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MICROCONTROLLER NAVIGATION AND MOTION CONTROL SYSTEM OF THE UNDERWATER ROBOTIC COMPLEX

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ABSTRACT

Research and development of Remotely Operated Vehicles and Autonomous Underwater Vehicles are urgent and promising global challenges. Development of navigation and motion control system remains a priority task when designing underwater robotics. The article presents the development results of navigation and motion control system of the underwater multiple robots, the schematic circuit diagram of developed electrical and structural navigation and motion control system, as well as a review of the existing technical solutions. The authors propose also the developed operation algorithm of the designed system modules, as well as schematic circuit diagram of the navigation and motion control system of the underwater multiple robots. Presented return-to-investment diagram is constructed on the basis of conducted feasibility study and estimated annual economic effect from implementation of the developed system. The developed system is effective and its implementation is quite relevant, since it can be used in most modern underwater robotics.

Keywords: underwater multiple robots, remotely operated vehicles, autonomous underwater vehicles, navigation system, robot, ROV, motion control system, AUV, underwater vehicle, underwater exploration, navigation, robotic system.

1. INTRODUCTION

Currently, due to the fact that the ocean attracts great attention to the problems of environmental protection and energy production, the demand in the use of underwater robotic systems for solving various problems of exploring the ocean essentially increases [1-48]. Underwater robotics is one of the most rapidly developing branches of robotics. Russia is one of the leaders in the underwater robotics industry.

Many advanced countries have now moved or are moving their production to multiple robots and robotic systems. Industrial robots are widely used in such industries as automotive, founding, lathing, machinery, as well as water exploration works salvage operations, etc. [24]. This is because one is freed from the heavy and harmful work fully or partially that allows improving work performance and reducing the number of jobs, which are not involved directly in the production, though are necessary for performing auxiliary works and services. All these works will be done by robots.

Robotics began its rapid development in the late 60-iess and early 70-ies [25], when the first models of industrial robots, immediately found application in various industries, were emerged in various branches of industry [24].

Due to the rapid evolution of computer technology, the development of robotics took a different turn - the robots began to decrease in size and weight, though this did not affect their productive capacities. The robotics software base was continuously improved, allowing much easier programming of robots and facilitating the work of staff. The opportunity to control and monitor robotic workshops became possible.

The relevance of developing of navigation and motion control systems of the underwater multiple robots consists in the following. In recent years, along with the use of large and expensive remote-controlled underwater robots, whose operation requires the availability of the special ship carriers with lifting devices, there is a global tendency of wide use of underwater mini autonomous vehicles intended for the search and inspection works at depths of up to 300 m. This tendency is accompanied by reduction in prices on vehicles as well as performance of deepwater operations in general. This increases the accessibility for both professionals and ordinary nonprofessional divers, who are fond of the underwater world. The function of underwater vehicles, such as the search and inspection of works at depths of up to 150 m, becomes relevant as well. In the 90-ies of the last century, a number of firms – JW Fishers Inc (USA), Hydrovision (UK), and Inuktun (Canada) began to design the so-called mini-ROVs (Remote Operated Vehicle) [7]. Study of possibilities of using new technologies has shown that it is possible to create devices with even smaller dimensions (micro-ROV) and less power consumption, while maintaining the same operation speeds. Such devices can carry out the survey by going inside the various submerged objects.

2. MATERIALS AND METHODS

The research methodology was based on the principles, provisions and conclusions contained in the works of Russian and foreign researchers involved in the development of underwater multiple robotic systems, underwater robotics motion control systems, as well as control and navigation systems.

Research of underwater multiple robotic systems as well as navigation and motion control systems of underwater robots were studied in a large number of scientific works carried out by Russian and foreign scientists.

The issues concerned with research and development of remotely operated vehicles and their modules are presented in the works of E. Licea, M.J. Grimble, A. Khadhraoui, L. Beji, S. Otmane, A. Abichou, etc.

The research results of underwater robotic systems and autonomous underwater vehicles, as well as use of underwater robotic systems for solving various problems are presented in the works of foreign and Russian authors: E. Fiorelli, T. I. Fossen, , S.I. Sagatun, M. Johnson-Roberson, N.E. Leonard, H. Mahesh, J. Yuh, R. Lakshmi, S. McMillan, Y. Petillot, D.A. Smallwood, L. Lapierre, D. Loebis, R. Sutton, J. Chudley, W. Naeem, A. Alvarez, M. Grasmueck, I.C. Robbins, A.V. Inzartsev, L.V. Kiselev, and Yu.V. Matvienko [1, 5, 6, 8, 12, 14-16, 19-23, 27, 30, 35].

The results of the navigation and control systems development for underwater robots are presented in the works of R. McEwen, H. Thomas, D. Weber, F. Psota, H. Kondo, T. Ura, L. Paull, S. Saeedi, M. Seto, H. Li, A. Khadhraoui, L. Beji, S. Otmane, Yu. Matvienko, E.S. Ogurtsov, V.M. Kureichik, S.F. Ogurtsov, N.A. Rylov, R.N. Rylov, A.V. Comany and others [3, 34, 40, 43].

Different approaches to the underwater vehicles control including underwater robots (sliding mode control, robust control, adaptive control, fuzzy control, nonlinear control and others) are presented in the research of D. R. Yoerger, J.-J. E. Slotine, E. Licea, M. J. Grimble, M. Narasimhan, N. Sahjendra, W. Jeen-Shing, C.S.G. Lee, J. Yuh, Y. Nakamura, S. Savant, and others [19-23] .

The development and study of hydro-acoustic navigation systems, sonar systems, and automated control systems was considered in the works of E.S. Ogurtsov, V.M. Kureichik, S.F. Ogurtsov, V.V. Kureichik and others [3, 9, 26, 28, 39].

The studies presented in this work were carried out using general scientific methods, conventional statistical techniques of information processing and decision making, decision making methods based on the optimization of performance indicators, search methods, methods of comprehensive economic analysis of business activities and system analysis approaches, as well as project management methods.

3. RESULTS AND DISCUSSIONS

3.1. An overview of some existing remotely operated underwater vehicles, developed by the Russian scientists, and their control systems

3.1.1. Underwater vehicles of RovBuilder series

Consider some of the characteristics and features of existing remotely operated underwater vehicles of RovBuilder series, developed and presented by LTD Underwater Technical Center "RovBuilder" (Russia).

The price of such a vehicle can be compared with the price of a personal computer with all the peripherals or the price of scuba diver accoutrements. All electronic hardware of such vehicles is made of advanced mass-produced imported industrial components. The mechanical component of the vehicle is designed at domestic production base. Each individual unit of the vehicle and the underwater vehicle as a whole pass several testing stages.

Remotely operated underwater vehicle of RovBuilder series is a modern underwater mini vehicle performing underwater works (video inspection) at a depth of 150 meters, controlled by means of above-water control panel with a cable length of 150 to 600 meters. Underwater vehicles of RovBuilder mini series differ in cable length and electric motor power.

Underwater robot of RovBuilder mini series is designed for:

- remote search, inspection and survey of underwater objects (pylons, water intakes, drains, cables, pipes, oil and gas pipelines, oil wells, etc.);
- survey of docking facilities, flood-gates structures and equipment, underwater parts of ships, floating landing stages, etc.;
- inspection of accumulation tanks and water reservoirs (inspection of equipment without removing from the water or water drain);
- exploration of the underwater world beauties and its inhabitants.

Basic option of underwater robot of RovBuilder mini series is equipped with:

1. Miniature video camera (with the rotation angle of 140 degrees, controlled by the operator);
2. Halogen lights (with the possibility of adjusting the illuminated zone in front of the vehicle).
3. The temperature-compensated depth sensor;
4. Electronic compass;
5. A communication cable.

Video system with lights provides visibility in the clear water in daylight of about 15-20 m. When turning on robot lights at full capacity, the visibility in clear water in dark conditions is 5-6 m.

There are three kinds of the underwater inspection vehicles of RovBuilder mini series:

- **RovBuilder mini-150:** is the modern underwater vehicle performing underwater works (video recording) at a depth of 150 meters by means of above-water remote control panel with a cable length of 150 meters.
- **RovBuilder mini-300:** is the modern underwater vehicle performing underwater works (video recording) at a depth of 150 meters by means of above-water remote control panel with a cable length of 150 meters.
- **RovBuilder mini-600:** is the modern underwater vehicle performing underwater works (video recording) at a depth of 150 meters by means of

above-water remote control panel with a cable length of 600 meters.

The system of remotely operated underwater vehicle includes:

- underwater robot;
- cable (from 150 to 600 meters);
- above-water remote control panel.

Underwater RovBuilder mini robot moves under water in all directions by means of two horizontal thrusters and one vertical thruster. Due to the improved hydrodynamics, the robot has high maneuverability. Video recording is carried out by miniature video camera, lighting is provided by halogen lights located in the lower part of the vehicle. The vehicle has a depth sensor and electronic compass. The measurement accuracy of the depth sensor is up to 10 cm, while the electronic compass allows navigating regardless of visibility conditions.

Motion control and operation modes of the vehicle are carried out by means of above- surface control panel. The video information, as well as the data on depth and vehicle course are displayed on the monitor screen in teletext mode.

The underwater robot system is connected to the video monitor, TV and/or VCR through a standard cable. The vehicle has an autonomous power supply (from the built-in inverter powered by rechargeable 12V battery) or external source of 220V. Maximum power consumption is 500W that allows working from ordinary car battery up to 3 hours (at the normal rate of consumption). The system allows operation of the power inverter with rectangular square wave (for stand-alone operation or on-board power network). Easy to transport and use, rapid deployment, high maneuverability, and ability of penetration into inspected underwater objects make the vehicle useful and convenient. The underwater vehicles are operated using advance computer and telecommunication technologies based on recent advances in microelectronics and high-frequency engineering.

Uunderwater vehicle of RovBuilder mini-150 series

RovBuilder mini-150 - is a modern underwater vehicle performing underwater works (video recording) by means of above-water remote control panel at a depth of 150 meters and having a cable length of 150 meters. This series of underwater robot, as recommended, can be used at depths of 50-70 meters at a mild current.

Main performance data of the underwater robot are shown in Table-1. The outside appearance of the RovBuilder mini-150 robot is presented in Figure-1.

Table-1. Main technical data of underwater RovBuilder mini-150 robot.

No.	Parameters	Performance data
1	Overall dimensions of the underwater vehicle	400mm×250mm×200mm
2	Weight of the underwater vehicle (complete vehicle system)	4.5 (34) kg
3	Maximum operational depth	150 m
4	External power supply	220V 50Hz , max 400W
5	Environment humidity	up to 100%
6	Operating temperature range: air (water)	-5° … +45°(0° … +25°C)
7	Number of thrusters (thrust of bollard pull for each thrust)	3 (1.3 kg)
8	Speed of horizontal movement	up to 1.3 m/s
9	Speed of vertical movement	up to 0.2 m/s
10	Cable length	150 meters

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Figure-1. The outside appearance of the RovBuilder mini-150 underwater vehicle.

Underwater vehicle of RovBuilder Mini-300 series RovBuilder mini-300 - is a modern underwater vehicle performing underwater works (video recording) by means of above-water remote control panel at a depth of 150 meters and having a cable length of 300 meters. This series of underwater robot, as recommended, can be used at depths up to 100 meters at a mild current.

Basic option of the underwater robot RovBuilder mini-300 is equipped with:

1. Miniature video camera (with the rotation angle of 140 degrees);
2. LED lighters (able to adjust the illuminated zone in front of the vehicle). Lights based video system provides visibility in the clear water in daylight of about 15-20 m.

The outside appearance of the RovBuilder mini-300 robot is presented in Figure-2.

Figure-2. The outside appearance of the RovBuilder mini-300 underwater vehicle.

3.1.2. Compact remotely operated underwater vehicles "GNOM"

The GNOM (dwarf) system developed and implemented by the Shirshov Institute of Oceanology of the Russian Academy of Sciences consists of a main unit, cable, above-water unit and a manual Sony control panel. The underwater module is produced as sealed aluminum cylinder with a porthole for the camera. Four mini-electromotors with propellers (two horizontal - mounted on the sides of the vehicle, and two vertical - along the vehicle body) are attached to the cylinder. Besides, float made of foam plastic is attached to the vehicle to give the unit neutral buoyancy. A color video camera, LED lighters and the electronics module, as well as the electronic compass and the depth sensor, whose membrane faces outward, are placed inside the cylinder. The above-water unit includes a power source, electronics for transmission of commands, data and video, and remote control joystick. There is a block design option with a flat monitor. The whole system with a control panel is housed in two portable shockproof suitcases. GNOM is equipped with a color high resolution video camera (450 TVL) with pitch servoactuator and digital zoom.

Performance specifications of GNOM-4-150 vehicles:

- Number of thrusters - 4;
- Horizontal movement speed - up to 1 m/s; vertical movement speed – up to 0.5 m/s;
- Operational depth - 100 m, maximum permissible depth – 120 m;
- Lighting: 35 white light LEDs, smooth regulation of front and side lighters;
- Color PAL CCD video camera , 0.5 lux, 450 TVL;
- Power supply and control block: 220 V network, built-in battery 7-12 Ah;
- Operating temperature range – -5 …+ 4^{5o}C;
- The weight of the underwater vehicle – 3 kg, complete system - 18 kg;
- The overall dimensions of the underwater vehicle - 320x150x120 mm;
- The vehicle is equipped with a depth sensor (with accuracy within 10-20 cm) and the compass transmitting the information to the video monitor in “teletext” mode.
- The vehicle has certain positive buoyancy due to the foam plastic float. The buoyancy is controlled by the ballast in the skids of the vehicle.

Up to date, a few dozen of GNOM vehicles have been produced. Among them the GNOM-4-150 is the most widespread, since it is designed to operate at depths up to 120 m and provided with 200 m long cable. The outside appearance of the GNOM-4-150 vehicle is presented in Figure-3. This vehicle weighs 3 kg, consumes 120W, and develops a horizontal speed of about 2 knots per hour. The availability of two vertical thrusters provides the vertical velocity of about 1 knot per hour, as well as the ability to tilt the vehicle and move it under the tilt up and down. The system is fully autonomous and can be transported by just one person.

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Figure-3. The outside appearance of the GNOM-4-150 underwater vehicle.

The GNOM underwater vehicles of this model are successfully operated for several years. This vehicle is used quite often at extreme depths because it, in spite of the aforementioned analogues, does not lose the maneuverability at deep dives.

3.2. Development of the structural scheme of the navigation system

Figure-4 shows a diagram depicting a set of functions implemented in developed system of navigation and motion control of the underwater multiple robots, in order to achieve its objectives.

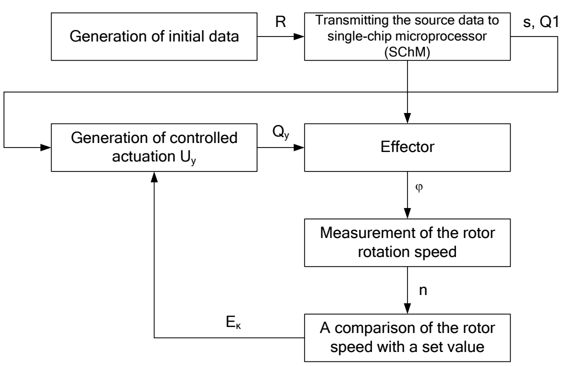

Figure-4. Set of functions implemented by the developed navigation system.

As it is obvious from the presented diagram, first the system calculates and prepares the initial data.

Further, the initial data are transmitted from the central computer into the memory of built-in microprocessor system (MPS) based on the single-chip microprocessor (SChM). Once the data is transmitted to the MPS of the system, the starting signal s is generated, and the MPS will start generating master controls Qy. At that, the thruster rotor will start rotating with a predetermined rotational speed proportional to the input master control Q1. The rotor rotation speed will be converted by the feedback sensor into a pulsed voltage with a frequency *f* and supplied to the input of a counter, which converts this voltage into a number *n* equal to the number of pulses coming from the sensor. The resulting number will be directly proportional to the rotor rate of rotation, worked out by thruster. It will be compared at each step with a reference number n_r stored in the MPS memory, and in case of mismatch, an appropriate master control Qy, proportional to the mismatch error E_k will be generated.

In accordance with the considered functional features of the developed navigation and motion control system of the underwater robotic vehicle and possible modes of its functioning, we can represent the structure of the control system. The structural scheme of the developed navigation and motion control system of underwater multiple robots is presented in Figure-6.

A servo motor of individual arm (of horizontally or vertically mounted thrusters) consists of a local control device based on a single-chip microcomputer, effector (EF) - DC motor, and the process interface unit (PIU) to coordinate the controlling unit and the motor, as well as directly the control object (the i-th arm) and feedback sensor (D).

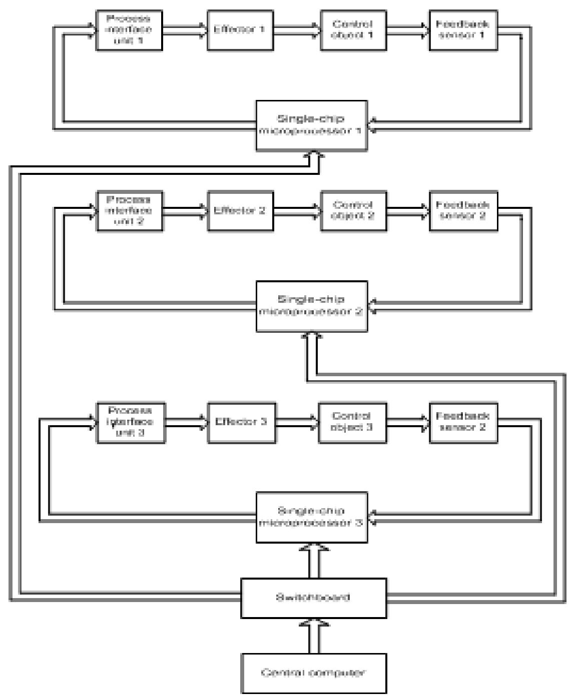

Figure-5. Structural diagram of the developed navigation system.

Single-chip microprocessor servo mechanisms are connected with a central computer via the RS-485 interface through the switchboard.

3.3. Development of operation algorithm of the designed navigation and motion control system

The developed navigation and motion control system can operate in two main modes:

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a. computing mode;

b. basic operation mode.

In a computing mode the system conducts calculation of control parameters, namely the rotor rate of rotation and the number of thrusters. The source data needed for the calculations are input into the central computer via the keyboard. The algorithm of control system functioning by the central computer in a computing mode is shown in Figure-6.

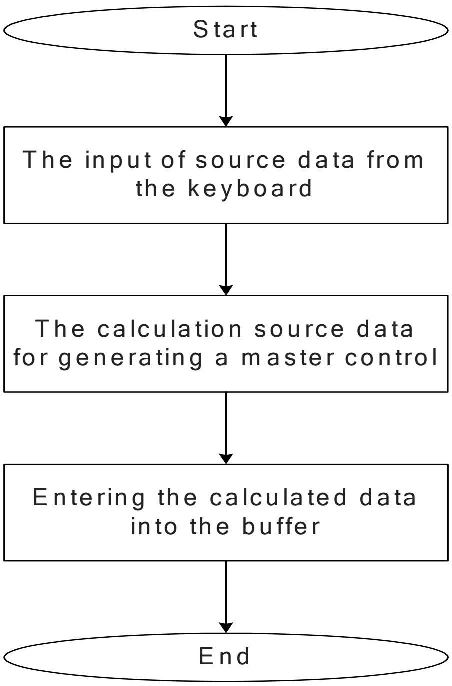

Figure-6. The algorithm of navigation and motion control system functioning in a computing mode.

In the basic mode of operation the local control devices, first, read the data from the serial port of a central computer, and secondly, generate master controls. This mode is responsible for controlling the rotation of the motor rotor and its speed reversal. The direction of rotation is indicated in the control word, transmitted together with the pulses duration and their number through the interface channel RS-485. Graph-scheme of the functioning algorithm of the developed navigation and motion control system of the underwater robotics, operating in a basic mode, is presented in Figure-7.

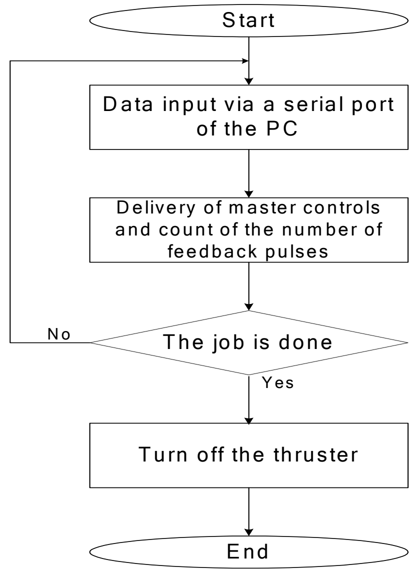

Figure-7. The functioning algorithm of navigation and motion control system in a basic mode of operation.

3.4. Development of an electrical circuit of the navigation and motion control system

Navigation and motion control system of the underwater multiple robots is designed on the basis of the MCS-51 family microcontroller of 8XC51FX type. To run microcontroller it is necessary to start the internal generator. Generator startup is carried out from an external quartz resonator with a frequency of 12 MHz, which is connected to capacitors C1 and C2. At power up, it is necessary to provide a reset pulse on the RESET leg. It should be kept during about 10 μs. This is done by incorporating the differentiating RC-chain into the supply circuit. The values of resistor and capacitor are 1 kOhm and 10 μf, respectively. The DD3 receiver-transmitter is designed on a MAX481 chip of MAXIM company. This is economy chip (consuming about 5 μa) and having high data transmission/reception rate.

We take K555LN1microcircuit as the DD2 inverter for feedback sensor.

The process interface unit is a switchboard that converts the input control impulse into control current flowing through the armature coil. The switchboard must provide the possibility of motor reversing, i.e. the current passage in two directions.

Diodes VD2 and VD3 are used in the circuit to enable the current to lock through them when the transistor is closed, rather than through the motor winding.

We use KT809A transistors in the switchboard as key elements of VT4 and VT5. These transistors are capable of switching a current of 1A and are suitable for this purpose in terms of their power and frequency characteristics.

The diagram of the whole power unit for switching the motor winding in one direction is shown in Figure-8.

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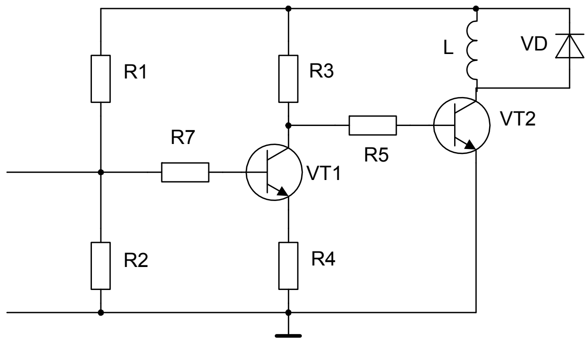

Figure-8. Schematic circuit diagram of the power unit.

Resistor R_5 is placed in the base circuit to protect transistor against sudden surge of current. It is recommended to choose R_5=100 Ohm. Another resistor R_7=1 kOhm is used for the same purpose [10].

Schematic diagram of the developed navigation and motion control system of the underwater multiple robots is presented in Figure-9.

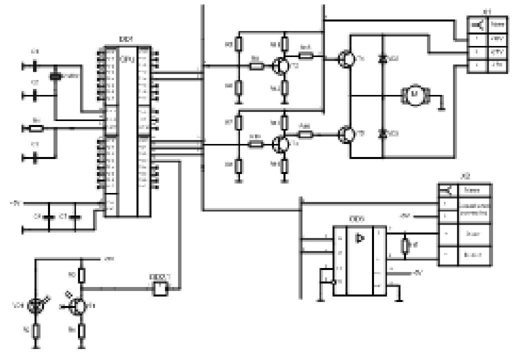

Figure-9. Schematic circuit diagram of the developed system.

3.5. The choice of the actuating motor

For designed motion control system of underwater vehicle we use RPM series motor. The motors of this series have independent excitation from permanent magnets and slot anchor. In this regard, the electromagnetic constant for a given series is of the order of 0.03 second. The most suitable motor is DMP-25-N1. The main parameters of this motor are given in Table-2 below [10].

Table-2. The main DMP-25-N1 motor parameters

	P_{nom}	η_{nom}	M_{nom}	M_p	I_{nom}	I_p	Efficiency	
B	W	rpm	MN m	MN m	A	A	%	h
12	2.77	6000	4.41	9.8	0.85	3.5	27	3000

3.6. Calculation of the developed system reliability

The probability of failure-free operation for the non-redundant system is:

$$P(tp)=\exp(-\Lambda^1 tp)=\exp(2.215*10^{-5}*2.7*10^3)=1.062,$$

where Λ^1 - is the failure rate of the units, calculated by the formula

$$\Lambda^1 = \sum_{i=1}^{9} \Lambda_i$$

Let tp=2700 h

Calculated mean time between failures of the developed navigation and motion control system of the underwater multiple robots is:

$$T = \frac{1}{\Lambda^1} = 4.52 \cdot 10^4 h$$

3.7. Feasibility study of the developed navigation and motion control system for the underwater multiple robots

Let conduct a feasibility study of microcontroller based navigation and motion control system of the underwater multiple robots. We choose ROVFURG-II as the counterpart system.

Table-3 shows the comparative characteristics of the developed system and the counterpart.

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Table-3. Comparison of the main characteristics of the developed system and its counterpart.

Evaluation criterion	Weight coefficient m_i	Unit measure	Project	Counterpart		
			K_i	K_i	q_i	$q_i \cdot m_i$
Number of thrusters	0.2	items	2	2	1.25	0.25
Power input	0.3	W	300	450	1.5	0.45
Vehicle mass	0.05	kg	2.1	2.4	1.14	0.06
Driver input voltage	0.2	B	27	40	1.48	0.3
Channel data rate	0.15	Kbyte/s	4800	2400	0.5	0.08

Table-4 presents the calculation results of the cost value and the wholesale price of the developed system.

Table-4. The calculation of the cost value and the wholesale price of the developed navigation system.

No.	Cost item	Cost, rubles
1	Materials, purchased parts and components	987.74
2	Base wages	206
3	Supplements to wages and salaries	41.2
4	Deductions from the wage fund	88.0
5	Equipment maintenance and operation costs	10.3
6	Rent and utilities costs	22.5
7	Energy costs	85,92
8	Overhead	360.41
9	Production cost	1802.07
10	Non-production expenses	54.06
11	Full production cost	1856
12	Projected profit	2791
13	Wholesale price	4647
14	VAT	163

The wholesale price of the counterpart is 11647 rubles.

The annual economic effect from implementation of the developed navigation and motion control system is a total cost savings obtained both in production and operation.

The amount of the annual economic effect is determined by:

$$E_a = \left[\left(Ex_1 \frac{p_1 + E_n}{p_2 + E_n}\alpha - Ex_2\right) + \frac{Oc_1 - Oc_2}{p_2 + E_n}\right] A_2 \qquad (1)$$

where Ex_1 and Ex_2 – are the discounted costs for the baseline and developed options, equal to the wholesale price Ex_1= 11,647 rubles., Ex_2 =4,647 rubles.

$\frac{p_1 + E_n}{p_2 + E_n}$ - is the derating factor reducing service terms to comparable form, p_1 and p_2 - are the values inverse to service life p_1=p_2=0.215. α=1; E_n = 0.285

A_2 – is the annual output of the new product production.

Oc_1 and Oc_2 – are the annual operating costs of user when employing basic and designed products.

Oc_1 - Oc_2 = 69,612 rubles.

A_2=1 item

α – is the derating factor to reduce both design options to the forms comparable in terms of their performance.

Calculate the annual economic effect from implementation of the developed system:

$$E_a = \left(11647 \cdot 1 - 4647 + \frac{69612}{0.5}\right) \cdot 1 = 146224\ rubles$$

The obtained calculations are presented in Table-4 showing performance indicators of the developed system and its counterpart.

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Table-5. Performance indicators of the developed system and its counterpart.

Indicators	Unit measure	Options		Absolute deviation (+,-)
		Basic	Projected	
Economic				
1) Total cost	ruble	4659	1856	-2803
2) Wholesale price	ruble	11647	4647	-7000
3) Operating costs	ruble	157766	88154	-69612
4) Total annual costs C_{ta}	ruble	162,425	90,010	-72415
5) annual economic effect (per 1 vehicle)	ruble		146,224	146,224

The annual economic effect from implementation of the developed navigation and motion control system of the multiple robots will be 146224 rubles.

Using obtained calculation results (Table-4) on total annual costs C_{ta} for the developed system and the annual economic effect we calculate and present the ROI evaluation graph.

Calculate the payback period and construct the ROI evaluation graph (Figure-10).

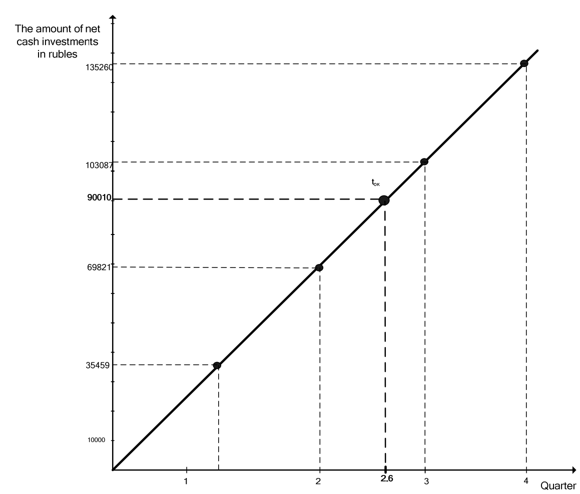

Figure-10. The return on investment chart.

The developed navigation and motion control system of the underwater multiple robots can be used in most modern underwater robotic systems and autonomous underwater vehicles (AUVs).

4. CONCLUSIONS

The article presents the results of development of microcontroller based navigation and motion control system of the underwater multiple robots, which are circumstantially explored and studied. The authors describe the block diagram and algorithmic structure of the developed navigation and motion control system, present its schematic circuit diagram, as well as carry out feasibility study. The annual economic effect from implementation of the developed navigation and motion control system of the underwater multiple robots amounts to 146224 rubles. The developed system is implemented and used in laboratories of the Southern Federal University, LLC Southern center of engineering and technology transfer and Kropotkin Railway College. The developed system of navigation and motion control can be used efficiently in the most modern underwater robots and autonomous underwater vehicles.

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