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RESEARCH ARTICLE

Control system for noise-resistant electronic speed controller of a brushless electric motor for an unmanned aerial vehicle

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Abstract
Objectives. The high demand for unmanned aircraft and their efficiency makes the production of their components a matter of relevance. One of these components is the speed controller of the brushless electric motor of the propeller motor group. At the current time, Russian industry, however, does not mass-produce them. In order to start production, control methods and algorithms for the hardware and software parts of devices of this type are needed. Criteria for selecting the main components also need to be formalized. The aim of this work is to develop a method for the software control of electric motors. This includes block diagrams and invariant algorithms and methods for the calculated selection of parameters of the main microcontroller of the electronic speed controller.
Methods. Methods of algorithmization, expert assessments, linear computational processes and experimental studies were used.
Results. The paper presents the theoretical basis for controlling the required motors. It proposes a block diagram of the implementation of the controller, and a technique for switching windings when controlling with a trapezoidal signal is proposed. Examples are given in the form of an oscillogram. Based on theoretical research, an invariant algorithmic apparatus was developed for building software for various types of microcontrollers. Block diagrams of all the main modules of the software are also presented. The main ones include: the event switching algorithm; and the main endless loop of the microcontroller. The requirements for microcontrollers to create the various types of speed controllers are formalized herein and presented in the form of a set of mathematical expressions. They enable the number of required peripheral devices and microcontroller ports to be calculated according to the requirements for the microcontroller, as well as the computing power of the core used.
Conclusions. Experimental studies show the reliability of the theoretical research presented herein. The results obtained can be used to select the optimal element base and develop software for speed controllers of electric motors of the propellers of unmanned aircraft.

Keywords: electric speed controller, algorithms, brushless direct current motor, unmanned aerial vehicle, noise-resistant solutions, software control, microcontroller

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НАУЧНАЯ СТАТЬЯ

Система управления помехоустойчивым электронным регулятором оборотов бесщеточного электродвигателя беспилотного воздушного судна

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Резюме
Цели. Высокая востребованность и эффективность беспилотных воздушных судов делают актуальным производство их компонентов, одним из которых является регулятор скорости вращения бесщеточного электродвигателя винтомоторной группы. Однако российская промышленность в настоящее время не производит их серийно. Для запуска производства необходимо разработать методики и алгоритмы управления для аппаратной и программной частей устройств данного типа, а также формализовать критерии выбора основных компонентов. Целью работы является создание методики программного управления электродвигателем, включающее структурные схемы, инвариантные алгоритмы и методики расчетного выбора параметров основного микроконтроллера регулятора оборотов.
Методы. Использованы методы алгоритмизации, экспертных оценок, линейных вычислительных процессов и экспериментальных исследований.
Результаты. Представлены теоретические основы управления электродвигателями винтомоторной группы. Предложены структурная схема реализации регулятора, методики коммутации обмоток при управлении с трапецеидальным сигналом, представлены осциллограммы сигналов. На базе теоретических изысканий разработан инвариантный алгоритмический аппарат построения программного обеспечения для различных типов микроконтроллеров. Представлены блок-схемы основных модулей программного средства: алгоритмов событийной коммутации и основного бесконечного цикла микроконтроллера. Формализованы требования к микроконтроллерам для создания различных типов регуляторов оборотов, представленные в виде набора математических выражений. Они позволяют выполнить расчет количества необходимых периферийных устройств и портов микроконтроллера согласно требованиям к регулятору, а также вычислительной мощности используемого ядра.
Выводы. Экспериментальные исследования показали достоверность представленных теоретических изысканий. Полученные результаты могут быть использованы для подбора оптимальной элементной базы и разработки программного обеспечения для регуляторов скорости вращения электродвигателей винтомоторной группы беспилотных воздушных судов.

Ключевые слова: регулятор скорости вращения электродвигателя, алгоритмы, бесщеточный электродвигатель, беспилотное воздушное судно, помехоустойчивые решения, программное управление, микроконтроллер

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Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

At the present time, most light unmanned aerial vehicles (UAVs) use electric propeller group motors (EPGs) [1, 2]. The current trend is to switch to electric propulsion for larger aircraft (ACs).

Electric UAVs use brushless three-phase electric motors [3]. Their rotation speed is controlled by switching phases and changing the currents flowing in the windings. In order to synchronize the commutation process with the rotation of the rotor, the position of permanent magnets relative to the windings must be determined. This can be achieved by sensors built into the electric motor [4]. This approach gives good results, but it is complicated and expensive. Therefore, the most widely used approach is to use back electromotive force (EMF) measured on the currently unconnected phase, in order to establish commutation torque [5, 6].

The vast majority of lightweight brushless UAVs currently in use do not have built-in sensors. They are controlled by electric speed controllers (ESC). The generally accepted architecture of lightweight UAV [7] assumes typical interfaces for connection of standardized components. In particular, the main and obligatory components of ESC consist of a connection interface for the electric motor windings (3 phase lines), and a control interface (digital or using pulse width modulation (PWM)). The electronic controller usually has one or more telemetry signal outputs.

At the current time, the Russian market offers a wide range of ESCs, covering practically all existing needs. However, all the solutions known to the authors are foreign. Their software and technical documentation are not publicly available. Thus, due to the dependence on foreign supplies, the production of new devices with extended functionality is problematic. This contradicts the policy of technological sovereignty.

TASK ASSIGNMENT

In order to resolve this problem, a methodology needs to be designed which will ensure the development and manufacture of rotation speed controllers for EPG electric motors for light UAVs. This consists of two elements: hardware development methodology (circuit solution); and program control methodology. This article focuses on the second of these.

Development of the program control methodology requires the principles of the controller construction to be selected, and the basic principles and algorithms of future software to be developed. An additional task is to develop a methodology for selecting microcontroller parameters according to the given characteristics of the controller.

The main elements which affect the noise resistance of the device are as follows: control interface cabling; telemetry; data transmission protocols; choice of component base; and the printed circuit board design. Of these, only the digital interface protocols are relevant to this paper. Their selection significantly affects the noise immunity of the system [8]. However, when developing the ESC controller, we are limited to the typical list of protocols supported by classical flight controllers. The development of additional control and telemetry protocols is possible only in conjunction with a specialized flight controller.

The program control methodology for lightweight UAV rotational speed controllers can developed in two ways: full software implementation of control algorithms; and control using specialized controllers with a high degree of integration. The first option includes a hardware solution in which a microcontroller or programmable logic integrated circuit [9] directly controls the driver of phase switching field-effect transistors. The second option uses a bundle of a general-purpose microcontroller and a specialized controller for brushless motor control.[1,2]

The use of specialized brushless motor controllers allows software development for the controller to be significantly simplified. This is because all algorithms are implemented in this product. The circuit design is also simplified. However, the disadvantages of this approach include: increased cost; increased size of the controller; and a lack of the necessary controllers for brushless motors produced in Russia.

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[1] A4960: Sensorless BLDC Motor Driver. https://www.allegromicro.com/en/products/motor-drivers/bldc-drivers/a4960. Accessed October 27, 2023.

[2] MOTIX™ BLDC Motor Control Ics. https://www.infineon.com/cms/en/product/power/motor-control-ics/bldc-motor-control-ics/. Accessed October 27, 2023.

Based on the results of the analysis, the following list of requirements to be met by the control system was compiled:

- sensorless control of three-phase brushless motors (based on the back EMF measurement);
- full software control mode without the use of specialized intermediate controllers;
- the need to maintain a PWM control signal;
- the need to maintain digital control protocols: Dshot[3], Proshot[4], Multishot[5];
- the need to maintain digital telemetry protocols: KISS[6], Dshot;
- the need to maintain analog output for the total current indication;
- the possibility for implementation based on Russian elements;
- the possibility for implementation of control devices for one or four electric motors.

THEORETICAL BASES FOR PROGRAM CONTROL OF UAV BRUSHLESS ELECTRIC MOTOR CONTROLLERS

The solution consists of three stages: development of algorithms and methods for controlling motor rotation; development of algorithms and methods for processing control commands; and development of algorithms and methods for forming the telemetry data. The second and third items are variable. Their implementation depends on specific protocols, the description of which is in the public domain.[7] Therefore, most of the attention will be paid to the first stage.

The general principles and models of program control of UAV electric motors based on electronic speed controllers are well known [10]. However, the focus here is narrower and more specific. In order to resolve it, it is necessary to consider the principles of controlling the used electric motors.

Brushless motors with concentrated windings and permanent magnet rotors are most common in light and medium-sized UAVs with EPG. They exceed 90% of the number of AC in the range up to 5 kg due to their weight, low cost and ease of use. These motors in Russian-language sources are often referred to as thyratron motors. In English-language literature the term brushless direct current (BLDC) motor is usually used [11].

UAV BLDC motors are usually supplied with trapezoidal voltage. This leads to certain disadvantages: torque ripple; generation of impulse noise; increased noise; and a slight reduction of the efficiency coefficient. These can be partially eliminated by using other control methods (e.g., using sinusoidal voltage). However, this approach is not justified due to the significant increase in UAV complexity and cost. Torque ripple and a certain reduction in efficiency are not critical for the EPG of lightweight UAVs. Propeller noise significantly exceeds electric motor noise. Impulse noise is suppressed by hardware filtering and specialized software methods.

The structural diagram of the hardware-software control system of UAV BLDC electric motor taking into account the data under consideration is shown in Fig. 1.

The microcontroller unit (MCU) generates a control signal to the drivers (DRV) of the field-effect transistors of the motor winding commutation. Control signals are generated through flight controller commands and feedback data. The feedback consists of a low-pass filter and a comparator. The low-pass filter filters out impulse noise during switching of motor steps and elimination of the PWM signal component. The comparator is used to determine the threshold level of the feedback EMF at which the subroutine of transition to the next step is started.

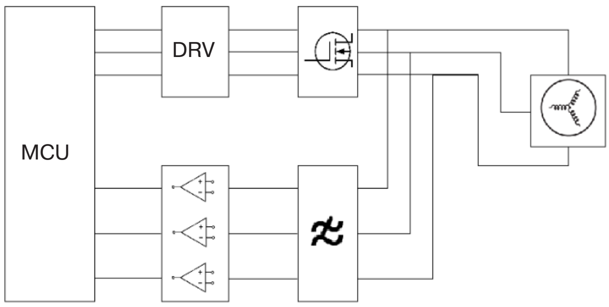

Fig. 1. Structural diagram of the hardware and software control system of the controller

Figure 2 shows a simplified view of the signals on the motor phases when the selected control methodology is used. The figure relates to a BLDC motor with one pair of poles, and shows one revolution. The solid line shows the ideal voltage change on each phase during one revolution. For example, phase A is energized with a positive polarity voltage for angle values up to 120°. Between 120° and 180°, phase A is disabled; while between 180° to 300°, the supplied power voltage has negative polarity.

The dashed line shows the back EMF, the shape of which is close to a trapezoid. When the supply voltage is

[3] DSHOT—the missing Handbook. https://brushlesswhoop.com/dshot-and-bidirectional-dshot/. Accessed October 27, 2023.

[4] Proshot—A new ESC protocol. https://oscarliang.com/proshot-esc-protocol/. Accessed October 27, 2023.

[5] What is Oneshot and Multishot in ESC. https://robu.in/what-is-oneshot-and-multishot-in-esc-difference-between-oneshot-and-multishot-esc-esc-calibration-protocol/. Accessed October 27, 2023.

[6] KISS ESC 32-bit series onewire telemetry protocol. https://www.rcgroups.com/forums/showatt.php?attachmentid=8524039&d=1450424877. Accessed October 27, 2023.

[7] Abdelrahman H. *Software Integration of Electronic Speed Controller* (*ESC*) *for an Unmanned Aerial Robot*: Bachelor Thesis. University of Twente. 2021. 23 p. https://essay.utwente.nl/87630/. Accessed October 27, 2023.

applied to the winding, the value of the back EMF is equal. When the winding is disconnected, it is formed as a result of generation. The design features of the motor require that the transition to the next step be performed at the moment when the back EMF crosses the zero mark [12].

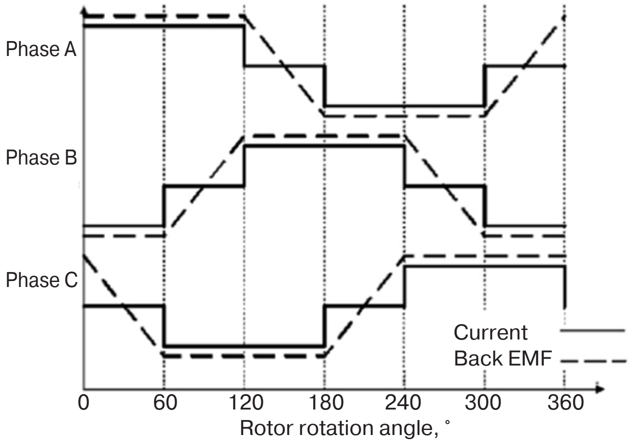

Fig. 2. Simplified view of signals on motor phases when using the selected control methodology

Thus, control based on back EMF allows for synchronous operation of the machine, while not determining rotation speed. The number of motor revolutions per minute is determined by the applied voltage and is calculated by the formula:

$$N = UK_{\mathrm{V}}k_{\mathrm{rm}}, \tag{1}$$

where U is the voltage on the windings, V; K_{V} is the speed factor, V^{-1} (shows the speed at which the motor will generate the back EMF of 1V); k_{rm} is the factor taking into account the peculiarities of the real electric machine (rm—real machine).

Thus, motor speed can be expressed through the switching frequency and the parameters of the electric machine:

$$N = \frac{n_{\mathrm{zc}}}{6n_{\mathrm{p}}}, \tag{2}$$

where n_{zc} is the number of zero crossings of the back EMF; n_{p} is the number of pole pairs of the electric motor.

However, transition to the next step is determined by back EMF. The number of revolutions is primarily dependent on voltage and motor design. Accordingly, the design determines the speed factor K_{V}.

The value of the resulting voltage on the windings is usually changed by means of PWM control. The design, which is currently under development, provides for a similar method of controlling rotation speed.

Figure 3 shows the oscillogram of the UAV BLDC motor during the operation. The signals in phases are close to the theoretical data as shown in Fig. 2. At the moment of active phase state, the PWM signal can be observed in the following figure.

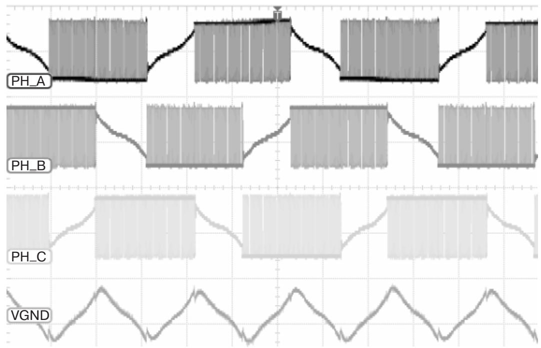

Fig. 3. Oscillograms of the AUV EPG operating BLDC motor. VGND is Virtual Ground

CONTROL SYSTEM ALGORITHMIZATION

Using theoretical research as a basis, we will formulate the methodology and control algorithms. A microcontroller was selected as a means of program control. Modern microcontrollers of sufficient power usually use architecture with hardware-level software abstraction [13, 14].

This approach provides a software tool structure which separates microcontroller hardware support from the core code that defines functionality.

Figure 4 shows the algorithm of the starting module of the control system proposed herein. After starting the program, device driver initialization functions are performed: I/O ports, timers, analog-to-digital converters (ADC), and others. Then the main block starts. This consists of an infinite loop of the microcontroller. In normal mode it is impossible to exit this block. Therefore, the error handler at the end of the block diagram can be executed only upon main block emergency termination. The driver initialization functions and the main block also have built-in error handlers. Their functionality is determined by the type of error and the place of its occurrence.

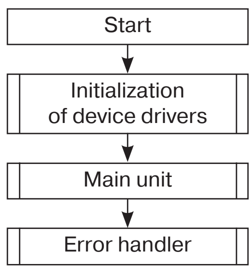

Fig. 4. Start module algorithm

Figure 5 shows the block diagram of the algorithm of the main module. It will be implemented as a separate file. The chosen architecture enhances security and emphasizes the abstraction of hardware from software implementation.

Fig. 5. Main module algorithm

Main module operation starts with device initialization and calibration. Here the ADC can be calibrated with subsequent start, start timers and direct memory access (DMA) controllers) in the specified mode. It configures the general-purpose ports and interrupts, as well as setting up and starting other devices. The sound and light signaling unit notifies the user of the successful start of the device operation. Next, the control protocol detection algorithm is started. The standards which are supported are set out in the Task Assignment section.

Before main cycle start, the settings are read out. The priority control protocol and rotation direction, as well as the normalization parameters of the control commands (if necessary) are stored in the flash memory.

The main cycle is an infinite microcontroller cycle. It executes the program code shown in Fig. 6. However, this functionality does not apply to the main motor control tasks. The main motor control tasks are not periodically time initiated, but related to hardware interrupts of the device.

The main cycle calculates the current speed and monitors the reverse command on a continuous basis. When a reverse command is received, it is displayed, and then memorized. The motor is stopped and the reverse flag for the switching function is set.

Also in the main cycle, the target speed is read by processing data from one of the control protocols

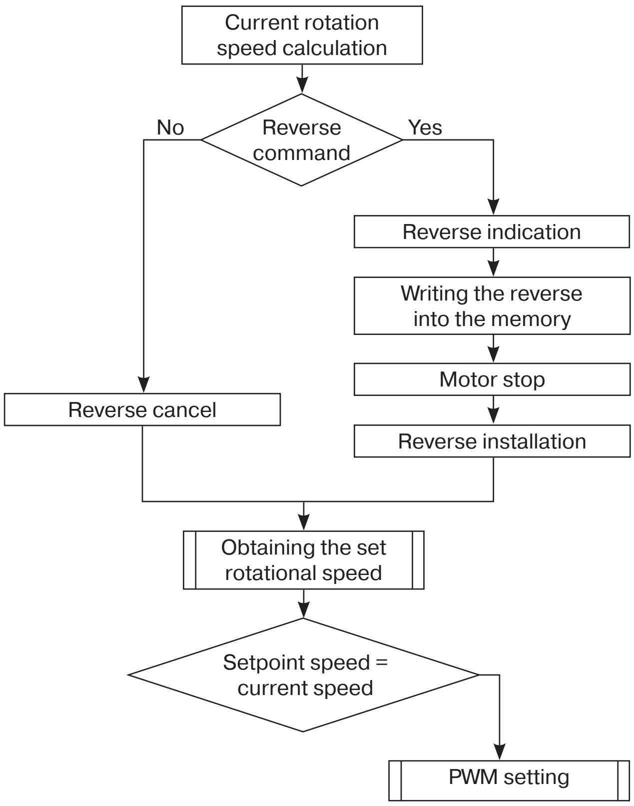

Fig. 6. Algorithm of the program main cycle

selected. If there is a difference between the current speed and the set speed, the phase voltage PWM control is set, in order to correct the speed.

The current speed is determined by measuring the frequency of interrupts. This corresponds to the zero crossing of the back EMF. The interrupt data processing functions initiate the winding switching program block.

Switching is performed according to the sequence shown in the table. The sequence of processes is shown in Fig. 2.

Table. Switching order of phases A, B, C

Step number	0	1	2	3	4	5
High level	A	B	B	C	C	A
Phase off	B	A	C	B	A	C
Low level	C	C	A	A	B	B

Block diagram of the switching algorithm is shown in Fig. 7. The phase for which one or another operation presented in the algorithm is performed differs at each switching step. The order of phase alternation is shown in the table and in Fig. 2.

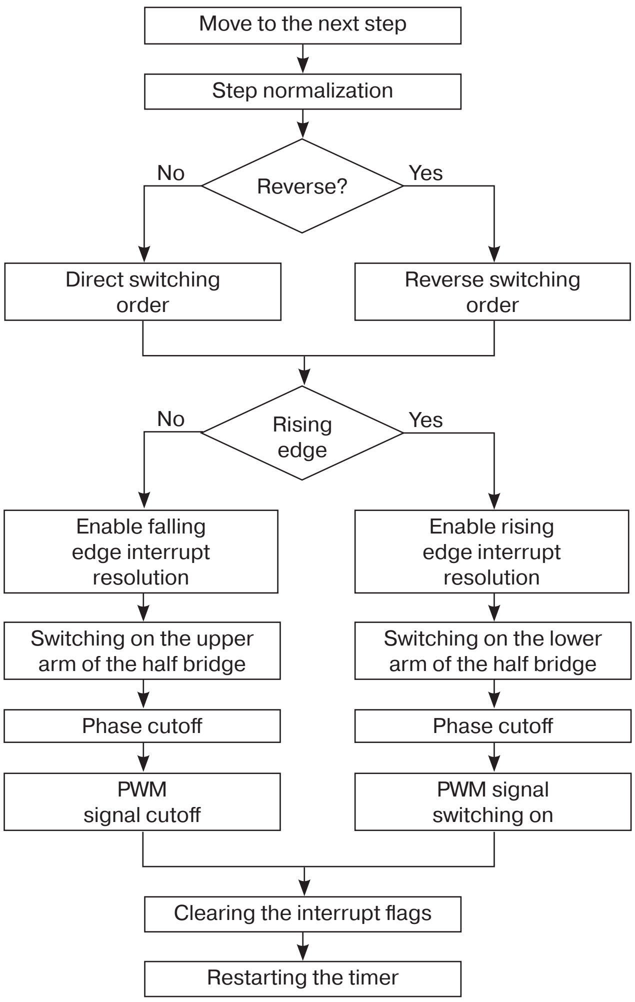

Fig. 7. Motor windings (phases) switching algorithm

The switching process is cyclic. It starts with switching to the next step. Step normalization is then performed (the step number is set to a value between 0 and 5). Switching is performed in forward or reverse sequence, depending on the state of the reverse flag.

The switching control function contains two branches which correspond to leading edge and trailing edge interrupts. When a rising edge interrupt is triggered, the corresponding interrupt is enabled. Then the lower key of the phase control half-bridge is turned on, the corresponding phase is switched off, and the DMA controller is turned on. This generates a PWM signal to control the motor phase voltage. In the event of a trailing edge interrupt, the sequence of operations is reversed.

When any of the branches of the branching operator are completed, the interrupt flags are cleared. Then the timer responsible for starting the motor is restarted.

The actual development has a significant number of additional program blocks, e.g., telemetry handling, error handling, and others. However, the scope of the current work does not allow them to be presented herein.

FORMALIZATION OF REQUIREMENTS TO THE APPLIED MICROCONTROLLERS

A microcontroller must be selected, in order to create the proposed control system. The development is invariant and therefore requires general criteria for the element base to be selected.

The microcontroller must have the required number of devices and ports, as well as to meet the performance requirements. Next, let us present a set of expressions describing the requirements for ports and devices.

The number of timer channels n_{tch} is determined by Eq. (3):

$$n_{tch} = 4n_{mot}, \tag{3}$$

where n_{mot} is the number of motors controlled by the controller.

Each motor needs to have 3 PWM signal outputs, in order to control the voltage on the winding. In modern microcontrollers, this functionality is allocated to timers. An additional timer channel is used to interpret the control protocols.

The number of general-purpose ports n_{Gpio} is defined by Eq. (4):

$$n_{Gpio} = 2 + 3n_{mot} + n_{resGpio}, \tag{4}$$

where $n_{resGpio}$ is the number of redundant general purpose ports, index Gpio stands for General purpose input output.

Two general purpose ports are used to control the indicator and to set reverse. For each motor, 3 general purpose phase disconnect ports are required: one for each phase. A further intention is to allocate a number of ports for potential expansion of the functionality of the unit.

The number of interrupt lines n_{int} is calculated as one interrupt for each phase of each motor using Eq. (5):

$$n_{int} = 3n_{mot}. \quad (5)$$

At least two lines need to be considered for programming the microcontroller, two power supply lines, analog inputs for measuring battery current and voltage, and ADC output for analog telemetry output. Based on this, let us calculate the total number of microcontroller pins n_{pin}:

$$n_{pin} = 9 + n_{tch} + n_{Gpio} + n_{int} + n_{res}, \quad (6)$$

where n_{res} is the number of additional redundant pins of the microcontroller.

Equation (6) can be represented by the number of motors:

$$n_{pin} = 9 + 10n_{mot} + n_{resCom}, \quad (7)$$

with the total reserve n_{resCom}, including the reserve of general-purpose ports, taken into account as a reserve summand.

In order to select a satisfactory microcontroller, the performance parameters of the computational core and peripheral devices need to be correctly defined.

The minimum PWM frequency requirements for timers are defined by Eq. (8):

$$f_{pwm} = 3Nn_p k_{pwm}, \quad (8)$$

where k_{pwm} is the coefficient determining the frequency parameters of PWM.

The constant factor 3 corresponds to three positive control pulses per revolution with one permanent magnet pole pair. k_{pwm} determines the number of PWM pulses per control pulse. The recommended value of $k_{pwm} \geq 10$.

The value of f_{pwm} can be expressed through the parameters of the applied AC electric motors:

$$f_{pwm} = 3UK_V k_{rm} n_p k_{pwm}. \quad (9)$$

Interrupt lines have requirements for minimum event response rates:

$$f_{int} = 2Nn_p. \quad (10)$$

The constant coefficient 2 is explained by two zero crossings of the back EMF per cycle at one pair of magnetic poles of the electric motor. Similarly to Eq. (9), Eq. (10) can be presented through the parameters of electric motors:

$$f_{int} = 2UK_V k_{rm} n_p. \quad (11)$$

Let us define the requirements for the microcontroller speed. In order to do this, the computing power required for individual modules needs to be summarized.

For program code executed in the body of an infinite loop of a microcontroller, the required computational performance P_{mc} is defined by Eq. (12):

$$P_{mc} = f_{mc} n_{mcInst}, \quad (12)$$

where f_{mc} is the repetition rate of the infinite loop, n_{mcInst} is the average number of instructions per loop step.

The main volume of calculations is performed in interrupt handlers. Equations (13) and (14) allow the necessary computing power required for them to be calculated:

$$P_{int} = 6n_{mot} n_p N n_{intInst}, \quad (13)$$

$$P_{int} = 6n_{mot} n_p UK_V k_{rm} n_{intInst}, \quad (14)$$

where $n_{intInst}$ is the number of instructions to process the interrupt body (switch cycle).

The constant factor 6 is due to two interruptions for each of the three phases in one cycle for a motor with one pair of poles.

The sum of computing power for the applied microcontroller P_Σ is defined by Eq. (15):

$$P_\Sigma = f_{mc} n_{mcInst} + 6n_{mot} n_p UK_V k_{rm} n_{intInst} + P_{add} + P_{res}, \quad (15)$$

where P_{add} is the computational power of additional modules, P_{res} is the reserve of computational power.

Computational power reserve should be at least 30% of the total value. For controllers with a small number of motors, this value is recommended to be increased.

EXPERIMENTAL STUDIES AND PRACTICAL RESULTS

Based on the methodology proposed herein, microcontrollers were selected to build controllers for one and four electric motors. For the first of them, the following minimum requirements were established: at least 22 pins, including 3 PWM lines and 3 interrupt lines. For the microcontroller of the four-motor controller, the corresponding parameters were: 55 pins, 12 PWM lines, and 12 interrupt lines.

The prototype software product developed pursuant to the algorithms considered herein, requires

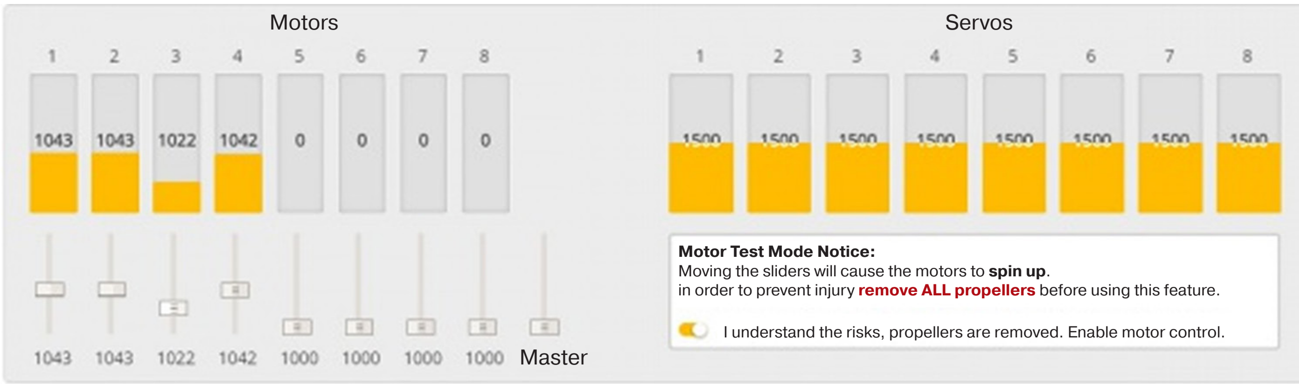

Fig. 8. Motor control in *BetaFlight*

a computational performance of not more than 20 DMIPS[8] for a single-motor controller and 75 DMIPS for a four-motor controller. The recommended microcontrollers need to have a performance rating of at least 30 and 100 DMIPS, respectively.

Other factors to be considered when selecting a microcontroller are its availability, as well as the inherent complexity of conducting development and electrical parameters. These factors are not considered in this paper. Given the complex combination of requirements, the STM32F103C8T6 microcontroller manufactured by STMicroelectronics, Switzerland, was used to build the first prototype of a single motor controller.

The maximum performance of this product is 90 DMIPS which exceeds the computing power requirements by several times. The requirements for peripherals and their number are similarly covered by the adopted device. With its low cost and wide availability, this choice can be considered optimal. However, STM32F103C8T6 pertains to the list of sanctioned products from non-friendly countries. Therefore, we considered alternative solutions.

The Russian 1921BK035[9] microcontroller produced by NIIET[10] was selected for the single-engine controller. The device is implemented on a 32-bit RISC core (reduced instruction set computer). It offers a performance rating of up to 100 DMIPS, and has all the necessary devices with the required parameters. This microcontroller theoretically allows us to produce a 2-motor controller.

It is proposed to build the four-motor speed controller on the basis of the K1921VK02T microcontroller from the same manufacturer. The device parameters significantly exceed those required (more than 200 DMIPS, 144 pins total).

The prototype controller assembled on STM32F103C8T6 was subjected to tests. For control purposes, digital protocols (Proshot, Dshot) and PWM signal operation were used. Control was performed by means of a *SpeedyBee F4 V3*[11] flight controller with *BetaFlight*[12] software installed. Rotation speed was set using the built-in configurator (Fig. 8). The Motors panel is used to control the rotation of the motors. The Servos panel is used to control the servos (not used in this work). The switch containing the information plate displayed in the lower right part of the figure authorizes the motors to turn on. The message asks you to confirm that the propellers have been removed and that you consent to the risks of enabling the motors.

A series of tests was used to rate the performance of the ESC controller. T-Motor Velox V2 V2207 1750KV BLDC motor (Feiying Technology, China) was used for load purposes. It is 5 inches in diameter and has an installed 4-inch pitch three-blade air propeller (Gemfan, China). It was powered by a 16.8V 4S battery (HRB, China).

Measurement of rotation speed was performed using a MEGEON™ 18005 (MEGEON, Russia) laser tachometer. Comparison of the results measured with the set values showed a difference of less than 5%.

During motor operation in cycles of 10 min, case heating did not exceed 70°C. The temperature of semiconductor components of the ESC controller was less than 80°C. The test object did not manifest any uncharacteristic sounds or other phenomena.

The phase signal oscillograms of the prototype controller are shown in Fig. 9. They indicate correct operation of the product. Insignificant delays of winding switching should, however, be noted. These delays will be eliminated in the future by making changes to the implementation of the commutation process algorithm.

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[8] Dhrystone MIPS—standard for comparing microcontroller performance.

[9] 1921BK035: microcontroller with reduced overall dimensions with functions for electric drive control (in Russ.). https://niiet.ru/product/1921%D0%B2%D0%BA035. Accessed October 27, 2023.

[10] https://niiet.ru/ (in Russ.). Accessed October 13, 2023.

[11] SpeedyBee. https://www.speedybee.com/speedybee-f405-v3-bls-50a-30x30-fc-esc-stack/. Accessed October 13, 2023.

[12] Betaflight. https://www.betaflight.com. Accessed October 13, 2023.

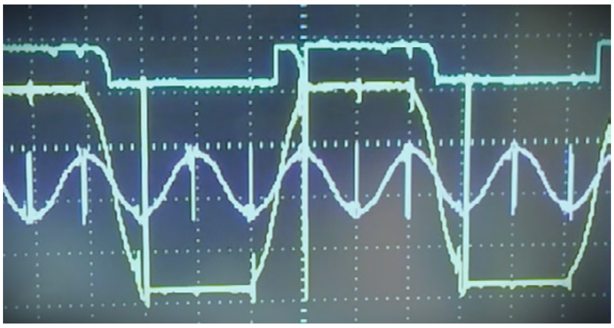

Fig. 9. Oscillograms obtained during the tests

CONCLUSIONS

In the development of in-house software for UAV BLDC motor controllers, invariant methods and algorithms are proposed to be used. They are based on the theoretical foundations of program control of this type of motor.

A methodology for defining the necessary microcontroller parameters for building a controller with the required characteristics was developed. This methodology prevents errors and optimizes microcontroller choice.

The results presented herein were tested. The methodology and algorithms formed the basis for the software development for a rotational controller prototype for a single UAV EPG engine. The test results provided a positive conclusion about the operability of the solution, and it was decided to continue its development. The main focus of further work will be to improve the software based on the algorithms considered in the article.

The testing process confirmed the suitability of the microcontroller selection method, according to the specified characteristics. The characteristics of peripheral devices fully correspond to operational ones. The calculated values of computing power differ from operational values by 10–15% upwards. Based on the results obtained, a positive conclusion can be made about the methodology presented in this paper.

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