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Development of Low-Cost Unmanned Aerogeophysical System Based on Light VTOL Aircraft

as an analogue of traditional airborne geophysics

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***Abstract*— The article describes the prospects and problems of creating low-cost unmanned systems for airborne geological prospecting of large areas with a simple topography. A novel electrically-powered unmanned aerial system (UAS) based on a vertical takeoff and landing (VTOL) aircraft was developed for low-altitude aerial geophysical surveying. The vehicle represents a 2.5 m flying wing with wing area of about 100 sq.dm with four engines for takeoff and landing and one thrust motor, max take-off weight is approximately 6 kg. The payloads are high-frequency fluxgate magnetometer, gamma radiometer, and optional solid-state LiDAR and multispectral cameras. To reduce electromagnetic interference from the thrust engine, the geophysical sensors are mounted at the winglets, and the marching engine located on the nose of the aircraft and shifted forward, not as usual with the flying wings. Magnetic and gamma-ray surveys are performed simultaneously, measurement frequency of magnetometer and radiometer is 10 Hz and 0.5 Hz respectively, which provides high density surveying. At a cruise velocity of 60-70 km/h and a flight time of over one hour, the unmanned system allows us to efficiently examine areas of up to several hundred square kilometers. The advantages of the created system include low cost price of the vehicle, possibility to decrease the survey altitude to record low-contrast geophysical anomalies without the risk to the aircrew, no need for special landing strip. Due to the low weight, in Russia the system falls within the scope of the Simplified Rules for lightweight UAV operations. The unmanned system can drastically increase the availability of geological and geophysical operations over vast areas with simple terrain and as such it is oriented towards replacing classical aerial geophysical surveying from plane and helicopter vehicles. The created system best corresponds to the challenges of geological prospecting on swampy and forested areas, including oil, gas and diamond-bearing provinces in the north of Eurasia, in Arctic region and offshore**

Keywords*— *unmanned aerial vehicle, UAV, aerial geophysics, VTOL, airborne magnetic prospecting, airborne gamma-ray survey

I. Introduction

The main prospects of locating new deposits both in Russia and worldwide are associated with the geological exploration of areas distant from the infrastructure, usually characterized by complex natural and terrain conditions: swampiness, forest coverage, which significantly reduces economic efficiency and environmental friendliness of the ground geological prospecting methods, since it requires cutting down profiles, construction of roads and bases for accommodation of field parties. At the same time, due to the high mobilization cost of aircrafts, conventional aerial geophysical surveys are only economically viable when operating at a regional scale, while the main trajectory of the geological prospecting sector is aimed at the development of private business, which is performing geological surveys on individual license areas.

In this regard, and in connection with the objective trends of digitization of the geological sector, robotized systems for geophysical prospecting based on unmanned aerial vehicles (UAVs) have been rapidly developing in the recent years. Besides lowering costs for mobilization and operation of aircrafts, such systems provide the ability to decrease velocity and altitude of the flight in a safe manner for the crew, follow the terrain more accurately, which increases informativeness of the data, since anomalies of the Earth's geophysical fields caused by objects in geological structure of the upper crust rapidly attenuate with increasing altitude. The first unmanned systems for aerial geophysical surveying, which appeared about 8 years ago [10, 11], were based on aircrafts with internal combustion engine (ICE), size up to several meters, runway takeoff and landing, and the survey was performed using one geophysical method – Magnetic Prospecting (Magnetic Prospecting is a method of geological mapping and prospecting, based on non-similar content of magnetic minerals, e.g. magnetite, pyrrhotine etc., in rock formations and geological structures. Presence of minerals with strong magnetic properties causes anomalies in the Earth's normal magnetic field). In Russia, development of magnetic prospecting system based on airborne UAVs was conducted within government's target policy for 2014-2016, although no commercial level technology has been developed [11] However, with emerging brushless motors and lithium polymer batteries there is now a possibility to create far cheaper and more maintenance-friendly unmanned aircrafts with electric motors, and the most popular ones are systems based on multirotor UAVs, which provide means for low altitude surveying with more detailed terrain drape. At the moment, there are multirotor systems that support quite a full range of prospecting geophysics methods, including magnetic prospecting, gamma radiometry and spectrometry (method based on non-similar contents of natural radionuclides, e.g. uranium, thorium, potassium-40) and lidar scanning, multispectral surveys etc [1 – 6, 9, 12]. High data quality and the ability to combine several methods on a single UAV have led to informativeness of data that in practice exceeds results of ground surveys at much higher economic efficiency [5, 6]. Quasi-terrestrial surveys effectively became a replacement for classical geophysical surveys on foot due to the proved high efficiency of robotized systems, and it already has been reflected in the Russian regulatory framework [7].

The authors have been developing and widely using multirotor systems for geophysical prospecting since 2014 [5, 6, 8]. The existing SibGIS UAS system supports the set of above geophysical methods at a cruise velocity of 30-40 km/h with a detailed terrain coverage, which provides a way to complete hundreds of linear kilometers of high quality geophysical survey, while a single pedestrian group performing ground survey with one or two methods at most will not be able to complete more than 5 - 8 linear km of survey a day, even under conditions with good terrain passability [5]. However, a multirotor UAV is characterized by relatively short flight time and, consequently, distance from takeoff point, which does not exceed a few kilometers. It requires the geophysical party to move around the area of prospecting. For the typical cases of ore prospecting, where sites are often characterized by complex terrain, but usually are not more than tens of square kilometers, this is insignificant. However, there is also another class of tasks related to the need to perform geological study on larger sites up to hundreds of square kilometers, the passability of which is complicated not by complex terrain, but by swampiness, rivers and forest coverage. In Russia, for instance, such regions include potentially oil, gas and diamond-bearing regions on the north-east of Eurasia within the Siberian platform. Due to relatively simple terrain such areas can be explored efficiently and at low altitudes with a help of long-range airborne vehicles. However, the use of the known systems based on large unmanned aircrafts with ICE in the Russian context is complicated by two key factors:

- Aircrafts with internal combustion engine, similar to those mentioned above, have a size of several meters and can takeoff and land only on the special landing strip. Due to swampiness and forest coverage construction of landing strips can be complicated, and in any case this factor decreases the efficiency of operations;

- UAVs weighing more than 25 kg in Russia do not fall under the Simplified Rules of Registration and Operation, and effectively are equivalent to the conventional manned aircrafts, which significantly complicates its use in geological practice.

Additional negative factors can be identified, which are especially relevant in the Russian context when performing work in regions distant from the infrastructure: high cost and low availability of components for creation the large petrol-powered UAVs, which is always reflected in the survey costs; difficulty in cancelling interference from ICE ignition system on geophysical equipment; relatively short life of ICE, high complexity of repair and maintenance of ICE during geological expeditions; considerable size of the vehicle reduces maneuverability and therefore limits the possibility of large-scale surveys etc.

In this regard, in our opinion, development of aerial geophysical systems based on light class aircrafts (under the Russian classification, less than 25 kg) equipped with electric engines, which are able to take off and land without the need to construct landing strips, and which would fall under the Simplified Rules of Registration and Operation, is of vital importance. Despite the fact that the flight time for the conventional light aircraft weighing few kilograms and with wing area of less than 100 sq dm usually does not exceed one to one and a half hours, combined with the speed of about 50-80 km/h this will give an opportunity to study areas of hundreds of square kilometers from one takeoff point, which would address current issues in prospecting of oil and gas deposits, geological exploration in the shelf area and in Arctic region, diamond-bearing provinces of Yakutia etc..

II. Development of Aerial Geophysical System

A. *Statement of problems*

In view of this, the objective of this work is the creation of aerial geophysical system based on a light class aircraft, which can be efficiently used for solving geological prospecting tasks under the conditions of simple terrain and large survey areas, while common multi-rotor systems are an effective replacement for ground surveys and surveys in difficult terrain. The new system must provide surveys by several geophysical methods simultaneously, since such approach leads to an increase in geological and economic efficiency of works. At a minimum, two most geologically universal methods of geophysical prospecting should be implemented - the above-mentioned methods of magnetic and gamma-ray surveying (traditional aerogeophysical systems based on manned aircrafts usually also include hardware for electromagnetic prospecting, but its implementation on the light UAVs is rather problematic, and in our opinion, is not necessary at the first stages of geological exploration). Besides, the cost price of the system should be low, and its maintenance must be as simple as possible, since the cost of geophysical survey directly depends on the cost of vehicle maintenance and includes its risk of damage and even losses. Aerial geophysical prospecting is used at the first stage of geological prospecting, in areas with yet uncertain prospects for the discovery of mineral resources, so high cost of geophysical prospecting at this stage is unacceptable.

The most difficult problem of creating aerogeophysical systems is the need to deal with electromagnetic interference from the aircraft engine and other electronics: both magnetometer and gamma radiometer (with vacuum photomultiplier tubes) are very sensitive to electromagnetic noise. Second of the important requirements was the ability to take off and land without the need to construct landing pads or runways. That being said, the authors had previously created methodological support and software, which provided the means to create flight missions for the autopilot and process data of low-altitude surveys, so these tasks were off the table.

B. *Discussion of the design of the UAS*

Aerodynamic aircrafts – planes – are characterized by the longest flight time and relative simplicity of manufacture from among the relatively compact and cheap types of aircrafts. Unmanned helicopters with similar load capacity require significantly larger costs on manufacture, and maintenance under unfavorable conditions of geological expeditions [11]. Dirigibles have problems with wind; besides, there are difficulties with supplying gas for filling the cylinders, and the cylinders themselves are impossible to manufacture outside specialized shops, at the same time, some combined schemes can be very interesting [13, 14]. However, helicopters and aerostats can takeoff vertically from a small landing pad, and the takeoff of unmanned plane-type aircraft weighing some several kilograms is usually performed using a stationary catapult. The catapult is installed at an angle of 8-15 degrees to the horizon and serves simultaneously as a runway and an acceleration device for the aircraft. The plane accelerates to a safe flight velocity and simultaneously gains altitude. Then begins the altitude gain with a gradual increase in the flight-path angle completing the full takeoff and starting the flight stage on the designated route. When approaching the landing, the aircraft descends to the safe obstacle clearance altitude, and try to performs landing according to one of two main options. The light plane either makes a "belly landing" (descends to a flat trajectory, and then sustainer engine starts a few seconds before the touchdown) or the engine shuts down at an altitude of under a hundred meters, deploying the parachute under the force of gravity and incoming air. Both these options proved inefficient during geological works in Siberia: usually there is no free area with soft grass for landing from low-level flight, and in the case of parachute landing the plane can be blown off by the wind into water obstacle or swamp, or it has a high chance to get caught in the tree branches and hang there, not being able to reach the ground. Therefore, in any case, there needs to be an arranged landing pad, free from obstacles. Transportation and deployment of the catapult and packing of the parachute system after each flight decrease the productivity of surveying.

As a result, there was a decision to create an aerial geophysical system based on an aircraft with plane design, but of advanced type – a plane with vertical takeoff and landing, free from the above disadvantages. As mentioned earlier, basic methods of geophysical surveying that are to be implemented within the system include magnetic prospecting and gamma surveying as the most geologically universal. To obtain accurate digital terrain models there is a possibility to add solid-state lidar scanning system, and multispectral cameras performing surveying in 6 channels (table 1), which gives an ability to calculate a range of classical multispectral indexes: Iron Oxide Ratio, WorldView Soil Index and New Iron Index, NDVI and many others.

Such system will extend the capability of the unmanned system to the required level:

- providing vertical takeoff and landing of an aircraft using takeoff/landing engines – propellers, rotating in the horizontal plane;
- no need to use the catapult launching or parachute landing of an aircraft, which will increase the useful load of the aircraft;
- implemented the basic methods of geophysical prospecting, in most cases providing an ability to successfully solve tasks of large-scale geological and geophysical mapping, and in some cases to search mineral deposits directly.

III. Description of the Created UAS

A. *VTOL Aircraft and payloads*

The development of the aircraft was carried out in several iterations, including flight tests and interference tests for the created geophysical sensors, with subsequent refinement of the UAV construction. Even now, despite the fact that a working version of the UAS has already been obtained, and it is quite suitable for effective work in real conditions, the version described in the article cannot yet be considered final.

Since we wanted to achieve the result as quickly as possible and with minimal costs, in the development process, components from serial UAVs and a lot of 3D printing were used. As the basis for creating a prototype of the new VTOL aircraft, the foam fuselage of the popular Skywalker X8 aircraft was used. During the development, its design was almost completely reworked, and the resulting version can only use wings of the serial model, but even they will require some tweaking before installation. For example, when it was identified that it was necessary to transfer the thrust motor from the tail to the bow, it was replaced by a carbon fiber and with a different internal layout.

The new UAV is of the "flying wing" type, one of the advantages of which is the fact that the lifting force is created by the whole surface of the plane, not only a part of it like in the conventional arrangement. The absence of the need to lift the fuselage and large control surfaces significantly reduces the power-to-mass ratio of the airframe and gives the ability to drastically increase the useful load mass. There are several versions of VTOL scheme implementation – a change in thrust vector of an engines (of which there can be three or four) or implementation of two separate engine-propeller groups – one for takeoff/landing and one for sustained flight. The second scheme was chosen, since it does not require implementing servomotors and other mechanisms for motor rotation. There is no possibility of a servo drive breaking, and even a marching engine failure, the UAV will be able to continue flying on the engines of the lifting group and successfully complete the mission without crash. These factors, which determine the high reliability of the system, are very important during field work in remote areas. Takeoff and landing of the designed vehicle is performed with a help of four brushless engines, and the flight is achieved by one thrust motor with a pulling propeller (Fig. 1).

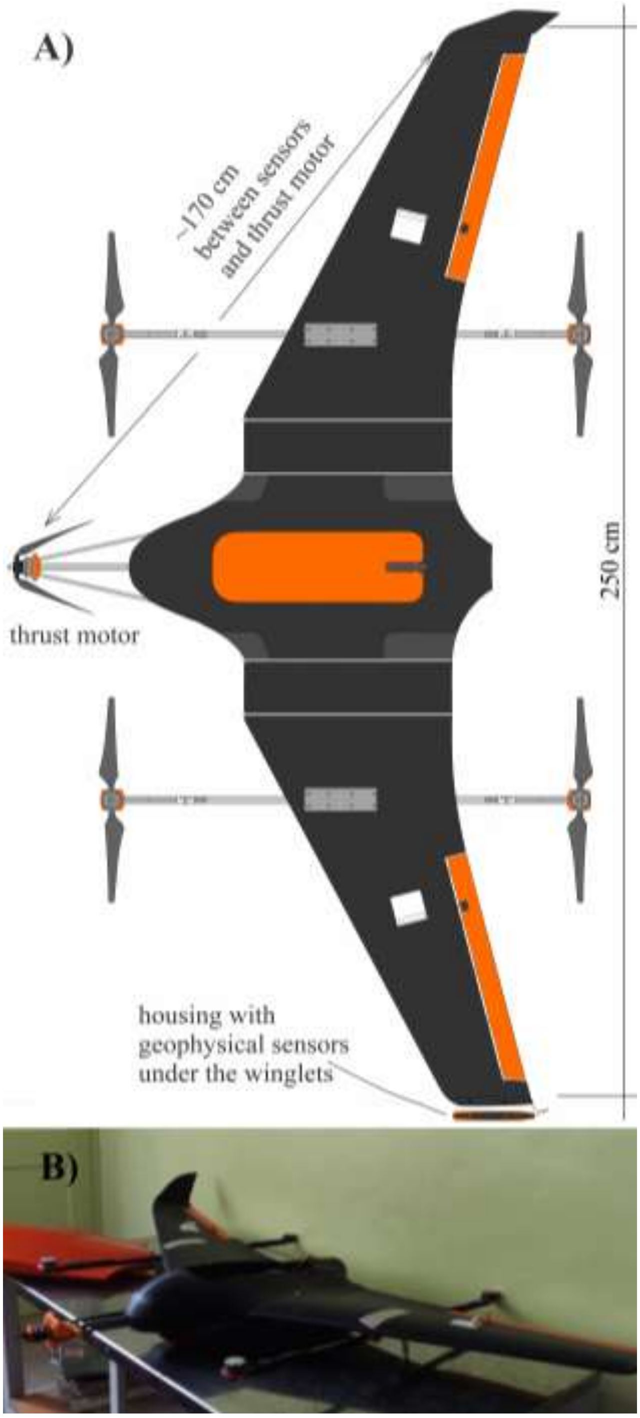

Fig.1. VTOL principal scheme (A) and photo (B)

The fuselage and center section of wings of the created UAV are now made not of foam, but of carbon using original matrices. This significantly increases internal volume for the equipment and provides convenient power wiring for motors and cabling for geophysical sensors without losing rigidity of the structure. The new center section of wing was also required to arrange propellers of the takeoff/landing group at a sufficient distance from the fuselage. Pylon fittings, which hold the engines, are positioned under the outer wing panel at the center of gravity of the airframe (43 cm from the nose) at a distance of 55 cm from the roll axis of the UAV. The pylon length is about 1 meter, so the takeoff/landing engine-propeller group forms a “quadcopter” with almost symmetrical frame with a diagonal of about 1.5 meters, and such arrangement provides good aircraft trim both in roll and pitch axes during takeoff and landing. The UAV landing is performed on three undercarriage legs, two of which are located under the pylons and the third one is at the nose part of the fuselage. Pylons are made of 15x15 mm carbon profile; under the motor mount there are tiny regulators (ESC) of Hobbywing Xrotor Micro 35A engines weighing only 9.5 grams. The 4008 330KV motors (weighing 85 grams) and 17’’ folding carbon propellers (20 grams) were used. The engine-propeller group configuration is not designed for long duration flight in the quadcopter mode, but with sufficient excess thrust provides takeoff and acceleration to cruise velocity, and is lightweight at the same time. The whole engine-propeller group together with pylons weighs less than 800 grams. The completed rig tests showed that the thrust of one engine of the takeoff/landing group at the gas level of 60% is 1,700 g; and in this mode at least during 6 minutes of operation at 25º neither the engine nor the regulator hidden in the pylon overheated. Considering that the UAV no longer requires a parachute system, the real increase in the mass relative to a conventional plane due to the addition of takeoff/landing group is insignificant. Besides, the increased mass of the UAV was compensated by the wing area that increased to 100 sq dm, and the possibility to install a battery with bigger capacity. The wingspan of the designed UAV is 2.5 meters, which is 20% larger than Skywalker X8. For the convenience of transportation, the fuselage is demountable, fittings of the removable wings are located about 40 centimeters from the roll axis right after the engine pylon fittings. To increase the maintainability, design of the wing fittings can support wings of the Skywalker X8, if needed. The trust motor with a 13’’ pulling propeller is mounted at the front of the fuselage, at a distance of 65 cm from the center of mass of the UAV. Typically, on “flying wings”, the motor is mounted at the rear of the fuselage, while it is in line with the ends of the wings, on which in this case winglets with sensors of the magnetometer and radiometer are installed. In this case, despite the considerable size of the frame, electromagnetic interference from the engine to the magnetometer sensor was significant. Since the electromagnetic field of the brushless motor is an ellipse with a "larger" axis perpendicular to the axis of rotation, the displacement of the motor along the "short" axis forward relative to the sensors made it possible to solve the problem of interference from trust motor. Distance from it to the geophysical sensors is more than 1.5 meters. Motors of the takeoff/landing group during geophysical survey are off and create no interference. Magnetometer and radiometer sensors are mounted at the wingtips in the 3D-printed pods (fig. 1 and 2A) that provide support for winglets.

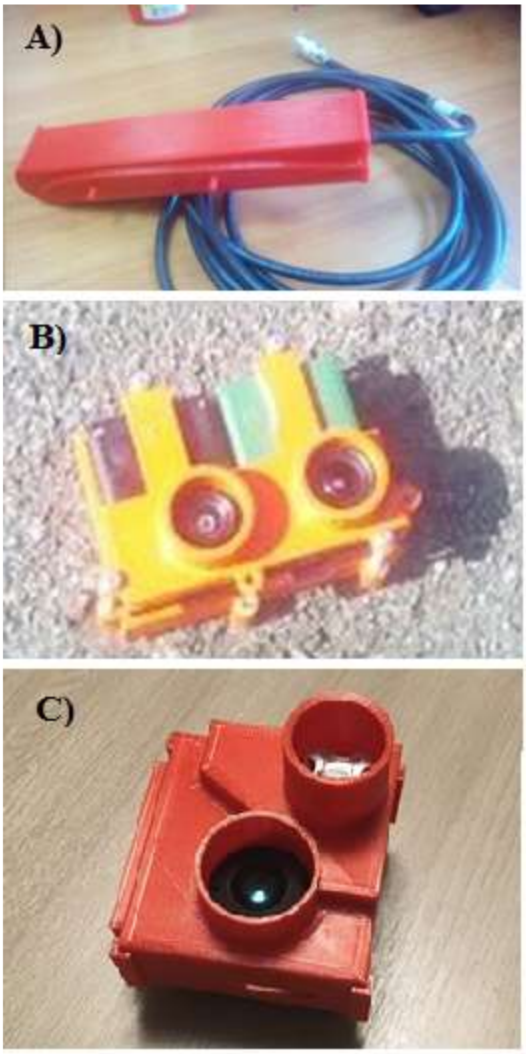

Fig.2. Payloads: (A) Housing with magnetometer sensor, (B) multispectral cameras, (C) one of LiDAR variants

Mass of both geophysical sensors with housing is adjusted to 180 grams for each. Sensor characteristics are given in the Table 1. Together with wires and electronics, the weight of basic geophysical equipment is less than 600 grams.

Data logger of geophysical sensors is inside the fuselage, and in the center part of the airframe there are two hatches for accommodation of aircraft hardware inside the aircraft body. The body incorporates flight controller Pixhawk 2.1 Edison Edition, equipped with Intel Edison micro-PC, radio control receiver, radiotelemetry unit with a range up to 40 km, trust motor speed controller, digital airspeed sensor, altimeter and 12 A/h LiPo battery. The advantage of the flight controller used is its open architecture, which provides additional capabilities. For example, it is possible to access data of the embedded inertial measurement unit (IMU) and satellite positioning system, which additionally can be programmed to save geodata in RAW format on an external flash card for its subsequent differential correction. This way, it is possible to increase accuracy of georeferencing of the results of measurements of geophysical sensors, multispectral cameras and solid-state liDAR up to a few centimeters. When using proprietary controllers, it would be necessary to additionally purchase differential satellite referencing system and implement inertial system within liDAR scanner, which would increase not only the cost of the system, but also its weight.

TABLE I. PAYLOAD CHARACTERISTICS

Payload	*Specifications*	*Weight (sensor+wires+housing), kg*	*Sampling rate, Hz*
Magnetometer	Fluxgate 3-axis, based on FGM3D100 sensor	0.18	10 or 20
Gamma-radiometer	2 x CsI(Tl) 8x100mm crystals with solid state photodetectors	0.18	0.5
Multispectral cameras	2 cameras 12 Mpix Five spectral channels: Visible Light RGB + Yellow 615nm and NIR 820nm	0.2 (without GPS module)	0.2 – 0.5
LiDAR (experimental prototype)	Based on one or two 16-segments solid-state M16-LSR modules (Ground Sampling Distance ~1.8 meters/pixel at flight height 80 m) NIR 905 nm	0.7	10-20

The total loaded weight of the aircraft with magnetometer and radiometer is about 6 kg.

B. Metodics of survey

UAV flight during geophysical survey is performed completely in automatic mode. First, using SibGIS Flight Planner software [6] an array of points of a flight mission is generated, which are located at a constant altitude above the accepted digital terrain model. For geophysical surveys the flight mission is created in the form of parallel profiles, spaced equally; 1:50,000 to 1:10,000 scales (500 or 100 meters between profiles) are the most reasonable for the described system design. In our opinion, on a larger scale, it is usually more rational to use unmanned geophysical systems based on multi-rotor UAVs. Point density in the flight task along the profile is determined by the terrain complexity. The created flight task is uploaded to the autopilot, takeoff and acceleration of the UAV are usually performed by the operator manually using the remote control. After achieving cruising velocity the unmanned system switches to autopilot mode, and after completing the flight task the plane returns to the launch pad, landing is usually performed manually. Geophysical measurements made during the flight are recorded in the memory of devices and can be additionally transmitted via telemetry to the ground station of the operator, georeferencing of the data is performed using satellite positioning systems. The battery is replaced, new flight task is uploaded, and once every few flights the data is downloaded from the geophysical devices and subsequently subjected to standard geospatial processing.

IV. CONCLUSION

As a result, a light unmanned system for complex surveying was created, based on electrically-powered vertical takeoff and landing airplane. The created VTOL system provides mobility and convenience in difficult landscape conditions, and safe takeoff and landing in a limited space. This type of UAV can perform flight tasks in places with difficult access, and also it does not need any special launch pads. Low mass and size of the UAV provide low mobilization costs and accessibility of surveying for small organizations and research groups, which could not access aerial geophysics before.

All original parts of the UAV design are 3D-printed, fuselage and wings are manufactured from fiber glass or carbon with the use of widely used materials and without any special equipment. As a result, the cost price of the airmobile part of the unmanned aircraft amounted to less than $1,500 including electronics, which is multiple times less than the cost of market equivalents. Low cost price provides the ability to perform complex geophysical survey using magnetic prospecting and gamma survey paying as low as $20 per linear kilometer, which is twice lower than surveying with multicopters.

Now UAV flight time with useful loads is about 70 minutes at a cruise velocity of 60-70 km/h, which gives the ability to move up to 30 km away from the takeoff point, and consequently to perform survey over areas of hundreds of square kilometers. In the future, the characteristics will be improved, since the described option is a working prototype and is constantly being improved. In particular, a new version of the fuselage is being manufactured, more suitable for the construction with a pulling engine than the adapted version of the Skywalker X8 fuselage. However, with the developed prototype it is possible to achieve performance of several hundred linear kilometers of survey per day.

It appears that the technology described in this article is the first in the world unmanned system for complex geophysical survey based on ultralight VTOL UAV. It is to be expected that similar robotized systems will appear and develop soon, which will drastically change the situation on the market of geological prospecting. The authors believe that much as multicopter surveys basically replaced conventional ground geophysical surveys (by a number of methods), adoption of systems with considerable flight time in the immediate future will significantly decrease the volumes of traditional aerial geophysics. The advantage of ordinary aerial geophysics as compared with the described technology is the availability of electromagnetic prospecting besides systems for magnetic and gamma survey, but the objective to implement several methods of electrical survey based on light vehicles is not an unsolvable one and is only a matter of time and willingness of the researchers.

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