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# APPLICATION OF FLIGHT DATA RECORDER DATA FOR REMOTE PILOT MATHEMATICAL MODEL VERIFICATION

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## Abstract

***Objective***: *the various goals were set in the given research, such as: to carry out flights and perform standard maneuvers on different control modes; to gather flight data from unmanned aerial vehicle flight controller; to select the data according to the performed maneuvers in the corresponding flight control modes; to perform decoding of raw logged data for further analysis; and to prepare data for their substitution into the developed mathematical model at yaw control channel.* ***Methods:*** *experimental flights have been conducted according to a clearly defined flight mission for obtaining specific on-board records from the appropriate unmanned aerial vehicles control channels. Board data were analyzed and decoded. Comparison of the real values of angular velocity obtained during flight in rudder control channel under different control modes was conducted.* ***Results:*** *the initial data of the unmanned aerial vehicles turn performance in the manual and semiautomatic control modes were obtained taking into account the sensitivity scale factor. Based on the real values of angular velocities the angular velocity dependence on time was constructed taking into account the unmanned aerial vehicles control mode. Data obtained from rudder control channel, angular velocity, were converted from raw to real values and ready for verification of designed mathematical model.* ***Discussion:*** *it can be stated that remote pilot performs maneuvers more smoothly in the semiautomatic control mode since the self stabilization of the system is achieved through the influence on the part of automatic control system.*

**Keywords:** automatic control system; data logging; flight controller; mathematical model; remote pilot; unmanned aerial vehicle.

## 1. Introduction

In recent decades, the development of unmanned aerial vehicles (UAVs) has been of great interest, and different kinds of autonomous vehicles have been studied and developed all over the world. In particular, UAVs have many applications in emergency situations; humans often cannot come close to a dangerous natural disaster such as an earthquake, a flood, an active volcano, or a nuclear disaster [1].

The issue of autonomous operation is one of the most important for today. Since the implementation of a complex task in manual control mode imposes many restrictions on a remote pilot (RP). Because of the limitations typical of human, UAVs have to be equipped with a flight controller (FC). The choice of the FC is made based on the reliability of the operation and the manner of execution of the planned mission, as well as based on the price / quality ratio in the context of small UAVs with weight up to 15 kg [2].

Beginning with 2009, team of developers from the USA presented and applied the Ardupilot FC. The work on the open source FC has attracted much attention from like-minded people, so the project succeeded, developed rapidly and continues to evolve today [3].

FC ArduPilot is a full-fledged solution for a UAV. In addition to remote controlled piloting, FC ArduPilot allows automatic control over a previously created route.

The given FC supports the flight execution by points. The FC allows two-way transmission of telemetry data from the aircraft to the ground control station (GCS) which includes phone, tablet, laptop, and data logging in the built-in memory of FC.

The key features of flight controller ArduPilot are the following:

1) 3 axis gyroscope, accelerometer, magnetometer;
2) on-board radio and telemetry communication;
3) real-time telemetry data transmission;
4) 6 degrees of freedom in InvenSense of accelerometer and gyroscope MPU-6000;
5) sensor of barometric pressure MS5611-01BA03;
6) board controller Atmel ATmega2560-16AU and ATMEGA32U-2 chip for processing and USB functions.

Flight data recording on UAV and concurrent real-time data transmission on GCS is an important parameter of the chosen “platform”. This feature provides flight data processing in terms of analysis of the current characteristics and testing out the settings made by the remote pilot.

## 2. Analysis of the Latest Research and Publications

The ArduPilot system, as an open source solution, is designed to fit a wide range of airframes. Also, it requires the user to program the code to fit a particular aircraft type and tune up the PID gains to achieve the desired performance. This involves a steep learning curve and requires time to adjust the gains. Within the time constraints inherent to term projects it is necessary to streamline the process and develop a set of instructions aimed to minimize the challenge involved [4], [11].

Now that the basic aerodynamic forces acting on the selected drones are clarified, we can create a control system that uses these forces to make the drone do what was planned. But in order to control a position, the position should be specified, and for this an *inertial measurement unit* is started. Inertia describes the tendency of objects at rest to stay at rest and objects in motion to stay in motion. In other words, inertia embodies Newton’s first law of motion [5].

Integrated circuits measure rotation. And such integrated circuits are called *gyroscopes*. In UAVs, gyroscopes are used to stabilize rotation [6].

By combining accelerometers to determine the direction of gravity and using gyroscopes to identify the rotation rates of UAVs, the aircraft keeps its level with the horizon and is prevented from spinning around [7].

UAV onboard equipment, especially flight controller (FC), provides a possibility to record inflight parameters through whole flight. Therefore, all data can be analyzed on the ground.

## 3. Aim of research

The main aim of research is verification of the coefficients in the theoretical mathematical model (1) with the help of data that was obtained from flight recorder of UAV FC.

The specified FC supports three flight control modes: Manual/Semiautomatic/Automatic.

The objectives of the research were identified as follows:

– during the flight it is necessary to perform standard maneuvers on different control modes;
– to gather flight data from UAV FC;
– to select the data according to the performed maneuvers in the corresponding flight control modes: Manual and Semiautomatic;
– to perform decoding of raw logged data for further analysis;
– to prepare data for their substitution into the developed mathematical model at yaw control channel.

## 4. Research results

Equipped with FC, UAV passed tuning and calibration of main sensors. Sensors are the main source of information about the current attitude of UAV in the air.

Sensor calibration is an important procedure for the correct operation of the UAV navigation system and stabilization at all control modes.

Semiautomatic control mode uses current data of the inertial system sensors for UAV attitude error compensation under the influence of wind, etc.

In order to perform verification of the developed mathematical model (1), it is necessary to decode flight data from the experimental flight of the selected UAV’s. The important parameters for the current research are obtained from Digital Motion Processor MPU-6000, shown on Fig. 1.

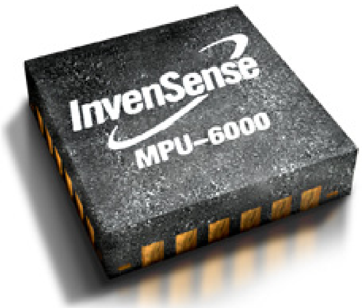

Fig. 1. General view of Motion Tracking device MPU-6000

6-axis Motion Tracking device that combines a 3-axis gyroscope, 3-axis accelerometer, and a Digital Motion Processor (DMP) all in a small 4x4x0.9 mm package.

For precision tracking [8] of both fast and slow aircraft motion, the parts feature a user-programmable gyroscope full-scale range of ±250, ±500, ±1000, and ±2000°/s (dps) and a user-programmable accelerometer full-scale range of ±2g, ±4g, ±8g, and ±16g.

Fig. 2. UAV M-10 “OKO-2”
used in experimental flights

The basic settings of the gyroscope of MPU-6000 correspond to the angular velocity measurement range ±2000°/s. Gyroscope sensor raw data are recorded according to word length 16 bit of Analog-to-Digital convertor with sensitivity scale factor, which specifically ranges angular velocity ±2000°/s equal to 16,4 LSB/°/s (Least Significant Byte) [8].

Conversion that takes into account the sensitivity scale factor, precise/real value of angular velocity data can be obtained at any time of the flight was used.

Results of the UAV yaw turn performance are presented in Table 1 at Manual and Semiautomatic control modes taking into account the sensitivity scale factor.

For execution of the experimental flights, the mobile Unmanned Aerial Complex (UAC) M-10 “OKO-2” [9] of SPCUA “Virazh” was used. General view of UAC is shown on Fig. 2. UAV remote pilot performed maneuvers at Manual and Semiautomatic control modes.

In Fig. 3 UAV flight path performed by RP in Manual control mode is shown. The trajectory is obtained from telemetry recording on the GCS, which is used during the flight for monitoring (creation / modification of the flight mission) and UAV control at take-off, horizontal flight and landing.

The yaw turn performance by UAV was the target maneuver of research. Time for maneuver execution was 15 seconds in each control mode.

*Table 1*

**Raw to real data conversion at flight control modes**

| Time, s | Manual | | Semiautomatic (Stabilize) | |
|---|---|---|---|---|
| | Raw data, LSB/°/s | Real value, °/s | Raw data, LSB/°/s | Real value, °/s |
| 1 | 177 | 10,8 | 310 | 18,9 |
| 2 | 121 | 7,37 | 297 | 18,1 |
| 3 | 178 | 10,85 | 273 | 16,64 |
| 4 | 189 | 11,52 | 292 | 17,8 |
| 5 | 111 | 6,77 | 310 | 18,9 |
| 6 | 279 | 17,0 | 250 | 15,24 |
| 7 | 278 | 16,9 | 202 | 12,31 |
| 8 | 224 | 13,65 | 275 | 16,77 |
| 9 | 155 | 9,45 | 173 | 10,55 |
| 10 | -27 | -1,64 | -3 | -0,18 |
| 11 | -20 | -1,21 | 123 | 7,5 |
| 12 | -132 | -8,05 | -4 | -0,24 |
| 13 | -292 | -17,8 | -70 | -4,26 |
| 14 | -234 | -14,27 | 64 | 3,9 |
| 15 | -100 | -6,09 | -41 | -2,5 |

Fig. 3. UAV performing yaw turn
in Manual mode

The UAV’s flight path performed by RP in Semiautomatic control mode is shown in Fig. 4. The trajectory is obtained from telemetry recording on the GCS.

Fig. 4. UAV performing yaw turn in Semiautomatic mode

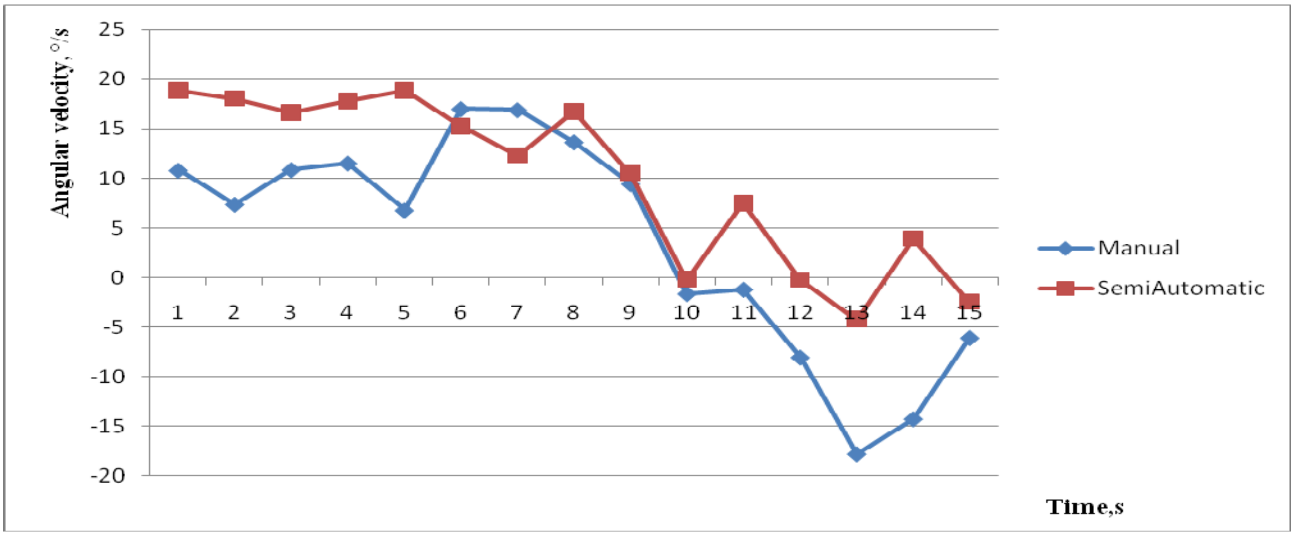

Fig. 5. Comparison of Gyroscope real values at Z (yaw) axis control channel in Manual/Semiautomatic modes

A graph shown in Fig. 5 is based on the real values of angular velocities and reflects dependence of the angular velocity on time, taking into account the UAV control mode.

The obtained values of the angular velocity sensor are required for the verification of the pre-designed mathematical model *"Remote pilot – Remote Control System – UAV"* [10]. Model component $m_Y^{\beta} / m_Y^{\delta_r}$ takes into account UAV angular velocity in the rudder control channel [11].

Control devices deflection law considering the remote pilot's actions in rudder control channel is represented by the following equation:

$$\delta_r = \frac{m_Y^{\beta}}{m_Y^{\delta_r}}\left[\tan^{-1}\left(\frac{B_{\max}e^{-kt}\left(-K\cos\omega t-\omega\sin\omega t\right)}{V_x}\right)+\right.$$

$$\left.\tan^{-1}\left(\frac{B_{\max}e^{-kt}\left[\left(\omega^2-K^2\right)-K\right]}{V_x}\left(\cos\omega t-3\omega\sin\omega t\right)\right)\right]+$$

$$\left[K_hT_{1h}K_{\dot{\psi}}^{r}(\dot{\varphi}_h(t-\tau)-\varphi_{mh}(t-\tau)\right]+\left[K_1K_{\dot{\psi}}^{r}(\varphi_h(t-\tau)-\right.$$

$$\left.\varphi_{mh}(t-\tau))\right]-\left[(T_{2h}+T_{Nh})K_{\dot{\psi}}^{r}\Delta\dot{\delta}_h(t)+K_{\dot{\psi}}^{r}\Delta\ddot{\delta}_h(t)\right] \quad (1)$$

Such a formulation of the mathematical formula and the performed experiments allow perform further mathematical calculations in the MathCad programme.

## 5. Conclusions

1. The software and hardware components of Ardupilot are analyzed as FC for UAV type M-10 "OKO-2".

2. Experimental flights have been conducted according to a clearly defined flight mission for obtaining specific on-board recorded data from the relevant UAV control channels.

3. The initial data of the UAV turn performance in the Manual and Semiautomatic control modes are obtained taking into account the sensitivity scale factor.

4. Based on the real values of angular velocities the angular velocity dependence on time is constructed with regard to the UAV control mode.

5. It has been proved that the remote pilot performs maneuvers more smoothly in the Semiautomatic control mode, which is observed from the angular velocity data obtained in the rudder control channel.

6. The data obtained from rudder control channel, specifically information about angular velocity, were converted from raw to real values and ready for verification of the designed mathematical model.

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### Застосування даних бортового самописця для верифікації математичної моделі дистанційного пілота

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**Мета:** провести експериментальні польоти та виконати стандартні маневри на різних режимах керування. Зібрати дані польоту з польотного контролера безпілотного повітряного судна. Вибрати дані відповідно до виконаних маневрів у відповідних режимах польоту. Виконати розшифровку необроблених даних для подальшого аналізу. Підготувати дані підстановки та верифікації в розроблену математичну модель у курсовому каналі керування. **Методи**: Експериментальні польоти проводилися відповідно до чітко визначеної польотної місії для отримання спеціальних бортових записів з відповідних каналів керування безпілотного повітряного судна. Дані підлягають аналізу та декодуванню. Порівняння реальних значень кутової швидкості, отриманих під час польоту в каналі керування рулем напрямку на обраних режимах керування. **Результати**: проведено експериментальні польоти та отримані конкретні бортові записи з відповідних каналів керування безпілотного повітряного судна. Отримано первинні дані виконання повороту безпілотного повітряного судна в режимах «Ручий» та «Напівавтоматичний» з урахуванням коефіцієнту масштабування чутливості. На основі значень реальних кутових швидкостей побудована залежність кутової швидкості від часу з урахуванням режиму керування безпілотного повітряного судна. Дані отримані з курсового каналу керування, власне кутова швидкість, перетворені з «сирих» до реальних значень та готові до верифікації в розробленій математичній моделі. **Обговорення:** Дистанційний пілот виконує маневри плавніше в режимі напівавтоматичному режимі керування, внаслідок впливу частини автоматичної системи керування, системи самостійної стабілізації положення судна.

**Ключові слова:** автоматична система керування; безпілотне повітряне судно; дистанційний пілот; запис даних; математична модель; польотний контролер.

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**Применение данных бортового самописца для верификации математической модели дистанционного пилота**

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**Цель**: провести экспериментальные полеты и выполнить стандартные маневры на разных режимах управления. Собрать данные полета с полетного контроллера беспилотного воздушного судна. Выбрать данные в соответствии с выполненными маневрами в соответствующих режимах полета. Выполнить расшифровку необработанных данных для последующего анализа. Подготовить данные подстановки и верификации в разработанную математическую модель в курсовом канале управления. **Методы**: экспериментальные полеты проводились в соответствии с четко определенной полетной миссией для получения специальных бортовых записей по соответствующим каналов управления беспилотного воздушного судна. Данные подлежат анализу и декодированию. Сравнение реальных значений угловой скорости, полученных во время полета в канале управления рулем направления на избранных режимах управления. **Результаты**: проведены экспериментальные полеты и получены конкретные бортовые записи из соответствующих каналов управления беспилотного воздушного судна. Получены первичные данные выполнения поворота беспилотного воздушного судна в режимах «Ручной» и «Полуавтоматический» с учетом коэффициента масштабирования чувствительности. На основе значений реальных угловых скоростей построена зависимость угловой скорости от времени с учетом режима управления беспилотного воздушного судна. Данные получены из курсового канала управления, собственно угловая скорость, преобразованные из «сырых» к реальным значениям и готовы к верификации в разработанной математической модели. **Обсуждение**: дистанционный пилот выполняет маневры более плавно в полуавтоматическом режиме управления, в результате воздействия части автоматической системы управления, системы самостоятельной стабилизации положения судна.

**Ключевые слова:** автоматическая система управления; беспилотное воздушное судно; дистанционный пилот; запись данных; математическая модель; полетный контроллер.

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