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ALGORITHMS OF CONTROLLING AN INFORMATION ROBOT CREATED ON THE BASIS OF UNMANNED AERIAL VEHICLES

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Abstract

Purpose: *The purpose of this article is to present the algorithms of control of unmanned aerial vehicles (UAVs) as part of the information robot.* ***Methods***: *The article considers the method of the theory of optimal control of dynamic systems, which was used to stabilize the UAV on a given trajectory, taking into account a possible change in the purpose of the movement.* ***Results***: *The first algorithm allows: to estimate the coordinates of the UAVs current position relative to a given trajectory; to develop the optimal control of the UAVs movement to a specified position taking into account a predetermined quality criterion; as well to identify the optimal points in time for the UAVs group maneuvering. The second one allows to stabilize the UAVs on a given trajectory, taking into account the possible change of the target movement at each time point on a selected interval, and to calculate the optimal time point and phase coordinate of the UAVs group separation.* ***Discussion***: *The proposed algorithms will allows, depending on the course of events, to promptly optimize the UAVs trajectories and redirect them to the required emergency zone in order to obtain accurate operational data about the victims, as well as to coordinate the actions of rescue teams.*

Keywords: unmanned aerial vehicles; optimal control; branching path

1. Introduction

Currently, the problems of preventing and eliminating emergency situations (ES) of natural and man-made nature are becoming more acute and urgent. The current trend in the use of unmanned aircraft systems for emergency prevention, liquidation of consequences of natural, man-made, environmental disasters indicates the increasing role of robotic aircraft systems of various types and purposes.

One of the promising areas of development of robotic aviation systems designed to liquidate the consequences of emergency situations, as well as to provide information and telecommunication support for search and rescue operations is creation of an information robot (IR) based on the UAVs.

IR is a compound dynamic system (CDS) [10], which elements are: basic UAV (UAV carrier); a group of (possibly different) UAVs (flying drones). All elements of IR equipped with multi-sensors, and exchange information with each other through the common information and telecommunication network. The base UAV is used as an air platform for delivery and initial deployment of drones in the area under study; for collecting, accumulating, preliminary processing of operational information received from the sensors, and retransmitting the received data in real time to the control center.

At the same time, control of UAVs as part of the information robot is more complicated than control of a single vehicle [3, 4, 7, 8]. This is due to the fact that in addition to control of flight and actions of vehicle itself, it is necessary to provide a certain relationship and consistency of its actions with other participants of the group, taking into account the group task [5]. For group control of UAVs, this article proposes to use a polyergatic system of motion control [9]. In solving a general task planning of UAVs' paths is assigned to the operator for such method of control.

The operator should solve a navigation task, i.e. assign a program path for the UAVs group, phase coordinate of group separation, time period when separation is allowed. However, in addition to a navigational task, there is the task of retaining (stabilizing) the group and single UAVs on the program path of motion and assigning the most favorable time for separation within a specified time interval.

2. Analysis of the research and publications

The efficiency of using the IR will depend on spatial coordinates and time instants when the structural transformations occur, as well controlling IR's components as they move along the path branches in time intervals between sequential structural transformations.

The paths of such CDS in the modern scientific literature have been called 'branching paths', knowing that they consist of sections of joint movement of constituent parts and segments of its individual movement to the target along separate path branches.

The prototypes in theory of such systems are systems considered in the publications of Bryson E., Ho Y. [1], Aschepkov L. T. [2], Sage A.P., White Ch.C. [11] and others.

3. Problem statement

However, all these publications were of a theoretical nature and did not contain detailed study, which would provide to design a computer-aided technology of optimal branching path automated synthesis and optimal control of CDS for each specific case.

Therefore, the scientific problem, related to improvement and development of methods of designing branching paths that would allow to solve on a real time basis the tasks of CDS' definition optimal paths of this type, is actual.

Moreover, there is still the task of adjusting the program trajectory of UAV traffic taking into account the changing operational situation in the emergency zone [5]. This article is devoted to the development of an algorithms that allow to stabilize UAV on a given trajectory of motion with allowance for possible retargeting at any given time in a given interval.

4. Problem Solution

4.1. Algorithm 1. Algorithm of stabilization of UAV on a given trajectory

It is assumed that the UAV group consists of two vehicles, the navigational task has been solved and the linear deterministic model of motion of the mark of current UAV position relative to the specified position is considered [1, 11]:

$$ {}_q\dot{x}={}_q\,a_q x(t)+{}_q\,b_q u(t), \qquad (1)$$

where ${}_qx(t)\in E^1$, ${}_qu(t)\in E^1$, $q-$ indices of path sections along which the UAVs are moving, 1-section of joint motion of the UAVs group $(q=1,11,12)$; 11, 12 - sections of motion of detached UAVs after separation. The diagram of the branching path is shown in Fig. 1.

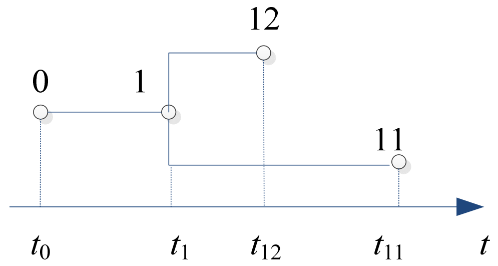

Fig. 1. The diagram of branching path

The operator needs to specify the coordinate of start point ${}_1\hat{x}(\hat{t}_0)$ of the UAV group's joint motion, time $\hat{t}_1$ and coordinate of the UAV group separation point ${}_1\hat{x}(\hat{t}_1)$, in order the UAV «11» reaches the point with coordinate ${}_{11}x(t_{11})=4$ in $t_{11}=6$ sec after start of the joint movement and subsequent separation and the UAV «12» reaches point ${}_{12}x(t_{12})=6{,}92$ after $t_{12}=4$ sec, where the coordinates are measured in conventional distance units, minimizing the criterion [2]

$$J=\frac{1}{2}\left\{{}_1F_1x^2(t_1)+\int_{t_0}^{t_1}\left[{}_1Q_1x^2(t)+{}_1R_1u^2(t)\right]dt+\right.$$
$$\left.+\sum_{j=1}^{2}{}_{1j}F_{1j}x^2(t_{1j})+\int_{t_0}^{t_{1j}}\left[{}_{1j}Q_{1j}x^2(t)+{}_{1j}R_{1j}u^2(t)\right]dt\right\}, \qquad (2)$$

where ${}_1F=0.3$; ${}_{11}F=0.1$; ${}_{12}F=0.2$; ${}_1Q=2$; ${}_{11}Q=1$; ${}_{12}Q=1$; ${}_1R=2$; ${}_{11}R=1$; ${}_{12}R=1$.

To solve task (1), (2), where it is assumed that ${}_1a=-2{,}5$; ${}_{11}a=-1$; ${}_{12}a=-1{,}5$; ${}_1b=1$; ${}_{11}b=0{,}5$; ${}_{12}b=0{,}5$, we use Bellman's principle of optimality [1].

On the assumption of (1) - (2), the expression for optimal control value will have the form

$$ {}_q\hat{u}=-{}_qR^{-1}{}_qb^T{}_qP(t)_q\hat{x}(t), \qquad (3)$$

where $t\in[t_{q^*},t_q]\,(q=1;q^*=0;q=11{,}12;q^*=1)$,

${}_qP(t)$ – solution of the differential equation

$$ {}_qP(t)=-{}_qP(t)_qa-{}_qa^T{}_qP(t)+$$
$$+{}_qP(t)_qb_qR^{-1}{}_qb^T{}_qP(t)-{}_qQ\ , \qquad (4)$$

for the corresponding boundary conditions:

$$ {}_qP(t_q)={}_qF\ (q=11{,}12),$$
$$ {}_1P(t_1)={}_1F+{}_{11}P(t_1)+{}_{12}P(t_1)\ (q=1). \qquad (5)$$

The main difference between the proposed algorithm for the optimal control calculating (3) - (5) from the known one is in the boundary condition (5) for $q=1$ when the boundary value for auxiliary variable ${}_1P(t_1)$ is calculated taking into account the values of the auxiliary variables ${}_{11}P(t)$ and ${}_{12}P(t)$ at the left end of branches «1-11» и «1-12» at $t = t_1$.

Using expressions (3)-(5) for the scalar problem (1)-(2), we obtain the following analytical expressions for calculating the phase coordinates and auxiliary variables included in the expression for optimal control calculating:

$$ {}_q\hat{x} = {}_q x(t_q)\ ch[\sqrt{\delta_q}(t_q - t) + \varphi_q]ch^{-1}\varphi_q, \quad (6)$$

$$ {}_qP(t) = {}_q R\left\{ {}_q a + \sqrt{\delta_q} th[\sqrt{\delta_q}(t_q - t) + \varphi_q]\right\} - {}_q b^{-2}, \quad (7)$$

where $t \in [t_{q^*}, t_q]\ (q = 1; q^* = 0; q = 11, 12; q^* = 1)$,

$$\varphi_{ij} = arth\left[\left(-{}_{1j}a + {}_{1j}b^2\ {}_{1j}F\ {}_{1j}R^{-1}\right)\delta_{1j}^{-\frac{1}{2}}\right],$$

$$\delta_{1j} = {}_{1j}Q\ {}_{1j}b^2\ {}_{1j}R^{-1} + {}_{1j}a^2 \quad j = (1, 2),$$

$$\varphi_1 = arth\left[\left(-{}_1a + {}_1b^2({}_{11}P(\hat{t}_1) + {}_{12}P(\hat{t}_1) + {}_1F\right)\delta_{1j}^{-\frac{1}{2}}\right],$$

$$\delta_1 = {}_1Q\ {}_1b^2\ {}_1R^{-1} + {}_1a^2.$$

The time $\hat{t}_1$ of separation of the UAV group is found from the condition ${}_{11}\hat{x}(\hat{t}_1) = {}_{12}\hat{x}(\hat{t}_1)$. Then, substituting $\hat{t}_1$ in the expressions for $\hat{t}_1$, we calculate the coordinates of separation point and further, assuming in expression (6) that $t = t_0 = 0$ at $q = 1$, we find ${}_1x(\hat{t}_0)$. As a result of the calculations, we get ${}_1x(\hat{t}_0) = 1{,}17$, $\hat{t}_1 = 1{,}094$ sec, ${}_1x(\hat{t}_1) = 1{,}59$.

Fig. 2 shows the graphs of joint and separate movement of the UAV.

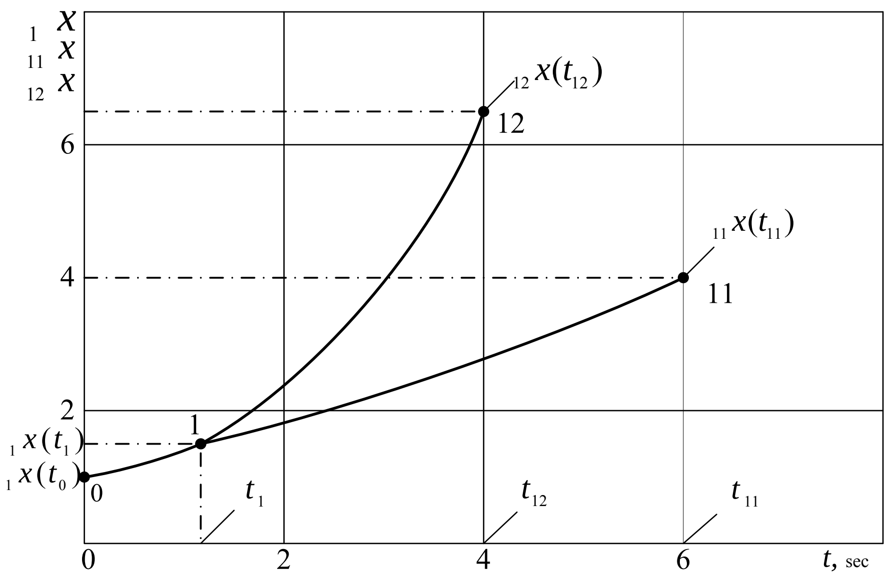

Fig. 2. Graphs of joint and separate movement of the UAV

The scientific novelty of the proposed algorithm lies in the fact that a branching path is considered as a model of UAVs group motion in the ergatic control system for the first time. Holding (stabilization) on this branching path is carried out by a criterion minimizing total energy expenditures and allowing to improve quality of transient processes.

Until now the task of holding a group of UAVs on a branching path was solved without considering the branching effect. The article for the first time proposes the algorithm how to take into account the branching effect in the task of UAVs group stabilization (holding). In this case, the time instants and coordinates for breaking-up of UAVs group are optimally selected.

4.2. Algorithm 2. Algorithm of stabilization of UAV on a given trajectory of motion with allowance for possible retargeting

The physical meaning of the problem is as follows. During the search operation in the emergency zone, the dispatcher can receive information about several possible areas of stay for objects that require prompt assistance. If the implementation of a search operation in the areas of possible stay of objects consecutive to guide the UAV and each of these areas, it could lead to an increase in the search operation time and negative consequences. Therefore, it is advisable to choose one of the zones (for example, the most probable one based on the primary signs) and send the UAV to it, but at the same time consider the possibility of its retargeting upon receipt of operational information about the stay of the object in another zone.

The dynamics of the movement of the marker of the current position of the UAV relative to the trajectory specified by the dispatcher and directed to the target, originally chosen as the true one, is described by a linear scalar equation [8, 9].

$$\dot{x} = ax(t) + \alpha u(t), \tag{8}$$

$$t \in [t_0, t_f], t_0 = const, t_f = \text{var}, \; x(t_0) = X_0, x(t_f) = X_f,$$

where X_0, X_f – is a known quantities.

A similar equation, but with different values of the coefficients, describes the dynamics of the movement of the marker of the current position of the UAV relative to its possible trajectory to the second target:

$$\dot{x}^0(\eta) = bx^0(\eta) + \beta u^0(\eta), \tag{9}$$

$$\eta \in [\tau, t_k^\tau], \tau \in [t', t''] \subset [t_0, t_f], \tau = const,$$

$$t_k^\tau = \text{var}, \; x^0(\tau) = x(\tau), \; x^0(t_k^\tau) = X_k,$$

where X_k –is a known value or function of τ.

It is required to optimize the process of stabilization of the UAV on the primary chosen trajectory so that the criterion

$$I = \int_{t_0}^{t_f} \gamma u^2 dt \to \min_{\substack{u(t)\, t \in [t_0, t_f], \\ u^0(\eta)\, \eta \in [\tau, t_k^\tau]}} \tag{10}$$

reached a minimum value under the condition that inequality:

$$I^0 = \int_{\tau}^{t_k^\tau} \varphi u^{0^2} d\eta \to A_1 \le 0, \; A > 0, A = A(\tau). \tag{11}$$

According to [1, 11], the optimal control, which delivers the minimum of the Hamiltonian

$$H(x, u, \lambda, t) = \gamma u^2 + \lambda(ax + \alpha u), \tag{12}$$

is calculated by the formula:

$$u(t) = -\frac{\alpha}{2\gamma}\lambda(t), \tag{13}$$

where $\lambda(t)$ satisfies the equations:

$$\dot{\lambda}(t) = -a\lambda(t), \; t \in [t_0, t_f] \backslash [t', t'']. \tag{14}$$

$$\lambda(t) = \lambda(t^{''}) + a\int_t^{t^{''}} \lambda(t)dt + \zeta^{-1}\int_t^{t^{''}} \lambda^0(\tau)d\nu(\tau), t \in [t', t''], \tag{15}$$

$$\zeta + \int_t^{t^{''}} d\nu(\tau) - 1, \zeta > 0, d\nu(\tau) \ge 0, d\nu(\tau)I^0 = 0.$$

According to (15), to calculate $\lambda(t)$ in the interval $[t', t'']$ it is necessary to know $\lambda^0(\tau), \tau \in [t', t'']$. For calculation $\lambda^0(\tau)$ it is necessary to find the optimal trajectory described by equation (9).

As a result of solving the system of equations

$$\begin{aligned} &\dot{\hat{x}}^0(\eta) = b\hat{x}^0(\eta) + \beta\hat{u}^0(\eta); \\ &\dot{\lambda}^0(\eta) = -b\lambda^0(\eta), \eta \in [\tau, \tau_k^\tau], \end{aligned} \tag{16}$$

where $\hat{u}^0(\eta) = -\beta(2\varphi)^{-1}\lambda^0(\eta), \; \eta \in [\tau, \tau_k^\tau],$ – is the control minimizing the Hamiltonian $H^0(x^0, u^0, \lambda^0, \eta) = \varphi u^{02} + \lambda^0(bx^0 + \beta u^0)$, we obtain

$$\lambda^0(\eta) = c_{\lambda_0} \exp\left[-b(\eta - \tau)\right], \tag{17}$$

$$\hat{x}^0(\eta) = \frac{\beta^2}{2b\varphi}c_{\lambda_0} \exp\left[-b(\eta - \tau)\right] + c_{\lambda_0} \exp\left[b(n - \tau)\right]. \tag{18}$$

Considering that

$$\hat{x}^0(\tau) = \hat{x}(\tau), \tau \in [t', t''] \; \hat{x}^0(\tau_k^\tau) = X_k^0,$$

$$\hat{H}^0(\hat{x}^0(\tau_k^\tau), u^0(\tau_k^\tau), \lambda^0(\tau_k^\tau), (\tau_k^\tau)) = 0,$$

we write the system of three equations

$$\begin{aligned} &\frac{\beta^2}{2b\varphi}c_{\lambda_0} + c_{x_0} = \hat{x}(\tau), \\ &\frac{\beta^2}{2b\varphi}c_{\lambda_0} \exp\left[-b\left(\tau_k^\tau - \tau\right)\right] + c_{x_0} \exp\left[b\left(\tau_k^\tau - \tau\right)\right] = X_k, \\ &c_{\lambda_0}c_{x_0}b = 0, \end{aligned} \tag{19}$$

with three unknowns c_{λ_0}, c_{x_0} and τ_k^τ from which we find c_{λ_0} as a function of $\hat{x}(\tau)$ and τ. It follows from (17) that $\lambda^0(\tau) = c_{\lambda_0}(\hat{x}(\tau), \tau)$.

Substituting $\lambda^0(\tau) = c_{\lambda_0}(\hat{x}(\tau), \tau)$. into equation (15), and solving it together with the equation for $\dot{\hat{x}}(t)$, we find the optimal trajectory and control of the system (8) in the time interval. $[t', t'']$. Outside the interval $[t', t'']$ equation (1) should be solved together with equations (13), (14).

Let $a = 1$, $\alpha = 2$, $\gamma = 1$, $b = 1{,}5$, $\beta = 1{,}5$, $\varphi = 1$, $t_0 = 0$, $x(t_0) = 8$, $X_f = 0{,}2415$, $X_k = 0{,}2231$, $t' = 0{,}5$, $t'' = 2{,}5$, $A = 2\varphi b / \beta^2[y^2(\tau) - X_k^2], t \in [t', t''],$

where

$y(\tau) = 0{,}0347\exp[2(\tau - t')] + 7{,}7434\exp[-2(\tau - t')]$.

Then we obtain that $\zeta = 0{,}8721$, $dv(\tau) = \mu(\tau)d\tau$, $\mu(\tau) = 0$ at $t \in [t', t''] \setminus [t_1, t_2]$. and $\mu(\tau) = 0{,}4905$ at $t \in [t_1, t_2]$, $t_1 = 1{,}3166$, $t_2 = 1{,}5773$.

Herewith, the optimal trajectory of the system (8) consists of three sections (Fig. 3):

$\hat{x}^{(1)}(t) = 8{,}1313\exp(-t) - 0{,}1313\exp(t),\ t \in [t_0, t_1]$;

$\hat{x}^{(2)}(t) = y(t),\ t \in [t_1, t_2]$;

$\hat{x}^{(3)}(t) = 1{,}197\exp(t_2 - t),\quad t \in [t_2, t_f]$,

where $t_f = 3{,}1780$, each of which corresponds to the optimal control.

$\hat{u}^{(1)}(t) = 8{,}1313\exp(-t),\ t \in [t_0, t_1]$;

$\hat{u}^{(2)}(t) = 11{,}6151\exp[-2(t - t')] - 0{,}1735\exp[2(t - t')],\ t \in [t_1, t_2]$;

$\hat{u}^{(3)}(t) = 1{,}197\exp(t_2 - t),\quad t \in [t_2, t_f]$.

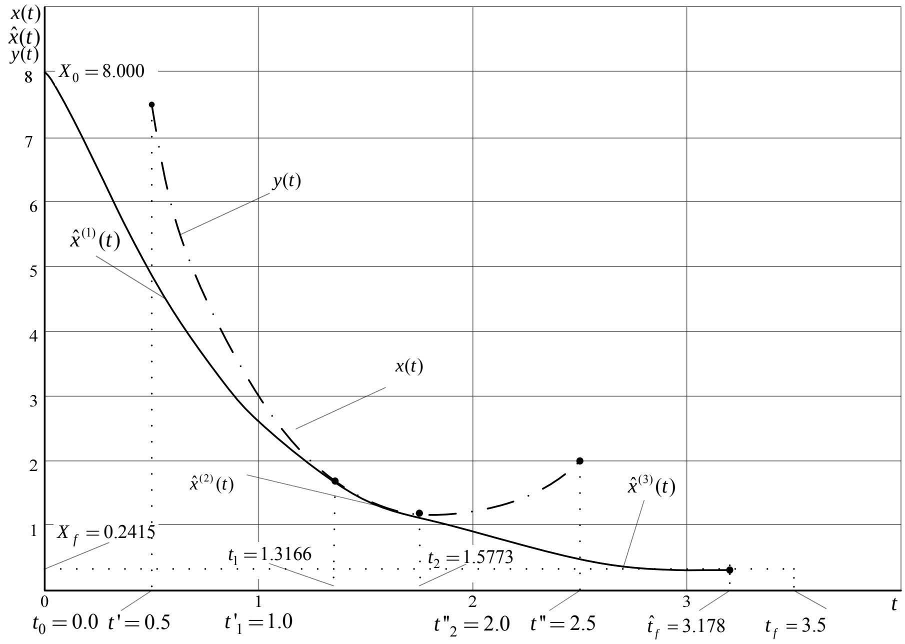

Fig. 3. Graphs of the optimal trajectory with an alternative

In the time interval $[t_1, t_2]$ the motion of the system occurs by restriction because

$$I^0 = 2\varphi b / \beta^2[\hat{x}^2(t) - y^2(t)] = 0 .$$

The optimal value of the time of arrival of the system (9) to the point X_k is calculated by the formula:

$$\tau_k^{\tau} = 1/b\ln[\hat{x}(\tau)/X_k] + \tau = 0{,}6666\ln\hat{x}(\tau) + \tau + 1,\quad \tau \in [t', t''].$$

The optimal value of the criterion (10) $\hat{I} = 32{,}1025$ which is somewhat larger than the value $\tilde{I} = 31{,}9708$ of the same criterion, calculated on the condition that the system (8) goes from point $x(t_0)$ to point $x(t_f)$ along the trajectory $\tilde{x}(t)$ (8) without taking into account the constraint (11).

However, the point $x(t_f)$ is reached in this case in time $\tilde{t}_f = 3{,}5 > \hat{t}_f$; and with violation of constraint (11) in the interval $[t'_1, t''_2]$, where $t'_1 = 1$, $t''_2 = 2$.

We consider a simplified solution of the problem, when the motion of the system (1) in the time intervals $[t_0, t'_1]$ and $[t''_2, t_f]$ occurs along a trajectory constructed without allowance for the constraint, and in the interval $[t'_1, t''_2]$ to limit.

Then the criterion (10) has the meaning $I = 32{,}3338 > \hat{I}$. Ratio $(I - \hat{I})/(\hat{I} - \tilde{I}) = 2{,}756$ shows that the use of necessary conditions for the optimality of a trajectory with an alternative makes it possible to almost in 3 times reduce the deterioration of the criterion (10) that would arise in the case of motion of the system (8) along the trajectory of the simplified version of the solution of the problem. The numerucal values are specified in relative units.

5. Conclusions

In the article is proposed the algorithms of stabilization of an unmanned aerial vehicle on a given trajectory of motion, which allows to estimate the coordinates of the current position of the UAV relative to a given trajectory and to identify the optimal moments for the execution of UAV maneuvers.

The synthesized algorithms generate the optimal control of the movement of the marker of the current position of the UAV to the given position with allowance for possible retargeting at each instant in a given interval with the given quality criterion.

The conducted researches showed that the received algorithms do not impose fundamental limitations on the possibility of its realization.

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Алгоритми керування інформаційним роботом на базі безпілотних літальних апаратів

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Мета: Метою даної статті є викладення алгоритмів керування безпілотними літальними апаратами (БПЛА) у складі інформаційного робота. **Методи**: У статті розглянуто метод теорії оптимального керування динамічними системами, який застосовувався для стабілізації БПЛА на заданій траєкторії руху, з урахуванням можливої зміни цілі руху. **Результати**: Перший алгоритм дозволяє оцінювати координати поточного положення БПЛА щодо заданої траєкторії, виробляти оптимальне, з урахуванням заданого критерію якості, керування рухом БПЛА до заданої цілі, а також ідентифікувати оптимальні моменти часу виконання групових маневрів БПЛА. Другий алгоритм дозволяє стабілізувати БПЛА на заданій траєкторії, з урахуванням можливої зміни цілі руху в кожен момент часу на заданому інтервалі, а також розрахувати оптимальний момент часу і фазову координату розділення групи БПЛА. **Обговорення**: Запропоновані алгоритми дозволять в залежності від розвитку надзвичайно ситуації оперативно оптимізувати траєкторії руху БПЛА і здійснювати їх перенацілювання в необхідну зону надзвичайної ситуації для отримання точної оперативної інформації про потерпілих, а також для координації дій рятувальних команд.

Ключові слова: безпілотні літальні апарати, оптимальне керування, розгалужена траєкторія

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Алгоритмы управления информационным роботом на базе беспилотных летательных аппаратов

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Цель: Целью данной статьи является изложение алгоритмов управления беспилотными летательными аппаратами (БПЛА) в составе информационного робота. **Методы**: В статье рассмотрен метод теории оптимального управления динамическими системами, который применялся для стабилизации БПЛА на заданной траектории движения, с учетом возможного изменения цели движения. **Результаты**: Первый алгоритм позволяет оценивать координаты текущего положения БПЛА относительно заданной траектории, вырабатывать оптимальное, с учетом заданного критерия качества, управление движением БПЛА к заданной цели, а также идентифицировать оптимальные моменты времени выполнения групповых маневров БПЛА. Второй алгоритм позволяет стабилизировать БПЛА на заданной траектории, с учетом возможного изменения цели движения в каждый момент времени на заданном интервале, а также рассчитать оптимальный момент времени и фазовую координату разделения группы БПЛА. **Обсуждение**: Предложенные алгоритмы позволят в зависимости от развития чрезвычайно ситуации оперативно оптимизировать траектории движения БПЛА и осуществлять их перенацеливание в требуемую зону чрезвычайной ситуации для получения точной оперативной информации о потерпевших, а также для координации действий спасательных команд.

Ключевые слова: беспилотные летательные аппараты, оптимальное управление, ветвящаяся траектория

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