Journal of KONBiN 2022
Volume 52, Issue 1
DOI 10.2478/jok-2022-0001

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# LOW COST AVIONICS SYSTEM FOR ULTRALIGHT AIRCRAFT
# Niskobudżetowy system awioniki dla samolotów ultralekkich

***Abstract:*** *The article presents a low cost avionics system for ultralight aircraft and paraplanes. The system contains Attitude and Heading Reference System, Air Data Computer and Primary Flight Display. Communication between units is via Wi-Fi. In the article design description was presented, as well as laboratory tests results. They are promising and the system is ready for in flight testing.*
**Keywords:** avionics system, ultralight aircraft, paraplane

***Streszczenie:*** *Artykuł przedstawia niskobudżetowy system awioniki dla samolotów ultralekkich i paraplanów. W jego skład wchodzą AHRS, centrala areometryczna oraz wyświetlacz parametrów lotu. Komunikacja pomiędzy modułami została zrealizowana z wykorzystaniem modułów Wi-Fi. W artykule przedstawiono rozwiązania konstrukcyjne oraz wyniki testów laboratoryjnych. Wyniki wstępnych badań są obiecujące i system jest gotowy do realizacji badań w locie.*
**Słowa kluczowe:** system awioniki, samolot ultralekki, paraplan

# 1. Introduction

Ultralight airplanes are intended for amateur use. The equipment requirements are lower than those of other classes of aircraft. The minimum equipment for ultralight construction is an altimeter, a speedometer, and a magnetic compass [20]. Ultralight airplanes with built-in electronic systems, such as integrated systems measuring barometric data as well as attitude and heading, are often found. Another class of popular flying structures are, e.g. paraplanes. In this case, aviation regulations do not require the installation of avionics systems, such as an altimeter, speedometer or magnetic compass, however, additional equipment is allowed, providing a secure attachment, preventing the possibility of falling off during the flight [20]. Low cost, easy to install and operate, and safe pilot equipment can give pilots of ultralight amateur aircraft or paraplane the opportunity to develop the skills of interpreting instrument indications and deepen their aviation knowledge. This publication presents an implemented example of a system consisting of AHRS, ADC systems, and a display on a mobile device, intended for low cost, ultralight aircraft and paraplanes.

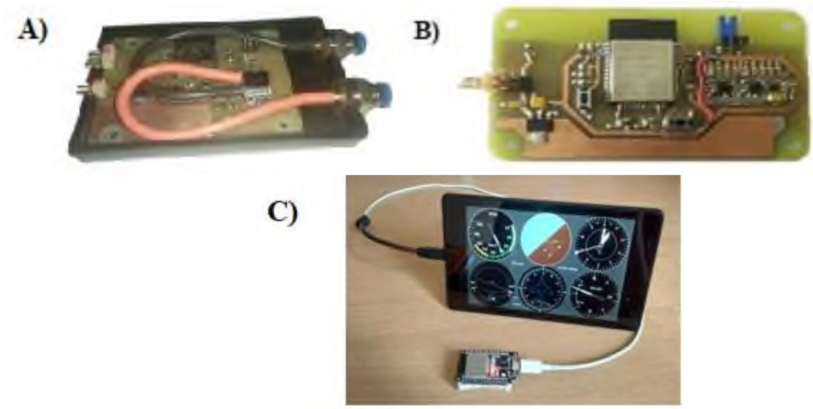


**Fig. 1.** System components: A) ADC unit, B) AHRS unit, C) PFD unit

# 2. An idea of the system

The aim of the project was to design a low-cost, wireless, integrated system of basic on-board instruments, consisting of a speedometer, altimeter, variometer, artificial horizon, turn indicator, and course indicator.

The system consists of three elements - the air data computer, the AHRS system, and the display. The display will show the pilot the basic flight parameters in the form of classic pilot instruments. The display will receive the above parameters from the AHRS system and the air data computer via wireless communication.

The lack of cables connecting the devices is characterized by the following advantages:
1. Significant reduction in the weight of the entire system
2. Significant reduction of assembly time and noninvasive assembly
3. Significant reduction of the risk of incorrect assembly (e.g. collision of control system elements with wires, e.g. wrapping and blocking by a wire of a moving element).

The disadvantages of the applied solution are undoubtedly:
1. Danger of intentional or accidental disturbances. However, for the described structure, it is low. Also, even in the event of a system malfunction, it is possible to continue the flight, as it is an additional system.
2. Increased demand for electricity. However, it is low, the system has its own battery power supply.

This analysis clearly shows that the advantages of the applied solution in the case of the described structure outweigh the disadvantages.

The designed system will be universal and implemented with the use of commonly available programming and hardware solutions (ESP32, ESP-NOW protocol, Arduino, Android Studio, PlaformIO), which will reduce the costs of prototyping and reduce the time necessary for execution. The structure of the system allows for independent work of members of the project team.

# 3. ADC Unit

There are many competitive solutions for air data computers on the market. Starting from the simplest, which provide only the basic amount of information, such as flight altitude and indicated speed, used mainly by RC modeling amateurs, to much more complex devices, used by civil and military aviation. These are characterized by greater accuracy and the number of calculated flight parameters.

The device was designed with the possibility of being used in both ultralight airplanes and paraplanes. For this reason, the device should be as small as possible, allowing easy assembly and disassembly. It must also be light to avoid adversely affecting the amount of payload of the aircraft. Due to the type of aircraft for which the device was designed, it will be characterized by low electricity consumption and the possibility of battery operation. The device, based on the measurement of absolute pressure, differential pressure, and temperature, will calculate basic flight parameters, such as barometric altitude, indicated airspeed, true airspeed, and vertical speed. Measurement data from the air data computer will be sent via a Wi-Fi wireless network to the selected PFD display. The device will communicate with the display via the ESP-NOW protocol and will be equipped with a UART interface for programming and diagnostics.

Based on the design assumptions, a block diagram of the designed air data computer was created and basic elements, such as a microcontroller and measurement sensors, were selected. The block diagram is presented in fig. 2.

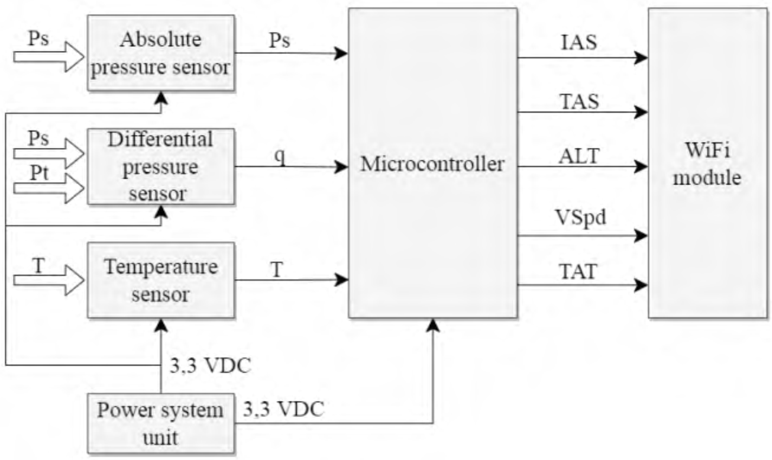


**Fig. 2.** Block diagram of the air data computer

The wiring diagram and printed circuit board design were made using EAGLE software. After creating the wiring diagram, the program automatically places the used elements in the board design. In addition, it informs about the connections of these elements with each other. The role of the designer is to properly arrange the elements and connect them with paths to obtain the image of the printed circuit board.

The printed circuit board is two-layer. All elements are on the top layer and the ground is on the bottom layer. Thanks to this division, it is easier to connect all the elements with each other, the circuit board looks neat, and, if necessary, it is easier to make corrections in such a prototype.

The system tests were carried out in the laboratory with the use of a calibrator. It was a Mensor Model 5014 device, used to calibrate pressure instruments.

First, the indications of the absolute pressure sensor were examined. Due to the lack of a port in the MS5611 sensor, it was necessary to use a vacuum chamber. The air data computer was placed in the chamber and then a manual vacuum pump was connected to it. Measurements were started from the currently prevailing atmospheric pressure, and then the pressure value was lowered by 500 Pa, and the obtained data were recorded. A total of 69 measurements were made, reaching the lowest pressure value of 37,800 Pa, which is equivalent to a height of 7,583.1 m according to the International Standard Atmosphere. The maximum altitude for an aircraft with the described system was assumed to be 7000 m. In the case of paraplanes and low cost ultralight, the maximum ceiling will be much lower.

The differential pressure sensor was tested. The static pressure port received the current atmospheric pressure, and a measuring instrument was connected to the total pressure port. A total of 69 measurements were made, reaching a pressure of 105,945 Pa, which at the current ambient pressure of 99240 Pa, corresponded to a dynamic pressure of 6705 Pa. The linearity of the characteristics of both sensors was found. To determine the scaling functions, the function approximation using the least-squares method was used.

After the pressure sensors were scaled, the possibility of measuring the angular velocity was tested on the basis of determining the time derivative of the barometric altitude. With direct differentiation of the height of the stationary device, instantaneous values reaching almost -40 [m/s] can be observed.

To eliminate the described noise, a Kalman filter was used. The Kalman filter is a recursive algorithm consisting of two phases. In the first phase (called prediction), an estimated state value and error covariance are determined from the state value and error covariance in the previous step. At the beginning of the second phase (called correction), the Kalman gain is calculated. It is something like the weight with which the correction phase will affect the estimated state. Then, on the basis of the measurement of the process, state estimates are made. The final step in the correction phase is to obtain the error covariance [9].

Figure 3 shows a comparison of the vertical speed before (blue line) and after filtration (orange line).

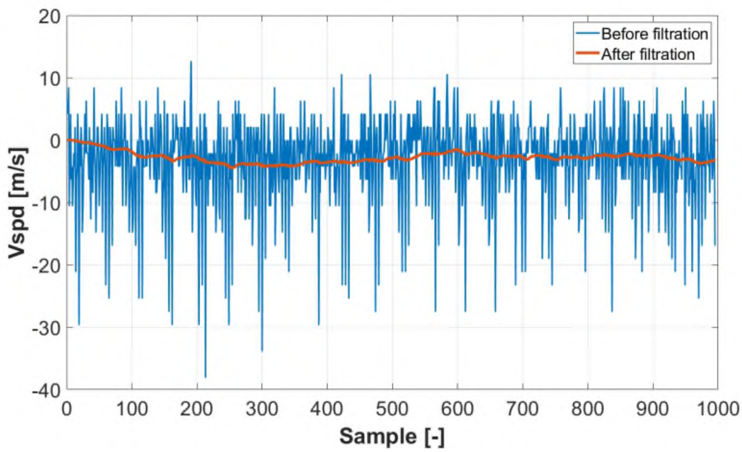


**Fig. 3.** Comparison of vertical speed measurement before and after filtration

Correct scaling and application of the described filtration made it possible to use the device to measure all required aerometric quantities [19].

# 4. AHRS unit

Figure 4 shows the general scheme of the designed AHRS. Based on measurements of angular rates, accelerations and magnetic heading it calculates attitude and heading angles. Presented solution contains the individual functional blocks necessary for the implementation of the adopted project assumptions.

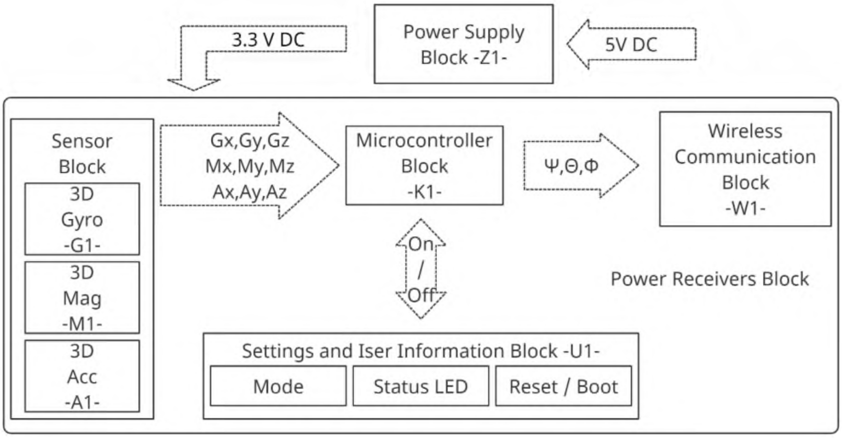


**Fig. 4.** Schematic structure of the designed device

The circuit board was designed taking into account the functional requirements such as the need of reducing the antenna interference and magnetic disturbances derived from power lines. The main components consist of:

- IAM-20380 [18], a digital three-axis gyroscope produced by TDK InvenSense, that has the AEC-Q100 qualification (passed the automotive industry test for correct operation in the entire temperature range)
- IAM-20381 [7], a digital three-axis accelerometer from TDK InvenSEnse, also AEC-Q100 qualified
- IIS2MDCTR [13], a digital three-axis magnetometer from STMicroelectronics
- The ESP32 WROOM 32D [2], a low-cost, low-power SoC microcontroller form Espressif Systems, fitted with an dual core 240MHz microprocessor and an integrated antenna, needed for communication via Wi-Fi (802.11 b / g / n) and Bluetooth (4.2 and BLE). It includes peripheral interfaces such as SPI, I2C and a UART interface for programming.

Figure 5 shows block diagram of calculations necessary for attitude calculation.

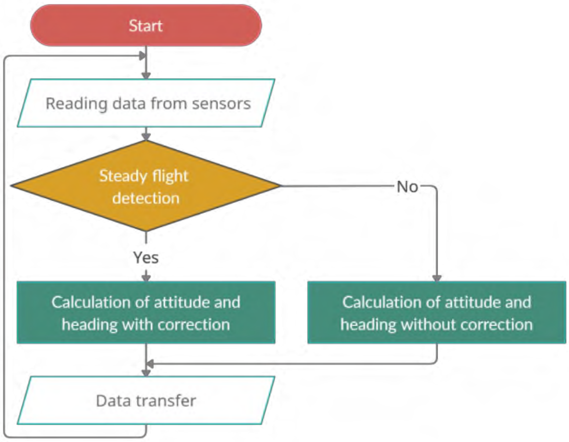


**Fig. 5.** Flow chart illustrating the methodology for calculation of the attitude and heading angles

Attitude and heading is calculated with the use of Euler angles transformation algorithm. For correction, complementary filter was implemented. To avoid influence of accelerations during dynamic states (e.g. centrifugal force), correction was switched off during dynamic states. For scaling and testing, following steps were realized:

1. The scaling of accelerometer and gyroscope as well as compensation of magnetic deviation (from hard iron and soft iron) has been carried out. Gyroscope and accelerometer were scaled with the use of MTG7 D.Marchiori (DMA) rotating table. Last squares method was implemented.

2. Proper measurement of attitude and heading was tested in laboratory conditions (static tests, quasi-dynamic states testing proper magnetic and gravity correction behaviour). The device was tested in the ranges of ± 90° pitch and roll, ± 180° yaw. Also communication tests were carried out. Figure 6 shows exemplary results in roll channel.

The next step is to carry out in flight tests.

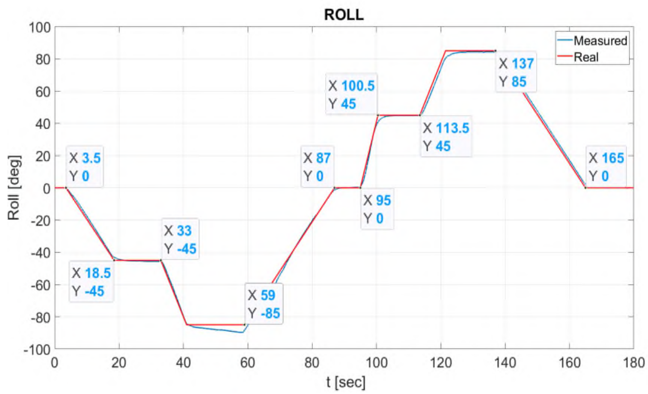


**Fig. 6.** The plot of the real and measured roll angle. Red line - given roll angle. Blue line - AHRS angle

The result indicates that the device meets the design assumptions in the pitch and roll channel. Attitude is calculated properly both, in static and dynamic conditions (e.g. turning). The used magnetometer turned out to be a problem. It has too little sensitivity and too large measuring range. This makes it difficult to properly calibrate, leading to greater than expected susceptibility to interference. The use of a different or an external additional magnetometer may constitute a continuation of the design work. Communication tests were successful. The system works fine in the pitch and roll channel.

# 5. PFD unit

It has been established that a mobile device with Android system (smartphone or tablet) will be acting as a display, to the USB port of which will be connected an ESP32 microprocessor, acting as an independent and reliable communication system. The advantage of this solution is gaining independence in the positioning of the display in relation to the antenna of the communication system (bypassing the elements of the aircraft structure, which may appear as screens preventing communication). The microprocessor chip program receives data from the air data computer and the AHRS system via wireless connectivity, and sends this data on to the Android device via the USB cable. The display application was written in the Android Studio development environment and works on any device [12]. The only requirement is that they support the USB OTG (On-The-Go) protocol so that the ESP32 microprocessor can be connected and powered by it [2]. The data visualization was chosen in the form of a basic six - a set of basic on-board instruments, which include a speedometer, altimeter, variometer, artificial horizon, turn indicator and a course indicator [15]. It is also possible to extend the software with other visualization variants (e.g. integrated indicator). The application receives data from the microprocessor, sorts it, calculates the altitude based on the received pressure and assigns it to the appropriate instrument. GNSS function could be provided by device's internal satellite navigation solution (depending on the device this could be GPS, GLONASS, GALILEO, Beidou).

The interface consists of screens imitating on-board analogue dial instruments and indications of TAS speed, temperature and atmospheric pressure in text form.

The atmospheric pressure from the air data computer is obtained in the Pa (Pascal) unit. It is converted into mmHg (millimeters of mercury) and given in text form in the top row between the altimeter and the variometer.

The outside air temperature is displayed in text form on the bottom row between the turn indicator and heading indicator to two decimal places. It is given in degrees Celsius.

The system tests were carried out in a laboratory that allowed for testing the AHRS systems and the air data computer cooperating with the display. The essence of the display test was to check communication with other systems.

Communication was successful, the devices connected to each other automatically. The connection was stable, there were no undesirable breakdowns of communication, even when the microcontrollers were separated by several meters. There was a noticeable delay (less than half a second) from the action performed to the response of the display. The elimination of these delays, especially the attitude and heading angles, may be the content of further research. Angles and angular velocities indicated on the display coincided with those set on the rotary table controller. This proves the correct operation of the AHRS system and correct communication between the systems. With the change of the set pressure, the speeds of IAS and TAS changed. Their values were identical to those read from the internal register of the air data computer- it proves proper communication between the systems [4].

# 6. Conclusions

The paper presents a system designed for ultralight amateur constructions, implemented as part of three engineering works. The conducted ground tests show that the system works properly and that after minor corrections (e.g. the use of an external, additional magnetometer) it is possible to use it in low cost ultralightand paraplanes. The next step is to perform flight tests [16]. The devices have independent power supply systems, and it is possible to install them without affecting the aircraft structure. They can be used both for the implementation of simple flight tests (e.g., measurement and recording of flight parameters for further analysis) and for use during training flights. The system is open and allows for further expansion. For example, it is possible to expand the PFD system with other indication systems, or integrate the air data computer and the attitude and heading reference system, and use the correction algorithms described in [11] and [10]. An important issue during the continuation of the work will be the elimination of delays in the PFD display. The advantage of the communication method used is the possibility of expanding the system with new modules. In summary, the results of the work are promising and enable both the practical use of the system and its development.

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