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# Information model of remote sensing of soil

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## ABSTRACT

This paper presents a comprehensive information model and open architecture for unmanned aerial vehicle (UAV)-based remote sensing of soil. The development of remote sensing technologies using unmanned aerial vehicles (UAVs) and sensors of various measurement methods makes it possible to contactless detect various anomalies. The reliability of information after its processing is achieved by a combination of measurement methods, the correct choice of contactless measurement tools, and the use of machine learning methods for data processing and training on known anomalies. The modular UAV platform supports adaptive sensor integration and real-time data fusion for precision agriculture, environmental monitoring, and post-conflict applications. The information model defines the structure and flow of data between UAV sensors, onboard processors, and the ground control station, incorporating a digital twin for dynamic environmental modeling. A minimum set of necessary tools has been selected, based on the measurements and processing of which there will be enough information to identify anomalies in the soil with a high degree of reliability. The scope of application of the obtained results is quite extensive: from precision farming, including monitoring crop diseases and chemical non-contact soil analysis, to identifying foreign inclusions and anomalies in areas where military actions took place.

**Keywords:** Unmanned aerial vehicle; information model; remote sensing; soil monitoring; digital twin; multisensor integration; geophysical survey; multimodal data fusion; UAV aerial image; cyberphysical systems; geographic information system

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## INTRODUCTION

Remote sensing (RSs) technologies have become an essential tool for monitoring and understanding environmental systems and processes. They offer the potential to transform ecological research through digital transformation, combining data, models, and domain knowledge while maintaining continuous coordination with real-world conditions. Unmanned aerial vehicles (UAVs) equipped with multisensor payloads expand these capabilities by enabling detailed spatial and temporal data acquisition. Miniaturization of sensors and improvement of their characteristics have led to the possibility of using UAVs for various tasks in agriculture, from environmental monitoring to searching for anomalies in the soil. The main advantages of UAV-based systems are the speed of inspection, independence from terrain, simplicity of design and high mobility.

However, most commercial UAV systems have closed architectures, limiting integration with specialized scientific sensors. This study proposes an open, modular UAV architecture with an information model that supports heterogeneous data collection, adaptive processing, and integration into a dynamic digital twin of the soil environment.

Key features of the proposed RSs-based approach include:

– integration of heterogeneous data: combining visual, spectral, temperature, radar, and geophysical information to build a comprehensive multidimensional representation of soil state;

– indirect measurements: assessing soil parameters via interpretation of image and sensor signals without physical contact;

– flexible connection of specialized sensors and models: enabling broadband radar, magnetometers, and multispectral cameras to operate jointly for deep and surface soil analysis;

– modular architecture: allowing expansion with new sensors, mathematical models, and adaptive algorithms;

– scalability: the digital twin adapts to environmental and contextual changes, supporting diverse applications such as erosion assessment, fertility mapping, and anomaly detection.

Object and subject of research. The object of research in this paper is unmanned aerial vehicles for environmental monitoring. The subject of research is the basic architecture of the drone and the minimum set of equipment for searching for anomalies in the soil.

## RELATED WORKS

Despite the fact that drone production is put on an industrial basis, they are usually focused on one application and their design does not imply their modification for another area of use. Therefore, for a new area – searching for anomalies in the soil, there is no ready-made solution and it is necessary to develop the architecture of the drone and ground station itself. At the same time, it is advisable to use ready-made solutions that have proven themselves well in serially produced drones as much as possible. This applies to equipment, communication protocols, and software. The most specific part of the equipment of drones for searching for anomalies in the soil is sensors.

The sensors used and proposed for use can be divided into several categories. One category includes sensors in the optical and near-optical range, and sensors based on electromagnetic resonance and magnetic field recording [1].

Multispectral cameras are designed to collect information in spectrally and radiometrically characterized ranges. The main differences between them are in the method by which they achieve spatial discrimination and the method by which they achieve spectral discrimination. One example of the use of such cameras is the detection and geolocation of peat fires using thermal imaging infrared cameras on drones [2]. Peat fires are difficult to extinguish once they have started and can continue to burn for months. Therefore, early detection is desirable. However, peat fields are usually located in areas with limited accessibility with frequent periods of fog and haze. Using drones equipped with thermal infrared cameras appears to be one of the most effective methods for rapid survey of large areas to detect thermal radiation from fires above and below the peat surface. In [2], a pipeline is proposed for thermal image segmentation using a pre-trained ResNet-50 model as an encoder for feature extraction. It achieved an accuracy of 94.2% on the test data.

In [3], multispectral cameras were used together with neural networks to collect data and manage waste. The paper proposes to integrate three components into a single closed-loop system: lightweight adaptive detection with multi-scale feature extraction, spatio-temporal motion modeling through Kalman filter-based trajectory prediction, autonomous decision making through comprehensive assessment of detection reliability, appearance similarity, and motion consistency. This made it possible to implement real-time operation with dynamic coordination of feature detection and tracking.

In [4], a highly effective rice height monitoring system is proposed using a multispectral camera mounted on a drone. The images of rice in flooded fields were analyzed using several different models to ensure the best results. Two sets of images obtained by two UAVs equipped with RGB cameras of the same resolution and GPS receivers of different accuracy were used for photogrammetry. For image processing, two methods were proposed to create crop height models, one based on a digital surface point cloud and a digital elevation point cloud. The other was based on a digital surface point cloud and a bathymetric sensor. A set of images obtained by another UAV equipped with a multispectral camera was used for multispectral photogrammetry. Among other results, it was noted that the more uniform the distribution of vegetation on the water surface, the better the performance.

The examples given demonstrate the high functional efficiency of using multispectral cameras in a wide range of applications due to the high information content of the resulting images. The advantages of such cameras, allowing their use on drones, are their low weight, the ability to georeference data using a GPS sensor, and various automatic operating modes [5]. The images from the camera are processed using AI and only then compared with information from other sensors. The main purpose of the spectral camera is to obtain initial information with subsequent processing, the results of which will be used to build a further strategy for surveying the territory. The resulting images allow not only to analyze the state of vegetation, but also to identify indirect signs of manmade anomalies, for example, differences in the structure of the soil after explosions or areas with metal inclusions. Particular attention is paid to synchronizing images with data from other sensors (metal detector and magnetometer), so that they can later be compared in a single coordinate system.

Magnetic sensors, or magnetometers, are a widely used tool for detecting anomalous magnetic zones [6], [7]. The basic principle is to change the direction or value of the magnetic field of the area under study compared to the reference value for the same area. The same sensor, located at a certain vertical distance from the main one, serves as a reference. This distance, usually 1 ... 1.5 meters, neutralizes magnetic disturbances that the main sensor registers. The difference in readings is used to analyze the disturbance of the magnetic field. The main area of application of such magnetometers is the search for fairly large metallic, ferromagnetic materials at great depths. The main disadvantage of such devices is their strong dependence on the direction of the Earth's magnetic fields, as well as their position relative to the surface. Ideally, the plane of the sensors should be perpendicular to the surface, which in practice is a rather non-trivial task. Various electrical engineering solutions are used to compensate for these shortcomings, which leads to higher prices for devices and worse performance. Another very significant disadvantage is the limited area of study when using such a sensor on a UAV. However, the deployment of magnetometry using unmanned aerial vehicles provided in [6], [8] a high-resolution, non-invasive approach to collecting magnetic field data in complex and potentially hazardous terrain (heavily contaminated soils, regions with volcanic activity), which contributed to the rapid and accurate mapping of the study area. In [6], drones with a magnetometer were used for mineral exploration in the mining industry. In the work, a three-dimensional magnetic susceptibility model was developed that provides a detailed representation of magnetic susceptibility variations in a repository. This model allowed for a comprehensive visualization of high susceptibility zones associated with ferromagnetic materials and low susceptibility zones correlating with diamagnetic materials such as lead, arsenic, cadmium, and zinc. The combined techniques highlight the effectiveness of drone-based airborne magnetometry in geophysical surveys, highlighting its potential for mineral exploration and waste management. In [8], an innovative approach to improving the accuracy of metal-sensitive magnetometers is proposed based on a three-step strategy. It includes the use of lightweight 3D-printed drone bodies, extended rods, and electrical shielding. The main objective of the system is to improve the accuracy of readings, especially in volcanic regions, thereby increasing safety and efficiency. The study highlights the need to integrate magnetometer data with other geophysical methods to understand metal deposits. This technology has potential applications in environmental protection, infrastructure inspection, and archaeology. The proposed approach involves the integration of drones equipped with magnetometers to improve the safety, efficiency, and accuracy of surveys inside volcanic regions. Various operating modes allow for fairly accurate determination of various magnetic anomalies in the soil.

Conventionally, metal detectors can be divided into two categories, each of which has its own advantages and disadvantages.

The first type of metal detectors is pulsed. The principle is based on irradiating the anomaly with a high-voltage electromagnetic pulse, which causes the excitation of a variable magnetic flux in metal-containing substances. This excitation is registered by the receiving coil, and the shape and duration of the response are used to analyze the surface being examined. The advantages of such a scheme include the relative simplicity of the design, static operation mode (the signal strength is proportional to the mass of the anomaly and does not depend on the speed of the receiving coil). The electromagnetic field generated by such a metal detector is a truncated cone, decreasing in diameter as it moves away from the coil. The disadvantage is the impossibility of discrimination of the type of metal (non-ferrous or ferrous). The sensitivity of such devices is lower than that of other types of metal detectors.

The second type of metal detector is resonant, in various variations, but operating on a similar principle. Two coils that are tuned to resonance, and any ferromagnetic object that gets into the coil zone causes a mismatch, which is registered. Discrimination (non-ferrous or ferrous metal) occurs according to the degree of frequency deviation (up or down), and the distance and/or size of the object according to the amplitude. The field generated by such a system resembles the plane of a shovel. A mandatory condition is the movement of the coil in such a way that the plane of the electromagnetic field is perpendicular to the direction of movement. This is the main disadvantage of this type of metal detector – the need to move at a certain speed, which is not always achievable when installed on a UAV.

The field of the first type of metal detector decreases with increasing depth and “dead” zones appears at the edges of the coil. The operating mode is static, i.e. the response will be directly proportional to the distance to the object and does not depend on the speed of the coil passing over this object. At the same time, the detection area does not depend on the orientation of the coil. In the second type of metal detector, the effect of reducing the area of the electromagnetic field is not so noticeable (more uniform distribution of the field over the area), but the orientation of the coil comes to the fore, as well as the need for a certain speed of movement of the coil (work in dynamic mode).


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Ground penetrating radars are a separate category of equipment for searching for anomalies [9]. The basic operating principle is a short powerful radio pulse directed towards the area under study. Any reflection of the radio wave that occurs at the site of a change in soil density is recorded by the receiver. Ground penetrating radars are of interest as a promising area. The use of ground penetrating radars allows expanding the range of studies, especially for searching for non-metallic objects or voids. The main problem of integrating such devices with small UAVs (with a carrying capacity of up to 3-4 kg) is associated with high energy consumption and requirements for antenna systems, which are difficult to implement with the carrying capacity of UAVs. The complexity of manufacturing a ground penetrating radar, especially in terms of manufacturing special directional antennas, and the high cost of components also play a certain role.

A separate area of searching and analyzing anomalies in the soil are sensors based on laser vibrometry. They use the Doppler Effect, recording changes in the passage of acoustic signals through the soil using a special laser. Although the method is considered very accurate in laboratory conditions, when transferred to a drone platform, it encounters the problem of vibration of the drone itself, which dramatically reduces the reliability of the readings. In the future, the use of vibrometry is possible in the development of a stabilized suspension with a very high degree of stabilization (thousandths of a degree along each axis), but in current conditions its use is limited.

The conducted review of sensors showed the presence of various technologies for detecting anomalies in the soil. Joint processing of signals received by various sensors seems promising for improving the quality and sensitivity of detecting anomalies in the soil. Achieving such collaborative processing requires developing a drone architecture that allows for a variety of sensors to be uniformly included for further processing.

## SYSTEM ARCHITECTURE

The UAV platform is based on a hexacopter configuration designed to carry up to 3 kg of sensors and instrumentation. It integrates a multi-zone metal detector, tri-channel magnetometer, multispectral camera, and dual lidar modules for altitude tracking and obstacle avoidance. The onboard STM32H743 microcontroller performs real-time data acquisition and preliminary signal processing. Communication with the ground control station (GCS) is managed through RFD900x and RTL8812 modems, providing reliable telemetry and high-speed data transmission. The system achieves stable flight for up to 25 minutes per mission, ensuring efficient area coverage.

A schematic of the UAV system configuration is illustrated in Fig. 1, Fig. 2, Fig. 3, Fig. 4 and Fig. 5.

To support high-resolution detection, custom sensors were developed. The multi-zone metal detector uses pulse excitation and differential channel analysis to identify metallic inclusions. The tri-channel magnetometer employs tunnel magnetoresistance (TMR) sensors with high sensitivity and low noise, capable of detecting weak magnetic fields. Both systems are synchronized via onboard microcontrollers, which filter noise and transfer data to the UAV controller. The ground station includes telemetry and control modules, operating Mission Planner software for mission setup, data collection, and visualization.Development of Multi-Zone Sensors and Ground Station

Taking into account the disadvantages of metal detectors described above, a multi-channel pulsetype metal detector should have the following characteristics:

– automatic ground balance,
– sensitivity to metal (10 UAH coin) – 34 cm,
– horizontal resolution (discrimination) – 35 cm, - sensor width – 105 cm, - number of zones – 3.

This metal detector allows the UAV to survey a 1-meter-wide area in one pass, which significantly increases the processing speed compared to a classic metal detector. To reduce false alarms, a system for compensating interference from brushless hexacopter motors has been implemented.

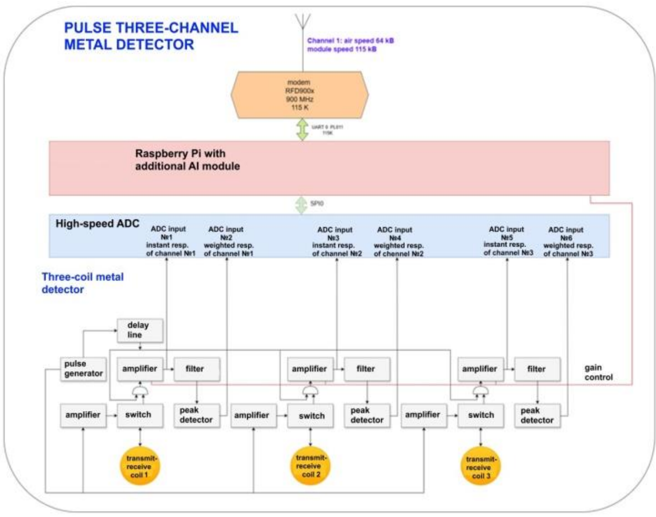


*Fig 1.* **Block diagram of a multi-zone metal detector**
***Source*: compiled by the authors**

The block diagram of a multi-zone metal detector with a part of the information processing and data transmission device is shown in Fig. 1. An additional advantage is the ability to work in different sensitivity modes, which can be adjusted both manually and automatically. This allows for a more thorough analysis of the local zone.

Using a multi-zone structure, namely three independent measurement channels in a single block, allows for a more accurate determination of the anomaly boundaries.

An example of a study of a territory using a three-zone sensor is shown in Fig. 2. It shows that a three-zone metal detector is connected to the hexacopter on the suspension, providing a survey zone width of 1 meter.

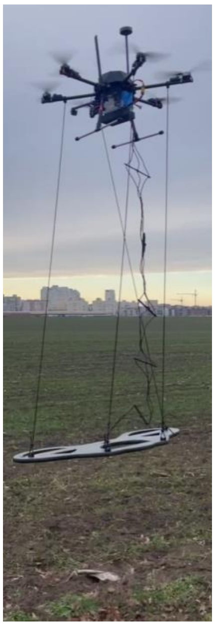

*Fig. 2*. **Hexacopter with a three-zone sensor on the gimbal**
***Source*: compiled by the authors**

Development of a multichannel magnetometer. Just like with a metal detector, the above-mentioned disadvantages are also inherent in a magnetometer. The most significant disadvantage is a small, about 30 cm in diameter, inspection area. For use on a UAV, the latter must perform a flight trajectory with a step of 30 cm, which will lead to a much smaller inspection area per flight. Therefore, a multi-zone magnetometer must also have three zones. Promising magnetic field sensors (TMR-sensor [10]) are selected as sensors, which are used for medical purposes to record weak magnetic fields generated by the human body.

The design of the current sensor is based on the tunnel magnetoresistance effect. In order to improve the detection accuracy of the sensor, this design uses a low-noise, high-sensitivity TMR chip; the sensor circuit uses a high-linear interface circuit to eliminate fixed bias; and a magnetic flux concentrator to improve sensitivity and noise immunity.

Experimental results show that the sensor achieves a sensitivity of 29.4 mV/V/mA, a linearity of 0.19 %, and an accuracy of 0.045 % in the range of ±100 mA, supporting current measurement from DC to 10.5 kHz. The proposed sensor has several advantages, including a wide measurement range, high accuracy, high resolution, and non-invasive measurement capability, making it suitable for detecting weak currents in smart grids.

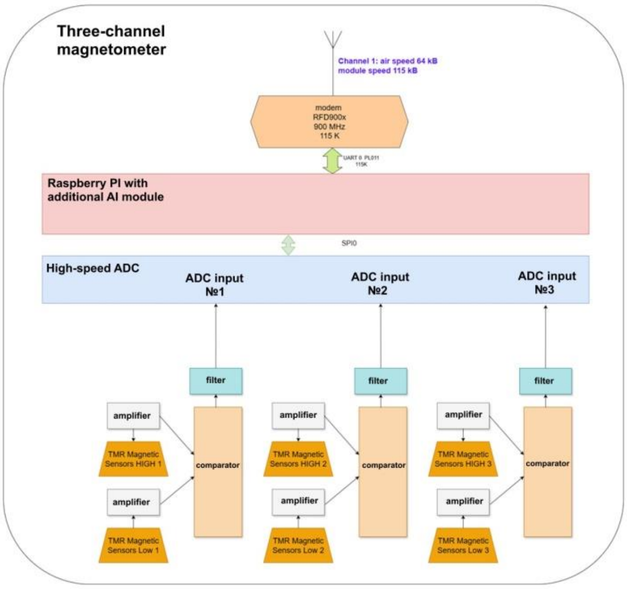


*Fig. 3*. **Structural diagram of a multi-zone magnetometer**
***Source*: compiled by the authors**

The use of TMR-sensors can significantly increase the sensitivity of the system and reduce its energy consumption. The use of three independent channels allows covering a survey strip up to 1 m wide, which makes the system more productive compared to the classic version.

The structural diagram is similar to the diagram of a multi-zone metal detector (Fig. 3).

As it can be seen from Fig. 3, the circuit contains three channels, each of which receives signals from a corresponding pair of TMR sensors. After filtering, these signals are sent to the ADC inputs, converted into digital form and processed in the processor. The processing results are transmitted to the ground station for further processing and integration with signals from other sensors.

*Selecting a UAV carrier*

To solve the tasks set for the developed metal detector, magnetometer and multispectral camera, two options for multicopter UAV carriers were considered: ready-made purchased solutions and custom manufacturing for specific needs.

The main criteria by which the solution was searched were as follows:

1) load capacity – up to 3 kg;

2) communication range – up to 5 km;

3) information transmission channels – at least three;

4) the ability to install various equipment (sensors and data processing devices) and power them from the on-board network;

5) Integration of the UAV control system with the sensor data processing system;

6) the ability to integrate your own software to organize a flight mission;

7) automatic operation of the drone during the mission, bypassing obstacles and maintaining a fixed, remotely set distance from the earth's surface;

8) availability of an RTK system [11], preferably operating without a provider providing NTRIP services (the operating range is assumed to be no more than 2 km, which is sufficient to meet this condition).

The RTK (Real-Time Kinematic) system is a high-precision positioning technology that improves the accuracy of satellite navigation system (GNSS) signals to the centimeter level in real time. It includes a base station with known coordinates, a mobile receiver (rover), and a data transmission channel through which correction signals are sent from the base to the rover, allowing its position to be accurately determined. RTK is used in surveying, construction, precision agriculture, and autonomous navigation to perform work with centimeter accuracy.

The principle of RTK is as follows.

1. The base station contains a fixed receiver installed at a point with known coordinates, receives signals from GNSS satellites (e.g. GPS, GLONASS);

2. The base station compares the received signals with their expected value, calculating accurate corrections for errors due to atmospheric conditions and other factors.

3. These correction data are transmitted to a mobile receiver, called a "rover", via a communication channel (e.g. radio modem, GPRS, Internet).

4. The rover receives the corrections and applies them to its own measurements, which allows it to determine its location with high, centimeter-level accuracy in real time.

NTRIP (Networked Transport of RTCM via Internet Protocol) is a protocol for transmitting corrections from base stations to mobile receivers via the Internet, which allows working in real time (RTK). The protocol is based on HTTP and is standardized by RTCM. A component of the system called an NTRIP caster collects data from base stations and transmits it to client receivers via the Internet.

NTRIP and RTK provide centimeter-level accuracy. However, NTRIP services can be affected by network congestion or signal loss. With RTK base stations that transmit correction signals via UHF radio; this will not be affected by network conditions. In addition, the advantage of an RTK base station is that it can cover a local area without depending on external networks or infrastructure. This makes it a good option for surveying areas that are not equipped with fixed communication channels. NTRIP service depends on network signals. If there is no signal, the signal is poor, or the area is outside the server's coverage area, it will not be able to provide location information. On the other hand, an RTK base station is much more adaptable, allowing users to move it to any desired location.

Stability of the structure to external conditions: the drone must remain stable in winds up to 12 m/s, which is a common value in field tests.

Flight time at full load (with the maximum weight of sensors) should be at least 22-30 minutes, which is the lower limit for missions.

Based on these criteria, the DJI Matrice 350 RTK quadcopter (and similar ones) [12] was considered as an example, as the closest in several parameters, such as points 1, 2 and partially point 8. However, it is not possible to find a UAV that meets the above requirements. Particularly critical points, such as 3-6, are almost impossible to implement in ready-made solutions. In commercial drones, the firmware is usually closed and integration with it is impossible. Some manufacturers provide an API for developers, but the capabilities are very limited. This means that despite the high level of automation and user-friendly interface, the architecture remains closed and access to "lowlevel" parameters is very limited. In reality, this means that it is impossible to configure the drone for demining and soil analysis tasks, which require working with non-standard sensors and additional units. At the same time, the cost of even a remotely similar UAV in terms of parameters is a very significant amount. Even in the case of using the API from the manufacturer, real integration is limited to only individual functions. This mainly concerns telemetry transmission and image processing. But such capabilities are not enough to work with electromagnetic sensors and magnetometers. At the same time, the cost of modifications and maintenance of such drones is very high and is not justified for research purposes. Also, existing commercial solutions have limited scalability and lack a unified approach to data format.

Taking into account all these requirements, it seems most appropriate to assemble your own UAV. A hexacopter-type frame was taken as a basis. The choice of this particular frame was justified by increased fault tolerance; even if one motor fails, the drone will be able to continue flying and complete the mission. The hexacopter design also provides greater stability when flying with heavy equipment and lower vibration values than quadcopter counterparts. Another advantage of this design is the ability to fold the beams and obtain a compact drone for transportation. Orange Cube + with Ardupilot software installed (freely distributed) was used as a flight controller [13]. The main advantage of this flight controller is a thermally stabilized sensor system (IMU), sensor duplication, and a dual-processor system. All this makes this flight controller stable in a wide temperature range and reliable in terms of any failures. The stability of the sensors is especially important during lowaltitude flights using a lidar. The use of the HERE4 [14] positioning system with its own processor and the RM3100 [15] noise-immune compass in conjunction with this controller provides this system with high performance, noise immunity and positioning on the ground even when the RTK system is turned off. HERE4 uses a precision F9P GPS sensor with a maximum horizontal position error of up to 0.9 m (conventional systems have this indicator at the level of 2.5 m). The ArduSimple [16] system was selected as a backup positioning system, which allows using all the advantages of the RTK system at short distances (up to 2-3 km) without an NTRIP subscription.

The main software for this controller is the open ecosystem ArduPilot [16]. The advantage and undoubted benefit of this open software is the ability to fully customize the drone for your tasks, add custom sensors and devices, integrate with an assistant computer, etc.

Independent channels are used as data transmission channels. Each data transmission channel is dedicated to its task, which eliminates mutual influence of information flows. For example, ELRS [17] works exclusively for drone control, since the main advantages of this system are ultra-low delays in transmitting commands to the drone. The BAYCK ELRS 900 MHz Nano Rx TCXO is selected for use in the system. It is an innovative receiver equipped with a TCXO for stable operation at 900 MHz. Temperature-compensated oscillators (TCXO) are quartz oscillators whose frequency drift is compensated by a built-in feedback circuit. The receiver has a T-shaped dipole antenna, which provides a strong signal and a stable connection over long distances. The added JST connector on the board makes it easy to connect without the need for soldering, which simplifies installation. With a high telemetry power of 50 mW and ease of use, this receiver becomes an ideal choice for UAVs.

RFD900x modems [18] (the latest generation of modems with a 32-bit processor) provide a backup communication channel for MAVLink [19] and RTK commands, and high-speed RTL8812 modems [20] are designed for streaming “heavy” data from a multispectral camera. MAVLink is a serial protocol that is most often used to transmit data and commands between vehicles and ground stations. The protocol defines a large set of messages that can be found in the common.xml and ardupilot.xml files. MAVLink messages can be sent over virtually any serial connection and are independent of the technology used (Wi-Fi, 900 MHz radio, etc.). Message delivery is not guaranteed, so ground stations or companion computers must frequently check the vehicle's status to determine whether a command has been executed.

The RFDesign RFD 900x kit allows you to remotely control an unmanned aerial vehicle via the Mavlink protocol and receive flight data at a distance of up to 40 km. The modem contains a new

ARM 32bit processor, supports 16-channel radio control transmission in parallel with telemetry, as well as full hardware support for AES-128 encryption of transmitted information. The frequency range is 902-928 MHz. The power of the radio modems is adjustable up to 1 W. The modems are configured via UART using AT commands, so you can adjust the radio link even in flight. Special attention should be paid to the support of work in MESH networks consisting of one or two base stations and a number of modules installed on drones. The RTL8812AU modem operates at frequencies of 2.4 and 5 GHz, has a power of about 150-200 mW.


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For autonomous operation, where the main factor in following the route is automatic tracking of obstacles and their flight around them, two lidars of different purposes are provided:

– a lidar for tracking the distance to the ground surface, with a resolution of up to 2 cm, operating at a height of 12 m,

– a lidar with a circular scanning diagram to avoid collisions with various terrain elements (bushes, trees, etc.).

The use of two different lidars is also explained by reliability considerations. The downwardfacing lidar provides high accuracy (plus or minus 2 cm, but it also depends greatly on the surface) of maintaining altitude on uneven terrain. And the circular lidar creates a map of the surrounding space, which allows the drone to avoid obstacles (go around obstacles) not only when flying on a mission, but also in manual mode.

Additional advantages of the drone include such features as ease of integration of new sensors, the ability to work with any equipment manufacturers, adaptation to different tasks. Also an important factor is the repairability of the UAV, since most of the equipment does not depend on a specific manufacturer and can easily be replaced with similar equipment. Most of the design is printed on a 3D printer and can easily be printed and modified. The use of 3D printing allows you to create not only lightweight, but also uniquely shaped body elements. Some elements, for example, antenna holders and GPS sensors, are designed specifically for electromagnetic isolation tasks.

Special attention was paid to the centering and weight distribution of the equipment. When designing, the battery location was taken into account so that the center of mass remained as close as possible to the geometric center of the hexacopter frame. These measures reduce vibrations, reduce the load on the motors (less energy to keep the frame in a horizontal position). Additionally, measures were taken to protect the compass and replaceable sensors from the influence of the drone's power unit.

The use of the open ArduPilot platform as the main software makes it possible to individually configure control algorithms and use non-standard sensors (you can add your own libraries and drivers), which is impossible in commercial solutions.

Another important factor is the integration of the flight controller with an assistant computer, which expands the capabilities of the UAV, especially in automatic mode during mission flight. In the developed system, this role is partially performed by Raspberry Pi 5, but the main purpose of the latter is to collect and pre-process data from sensors. A module based on this board and the AI coprocessor board performs data pre-processing tasks, such as filtering noise and compressing images before transmitting to the ground station. This leads to unloading of data transmission channels, as well as increasing the efficiency of transmission. In addition, Raspberry Pi 5 provides flexibility in loading new data processing algorithms for its own sensors. The general structure of the UAV is shown in Fig.4.

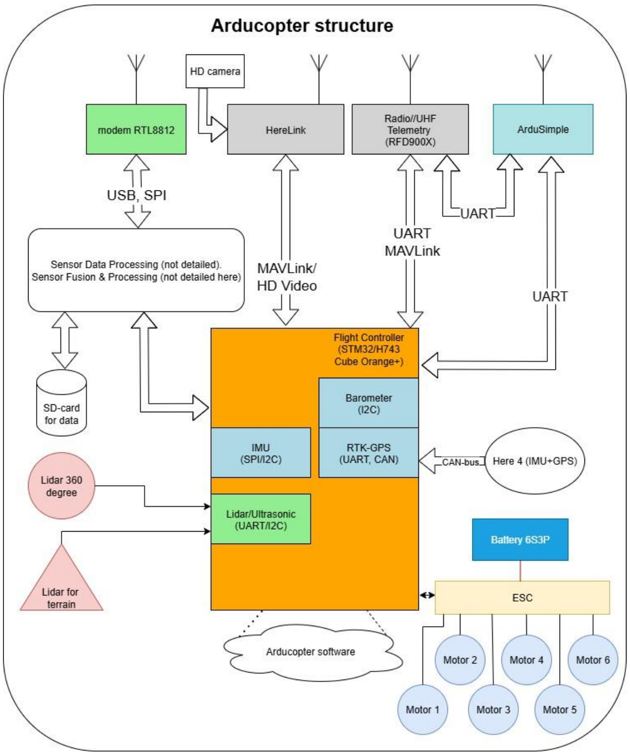


*Fig. 4.* **Structural diagram of a hexacopter**

***Source*: compiled by the authors**

From Fig. 4 it is clear that the central unit of the hexacopter equipment is the STM32H743 microcontroller. It is responsible for the drone's flight along a given route, based on RTK-GPS data, commands from the ground station and data from the lidars. To do this, it forms control for 6 motors. Simultaneously with flight control, the microcontroller performs primary processing of sensor readings. Data from the sensors is both transmitted to the ground station and recorded synchronously with the corresponding coordinates on the SD card.

STM32H743xI/G devices [21] are based on the high-performance ArmCortex-M7 32-bit RISC core operating at up to 480 MHz. The Cortex-M7 core features a floating point unit (FPU) which supports Arm double-precision (IEEE 754 compliant) and single-precision data-processing instructions and data types. STM32H743xI/G devices support a full set of DSP instructions and a memory protection unit (MPU) to enhance application security.

STM32H743xI/G devices incorporate high-speed embedded memories with a dual-bank Flash memory of up to 2 Mbytes, up to 1 Mbyte of RAM (including 192 Kbytes of TCM RAM, up to 864.

Kbytes of user SRAM and 4 Kbytes of backup SRAM), as well as an extensive range of enhanced I/Os and peripherals connected to APB buses, AHB buses, 2x32-bit multi-AHB bus matrix and a multi layer AXI interconnect supporting internal and external memory access.

All the devices offer three ADCs, two DACs, two ultra-low power comparators, a low-power RTC, a high-resolution timer, 12 general-purpose 16-bit timers, two PWM timers for motor control, five low-power timers, a true random number generator (RNG). The devices support four digital filters for external sigma-delta modulators (DFSDM). They also feature standard and advanced communication interfaces.

*Development of the ground station*

The ground station plays a key role in the system: it provides two-way transmission of commands and telemetry, reception of video stream and data from sensors, planning and loading of missions based on data processing. The ground station receives all communication channels with the drone and equipment, carries out flight control in manual and automatic modes, as well as software for mission planning and saving research data. The structural diagram of the ground station is shown in Fig. 5.

Conventionally, the ground station can be divided into the following modules and equipment.

1. Radio modems:

– telemetry based on RFD900x modems, this is one of the main channels for exchanging telemetry via the MAVLink protocol. The operating range is 20 km or more (with directional antennas);

– RTL8812 modem for transmitting large amounts of data (video stream from a multispectral camera. Shown in the diagram as a separate module, but is part of the ground station with LoRa and WiFi;

– LoRa modem - a backup data transmission channel at low speeds, used to transmit commands and high-reliability signals).

2. Video and control:

– HereLink combines HD video and telemetry transmission via MAVLink, providing the operator with full control of the drone. The main purpose of the camera is to record the surveyed area in high quality;

– diversity receiver & HD monitor – receiving analog video from the course camera, as well as displaying (duplicate channel) with HereLink;

– radiomaster TX12 remote control – manual control of the drone.

3. Positioning:

– Here 4 Base (RTK) reference station for high-precision correction of drone coordinates, requires Internet access and a subscription from a provider for geolocation. Used as a backup navigation channel at long (more than 3 km) distances;

– ArduSimple – the main channel for high-precision correction of drone coordinates does not require a subscription from a provider.

4. Processing and storage:

– operator's tablet. Launching the Mission Planner software, collecting data with partial processing (and transferring to the data cloud), storing telemetry and sensor data; - SD card for data storage – local storage.

5. Network devices (ground station module with LoRa and Wi-Fi):

– Wi-Fi router – as a backup channel for the RTL8812 modem and as an access point for communication with the tablet and the Internet;

– USB hubs and TTL (UART) to USB converters – for connecting all peripherals (modems and receivers) included in the ground station;

– power supply unit consisting of a charger and battery. Powers all equipment of the ground station.

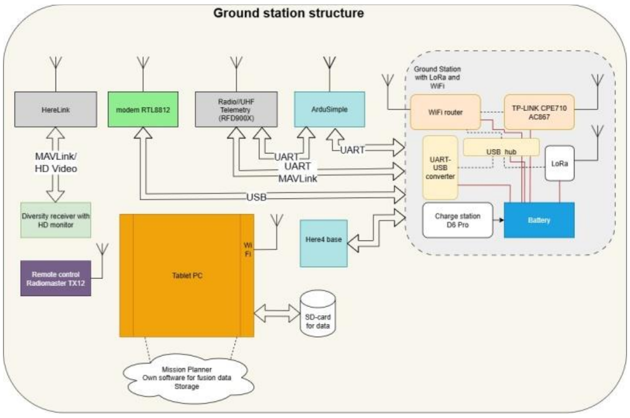


*Fig 5*. **Structural diagram of the ground station.**
***Source*: compiled by the authors**

The ground station is built on a modular principle, providing independent communication channels for drone control, video transmission and streaming data from sensors. RFD900X and RTL8812 radio modems, the HereLink system, and backup LoRa channels are used. The station is integrated with the Mission Planner software and its own data fusion system, which allows the operator not only to control the drone, but also to analyze data from multispectral cameras, magnetometers and metal detectors in real time. The architecture provides for channel redundancy, mobility and the ability to quickly replace or expand equipment. Another advantage of this architecture is the mobility of the station itself – the equipment is compact and easily fits into several cases.

## INFORMATION MODEL

The information model represents the conceptual and analytical foundation of the UAV-based remote sensing system. It defines how data are collected, processed, and transformed into actionable insights for soil analysis and environmental monitoring. The model ensures interoperability among heterogeneous sensors and enables integration of geophysical, spectral, and radar data within a unified framework [22].

*Structure of the Information Model*

The information model consists of four hierarchical layers that establish a complete data and control loop between UAV sensors, the onboard controller, and the ground control station [23], [24]:

Data Acquisition Layer: Integrates raw signals from UAV-mounted sensors such as metal detectors, magnetometers, ground-penetrating radar, and multispectral cameras. Each data stream is timestamped and georeferenced to ensure spatial consistency.

Communication Layer: Provides reliable bidirectional data transfer using RTK positioning, MAVLink telemetry, and redundant radio channels (RFD900x, RTL8812). It ensures synchronization of all onboard subsystems and maintains data integrity during UAV missions.

Analytical Layer: Performs signal preprocessing, calibration, and fusion. Machine learning algorithms classify anomalies, estimate soil parameters (moisture, density, metallic content), and reduce uncertainty through probabilistic modeling.

GIS & Decision Support Layer: Integrates analytical outputs into a digital twin of the observed area. The digital twin continuously updates based on sensor feedback, allowing visualization, prediction, and planning of further UAV missions.

*Extended Description and Data Flows*

The model functions as a multilayer ecosystem for real-time data management. Raw sensor signals pass from the Data Acquisition Layer to the Analytical Layer, where preprocessing removes noise and normalizes values. Processed data are then fused using AI-based models to create a unified representation of the soil state. The Communication Layer ensures that all telemetry and geospatial data are synchronized and transmitted to the Ground Control Station for further analysis. The GIS & Decision Support Layer employs a digital twin that mirrors soil conditions, visualizes detected anomalies, and provides feedback to mission control for adaptive planning.

This feedback mechanism establishes a closed data cycle: information from the digital twin can modify mission parameters, such as flight path, altitude, or sensor activation sequence. As a result, the UAV system evolves from static measurement to adaptive remote sensing, optimizing data quality and operational efficiency.

*Table 1.* **Structure of the Information Model**

| Layer | Inputs | Processes / Functions | Outputs |
|---|---|---|---|
| Data Acquisition | Sensor readings (spectral, magnetic, radar, positional) | Signal collection, timestamping, georeferencing | Raw synchronized datasets |
| Communi cation | Telemetry, RTK corrections, radio links | Transmission, buffering, synchronizati on | Reliable data stream to ground station |
| Analytical | Preprocessed data from multiple sensors | Filtering, fusion, classification, AI-based anomaly detection | Soil parameter estimates, anomaly maps |
| GIS & Decision Support | Analytical results, digital twin data | Visualization, environmental modeling, mission feedback | Updated digital twin, optimized mission parameters |

***Source*: compiled by the authors**

*Integration and Application*

The information model is fully integrated with the UAV’s onboard systems and the ground station, supporting interoperability through open data standards. It enables adaptive mission control, improves anomaly detection accuracy, and supports scalable environmental and agricultural applications. The architecture promotes long-term environmental monitoring by linking physical measurements with digital simulation models, ensuring that each mission enhances the predictive capabilities of the digital twin.

As shown in Fig. 6, the information model follows a four-layer hierarchical structure, vertically connecting the UAV’s physical sensing modules with cloud-based analytical and GIS layers. Each upward data flow corresponds to a transformation of physical measurements into interpreted knowledge, while downward feedback flows guide mission planning and adaptive sensor control.

The upward data flow (bottom to top) transmits raw spectral, magnetic, and radar signals from UAV sensors to the Analytical Layer, where AI algorithms perform data fusion, classification, and calibration. Processed data are then transferred to the digital twin within the GIS & Decision Support Layer, generating spatial maps, anomaly localization, and temporal models of soil behavior. The downward feedback loop provides updated parameters to the UAV navigation and mission management subsystems, allowing real-time optimization of flight trajectories and sensor activation sequences [25].

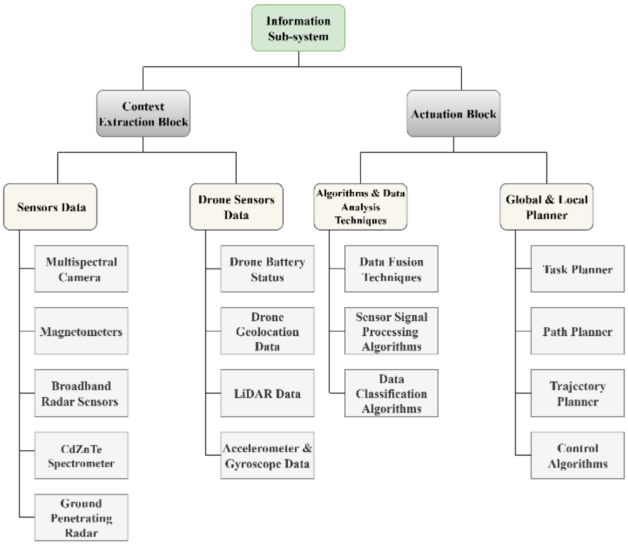


*Fig. 6*. **Information model**

***Source*: compiled by the authors**

The integration between layers is event-driven: sensor triggers initiate analytical processing, analytical outcomes update the GIS twin, and GIS feedback optimizes future flight paths. This continuous bidirectional communication ensures that the system maintains synchronization between field measurements and the evolving digital twin.

Thus, Fig. 6 not only visualizes the logical hierarchy but also illustrates the data feedback mechanisms that make the UAV-based remote sensing system adaptive, predictive, and self-learning.

## EXPERIMENTAL RESULTS

Field tests were conducted to validate system performance. The UAV demonstrated stable operation in winds up to 12 m/s, maintaining centimeter-level altitude control. Integrated multisensor data allowed precise mapping of anomalies and soil variations. The combination of magnetic and spectral data increased detection accuracy by approximately 20% compared to single-sensor systems. All test results confirm the efficiency of the modular UAV architecture and data fusion approach.

## DISCUSSION

The open UAV platform with the proposed information model enhances adaptability and data quality in remote soil sensing. Unlike closed commercial systems, the ArduPilot-based design supports custom sensor integration and algorithm development. The digital twin provides a continuously updated view of soil conditions, enabling early detection of erosion, contamination, or buried anomalies. This integration of physical sensing and digital modeling bridges the gap between measurement and interpretation, forming the foundation for advanced environmental analytics.

## CONCLUSIONS

An open UAV architecture and a comprehensive information model for soil remote sensing have been developed. The system integrates multisensor data streams and supports adaptive analytical workflows through a digital twin of the soil environment. The results confirm the feasibility and scalability of the approach for agricultural and environmental monitoring. Future work will focus on incorporating AI-driven classification models and expanding cloud-based GIS integration for large-scale deployments.

The work involved developing an open UAV architecture using standard hardware components, software, and a unified data transfer format. This allows for the rapid implementation of both the basic design and the connection of additional equipment in the required range. The unified data transfer format allows for the use of any processing processors both on the UAV itself and in the ground station. The developed architecture allows for its rapid adaptation and implementation for surveying large areas of terrain for anomalies, such as mines and unexploded ordnance.

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# Інформаційна модель при дистанційному моніторингу ґрунту

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## АНОТАЦІЯ

У статті представлено комплексну інформаційну модель та відкриту архітектуру для дистанційного зондування ґрунту на базі безпілотних літальних апаратів (БПЛА). Розробка технологій дистанційного зондування з використанням безпілотних літальних апаратів (БПЛА) та датчиків різних методів вимірювання дозволяє безконтактно виявляти різні аномалії. Достовірність інформації після її обробки досягається поєднанням методів вимірювання, правильним вибором інструментів безконтактного вимірювання та використанням методів машинного навчання для обробки даних та навчання на відомих аномаліях. Модульна платформа БПЛА підтримує адаптивну інтеграцію датчиків та об'єднання даних у реальному часі для точного землеробства, моніторингу навколишнього середовища та постконфліктних застосувань. Інформаційна модель визначає структуру та потік даних між датчиками БПЛА, бортовими процесорами та наземною станцією керування, включаючи цифрового двійника для динамічного моделювання навколишнього середовища. Обрано мінімальний набір необхідних інструментів, на основі вимірювань та обробки яких буде достатньо інформації для виявлення аномалій у ґрунті з високим ступенем надійності. Сфера застосування отриманих результатів досить широка: від точного землеробства, включаючи моніторинг хвороб сільськогосподарських культур та хімічний безконтактний аналіз ґрунту, до виявлення сторонніх включень та аномалій у районах, де відбувалися військові дії.

**Ключові слова:** Безпілотний літальний апарат, інформаційна модель, дистанційне зондування, моніторинг ґрунту, цифровий двійник, мультисенсорна інтеграція, геофізичне дослідження, мультимодальне об'єднання даних, аерофотознімок з БПЛА, кіберфізичні системи, геоінформаційна система

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