UDC 331.461.2(043):669.43.22

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# THE CONCEPT OF BUILDING A ROBOTIC SYSTEM FOR MONITORING THE QUALITY OF ORES IN A NATURAL OCCURRENCE

*This paper presents the development of an air robotic system for monitoring the quality of ores in natural occurrence based on a specialized EDXRF device installed on a UAV equipped with technical vision. The sampling trajectory is selected using a depth camera. Electronic units were made and the designs of the main blocks of the structural diagram of the device were developed. The results are presented on the development and combination of the excitation and detection unit, as one of the main elements of the domestically produced specialized device (SD), which provides a significant expansion of the range of determined elements, an increase in the detection limit and the reliability of ore sampling in natural occurrence. On the basis of the developed main blocks and electronic components, a block diagram and a model of an energy-dispersive X-ray fluorescent device were developed on a modular basis, providing the necessary flexibility in adapting the device to various analytical tasks and unmanned aerial vehicles. Taking into account the developed technical and structural characteristics of the joint venture, a UAV was selected – a PX4 Vision quadrocopter equipped with technical vision with optimal characteristics.*

*Based on the new developments of the structural scheme of the SD and its combination with the PX4 Vision quadrocopter, a model of an air robotic system for monitoring the quality of ores in natural occurrence was created, which will be used at mining enterprises in Kazakhstan.*

***Keywords:*** *ore, natural occurrence, sampling, elemental composition, X-ray fluorescent device, block diagram, robotization, UAV, robotic system*
***DOI:*** *10.17580/em.2023.01.15*

## Introduction

Nowadays a clear understanding has been formed that the level of industrial development of the state should be determined not by their resource capabilities and the size of the production of products with a low level of technological processing, but by the degree of development of science-intensive, technologically advanced industries. One of the key aspects of a new type of innovative development in the field of high technologies is analytical instrumentation, based on the development of high-precision energy-dispersive X-ray fluorescent analytical instruments and their modifications [1, 2], which are widely used to solve various problems [3–6].

Active implementation of energy-dispersive X-ray fluorescent devices (EDXRF) of various modifications (stationary and portable) into production began in the mid-90s of the last century. The most common among them are the developments of foreign companies Bruker, Philips, Spectro Analytical (Germany), Oxford Instruments (Great Britain), Panalytical (Holland), Thermo Niton, Innov-X Systems (USA), etc. [7–9].

Similar devices were developed by Russian scientists: the Institute of Physical and Technical Problems (Dubna), NPO Burevestnik (St. Petersburg), the Institute of X-ray Optics (Moscow) and a number of others, however, they have not received such wide application in practice as foreign ones.

In the enumerated number of well-known developments, one cannot ignore the successes of Kazakh scientists who successfully compete in the world market with the above-mentioned foreign firms. Systematic research in this direction is carried out by specialists of AspapGEO LLP (Almaty), the only developer of domestic basic instruments for analytical express analysis. Today, they have created a wide range of stationary (RLP-21) and portable (RPP-12) devices that are not inferior in technical characteristics, and in some parameters even have some advantages over foreign analogues [10, 11].

The positive results of systematic studies allowed the specialists of AspapGEO LLP to create new EDXRF modifications equipped with high-tech solutions ("know-how"), and having a fundamentally new, powerful software and methodological support. On their basis, high-tech robotic systems for automatic quality control of ores and concentrates – ore control stations (RKS) have been developed that provide continuous quality monitoring on the conveyor belt. Only in the subdivisions of Kazakhmys Corporation LLP – at Zhezkazganskaya, Balkhashskaya, Karagaylinskaya and Nurkazganskaya plant 10 RKS-21 complexes were commercialized [12].

A far from complete list of the listed successes of Kazakh scientists and engineers in the field of creating integrated domestic high-tech systems based on EDXRF formed the basis of a new direction in instrumentation – the development of digitalization of enterprises, which allows solving complex scientific and practical problems at a qualitatively new level [13–15]. The importance of this task is enhanced by the fact that there are no effective ways to safely test the quality of ores in their natural occupation: in hard-to-reach and dangerous places. Although foreign firms advertise the possibility of using their devices to solve this problem, as it is pointed out in [16], it is nothing more than a declaration. Overseas miners, especially in the US, do not test ore in situ, and avoid mining ore underground. They carry out mass sampling with their subsequent analysis in laboratories using the usual technology. This approach takes place where there is a sufficient number of well-equipped laboratories and there are no problems with sampling and transportation of samples.

In Kazakhstan, the same as in Russia, the extraction of ores by underground methods is widespread. Well-equipped laboratories are limited; they are usually located in large cities at a big distances from ore deposits. This makes transporting samples to the laboratory pointless or even impossible. Most mines currently do not have any analytical base at all. Attempts to use foreign instruments for testing ores in natural occurrence are ineffective. All foreign devices were developed with a focus on the analysis and sorting of alloys, i.e. to the analysis of homogeneous objects with a relatively flat surface [16]. From a technical point of view, their main disadvantages are the small area of illumination of the analyzed sample and not optimal, given the characteristics of the object of analysis, configuration. An example of this is the testing of devices from ThermoNiton and Innov-X Systems at mining and metallurgical enterprises in Kazakhstan, which have shown their unsuitability for work in our harsh technological and climatic conditions. These shortcomings, taken together, necessitate the development of high-tech, safe methods for testing ores in situ, directly at deposits, in natural occurrence, taking into account the specifics of domestic mining enterprises.

One of the elements of the digital modernization of the mining and metallurgical complex (MMC) is robotization and the introduction of intelligent systems. Currently, unmanned aerial vehicles (UAVs) are widely used in the industry to perform various production tasks: mine surveying, terrain mapping, waste monitoring, etc. [17, 18].

The development of robotics is a global trend and an indicator of the level of scientific and technological development of industrialized countries. In the world, the growth rate of the industrial robotics market outstrips the growth of world GDP: over the past ten years, the average annual growth in sales of industrial robots has amounted to more than 12%. The service robotics market is growing faster, as evidenced by a sharp 25% increase in sales of professional service robots in 2017. The IFR robotization density indicator (the number of robots per 10 thousand people) employed in industry in South Korea is 631, Singapore – 488, Germany – 309, Japan – 303, USA – 189, in Russia – 2. In the medium term, it should expect a smooth transition of the work of service companies to unmanned technologies for exploration, monitoring, mining and processing of ore. Unfortunately, according to this indicator, Kazakhstan is not even among the analyzed countries.

The creation of innovative aerial robots for monitoring ores in natural occurrence has a fundamental importance for the MMC of Kazakhstan and can be counted as an urgent task. Along with ensuring the safety of working personnel when working in dangerous hard-to-reach areas, the development of this area will have a direct impact on the widespread use of digital technology, intelligent robotic systems, the development of new research methods, the development of innovative robot design tools, as well as the training of highly qualified scientific and engineering personnel.

This paper presents the development of an air robotic system for monitoring the quality of ores in natural occurrence based on a specialized EDXRF device installed on a UAV equipped with technical vision.

## Research methods

To solve this problem, a wide range of research methods was used in the work. The role of the UAV is performed by the PX4 Vision quadrocopter, which is a multi-link electromechanical system consisting of a platform, four fast-rotating hingeless rotors with blades with controlled electric drives [19].

The design, simulation, and systems analysis process for all UAVs is essentially very similar, and is largely based on methodologies originally developed in the aerospace community for full-scale rotorcraft design and evaluation [20]. Mathematical modeling of the kinematics, dynamics and intelligent system of the selected UAV was carried out taking into account non-linear geometric, dynamic and elastic characteristics. Based on the analysis of specific characteristics, the flight dynamics of the entire robotic platform was evaluated. SLAM technology was used to develop a system for planning and working out movement with elements of semi-automatic control, which allows the robot to build a map of the environment while simultaneously using it to calculate its location [21].

The development of applied programs for numerical calculation was carried out on the basis of the analytical environment of Maple, Matlab and its modules.

APM Winmachine, Autodesk Inventor computer systems and MSC Nastran and Adams software systems were used to conduct a comparative analysis and interpretation of the results of analytical, experimental and numerical studies, develop an intelligent control system and methods for their adjustment, as well as methods for experimental and design studies of an experimental sample of an air robot.

## Results and discussion

An important task in creating a robotic system for monitoring the quality of ores in natural occurrence is the selection and development of the EDXRF and UAV design, which should be combined into a common complex and work as a single organism.

*Choice and justification of the block diagram and construction of EDXRF.*

Given the wide range of tasks that can be solved by robotic systems using unmanned aerial vehicles and EDXRF, it is advisable to develop them on a modular basis. This will provide the necessary flexibility in adapting the instrument to different analytical tasks and unmanned aerial vehicles. The efficiency of using the modular principle is significantly increased due to a change in the approach to ensuring radiation safety in the development of such devices.

Taking into account the features of the above systems, when developing a specialized EDXRF (SD), special attention was paid to the following fundamental points:

- ensuring optimal measurement modes;
- weight and size characteristics;
- energy consumption;
- peculiarities of ensuring radiation safety;
- features of emergency prevention;
- managing and analytical programs;
- wide interface possibilities.

The block diagram of the SP is shown in **Fig. 1**.

As a source of primary X-ray radiation, the possibilities of using various emitters based on small-sized metal-ceramic X-ray tubes of the penetrating type, both in the form of monoblocks and cable [22], were studied. The results of preliminary studies have shown the expediency of using at this stage an X-ray emitter of the MAGNUM brand manufactured by MOXTEK [23] with the following main parameters: high voltage – up to 40 kV; tube current – up to 0.1 mA; maximum power – 4 watts. Emitter weight – 360 g.

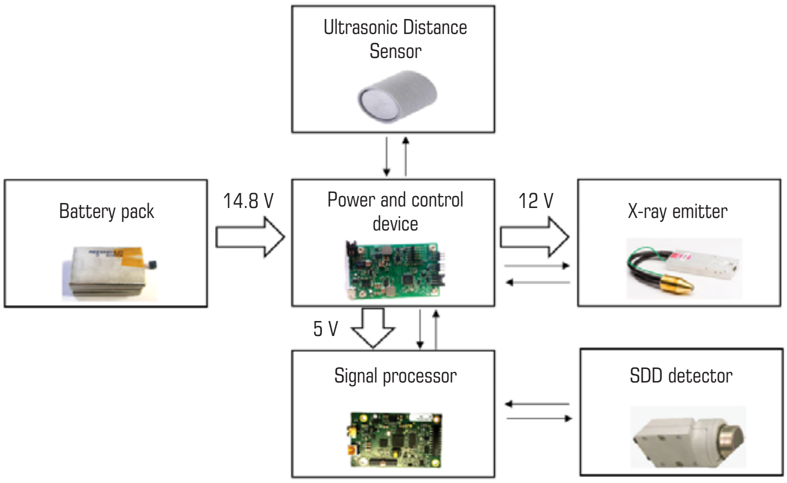

**Fig. 1. The block diagram of a specialized EDXRF (SD)**

Amptek's compact AXR FAST SDD detector is used as an X-ray detector, which has high performance at a detector operating temperature of 270 K, which significantly reduces power consumption. The selected detector has proven itself well in the operation of RPP-12 field devices in various climatic conditions [10]. The mass of the detector, including the weight of the PA-230 preamplifier, is 25 g.

The single-board DP5-X device was chosen as the spectrometric system, combining a digital signal processor and all the necessary power to work with the AXR FAST SDD detector. This device has excellent design dimensions (48x64 mm), low power consumption, high spectrometric performance and wide interface capabilities.

The developed device for power supply and control of the device implements the main functions necessary for testing in natural occurrence and takes into account the features of the operation of the system being created:

- supplies power to all units of the device;
- monitors the state of the battery and provides the possibility of its "hot" replacement;
- controls the spectrometric system and parameters of the detector, X-ray emitter and monitors their status;
- monitors the state of the environment (pressure, temperature, air humidity);
- ensures correct functioning of radiation protection elements;
- contributes to the warning about the possibility of emergencies;
- provides interaction with the basic control and information processing device.

In the developed robotic system, the traditional approach to ensuring radiation safety has been fundamentally changed. When operating a robotic system, the process is controlled remotely – at a considerable distance from the testing site, which minimizes the requirements for ensuring radiation protection near the device. The requirements for ensuring radiation safety in the event of emergency and emergency situations come to the fore. Along with software shutdown of the X-ray emitter based on the results of the analysis of the possible occurrence of radiation hazard, the control device provides hardware shutdown of the X-ray emitter by control commands from inertial measuring devices (IMUs) that respond to emergency situations.

A three-axis accelerometer (H3LIS331DL) is installed on the control board, to which an ultrasonic distance sensor MB7060-700 is connected. It is possible to connect additional IMUs to provide hardware shutdown of the X-ray emitter, which are programmed via the I2C interface.

The power supply and control device is located on the DP5-X board and is interfaced with it (**Fig. 2**). The total weight of the power supply and control unit with the DP5-X board is 33 g.

The battery pack consists of 4 Li-ion batteries with a capacity of 1.8 Ah. With an average power consumption of all electronic components of the device ~ 10 W, the battery pack ensures continuous operation of the device for more than 2 hours.

Battery pack dimensions: 44x62x20 mm, weight – 120 g. The total weight of all SD units without mounting elements is 570 g.

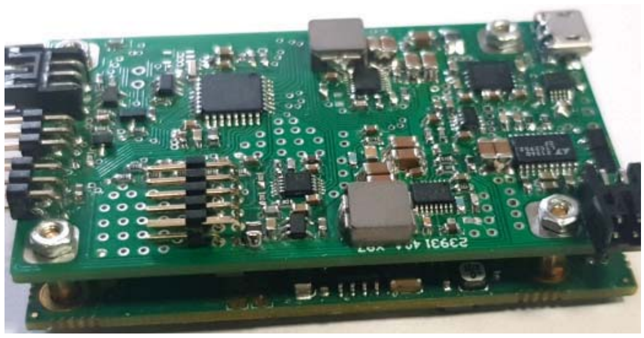
**Fig. 2. General view of the DP5-X board with a power supply and control device placed on it**

The control and analytical software is implemented on the basis of the Analyzer and SbsWin software packages used in the EDXRF line (RPP-12; RLP-21; RKS-21) developed by AspapGEO LLP.

The high-resolution structured light camera [24] was chosen as the depth camera, taking into account the proposed initial sampling objects. Required basic characteristics of the depth camera: resolution of at least 1280x960; working distance from 0.3 to 4 m; error no more than ± 0.5%; performance at least 54 FPS. Potentially, such a chamber makes it possible to use SLAM technology, to automatically select the optimal sampling trajectory.

The developed design and technological parameters of the main units of the SD, equipped with a depth camera, allow us to proceed to the stage of choosing the optimal UAV, which forms the basis of the robotic system.

*Selection and justification of the design and technical characteristics of the UAV.*

The main requirements for the UAV are specified taking into account the design and technical characteristics of the developed SD:

- payload not less than 700 g;
- optimal dimensions ($d \leq 550$ mm; $h \leq 200$ mm);
- minimum drift when hovering;

• availability of a free USB port at the flight computer to connect the SD;
• the presence of a manual control panel;
• availability of GPS;
• availability of Wi-Fi;
• power supply 14.8 V;
• the presence of a depth camera of the Structured Light type;
• open source software.

Based on the above requirements, the PX4 Vision quadrocopter equipped with the Structure Core camera was chosen as the UAV.

A general view of the PX4 Vision quadrocopteris shown in **Fig. 3.**

The total weight of the PX4 Vision quadrocopter with depth camera is 877 g (without battery). The quadrocopter consists of the following main components:

• frame made of 5 mm 3k carbon fiber;
• propellers T6054;
• engines: T-MOTOR F60 PRO KV1750;
• Pixhawk 4 flight controller with IMU (accelerometer-gyroscope ICM-20689, magnetometer IST8310, barometer MS5611, accelerometer-gyroscope BMI055);
• Up Core flight computer with a free USB port and Wi-Fi;
• computer power controller;
• control system power supply controller;
• four speed controllers;
• M8N GPS module;
• battery pack.

**Fig. 4** shows a block diagram of a PX4 Vision quadrocopter with a depth camera.

Key Specifications of PX4 Vision quadrocopter and Structure Core depth camera:

• loading capacity ~ 800 g.;
• dimensions: d = 432 mm; h = 165 mm;
• hovering drift: ±0.15 m in the vertical plane and ±0.25 m in the horizontal plane;
• depth camera resolution 1280x960; working distance from 0.3 to 5 m; error ± 0.17%; speed 60 FPS.

To control the quadrocopter, additionally a Jumper T18 control panel and an FrSky R-XSR micro receiver for it were purchased.

The developed SDwas installed on the PX4 Vision quadrocopter, taking into account the optimization of the measurement geometry, reliability, operating and maintenance conditions, and balancing. The total weight of the SD with all the elements on the quadrocopter, was 690 g.

A general view of the developed robotic system for monitoring the quality of ores in natural occurrence is shown in **Fig. 5**.

Thus, the concept of constructing a robotic system for monitoring the quality of ores in natural occurrence is proposed, in which an X-ray fluorescent energy-dispersive device is used as a measuring device, the movement of which is performed by an unmanned aerial vehicle, and the sampling trajectory is selected using a depth camera.

Preliminary tests of the developed airborne robotic system showed the validity of the chosen concept of its construction, the correct functioning of all devices and the effectiveness of the software products used. In our opinion, it will be possible to talk about the results of testing the robotic system as a whole after the completion of system studies that are currently being carried out at the mining enterprises of Kazakhmys Corporation LLP.

### Conclusions

1. Based on the analysis of the existing scientific and technical background on the use of UAVs for solving various problems of the metallurgical and metalworking industries, the fundamental possibility of creating a multifunctional robotic system for monitoring the quality of ores based on a PX4 Vision quadrocopter equipped with technical vision is shown.

2. The possibilities of using a new modification of a specialized X-ray fluorescent energy-dispersive device (SD) of a modular type, oriented to operation in the proposed robotic system, are shown. A block diagram of the device has been developed and optimal design and technical characteristics have been selected.

3. Methods for designing an intelligent system (IS) based on SLAM technology are described. Taking into account the technical and structural characteristics of the joint venture, an UAV was selected - a PX4 Vision quadrocopter equipped with a depth camera with the necessary technical characteristics.

**Fig. 3. Quadrocopter PX4 Vision**

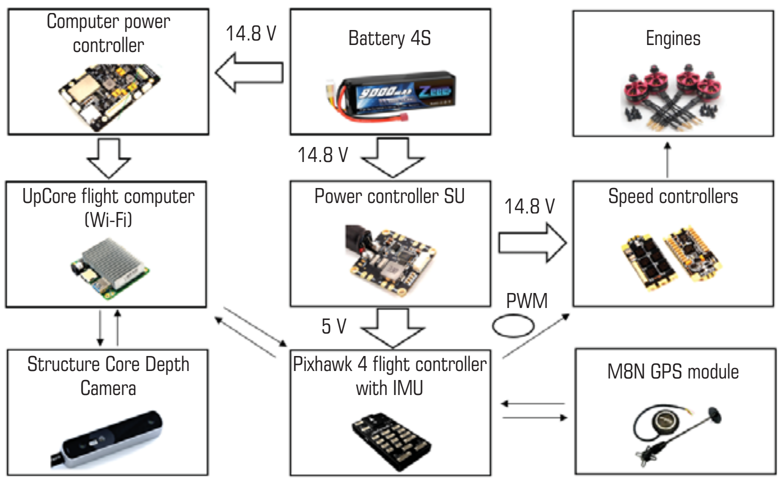


**Fig. 4. PX4 Vision quadcopter block diagram**


**Fig. 5. Robotic system for monitoring the quality of ores in natural occurrence:**

*1* – SDD detector; *2* – X-ray emitter; *3* – distance sensor; *4* – electronics block; *5* – battery pack

4. Based on the developed new solutions, a model of a multifunctional robotic system for monitoring the quality of ores in natural occurrence was created, which will be used in the mines of Kazakhmys Corporation LLP.

**Acknowledgement**

*Research is being carried out within the framework of grant funding from the Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan for 2021-2023 in the priority area "Information, communication and space technologies" of the project AP09260493 "Development of a hardware and software complex of an air robotic system for monitoring the quality of ores in natural occurrence".*

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