Atmospheric air pollution monitoring using flying robotics

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Abstract. This article discusses a method for detecting a source of atmospheric air pollution (for example, carbon monoxide) using flying robotic equipment. The relevance of this study is the autonomy of methods for detecting a source of pollution with a given accuracy. To achieve this goal, the scheme of a mobile instrument platform in the form of an electromechanical system and the problem of finding a source of pollution were considered. By calculation and experiment, the radius of the circle and the speed at which the maximum and minimum CO concentration will be measured were obtained, an algorithm for the method for determining the coordinates of the CO concentration source based on a mobile instrument platform was proposed.

1. Introduction

The health of the city's population depends on many factors, among which the state of the environment takes a significant place. Air pollution with toxic gases is one of the reasons for the accumulation of harmful mutations in the human body, which will be inherited by subsequent generations [1].

Existing systems for monitoring emergency emissions provide continuous measurement of concentrations of toxic gases in the air, as well as current values of meteorological parameters at potentially hazardous facilities. Air sampling is carried out at stationary stations equipped with the necessary equipment and automatic gas analyzers. However, the stationarity of such sensors-analyzers of gas contamination makes it impossible to ensure such monitoring in all areas of the facility and its surrounding area. One of the monitoring options is an inspection of the facility by a technical service employee, but this method has a number of significant drawbacks, including a threat to human health. Thus, there is a problem of promptly obtaining sufficient information (initial emission parameters, data on meteorological conditions, etc.) about the hazardous situation at the workplace and adjacent territories, necessary and sufficient for taking appropriate measures [2].

One of the ways to further improve environmental safety systems is the use of mobile instrument platforms (MIP) moving to the source of toxic gases, using the example of carbon monoxide (CO) and allowing to determine its coordinates [3-5].

Therefore, the purpose of this study is to increase the efficiency of the method and means of environmental monitoring of atmospheric air through the use of mobile instrument platforms, the control system of which is based on the use of dynamic models and algorithms for traffic control based on the concentration of toxic gas (for example, CO), measured by an onboard gas analyzer. The main tasks that need to be solved during experimental studies are the task of testing the efficiency of the concept of determining the azimuth by the on-board computer, ensuring the movement of the mobile gas analyzer in the direction of increasing the CO concentration, determining the radius along
which the movement will occur at the moment of fixing the minimum and maximum CO concentration, the speed of movement around the circle, as well as the algorithm of the method for determining the coordinates of the source of pollution.

2. Materials and methods

The transition to mobile gas analyzers makes it possible to simplify the system of the environmental monitoring system in many respects, since one mobile sensor can replace dozens of gas analyzers installed permanently [6-8]. The use for these purposes, the most common today, of multi-rotor flying platforms for mobile gas analyzers turns out to be irrational due to the fact that the air flows created by the propellers affect the convection and diffusion process in the MIP operation zone, which significantly distorts the readings of the gas analyzer. [9].

Scientists from NASA got a picture of the visualization of air flows around the quadcopter during its flight. It has been shown that the air flows created by the propellers are turbulent, in addition, there are significant air pressure drops. As the propellers move over the aircraft body, air turbulence is created. When the propellers pass over the drone's beams, the fuselage creates a powerful downward force, which reduces the overall thrust of the aircraft. All this negatively affects the operation of the gas analyzer.

Therefore, to create the MIP, it was necessary to create a new class of small devices that allow them to stay in the air for a long time. At the same time, it is important to minimize the influence of the air flows generated by the flapping wing on the measuring system of the gas analyzer installed on board. Small-sized semiconductor gas analyzers have a light weight of about 3g, which allows them to be installed on small-sized flying platforms. Such qualities are possessed by aircraft made according to the flapping wing scheme, a distinctive feature of which is the possibility of movement in a gliding mode, in which there is a smooth flow of the aircraft with a laminar air flow, which favorably affects the measurement results [9].

To construct mathematical models of the movement of a mobile instrument platform, it is proposed to consider an object in the form of a simplified electromechanical system (Figure 1).

Figure 1. Design scheme of the mobile instrument platform (MIP).

The center of mass of the body moves in space with a speed $v_c$, and the body rotates around the center of mass with an angular velocity $\omega$. MIP moves in space under the action of distributed forces arising from the interaction of system elements with the environment $F_i$, reduced to traction $T$ and lift $Q$, the force arising from the interaction of the tail unit and the incident air flow $R_2$ and weight forces $m_ig$. The wing plate rotates at an angle $\phi_{12} = \phi_{32}$ and angle $\alpha_1$. 
Consider the problem of finding a source of toxic gas and planning a trajectory to it, taking into account the environment [10, 11]. As the main criterion, we use the level of CO concentration in the air recorded by the MIP. An increase in concentration is a defining sign for the movement of a mobile gas analyzer (MGA) towards the source of CO (Figure 2). As an example, we use a fire with the release of a large amount of carbon monoxide (CO).

Figure 2. Movement diagram of the mobile instrument platform to the ignition source (CO concentration).

The MIP takes off from any horizontal surface to a certain height \( H \) in accordance with the flight task. Further, to select the direction of movement, the apparatus begins to move in a circle, of radius \( R \), during movement along which the minimum and maximum concentration of CO is fixed for further choice of the direction of movement in the direction of increasing CO concentration, according to the following law:

\[
Z = H, \quad X = R \cos(\Omega t), \quad Y = R \sin(\Omega t),
\]

where \( R \) – overflight radius, \( \Omega R \) – maximum speed of movement of the center of mass of MGA along the trajectory. The trajectory equation has the form:

\[
X^2 + Y^2 = R^2.
\]

To simulate the movement of the MPP along a given trajectory, it is proposed to use a model of a three-link electromechanical system with an oscillatory movement of the outer links, leading to the formation of both the lift force and the thrust force, realized by using the effect of "asymmetry" of the wing shape and speed [12]. An ultrasonic range finder is also installed on the body, which determines the distance to the obstacle, information from which allows you to correct the trajectory of the MIP. The temperature of the environment \( t^\circ \) controlled by the onboard sensor rises when approaching an ignition source. If the condition \( t^\circ < t_0^\circ \), where \( t_0^\circ \) - limiting temperature, is satisfied further flight towards the source of ignition is terminated [13].

The presence of a CO concentration gradient and the ability to measure this parameter using a mobile sensor allows you to accurately find the source of CO concentration. Even at a distance of 60-90 meters, an increased concentration of CO is observed, which allows moving along the concentration gradient in the direction of increasing concentration.

3. Research results

During the experiments, the question of choosing the radius of the circle was solved, at which a guaranteed determination of the concentration gradient is possible:

\[
R = R\left(\frac{dC}{dL}\right)
\]

When conducting experimental studies of the concentration gradient using the approximate formula:  

3
where $L^2=(x_1-x_2)^2+(y_1-y_2)^2$.

$\Delta C=\text{CO}_1-\text{CO}_2$ difference between maximum and minimum concentration.

To determine the radius of a circle, you can apply the formula:

$$R = \frac{R_0}{a + \frac{\Delta C}{L}}$$

Parameters of $R_0$, $a$ - determined experimentally.

The radius of the circle depends on the magnitude of the concentration gradient, which increases when approaching the fire source. The conducted studies have shown (Tables 1, 2) that for a confident determination of the azimuth, the radius of the circle should be at least 5 meters, the difference between the maximum and minimum concentration is $\Delta C=0.09$ conventional units at $L=9$ m or approximately 2-3 ppm, what is confidently recorded by the on-board device.

### Table 1. CO concentration for $R = 3$ m.

| Name                      | Point number |
|---------------------------|--------------|
|                           | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ |
| Calculation               | 0.33  | 0.31  | 0.301 | 0.30  | 0.31  | 0.32  | 0.33  |
| Experiment                | 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 2. CO concentration for $R = 5$ m.

| Name                      | Point number |
|---------------------------|--------------|
|                           | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ |
| Calculation               | 0.34  | 0.31  | 0.29  | 0.288 | 0.29  | 0.3  | 0.34  | 0.35  |
| Experiment                | 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  |

Further increase in the radius makes it possible to increase the sensitivity and accuracy of measurements; however, a significant increase in the radius of the circle leads to an increase in the flight time and, accordingly, to a decrease in the speed of the measurement method.

Therefore, the optimal radius should be considered the radius $R = 5-7$ m. In fact, this radius determines the error with which the coordinates of the ignition source are determined. Since the selected CO concentration measurement sensor registers the concentration at a distance of $L = 50-70$ meters. Then the relative measurement error can be estimated as the ratio:

$$\lambda = \left(\frac{R}{L}\right) \cdot 100\% = 10\%$$

Also, climatic and mechanical factors play a role in the measurement accuracy, as well as the modes of electric power supply of sensors and electric drives of the mobile platform. In this case, the studies were carried out under the following climatic conditions: air temperature 23-26 °C, pressure 750-760 millimeters of mercury, wind 1-3 m/s. Mechanical factors, as well as the modes of electrical power supply, did not change.

The second question, to which it was necessary to find an answer during the experiments, is how fast it is necessary to move along the trajectory so that the onboard measuring system could register the concentration at a point. It has been experimentally established that the speed of the vehicle along the trajectory can vary from the minimum angular velocity of 0.3 1/s, which for a radius of 5 m...
corresponds to the linear velocity of 1.5 m/s to the values of the maximum angular velocity of 2.0 1/s, which corresponds to a linear speed of 10 m/s. Thus, the maximum flight time of the entire trajectory with a radius of 5 m is \( T = \frac{L}{V} = \frac{31.4}{1.5} = 20.9 \text{ s} \), and the minimum \( T = \frac{L}{V} = \frac{31.4}{10} = 3.1 \text{ s} \).

Since the sensor measuring CO has a response time of approximately 1.5 s. Then this factor limits the speed of the MIP along the trajectory.

If we assume that CO measurements take place at \( n \) points on the trajectory, then the time of movement should exceed \( n \times 1.5 \).

When measuring the CO concentration at 8 points, the time of flight of the sensor along 1/8 of the circle will be 2.6 s for the minimum speed, and 0.39 s for the maximum, respectively.

Therefore, the maximum speed should be limited to the sensor speed of 1.5 s. Accordingly, the time of flight along the trajectory will be 12 s and the speed will be \( V=\frac{L}{T}=\frac{31.4}{12}=2.6 \text{ m/s} \).

Based on the experimental studies, an algorithm was developed for the method for determining the coordinates of the source of CO concentration based on a mobile instrument platform:

1. When an increased concentration is detected of \( \text{CO} > a \) in the air, flying mobile platform, located at point B with coordinates \( x_B, y_B \) takes off vertically to a height \( H_0 \), which is determined by the parameters of the warehouse and hangs at this height.

2. Then the mode is switched to movement along this circle of radius \( R = 5 \text{m} \), at this stage, at the given points, the coordinates of which are determined by the compensated signal of the GPS system and the local navigation system, the CO concentration is measured. The absolute error in determining the coordinates of points is 0.3 - 0.7 m. Therefore, to obtain reliable data, the flight can occur several times.

3. Based on the results of these measurements at the measurement points of the CO concentration, the on-board computer determines the average concentration value at the points.

4. The comparison unit determines the points with the maximum and minimum CO concentrations on this circle and then the direction of movement towards the maximum concentration is calculated.

5. There is a switch to the mode of movement along a horizontal straight line in accordance with the specified trajectory at a distance \( L = 10\text{-}20 \text{m} \) to a point with coordinates \( x_1, y_1 \). In this position, the flying platform stops and hovers at a certain height \( H_1 \).

6. Next, the mode is switched to the movement of the circle, at the given points of which the CO concentration is measured. To obtain reliable data, the flight takes place three times.

7. The comparison unit determines the points with the maximum and minimum CO concentrations on this circle and then the direction of movement towards the maximum concentration is calculated.

8. There is a switch to the mode of movement along a horizontal straight line in accordance with the trajectory calculated at the previous stage at a distance of \( L = 10\text{-}20 \text{m} \) to a point with coordinates \( x_2, y_2 \). In this position, the flying platform stops and hovers at a certain height \( H_2 \).

9. Next, the mode is switched to the movement of the circle, at the given points of which the CO concentration is measured. The comparison unit determines the points with the maximum \( \text{CO}_{\text{max}} \) and minimal \( \text{CO}_{\text{min}} \) concentrations CO, if \( \text{CO}_{\text{max}} - \text{CO}_{\text{min}} \) is less than some positive number and the process of motion stops, and the coordinates \( x_2, y_2 \) correspond to the coordinates of the ignition source with an absolute error of 5m.

**4. Conclusions**

In this study, the issue of improving environmental safety systems using mobile instrument platforms moving to a source of toxic gases was considered, using the example of carbon monoxide (CO) and allowing to determine its coordinates. To achieve this goal, a design scheme of a mobile instrument platform was proposed, a scheme of MIP movement to a source of CO concentration, and using experimental data, the radius of a circle and a speed of movement along it were calculated, an
algorithm for a method for detecting a pollution source was proposed. However, further development is hindered due to insufficient research of MIP design methods, analysis of connections between subsystems, calculation methods built on mathematical models that adequately describe the main modes of motion of a mobile instrument platform.

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