Estimation of wind parameters on flying objects

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Abstract: The article presents proposal of wind parameters measurement and estimation on any flying object board. This system uses three sources of information: heading measurement (heading system or attitude heading reference system, AHRS), measurement of speed relative to air (pressure speedometer), estimation of track over Ground and route speed by means of GPS receiver. Verification of the presented solution was carried out based on off-line calculations using data logged on-board of PLZ M-20 Mewa airplane as well as on the results of error analysis.

Keywords: measurement, estimation, wind speed and direction, airspeed, heading, track over Ground, route speed

1. Introduction

Direction and speed of wind are very important parameters for mission planning of a flying object [2], [3]. These parameters indirectly affect feasibility of mission. And in case of feasibility they have influence on mission plan, duration of mission and even on fuel consumption. Speed and direction of wind along with parameters of flying object such as airspeed ([1, 4]), route speed and heading, as well as, track over Ground build the so-called triangle of speeds. This triangle constitutes the navigation basis [2]. Fig. 1 presents an exemplary triangle of speeds. After analysis of this figure, the following detailed conclusions can be reached:

- for a fixed vector of airspeed for two directions of flight (heading), airspeed will be equal to ground speed (route speed),
- for the above described situation, ground track will be equal to heading for directions parallel to wind direction, and, in this particular case, the value of wind speed will be equal to difference of route speed and airspeed.

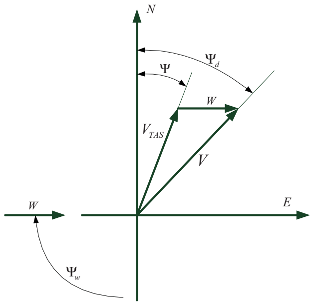

Fig. 1. Triangle of speeds
Rys. 1. Trójkąt prędkości

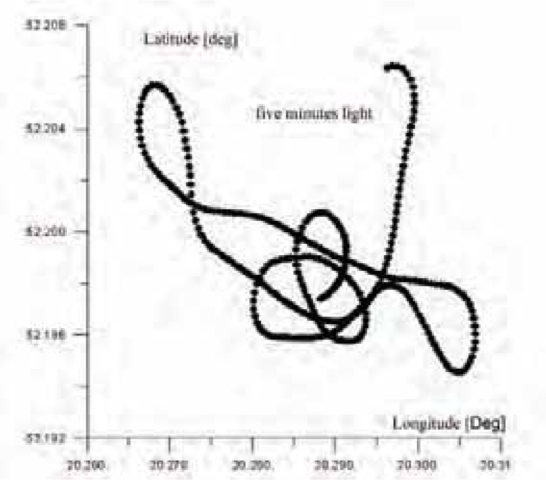

Fig. 2. Trajectory of a five-minute duration test flight
Rys. 2. Trajektoria pięciominutowego lotu testowego

Figures 3 and 4 present diagrams of the route speed and the airspeed for trajectory of the five minutes duration flight shown in fig. 2.

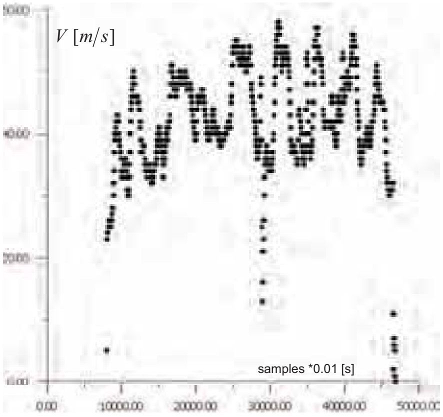

Fig. 3. The route speed from GPS receiver during the 5 minutes flight
Rys. 3. Prędkość podróżna uzyskana z odbiornika GPS podczas pięciominutowego lotu

As it can be seen, the airplane maneuvered at short period of time making circles, thus changing heading and track in whole ranges. The recorded speeds are subtracted from each other and the result is presented as the function of track over Ground on the plot in fig. 5.

Double amplitude of this plot is the double amplitude of wind speed (denoted $2W$ in the figure). The angle related to the maximum of this curve is the direction of wind (i.e., the wind is blowing from this direction).

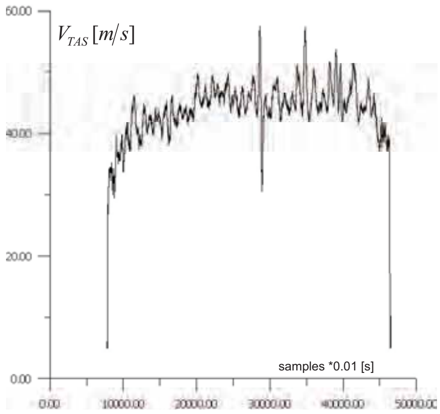

Fig. 4. Airspeed from Pitot tube during 5 minutes flight

Rys. 4. Prędkość względem powietrza uzyskana z rurki Pitota podczas pięciominutowego lotu

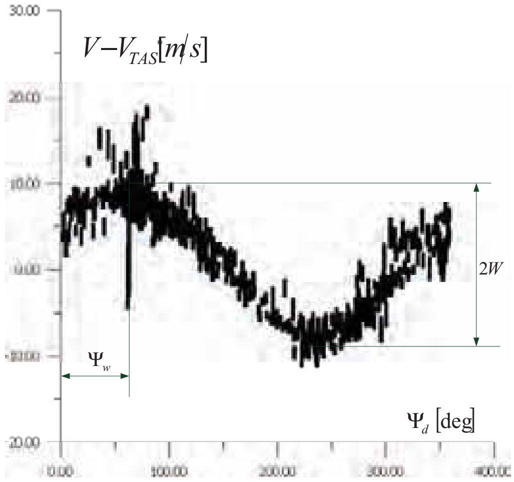

Fig. 5. Difference of route speed and airspeed versus track over ground for flight trajectory shown in fig. 2

Rys. 5. Różnica prędkości podróżnej i prędkości względem powietrza w funkcji kąta drogi dla trajektorii lotu pokazanej na rys. 2

The presented test easily lets us estimate parameters of wind. But practical use of such a procedure is not simple. A flying object performing specific mission can have some problems with periodic parts of flight such as circulation (change of the heading and track over the whole range of angle).

2. Algorithm of computation of wind parameters

Fig. 6 presents basis for derivation of relationships to calculate wind speed and its direction on the horizontal plane. Airspeed V_{TAS} is measured by Pitot tube placed alongside the airplane axis. Placement of airplane symmetry axis on the horizontal plane is described by heading angle Ψ. Route speed of the airplane V is the vector sum of airspeed and wind speed (fig. 6). Track over Ground is denoted by Ψ_d angle. Wind is defined by two parameters: wind speed W and direction (angle) of wind Ψ_w. These parameters ought to be estimated during flight.

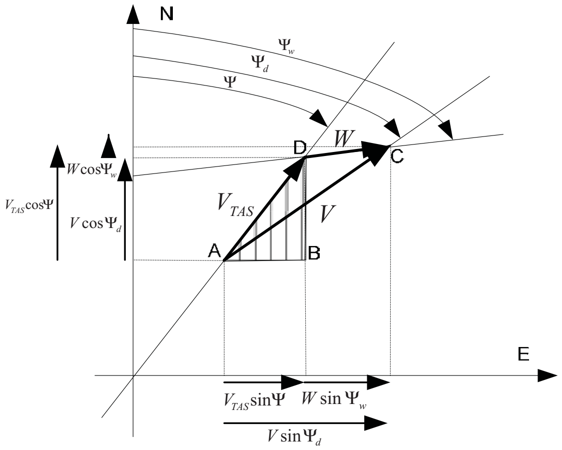

Fig. 6. Flight parameters on a horizontal plane

Rys. 6. Parametry lotu na płaszczyźnie poziomej

In order to carry out the estimation, one has to have two equations with two unknowns: speed and direction of wind. The first equation is the result of adding speed vectors in the speed triangle ACD in fig. 6. The absolute value of wind speed is calculated based on this figure:

$$W^2 = V_{TAS}^2 + V^2 - 2V_{TAS}V\cos(\Psi_d - \Psi) \tag{1}$$

All values on the right side of the equation are known, they are results of measurement of attitude reference system (Ψ), GPS receiver (V, Ψ_d) and speed derived from dynamic pressure (V_{TAS}). The absolute value of wind speed can be obtained from relation (1).

The value of speed relative to air V_{TAS} can be expressed in the following way (triangle ABD in fig. 6):

$$\begin{aligned} V_{TAS}^2 &= \left(V\sin\Psi_d - W\sin\Psi_w\right)^2 \\ &+ \left(V\cos\Psi_d - W\cos\Psi_w\right)^2 \end{aligned} \tag{2}$$

After inserting the wind speed W to this equation there is one unknown value, wind angle Ψ_w, which ought to be determined. To do so, the above equations have to be transformed to the form:

$$A_1\sin\Psi_w + A_2\cos\Psi_w = A_3 \tag{3}$$

where:

$$A_1 = \sin\Psi_d$$
$$A_2 = \cos\Psi_d$$
$$A_3 = \frac{V_{TAS}^2 - V^2 - W^2}{-2VW}$$

Next, this equation is transformed to quadratic equation form, by exploiting the relations:

$$\begin{aligned} \sin\Psi_w &= \frac{2\tan\frac{\Psi_w}{2}}{1+\tan^2\frac{\Psi_w}{2}} \\ \cos\Psi_w &= \frac{1-\tan^2\frac{\Psi_w}{2}}{1+\tan^2\frac{\Psi_w}{2}} \end{aligned} \tag{4}$$

The obtained quadratic equation reads:

$$B_1X^2 + B_2X + B_3 = 0 \tag{5}$$

where:

$$X = \tan\frac{\Psi_w}{2}$$
$$B_1 = -A_2 - A_3$$
$$B_2 = 2A_1$$
$$B_3 = A_2 - A_3.$$

The solution of this equation is:

$$\Delta = B_2^2 - 4B_1B_3$$
$$X_{1,2} = \frac{-B_2 \pm \sqrt{\Delta}}{2B_1} = \frac{-B_2 \pm \sqrt{B_2^2 - 4B_1B_3}}{2B_1} \qquad (6)$$

As it can be seen, there will be two solutions, $\Psi_w = 2\arctan(X_{1,2})$. The case of a single solution is possible as well, for $\Delta = 0$. From those two solutions is chosen the one which satisfies condition $\Psi_d > \Psi$, taking into account conversion of measurement of angles during passing of value from below 360 deg to above zero value.

3. Results derived from flight tests

Figures 7 to 10 present the results of measurements and calculations performed on data recorded during flight of type PZL M-20 Mewa airplane. Flights were conducted at altitude of 1000 m above sea level, at strong wind conditions. A ten minutes period of flight with strong gusts of wind was chosen for presentation. Plots in fig. 7 and fig. 8 show measured and recorded values of speed of airplane (relative to air and ground) as well as heading and track. The speed relative to air was measured by means of Air Data System (type CA 05), and the route speed by means of GPS receiver. The track over Ground was also measured by the GPS. Heading was estimated by Attitude Heading Reference System (AHRS type IG-500N). Plots in fig. 9 and fig. 10 present estimated values of speed and direction of wind. These parameters were calculated according to relationships presented earlier. The value of wind direction angle is the direction from which the wind is blowing.

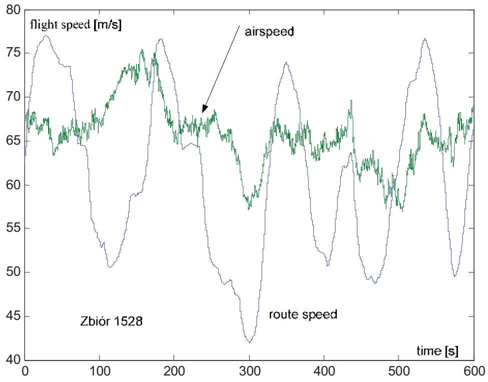

Fig. 7. Measured and recorded speeds of airplane flight

Rys. 7. Zmierzone i zarejestrowane prędkości lotu samolotu

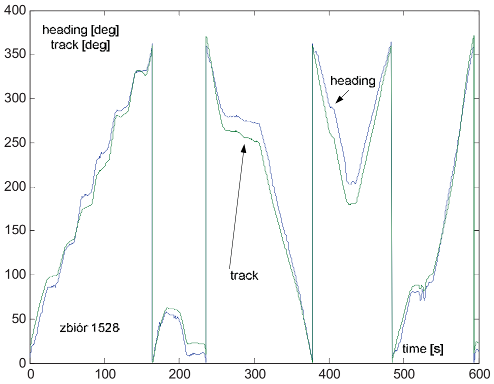

Fig. 8. Measured and recorded angles: track and heading of airplane

Rys. 8. Zmierzone i zarejestrowane kąty: kąt drogi i kurs samolotu

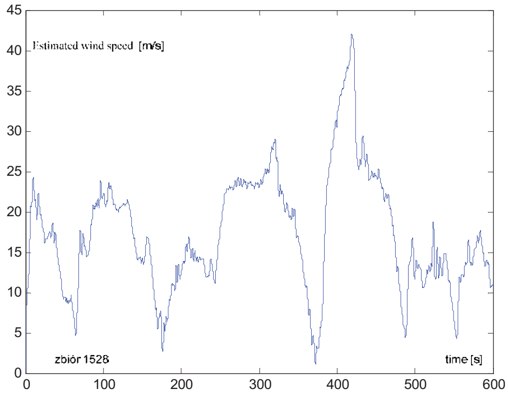

Fig. 9. Estimated values of wind speed

Rys. 9. Oszacowane wartości prędkości wiatru

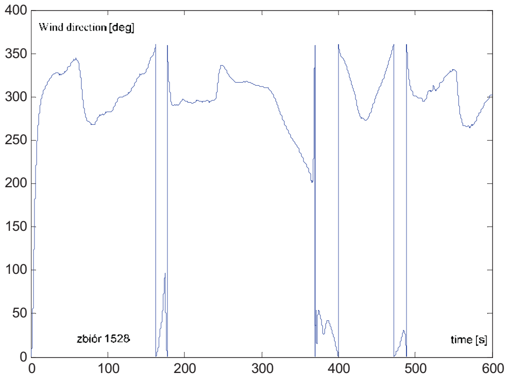

Fig. 10. Estimated values of angle of wind direction

Rys. 10. Oszacowane wartości kąta kierunku wiatru

4. Analysis of wind parameters estimation errors

The function, which describes the wind speed (1), is dependent of variables: V_{TAS}, V, Ψ_d and Ψ. Error of calculation of wind speed ΔW is influenced by the values of errors of the mentioned variables. It is computed from the expression:

$$\Delta W = \frac{\partial W}{\partial V_{TAS}}\Delta V_{TAS} + \frac{\partial W}{\partial V}\Delta V + \frac{\partial W}{\partial \Psi_d}\Delta\Psi_d + \frac{\partial W}{\partial \Psi}\Delta\Psi \tag{7}$$

where:

ΔW – estimated accuracy of wind speed,
ΔV_{TAS} – accuracy of airspeed measurement,
ΔV – accuracy of route speed measurement,
$\Delta\Psi_d$ – accuracy of track over Ground measurement,
$\Delta\Psi$ – accuracy of heading estimation,

and the corresponding partial derivatives have the form:

$$\frac{\partial W}{\partial V_{TAS}} = \frac{2V_{TAS} - 2V\cos(\Psi_d - \Psi)}{2\sqrt{V_{TAS}^2 + V^2 - 2V_{TAS}V\cos(\Psi_d - \Psi)}},$$

$$\frac{\partial W}{\partial V} = \frac{2V - 2V_{TAS}\cos(\Psi_d - \Psi)}{2\sqrt{V_{TAS}^2 + V^2 - 2V_{TAS}V\cos(\Psi_d - \Psi)}},$$

$$\frac{\partial W}{\partial \Psi_d} = \frac{2V_{TAS}V\sin(\Psi_d - \Psi)}{2\sqrt{V_{TAS}^2 + V^2 - 2V_{TAS}V\cos(\Psi_d - \Psi)}},$$

$$\frac{\partial W}{\partial \Psi} = \frac{-2V_{TAS}V\sin(\Psi_d - \Psi)}{2\sqrt{V_{TAS}^2 + V^2 - 2V_{TAS}V\cos(\Psi_d - \Psi)}}.$$

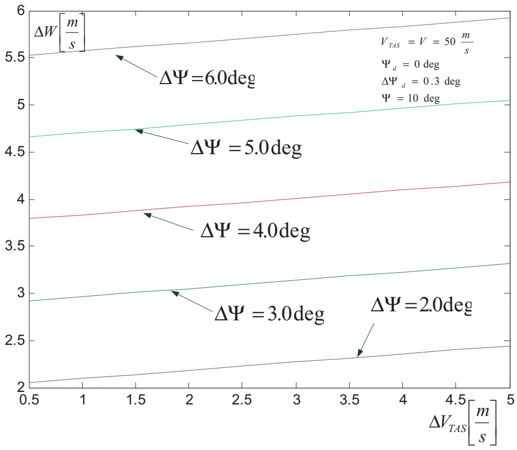

Fig. 11. Error of estimation of wind speed versus accuracy of airspeed and heading accuracy

Rys. 11. Błąd estymacji prędkości wiatru w funkcji dokładności prędkości względem powietrza oraz dokładności kursu

In the expression (7) absolute values of derivative values ought to be calculated. The fig. 11 and fig. 12 present example diagrams of error of estimation of wind speed versus accuracy of airspeed estimation and selected parameter. In fig. 11 this parameter is accuracy of heading estimation, and in fig. 12 is accuracy of track measurement. Plots in both figures were derived on assumption that airspeed is equal to route speed and value of heading is 10 deg and track is 0 deg.

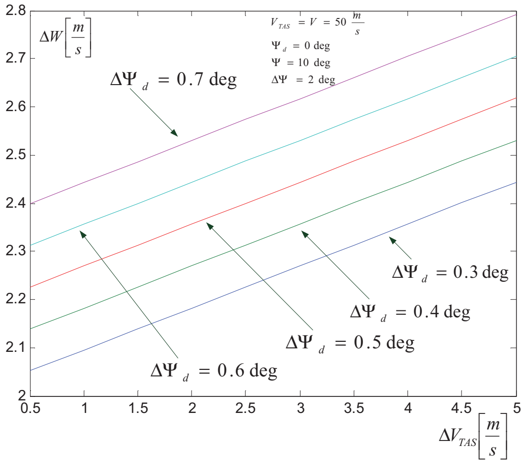

Fig. 12. Error of wind speed estimation as a function of accuracy of airspeed and track accuracy

Rys. 12. Błąd estymacji prędkości wiatru w funkcji dokładności prędkości względem powietrza i dokładności kąta drogi

As it is shown, the graphs of error of wind value estimation versus accuracy of airspeed are linear (for the presented examples).

Errors of wind direction were estimated in similar manner. Basic equation is presented below (12).

$$\Delta\Psi_w = \frac{\partial\Delta\Psi_w}{\partial\Psi_d}\Delta\Psi_d + \frac{\partial\Delta\Psi_w}{\partial V_{TAS}}\Delta V_{TAS} + \frac{\partial\Delta\Psi_w}{\partial V}\Delta V + \frac{\partial\Delta\Psi_w}{\partial W}\Delta W \tag{8}$$

where:

$\Delta\Psi_w$ – estimated accuracy of wind direction.

Assuming that $V_{TAS}=V=50$ m/s and $\Delta V=0.1$ m/s, $\Delta\Psi_d=0.3$ deg and $\Delta W=5$ m/s for $\Psi_d=0$ deg and $\Psi=10$ deg, there was presented a plot of error of wind direction as a function of wind speed for various accuracy values of estimation of object speed relative to air (fig. 13). Among input values necessary for calculations of wind speed and wind direction, measurements realized using satellite navigation receiver (Ψ_d and V) are relatively accurate. Much more worse are heading and airspeed measurements (Ψ and V_{TAS}). Plot in fig. 13 shows, that for low wind speeds the accuracy of estimation of wind direction deteriorates radically reaching errors at the level of some tens of deg for wind value near zero. The accuracy of estimation of airspeed has important influence on magnitude of this error.

In turn, in fig. 14 the relation of error of wind direction as a function of wind speed is presented for fixed accuracy of airspeed ($\Delta V_{TAS}=1.5$ m/s), also for various values of wind speed accuracy (ΔW in range 2÷10 m/s).

Here as well, the process is non-linear. Rapid increase of error of wind direction occurs for low wind speeds. In contrast, the error of wind speed grows with increasing wind speed.

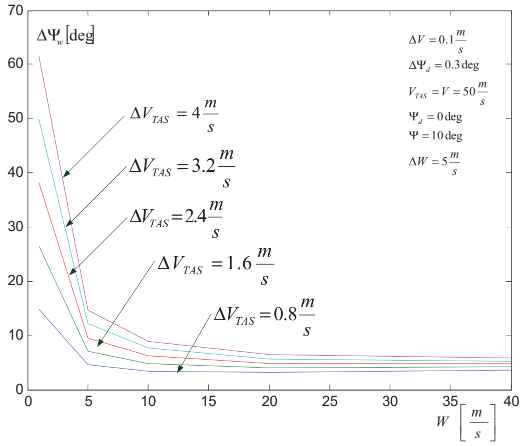

Fig. 13. Error of wind direction relative to airspeed accuracy and accuracy of wind speed estimation

Rys. 13. Błąd kierunku wiatru względem dokładności prędkości względem powietrza i dokładności szacowania prędkości wiatru

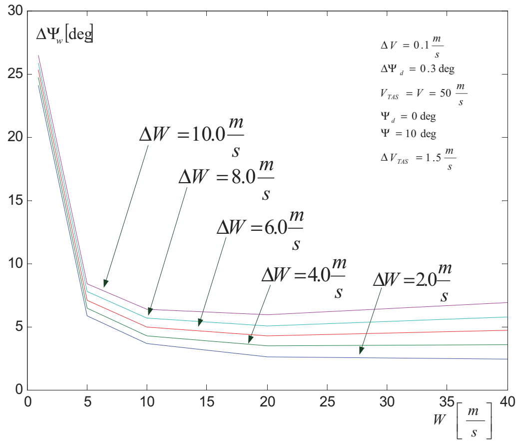

Fig. 14. Error of wind direction relative to accuracy of wind speed and route speed

Rys. 14. Błąd kierunku wiatru względem dokładności prędkości wiatru i prędkości podróżnej

5. Conclusions

The presented algorithm enables estimation of wind parameters on any flying object equipped with elementary components of instrumentation for measuring the airspeed (V_{TAS}), route speed (V), heading (Ψ) and track over Ground (Ψ_d). Fig. 15 depicts the typical measuring system for carrying out this task. As it can be seen, it incorporates three sources of information: GPS receiver, attitude heading reference system (AHRS), and air data computer (ADC).

From the conducted analyses of errors it follows that accuracy of heading and airspeed are fundamental for accuracy of wind parameters. Typical error values of track and route speed (obtained from the GPS receiver) are significantly lower (near one order of magnitude) than error values of airspeed and heading, and their influence on wind speed and wind direction accuracy is very low. One of important drawbacks of the method, is possibility of GPS signal disappearing, because in that case any measurement is not possible.

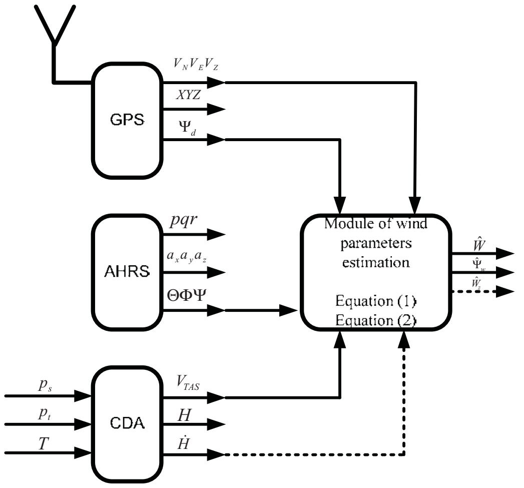

Fig. 15. Measuring system for wind parameters estimation

Rys. 15. Układ pomiarowy dla szacowania parametrów wiatru

The conclusion from fig. 13 and fig. 14 is that increase of wind direction errors for low airspeeds and for increasing error of measurement of airspeed value is substantial. This effect can be noticed in fig. 10, where estimated wind direction is rapidly changing at moments when the wind speed is decreasing to near zero values (Fig. 9).

The proposed wind parameters estimation system can be applied as one of main diagnostic systems of speed measurement on a flying object. Obtained very low probable estimated parameters of wind can be a better indicator of malfunction of speed measurement channel than simple comparison of route speed with airspeed.

The measuring system presented in fig. 15 can be upgraded with estimator of vertical component of wind speed (marked with dashed line).

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Estymacja parametrów wiatru na obiektach latających

Streszczenie: W artykule przedstawiono propozycję pomiaru i estymacji parametrów wiatru na dowolnym obiekcie latającym. W systemie tym wykorzystano trzy źródła informacji: pomiar kursu (układ kursowy lub układ odniesienia pionu i kierunku AHRS), pomiar prędkości względem powietrza (prędkościomierz ciśnieniowy) oraz pomiar kąta drogi i prędkości podróżnej za pomocą odbiornika GPS. Weryfikacja podanego rozwiązania została przeprowadzona w oparciu o wykonane w trybie off-line obliczenia na podstawie danych z lotu samolotu PZL M-20 Mewa oraz na podstawie przeprowadzonej analizy błędów.

Słowa kluczowe: pomiary, estymacja, prędkość i kierunek wiatru, prędkość względem powietrza, kurs, kąt drogi, prędkość podróżna

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