Hardware-software system for studying the effectiveness of propeller-engine groups for unmanned aerial vehicles

V A Morozov¹,², A M Yahin², A E Zhirova² and A V Parshin¹,²

¹Irkutsk National Research Technical University, 83, Lermontov str., Irkutsk, 664074, Russia
²Vinogradov Institute of Geochemistry SB RAS, 1A, Favorsky str., Irkutsk, 664033, Russia

E-mail: raulett@gmail.com

Abstract. The subject of the article is the development of a laboratory tester for the study of the effectiveness of propeller-engine groups (PEG) of electric unmanned aerial vehicles (UAV). The need to create such solutions is due to the fact that the development and testing of unmanned platforms in the format of prototypes and their flight tests are time-consuming and expensive processes, it is not possible to assess the limit parameters of motors and their electronic speed controllers (ESC). Hardware devices and software for testing PEG separately can reduce the cost and speed up this process, as well as make the result more optimal both in terms of technical parameters and in terms of economic efficiency. A solution has been developed that allows to measure the motor amperage, the generated thrust of PEG, the voltage on the battery, the temperature of the motor, and then calculate PEG effectiveness indicators on their basis, visualize them in graphs, and thus compare the thrust and energy efficiency of various engine-propeller groups with propellers up to 30” in size.” It is shown how the test results allow you to choose the optimal solution for assembling propeller-motor groups for light and medium UAV, and optimally design unmanned platforms for airborne geophysical prospecting.

1. Introduction

Since the advent of technology of brushless electric motors and lithium-polymer batteries, the rapid development of robotic vehicles has started - unmanned aerial vehicles (UAV) are the prior. Light UAV (up to 30 kg), equipped with a variety of payloads, are now widely used in engineering surveys, agriculture, environmental monitoring and many other areas of human activity. One of the most promising and dynamically developing applications for UAV is the geological industry. Over the past 5 years, various unmanned systems for performing geophysical exploration have become widespread [1–8], the authors also develop their own complex of unmanned technologies SibGIS UAS [9, 10], on the basis of which implemented methods of magnetic, gamma and electromagnetic surveys, as well as aerial photography and lidar scans. With the ever-increasing complexity of the working conditions associated with the transition to more and more hard-to-reach and unfavorable sites in difficult landscape conditions, unmanned platforms are becoming increasingly demanding. The long range and flight time, the lowest possible price of the UAV itself, which determines the costs of its operation and depreciation, and ultimately the cost of the survey, raise the question of constant optimization of the UAV design.

One of the significant components of the cost both at the stage of assembly of the finished UAV, and at the stage of development work, is the propeller-engine group (hereinafter PEG) of the aircraft. The
propeller group on the UAV with electric motors consists of a propeller, a motor, and an engine speed regulator (ESC). When designing an unmanned platform, we are faced with the task of choosing the best combination of them. The characteristics that are important when choosing PEG are: PEG thrust (both maximum and effective), PEG efficiency (traction to power consumption ratio), and price.

Testing UAV components with the flight test method of the UAV prototype is not optimal, since at least 4 component samples must be purchased to assemble the prototype, all procedures for “closing the airspace” (according to Russian law) must be carried out for the organization of flight tests, battery charging and direct flights will take a lot of time. However, it will not be possible to assess the extreme operating conditions of PEG, as this will lead to an accident and high economic costs.

Thus, it seems reasonable to create a specialized test bench for PEG based on brushless motors.

The requirements for the test bench under development are the following:

- Possibility to measure PEG thrust;
- Possibility to measure the amperage supplied to the motor;
- Possibility to measure voltage on the battery;
- Possibility to measure the temperature of the motor;
- Possibility of installation for testing sufficiently large propellers and powerful motors (screws up to 30 inches);
- Possibility to transfer the received data to a PC for storage and analysis;
- The presence of software that allows you to conveniently analyze the characteristics of PEG: their energy consumption, thrust, efficiency (as the ratio of thrust to energy consumption), temperature.

At the moment, devices which fully comply with these requirements are not presented on the market in free sale. Serial testers (https://rcsearch.ru/-c4065, http://chinasey.ru/i/32820081281.html and the like) are small and suitable only for hobby level PEG testing - install and test powerful PEGs with propellers greater than 12 inches and a thrust greater than 3-5 kg is impossible. Also, there is no possibility of connecting them to a computer for the accumulation and analysis of data. In this regard, specialists create devices suitable for their tasks on their own (http://www.parkflyer.ru/ru/blogs/view_entry/9651/, https://habr.com/ru/post/187146/). This article describes the construction in detail and presents the results of using the laboratory tester created by the authors, which allows reproducing its design to any interested researcher.

2. Materials and methods

When developing the test bench for PEG, the following components were selected:

- tensor sensor (bridge), for measuring the impact force from PEG;
- HX711 ADC for digitizing a signal from a load cell;
- Current sensor ACS758LCB-050B;
- ADC for measuring voltage on the battery built into the ATmega328P microcontroller;
- DS18B20 digital temperature sensor in the sleeve, for measuring the temperature of the motor stator;
- microcontroller ATmega328P, with strapping. To collect data from sensors, process them and transfer them to a PC via serial connection;
- Radiolink R12DS remote control module, for providing PEG remote control, for security purposes;
- a battery for powering the PEG. The tests were conducted with the help of a 6s Li-PO battery with a nominal voltage of 24V, but the design of the stand provides for the installation of other batteries.
The created frame provides a rigid installation of the engine to transfer force to the tensor sensor, and it also allows to rigidly fix the resulting structure to the support (a table was used during the tests). The design ensures that the thrust-generating screw is removed from the support in order to avoid errors from the reverse aerodynamic effect of the support on the screw. The motor controller was mounted on the frame. The remaining components were housed in a separate housing. The screw was mounted on the motor in such a way that the PEG rod was directed vertically down towards the support. The PEG was controlled for safety reasons by radio, by directly connecting the remote control receiver to the engine speed controller. The calibration of the strain gauge + ADC HX711 system was carried out by selecting coefficients using gram standards of 1000 g. The current sensor ACS758 was calibrated by setting the coefficients from the accompanying documentation. The sensor was connected to the rupture of the power line of the ESC (Figure 1).

Since the ATmega328P built-in ADC can measure voltages in the range from 0 to 5 volts, a 6:1 voltage divider was used to provide the ability to measure voltage on a 30 volt battery. Calibration of the ADC for measuring the voltage on the battery was performed by selecting the coefficients using the AD584 reference voltage source. The temperature sensor was mounted on an aluminum plate, which was fastened to the motor stator, thus, the mounting method introduced its error in temperature measurements, however, the relative temperatures of different motors were shown with sufficient accuracy for our purposes. The sensors were connected to a board based on ATmega328P to collect data, process it and transfer it to a PC.

The battery supplies only PEG. The microcontroller and sensors are powered from a 5 volt source via a USB connection from a PC or from another 5v source.

The specifics of the energy consumption of brushless motors is such that it causes quite strong fluctuations in current and voltage in the power circuit. To smooth out these oscillations, filtering by means of a microcontroller using the moving average algorithm was used.

The results of measuring is transmitted by the microcontroller to the PC via the serial port as a string of data. The line contains the following information: start ime; thrust data in grams; current; battery voltage; temperature measured. Before starting the measurements, the microcontroller resets the strain gauge to level out the influence of the PEG mass and structural elements of the tester construction. A developed software utility is working on the PC to receive and process the received data. After transferring to a PC, based on the data received from the microcontroller, the efficiency indicator “motor thrust / current” is calculated, expressed in grams per ampere. Indications of voltage, current, temperature and efficiency are shown on the screen in real time in the form of graphs (Figure 2a). Also, data is written to a file for storage and subsequent analysis.
Figure 2. The results obtained by the tester, from left to right, from top to bottom. a - Interface for monitoring indicators during the operation, b - Visualization of raw test data in the form of a point cloud (traction, efficiency). c - Visualization of measurements of several PEG s in the form of approximating curves in a form convenient for comparison.
For processing and visual analysis of the obtained test results, appropriate software was developed. It provides the graphs of PEG efficiency (dependence of PEG thrust on current) in the form of a point cloud, where the X coordinate of the point is the thrust generated by PEG, and the Y coordinate is the calculated motor efficiency (Figure 2b), then the point cloud can be approximated polynomial of the third degree. Thus, we get a simplified view of the dependence of PEG efficiency on the traction it creates. Based on previously obtained data, the developed utility allows sharpening several approximating graphs and displaying them on the screen to simplify the analysis and comparison of different PEGs (Figure 2c).

During the experiments, the following testing methodology was used. After assembling the tester for installing PEG on it, and connecting the ESC to the power, the ESC was calibrated. The controller with the sensors connected to it was connected to the operator's PC and power was supplied to it. After that, the controller zeroed the load readings to consider only the PEG thrust, but not its own mass. Then, in the software - the operator’s workplace, on the PC, the names of the PEG components: the ESC, motor and propeller were recorded, and measurements were started. Motor traction was controlled manually using a remote control for safety reasons. The thrust of the motors was controlled by a rotary engine control handle (ECH). The operator began to rotate the ECH until the screw began to rotate. After that, thrust was added approximately 10% each and results were accumulated at each stick position for 30-40 seconds, with real-time monitoring of sensor readings. After reaching the engine thrust> 90% in this mode, measurements were taken for about 2 minutes, with temperature monitoring, to identify problems with the reliability of the motor in extreme operating conditions.

3. Testing PEG and its results.

Let us consider the effect of testing PEG variants on the example of a number of samples planned for use in mid-sized UAV hexacopter (Parshin et al, 2018) used in the composition of the airborne geophysical complex of 10-12 kg. The aim of the test was to select PEG, which works best in the thrust range from 1300g to 2000g, and is capable of delivering, if necessary, thrust of 2200 - 2500g for at least 10 minutes without overheating. The regulators were: HOBBYWING XRotor Pro 40A, HOBBYWING XRotor Pro 50A, T-MOTOR Flame 70A. Motors tested: T-MOTOR MN5212 340KV, T-MOTOR MN501S-300KV, T-MOTOR MN501S-360KV, custom-made OEM motor 5010-340kv, QX-motor 6008, TAROT 5008 340KV, T-MOTOR P60 KV340. As propellers we used TAROT 17 * 5.5, Tarot 18 * 5.5, T-MOTOR 18 * 6.1, T-MOTOR 20 * 6, TAROT 17 * 5.1 3-blade.

![Figure 3. Comparison of propellers 18 * 5.5 tarot and 18 * 6.1 t-motor.](image-url)

The experiment included optimizing an unmanned complex with an emphasis on economic efficiency, since the cost of the tested components varies by a multiple: the cost of motors ranges from $ 25 (OEM 5010-340kv) to $ 120 (T-MOTOR MN5212), propellers from $ 20 (TAROT 17*5.5) to $ 166 (T-MOTOR 20*6), ESCs from $ 25 (Xrotor Pro 40) to $ 70 (TMOTOR Flame 70).

PEG using P60 motors was tested for comparison, since such PEG is not applicable in the UAV frame configuration under development.
Based on the test results, some conclusions can be drawn. In particular, the installation of a ESC more powerful than necessary affects the test results minimally, within the limits of measurement error. Insufficient power of the ESC leads to its overheating and emergency stop of the motor. Replacing the TAROT 18*5.5 propeller with the T-Motor 18*6.1 gave a noticeable increase in efficiency, about 15% with a draft of 1.5 kg (Figure 3). The cheap OEM-5010 motor turned out to be close in efficiency (difference of ~ 5% with a pull of 1.5 kg) to the most effective in the tested size T-MOTOR MN5212 (Figure 4), while other engine designs, including expensive ones. Replacing TAROT 17*5.5 two bladed propellers with TAROT 17*5.1 three-bladed propellers has practically no effect on efficiency, while switching to a larger propeller size gives a noticeable increase in it (Figure 5). The transition to more powerful P60 motors with large T-MOTOR or 20*6 propellers gives a noticeable increase in efficiency over the entire range and a margin in peak traction, which can be useful when designing UAV lifting configurations (Figure 6).

Also, according to the results of the experiments, motors were identified that, despite the successful declared characteristics, could not pass the tests in all thrust ranges. So, the Tarot 5008 340KV and QX-motor 6008 motors with a pull of up to 1,500 grams looked pretty attractive in terms of efficiency and price, but with a pull of more than 2,000 grams they overheated, and eventually these motors burned.
4. Conclusion
The developed tester has shown its high efficiency in the development of UAV. So, if in the case under consideration the choice of components for propeller groups was carried out in the classical way - by testing the UAV prototype in the format of flight tests at cruising speed, then Tarot 5008 would most likely be recognized as the most successful motors due to their low price and high availability in the Russian market. However, if any emergency situation happens (e.g. a strong wind), they would burn out and the unmanned aerial system would crash. This would certainly lead to serious economic and reputational losses, up to the disruption of work, since the expedition team performing the geophysical survey could have spare engines of another model. In addition, when using the developed tester, the entire PEG testing cycle took only one working day, while full-scale testing on a flying prototype would take at least a week. The use of such devices seems to be absolutely necessary in the design of UAV for professional applications in science and industry.

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