APLICAÇÃO DE SISTEMAS ROBÓTICOS MÓVEIS VOADORES PARA DETECÇÃO PRECOCE DE UMA FONTE DE IGNIÇÃO

APPLICATION OF PORTABLE FLYING ROBOTIC SYSTEMS FOR EARLY DETECTION OF AN IGNITION SOURCE

ИСПОЛЬЗОВАНИЕ МОБИЛЬНЫХ ЛЕТАТЕЛЬНЫХ РОБОТОТЕХНИЧЕСКИХ СРЕДСТВ ДЛЯ РАННЕГО ОБНАРУЖЕНИЯ ИСТОЧНИКА ВОЗГОРАНИЯ

POLYAKOV, R. Yu.^{1*}

¹ Bunin Yelets State University, Russia.

* Corresponding author
e-mail: ryu.polyakov@bk.ru

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RESUMO

Recentemente, o desenvolvimento de modernos equipamentos e métodos de detecção precoce de fontes de ignição tornou-se relevante devido ao grande número de incêndios, bem como aos danos materiais e humanos por eles causados. Este estudo teve como objetivo desenvolver um método de busca da fonte de ignição pelo movimento de um analisador móvel de gases em direção ao aumento da concentração de monóxido de carbono (CO) emitido nos estágios iniciais de incêndio. Foi utilizado um algoritmo baseado no método de detecção espacial e definição de trajetória garantida para mover o analisador de gás móvel em direção a um aumento na concentração de acordo com o método simplex e Kiefer. A dependência da velocidade do motor com a tensão de alimentação, a velocidade angular do motor com a tensão de alimentação, a força de tração na frequência de batimento das asas, a tensão de alimentação bem como a energia consumida pelo motor durante a propulsão foram calculadas. Para determinar a direção do azimute em direção ao movimento de aumento da concentração de CO, foi obtida uma equação que tornou possível determinar a concentração de CO em função da distância da fonte de monóxido de carbono. Um diagrama da dependência do gradiente na distância ao ponto de ignição foi traçado e o número de pontos na trajetória na qual a concentração de CO é medida foi determinado. Uma das formas de aprimorar ainda mais os métodos de detecção precoce de incêndio é a utilização de analisadores móveis de gás, na movimentação até a fonte de ignição, e na determinação de suas coordenadas com o aumento da concentração de CO. No entanto, o desenvolvimento posterior é restrito devido à pesquisa insuficiente de métodos de design de analisadores de gás móveis, análise de comunicação entre subsistemas e métodos de cálculo baseados em modelos matemáticos que descrevem adequadamente os modos básicos de movimento dos analisadores de gás móveis.

Palavras-chave: monóxido de carbono, simulação de movimento, analisador de gases.

ABSTRACT

Recently, the development of modern equipment and early detection of ignition sources has become relevant due to many fires and the material and human damage caused by them. This study aimed to develop a method of searching for the ignition source by moving a mobile gas analyzer towards increasing the concentration of carbon monoxide (CO) emitted in the initial stages of fire. According to the simplex and Kiefer method, an algorithm based on the spatial detection method and guaranteed trajectory definition was used to move the mobile gas analyzer towards increasing concentration. The dependence of the engine speed on the supply voltage, the angular speed of the engine with the supply voltage, the tractive force at the wing flap frequency, the supply voltage as well as the energy consumed by the engine during propulsion were calculated. To determine the direction of the azimuth towards the movement of increasing the concentration of CO, an equation was obtained that made it possible to determine the concentration of CO as a function of the distance from the carbon monoxide source. A diagram of the gradient dependence on the distance to the ignition point was plotted, and the number of points on the trajectory on which the CO concentration is measured was determined. One way to further improve early fire detection methods is to use mobile gas analyzers in the ignition source movement and determine their coordinates with the increase in CO concentration. However, further development is restricted due to insufficient research on design methods for

mobile gas analyzers, communication analysis between subsystems, and calculation methods based on mathematical models that adequately describe the basic modes of movement of mobile gas analyzers.

Keywords: *carbon monoxide, movement simulation, gas analyzer.*

АННОТАЦИЯ

В последнее время разработка современных средств и методов раннего обнаружения источников возгорания стала актуальной в связи с большим количеством пожаров, а также материальным ущербом и человеческими жертвами, причиняемыми ими. Целью настоящего исследования являлась разработка метода поиска источника возгорания по движению мобильного газоанализатора в сторону увеличения концентрации монооксида углерода (СО), выделяющегося на начальных стадиях пожара. Был использован алгоритм, основанный на методе зондирования пространства и определения траектории, гарантирующий перемещение мобильного газоанализатора в сторону увеличения концентрации в соответствии с симплексом и методом Кифера. Рассчитана зависимость частоты вращения двигателя от напряжения питания, угловой скорости двигателя от напряжения питания, тягового усилия от частоты взмаха крыла, напряжения питания, а также мощности, потребляемой двигателем при движении вперед. Для определения направления азимута движения в сторону увеличения концентрации СО получено уравнение, позволяющее определить концентрацию СО в зависимости от расстояния от источника монооксида углерода. Построена диаграмма градиентной зависимости от расстояния до точки воспламенения и определено количество точек на траектории, в которых измеряется концентрация СО. Одним из путей дальнейшего совершенствования методов раннего обнаружения пожара является использование мобильных газоанализаторов, перемещающихся к источнику возгорания, и определение его координат с увеличением концентрации СО. Однако дальнейшее развитие сдерживается недостаточными исследованиями методов проектирования мобильных газоанализаторов, анализа связей между подсистемами и методов расчета на основе математических моделей, адекватно описывающих основные режимы движения мобильных газоанализаторов.

Ключевые слова: *угарный газ, моделирование движения, газовый анализатор.*

1. INTRODUCTION:

Recently, the development of modern equipment and methods of early detection of ignition sources has become relevant because of the massive number of fires and the material damage and human casualties caused by them (Sudhakar *et al.*, 2020; Estrada and Ndomab, 2019; Beck, Teacy, Rogers, and Jennings, 2018). Thus, in 2019, 471.537 cases of fire were registered in Russia. During them, 226,319 people and pieces of material assets to 62.2 billion rubles have been saved. Unfortunately, 8,567 people, including 406 children, could not avoid deaths, 9,477 people were injured, and material damage from the fires amounted to 18.2 billion rubles. Compared to the last year, the number of fires increased by 257%, deaths - by 8.3%, the amount of material damage increased by 17.1%, and the number of injured decreased by 1.8%. There were 1292 fires on average daily. Twenty-three people died, twenty-six people were injured on average, and the daily damage was 49.8 million rubles (Russian Ministry for Emergency Situations, 2020).

Fire detectors are used to prevent fire at an early stage in most cases. Such sensors are

based on three parameters: the concentration of smoke particles in the air, ambient temperature, and the radiation of the open flame. Depending on the detection principle, fire detectors are divided into smoke detectors (optical, spot, linear, ionization), thermal detectors (contact, power cables), flame detectors (ultraviolet and infrared), and gas analyzers. Thermal and flame detectors are in many ways inferior to smoke and gas analyzers, which indicates their obvious choice (Fyodorov, Lukyanchenko, and Sokolov, 2005, 2006; Poroshin and Surkov, 2016; Goremykin, Lukashevich, and Alekseev, 2017; Sychev, Sitnikov, and Rakityansky, 2018; Chlenov, Menkeev, Darbakov, Kiselev, and Chernenko, 2018).

However, plural studies have shown that smoke can be released to a level that triggers the smoke detector (Saidulin, 2009; Tamura, 2008; Chew, Wong, and Ho, 2001; Kolodyazhny and Kolosova, 2015; Bogomaz, 2017; Malashkina and Lobaznov, 2011; Betting *et al.*, 2019). This fact significantly reduces the effectiveness of such devices.

Carbon monoxide (CO) is a toxic gas formed in connection with burning any carbon-containing products and materials, the

concentration of which reaches 20-80 ppm at an early stage. Even at low concentrations, CO can already cause dizziness, disorientation and prevent conscious action of people when taking priority measures during a fire (Kozubovsky, Misevich, and Ivanchuk, 2015; Jasim, Hamed, and Abid, 2020; Mohammed, Kamal, Resheq, and Alabdraba, 2019). It is known that when the CO concentration increases up to 0.08%, there is a slight degree of carbon monoxide poisoning, the symptoms of which are headache, dizziness, suffocation, and general weakness. The intermediate severity of poisoning comes at a concentration of 0.32%, which causes motor paralysis and faintness. At a CO concentration of 1.2% and above, a fulminating form of poisoning develops when a person gets a lethal dose for a couple of breaths; in this case, the mortality occurs within 3 minutes (Heightman, 2010; Basharin et al., 2015; Kazantsev and Krasilnikov, 2019; Basharin, Halimov, Tolkach, and Kuzmich, 2018).

Therefore, 80% of deaths accounted for carbon monoxide poisoning. Transition to the application of gas-sensitive CO concentration sensors in fire protection systems allows for the detection of a hazardous fire situation at an early stage when it is possible to take measures to stop the dangerous process and prevent fire (for example, to switch off the power supply and stop the dangerous overheating of the wiring insulation). At the initial stage, when a small amount of material smolders, the carbon monoxide dissolves in the room volume, and its concentration is low. Hence the requirement for the sensitivity threshold of the sensors is formulated. The appearance of high-sensitivity semiconductor sensors that can detect CO concentration starting from 10 ppm can improve fire early detection efficiency.

This study aimed to develop a method of finding the fire source by moving the portable gas analyzer towards a rise in carbon monoxide concentration emitted during the initial stages of fire.

2. MATERIALS AND METHODS:

One way to improve the fire protection effectiveness is the transition from permanently fixed GA to portable gas analyzers (MGAs). It is a new direction in developing and creating fire protection systems based on the application of portable aerial vehicles that perform the ignition source search and detection with the required degree of accuracy. Simultaneously, algorithms for the movement control of the MGA to the

ignition source start to play a crucial role in such systems (Semiz and Polat, 2020; Babel, 2014).

As it has been analyzed earlier by Efimov, Polyakov, and Yatsun, 2017; Polyakov, Efimov, and Yatsun, 2015, special attention should be paid to the solution of the scientific and technical problem on the development of methods for planning the movement trajectory of the MGA to the ignition source, simulation of movement modes of the devices associated with measuring the concentration of CO, which are currently insufficiently studied.

The transition to portable gas analyzers makes it possible to simplify the fire alarm system in many ways because one portable sensor can replace dozens of permanently fixed gas analyzers. Consequently, the MGA development has required small units with flapping wings that allow a long time to stay in the air. In this case, the airflows generated by the flapping wings practically do not affect the gas-air mixture when measuring CO concentration (McKinnon and Schoellig, 2020).

It is reasonable to use aerial vehicles with vertical-takeoff-and-landing functions as a portable platform, hovering at a specific point and horizontal flight. The primary flight criterion is the MGA movement in the direction of increasing carbon monoxide concentration, taking into account external disturbances and obstacles (Polyakov, 2019). The ignition source search problem and planning the movement trajectory to it will be considered taking into account the environment. As the primary criterion, the authors use the level of CO concentration in the air registered by the MGA. The increase in concentration is a determining feature for the portable gas analyzer movement towards the ignition source (Figure 1).

The MGA takes off from any horizontal surface to a specific height H according to the flight assignment. Then, to select the direction of movement, the device starts the movement in a circle of the radius R , according to the following law:

$$Z = H, \quad (\text{Eq. 1})$$

$$X = R \cos(\Omega t), \quad (\text{Eq. 2})$$

$$Y = R \sin(\Omega t), \quad (\text{Eq. 3})$$

R is the radius of the flight area, ΩR is the maximum speed of the MGA center of masses along its trajectory. The trajectory equation is as follows:

$$X^2 + Y^2 = R^2 \quad (\text{Eq. 4})$$

For the simulation of the MGA movement along a specified trajectory, it is proposed to use a model of the three-link electromechanical system with the oscillatory movement of external links, leading to the formation of both lifting force and thrust force, implemented by the application of the "asymmetry" effect of wing shape and speed. An ultrasonic distance measurement device is also installed on the body, which determines the distance to the obstacle, the information from which allows you to correct the MGA trajectory. When approaching the ignition source, the temperature t° of the environment increases, which the onboard sensor monitors. If the condition that

$$t^\circ < t_0^\circ, \quad (\text{Eq. 5})$$

Where t_0° is the limit temperature, is fulfilled, the other flight towards the ignition source is stopped.

The gradient of CO concentration and measuring this parameter with a portable sensor allows for the accurate ignition source. Even at a distance of 60-90 meters, there is an increased CO concentration, which helps the MGA move along the concentration gradient towards increasing the concentration.

An algorithm based on space sensing and trajectory definition has been developed to select the direction of movement. This algorithm guarantees the movement of MGA towards increasing CO concentration following simplex and Kiefer methods (Figures 2 and 3), according to paper (Emelianova, Poliakov, Efimov, and Yatsun, 2018).

The movement in space begins with the application of two-dimensional simplexes. As the MGA approaches the ignition source, it is proposed to search based on planning the straight-line segments, which allows for moving towards the increasing CO concentration with fixation of one of the coordinates, according to papers (Tang and Kumar, 2018; González-Sieira, Cores, Mucientes, and Bugarín, 2020). As illustrated by Figure 4, the position of the ignition source A (the point with the maximum concentration of CO) is set by an unknown radius-vector r_A , and the position of the MGA at the initial moment is set by the radius-vector r_B , respectively. The objective is to determine the position of point A from the values of CO concentration measured by the onboard sensor, from the predetermined initial position of MGA,

defined by the vector r_B under the known coordinates of obstacles C , represented by the vector r_C in the minimum time, according to thesis (Polyakov, 2019).

The search process is completed if the MGA falls into the point A^1 defined by the radius vector r_{A^1} . Herein the position of the point A^1 is determined by the value of the radius vector.

$$r_{A^1} = r_A + r_{eA} \quad (\text{Eq. 6})$$

The point A^1 is located inside the sphere with radius r_C , whose position is determined by the value of the radius-vector

$$r_C = r_A + r_e \quad (\text{Eq. 7})$$

The radius-vector r_e module determines the permissible error occurring when determining the position of the point A in space.

The MGA is considered as a controlled electromechanical system consisting of three links. The calculation scheme of the device is illustrated in Figure 5. The considered electromechanical system has 12 degrees of freedom. Six generalized coordinates describe the central link 2; simultaneously, two generalized coordinates have external links 1 and 3 (wings). It is assumed that the wings are attached to the body through cylindrical joints. In these joints, controlled electric drives are mounted, making it possible to rotate the wings relative to the body at predetermined angles by two coordinates. Therefore, currents received by the windings of electric motors that drive the external links, are also generalized coordinates.

Since the cylindrical joints can rotate relative to the body at a specific angle, this property of the joints makes it possible to simulate the external links intricate movement pattern. The movement of such an object takes place in the absolute OXYZ coordinate system. With the body (the second link of the triplet), the relative portable system of coordinates $C_2X_2Y_2Z_2$ is associated, the beginning of which coincides with the gravity center of the body C_2 . Axis C_2X_2 of this coordinate system is produced parallel to the longitudinal axis of the body, the axis C_2Y_2 is directed perpendicular to the plane $C_2X_2Z_2$, and the axis C_2Z_2 is directed perpendicular to the plane $C_2X_2Y_2$. The $C_2X_2Z_2$ plane is the symmetry plane of the body.

The coordinate systems $O_iX_iY_iZ_i$ ($i = 1, 3$) are associated with links 1 and 3, and the axes O_iX_i coincide with the axes of rotation of the

external links, and the axes $O_i Y_i$ belong to the wing plane and pass through the points C_i . For all changes in the MGA position relative to the absolute OXYZ coordinate system, both linear and angular, the associated coordinate systems move with it.

The radius-vector unambiguously determines the position of the mass center of the body (link 2) of the transport platform in space relative to a fixed coordinate system $R_{C_2} = (X, Y, Z)^T$. The orientation of the body in space is defined by the plane angles defining the vector $\theta = (\varphi, \psi, \theta)^T$. The gas analyzer 4 is installed in the front part of the fuselage. Here rangefinders 5 are also installed, which determine the distance to obstacle 6. It is accepted that the mass center of the body moves in space with the velocity $\bar{v}$, and the robot body rotates around the mass center with angular velocity $\bar{\omega}$. The MCA moves in space under the action of distributed forces arising from the interaction of system elements with the environment F_i , resulting in the tractive force T and lifting force Q . The force R_2 arising because of the interaction of tail assembly and relative airflow. This force magnitude and direction depend on flight control surfaces speed and angles β_1, β_2 . Besides, weight forces $m_i g$ act on the vehicle.

Differential equations in vector form, describing the movement of the mass center in a fixed coordinate system is as follows:

$$(m_1 + m_2 + m_3) \frac{d\bar{v}}{dt} + m_1 \left(\dot{T}_{20} \dot{T}_{12} \bar{r}_{C_2 C_1}^{(1)} + T_{20} \ddot{T}_{12} \bar{r}_{C_2 C_1}^{(1)} \right) + m_3 \left(\dot{T}_{20} \dot{T}_{32} \bar{r}_{C_2 C_3}^{(3)} + T_{20} \ddot{T}_{12} \bar{r}_{C_2 C_3}^{(3)} \right) = \sum m_i g + T_{12} T_{20} F_1^{(1)} + T_{32} T_{20} F_3^{(3)} \quad (\text{Eq. 8})$$

To describe the rotational movement, it was used the theorem of angular momentum change, as shown in equation 9.

$$\frac{d\bar{L}}{dt} = \sum \bar{M}_C^e \quad (\text{Eq. 9})$$

Moreover, the angular momentum of the considered mechanical system is described by equation 10.

$$\bar{L} = L_{C_2} + \sum \bar{L}_i \quad (\text{Eq. 10})$$

Where L_{C_2} the angular momentum of the body relative to the mass is center of the body;

$\bar{L}_i$ is the angular momentum of the i -wing relative to the mass center; $\sum \bar{M}_C^e = (M_{x_2}, M_{y_2}, M_{z_2})^T$ is the resultant vector of moments of external forces.

Substituting the values of the angular momentum of the system in the assumption of low masses of the external links, it is found the corresponding relations reflecting the theorem of angular momentum change in projections to the associated coordinate system. As a result, a system of differential equations describing the rotational movement of MGA can be obtained.

$$\begin{cases} J^x \dot{\omega}_x + \omega_y \omega_z (J^z - J^y) = M_{x_2} \\ J^y \dot{\omega}_y + \omega_x \omega_z (J^x - J^z) = M_{y_2} \\ J^z \dot{\omega}_z + \omega_x \omega_y (J^y - J^x) = M_{z_2} \end{cases} \quad (\text{Eq. 11})$$

where $J^x, J^y, J^z, \omega_x, \omega_y, \omega_z$ are axial moments of inertia and projections of angular velocity.

Eqs (8) and (11), taking into account the Euler kinematic equations, form a differential equations system describing MGA movement in space. The theoretical studies carried out make it possible to propose a method for determining the ignition source; however, due to the complexity of the considered MGA, it is necessary to supplement mathematical modeling results with experimental data.

One of the primary tasks to be solved in experimental research is verifying the azimuth definition concept by the onboard computer, which provides MGA movement towards a rise in the CO concentration. This task is solved using the onboard control system of the portable gas analyzer. It is necessary to check how useful in terms of accuracy and processing speed the calculation of the movement direction, determined by the azimuth angle, read from the north direction of the meridian, and the direction of the reference point with the maximum content of CO.

For the experimental study of the primary aerodynamic characteristics of the MGA based on the university, a multifunctional test-bed was developed to study the possibilities of CO registration in different modes of movement along a circular trajectory, the general view of which is presented in Figure 6. In Figure 6, the positions of the primary structural elements of the mechanism represented as: 1 – the base; 2 – the rack; 3 – the encoder; 4 – the accelerometer; 5 – rods; 6 – the MGA mounting bracket; 7 – the servo-machine; 8 – the electronics module; 9 – batteries.

In the course of the research, the test-bed design was improved to increase the functionality and accuracy of the measurements.

3. RESULTS AND DISCUSSION

With the help of the experimental test-bed, the values of angular velocity for the minimum angular velocity of 119 rpm and the maximum angular velocity of 190 rpm have been determined, which corresponds to the linear speed of MGA when moving in a circle of 1.5 m/s and 3.0 m/s. Angular velocity values were obtained at different voltages, namely at 2.5 V, 3 V, 3.5 V, and 4 V, as illustrated in Figure 7.

The dependencies of motor speed on the power supply voltage and the dependencies of motor angular velocity on power supply voltage have been determined (Polyakov, 2019). Special attention was paid to determining the propulsion created by the flapping wing. With the help of this test-bed, an experiment has been conducted, because of which the dependence of tractive force on the flapping frequency and power supply voltage has been determined. In addition, the dependence of the power consumed by the electric motor during propulsion has been determined. To experiment, a precision balance and photo strobe tachometer are used, making it possible to measure the rotation speed of the wing. The results of experimental studies are presented in Table 1.

Studies have demonstrated that the speed of MGA depends on the frequency of wing flapping, which in turn is determined by the angular velocity of the motor. Thus, this dependence makes it possible to change the flying speed of the platform, being especially essential when moving the MGA on a circular trajectory during CO concentration measurement. The data obtained makes it possible to determine the time spent in the air by the flying platform. At average speed, angular velocity equals 40-50 rad/s, which corresponds to ≈ 8.5 -10.5 W/N. Currents in the motor winding are equal to 0.12-0.16 A. Thus, for the operation of the air for more than 1 hour, it is necessary to have a battery capacity of at least 0.2 A/h.

Determination of the relative concentration of CO at a distance from a toxic gas source is carried out by formula: $C = C_x/C_{max}$, where C is the relative CO concentration; C_x is the CO concentration at a distance x from the source; C_{max} is the CO concentration in the source. The velocity of air masses influences the distribution of CO in

space in the ignition source area. At zero velocity of air masses, the CO concentration decrease depending on the distance can be determined by the diagram in Figure 8, obtained experimentally.

The problem of approximation of this dependence by a polynomial of the second order has also been solved:

$$C = a_2x^2 + a_1x + a_0 \quad (\text{Eq. 12})$$

To find the constants a_0 , a_1 , and a_2 , boundary conditions have been formulated.

- 1) When $x=0$, $C=1$, then:

$$a_2x^2 + a_1x + a_0 = 1$$

$$a_0 = 1$$

- 2) When $x=40$, $C=0.3$, then:

$$1600a_2 + 40a_1 = -0,7$$

- 3) When $x=15$, $C=0.6$, then:

$$225a_2 + 15a_1 = -0,4$$

- 4) Solving a system of equations:

$$\begin{cases} 1600a_2 + 40a_1 = -0,7 \\ 225a_2 + 15a_1 = -0,4 \end{cases}$$

$$\begin{cases} a_2 = 0,00037 \\ a_1 = -0,0325 \end{cases}$$

As a result, an equation has been obtained that allows for determining the CO concentration as a function of distance from the carbon monoxide source:

$$C = 0,00037x^2 - 0,0325x + 1 \quad (\text{Eq. 13})$$

The formula has also determined the dependence of the concentration gradient on the x coordinate:

$$\frac{dC}{dx} = 0,00037x - 0,0325 \quad (\text{Eq. 14})$$

Using the obtained expression, a diagram of gradient dependence on the distance to the ignition point has been plotted (Figure 9). The maximum gradient value equals 0.00325, and at a distance of 80-90 m from the source, the gradient tends to zero.

The conducted studies have demonstrated that the concentration gradient varies depending on the distance to the toxic gas source. At least two areas can be distinguished: I – the area with the high gradient level (0-40 m);

II – the area with the low gradient level (40-80 m).

For effective sounding of space to find concentration values at predetermined points, the most optimal is a circle located in the horizontal plane. When conducting experimental studies, it is essential to determine the number of points on the trajectory in which the CO concentration is measured. The number of control points varied in the range of 2, 4, and 8. The circle radius varied from 1 m to 10 m. The scheme of the experiment is presented in Figure 10. The determination of the distance from the point where the CO concentration measurement is achieved by the equation 15.

$$L_i = \sqrt{(x_a + R \sin \varphi_i)^2 + (y_a - R \cos \varphi_i)^2} \quad (\text{Eq. 15})$$

R is the radius of the MGA trajectory; x_a and y_a are coordinates of the ignition source; (i) the central angle determines the position of measurement points.

The formula shall determine the CO concentration in the points:

$$C_i = 1 - 0,0325L_i + 0,00037L_i^2 \quad (\text{Eq. 16})$$

The results of several calculations for different radii are presented in Tables 2 and 3. Based on the research results, a methodology has been developed to determine the azimuth for the MGA movement towards a rise in CO concentration. The onboard computer analyzes the data array obtained in Table 1 and Figure 8, and the coordinates of the point with maximum x_1 , y_1 , and minimum x_2 , y_2 concentrations are determined. The coordinates of these points are then used to calculate the equation of a straight line passing through these two points:

$$(y_1 - y_2)x + (x_2 - x_1)y + (x_1y_2 - x_2y_1) = 0 \quad (\text{Eq. 17})$$

In other words, it was obtained the general equation of a straight line on a plane in Cartesian coordinates:

$$Ax + By + C = 0 \quad (\text{Eq. 18})$$

Where A and B are not equal to zero simultaneously.

The formula can determine the tangent of the angle determining the movement vector towards the maximum concentration:

$$\text{tg } \varphi = \frac{(x_1 - x_2)}{(y_1 - y_2)} \quad (\text{Eq. 19})$$

If the maximum concentration is measured in the point C_8 with coordinates $x_1 = 3.54$; $y_1 = 3.54$, and the minimum concentration is measured in the point C_5 with coordinates $x_2 = 0$; $y_2 = -5$, then:

$$\text{tg } \varphi = \frac{(x_1 - x_2)}{(y_1 - y_2)} = \frac{3,54}{(3,54+5)} = 0,41 \quad (\text{Eq. 20})$$

hence $\varphi = \arctg(0,41) = 0,39$ or $\varphi = 22,2^\circ$.

The resulting angle determines the straight position of the line relative to the North and makes it possible to find the azimuth of the direction of further MGA movement. In the course of experiments, the issue of choosing the circle radius, at which the concentration gradient can be guaranteed determined, was solved:

$$R = R\left(\frac{dC}{dL}\right) \quad (\text{Eq. 21})$$

When conducting experimental studies of the concentration gradient, it was calculated using the approximate formula:

$$\frac{dC}{dL} = \frac{\Delta C}{L} \quad (\text{Eq. 22})$$

Where $L^2 = (x_1 - x_2)^2 + (y_1 - y_2)^2$

$\Delta C = CO_1 - CO_2$ is the difference between the maximum and minimum concentration.

The following formula can be applied to determine the circle radius:

$$R = \frac{R_0}{a + \frac{\Delta C}{L}} \quad (\text{Eq. 23})$$

Parameters R_0 and a are determined experimentally. The circle radius depends on the concentration of the gradient value, which increases as the MGA approaches the ignition point. The conducted researches have shown that for the confident determination of the azimuth, the circle radius should be not less than 5 meters, and the difference between the maximum and minimum concentration equals $\Delta C = 0,09$ of standard units at $L = 9$ m or approximately 2-3 ppm, confidently registered by the onboard recorder.

Further increase in radius makes it possible to increase the sensitivity and accuracy of measurements; however, a significant increase in the circle radius leads to a rise in the flight time and, consequently, to a decrease in the measurement of the method processing speed. Therefore, the optimal radius should be considered the radius $R = 5-7$ m. This radius determines the error with which the coordinates of the ignition source are determined. Since the selected sensor, measuring the CO concentration, registers the concentration at the distance of $L = 50-70$ meters, then the relative error of measurement can be estimated as a ratio:

$$\lambda = \left(\frac{R}{L}\right) \cdot 100\% = 10\% \quad (\text{Eq. 24})$$

The climatic and mechanical factors and modes of electrical power supply of sensors and electric drives of the portable platform affect the accuracy of the measurement. In this case, the research was carried out under the following climatic conditions: air temperature was equal to 23-26 °C, the pressure was equal to 750-760 mm Hg, and the wind was equal to 1-3 m/s. Mechanical factors and electric power supply modes, did not change.

The second question, which was to be answered during the experiments, was how fast it was necessary to move along the trajectory so that the onboard measuring system could register the concentration at the point. It was experimentally determined that the speed of the apparatus along the trajectory could vary from the minimum angular velocity of 0.3 1/s, which for a radius of 5 m corresponds to a linear velocity of 1.5 m/s to the maximum angular velocity of 2.0 1/s, which corresponds to a linear velocity of 10 m/s. Thus, the maximum flight time of the whole trajectory in case of 5 m radius equals $T = L/V = 31.4/1.5 = 20.9$ sec, and the minimum flight time equals $T = L/V = 31.4/10 = 3.1$ s.

Since the sensor measuring CO concentration has a processing speed of approximately 1.5 seconds, this factor limits the movement speed of the MGA along the trajectory. In case it is considered that CO concentration measurements take place in n points on the trajectory, the movement time should exceed $n \cdot 1.5$. When measuring the CO concentration in 8 points, the sensor flight time along the 1/8 of the circle will be equal to 2.6 s for the minimum speed and 0.39 s for the maximum speed, respectively. Therefore, the

maximum speed should be limited by the sensor processing speed of 1.5 s. Accordingly, the flight time along the trajectory will be 12 s, and the speed, in this case, will be $V = L/T = 31.4/12 = 2.6$ m/s.

Another issue to be solved by experiments - it is the number of points on a circle in which the CO concentration should be registered. A small step makes it possible to increase the accuracy of azimuth determination. Still, it will require many experiments, and a massive step reduces the probability of accurate azimuth finding. Again, the processing speed of the sensor is a decisive factor in this case. As it has been determined, the movement time along the trajectory T should be greater than $n \cdot 1.5$. Hence, the number of points growth leads to the fact that the minimum movement time increases, and the speed along the trajectory decreases. So when $n = 12$, the authors have $T = 18$ s, which corresponds to the speed $V = L/T = 31.4/18 = 1.74$ m/s, close to the minimum speed of MGA and corresponds to 1.5 m/s. Therefore, it is further accepted that $n = 8$.

According to the accepted in this method step-by-step principle of movement in space along the response surface, the steepest ascent can be performed many times until an almost stationary area where the concentration gradient is close to zero is reached.

4. CONCLUSION:

Thus, the article has considered general fire safety issues, namely, the early detection of the ignition source by determining the azimuth for the MGA movement towards a rise in CO concentration. The schemes of MGA movement towards the ignition source have been studied, and the three-link electromechanical system has been considered to achieve this goal. By experimental methods, there have been found the dependencies of the electrical motor speed of rotation on the power supply voltage and the dependencies of the motor angular velocity on the power supply voltage, the dependence of the tractive effort on the wing flapping frequency and power supply voltage, the dependence of the power consumed by the electric motor during propulsion. An equation has been obtained to determine the direction of azimuth towards the movement of CO concentration increase to determine the CO concentration depending on the distance from the carbon monoxide source, a graph of gradient dependence on the distance to the fire point has been drawn, the number of points on the trajectory in which the CO

concentration is measured has been determined, the optimal speed and the radius along which the CO concentration is measured has been determined. However, subsequent development is constrained by insufficient research of MGA design methods, the analysis of links between subsystems, and calculation methods based on mathematical models that adequately describe the primary modes of the MGA movement.

5. REFERENCES:

1. Babel, L. (2014). Flightpath planning for uncrewed aerial vehicles with landmark-based visual navigation. *Robotics and Autonomous Systems*, 62(2), 142-150.
2. Basharin, V.A., Grebenyuk, A.N., Markizova, N.F., Preobrazhenskaya, T.N., Sarmanaev, S.H. and Tolkach, P.G. (2015). Chemical substances as affecting the factor of fires. *Military Medical Journal*, 336(1), 22-28.
3. Basharin, V.A., Halimov, Yu.S., Tolkach, P.G. and Kuzmich, V.G. (2018). Acute carbon monoxide intoxication. *Military Medical Journal*, 339(4), 12-18.
4. Beck, Z., Teacy, W.T.L., Rogers, A. and Jennings, N.R. (2018). Collaborative online planning for automated victim search in disaster response. *Robotics and Autonomous Systems*, 100, 251-266.
5. Betting, B., Varea, E., Gobin, C., Godard, G., Lecordier, B. and Patte-Rouland, B. (2019). Experimental and numerical studies of smoke dynamics in a compartment fire. *Fire Safety Journal*, 108, 102855.
6. Bogomaz, A.M. (2017). Filling the premises with smoke during fires. *Bulletin of the Civil Defense Academy*, 4(12), 6-11.
7. Chew, M.Y., Wong, N.H. and Ho, J.C. (2001). Smoke control in confined space. *Journal of Applied Fire Science*, 10(2), 109-125.
8. Chlenov, A.N., Menkeev, A.I., Darbakov, D.V., Kiselev, K.V. and Chernenko, S.A. (2018). The current state and prospects of development of fire detectors. In *Historical Experience, Modern Problems, and Prospects of Educational and Scientific Activity in the Field of Fire Safety*. Papers presented at the International Scientific and Practical Conference (pp. 375-379).
9. Efimov, S.V., Polyakov, R.Yu. and Yatsun, S.F. (2017). Method of early fire detection with the help of portable gas fire detectors. *Proceedings of Federal State Budgetary Educational Institution of Higher Education «Southwest State University»*, Series: *Technique and Technology*, 4(25), 81-89.
10. Emelianova, O.V., Poliakov, R.Yu., Efimov, S.V. and Yatsun, S.F. (2018). Portable flying complex for early detection of the fire sources. *Fundamental and Applied Problems of Technique and Technology*, 3(329), 136-141.
11. Estrada, M. and Ndomab, A. (2019). The uses of uncrewed aerial vehicles –UAV's (or drones) in social logistics: Natural disasters response and humanitarian relief aid. *Procedia Computer Science*, 149, 375-383.
12. Fedorov, A.V., Lukyanchenko, A.A. and Sokolov, A.V. (2006). Experimental Studies of hydrogen and carbon oxide concentration fields at the early stage of fire at the premises and determine safe installation places of gas fire detectors. *Fire and Explosion Safety*, 15(3), 74-84.
13. Fyodorov, A.V., Lukyanchenko, A.A. and Sokolov, A.V. (2005). Analytical review of gas fire detectors. *The technology of Technosphere Safety*, 1(1), 5.
14. González-Sieira, A., Cores, D., Mucientes, M. and Bugarín, A. (2020). Autonomous navigation for UAVs managing movement and sensing uncertainty. *Robotics and Autonomous Systems*, 126, 103455.
15. Goremykin, A.A., Lukashevich, N.D. and Alekseev, V.F. (2017). Principles of fire detectors selection for premises protection. In A.A. Savochkina (Ed.), *Modern Problems of Radio Electronics and Telecommunications "RT-2017."* Papers presented at the 13th

- International Youth Scientific and Technical Conference, Sevastopol, 20-24 November. Sevastopol, Russia: Sevastopol State University.
16. Heightman, A.J. (2010). *The silent killers. CO monitoring adds a new dimension to firefighter rehab and emergency care*. San Diego, CA: Elsevier.
 17. Jasim, O.Z., Hamed, N.H. and Abid, M.A. (2020). Urban air quality assessment using integrated artificial intelligence algorithms and geographic information system modeling in a highly congested area, Iraq. *Journal of Southwest Jiaotong University*, 55(1). Retrieved from <http://jsju.org/index.php/journal/article/view/517>
 18. Kazantsev, S.Y. and Krasilnikov, V.I. (2019). Medical and biological aspects of carbon monoxide damage to the body. *Actual Problems of Medicine and Biology*, 1, 13-16.
 19. Kolodyazhny, S.A. and Kolosova, N.V. (2015). Calculation of parameters of combined extract-and-input ventilation for the protection of buildings from smoke spreading during a fire. *Scientific Journal Engineering Systems and Structures*, 3(20), 68-76.
 20. Kozubovsky, V.R., Misevich, I.Z. and Ivanchuk, M.M. (2015). Comparative analysis of gas detectors for early fire detection. *Bezpieczenstwo Technika Pożarnicza*, 40(4), 107-122.
 21. Malashkina, V.A. and Lobaznov, A.V. (2011). Intercomparison of methods of fire early stage detection. *Mining Information-Analytical Bulletin (Scientific and Technical Journal)*, S7, 79-89.
 22. McKinnon, C.D. and Schoellig, A.P. (2020). Estimating and reacting to forces and torques resulting from common aerodynamic disturbances acting on quadrotors. *Robotics and Autonomous Systems*, 123, 103314.
 23. Mohammed, Z.B., Kamal, A.A.K., Resheq, A.S. and Alabdraba, W.M.Sh. (2019). Assessment of air pollution over Baghdad City using fixed annual stations and GIS techniques. *Journal of Southwest Jiaotong University*, 54(6). Retrieved from <http://jsju.org/index.php/journal/article/view/428>
 24. Polyakov, R.Yu. (2019). *A portable instrumental platform for the ecological monitoring system of the atmospheric air pollution by the toxic gases*. Kursk, Russia: Southwest State University.
 25. Polyakov, R.Yu., Efimov, S.V. and Yatsun, S.F. (2015). Robot-insektoper for environmental monitoring. *Bulletin of Voronezh Institute of the State Fire Service of State Ministry of Emergency Situations of Russia*, 3(16), 48-51.
 26. Poroshin, A.A. and Surkov, S.A. (2016). Development directions for testing methods of gas fire detectors. *The Problems of Risk Management in the Technosphere*, 2(38), 33-37.
 27. Russian Ministry for Emergency Situations. (2020, April 17). *Reports with a summary and analysis of compliance practices, standard, and mass violations of mandatory requirements*. Retrieved from http://www.consultant.ru/document/cons_doc_LAW_355636/6727b4a58823f036bde5f951f6715d6f8b9dee5e/
 28. Saidulin, E.N. (2009). Gas fire detectors: Detection of fire at an early stage. *Safety Algorithm*, 6, 32-34.
 29. Semiz, F. and Polat, F. (2020). Solving the area coverage problem with UAVs: A vehicle routing with time windows variation. *Robotics and Autonomous Systems*, 126, 103435.
 30. Sudhakar, S., Vijayakumar, A.V., Kumar, C.S., Priya, V., Ravi, L. and Subramaniaswamy, V. (2020). Uncrewed aerial vehicle (UAV) based forest fire detection and monitoring for reducing false alarms in forest-fires. *Computer Communications*, 149, 1-16.
 31. Sychev, I.V., Sitnikov, A.I. and Rakityansky, A.A. (2018). Application of gas fire detectors upon detection of fire. *Fire Safety: Problems and Perspectives*, 1(9), 864-866.

32. Tamura, G.T. (2008). *Smoke movement and control in high-rise buildings*. Moscow, Russia: Russian State Library.
33. Tang, S. and Kumar, V. (2018). Autonomous flight. *Annual Review of Control, Robotics, and Autonomous Systems*, 1, 29-52.

Figure 1. The movement scheme of the portable gas analyzer (MGA) to the ignition source

Figure 2. Spatial scheme of the portable gas analyzer (MGA) movement to the ignition source by the simplex method. A is the point with the maximum concentration of CO; B is the initial position of the MGA; Q is the concentration of CO.

Figure 3. Spatial scheme of the portable gas analyzer (MGA) movement to the ignition source by Kiefer's method. A is the point with the maximum concentration of CO; B is the initial position of the MGA; Q is the concentration of CO

Figure 4. Scheme of portable gas analyzer (MGA) movement to the ignition source. A is the ignition source; B is the initial position of the MGA; C is the obstacle; M_i is the intermediate position of the MGA

Figure 5. Calculation scheme of the portable gas analyzer

Figure 6. General view of the 3D model of the test-bed

Figure 7. Dependency diagram of the electrical motor angular velocity on the power supply voltage

Figure 8. Change in the relative CO concentration as a function of distance from the ignition source

Figure 9. Change in the gradient of CO concentration as a function of distance from an ignition source

Figure 10. Experimental design for determination of CO concentration during MGA movement in a circumferential direction

Table 1. Results of experimental research

ω , rad/s	T, h	I, A	N, B _T	λ , W/H
15.70	0.00	0.02	0.01	-
28.26	0.01	0.06	0.06	6.75
37.68	0.02	0.10	0.15	8.44
48.15	0.03	0.15	0.30	10.21
56.52	0.04	0.21	0.53	12.81
64.89	0.05	0.26	0.78	14.36
72.64	0.07	0.31	1.09	16.29
80.59	0.08	0.36	1.44	18.33

Table 2. CO concentration for $R = 3$ m

Point number									
Name		C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈
Calculation	C _P	0.33	0.31	0.301	0.30	0.30	0.31	0.32	0.33
Experiment	C ₃	0.34	0.32	0.29	0.29	0.28	0.31	0.33	0.34
Distance to the ignition point	L. m	33.6	35.6	37.8	39.0	37.8	36.8	34.91	33.1

Table 3. CO concentration for $R = 5$ m

Point number									
Name		C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈
Calculation	C _P	0.34	0.31	0.29	0.288	0.29	0.3	0.34	0.35
Experiment	C ₃	0.36	0.33	0.30	0.29	0.28	0.31	0.35	0.37
Distance to the ignition point	L. m	32.02	35.42	39.05	40.97	40.31	37.36	33.54	31.7