Testing of the attitude and heading reference system

Andrzej Tomczyk

The author

Andrzej Tomczyk is with the Department of Avionics and Control, Rzeszów University of Technology, W.Pola 2, 35-959 Rzeszów, Poland

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Abstract

Rzeszów University of Technology has undertaken the task of designing and providing of equipment to a flying laboratory. This paper presents basic design principles of the Inertial Reference Unit (IRU) which employs measuring signals from the Fiber Optic Gyros (FOG), accelerometers and electronic compass module. A microcomputer follows the algorithm of complementary filtration for of calculating the Euler angles for the aircraft attitude (pitch, roll and heading), angular rates, and linear accelerations. The correction systems that minimize error of the steady-state measuring have been employed. The results of computer simulations, lab tests and selected flight tests have also been presented. The Inertial Reference Unit μIRU-1 was tested in flight on board of the general aviation aircraft PZL-110 "Koliber". It has been confirmed that metrological properties of the system are appropriate for the purposes of teaching process. Currently, a modified version of the unit is being prepared. The new IRU is planned as a main reference unit for integrated flight control system of general aviation aircraft.

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Strapdown platform – basic mathematics relationships

All sensors of the IRU are placed on the platform that is fixed to the aircraft. This way, the aircraft becomes a measurement platform. A computer must be used to transform the input signals to the Earth-fixed coordinate system. The measuring body-fixed $(0x_By_Bz_B)$, Earth-fixed coordinate system $(0x_Gy_Gz_G)$, respectively, and the relations between them are shown in Figure 1.

The angular rates transformation reads:

$$\frac{d}{dt}\begin{bmatrix}\Phi\\ \Theta\\ \Psi\end{bmatrix} = \begin{bmatrix}1 & \sin\Phi\cdot\mathrm{tg}\Theta & \cos\Phi\cdot\mathrm{tg}\Theta\\ 0 & \cos\Phi & -\sin\Phi\\ 0 & \dfrac{\sin\Phi}{\cos\Theta} & \dfrac{\cos\Phi}{\cos\Theta}\end{bmatrix} \times \begin{bmatrix}p\\ q\\ r\end{bmatrix} \quad (1)$$

$$\begin{bmatrix}p\\ q\\ r\end{bmatrix} = \begin{bmatrix}1 & 0 & -\sin\Theta\\ 0 & \cos\Phi & \sin\Phi\cdot\cos\Theta\\ 0 & -\sin\Phi & \cos\Phi\cdot\cos\Theta\end{bmatrix} \times \frac{d}{dt}\begin{bmatrix}\Phi\\ \Theta\\ \Psi\end{bmatrix} \quad (2)$$

As we can see, we cannot calculate of $d\Psi/dt$ and $d\Phi/dt$ if pitch angle Θ reaches $\pm 90°$. This obstacle can be overcome by using quaternion algebra for the transformations (Gosiewski, 1999; Narkiewicz, 1999). The attitude quaternion $\boldsymbol{Q}$ is defined as the vector that contains four components:

$$\boldsymbol{Q} = [a, b, c, d]^T, \quad a^2 + b^2 + c^2 + d^2 = 1 \quad (3)$$

The propagation of the quaternion in time is described by the differential equations:

$$\frac{d}{dt}\boldsymbol{Q} = \frac{d}{dt}\begin{bmatrix}a\\ b\\ c\\ d\end{bmatrix} = \frac{1}{2}\begin{bmatrix}a & -b & -c & -d\\ b & a & -d & c\\ c & d & a & -b\\ d & -c & b & a\end{bmatrix} \cdot \begin{bmatrix}0\\ p\\ q\\ r\end{bmatrix} \quad (4)$$

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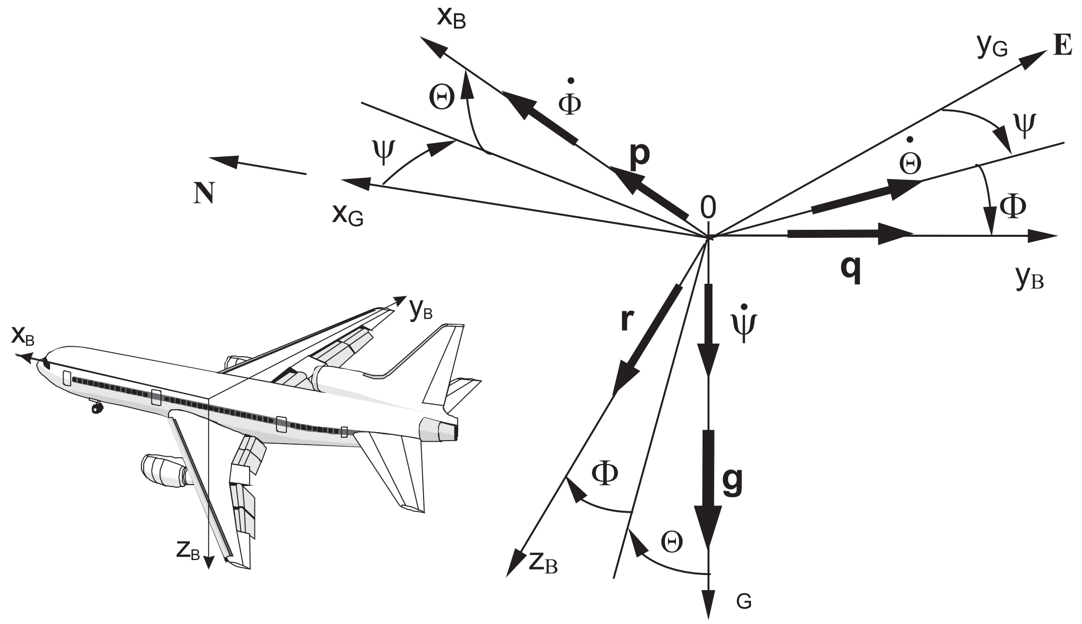
Figure 1 Body-fixed ($0x_By_Bz_B$) and Earth-fixed coordinate system ($0x_Gy_Gz_G$): p, q, r – angular rates in the body-fixed coordinate system, ρ – pitch angle, φ – bank angle, Ψ – heading, g – acceleration of gravity



or

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 0 & -p & -q & -r \\ p & 0 & r & -q \\ q & -r & 0 & p \\ r & q & -p & 0 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}$$

The Euler angles can be calculated as a quaternion components function as follows:

$$\begin{aligned} \sin\Theta &= 2(ac - db) \\ \mathrm{tg}\Phi &= \frac{2(ab + cd)}{a^2 - b^2 - c^2 - d^2} \\ \mathrm{tg}\Psi &= \frac{2(ad + bc)}{a^2 + b^2 - c^2 - d^2} \end{aligned} \qquad (5)$$

IRU principle of operation

The strapdown IRU operating is based on the following sensors:

- rate gyros (Fiber Optic Gyro - FOG),
- inclinometers or accelerometers,
- magnetic compass module (magnetometer).

The scheme of hardware concept is presented in Figure 2.

The basic sensors are rate gyros. However, the information of gyro is in short-term accurate only due to the Earth rate and gyro drift. We can eleminate the influence of these errors by using a high-pass filter (see Figure 3). It means that we have to use the correction signals of a good long-term performance. The inclinometer is applied as a sensor of pitch (Θ_G) and roll (Φ_G) angles in the Earth fixed coordinate system. The yaw angle (heading Ψ_B) correction signal is produced by the magnetic compass module (magnetometer). Short-period disturbances of the inclinometer and magnetometer output signals are filtered by the low-pass filter. The high-pass and low-pass filters create so called complimentary filter (Collinson, 1996; Popowski and Kaźmierski, 1995). Figure 3 shows the complimentary filters to estimate the roll angle, for example.

However, the influence of the correction signals must be controlled. In some cases, the correction signals introduce bigger errors, for example $\Phi_G = 0$ for typical turn at $\Phi \neq 0$. Therefore, the logical correction box is used, which inserts a switch to enable/disable the correction signals. This switch can be activated by several parameters. The switch conditions are:

ON – Normal operation, the correction signals are used,

OFF – The correction signals are switched off, if the following conditions are met (Tomczyk and Pieniążek, 1998):

- Turn is executed at the rate r and during time T_R, and: $|r| > r_{OFF}$ and $T_R > T_{OFF}$; $r_{OFF} = 0.1 \div 0.5°/\mathrm{s}$, $T_{OFF} = 3 \div 12\,\mathrm{s}$
- Error signal of the magnetometer is detected. The build-in inclinometer

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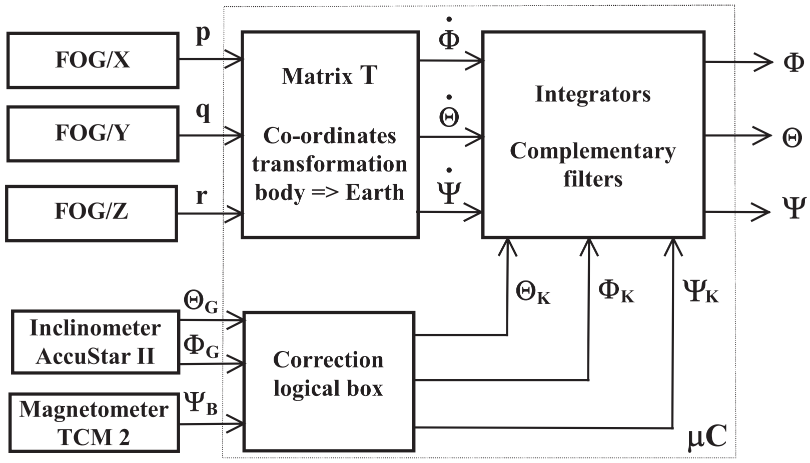
Figure 2 Preliminary concept of hardware



- delivers an error message if the inclination angle becomes too big, the maximum inclination angle is about 25°.
- True airspeed change is too quickly which means that inclinometer error is a big one:

$$\left|\frac{\mathrm{d}}{\mathrm{d}t}(\mathrm{TAS})\right| \geq a_{X\max};$$

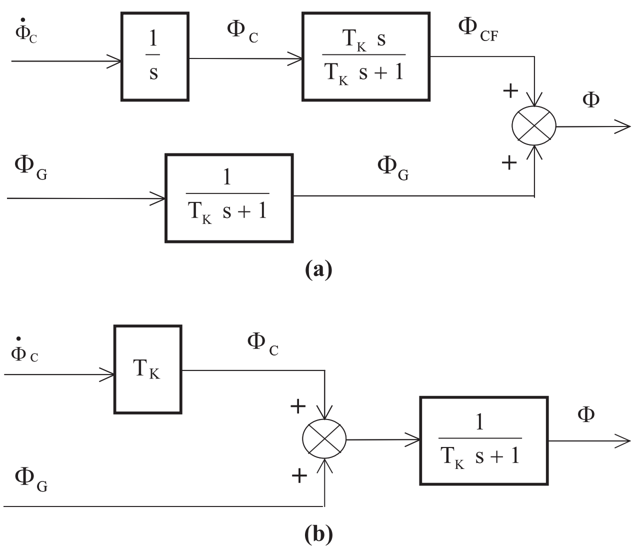
$$a_{X\max} = 0.2 \div 0.5\,\mathrm{m/s^2}$$

Attitude and heading calculation errors

There are three types of errors:

(1) Static error; that results the influence of steady-state sensor errors: drift of fiber optic gyros and inclinometer scaling errors,
(2) Dynamic errors; regarding the effect of short-period acceleration on the sensor caused by turbulence and aircraft maneuvers,
(3) Magnetometer error as a result of the aircraft longitudinal acceleration and transversal acceleration during turn.

Figure 3 Complementary filter to estimate the bank angle Φ, T_K – time constant; a) principle of operation, b) complementary filtering in practice



For example: the bank angle static error $\Delta\Phi$ caused by the gyro drift $\Delta\dot{\Phi}$ and inclinometer error $\Delta\Phi_G$ can be calculated (Tomczyk and Pieniążek, 1998):

$$\Delta\Phi = \lim_{s\to 0} s\frac{1}{T_K s+1}\left(\frac{1}{s}T_K\Delta\dot{\Phi} + \frac{1}{s}\Delta\Phi_G\right) = T_K\Delta\dot{\Phi} + \Delta\Phi_G \quad (6)$$

where: T_K – time-constant of the complimentary filter, s – Laplace's operator.

The dynamic error of the bank angle $\mathrm{d}\Phi$ is a function of the noise frequency ω_K and can be described by the formula:

$$\mathrm{d}\Phi = \frac{A_y}{g\sqrt{1+T_K^2\omega_k^2}}; \quad (7)$$

where A_y – mean value of the lateral acceleration amplitude, g – acceleration of gravity.

During a non-steady flight the horizontal acceleration causes the error of magnetometer. Figure 4 shows influence the longitudinal acceleration and Figure 5 explains the lateral acceleration effect on the magnetometer output signal (magnetic heading Ψ_B) which is used as a long-term correction signal. Error of magnetometer may be compensated using the formula:

$$\Psi_K = \Psi_B + D_X + D_Y \quad (8)$$

where: Ψ_K – corrected value of the magnetic heading, Ψ_B – measured value of the heading,

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D_X – correction of the longitudinal acceleration error, D_Y – correction of the lateral acceleration error.

Figures 4 and 5 show the relation between magnetic heading Ψ_B, bank angle Φ, inclination angle γ, longitudinal a_x, lateral a_y and vertical a_z accelerations, respectively, where H is a vector of the Earth magnetic field intensity, g – acceleration of gravity.

After a few transformations, we can write the following formulas:

$$\operatorname{tg} D_X = \operatorname{tg}\gamma \cdot \sin\left(\operatorname{arctg}\frac{a_x \cdot \sin\Psi}{g + a_z}\right) \tag{9}$$

$$\operatorname{tg} D_Y = \operatorname{tg}\gamma \ \sin\left[\left(\Phi + \operatorname{arctg}\frac{a_y}{g + a_z}\right)\cos\Psi\right] \tag{10}$$

For small values of pitch and bank angles we can calculate the approximate value of heading error from the formula:

$$D_X + D_Y = \operatorname{tg}\gamma\left[\frac{a_x}{g}\sin\Psi + \left(\Phi + \frac{a_y}{g}\right)\cos\Psi\right] \tag{11}$$

The Euler angles are calculated using a discrete version of the complementary filter showed in Figure 3. For example, the bank angle $\Phi(k)$ is evaluated at the k^{th} step as:

$$\begin{aligned}\Phi(k) &= b\Phi(k-1) + T_K(1-b)\dot{\Phi}_C(k) \\ &\quad + (1-b)\Phi_K(k); \\ b &= \exp\left(-\frac{\Delta T}{T_K}\right)\end{aligned} \tag{12}$$

where: ΔT – period of calculation, T_K – time constant of the complimentary filter.

If the correction signal is switched off by correction logical box, the bank angle is calculated as an integral of the roll rate:

Figure 4 Influence of the longitudinal acceleration a_x on the heading error D_X

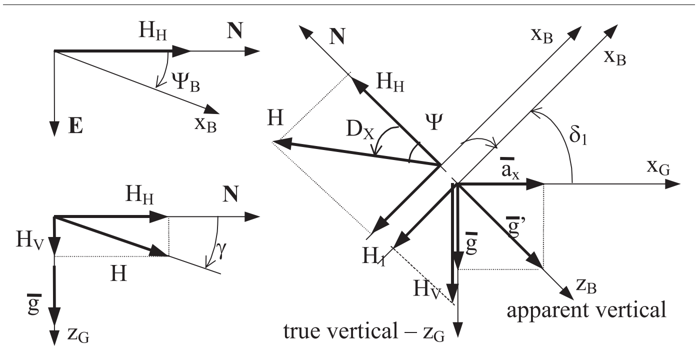
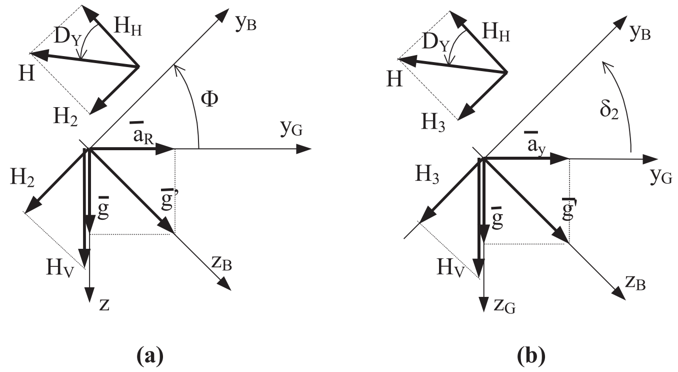


Figure 5 Influence of the bank angle Φ (a) and lateral acceleration a_y (b) on the error D_Y of the measured heading



$$\Phi(k) = \Phi(k-1) + \Delta T\dot{\Phi}_C(k) \tag{13}$$

The algorithm of attitude and heading calculations was verified by a computer simulation. Sample of pitch angle calculation for a flight in atmospheric turbulence are presented in Figure 6.

Laboratory and flight tests

The Inertial Reference Unit was designed, built and tested in the Department of Avionics and Control, Rzeszów University of Technology. Figure 7 shows the sensors of the Inertial Reference Unit called μIRU-1.

The laboratory tests confirm the static performance of the sensors and on-board computer. The reached accuracy of the attitude angles was better than 0.6° after maneuvers and 0.3° in a steady-state position. The heading error was bigger and depended on the space orientation of magnetometer and magnetic compass deviation (Vandenberghe and Vuylsteke, 1998). Figure 8 shows the maximal value of magnetic heading error during laboratory test (there are some non-steady magnetic field disturbances). There is error of correction signal only; the error of measured heading (output signal) is smaller because is calculated using complementary filter.

The flight tests ware carried at on-board of the general aviation aircraft PZL-110 "Koliber" (Tomczyk, 2000). The μIRU-1 measurement system was fastened to the platform located on the cockpit (Figure 9). The examples of bank angle and heading time history measured during a flight in atmospheric turbulence are presented in Figure 10.

Figure 6 Computer simulation of the pitch angle calculations: $\Delta\Theta$ – error of calculation, Θ_T, Θ_C – true and calculated values of the pitch angle, q_T, q_C – true and calculated values of the pitch rate

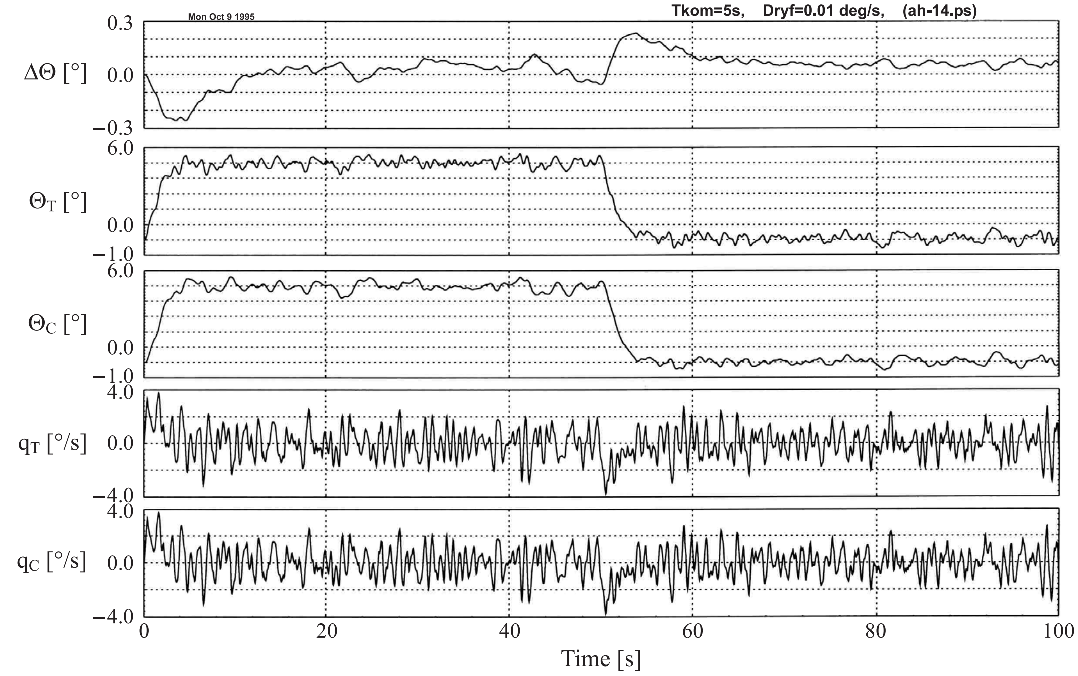


Figure 7 Sensors of the Inertial Reference Unit μIRU-1: 1 – Fiber Optic Gyro Litef μFORS-36, 2 – inclinometer AccuStar II, 3 – magnetometer Precision Navigation TCM-2

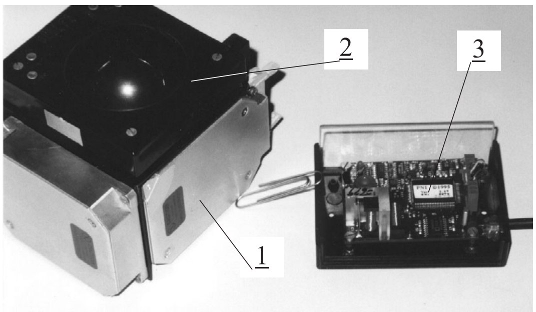
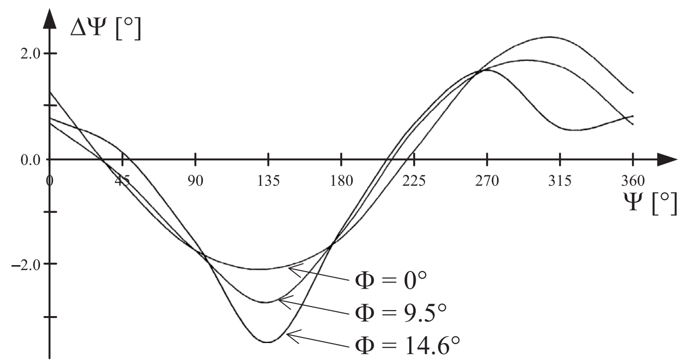


Figure 8 Magnetic heading error as a function of the bank angle Φ and actual value of aircraft heading Ψ



Conclusions

The results of the laboratory and flight tests of the Inertial Reference Unit μIRU-1 proof that it can be used as a primary attitude and heading reference system for unmanned and

Figure 9 PZL-110 "Koliber" aircraft as a test platform (a) and on-board measuring equipment in the cockpit (b): FC – Flight Data Processing Computer, ADC – Air Data Computer, GPS – receiver of the satellite navigation system, AHRS – Attitude and Heading Reference System (μIRU-1), SCB – Signaling and Control Box

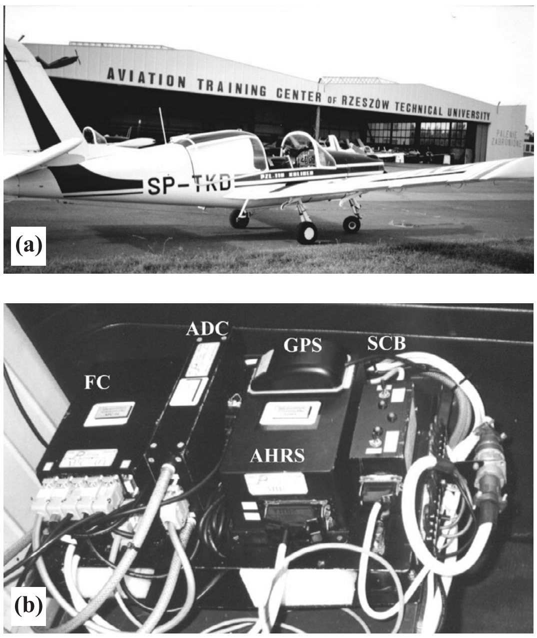


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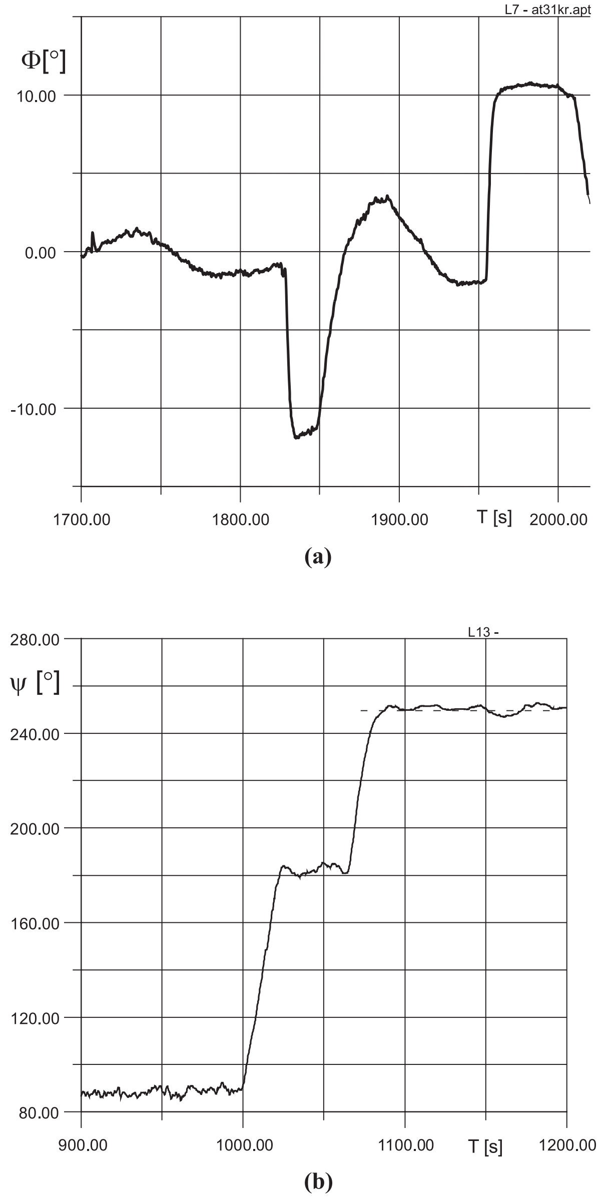
Figure 10 Time history of the bank angle (a) and heading (b) on a flight in atmosphere turbulence



general aviation aircraft. The basic performance of a few AHRSs is shown on Table I. The accuracy of the micro inertial reference unit μIRU-1 is not too high, so it will not be used in very precise applications.

Figure 11 PZL M-20 "Mewa" aircraft as a Flying Laboratory at Rzeszów University of Technology

The general properties of strapdown systems can be described as typical advantages and disadvantages (Lawrance, 1993; Titterton and Weston, 1997). The strapdown system is lighter, simpler, cheaper, and easier to arrange in limited spaces. A simpler structure withstands shock and vibration better because it is easier to shock mount it due to its lighter weight. Not used of mechanical components, such as gimbals gyros, slip rings or bearings but electronics, the reliability of the system is increased. The main disadvantages are: difficulty in achieving the best alignment of sensors, unique dynamic errors such as torque errors, bias errors of sensors appeared due to the body motion are accumulated (correction action is necessary) and requirement of computer fast enough to do all the strapdown calculation in a few milliseconds.

At present, a modified version of the IRU is being prepare. The μIRU-2 to be used in the flying didactic laboratory as a main altitude and heading reference system (Tomczyk, 1999). The two-engine executive PZL M20 "Mewa" aircraft will be used for this purpose Figure 11. The second set of μIRU-2 is planned as a main reference unit for integrated flight control system of general

Table I Performance of some attitude and heading reference systems

Producer	LITTON	LITTON	BAe	LITEF	RUT
Name	LTR-81	LISA-400	MAHRS702	LCR93	μIRU-1
Parameter ↓			Accuracy		
Attitude [°]	0.5	0.2	0.2	0.5	0.6
Heading [°]	2	0.5	0.5	2	2
Body rate [°/s]	0.1	0.4	0.5	0.1	0.02
Acceleration [g]	0.01	0.05	0.05	0.01	0.05 (option)
MTBF [hours]	> 6500	> 4000	> 4500	> 5000	NA
Power cons. [W]	68	90	55	25	20
Weight [kg]	13	6.2	7	3	2.5

aviation aircraft (Tomczyk, 2001). The specialized Fly-by-Wire control system, equipped with the set of sensors, is designed as a handling qualities augmentation system for small airplanes.

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