Modeling the optimal route of unmanned systems during the extinguishing of industrial and natural fires

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Abstract. The scientific relevance of this study lies in the absence of operational principles as well as control algorithms over the group of quadcopters in order to monitor situation during the state of emergency and for application with decision-making system. As a part of the study, models and algorithms were created, which allow the group of quadcopters to undertake concurrent work as well as to ensure mutual coordination. Instructional guidelines were developed on the usage of unmanned aerial vehicles for emergency prevention and mitigation. We thoroughly studied and employed a bidimensional motion simulation of the quadcopter in path and full circle; movement changes of drone population; three-dimentional motion of the group of quadcopters in a predetermined path.

1. Introduction
Our country has its own special features: an immense territory, low overall population density along with high density of people in big cities, regions which often suffer from natural emergencies such as floods, earthquakes, forest fires, landslides etc. All abovementioned hinders MSE functioning therefore it must always be in the state of permanent readiness and swift response [1].

Currently structural units of MSE of Russia are being refurbished with such technical equipment as to explore vast hardly accessible emergency areas of natural, man-caused or terrorism-related type. For this purpose, territorial bodies of MSE sign agreements with aircraft enterprises or make use of airpower residing in regional centers [2]. However, manned airpower has several disadvantages: not financially viable due to its cost; slow response time (up to 6 hours); considerable dependence on weather conditions etc.

The number of challenges makes it necessary to find the most effective way to improve functioning of the MSE of Russia. This number includes relative insufficiency of manpower working at MSE, necessity for keeping lives of emergency response group members under conditions of major man-caused disasters complicated by radioactive, chemical and biological objects; considerable budget limitations.

One of the more effective solutions to this problem is to make use of unmanned aerial vehicles (UAV) not only for military purposes but also for emergency management practices [3]. Unmanned aerial vehicle is a plane or a helicopter either radio-controlled by an operator or autonomously controlled by special software. The capacity of such vehicles is mostly defined by their flying altitude. Today the altitude is limited to 20 km and to 30 km in the long run. Considering such an altitude, an unmanned aircraft can be compared to a satellite. UAV can keep track of about million sq. km in area, monitoring the situation in real-time mode across the entire region.

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The aim of this study was to develop instructional guidelines on the usage of unmanned aerial vehicles for emergency prevention and mitigation and to create an algorithm to control a group of quadcopters in multi-agent environment with both optimization and decision-making methods implemented [4].

The objectives of the study:
1. To provide a thorough literature overview on the subject of graduation thesis.
2. To examine UAV characteristics and its capacity while using for emergency prevention and mitigation.
3. To ascertain the most appropriate establishing control over the use of UAV forces for emergency prevention and mitigation.
4. To develop instructional guidelines on the use of UAV for emergency prevention and mitigation.
5. To develop a model and to create and code an algorithm that would allow the group of quadcopters to undertake concurrent work as well as to ensure mutual coordination.

The results of this study were expected to be recommendations on effective use of UAV.

2. Relevance of the study
1. We thoroughly studied and employed the two-dimensional motion simulation of the quadcopter in polygonal line and full circle; movement changes of drone population; three-dimensional motion of the group of quadcopters in a predetermined path [5].
2. We developed a model which defined the requirements for controlling actions: control of triaxial linear velocity and control of roll, pitch and yaw errors correction.

3. Use of UAV in MSE operational activities
At the present time, MSE of Russia is running the process of technical refurbishment. The point of this process is to improve efficiency of MSE functioning and response time in terms of emergency mitigation. One of the most promising decisions is to embed UAV system into the MSE technological infrastructure.

The starting point for development of legal framework on UAV use is to define a concept of UAV through the regulatory act as well as classify them by size, operational range, pay load, etc.

The definition of UAV has been given since 1 November 2010 after the Federal regulation on the Russian Federation airspace management approved by a decision of Government of the Russian Federation of 11 March 2010 №138 entered into force. Item 2 of the regulation defines UAV as “an aerial vehicle which operates the flight without a pilot (personnel) on board and is controlled automatically while airborne or by an operator from the control point or both [1, 6].

The system providing automatic control over air complex (AC) can be seen as a top-down structure that contains control signals (descending) and data signals (ascending). We analyzed three levels of automatic AC control, models which were used to make up controlling actions and top level of control which was completely under command of human-operator. It is important to stress that the operator, as a rule, has the possibility to control any of the lower levels and to determine:
1. A running task for air complex control system (ACCS);
2. An action for specific UAV to perform;
3. Desired value for some state parameter of UAV.

The operator can get all the information needed about AC components status (except visual information from the environment) with the help of display device. The device is commonly included in ACCS.

There are strict requirements imposed on AV equipment to make sure that all equipment is fail-safe. The tier 1 equipment assures reliability of the entire UAV complex. Top-tier includes navigational equipment, manual landing system, servo-unit and automatic recovery system. The rest (payload unit) is a part of tier 2 equipment [2,7].
As a rule, during the flight the AV is automatically controlled by integrated navigation and control system consisting of:

1. Satellite communication receiver to receive information from GLONASS and GPS;
2. Inertial sensor system to estimate attitude and motion rate of AV;
3. Air data system to measure altitude and airspeed;
4. Different types of antennas to perform the variety of tasks.

Integrated navigation and control system provides:

1. Desired track flight (with the defined positioning data and turning points);
2. Route job change or recovery to the starting point if commanded by ground control point;
3. Fly-around of a spot;
4. Autofollowing the target;
5. Stabilization of AV attitude angles;
6. Maintenance of altitude, ground-speed and airspeed;
7. Collection and relaying of telemetered data, flight parameters and mission equipment status;
8. Program control over mission equipment.

Airborne communication system:

1. Functions within authorized bandwidth;
2. Provides data relay from board to ground and from ground to board.

Data relayed from board to ground:

1. Telemetry data;
2. Video and photo streaming.

Data relayed from ground to board consists of controlling commands for AV and mission equipment.

Data relayed from AV is systematized depending upon the degree of a threat. Systematization is carried out by ground control station (GCS) operator or AV on-board computer. The second case scenario suggests that AC software includes elements of AI providing quantitative criteria and levels of danger for the threat. These criteria can be provided by expert analysis in such a way to minimize the probability of false alarm activation.

There are no differences between unmanned and manned flights. AV are equipped with targeting systems, integrated radar facility, sensors and cameras.

UAV of plane and helicopter type run on electric motors or internal-combustion engines (ICE).

UAV unit must consist:

1. A minimum of two aerial vehicles;
2. GCS completed with a laptop of a special design (shockproof, moisture-protective, dustproof);
3. Receiver-transmitter antenna fitted with autotracer and umbilical cord;
4. Pole and (or) a tripod to set a receiver-transmitter antenna;
5. Charging set (or a battery charger) with a package of accumulator batteries or fuel and lubricant materials load for UAV engines;
6. Launcher;
7. Maintenance parts kits and service equipment to perform minor field repairs.
8. Flight operation manual.

Depending on UAV type, video and photo cameras should be installed in a fuselage nose section, on wings or under the fuselage. Camera lenses can be motionless or have one or two degrees of freedom and support variable focal length:

1. The most preferable cameras for area monitoring are ring-type cameras installed on gyro-stabilized platform under UAV fuselage and providing panoramic view of the lower hemisphere.
2. The most preferable photo cameras for area survey are cameras fixed in a motionless position on wings or under UAV fuselage.

UAV exploitation in work environment is divided into following stages:

1. Preliminary preparation;
2. Preflight preparation;
3. Flight execution (takeoff, routing, landing);
4. Ground job (data processing).

Operator duties while executing a flight in a video surveillance mode:
1. Target detection (as a whole);
2. Target recognition by the entirety of unique features (identification of unique features);
3. Verbal description of the target (i.e. “wildfire location”, “land space and character of damage area”, “a car”, “a boat”, “a man”, etc.);
4. Locking the target position;
5. Surveillance and tracking of the target (recording at any given time).

To execute surveillance operation, the operator preliminary plans a UAV flight route which depends on current task and terrain characteristics. In generic case of aerial area survey or target detection, UAV heads for the monitoring area and executes a flight there according to operator’s program. UAV relays video images of area and objects received during the flight to GCS in real-time scale. The operator makes an assessment of incoming data, adjusts the flight route if needed, and manipulates on-board equipment (for example, a video camera).

The most important feature of UAV surveillance is a possibility to re-approach the target multiple times and holding the video image of the target for a certain period of time [8].

Flight route should be planned in such a manner as to provide the survey of the entire operating area.

Planning the flight route instructions:
1. It is recommended to take outstanding and clearly visible reference objects as turning points (river knees, cross-roads, solitary buildings, etc.).
2. The first turning point (departure point) is put near the starting point.
3. The distance between GCS antenna and the farthest turning point should not interrupt constant video and telemetry data reception from the UAV board.
4. Preferably, the flight path should not lay near high-voltage lines and objects emitting intense electromagnetic radiation (position-radar stations, receiver-transmitter antennae, etc.).
5. The estimated time of flight must not exceed 2/3 of endurance capability recommended by manufacturer.
6. It is necessary to provide no less than 10 minutes of flying time to perform takeoff and landing.

The most reasonable route for the general area survey is a circle race route (Figure 1). The main advantages of this method are sufficient coverage, operability and swiftness of the survey, possibility to observe poorly accessible area, relatively simple planning of the flight assignment and quick processing of received data. The flight route must provide full view of the operating area. UAV should fly into wind during the first half of the route in order to rationally calculate UAV energy consumption.
In order to provide a detailed observation of a particular area it is reasonable to use linear mutually parallel routes (Figure 2).

When the aerial survey of the area is needed, it is recommended to use parallel routes (Figure 3). While planning a route, operator must take into account maximum width of the UAV camera’s field of view on UAV command altitude. Fields of view of many UAV should overlap each other’s edges for 15-20%.
Fly-around is used during inspection of a particular object (Fig. 4). It is widely used in cases when co-ordinates are known and the status of the object needs to be reported.

4. Proposed Method
The most important task in terms of group-wide use of UAV is to define the number of them required to execute a particular operation. The solution exerts major influence on the choice of methods and means of control over the airborne UAV grouping, operating unit formation, service support, etc.
It stands to mention that existing literature does not raise the problem of defining objective UAV groupings level [9].

This part of the study deals with assignment and solution to tasks concerning UAV grouping level optimization.

Let us exemplify the optimum quantity of UAVs given the random current of use requests.

Assume that it is to find a number of UAVs to monitor the emergency or pre-emergency engineering status of products pipelines in poorly accessible area for the benefit of fuel-and-energy company which consists of \( m = 7 \) organizations. Let us consider \( T_1 = 240 \) min and \( T_2 = 600 \) min. Then the values of intensity of request stream are: \( \lambda = 0.042 \) min\(^{-1}; \) \( \mu = 0.0017 \) min\(^{-1}\).

All the compromised solutions obtained by the numerical technique are charted into Table 1.

**Table 1. All the compromised solutions to the problem**

| The number of compromised solution | Optimum quantity of UAV in grouping, \( N \) | Requests awaiting ratio, \( k_1 \) | UAV downtime ratio, \( k_2 \) |
|-----------------------------------|---------------------------------|----------------------------|-----------------|
| 1                                 | 2                               | 0.62                       | 0.06            |
| 2                                 | 3                               | 0.54                       | 0.23            |
| 3                                 | 4                               | 0.51                       | 0.39            |
| 4                                 | 5                               | 0.50                       | 0.51            |

Let the solution be: \( N_0 = 3, k_1^0 = 54\%, k_2^0 = 23\% \). The latter means that if a company uses a group of three UAVs, the equated interest of queued requests will be 54\% and 23\% of UAV at the average will stay idle.

Table 2 shows the solutions of the problem in case when the probability of UAV flight failure \( q = 0.05 \).

**Table 2. Solutions to the problem with probability of UAV flight failure**

| The number of compromised solution | Optimum quantity of UAV in grouping, \( N \) | Requests awaiting ratio, \( k_1 \) | UAV downtime ratio, \( k_2 \) |
|-----------------------------------|---------------------------------|----------------------------|-----------------|
| 1                                 | 2                               | 0.64                       | 0.05            |
| 2                                 | 3                               | 0.55                       | 0.20            |
| 3                                 | 4                               | 0.52                       | 0.35            |
| 4                                 | 5                               | 0.51                       | 0.46            |

The results showed in Tables 1 and 2 almost do not change because of the high integrity level (\( q = 5\% \)) of current non-military UAC [10].

We also defined the optimum quantity of UAVs for forest and grass fire monitoring in big regions and the number of UAV grouping to monitor gas pipelines of long mileage.

**5. Conclusion**

In this study we tried to resolve a current problem of group-wide use of unmanned aerial vehicles using integrated (systematic) approach. Following theoretical and practical questions open up new notions on the topic of group-wide use of UAV in various military and civil assignments [11, 12]:

1. The development of well-defined ranking system for unmanned units’ types in military and civil sectors of UAV application.
2. The development of organizational structure for unmanned units.
3. The method development of group-wide UAV use of different types such as informational, auxiliary, simulated UAV of both plane and helicopter types.
4. Introducing into practice of unmanned units application the high-tech information technology of planning and organizing the use of groupings of various types of UAVs in their operations;
development of mathematical methods and formation algorithms for different types of spatial structure of UAV groups;
5. Detailed development of methods for specification and formal description of the required single and grouped UAV flight paths;
6. Development of formal methods and algorithms for traction control of UAV power units based on piston and electric engines, as well as steering surfaces of UAV of non-standard structural schemes (“duck”, “tailless”, “flying wing”, etc.);
7. A detailed development of methods and algorithms for the formation of control laws for UAV of helicopter types when they move along the required group paths.

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