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METHOD OF DYNAMIC PROGRAMMING FOR INFORMATION ROBOT'S BRANCHING PATH OPTIMIZATION

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Abstract**—***The article describes and proves the necessary and sufficient conditions for optimality of information robot's branching path with branching profile containing the central and lateral branches without interaction of subsystems after separation. The formulated conditions make it possible to determine the optimal coordinates and instants of the branching time of the trajectory, as well as the optimal controls and trajectories of the components of the information robot to the specified purposes along the hotel branches of the trajectory after they are separated from the carrier. The practical importance of the obtained conditions lies in the fact that it is possible to develop on its base the computational procedures for on-line calculation of optimal branching paths of such compound dynamical systems.*

Index Terms—Compound dynamic system; optimal control; branching path.

I. INTRODUCTION

At the present time the problems of preventing and eliminating natural and technogeneous emergencies become more critical and actual.

Creation of an information robot (IR) based on unmanned aerial vehicle (UAV) is one of the promising tendencies for development of systems intended to eliminate consequences of emergency situations, as well as to provide information and telecommunications support for search and rescue operations.

Information robot is a compound dynamic system (CDS) [1], [3], its elements are: a basic UAV (UAV-carrier); a group of various mobile UAVs (drones) interconnected by a common information and telecommunications network.

The basic UAV is used as an airplane for drones delivery and primary deployment in studied (investigated) area; to collect, accumulate, preprocess on-line data received from the drones; and to retransmit real-time received data to a command control post.

Depending on the tasks to be performed, the following scenarios of drones dropping can be provided:

– drones dropping at specified point with subsequent return to the basic UAV or other platform;

– drones dropping at specified point with subsequent grouping for data exchange and synchronization;

– drones dropping at specified point without subsequent return.

Depending on built-in scenario, separate drones can operate as independent repeaters or data storage devices, as well as a network of interacting nodes, and can be used as a repeater for other drones.

The advantage of using the proposed IR for monitoring potential dangerous areas, capable to transmit real-time condition information to the relevant government authorities for making operational and adequate actions, is obvious since it can replace aircraft and helicopters during operations related to hazard to crew members lives

II. PROBLEM STATEMENT

When using the IR, the actual problem, related to the optimal control of its components while they move toward specified targets, arises.

The paths of such CDS in modern scientific literature have been called as 'branching' [2], since they consist of sections of joint movement of constituent parts and areas of its individual movement to the target along separate branches of the path.

To ensure continuous monitoring of the areas under emergency, it is necessary to arrange the drones optimally in respect to covering the monitored zone, as well as the uninterrupted transmission of on-line data to the base UAV.

It will depend on the optimal choice oa coordinates and dropping time of drones, as well optimal motion of the base UAV to the dropping point and optimal motion of drones to the target along path branches after their dropping.

The task of IR optimal control will be to find the optimal control vector that minimizes energy consumption for control, provides the maximum coverage of monitored area and uninterrupted transmission of information about its condition.

The purpose of this article is to determine the necessary and sufficient conditions for optimality of information robot's branching path with branching profile containing the central and lateral branches without interaction of subsystems after separation.

III. Method of Dynamic Programming for Information Robot's Branching Path Optimization

We consider as an example the motion of a hypothetical IR with the path branching profile containing the central and lateral branches without the interaction of the elements after separation.

Assume that k subgroups of various drones (in sum, there will be subgroups $\sum_{i=1}^{k} r_i$, i.e. in each subgroup r drones) are on board the basic UAV.

Completed IR starts from the point

$$\left({}_1x(t_0), t_0\right) \in Q_{0.} \qquad (1)$$

During flight at points

$$\left({}_ix(t_i), t_i\right) \in Q_i \ \left(t_{i-1} < t_i,\ i = \overline{1,k}\right) \qquad (2)$$

from the base UAV k times r_i sub-groups of drones are separated (Fig. 1), which move to the final points where they are stopped.

$$\left({}_{ij}x(t_{ij}), t_{ij}\right) \in Q_{ij} \ \left(i = \overline{1,k},\ j = \overline{1,r_i}\right), \qquad (3)$$

where r is the quantity of drones in i subgroup; i is the subgroup index $i = \overline{1,k}$, j is the index of drone related to subgroup r_i.

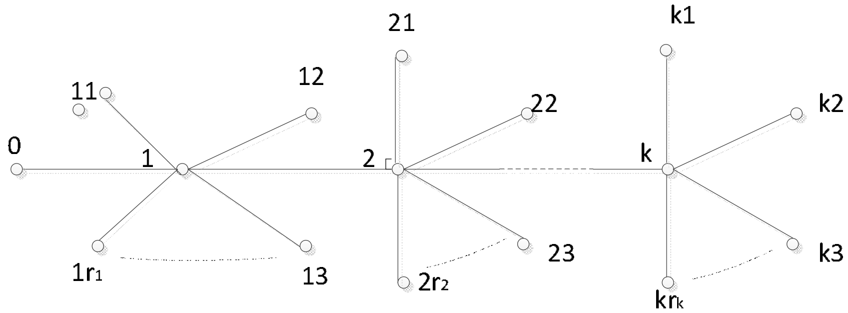

Fig. 1. The branching profile of the IR's motion

Dynamics of completed IR motion is described by equations

$${}_\beta\dot{x} = {}_\beta f({}_\beta x, {}_\beta u, t),\ \ t \in [t_{\beta^*}, t_\beta]\ , \qquad (4)$$

$${}_\beta x \in E^n \quad {}_\beta u \in E^{m_\beta},$$

$$\left(\beta = i,\ \beta^* = i-1;\ \beta = ij,\ \beta^* = i;\ i = \overline{1,k};\ j = \overline{1,r_i}\right),$$

on which the restrictions are applied [3]

$$\left({}_\beta x(t), {}_\beta u(t)\right) \in G_\beta(t)\,, \qquad (5)$$

where ${}_\beta x$, ${}_\beta u$ is the phase vector related to the class of piecewise smooth functions and control vector related to the class of piecewise continuous functions, corresponding βth time interval between structural transformations of the IR, dimension n and m_β; G_β is the bounded set of space E^{n+m_β}; t_{β^*}, t_β are moments of start and end of drones motion along the considered path branch, ${}_\beta u(t) = {}_\beta u(t+0) = \lim_{\tau \to t+0} u(t)$, $t_{\beta^*} \le t \le t_\beta$.

At the moments of drones separation for all phase coordinates, the following conditions must be satisfied [4]

$$x_i(t_i) - x_{ij}(t_i) = 0, \quad \left(i = \overline{1,k};\ j = \overline{1,r_i}\right), \qquad (6)$$

$$x_i(t_i) - x_{i+1}(t_i) = 0,\ (i = \overline{1,k-1})\,. \qquad (7)$$

In addition to the nth coordinate, describing the change in IR's mass, for which the following relationships must be satisfied [4]

$${}_ix_q(t_i) = {}_{i+1}x_q(t_i) = {}_{ij}x_q(t_i),$$

$$(\ i = \overline{1,k-1},\ q = \overline{1,n-1}),$$

$${}_kx_q(t_k) = {}_{kj}x_q(t_k)\ \ (\ q = \overline{1,n\text{-}1})\,,$$

$${}_ix_n(t_i) = {}_{i+1}x_n(t_i) + \sum_{j=1}^{r_i} {}_{ij}x_n(t_i)\ \left(i = \overline{1,k-1}\right),$$

$${}_kx_n(t_k) = \sum_{j=1}^{r_k} {}_{kj}x_n(t_k). \qquad (8)$$

Control $u_\beta(t)$, phase coordinates $x_1(t_0), x_\beta(t_\beta)$, points of time t_0, t_β $(\beta = i, ij; i = \overline{1,k}\,; j = \overline{1,r_i})$ should be choosen in such a way as to minimize the criterion [4]

$$I = I\Big(t_0, t_i..., t_k;\ t_{11}, ..., t_{kr_k};\ {}_1x(t_0),\ {}_1x(t_1)...,\ {}_kx(t_k),\ {}_{11}x(t_{11})...,\ {}_{kr_k}x(t_{kr_k});\ {}_1x(\cdot),\ {}_1u(\cdot);\ ...,\ {}_kx(\cdot),\ {}_ku(\cdot),\ {}_{11}x(\cdot), {}_{11}u(\cdot), ...,\ {}_{kr_k}x(\cdot),\ {}_{kr_k}u(\cdot)\Big) = \sum_{i=1}^{k} I_i + \sum_{j=1}^{r_i} I_{ij} \to \inf, \tag{9}$$

where $I_\beta = S_\beta({}_\beta x(t_\beta), t_\beta) + \int\limits_{t_{\beta^*}}^{t_\beta} \Phi_\beta({}_\beta x,\ {}_\beta u, t)dt$

$\left(\beta = i, \beta^* = i-1;\ \beta = ij, \beta^* = i;\ i = \overline{1,k};\ j = \overline{1,r_i}\right).$

Criterion of optimality (9) corresponds to Boltza's form, where function $S_\beta(\cdot)$ physically reflects the requirements for values of the coordinates of the IR elements motion at the moments of start and end, as well as for values of time points themselves.

The criterion integral terms express the requirements for IR elements character of motion along the corresponding path branches. The interference of elements in time interval $[t_{\beta^*}, t_\beta]$ is reflected in equation of its motion (4) and in particular integral criteria I_i, I_{ij}.

Thus, the problem of IR optimal control is to search for optimal controls and paths of subsystems motion along the sections of discontinuous trajectory that minimize criterion (9), as well to find the optimal time instants and phase coordinates when and where the structural transformations of IR occur (see Fig. 1).

The method of dynamic programming allows us to solve this task in the following formulation [6], [7].

We denote by $\Delta({}_\beta x, t_{\beta^*}, t_\beta)$ the set of all controls ${}_\beta u(\cdot)$ defined on interval $[t_{\beta^*}, t_\beta]$ satisfying conditions (5) and such that the path of system (4) is also defined on interval $[t_{\beta^*}, t_\beta]$. Suppose that $\Delta({}_\beta x, t, t_\beta) \neq \varnothing$.

The process ${}_1x(t)$, ${}_1u(t)$, ${}_2x(t)$, ${}_2u(t)$,..., ${}_kx(t)$, ${}_ku(t)$, ${}_{11}x(t)$, ${}_{11}u(t)$,..., ${}_{kr_k}x(t)$, ${}_{kr_k}u(t)$ is called an admissible process of problem (1) – (9) if the functions ${}_\beta x(t)$, ${}_\beta u(t)$, $(\beta = i, ij;\ i = \overline{1,k};\ j = \overline{1,r_i})$, are defined on some interval $[t_{\beta^*}, t_\beta]$, where t_0, ${}_1x(t_0)$, t_β, ${}_\beta x(t_\beta)$ $(\beta = i, ij; i = \overline{1,k}; j = \overline{1,r_i})$ satisfy inclusions (1) – (3), ${}_\beta u(\cdot) \in \Delta({}_\beta x, t_{\beta^*}, t_\beta)$, ${}_\beta x(\cdot)$ is the path of system (4).

According to Bellman's optimality principle, an admissible process is a solution of the task (1) – (9), i.e. optimal process [7], if the following condition is complied

$$I = I\Big(\hat t_0, \hat t_1 ..., \hat t_k; \hat t_{11}, ..., \hat t_{kr_k};\ {}_1\hat x(\hat t_0),\ {}_1\hat x(\hat t_1)...,\ {}_k\hat x(\hat t_k),\ {}_{11}\hat x(\hat t_{11})...,\ {}_{kr_k}\hat x(\hat t_{kr_k});\ {}_1\hat x(\cdot),\ {}_1\hat u(\cdot);...,\ {}_k\hat x(\cdot),\ {}_k\hat u(\cdot),\ {}_{11}\hat u(\cdot),...,\ {}_{kr_k}\hat x(\cdot),\ {}_{kr_k}\hat u(\cdot)\Big)$$

$$= \inf_{{}_1x(t_0), t_0) \in Q_0} ... \inf_{({}_kx(t_k), t_k) \in Q_k} \inf_{({}_{11}x(t_{11}), t_{11}) \in Q_{11}} ... \inf_{({}_{kr_k}x(t_{kr_k}), t_{kr_k}) \in Q_{kr_k}} \inf_{({}_1u(\cdot) \in \Delta({}_1x(t_0), t_0, t_1)} ... \inf_{({}_ku(\cdot) \in \Delta({}_kx(t_{k-1}), t_{k-1}, t_k)} \inf_{({}_{11}u(\cdot) \in \Delta({}_{11}x(t_1), t_1, t_{11})} ... \inf_{({}_{kr_k}u(\cdot) \in \Delta({}_{kr_k}x(t_k), t_k, t_{kr_k})} I\Big(t_0, t_1, ..., t_k; t_{11}, ..., t_{kr_k};\ {}_1x(t_0),\ {}_1x(t_1), ...,\ {}_kx(t_k),\ {}_{11}x(t_{11}), ...,\ {}_{kr_k}x(t_{kr_k});\ {}_1x(\cdot),\ {}_1u(\cdot);...;\ {}_kx(\cdot),\ {}_ku(\cdot);\ {}_{11}x(\cdot),\ {}_{11}u(\cdot),...,\ {}_{kr_k}x(\cdot),\ {}_{kr_k}u(\cdot)\Big) = \hat I.$$

We formulate the necessary optimality conditions of a branching path along which the IR moves (see Fig. 1).

For the optimality of admissible process of task (1) – (9) it is necessary and sufficient that the functions exist $V_\beta({}_\beta x(t), t)$, $t \in [t_{\beta^*}, t_\beta]$ and they:

1) have piecewise-continuous partial derivatives and satisfy the equations [7]

$$-\frac{\partial V_\beta}{\partial t} = \inf_{({}_\beta X, {}_\beta U) \in W_\beta(t)} \left[\Phi_\beta\left({}_\beta x, {}_\beta u, t\right) + \left(\frac{\partial V_\beta}{\partial_\beta x}\right)^{\mathrm{T}} {}_\beta f({}_\beta x, {}_\beta u, t) \right]\Bigg|_{{}_\beta X} \tag{10}$$

everywhere on the line $[t_{\beta^*}, t_\beta]$ $(\beta = i, \beta^* = i-1;$ $\beta = ij, \beta^* = i;$ $i = \overline{1,k};$ $j = \overline{1,r_i})$, where these derivatives exist;

2) are connected by boundary conditions

$$V_{ij}\left({}_{ij}x(t_{ij}), t_{ij}\right) = S_{ij}\left({}_{ij}x(t_{ij}), t_{ij}\right)\Big|_{\left({}_{ij}x(t_{ij}),\ t_{ij}\right) \in Q_{ij}}, \tag{11}$$

$$V_i({}_ix(t_i), t_i) = \left[\sum_{j=1}^{r_i} V_{ij}\left({}_{ij}x(t_i), t_i\right) + \zeta(i) V_{i+1}\left({}_{i+1}x(t_i), t_i\right) + S_i({}_ix(t_{ij}), t_{ij}) \right]\Bigg|_{{}_jx(t_i)}, \tag{12}$$

where $\zeta(i) = \begin{cases} 1, & i = \overline{1, k-1}, \\ 0, & i = k, \end{cases}$

3) satisfy relations (8) and condition

$$\hat{I} = \inf_{({}_1x(t_0),t_0)\in Q_0} \dots \inf_{({}_kx(t_k),t_k)\in Q_k} \dots \inf_{({}_{kr_k}x(t_{kr_k}),t_{kr_k})\in Q_{kr_k}} \left[V_1\left({}_1x(t_0), t_0; {}_1x(t_1), t_1; \dots {}_kx(t_k), t_k; {}_{11}x(t_{11}), t_{11}; \dots {}_{kr_k}x(t_{kr_k}), t_{kr_k} \right) \right]. \quad (13)$$

Let us prove the validity of formulated optimality conditions (10) – (13).

We represent equation (4) in the block form

$$ {}_i\dot{X} = \begin{bmatrix} {}_i\dot{x}^{(1)} \\ {}_i\dot{x}^{(2)} \\ \vdots \\ {}_i\dot{x}^{(r_i)} \end{bmatrix} = \begin{bmatrix} {}_if^{(1)}\left({}_ix^{(1)}, {}_iu^{(1)}, t\right) \\ {}_if^{(2)}\left({}_ix^{(2)}, {}_iu^{(2)}, t\right) \\ \vdots \\ {}_if^{(r_i)}\left({}_ix^{(r_i)}, {}_iu^{(r_i)}, t\right) \end{bmatrix} \quad (14)$$

where ${}_ix^{(j)} \in E^n$, ${}_iu^{(j)} \in E^{m^{(j)}}$, $t_{\beta^*} \le t \le t_\beta$, ${}_i\dot{x}^{(j)} = {}_if^{(j)}\left({}_ix^{(j)}, {}_iu^{(j)}, t\right)$ is the equation of type (4); $i = \overline{1,k}$; $j = \overline{1,r_i}$, k is the number of subgroups of drones on board the base UAV in the interval $[t_{\beta^*}, t_\beta]$.

When it is considered that $\Phi_i\left({}_iX, {}_iU, t\right) = \sum_{j=1}^{r_i} \Phi_i^{(j)}\left({}_ix^{(j)}, {}_iu^{(j)}, t\right)$ [1] equation (10) will have the following form [7]

$$-\frac{\partial V_i}{\partial t} = \inf_{\left({}_ix^{(r_i)}, {}_iu^{(r_i)}\right)\in W^{(r_i)}(t)} \sum_{j=1}^{r_i} H_i^{(j)}\left({}_ix^{(j)}, {}_iz^{(j)}, {}_iu^{(j)}, t\right) = \sum_{j=1}^{r_i} \inf_{\left({}_ix^{(j)}, {}_iu^{(j)}\right)\in W^{(j)}(t)} H_i^{(j)}\left({}_ix^{(j)}, {}_iz^{(j)}, {}_iu^{(j)}, t\right)$$

$$= \sum_{j=1}^{r_i} \hat{H}_i^{(j)}\left({}_i\hat{x}^{(j)}, {}_iz^{(j)}, {}_i\hat{u}\left({}_i\hat{x}^{(j)}, {}_iz^{(j)}, t\right)\right)\Bigg|_{{}_i\hat{x}^{(j)}, {}_i\hat{u}^{(j)}},$$

where

$$H_i^{(j)} = \Phi_i^{(j)}\left({}_ix^{(j)}, {}_iu^{(j)}, t\right) + {}_iz^{(j)\mathrm{T}}\, {}_if^{(j)}\left({}_ix^{(j)}, {}_iu^{(j)}, t\right),$$

$$\hat{H}_i^{(j)} = \left[\Phi_i^{(j)}\left({}_i\hat{x}^{(j)}, {}_i\hat{u}^{(j)}\left({}_i\hat{x}^{(j)}, {}_iz^{(j)}, t\right), t\right) + {}_iz^{(j)\mathrm{T}}\, {}_if^{(j)}\left({}_i\hat{x}^{(j)}, {}_i\hat{u}^{(j)}\left({}_i\hat{x}^{(j)}, {}_iz^{(j)}, t\right), t\right) \right]\Bigg|_{{}_i\hat{x}^{(j)}, {}_i\hat{u}^{(j)}},$$

$W_{i,u}^{(j)}\left({}_ix^{(j)}(t), t\right)$ is the cross-section $W_i^{(j)}(t)$ for each fixed ${}_ix^{(j)}(t)$; $W_{i,x}^{(j)}(t)$ is the projection $W_i^{(j)}(t)$ onto n-dimensional Euclidean space with elements ${}_ix^{(j)\mathrm{T}} = \left({}_ix_1^{(j)}, \dots, {}_ix_n^{(j)}\right)$ for which we can write $2q$ vector canonical equations [6]:

$${}_i\dot{\hat{x}}^{(j)} = \frac{\partial \hat{H}_i^{(j)}}{\partial\, {}_iz^{(j)}}, \quad {}_i\dot{z}^{(j)} = -\frac{\partial \hat{H}_i^{(j)}}{\partial\, {}_ix^{(j)}} \quad (15)$$

Note that ${}_i\dot{\hat{x}}^{(j)} = {}_if^{(j)}\left({}_i\hat{x}^{(j)}, {}_i\hat{u}^{(j)}, t\right)$, ${}_i\hat{u}^{(j)}\left({}_i\hat{x}^{(j)}, {}_iz^{(j)}, t\right)$ is determined from relation $\frac{\partial \hat{H}_i^{(j)}}{\partial\, {}_iu^{(j)}} = 0$, if ${}_i\hat{u}^{(j)}$ is an interior point of the region $W_{i,u}^{(j)}({}_ix^{(j)}(t), t)$ and ${}_i\hat{u}^{(j)} = {}_i\hat{u}^{(j)}({}_i\hat{x}^{(j)}(t), t)$ from relation $\frac{\partial \hat{u}_i^{(j)}}{\partial\, {}_iz^{(j)}} = 0$, if ${}_i\hat{u}^{(j)}$ is a member of the boundary of this region.

We will seek $V_i\left({}_ix^{(1)}(t), \dots, {}_ix^{(r_i)}(t), t\right)$ in the form of

$$V_i\left({}_ix^{(1)}(t), \dots, {}_ix^{(r_i)}(t), t\right) = \sum_{j=1}^{r_i} V_i^{(j)}\left({}_ix^{(j)}(t), t\right). \quad (16)$$

Then ${}_iz^{(j)} = \frac{\partial V_i^{(j)}}{\partial\, {}_ix^{(j)}}$ and from equations (15), (16) we follow to Hamilton–Jacobi equation [6]

$$-\frac{\partial V_i^{(j)}}{\partial t} = \Phi_i^{(j)}\left({}_i\hat{x}^{(j)}, {}_i\hat{u}^{(j)}, t\right) + \left(\frac{\partial V_i^{(j)}}{\partial\, {}_ix^{(j)}}\right)^{\mathrm{T}} {}_if^{(j)}\left({}_i\hat{x}^{(j)}, {}_i\hat{u}^{(j)}, t\right),$$

and then, to Bellman equation

$$-\frac{\partial V_i^{(j)}}{\partial t} = \inf_{\left({}_ix^{(j)}, {}_iu^{(j)}\right)\in W_i^{(j)}(t)} \left[\Phi_i^{(j)}\left({}_ix^{(j)}, {}_iu^{(j)}, t\right) + \left(\frac{\partial V_i^{(j)}}{\partial\, {}_ix^{(j)}}\right)^{\mathrm{T}} {}_if^{(j)}\left(x_i^{(j)}, u_i^{(j)}, t\right) \right]\Bigg|_{{}_ix^{(j)}}.$$

Due to mutual independence of IR components motion after separation, it is possible to argue that Bellman function $V_i^{(j)}\left({}_ix^{(j)}(t), t\right)$ is continuous on the entire path of jth subgroups motion.

Between time of separation and end of motion of the jth subgroup, the Bellman function has piecewise-continuous derivatives $\frac{\partial V_i^{(j)}}{\partial_i x^{(j)}}$, $\frac{\partial V_i^{(j)}}{\partial t}$, and satisfies Hamilton–Jacobi equation everywhere where these derivatives exist.

In summary, necessary and sufficient conditions for optimality of information robot's branching path with branching profile containing the central and lateral branches are proved.

It should be noted that the conditions (11) – (14) also can be validated by the method described in Paper [8].

IV. CONCLUSION

The article describes and proves, in terms of optimal control theory, the necessary and sufficient conditions for optimality of information robot's branching path with branching profile containing the central and lateral branches without interaction of subsystems after separation.

The formulated conditions allow determining the optimal coordinates and instants of path branching, as well as the optimal controls and IR components' paths to specified targets along the separate path branches after its separation from the UAV-carrier.

The proposed method is part of the mathematical support of the computer-aided design system and can be used to model computational algorithms involving specific interaction of IRs elements of specific types.

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О. М. Тачиніна. Метод динамічного програмування для оптимізації розгалуженої траєкторії руху інформаційного робота

У статті сформульовано і доведено необхідні та достатні умови оптимальності розгалуженої траєкторії руху інформаційного робота зі схемою розгалуження траєкторії, що містить центральну і бічні гілки без взаємодії підсистем після поділу. Сформульовані умови дозволяють визначити оптимальні координати і моменти часу розгалуження траєкторії, а також оптимальні управління і траєкторії руху складених елементів інформаційного робота до заданих цілей по окремим гілкам траєкторії після їх відділення від носія. Практична значимість отриманих умов полягає в тому, що на їх основі можливо розробляти обчислювальні процедури для оперативного розрахунку оптимальних розгалужених траєкторій такого роду складених динамічних систем.
Ключові слова: складена динамічна система; оптимальне керування; розгалужена траєкторія.

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Е. Н. Тачинина. Метод динамического программирования для оптимизации ветвящейся траектории движения информационного робота

В статье сформулированы и доказаны необходимые и достаточные условия оптимальности ветвящейся траектории движения информационного робота со схемой ветвления траектории, содержащей центральную и боковые ветви без взаимодействия подсистем после разделения. Сформулированные условия позволяют определить оптимальные координаты и моменты времени ветвления траектории, а также оптимальные управления и траектории движения составных элементов информационного робота к заданным целям по отдельным ветвям траектории после их отделения от носителя. Практическая значимость полученных условий состоит в том, что на их основе возможно разрабатывать вычислительные процедуры для оперативного расчета оптимальных ветвящихся траекторий такого рода составных динамических систем.
Ключевые слова: составная динамическая система; оптимальное управление; ветвящаяся траектория.

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