INTEGRATED MODULAR MEASUREMENT SYSTEM FOR IN-FLIGHT TESTS

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Summary

During the development of the aircraft structure, test flights are indispensible. In some experiments additional sensors are mounted, which often leads to certain technical problem. In particular, changes of the structure are necessary and additional costs are generated. Therefore, advanced measurement methods enabling an analysis of several parameters without adding special sensors are developed. One of the projects focused on problems of measurement during the flight is the AIM2 project in the frames of FP7. During research mobile optical measurement systems and application rules are developed As described in references [1, 2], the AIM project - Advanced In-flight Measurement Techniques – focused on the application of modern optical measurement techniques in industrial wind tunnels for the purpose of flight testing. Possibilities to measure wing and rotor deformation, surface pressure distribution, heat distribution and flow velocity fields in a non-intrusive way and with a minimal sensor setup were presented in the AIM project. Also, the most important challenges connected with industrial implementation of methods demonstrated in the AIM project were taken into consideration. The research is being continued in AIM² project. AIM2 aims at the development of measurement methods for easy and typical applications to in-flight testing with industrial requirements.

In order to test the optical measurement methods, additional flight data are required. The data required are angular rates in the body frame, Euler angles, accelerations, IAS, TAS, altitude. This article describes a system which is used in the project for additional data measurements. The whole system will be mounted on the board of the PW-6 glider.

Keywords: data acquisition, monitoring, flight tests.

ZINTEGROWANY MODUŁOWY SYSTEM POMIAROWY DLA BADAŃ W LOCIE

Streszczenie

Podczas prac projektowo-rozwojowych powiązanych z projektowaniem konstrukcji lotniczych, niezbędne jest wykonanie prób w locie. Niektóre testy wymagają montażu dodatkowych czujników, co często jest powodem różnego typu problemów technicznych. Często w takich sytuacjach niezbędne są zmiany w strukturze konstrukcji, co generuje dodatkowe koszty. Dlatego rozwijane są metody umożliwiające analizę różnego typu parametrów, które nie wymagają montażu dodatkowych sensorów. Jednym z projektów, który koncentruje się na problematyce pomiarów podczas prób w locie jest projekt AIM2, realizowany w ramach 7 Programu Ramowego Unii Europejskiej. Podczas badań, rozwijane są mobilne optyczne systemy pomiarowe oraz ich aplikacje. Jak opisuje bibliografia [1, 2], projekt AIM - *Advanced In-flight Measurement Techniques* koncentrował się na zastosowaniu w badaniach w locie współczesnych technik pomiarowych, które są stosowane podczas badań w tunelach aerodynamicznych. W projekcie AIM, przy minimalnym zestawie czujników oraz bez ingerencji w strukturę konstrukcji, zostały zaprezentowane możliwości pomiaru deformacji skrzydła oraz wirnika, rozkładu ciśnień na powierzchni, rozkładu ciepła oraz prędkości przepływu. W ramach projektu AIM przeanalizowano również najważniejsze wyzwania związane z implementacją przemysłową demonstrowanych metod. Badania są kontynuowane w ramach projektu AIM². Projekt ten ma na celu rozwój metod pomiarowych w celu ułatwienia ich stosowania podczas badań w locie, zgodnie z wymaganiami przemysłowymi.

W celu testów metod optycznych, wymagane są dodatkowe dane pomiarowe: prędkości kątowe w układzie współrzędnych związanym z samolotem, kąty Eulera, przyspieszenia, prędkości lotu IAS oraz TAS, wysokość. Niniejszy artykuł opisuje system, który użyty zostawł w projekcie dla celów pomiaru dodatkowych danych. System jest wykorzystywany podczas prób na pokładzie szybowca PW-6.

Słowa kluczowe: akwizycja danych, monitorowanie, próby w locie.

1. MEASUREMENT SYSTEM - GENERAL IDEA

The general scheme of the measurement system is presented in figure 1. The system measures such parameters as:

- attitude angles (pitch, roll, yaw),
- angular rates in body frame (p, q, r),
- accelerations in body frame (ax, ay, az),
- static and dynamic pressure,
- angle of attack and slide-slip angle,
- GPS parameters (latitude, longitude, track angle, height),
- time data.

All units are connected to the CAN data bus. Data are registered with the use of specialized software on the board of a PC computer, which is connected to the CAN bus with the use of a CAN-USB interface. The system contains an integrated AHRS+GPS+ADC module, A/D and a digital input. To the integrated AHRS+GPS+ADC module, and two A/D inputs an aerodynamic probe is connected. The aerodynamic probe enables the measurement of the total and dynamic pressure, the slide-slip angle and the angle of attack.

2. INTEGRATED AHRS+GPS+ADC

The unit measures angular rates, accelerations, static and dynamic pressures, GPS data. For pressures, sensors MPXV5010DP and MPXAZ6114AP were used [3, 14]. For angular rates L3G4200D, for acceleration LSM303DLHC were applied [4, 5]. Additionally, the implemented software calculates attitude angles (pitch, roll, yaw). The calculation algorithm is based on quaternion algebra. Details of attitude calculation with the use of algebra is described e.g. in bibliography [8, 10, 14]. Quaternion is a number system that extends the complex numbers. It can be presented as four dimensional vector. Measuring angular rates in the aircraft body frame, quaternion derivatives can be calculated:

$$\dot{\varepsilon} = \frac{1}{2} L_e \times \overline{\Omega}_K \tag{1}$$

where:

$$\varepsilon = \begin{bmatrix} e_0 \\ e_1 \\ e_2 \\ e_3 \end{bmatrix} \text{ - quaternion}$$

$$L_e = \begin{bmatrix} -e_1 & -e_2 & e_3 \\ e_0 & -e_3 & e_2 \\ e_3 & e_0 & -e_1 \\ -e_2 & e_1 & e_0 \end{bmatrix}$$

$$\overline{\Omega}_K = \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

Next, from quaternion, attitude and heading is obtained:

$$\tan\Phi = \frac{2(e_0 e_1 + e_3 e_2)}{e_0^2 - e_1^2 - e_2^2 + e_3^2} \tag{2}$$

$$\sin\Theta = 2(e_0 e_2 - e_3 e_1) \tag{3}$$

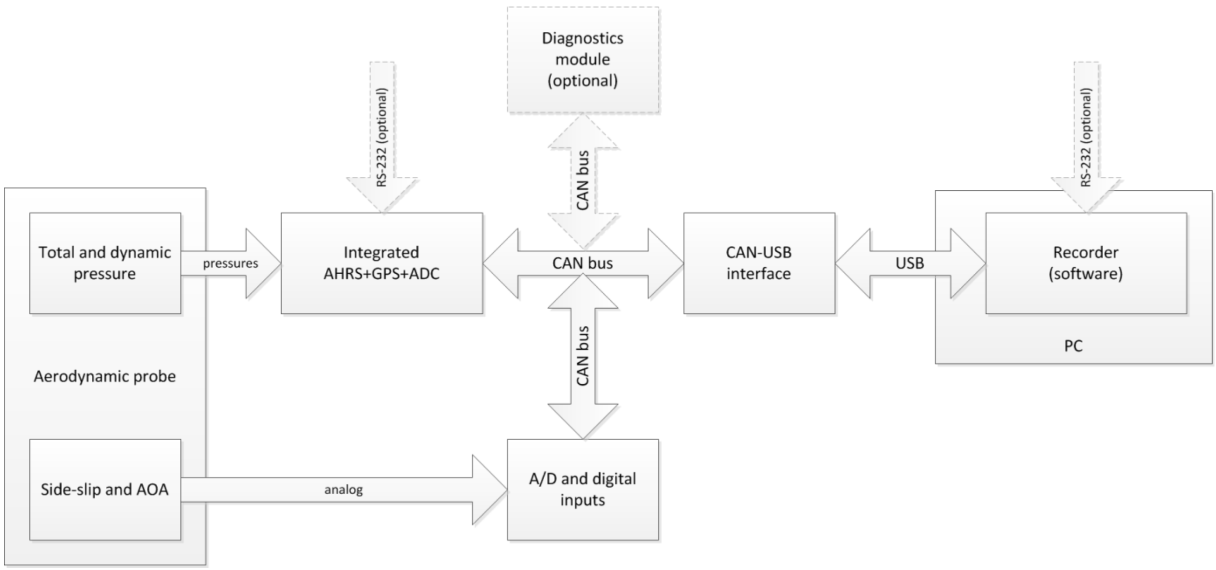


Fig. 1. General scheme of the system

$$\tan\Psi = \frac{2(e_0 e_3 + e_1 e_2)}{e_0^2 - e_1^2 - e_2^2 + e_3^2} \tag{4}$$

The advantage of applied algorithm is the possibility of measurement of Euler angles in all aircraft configuration. Additionally, numerical errors can be corrected with the use of quaternion norm, as described in [8]. Quaternion norm equals always 1:

$$E = e_0^2 + e_1^2 + e_2^3 + e_3^2 = 1 \tag{5}$$

If numerical errors appear, the quaternion norm E obtains values different from 1. Exemplary correction equation is presented below:

$$\begin{bmatrix} e_0 \\ e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} e_0 \\ e_1 \\ e_2 \\ e_3 \end{bmatrix} \cdot \frac{1}{\sqrt{E}} \tag{6}$$

Correction of gyroscopes measurement errors is based on complementary filtering. During turning, gravity correction in the roll channel is switched off. Due to aircraft dynamic properties, correction based on gravity angles calculated from accelerations cannot be switched on continuously. In the solution proposed, correction is switched off during turning in roll channel. All measurement data are registered, which means that in the case of problems attitude and speeds calculation can be additionally realized offline. The module sends attitude and heading angles, as well as all measurements to the can bus. All data are registered on a PC computer.

All sensors were calibrated. For example, the static pressure sensor was calibrated in range 450 – 1020 hPa. Taking into consideration pressure distribution in the function of height, measuring points in the range 900-1020 hPa were taken with a step 10 hPa. Next, measuring points in range 800-900 – each 20 hPa – were taken, and measuring points in the range 450 – 800 hPa – each 50 hPa. Figure 3 shows dependence between the pressure and sensor raw output.

Dynamic pressure is required for aircraft speed calculation (IAS, TAS, CAS). For sensor scaling, pressure points characteristic for PW-6 instrument airspeed (IAS) were chosen. Pressures used for scaling were representative for IAS from 50 km/h to 220 km/h, with a step of 10 km/h. Figure 4 shows the results of calibration.

It was assumed that the static characteristic of applied sensors is linear for both the static and dynamic pressure. Scaling coefficients were calculated with the use of least squares method. The system sends static and dynamic pressure to the CAN bus. The data are registered, and all aerodynamic data can be calculated offline.

Fig. 2. Integrated AHRS+GPS+ADC module

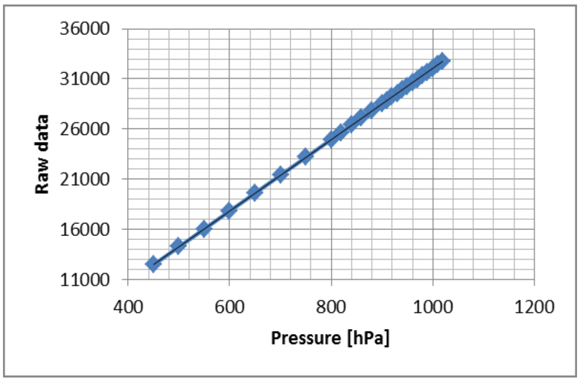


Fig. 3. Static characteristic of raw data for static pressure

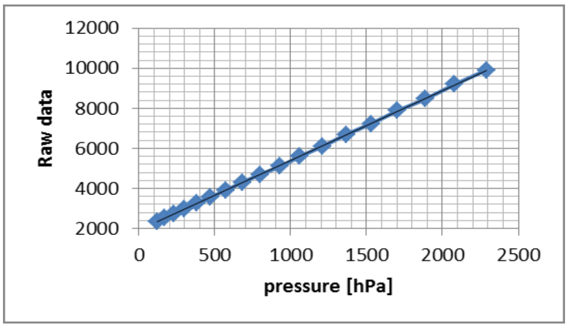


Fig. 4. Static characteristic of raw data for dynamic pressure sensor

3. A/D AND DIGITAL INPUTS UNIT

Figure 5 shows A/D and a digital inputs unit. It is used for the measurement of the angle of attack and slide-slip angles. The unit measures analog inputs and sends them to the CAN bus. Next, it transfers the information measured from the angle of attack and slide-slip angle probes to the CAN bus. Values from potentiometers are sent to the CAN bus as raw data, and consequently, offline analysis is required.

4. PC DATA RECORDING SYSTEM

The system consists of a PC computer with a CAN-BUS interface and necessary software. The most important unit is the CAN-monitor system [11]. Figure 6 shows an exemplary window of the system. Each frame is recorded in the file, with information about the CAN-USB system time. The system enables visualization of all data sent in the CANAerospace standard. The open CANAerospace protocol is described in [12]. In the recording and visualization system, each measurement has a separate CAN frame with a unique, normalized identifier. This solution offers the possibility of data synchronization. After every in-flight experiment, data are decoded with the use of decoding software. Figure 7 shows an exemplary window of the data decoding software. For data decoding, all identifiers must be introduced to the ID windows. Figure 8 shows an exemplary view of decoded data. Each measurement is in a distinct column. The first column is always time (seconds). The first row gives information about data in each column (unique information in CAN aerospace protocol).

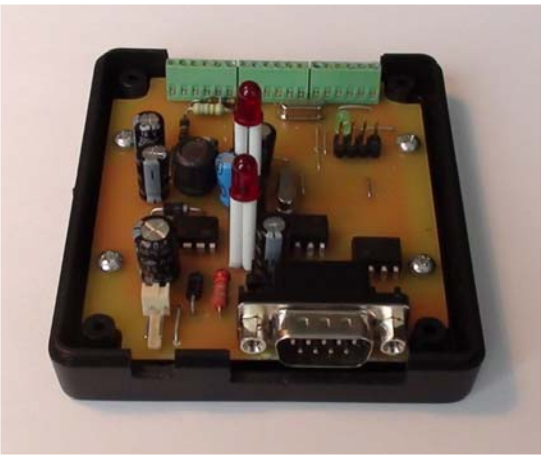


Fig. 5. A/D and digital inputs unit

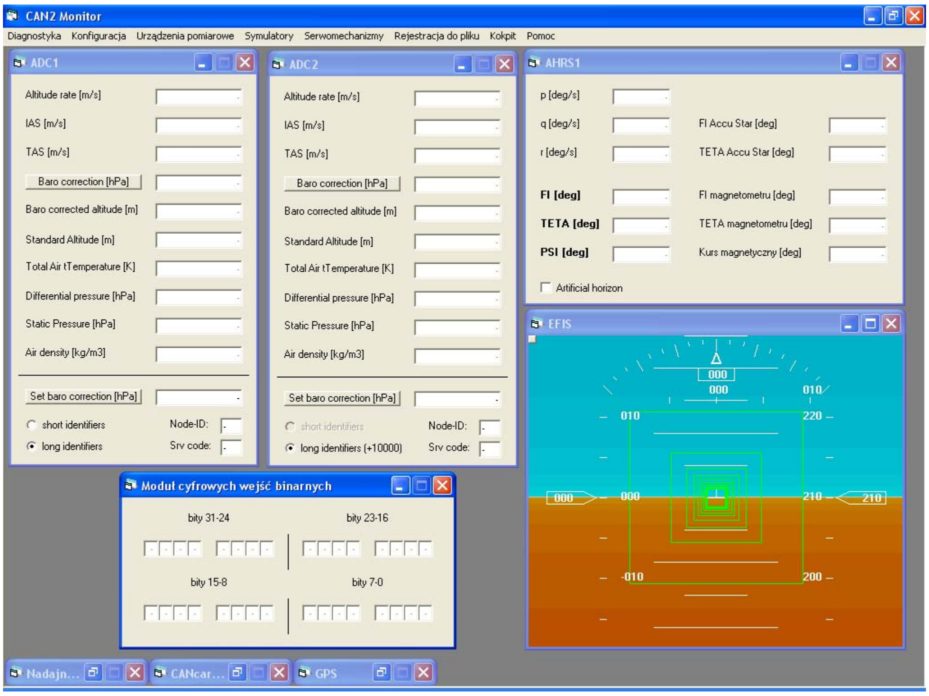
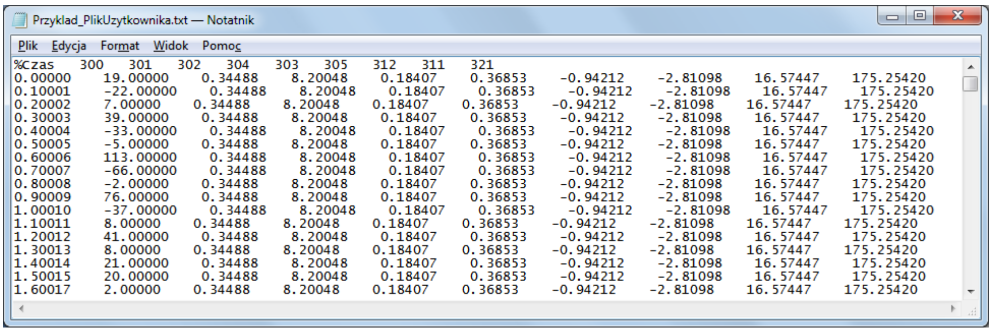


Fig. 6. Exemplary window of CAN monitor system



%Czas	300	301	302	304	303	305	312	311	321
0.00000	19.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
0.10001	-22.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
0.20002	7.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
0.30003	39.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
0.40004	-33.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
0.50005	-5.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
0.60006	113.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
0.70007	-66.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
0.80008	-2.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
0.90009	76.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
1.00010	-37.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
1.10011	8.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
1.20012	41.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
1.30013	8.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
1.40014	21.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
1.50015	20.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420
1.60017	2.00000	0.34488	8.20048	0.18407	0.36853	-0.94212	-2.81098	16.57447	175.25420

Fig. 7. Exemplary file with decoded data

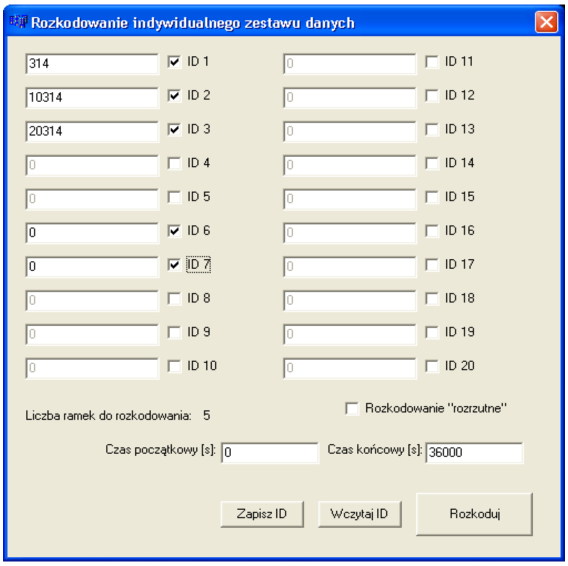


Figure 8. Data decoding software.

5. FLIGHT TESTS

The complete integrated modular measurement system was installed on the board of a PW-6U experimental glider (Fig. 9 and 10). Static pressure, dynamic pressure, angle of attack (AOA) and angle of sideslip (AOS) probes were mounted on the extension arm, on the top of glider's fuselage (Fig. 11). The PW-6U, equipped with the experimental system, was ground towed in the area of the EPRJ airport. Figure 12 presents ground speed (GS) obtained from a GPS receiver. The glider reached GS=45 km/h without any significant change in altitude (Fig. 13). Glider did not lift off in the fact because this experiment was planned as an extended ground test. Plot of dynamic pressure, connected with airspeed, is presented in figure 14. Course of runway (270 deg) was maintained precisely (Fig. 15) during the whole test.

Fig. 9. General view of PW-6U glider prepared for AIM experiments

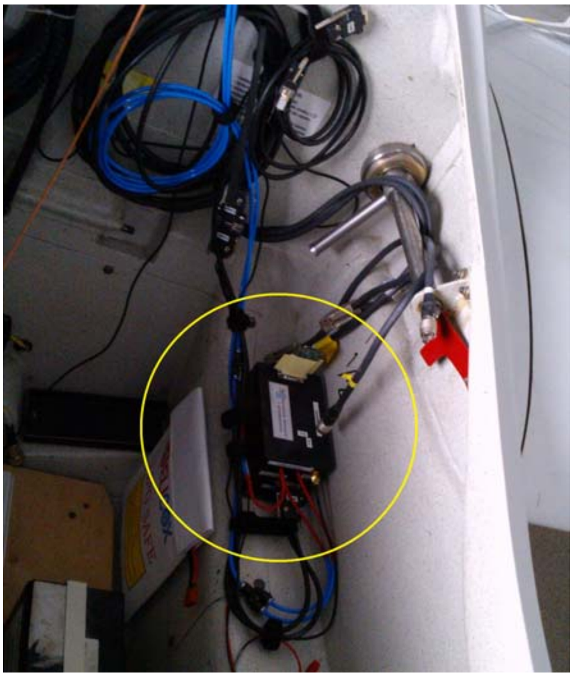


Fig. 10. Integrated AHRS+ADC+GPS mounted on the board of PW-6U glider

Fig. 11. Aerodynamic probe (with red plugs)

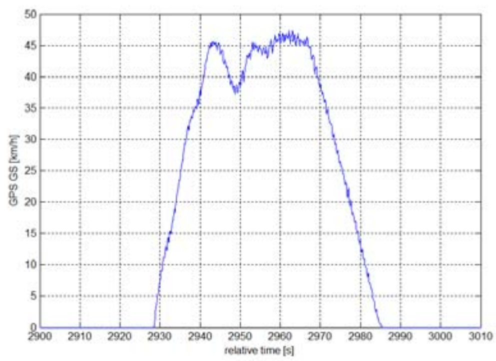


Fig. 12. Ground speed recorded during towing with a car (EPRJ airport, runway 27, Aug 14, 2013)

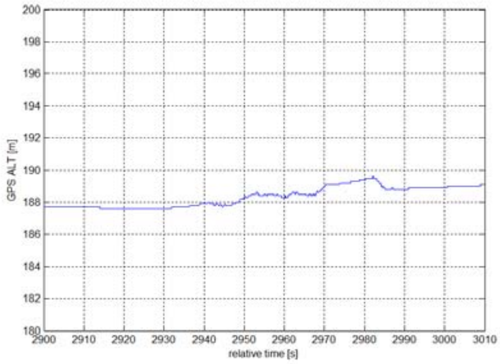


Fig. 13. GPS altitude recorded during towing with a car

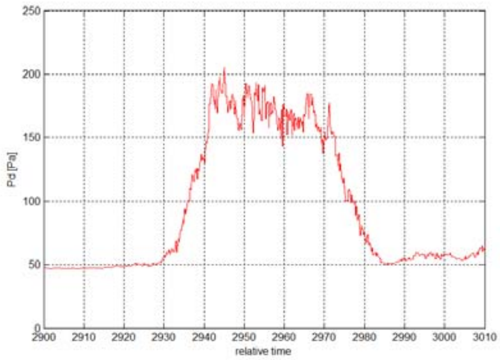


Fig. 14. Dynamic pressure, plot related to figure 11

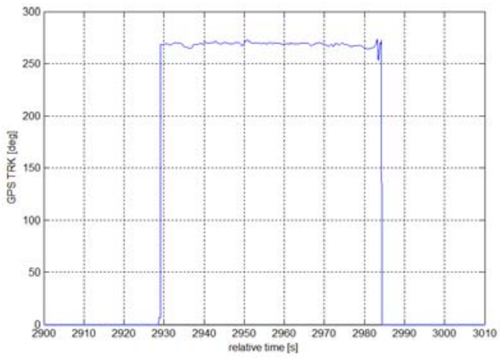


Fig. 15. GPS true track related to figure 12-14

Fig. 16 presents recorded roll and pitch. Just before towing, the longitudinal as well as the lateral axis of the glider were situated nearly horizontally. The pitch angle was increased initially, but at the end of towing its value was decreased and, after braking, it stabilized nearly at zero. After braking the bank angle reached 10 degrees because of lowering of the glider's right wing. Raw data obtained from MEMS (Micro Electro-Mechanical Systems) gyroscopes are presented in Figures 17-19. Angular rate in the lateral motion was featured by maximum range of variability (Fig. 17) and it reached ±20 deg/s during towing. Angular rate did not exceed ±10 deg/s longitudinally (figure 18) and ±5 deg/s in the yaw axis (figure 19).

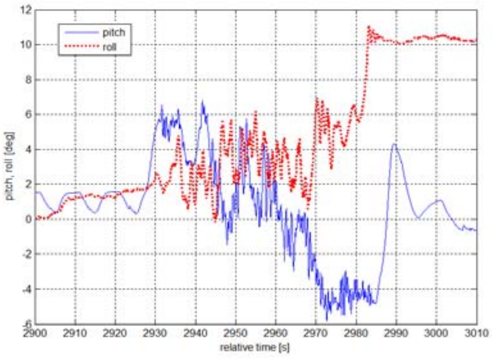


Fig. 16. Pitch and roll related to fig. 12-15

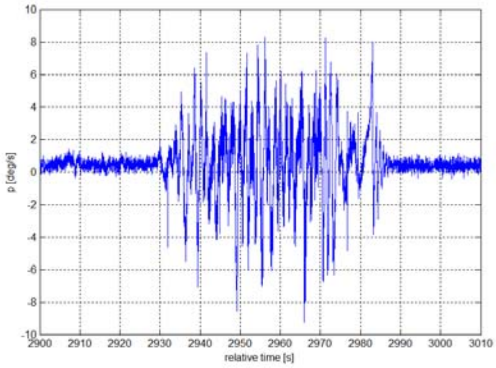


Fig. 17. Plot of angular rate p

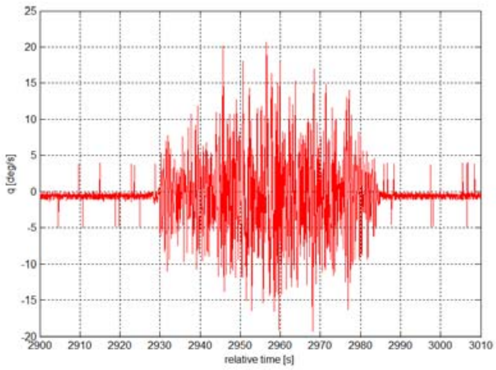


Fig. 18. Plot of angular rate q

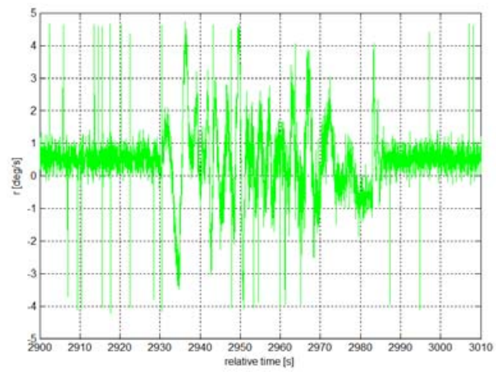


Fig. 19. Plot of angular rate r

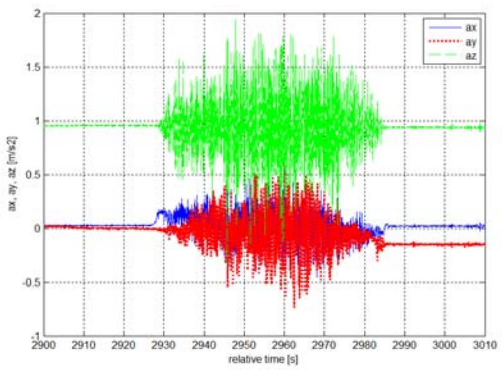


Fig. 20. Accelerations rates related to figure 11

Maximal variablity of recorded accellerations (±1 m/s^2) was recorded in axis z (vertically). Other accellerations remain generally in range ±0.5 m/s^2 (Fig. 20). Applied AOA and AOS probes can work in the range of ±30 deg, however their indications can be interpreted after exceeding about 35 km/h airspeed. This condition was obtained between 2940-2970 s (Fig. 21). In this period, AOA is negative or approaches zero because, during towing with a car, the pilot was not allowed to lift the glider off the ground Because of side wind compensation (wind from direction 180 deg), AOS reached 12 deg and was generally positive.

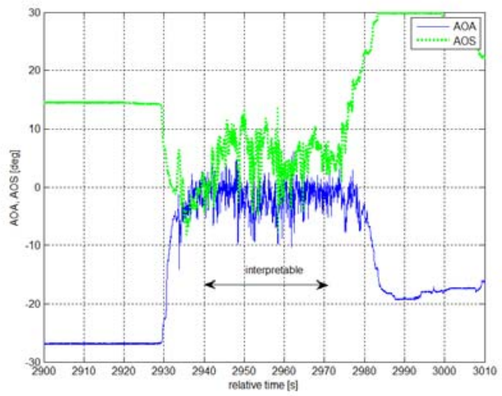


Fig. 21. Angle of attack and angle of sideslip related to figure 11

5. CONCLUSIONS

As presented in the article, the system registers the most important aeronautical data. It is universal and open for development. Additional units can be added. The only requirement is communication with the use of the CAN data bus with a CAN aerospace protocol. The unit was tested preliminarily during the flight. Data measured via an analogical measurement unit with the same sensors were used for an autonomous flight of a small UAV [6, 7, 9, 15]. The measurement system aids development of optical methods for in flight testing.

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