

DEVELOPMENT AND DEBUGGING OF SOFTWARE FOR THE IMPLEMENTATION OF A BACKUP RADIO CHANNEL FOR UAV CONTROL

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The development of unmanned aerial vehicles (UAVs) in recent years has significantly expanded the possibilities for building mobile, rapidly deployable communication systems. One promising area is the use of unmanned aerial vehicle (UAV) as airborne mast, allowing for the rapid raising of relay equipment to a significant height. This article, based on a functional diagram of a fiber-optic communication line (FOCL) control system with power supply via a wire between the control center and the UAV used as an airborne communication mast, implements M-sequence encoding of a backup radio control channel. The following circuits have been developed: an onboard Direct Current to Direct Current (DC-DC) converter, a power supply for the onboard equipment, and an M-sequence unit. The article presents the results of developing a functional diagram of the control and power supply system for an unmanned aerial vehicle. To implement a backup, interference-resistant radio control channel, software is being developed using the Quartus II computer-aided design (CAD) system, which is designed for developing digital devices on programmable logic integrated circuits (FPGAs) and provides M-sequence encoding of data packets.

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Introduction

In previous research, the author developed a functional diagram of a fiber-optic communication line (FOCL) control system and a circuit for providing power via a wire between the control center and the unmanned aerial vehicle (UAV).

Mast devices built on wheeled chassis, with heights ranging from 20 to 50 meters, require 30 minutes to several hours to deploy the system. During this time, it is necessary to:

- stabilize and level the vehicle platform on the outriggers;
- raise the mast sections to the required height;
- install and tension cables to prevent the platform from tipping over in strong winds.
- lay cables from the ground station to the communication devices located on the tower;

The construction of permanent telecommunications masts now takes several weeks to months. This is because their installation requires:

- selecting the correct location for the antenna mast, with a clear line of sight to ensure stable communication with subscribers;
- design and develop the communications tower structure;
- prepare the site;
- manufacture the components and assemble the mast;
- install the communications equipment and lay the cables.

The deployment time of an airborne communications mast is now measured in minutes (from 5 to 15 minutes). Once the unmanned aerial vehicle reaches its destination, it launches. Once it reaches the required altitude, signal relaying begins. This is a significant advantage in situations where every minute is crucial, such as during search and rescue operations or combat situations.

Despite its high potential, the previously discussed technology of using an unmanned aerial vehicle as an airborne communications mast has a number of significant limitations that cannot be ignored.

1. Limited battery capacity, and therefore flight time, are the main technical barrier to implementing this technology.

2. Using radio communications to control an airborne communications mast makes the system vulnerable to interception by an adversary, which can lead to the loss of the drone and the leakage of

classified information. When exposed to electronic warfare, control of the unmanned aerial vehicle systems becomes impossible, resulting in the crash and destruction of the communications node.

3. Strong dependence on weather conditions is also a serious drawback of unmanned platforms. Strong winds, icing, and heavy rainfall can make unmanned aerial vehicle flight impossible or dangerous.

The range of telecommunications devices mounted on traditional antenna towers is highly dependent on terrain and the presence of various obstacles in the signal path.

Mountainous or rugged terrain creates so-called "dead zones," where the base station's signal either fails to reach the tower or is very weak, preventing proper communication between the tower-mounted transceivers and subscriber radios located within the zone. Eliminating this problem requires increasing the number of fixed towers, which significantly increases the cost of the entire communications system.

Using an airborne telecommunications platform offers a significant advantage in this regard. A unmanned aerial vehicle can vary its altitude from a few to several hundred meters, allowing it to cover areas otherwise inaccessible with ground-based towers. Thus, by varying its altitude, it becomes possible to adapt the coverage area to the current needs.

Unmanned platforms have a significant advantage in terms of survivability and vulnerability due to their high mobility and low observability. If threatened, the aircraft can quickly reposition or land. The loss of a single unmanned aerial vehicle is not catastrophic, as it can be quickly replaced by a backup, demonstrating the high fault-tolerance of the entire communications system.

A fiber-optic line is essentially a subtype of a wired communication channel. However, it uses fiber-optic cable as the transmission medium, in which the signal propagates as modulated light pulses [1, 2].

The only viable solution to the first two problems today is to use a wired power supply from a ground station and a fiber-optic communication line as the control channel for the aerial mast. This is the focus of the author's previous research.

The complete functional diagram of the wired power and fiber-optic control system for an unmanned aerial vehicle used as an aerial mast is shown in Figure 1.

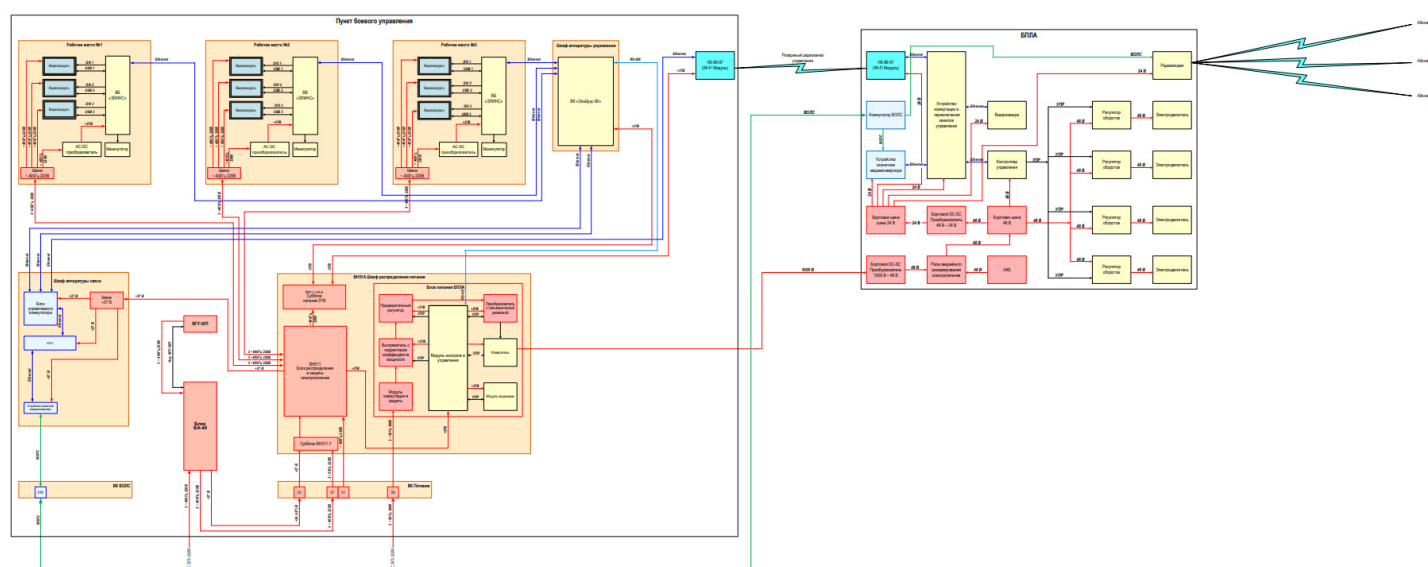


Fig. 1. Functional diagram of the fiber-optic power and control system for an unmanned aerial vehicle

Initial data for the development:

- unmanned aerial vehicle payload: at least 50 kg
- flight altitude: at least 100 m

Power is supplied to the control center from a diesel generator. The generator's output voltage can fluctuate significantly, significantly affecting the operation of the control console systems.

The development involves the use of an airborne mast for communications in special-purpose vehicles. During the implementation of measures to improve the mobility and technological advancement of communications equipment, the decision was made to use an unmanned platform to house the electronic systems onboard.

The aerial mast is connected to the control center via fiber-optic communication lines using a tactical optical cable, bundled with a power cable and wound onto a special reel to ensure the cable can be coiled and deployed during takeoff, landing, and altitude changes.

A type SO-156 connector will be used for connection to the equipment container's input box, while lightweight FC optical connectors are used on the mast side.

To prevent complete loss of control over the unmanned platform in the event of a break or damage to the cable, the mast must be equipped with a backup communication channel.

The optimal solution to this problem is the use of a radio module. In an emergency, this will allow the transmission of information to the subscriber to be terminated, other participants in the broadcast will be alerted to the failure, and an emergency landing can be performed.

A UV-89-07 Wi-Fi module was selected as a device capable of transmitting control commands to the mast, ensuring its mobility, and relaying information from the unmanned aerial vehicle to the complex's subscribers. The main characteristics of this device are summarized in Table 1.

Table 1

Main Characteristics of the UV-89-07

Characteristic name	Value
Operating frequency range	5.1 – 5.35 GHz
Transmitter power	No more than 0.6 W
Bandwidth of the transmitting and receiving channel	No less than 2 Mbps
Communication range	Up to 1 km
Power consumption	No more than 10 W

This module enables data exchange with similar devices using a multipoint-to-point configuration, where the module in multipoint mode is the master, and the device operating in point-to-point mode is the slave. Slave devices cannot communicate with each other.

In this system, the radio module installed onboard the unmanned aerial vehicle (unmanned aerial vehicle) is the slave, while the one located in the control center is the master. Data transfer between the radio device and the switch at the unmanned aerial vehicle control center or onboard the unmanned aerial vehicle occurs via a 10/100 Mbps Ethernet interface.

The unmanned aerial vehicle power supply output is expected to have a DC voltage of approximately 1000 V. This voltage is required to transmit 10 kW of power using a cable with minimal cable thickness.

The development of the onboard unit is subject to strict weight and size requirements. Its primary function is to step down the 1000 V input voltage to 48 V to power the controller and power units. The functional diagram of the step-down Direct Current to Direct Current (DC-DC) converter is shown in Figure 2.

The electrical circuit is based on parallel-connected pulse modules with galvanic isolation. Using five such stages with a rated power of 2000 W each produces a total output of 10 kW.

Given the module's 95% efficiency and conversion factor, the maximum power consumption at 1000 V will be approximately 10,526 W at 10.5 A. Using a 1.5 mm² cable approximately 100 m long, the voltage loss will be approximately 0.6 V per meter, resulting in approximately 940 V being supplied to the onboard DC-DC converter input.

The onboard unit's output voltage can vary from 51 V (at idle) to 45 V (at maximum load), which is acceptable for operating the speed controllers and electric motors. Voltage from the DC-DC converter's output is fed to the emergency power backup relay. A backup lithium-polymer battery (Li-PO) is also connected to it.

When operating from the ground power grid, the relay compares the voltage supplied by the onboard DC-DC converter and the battery. If the ground power fails or drops significantly, the relay automatically switches to the backup battery.

The onboard 48V bus distributes power to all controls operating at this voltage. Non-standard fiber-optic and radio control devices are powered by a DC voltage of 21-29V, requiring the installation of an additional step-down DC-DC converter [7].

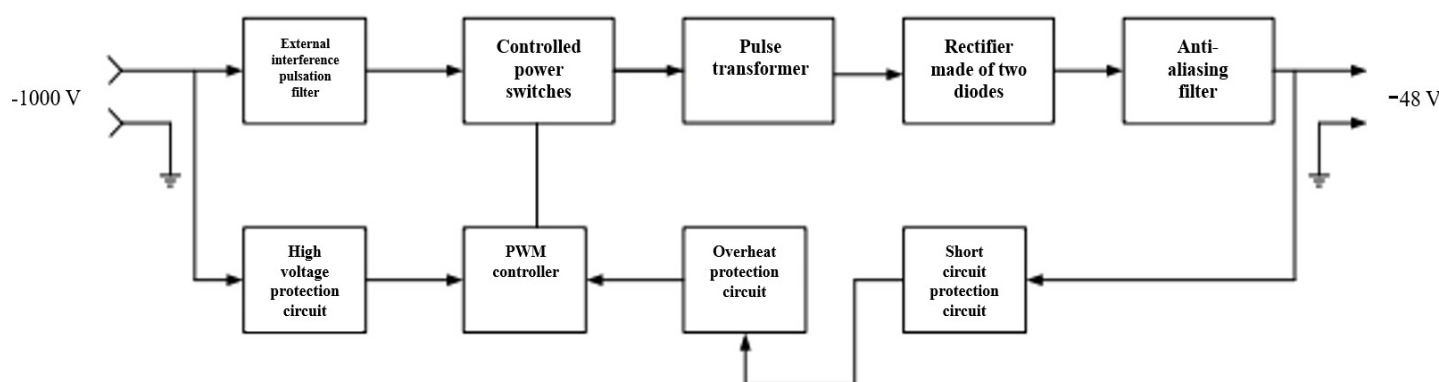


Fig. 2. Functional diagram of the on-board DC-DC converter

Developing the software code involves creating a model based on a block diagram, which reflects the functional diagram of the control module, assembled from basic logic components: and/or gates, multiplexers, triggers, etc. The module is organized into three blocks:

1. control command block
2. -sequence generation block
3. Hamming code generation block

Control Command Block Development

This block is built on a specific set of commands. Each command corresponds to a unique binary combination, which is stored as a sequence written in constant elements. The diagram is shown in Figure 3.

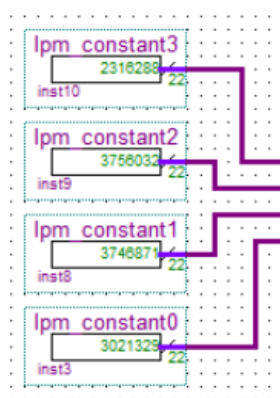


Fig. 3. Constant elements in which code combinations are written

The following code combinations were chosen for control commands:

- gas – 10001101011 (11 bits);
- yaw – 11100101010 (11 bits);
- pitch – 1110010010110000110111 (22 bits).

The selection of a command for transmission to the airmobile mast is carried out by specifying its number on the STATIC_COMMAND element. The selected binary sequence is sent to shift registers, which generate a strobe signal (INFO_STROBE).

The active level of such a signal is a logical one. Its leading edge is synchronized with the beginning of the transmission of the information sequence, and the trailing edge is synchronized with its end. The control command block diagram is shown in Figure 4.

When STATIC_COMMAND = 10, the next element receives the INFO_IN information sequence, which corresponds to the "yaw" command, as well as the INFO_STROBE signal. The binary sequence is shown in Figure 5.

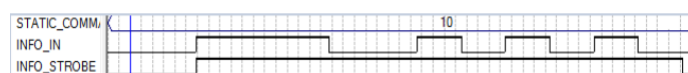


Fig. 5. Binary sequence for the "yaw" command

Changing the STATIC_COMMAND value to 01 changes the code sequence to "pitch" and generates a new strobe signal. The binary sequence is shown in Figure 6.

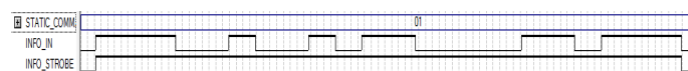


Fig. 6. Binary sequence for the pitch command

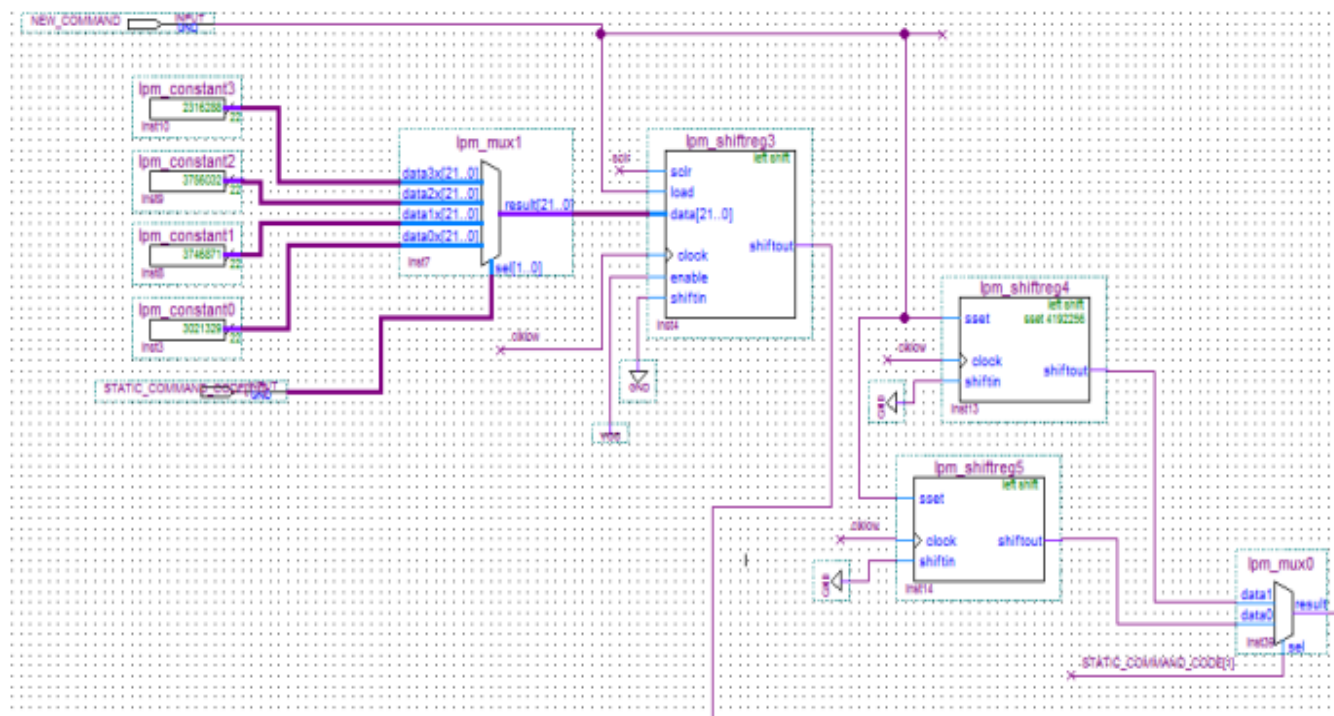


Fig. 4. Control Command Block

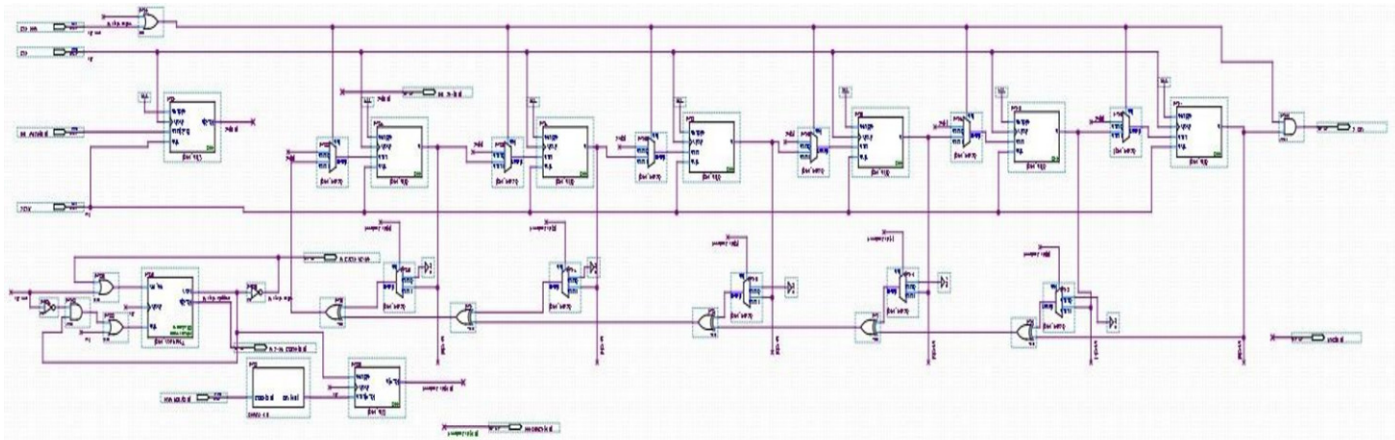


Fig. 7. Functional diagram of the M-sequence block

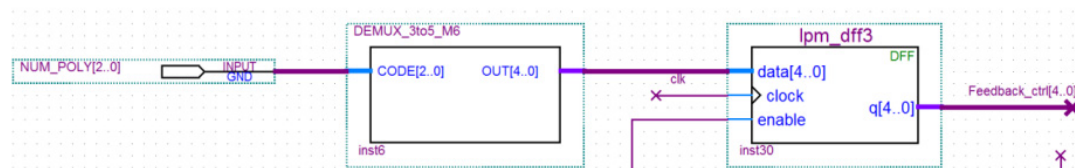


Fig. 8. Feedback configuration selection and fixation node

M-Sequence Generation Block Development

Table 2

An M-sequence is a pseudo-random binary sequence with the maximum possible repetition period for a given circuit, defined by the formula $N = 2^m - 1$, where m is the bit depth of the linear feedback shift register (LFSR) that generates this type of sequence. Each bit of the shift register can only take two values – one or zero – as it is an element built on binary logic [3-6].

An important property of the M-sequence is that any combination of m symbols occurs no more than once per period. A 6-bit linear feedback shift register was chosen for the implementation, resulting in a sequence period of 63. The basis for constructing this shift register is a generator polynomial whose degree is equal to the register's bit depth. The coefficients of the polynomial determine the feedback structure.

For a 6-bit register, there are six 6th-degree polynomials. The bit depth of a linear-feedback shift register circuit contains m D-flip-flops, the input of each of which (except the last) is connected to the output of the next.

The input of the last (highest) flip-flop is fed with the result of the modulo-2 addition (XOR) operation from the outputs of those flip-flops whose numbers correspond to the non-zero coefficients of the low-order terms of the selected polynomial. The circuit is shown in Figure 7 [8-10].

During the development of this circuit, the ability to select one of the six existing generator polynomials was implemented. To do this, a 3-bit combination corresponding to one of the possible polynomials must be fed to the NUM_POLY[2...0] input before the M-sequence is generated. The polynomials and corresponding combinations are presented in Table 2.

Correspondence of Code Combinations to Generator Polynomials

NUM_POLY	Generator polynomial
000	$x^6 + x + 1$
001	$x^6 + x^4 + x^3 + x + 1$
010	$x^6 + x^5 + 1$
011	$x^6 + x^5 + x^2 + x + 1$
100	$x^6 + x^5 + x^3 + x^2 + 1$
101	$x^6 + x^5 + x^4 + x + 1$

The selected NUM_POLY combination is fed to the decoder, which generates a 5-bit control signal. Each bit of this signal controls the on/off of the feedback loops of the D-type flip-flops included in the shift register. The configuration is stored in a special register until the end of the M-sequence generation. The circuit diagram is shown in Figure 8 [11-14].

Feedback control is implemented using lpm_mux0 multiplexers, controlled from the Feedback ctrl bus. The schematic is shown in Figure 9.

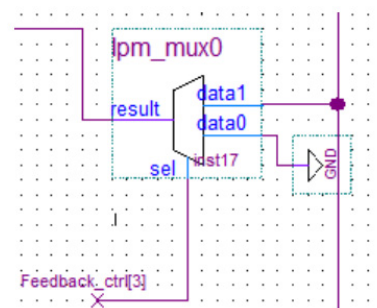


Fig. 9. Feedback connection diagram via multiplexers

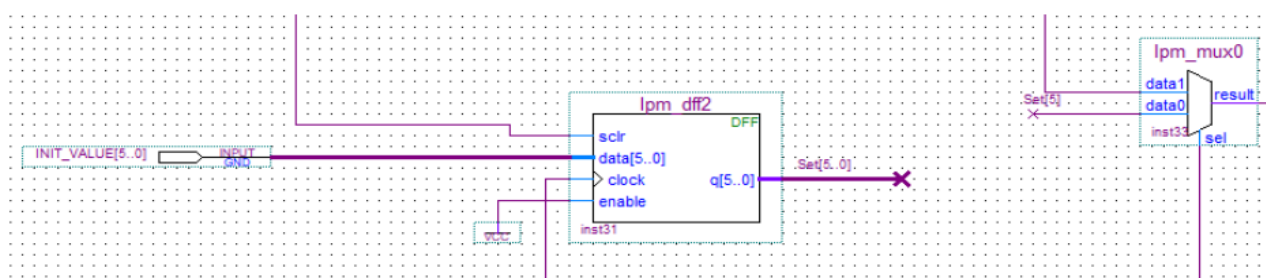


Fig. 10. Schematic diagram of the initial setup unit of the shift register with linear feedback

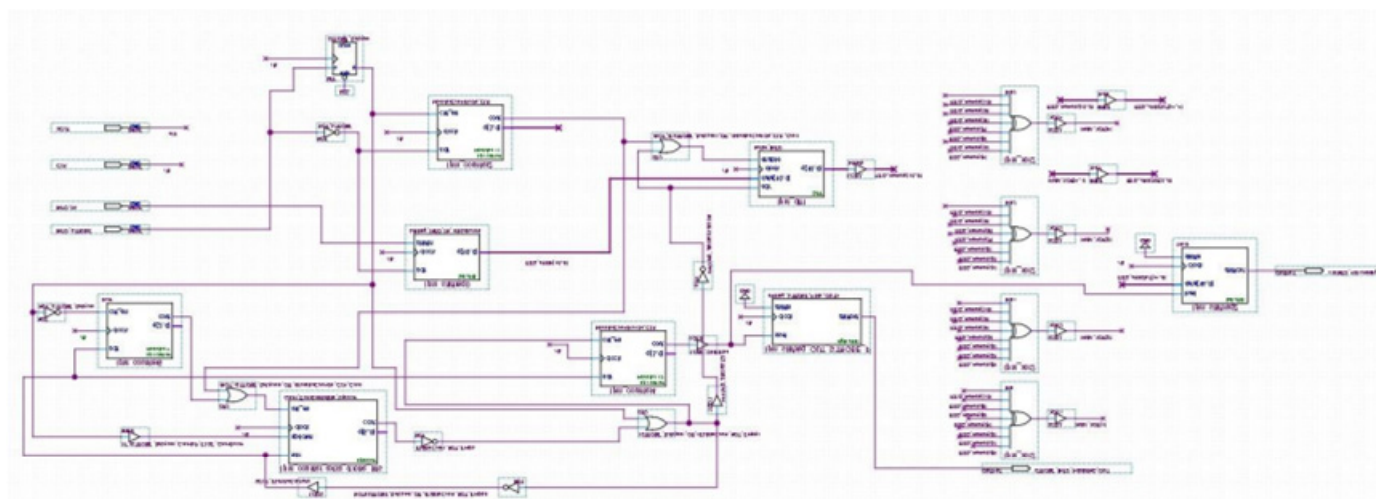


Fig. 11. Functional diagram of the Hamming code complement block

The block operates as follows:

1. INFO_IN information bits are fed sequentially to the input of the lpm_shiftreg0 shift register, which outputs them over the parallel REG shiftin [10..0] bus, 11-bit at a time.
2. The received 11-bit word is stored in the lpm_dff1 register. This allows the receiving shift register to simultaneously receive the next word while the current one is being processed.
3. Each information bit from the buffer register, in accordance with Table 1, is fed to the corresponding inputs of the exclusive-or elements (lpm_xor2), where four check bits are calculated: HMM_XOR[1] = 0, HMM_XOR[2] = 0, HMM_XOR[3] = 1, HMM_XOR[4] = 0.

The multi-input modulo-2 adder was replaced with five two-input adders, which sequentially sum the output of a D-flip-flop either to the output of the next D-flip-flop, when feedback is enabled, or to a logical zero, when the operating system is disabled.

Since a zero state for all flip-flops is prohibited (resulting in the generator freezing), an initial setup mechanism was added to the circuit. An arbitrary non-zero 6-bit value is written to the register via the INIT_VALUE [5...0] input. Additional multiplexers are used to load this value.

During the initialization phase, these multiplexers apply the INIT_VALUE value to the inputs of the D-flip-flops, and during the operating phase, they switch to signals from the feedback circuit and previous bits. The circuit diagram of the unit is shown in Figure 10.

Hamming Code Complement Block

The Hamming code belongs to the class of error-correcting codes capable of detecting and correcting single errors and fixing double errors.

The process of generating check bits (p) for the (15,11) code is described by the following relations, where D0 – D10 are the bits of the original information combination. The logic is presented in Table 3.

Table 3

Logic for Generating Check Bits of the Hamming Code

Initial information sequence	D0	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
Hamming code check bits											
p0											
p1											
p2											
p3											

Explanations for the table using formulas:

$$p_0 = D_0 + D_1 + D_3 + D_4 + D_6 + D_8 + D_{10}$$

$$p_1 = D_0 + D_2 + D_3 + D_5 + D_6 + D_9 + D_{10}$$

$$p_2 = D_1 + D_2 + D_3 + D_7 + D_8 + D_9 + D_{10}$$

$$p_3 = D_4 + D_5 + D_6 + D_7 + D_8 + D_9 + D_{10}$$

For example, let's select the polynomial $x^6 + x + 1$, which corresponds to a NUM_POLY combination of 000 and an initial value of INIT_VALUE [5...0] = 000001. After loading these parameters and receiving the enable signal CLK_ENA, generation begins.

At each clock cycle, the register contents are shifted, the least significant bit is output, and the most significant bit is written to the XOR result of the zeroth (in this polynomial) and first bits. After 63 clock cycles, the register state repeats, and the sequence begins again. The CLK_ENA signal also controls the lock on changes to the initial value and polynomial configuration during generation.

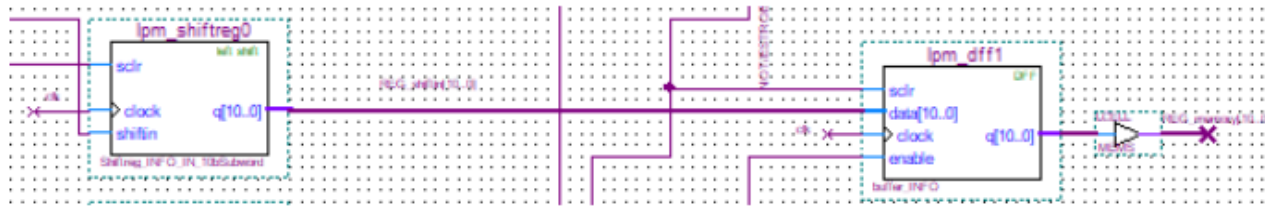


Fig. 12. Conversion of serial code to parallel code

The Hamming code complementation block. The circuit is shown in Figure 11.

The algorithm is clearly shown in Figures 12 and 13.

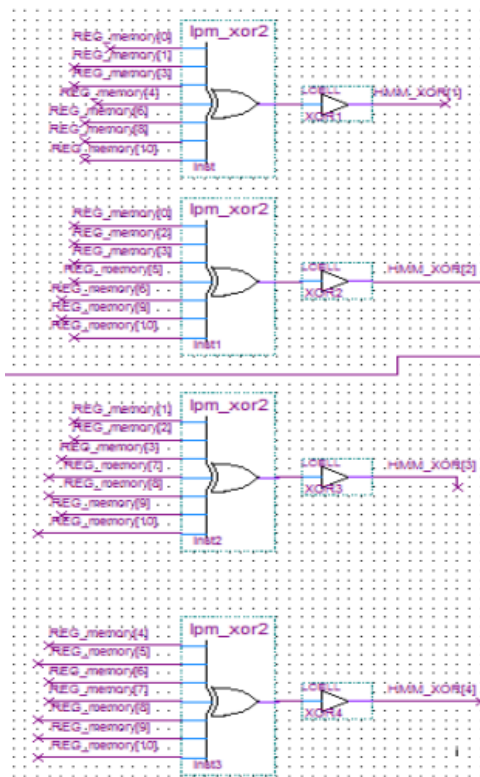


Fig. 13. Generating Check Symbols

1. Using the concatenation operation in inst7 and inst8, four calculated check symbols are appended to the original information bits, forming a 15-bit codeword.

2. The generated sequence of binary symbols is loaded into the output shift register lpm_shiftreg2 via the parallel bus and is output sequentially from the 11bINFO_4bHamming output.

The execution of the operation and the output register are shown in Figures 14 and 15.

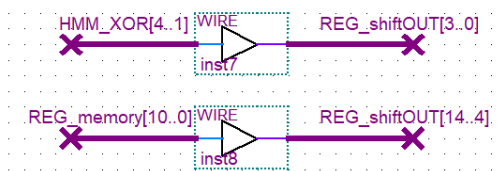


Fig. 14. Scheme of execution of the concatenation operation

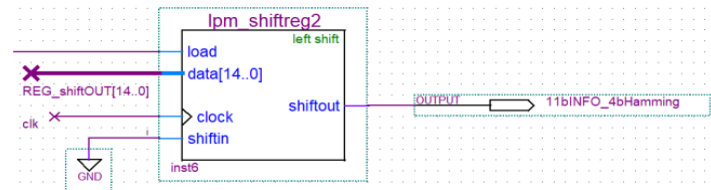


Fig. 15. Output Shift Register

3. To synchronize subsequent blocks, a STROBE_INFO_HAMMING_OUT strobe pulse is generated. It is generated by the lpm_shiftreg_OUT_STROBE_P shift register, indicating the beginning and end of the 15-bit sequence to the M-sequence generation block.

The generation of the strobe signal and its output sequence are shown in Figures 16 and 17.

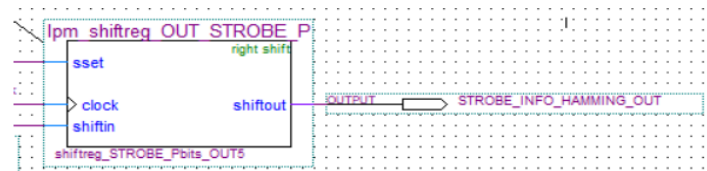


Fig. 16. Formation of a strobe signal



Fig. 17. Output sequence with strobe signal

The resulting 15-bit sequence is encoded using an M-sequence to improve signal noise immunity. This operation is performed using an exclusive-or-not (XNOR) logic element.

The clock frequencies of the blocks are synchronized such that during the transmission of one bit of the information sequence with additional Hamming symbols, the M-sequence block has time to fully output its entire 63-bit period. The STROBE_INFO_HAMMING_OUT strobe triggers the generation of the M-sequence, ensuring the synchronous start of the two sequences. The XNOR element receives the information bit and the M-sequence bits.

If the information symbol is "1," the output displays the normal M-sequence bit values; if the information bit is "0," the output displays an inverted version of the M-sequence. Thus, the circuit outputs a continuous bit stream consisting of alternating direct and inverted M-sequence symbols, which correspond to the bits of the encoded message. The output sequence of the circuit is shown in Figure 18.



Fig. 18. Code sequence at the circuit output

Justification of Development Feasibility

The justification of the feasibility of developing a software product can be conducted based on the results of comparing the new version with an existing equivalent, determining the quantitative values of quality characteristics and their significance [15].

All characteristics selected for analysis and their values are summarized in Table 4.

Table 4

Approximate scale of novelty of proposals

Software Quality Characteristics	Units of measurement	Values of PP quality characteristics		The importance of characteristics
		Analogue	New option	
Suitability	Points	3	4	0,3
Error Resistance	Points	2	3	0,4
Understandability	Points	3	4	0,1
Changability	Points	4	5	0,1
Structured	Points	3	4	0,1

Since the software product being developed is not final, the technical level of the developed version must be linked to the degree of influence it has as a component on the final outcome of the functioning of the system at a higher level of the hierarchy.

The technical level index of software product development will be equal to:

$$J_{tl} = 1,39 * (0,25 + 1) = 1,73 \quad (1)$$

Based on the technical level index (1) of software development, one can conclude that the solutions obtained as results of the evaluated development are superior to those of similar developments conducted previously. This is largely due to the development of personal computers and software products used in the study, as well as a rational approach to planning and development.

The cost-effectiveness of development costs when using its results in scientific applications is $E = 1.48$. A coefficient of $E > 0.5$ corresponds to a science-intensive product and indicates a full return on investment within two years. Therefore, the ongoing development of software for implementing a backup radio control channel for an unmanned aerial vehicle used as an airborne communications mast can be considered cost-effective.

During the development process, the developer's working conditions were assessed based on an analysis of the following production factors: indoor microclimate, vibroacoustic factors (noise), lighting environment, non-ionizing radiation, and work severity and intensity. The assessment revealed that all factors meet established standards.

Conclusion

During the development process, potential operational issues with the wired power supply system and fiber-optic line were taken into account. Therefore, to ensure their reliability, a backup radio control channel and onboard lithium-polymer battery were added to the design. This ensures that, in the event of a failure of the primary systems, the mast can complete its mission and land safely.

To ensure the backup radio channel's noise immunity, software for the control module was developed in the Quartus II environment using a functional logic diagram. The diagram includes three main blocks: a control command block, an M-sequence generator,

and a Hamming code generator. This software is intended to be installed on a programmable logic integrated circuit (PLC) included in the UV-89-07 radio control unit.

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РАЗРАБОТКА И ОТЛАДКА ПРОГРАММНОГО ОБЕСПЕЧЕНИЯ ДЛЯ РЕАЛИЗАЦИИ РЕЗЕРВНОГО РАДИОКАНАЛА УПРАВЛЕНИЯ БПЛА

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Аннотация

Развитие беспилотных летательных аппаратов (БПЛА) в последние годы существенно расширило возможности построения мобильных, быстро разворачиваемых систем связи. Одним из перспективных направлений стало использование беспилотного летательного аппарата в качестве аэромобильной мачты, позволяющей оперативно поднимать ретрансляционное оборудование на значительную высоту. В данной статье на основе функциональной схемы системы управления по волоконно-оптическим линиям связи (ВОЛС) с обеспечением электропитания по проводу между пунктом управления и беспилотным летательным аппаратом, используемым в качестве аэромобильной мачты связи реализовано кодирование резервного радиоканала управления с помощью М-последовательности. В том числе разработаны схемы: бортового Direct Current to Direct Current (постоянный ток в постоянный ток, DC-DC) преобразователя, обеспечения электропитания бортового оборудования, блока М-последовательности. Представлены результаты разработки функциональной схемы системы управления и обеспечения электропитания беспилотного летательного аппарата. Для реализации резервного помехозащищенного радиоканала управления разрабатывается программное обеспечение в системе автоматизированного проектирования (САПР) Quartus II, предназначенной для разработки цифровых устройств на программируемых логических интегральных схемах (ПЛИС) и обеспечивающей кодирование информационных посылок с помощью М-последовательности.

Ключевые слова: БПЛА, система управления, резервный радиоканал, DC-DC, блок команд управления, РСЛОС, помехоустойчивое кодирование, двоичное кодирование.

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