.487520 W, 62.150631 S)
flyTo (58.486462 W, 62.151036 S)
fromTo (58.485084 W, 62.152834 S)
[scratch3]=1
fromTo (58.485084 W, 62.175310 S)
[scratch3]=0
flyTo (58.487009 W, 62.175759 S)
flyTo (58.486528 W, 62.177512 S)
flyTo (58.485469 W, 62.177108 S)
fromTo (58.484091 W, 62.175310 S)
[scratch3]=1
fromTo (58.484091 W, 62.152834 S)
[scratch3]=0
  
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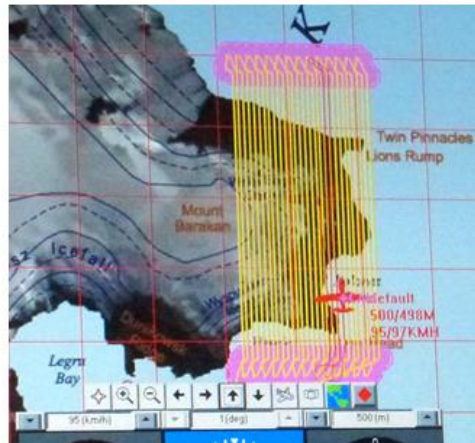


Fig. 18. Tof the \*.fly file and its visualization on the mission ground station

to create a decoding module. The example of the syntax of this file as well as the visualization of the planned route, created by this file at a ground station computer screen is shown in Fig. 18.

## 5. Comparative analysis of photogrammetric missions

The software described in chapter 4 was used for the analysis of photogrammetric flights performed during Antarctic missions in the years 2014 and 2015. This article presents the analysis of three such flights which are characterized by

the fact that they were made along the exact same route and on the same altitude (350 m a.s.l.) on different days and therefore in different atmospheric conditions. The basis for the analysis are the data from the onboard signal recorder integrated with an autopilot. The analyzed flights were carried out over Point Thomas, located at the confluence of Admiralty Bay and Ezcurra Inlet, on 27 November 2014 and on 10 and 16 November 2015. In each of these cases the flights were performed in conditions described as „a weather window” (this term was used to describe the weather suitable for carrying out flights; these periods were usually short and occurred, on average, once every 10 days).

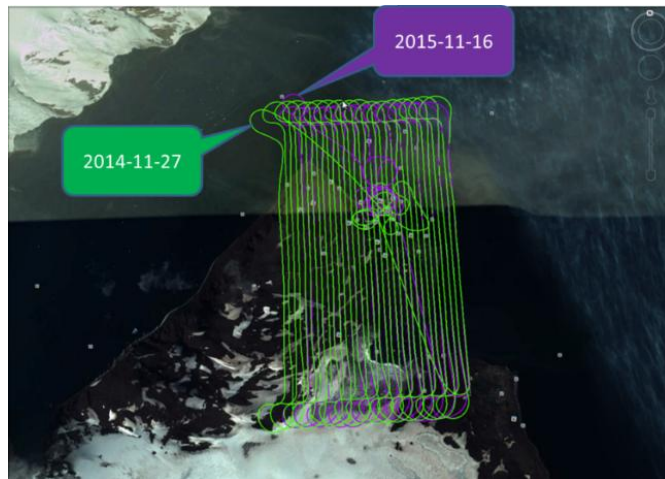


Fig. 19. Comparison of the same photogrammetric flight routes flown over in 2014 and 2015

The first analysis concerns two flights made in very light wind (performed on 27 Nov. 2014 – wind of 3 m/s from the 245° direction and 16 Nov. 2015 – wind 0,5 m/s from the 0° direction). The same 29 lines of the photogrammetric rides were selected for the analysis (Fig. 19). Fig. 20 presents the examples of time courses of speed and of the load factor recorded during one of such flights.

Fig. 21 shows recorded values of the load factor in relation to speed. It can be learned from the graph in what range of loads the plane operated when performing photogrammetric missions in subsequent years. It can be seen that the first flight took place in slightly more turbulent atmospheric conditions than the second one. It follows from Fig. 21 that the loads recorded during both flights were small compared to the strength of the airframe, which is normal in mild atmospheric conditions.

In order to characterize both flights in more detail statistical analyses of movements of each of the controls were conducted. Fig. 22 presents the results of these analyses in the form of histograms. They present a number of occurrences of different positions of the controls on the same section of the flight route (excluding the take off and the landing). One interesting feature of the histogram can be observed

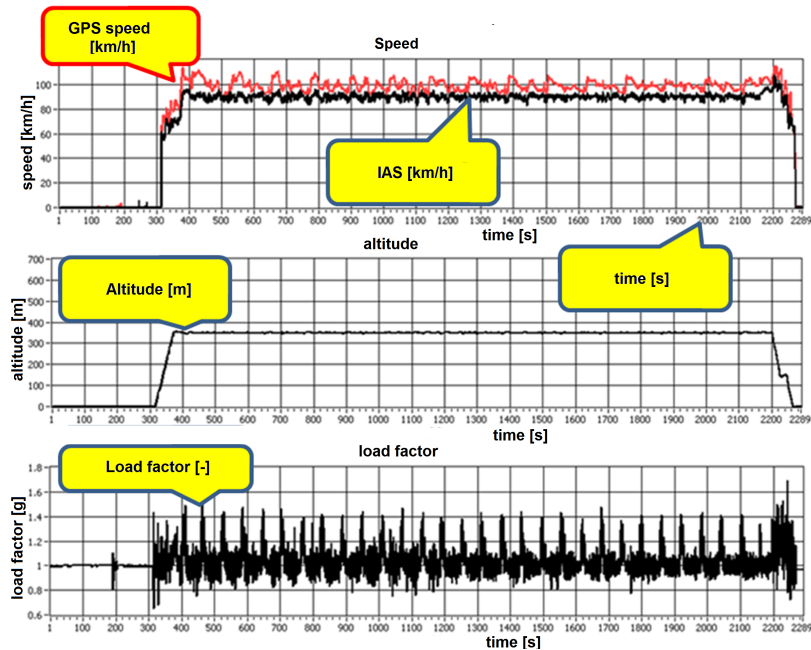


Fig. 20. Time courses of the load factor and speed

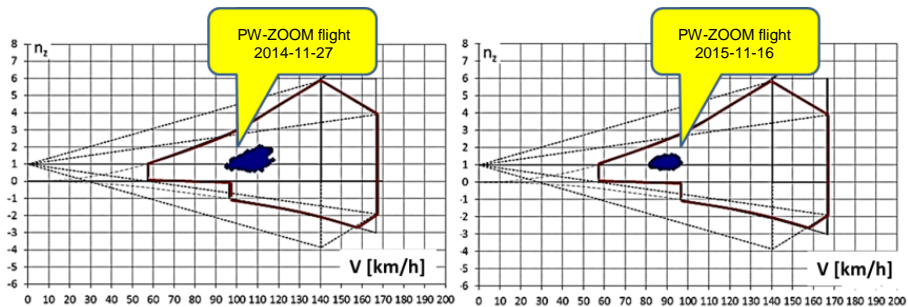


Fig. 21. Loads during analyzed flights against the envelope of operational loads

concerning the elevator deflection, which consist in the fact that the statistical distribution of its upward and downward movements is not symmetrical. It was noted that it is related to the programmed turning maneuvers performed in order to enter the subsequent route lines. The high number of repeating turns makes this feature visible in the histograms. The remaining histograms are more symmetrical and show similarity to one another.

The aim of the second analysis was to show and compare the oscillation of the optical axis of the photo-camera in relation to the vertical position. The position of the point at which the optical axis of the photo-camera is aiming (a photo-point) depends on the flight altitude, as well as on the roll and pitch angle of the plane.



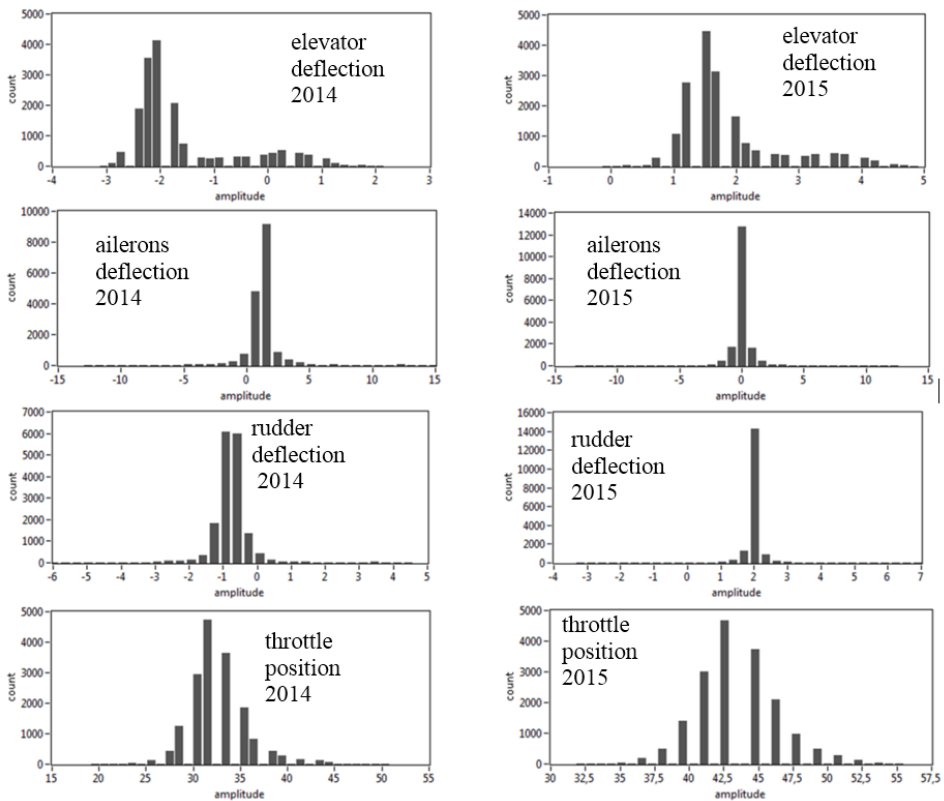


Fig. 22. Histograms of deflection of individual control surfaces during the analyzed flights

Because of that two charts were created to show the position of photo-points in relation to the route flown (both presented on a surface representing the sea level – Fig. 23).

Having the photo-points and the orthogonal projection of the flight trajectory onto the ground surface, a statistical analysis of the deviation of their position

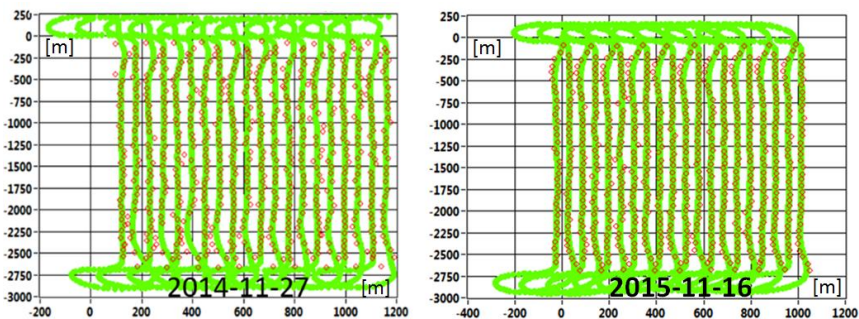


Fig. 23. Position of photo-points on the ground surface in relation to the PW-ZOOM flight route

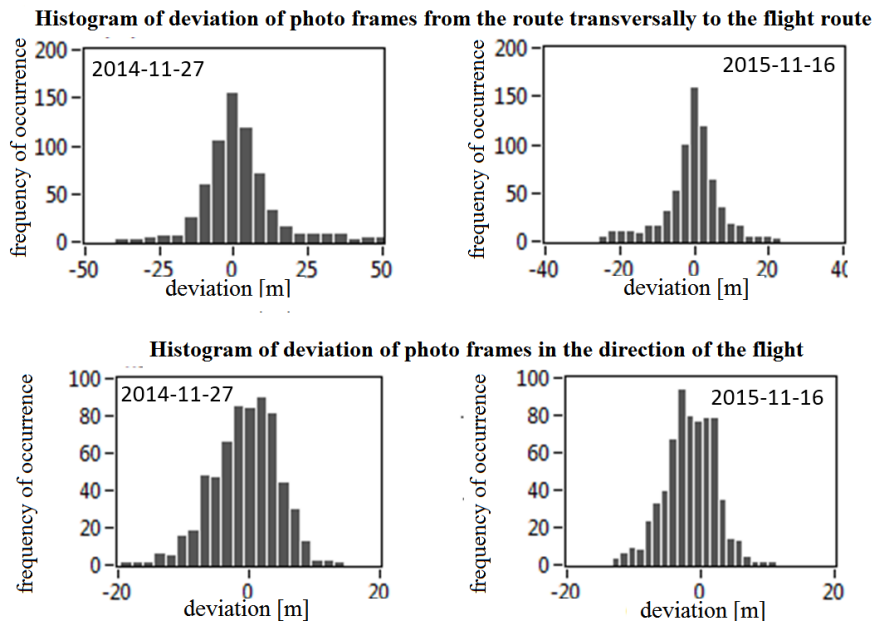


Fig. 24. Histograms of deviation of photo-points on the ground

from the projection of the flight route was conducted. Fig. 24 shows the results of the analyses in the form of histograms of transverse and longitudinal deviation. It can be noted that for more turbulent conditions occurring in the year 2014, an increase in the deviation of photo-points from the flight route could be observed. In both cases the deviations are not large, which demonstrates the suitability of the PW-ZOOM plane for this type of missions.

The third analysis concerns the statistics of deviation of photo-points from the planned flight route. The analysis was extended to include the third flight which was performed on exactly the same route as the previous two flights but was different in such way that the route was reversed (i.e. the plane covered the subsequent lines of the photogrammetric rides in the order opposite to the two previously analyzed flights and the turns were made in the opposite direction). The wind was 10 m/s from 259° direction. Considering that the terrain over which the plane was flying was mountainous, such wind speed and direction cause high turbulence.

Seven exact same lines of photogrammetric rides were chosen for the statistical analysis (Fig. 25) and for each of them the mean value of deviation of a photo-point from the planned flight route was calculated, as well as the standard deviation (Table 1). In the lower row of the table all calculated values were averaged. For all flights the mean value of the distance of a photo-point from the planned route is below 1.6 m which is a value demonstrating the PW-ZOOM plane's good suitability for performing photogrammetric missions. Fig. 26 presents the positions of the fields of deviations calculated as the mean value plus/minus the standard deviation.

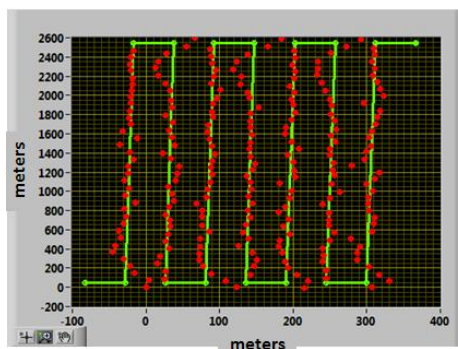


Fig. 25. Position of photo-points in relation to the planned route (for the flight of 2015-11-16)

Table 1.

Statistics of photos dispersion

16.11.2015		27.11.2014		10.11.2015	
Wind speed	Wind direction	Wind speed	Wind direction	Wind speed	Wind direction
0.5 m/s	0 deg	3 m/s	245 deg	10 m/s	259 deg
The mean of photo-points deviations from the planned flight route (m)	Std Dev	Mean	Std Dev	Mean	Std Dev
-2,83	7,8	0,99	14,07	3,37	22,31
2,94	13,01	0,13	12,57	1,59	18,25
-0,01	13,53	1,79	21,94	2,04	20,86
0,62	10,31	0,22	13,08	1,67	17,75
0,36	11,65	-0,4	13,65	1,32	14,26
1,01	11	-1,53	13,77	0,98	15,9
2,4	12,36	0,16	13,2	-0,26	16,75
0,64	11,38	0,19	14,61	1,53	18,01

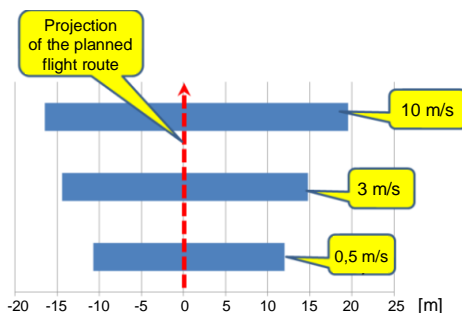


Fig. 26. Position of photo-points in relation to the planned route (for the flight of 2015-11-16)

## 6. Summary

The article presents the analyses concerning selected aspects of photogrammetric missions of the PW-ZOOM aircraft. Histograms are presented, which show the deflections of control surfaces in two flights conducted in automatic mode along the same route and in similar weather conditions (winds below 3 m/s). A fairly good similarity in terms of quality and quantity was determined with regard to histograms of control surfaces deflection coming from the autopilot. The dissipation of the position of photo-points on the surface representing the sea level in relation to the vertical projection of the flight trajectory onto this surface and the dissipation of these points in relation to the vertical projection of the planned flight route were analyzed. It was found that, in all analyzed cases, the deviations are not large (90% of them do not exceed 20 m). The photographic material obtained from these flights made it possible to create an orthophotomap and a 3D image of the area (Fig. 27). Maximum wind speeds at which the PW-ZOOM planes operated in Antarctica were approx. 13 m/s and also, at this speed, the obtained photo material was suitable for creating the orthophotomaps. The consequence of operating at stronger winds is that one may not neglect the increased deflection of the optical axis of the photo-camera from the vertical position and the data concerning the angles of the optical axis of the camera should be available for each photo.

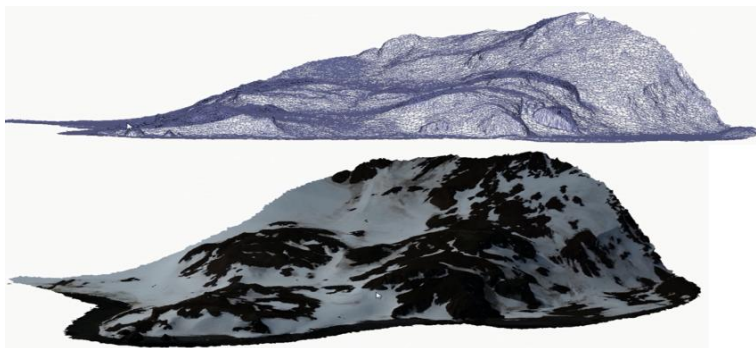


Fig. 27. 3-D image of the area obtained as a result of conducting the flights described in this article

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