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FUZZY MODELS IN PROBLEMS OF COMPLEX SYSTEMS CONTROL

An analytical review of existing models and methods of applied problem solving is performed. The necessity of developing of fuzzy models of mobile objects is shown. A new formal model of mobile objects control as minimization of the control error is developed. It is shown that the problem of optimal mobile objects control is to find the optimal (or suboptimal) function of mobile objects control. Depending on the values of certain external parameters, this function returns a value that determines the future direction of the mobile object movement.

One of the most perspective approaches to the control function optimization is development and adjustment of fuzzy model of mobile object movement. Development of a model based on fuzzy rules will provide its flexibility. The fuzzy model as a set of production rules has been further developed. This model, unlike the existing ones, allows minimizing the error of mobile objects control. The adequacy of the developed models has been confirmed. It was shown that these models provide good mobile objects control.

Keywords: mobile object, fuzzy model, movement control, production rules, model adequacy, track, trajectory.

INTRODUCTION

Seeing the necessity of exact description of operating systems and increasing demands for solving the problems of intelligent control, there is a need to develop the theory of mathematical modeling. In the framework of the theory of mathematical modeling the formal procedures are used. These formal procedures take into account information heterogeneity, multicriteriality, dynamics of the quality and efficiency, and also uncertainties, which can be either stochastic or fuzzy.

Selecting the model type of a complex system and mathematical modeling tools to use depend largely on information quality and uncertainty type. Fuzzy approach is usually used when the system is so complex that it's impossible to build its mathematical model in traditional sense, or when the model exists, but to calculate it, significant computational resources are needed [1].

Complex system modeling in the form of fuzzy systems doesn't usually require knowledge of the system structure. However, in problems related to quality assessment of operation of the system consisting of a number of subsystems, or in problems of evaluating the degree of achievement of interacting goals, fuzzy model should take into account the system structure [2].

In this case the modeling tool is fuzzy logics and, in particular, one of its basic concepts – that is, function of fuzzy variables. However, existing algorithms for operating with such functions are not oriented to practical use.

The purpose of this research is increasing the quality of process control under uncertainty of objects operating. In this paper we also explore approaches of optimizing the complex objects control as a criterion for increasing the control adequacy.

1 RESEARCH PROBLEM STATEMENT

Let the production area be a rectangular field divided into unit cells. There are L loads and K mobile objects in this area. Mobile objects can move the loads.

Because of delivery of L_1 new loads it is required to move $L_2 \subseteq L$ loads to other cells, using mobile objects. The total time to perform this task should not exceed the time limit:

$$\tau \le \tau^*, \qquad (1)$$

where τ^* is the time remaining before new loads arrival. If the time of moving the loads $\tau > \tau^*$, the task should be modified to meet the requirement (1).

In paper [3] the model of mobile objects transportation in the production area is proposed. According to this model, mobile objects move discretely, from the center of one cell to the center of another one. To solve a number of practical problems, we need to modify the model, because mobile object is usually represented as a physical agent, which has a certain size and moves continuously.

The problem of optimal mobile objects system control is to find a certain optimal (or suboptimal) function of mobile object control. Depending on the values of certain external parameters, this function takes a value which determines the further direction of the mobile object [4].

One of the most perspective approaches to the control function optimization is development and adjustment of fuzzy model of mobile object movement [5]. Development of a model based on fuzzy rules will provide its flexibility, because even under changing environmental parameters (for example, unforeseen obstacles to the mobile object) the rules don't change.

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Thus, our tasks are:

– to analyze existing models and methods for solving similar problems;

– to develop the formal model of mobile object movement along given trajectory;

– to review and analyze different approaches to mobile objects control optimization;

– to develop and adjust the fuzzy model of mobile object movement;

– to verify the adequacy of resulting model.

2 ANALYSIS OF EXISTING SOLUTIONS

Recently, the use of automated systems in different areas of life becomes more and more popular. Therefore, development of models and methods for mobile objects movement is a subject of many works. Let's consider and analyze the main approaches that offered in these works.

In paper [5] the automaton model of adaptive mobile objects control based on fuzzy logics is considered. To adjust the fuzzy control system, it is proposed to use a probabilistic automaton with training.

The proposed model is rather perspective, it has several disadvantages. Firstly, in this model it is assumed that the mobile object always can bypass the obstacle. In our model being developed, the borders of mobile object trajectory are always considered as obstacles, and mobile object can never bypass them. Secondly, proposed model allows the mobile object only to bypass the obstacles, but not to move to a fixed point, and, of course, mobile object trajectory isn't being optimized. Thereby, we cannot use this model to solve our problem.

In paper [6] the teaching model of a robot following the certain mobile object is considered. In this work it is also proposed to use the system of fuzzy rules. There are also considered several different methods for the system adjustment.

The main disadvantage of this approach is that it doesn't take into account the possible obstacles the robot may not bypass, because the trajectory of mobile object does already define the trajectory of the robot which follows it.

Thus, to solve this problem we need to modify the existing approaches.

3 FORMAL MODEL DEVELOPMENT

Let r_i be a mobile object with defined trajectory

$$tr\left(G_{r_i}\right)=\left\{\left(x_i^{(0)},y_i^{(0)}\right),\left(x_i^{(1)},y_i^{(1)}\right),\ldots,\left(x_i^{(e)},y_i^{(e)}\right)\right\},$$

which represents the sequence of cells the object r_i should move to perform the task [3]. Now we develop the model of mobile object movement along this trajectory.

Let each cell be a square of size $s \times s$, and let mobile object be a rectangle with length a and width b, where $b < a < s$. Let $v_{\max}$ and $\omega_{\max}$ be maximum linear velocity and maximum angular velocity of mobile object, respectively.

Introduce the following assumptions:

1) mobile object always either moves with maximum linear velocity $v_{\max}$ or doesn't move at all;

2) velocity $v_{\max}$ is small enough to neglect the time of mobile object acceleration and deceleration;

3) velocity $v_{\max}$ is small enough and traction with surface is big enough to neglect the skid of mobile object for all possible values of its angular velocity;

4) angular velocity $\vec{\omega}=\vec{\omega}(t)$ of mobile object can be changed fast enough to neglect the influence of angular acceleration on movement of this object;

5) to make the movement safe, distance from the mobile object to an obstacle or to the trajectory border is needed to be not less than $\delta_{\min}$. It is also guaranteed that $b+2\delta_{\min}<s$;

6) decision about angular velocity change, acceleration or deceleration of mobile object is made as a result of measurements obtained by mobile object vision system. These measurements are made with the period $\tau_{\min}$;

7) maximum angular velocity $\omega_{\max}$ is small enough not to allow the mobile object to turn safely in the opposite direction;

8) when mobile object moves, it doesn't stop and doesn't face any obstacles.

Then we have

Statement 1. Position of mobile object at time t can be uniquely determined by its coordinates $\left(x_i^{(k)},y_i^{(k)}\right)$, its direction $\vec{v}^{(k)}$ and its angular velocity $\vec{\omega}^{(k)}$ at time $k=t-\tau_{\min}$. Moreover, mobile object moves along a straight line if $\omega=0$, and along a circular arc with radius $R=\dfrac{v}{2\pi\omega}$ otherwise.

Definition 1. Track $\theta(t)$ of the mobile object r_i is a curve traversed by center O of object during its movement (see Fig. 1).

Statement 2. Track $\theta(t)$ of the mobile object r_i can be uniquely determined by its initial coordinates $\left(x_i^{(0)}+\dfrac{s}{2},y_i^{(0)}+\dfrac{s}{2}\right)$, its initial direction $\vec{v}_i^{\,0}$ and sequence of its angular velocities $\left\{\omega_i^{(0)},\omega_i^{(\tau_{\min})},\omega_i^{(2\tau_{\min})},\ldots,\omega_i^{(n\tau_{\min})}\right\}$ at time $0,\tau_{\min},2\tau_{\min},\ldots,n\tau_{\min}$ respectively, where $n\tau_{\min}$ is the first moment of time when object would be entirely inside the cell $\left(x_i^{(e)},y_i^{(e)}\right)$.

Consequence 1. Then, using statement 2, we can obtain

$$\theta(t)=\theta\left(\omega_i^{(0)},\omega_i^{(\tau_{\min})},\omega_i^{(2\tau_{\min})},\ldots,\omega_i^{(n\tau_{\min})}\right). \qquad (2)$$

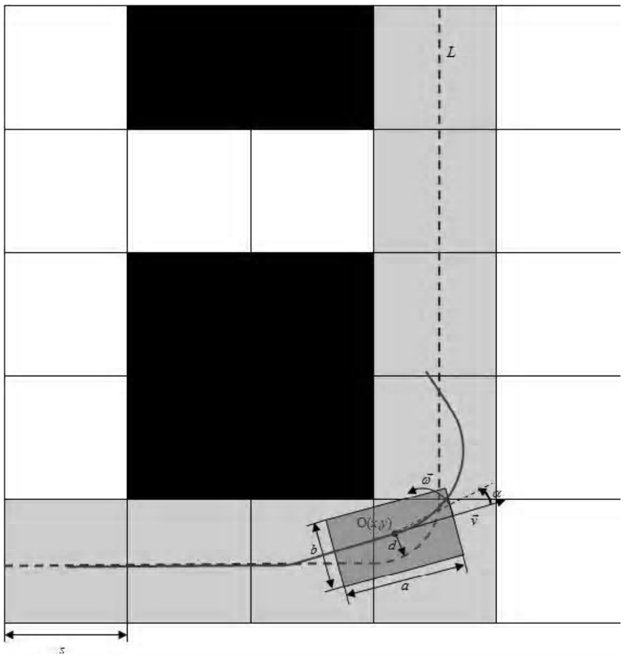

Fig. 1. Example of mobile object movement along its trajectory

Definition 2. Correct track $\theta_R(t)$ of the mobile object r_i, *corresponding to the trajectory* $tr\left(G_{r_i}\right)$, is a track satisfying the following conditions:

1) at any time of mobile object movement along the trajectory $tr\left(G_{r_i}\right)$ distance from the mobile object border to the nearest obstacle and to the borders of trajectory is not less than $\delta_{\min}$;

2) $\left|\omega_i^{(k\tau_{\min})}\right| \le \omega_{\max}$ for all $k = 0,1,...,n$;

3) at time $\omega_i^{(n\tau_{\min})}$ mobile object is entirely inside the cell $\left(x_i^{(e)}, y_i^{(e)}\right)$.

Let's denote as $\Theta_R(r_i)$ the set of correct tracks θ_R, corresponding to the trajectory $tr\left(G_{r_i}\right)$ of the mobile object r_i.

Definition 3. Length $|\theta_R|$ of correct track is the distance passed by mobile object along this track.

Statement 3. If a mobile object moves without stops, the length of its correct track can be defined as

$$|\theta_R| = v_{\max} \cdot \tau_{\min} \cdot n,$$

where n is an amount of measurements made during its movement.

Let $L_{tr} = L_{tr}\left(G_{r_i}\right)$ be a line equidistant from the borders of the trajectory $tr\left(G_{r_i}\right)$ (in Fig. 1 it is dashed). Suppose also that the measurements made with the period $\tau_{\min}$, define the following parameters:

– *Shift* d of mobile object center relative to the line L_{tr} (if mobile object is situated to the left of line L_{tr}, shift is considered to be negative, otherwise it is positive);

– *Rotation angle* α of the mobile object relative to the line L_{tr} (clockwise direction is considered to be positive). Note that if the object is rotated to the left relative to the line L_{tr}, then $\alpha > \pi$ and we can consider negative angle $\alpha - 2\pi$.

Consider the *regulation function* $\varphi = \varphi(d,\alpha)$, which, depending on the shift d and rotation angle α, returns angular velocity $\omega : |\omega| \le \omega_{\max}$ the mobile object needs to reach until the next measurement of shift and angular velocity, or a certain big number $W \gg \omega_{\max}$, which means that the mobile object needs to stop.

Definition 4. The regulation function $\varphi_R(d,\alpha)$ *is correct* if for all possible trajectories $tr\left(G_{r_i}\right) \in TR\left(G_{r_i}\right)$ it returns such a sequence of angular velocities $\{\omega_0, \omega_1, ..., \omega_m\}$, that track $\theta(\omega_0, \omega_1, ..., \omega_m) \in \Theta_R(r_i)$.

Denote the family of correct regulation functions by $\Phi = \Phi(d,\alpha)$.

Definition 5. The track $\theta = \theta(\omega_0, \omega_1, ..., \omega_m)$ is called a *track according to regulation function* $\varphi(d,\alpha)$, if

$$\forall i = \overline{1,n} : \omega_i = \varphi(d_{i-1}, \alpha_{i-1}),$$

where d_k and α_k are the values of mobile object shift and rotation angle respectively at time $k\tau_{\min}$.

Denote such track by θ_φ. Note that as φ is a correct regulation function, $\theta_\varphi \in \Theta_R(r_i)$.

Then the formal model of mobile objects control is as follows:

$$\max_{\substack{tr\left(G_{r_i}\right) \in TR\left(G_{r_i}\right) \\ \{\tau_j\}}} \frac{|\theta_\varphi|}{\left|L_{tr}\left(G_{r_i}\right)\right|} \to \min_{\varphi \in \Phi}, \qquad (3)$$

where $\left|L_{tr}\left(G_{r_i}\right)\right|$ is the length of line equidistant from the borders of the trajectory; $\{\tau_j\}, j \in J$ are time dependencies.

Optimization problem (3) is the task of finding such a regulation function φ, that the given initial conditions provides the mobile object movement along the track which is the closest to the line L_{tr}.

4 FUZZY MODEL DEVELOPMENT IN MOBILE OBJECTS CONTROL OPTIMIZATION PROBLEMS

Note that as family $\Phi(d,\alpha)$ can correspond to an infinite number of functions $\varphi(d,\alpha)$, and also checking the correctness of regulation function is a rather difficult problem [3], it doesn't seem possible to find an exact solution of problem (3). That's why we propose to search the suboptimal function $\varphi^*(d,\alpha)$, that is, such a function φ^*, for which we have

$$1,00 \le \max_{\substack{tr(G_{r_i})\in TR(G_{r_i}) \\ \{\tau_j\}}} \frac{\left|\theta_{\varphi^*}\right|}{\left|L_{tr}\left(G_{r_i}\right)\right|} < 1,02, \quad (4)$$

that is, track θ_{φ^*} is not more than 2 % longer than line $L_{tr}\left(G_{r_i}\right)$.

One of the simplest approaches to solve this problem is a formal definition of the function $\varphi^*(d,\alpha)$. Use the fact that we know the form of the trajectory $tr\left(G_{r_i}\right)$ and, thus, the form of line L_{tr}: if the assumptions 1) – 8) are correct, it can be represented as a sequence of segments and arcs. Then after the next measurement of parameters d_k и α_k the value $\omega_{k+1} = \varphi(d_k, \alpha_k)$ can be found using the following considerations [5]:

– If $d_k \le 0$ and $\alpha_k < 0$, then mobile object is moving to the left away from line L_{tr}, so we need to turn it to the right with maximum possible angular speed: $\omega_{k+1} = \omega_{\max}$;

– Similarly, if $d_k \ge 0$ and $\alpha_k > 0$, then mobile object is moving to the right away from line L_{tr} and $\omega_{k+1} = -\omega_{\max}$;

– If $\alpha_k = 0$, then mobile object is moving parallel to the line L_{tr} and we don't need to turn: $\omega_{k+1} = 0$;

– If $d_k < 0$ and $\alpha_k \ge 0$, then mobile object is approaching to the line L_{tr} from the left, and we need to choose in such a way that when mobile object reaches the line L_{tr}, its rotation angle is as close to zero as possible;

– If $d_k > 0$ and $\alpha_k \le 0$, we should choose ω_{k+1} similarly.

As a result, we receive the regulation function φ^*, which is defined as follows:

$$\phi^*(d,\alpha) = \begin{cases} \omega_{\max} \; if \; d \le 0 \; and \; \alpha \le 0, \\ -\omega_{\max} \; if \; d \ge 0 \; and \; \alpha > 0, \\ \min\left(\dfrac{v_{\max}(1-\cos\alpha)}{d}, \omega_{\max}\right) if \; d > 0 \; and \; \alpha \le 0, \\ \max\left(\dfrac{v_{\max}(1-\cos\alpha)}{d}, -\omega_{\max}\right) if \; d < 0 \; and \; \alpha \ge 0, \\ 0 \; if \; d = 0 \; and \; \alpha = 0. \end{cases} \quad (5)$$

The experiment showed that the resulting function φ^* in our model provides good mobile objects control.

However, this approach has several disadvantages.

Firstly, it works only for the given model of mobile object moving. If the obstacles appear on its path, or traction with surface is not big enough to neglect its skid, function will not provide good control any more.

Secondly, this approach requires the exact values of parameters d and α to be measured, and these measurements requires a rather expensive machine vision system.

Thirdly, to provide the safe mobile object movement, the parameters measurements should be performed rather often. This reduces the life of the machine vision system.

We propose another approach – that is, fuzzy model development to find the function φ^*. On the one hand, fuzzy model is more universal and doesn't use the assumptions about mobile object movement. On the other hand, it doesn't require the exact values of parameters d and α – we only need to know the classes they belong to.

In [7] it was proposed to use the models of fuzzy inference in form

$$\{if \; x \; is \; \mu(x) \; then \; y \; is \; \mu(y)\}. \quad (6)$$

to solve problems on fuzzy variables.

To develop the fuzzy model we propose the method consisting of the following steps:

Step 1. Define fuzzy terms and their membership functions for parameters d, α and ω.

It was decided to choose 6 fuzzy terms for each parameter:

Shift $\bar{d}$: «Big negative» – $\tilde{d}_1$, «Medium negative» – $\tilde{d}_2$, «Small negative» – $\tilde{d}_3$, «Small positive» – $\tilde{d}_4$, «Medium positive» – $\tilde{d}_5$, «Big positive» – $\tilde{d}_6$;

Rotation angle $\bar{\alpha}$: «Big negative» – $\tilde{\alpha}_1$, «Medium negative» – $\tilde{\alpha}_2$, «Small negative» – $\tilde{\alpha}_3$, «Small positive» – $\tilde{\alpha}_4$, «Medium positive» – $\tilde{\alpha}_5$, «Big positive» – $\tilde{\alpha}_6$;

Angular velocity $\bar{\omega}$: «Big negative» – $\tilde{\omega}_1$, «Medium negative» – $\tilde{\omega}_2$, «Small negative» – $\tilde{\omega}_3$, «Small positive» – $\tilde{\omega}_4$, «Medium positive» – $\tilde{\omega}_5$, «Big positive» – $\tilde{\omega}_6$.

For all the fuzzy terms it was decided [8] to choose the membership functions in the form

$$\mu(x) = \begin{cases} e^{-\frac{(x-h)^2}{2\cdot\sigma^2}}, \; x \in [x_{\min}, x_{\max}], \\ 0, \quad x \notin [x_{\min}, x_{\max}], \end{cases} \quad (7)$$

where h is an average value of the membership function; σ is the steepness of the membership function; segment $[x_{\min}, x_{\max}]$ equals to $[-1,0]$ for fuzzy terms corresponding to negative parameters values, and equals to for fuzzy terms corresponding to positive parameters values.

Step 2. Form the following system of production rules:

R_{ij} : **If** $d \in \tilde{d}_i$ **and** $\alpha \in \tilde{\alpha}_j$ **with weight** w_{ij} **then** $\omega \in \tilde{\omega}_k$,

where $\tilde{d}_i$, $\tilde{\alpha}_j$, $\tilde{\omega}_k$ are fuzzy terms for parameters d, α and ω respectively.

To do this, we decided to use the formula (5) being universal for the given control model. To define approximately, which parameters belong to which fuzzy terms, we can divide the segment $[-1,1]$ into 6 equal parts.

Step 3. Generate a training sample to adjust the fuzzy model parameters, that is, fuzzy terms distribution parameters $\tilde{d}_i$, $\tilde{\alpha}_j$, $\tilde{\omega}_k$ and rules weights w_{ij}.

It was decided to generate $N = 50$ random pairs of parameters (d_i, α_i), and then use formula (5) to define ω_i.

Step 4. Adjust the received fuzzy model to make the error $\varepsilon_\tau \to 0$.

The problem of optimal adjustment of the model $F = F(P, W)$ can be formulated as a problem of minimizing the discrepancy of the function $y^F(X)$ on the learning sample:

$$R = \frac{1}{N}\sum_{j=1}^{N}\left(\bar{\omega}(X_j) - y^F(X_j)\right)^2 \to \min_{(P,W)\in G}, \qquad (8)$$

where G is the set of constraints for vectors P and W.

To solve the problem (8) it was decided to use the modified method of very fast annealing.

Thus, we received the fuzzy model F. To make a decision if it can be applied in practice, we need to check its adequacy.

5 MODEL ADEQUACY IN PRACTICAL APPLICATIONS

After we defined the parameters of fuzzy model F, we need to check its adequacy. If regulation function $\varphi(d, \alpha)$ corresponding to this model is not correct, then the model is inadequate and we need to readjust it.

To check the mode adequacy it is proposed to simulate the process of movement of mobile object r_i along the trajectory according to fuzzy model F with different possible values of initial parameters d_0 and α_0 (that is, initial shift and rotation angle) and different trajectories $tr\left(G_{r_i}\right)$.

The simulation showed that for the values $s = 2\ m$, $a = 2\ m$, $b = 1.2\ m$, $\delta_{\min} = 0.1\ m$, $v_{\max} = 2\ m/s$, $\tau_{\min} = 0,05\ s$, $\alpha_{\max} = \frac{\pi}{6}$, $\omega_{\max} = \frac{2\pi}{3}\ s^{-1}$ the model is adequate – the mobile object moves along the correct track for all possible d_0 and α_0.

Fig. 2 shows an example of modeling the movement of mobile object r_i along the trajectory $tr\left(G_{r_i}\right)$. Here line L_{tr} equidistant from the trajectory borders is dashed, and track $\theta(r_i)$ of mobile object is a solid line. The initial point of mobile object is indicated by the circle.

Fig. 2 shows that the error of the trajectory

$$\varepsilon = \frac{\left|L_\phi - L_u\right|}{L_u}, \qquad (9)$$

where $L_u = \left|L_{tr}\left(G_{r_i}\right)\right|$ is the length of the estimated track and $L_\phi = \left|\theta_\varphi\right|$ is the length of actual track, tends to zero, and $\varepsilon \geq 0$.

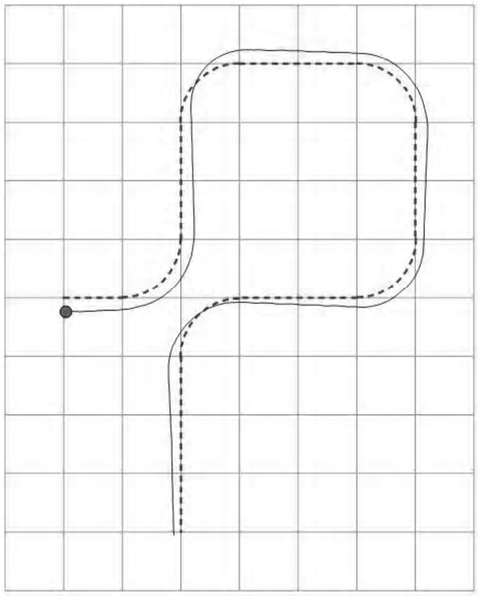

Fig. 2. Example of modeling the mobile object movement according to fuzzy model F

In the experiment on the length $L \leq 300\ m$ it was obtained that $\varepsilon < 0,015$, and it meets the suboptimality criterion (4).

CONCLUSIONS

1. An analytical review of existing models and methods for solving applied problems is made. The necessity of developing fuzzy models for mobile objects is shown.

2. A new formal model of mobile objects control is developed. This model represents the minimization of the ratio of actual and estimated track lengths.

3. Fuzzy model as a set of production rules has been further developed. This model, unlike the existing ones, allows minimizing the error of mobile objects control. The adequacy of the developed models has been confirmed.

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НЕЧЕТКИЕ МОДЕЛИ В ЗАДАЧАХ УПРАВЛЕНИЯ СЛОЖНЫМИ СИСТЕМАМИ

Выполнен аналитический обзор существующих моделей и методов решения прикладных задач. Показана необходимость разработки нечетких моделей мобильных объектов. Разработана новая формальная модель управления мобильными объектами как минимизация ошибки управления. Показано, что проблема оптимального управления системой мобильных объектов заключается в нахождении некоторой оптимальной (либо субоптимальной) функции управления мобильным объектом. В зависимости от значений определенных внешних параметров эта функция принимает значение, определяющее дальнейшее направление движения мобильного объекта.

Одним из наиболее перспективных подходов к оптимизации функции управления представляется разработка и настройка нечеткой модели движения мобильного объекта. Разработка модели на основе нечетких правил обеспечит универсальность модели. Получила дальнейшее развитие нечеткая модель в виде множества правил продукции, которая, в отличие от существующих моделей, позволяет оптимизировать управление мобильными объектами. Подтверждена адекватность моделей. Показано, что полученная модель обеспечивает хорошее управление мобильными объектами.

Ключевые слова: мобильный объект, нечеткая модель, управление движением, правила продукции, адекватность модели, трасса, траектория.

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НЕЧІТКІ МОДЕЛІ У ЗАДАЧАХ КЕРУВАННЯ СКЛАДНИМИ СИСТЕМАМИ

Виконано аналітичний огляд існуючих моделей та методів розв'язання прикладних задач. Показано необхідність розробки нечітких моделей мобільних об'єктів. Розроблено нову формальну модель керування мобільними об'єктами як мінімізацію помилки керування. Показано, що проблема оптимального керування системою мобільних об'єктів полягає у знаходженні деякої оптимальної (або субоптимальної) функції керування мобільним об'єктом. Залежно від значень певних зовнішніх параметрів ця функція приймає значення, що визначає подальший напрямок руху мобільного об'єкта.

Одним з найбільш перспективних підходів до оптимізації функції керування представляється розробка та налагодження нечіткої моделі руху мобільного об'єкта. Розробка моделі на основі нечітких правил забезпечить універсальність моделі. Отримала подальший розв'язок нечітка модель у вигляді множини правил продукції, яка, на відміну від існуючих моделей, дозволяє оптимізувати керування мобільними об'єктами. Підтверджено адекватність моделей. Показано, що отримана модель забезпечує добре управління мобільними об'єктами.

Ключові слова: мобільний об'єкт, нечітка модель, керування рухом, правила продукції, адекватність моделі, траса, траєкторія.

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