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AUTOMATION SYSTEMS IN SCIENTIFIC RESEARCH AND INDUSTRY

Adaptive Control of Motion of a Group of Robots Along a Prescribed Trajectory

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Abstract—A control method and software structure for solving the problem of control of motion of a group of robots along a prescribed trajectory with preserving a chosen configuration under conditions of unsteady dynamic characteristics of individual robots is proposed.

Keywords: control of a group of mobile robots, synthesis of automatic control systems, adaptation of controller parameters, modeling, Robot Operating System.

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INTRODUCTION

In solving various problems of observations, investigations of large-area environment, or cargo transportation, joint application of comparatively simple robots within one group is more effective that the use of one sophisticated robot [1]. At the same time, design of a system consisting of a set of devices jointly operating as a team requires specialized control methods and algorithms that differ from methods used to control an individual robot [2].

The use of mixed groups of robots acting in different media offers a possibility of extending the area of applicability of such heterogeneous systems by means of eliminating constraints on the actions of individual representatives of such a group. Petrovic et al. [3] proposed to organize a symbiotic robotic system consisting of a quadrotor-type unmanned aerial vehicle (UAV) and an unmanned ground-based transportation vehicle. In that system, the ground-based vehicle ensured a safe area for UAV landing and UAV transportation to large distances, while the UAV increased the degree of freedom of ground-based vehicle motion by means of its carrying over impassable obstacles. It was implied that the system would be controlled by a decentralized algorithm of coordinated interaction.

To solve the problem of determining the moving target position, a fault-proof system of combined control by a group of robots acting in two media (ground/water) is needed [4], which implies creation, maintaining, and switching of various configurations of bonds between the robots with the use of optimization mechanisms for constructing robot control laws and an extended Kalman filter for estimating the position of each robot. This approach to cooperative tracking of the target allows minimization of the error of determining the target position predicted with the use of the extended Kalman filter, which is achieved by calculating the ultimate covariation. In addition to the target position uncertainty, the optimality criterion also includes a function depending on the predicted distance between all robots acting in cooperation, which determines the repulsion force for preventing collisions. Thus, a flexible adaptive configuration and local-optimal control are formed, which allow one to take into account the constraints on the search for the target, motion of each robot, and motion of the target itself.

An important element in design of control systems for group interaction of robots in different media is to ensure system immunity to failure situations resulting in the loss of efficiency of control by individual robots. Cooperating interaction of robots can be based on the “leader–follower” scheme, where the leader moves along a prescribed trajectory, while the followers have to maintain a specified configuration with respect to the leader position. The controller synthesis is based on minimizing the deviations of the follower robots from their required positions. To develop such systems, it is reasonable to use approaches based on the principles of centralization and decentralization [5–7].

The present paper describes a method for constructing a system used to control a group of mobile robots with a differential drive as applied to the problem of coordinated motion along a prescribed trajectory under the conditions of disturbances and partial loss of the control efficiency. A multi-contour structure of the control system supplemented with blocks for adaptation to actions of unknown and variable factors is proposed.

FORMULATION OF THE PROBLEM

Onboard systems of robot control are designed on the basis of universal systems, such as the Robot Operation System (ROS) and Player Project, or specialized software unique for each robot. Such onboard systems include the lower level responsible for obtaining data from sensors and motor controlling and the upper level responsible for communication mechanisms and for motion control and interaction algorithms. The input parameters for the lower level of the onboard control system in universal and many specialized systems are commands for setting the linear and angular velocities of robot motion. However, the robot motion parameters are significantly affected by various external and internal factors, e.g., unsteady characteristics of drives, inhomogeneity of the motion surface, and presence of unknown obstacles and loads [8, 9]. Because of the action of these factors, the prescribed dynamic characteristics cannot be provided by the lower level control systems. Under such conditions, it is reasonable to supplement the upper level control system by an adaptation contour, which can compensate for the dynamic characteristics of individual robots, which are not known in advance, or for changes in these characteristics in the course of motion of the robots.

Thus, the task of the present study is to determine the structure and parameters of the control system for motion of a group of robots along a prescribed trajectory with an error of maintaining a specified configuration within 5% of the distance between the robots and to develop software for this system.

It is planned to reduce the problem of controlling the motion of a group of robots to the problem of tracking each robot and its desirable position $\mathbf{x}_{ri}$ with respect to the center of the group, which is determined by the required trajectory and distribution of the robots, under the condition of maintaining a specified distance between all robots of the group [10]. The required trajectory of group motion is formed as programmed motion of the target point along piecewise-linear segments between specified points on the path or along a spline based on these points.

The motion of the ith robot with controlled linear and angular velocities is described by the differential equation in the vector-matrix form [11]

$$\dot{\mathbf{x}}_i = \mathbf{f}(\mathbf{x}_i)(\mathbf{u}_i - \mathbf{m}_i(t)), \tag{1}$$

where $\mathbf{x}_i = [x_i, y_i, \psi_i]^\top$ is the vector of state of the ith robot (coordinates and angle of approach), $\mathbf{u}_i = [v_i, \omega_i]^\top$ is the vector of control commands for the linear and angular velocities, $\mathbf{m}_i(t) = [m_{vi}(t), m_{\omega i}(t)]^\top$ is the vector of time-dependent disturbances induced by wheel slipping, changes in the loads and battery charge, and other factors, and $\mathbf{f}(\mathbf{x}_i)$ is a matrix function of the form $\mathbf{f}(\mathbf{x}_i) = \begin{bmatrix} \cos\psi_i & \sin\psi_i & 0 \\ 0 & 0 & 1 \end{bmatrix}^\top$. Let the magnitude of disturbances and the rate of their variation be bounded:

$$|m_{vi}(t)| \leqslant m_{vi\max}; \quad |m_{\omega i}(t)| \leqslant m_{\omega i\max}; \quad |\dot{m}_{vi}(t)| \leqslant \dot{m}_{vi\max}; \quad |\dot{m}_{\omega i}(t)| \leqslant \dot{m}_{\omega i\max}. \tag{2}$$

Our goal is to ensure reduction of the error of tracking the required object position in a steady regime of motion of objects described by model (1) with disturbances under constraints (2). The process is described by the equation

$$\dot{\mathbf{x}}_i = \mathbf{F}(\mathbf{x}_i), \tag{3}$$

where $\mathbf{F}(\mathbf{x}_i)$ is the vector of desired values of the higher derivatives of the state variables: $\mathbf{F}(\mathbf{x}_i) = \mathbf{A}(\mathbf{x}_{ri} - \mathbf{x}_i)$.

Let us consider a method for constructing a tracking system, which ensures control of passing of an individual robot to a prescribed point in the space of coordinates, correction of the position of this point for maintaining the configuration of the group of robots and their coordinated motion with cargo relocation, as well as adaptation of controller parameters to changes in the dynamic characteristics of the robots in the course of their motion.

CONTROL METHOD

Using the method of solving the inverse problem of dynamics [12–14] and equating the right sides of Eqs. (1) and (3), we can write

$$\mathbf{F}(\mathbf{x}_i) = \mathbf{f}(\mathbf{x}_i)(\mathbf{u}_i - \mathbf{m}_i(t)). \tag{4}$$

Multiplying both parts of Eq. (4) by $\mathbf{f}^\top(\mathbf{x}_i)$ and taking into account that $\mathbf{f}^\top(\mathbf{x}_i)\mathbf{f}(\mathbf{x}_i) = \mathbf{I}$ in the case considered here, we obtain the equation for the control law that ensures a specified time of convergence of the processes to the desired state in accordance with Eq. (3):

$$\mathbf{u}_i = \mathbf{f}^\top(\mathbf{x}_i)\mathbf{F}(\mathbf{x}_i) + \mathbf{m}_i(t). \tag{5}$$

The control law (5) contains an unknown unsteady parameter $\mathbf{m}_i(t)$. Therefore, instead of Eq. (5), the control law is considered in the form of an equation with automatically tuned parameters aimed at correcting the control procedure so that the system should be invariant to the acting disturbances:

$$\mathbf{u}_i = \mathbf{f}^\top(\mathbf{x}_i)\mathbf{F}(\mathbf{x}_i) + \boldsymbol{\Theta}_i. \tag{6}$$

Here $\boldsymbol{\Theta}_i$ is the vector of automatically tuned parameters. Equation (6) determines the structure of the system with adaptive control. The algorithm of tuning the parameters of the vector $\boldsymbol{\Theta}_i$ is based on the equation of the form [15]

$$\dot{\boldsymbol{\Theta}}_i = -\mu^{-1}\mathbf{L}(\mathbf{x}_i)(\mathbf{F}(\mathbf{x}_i) - \dot{\mathbf{x}}_i), \tag{7}$$

where μ is a small positive coefficient and $\mathbf{L}(\mathbf{x}_i)$ is an auxiliary matrix function determined from the condition of stability of a closed system. Equation (7) is a particular case of the algorithm of the velocity gradient in the differential form [16].

Equation (1) with the control law (6) describes a slow contour of control of the robot displacement to a point with prescribed coordinates. Equation (7) with a sufficiently small parameter μ is a fast internal contour, which allows control to be corrected and specified dynamic characteristics of the robot under disturbed conditions to be provided.

The analysis of the processes in a closed system and the search for the form of the function $\mathbf{L}(\mathbf{x}_i)$ are performed by the method of motion separation [17]. For this purpose, we introduce the fast time $\tau = \mu^{-1}t$. In this case, the equations for the processes in a closed system take the form

$$\begin{cases} \mu^{-1}\dfrac{d}{d\tau}\boldsymbol{\Theta}_i = -\mu^{-1}\mathbf{L}(\mathbf{x}_i)(\mathbf{F}(\mathbf{x}_i) - \mathbf{f}(\mathbf{x}_i)(\mathbf{u}_i - \mathbf{m}_i(\tau))); \\ \mu^{-1}\dfrac{d}{d\tau}\mathbf{x}_i = \mathbf{f}(\mathbf{x}_i)(\mathbf{f}^\top(\mathbf{x}_i)\mathbf{F}(\mathbf{x}_i) + \boldsymbol{\Theta}_i - \mathbf{m}_i(\tau)). \end{cases} \tag{8}$$

As $\mu \to 0$ for bounded parameters of the disturbances (2), we have

$$\begin{cases} \mathbf{x}_i = \text{const}, \qquad \mathbf{m}_i(\tau) = \text{const}, \\ \dfrac{d}{d\tau}\boldsymbol{\Theta}_i = \mathbf{L}(\mathbf{x}_i)(\mathbf{F}(\mathbf{x}_i) - \mathbf{f}(\mathbf{x}_i)(\mathbf{u}_i - \mathbf{m}_i)). \end{cases} \tag{9}$$

In view of Eq. (6), we obtain

$$\frac{d}{d\tau}\boldsymbol{\Theta}_i = \mathbf{L}(\mathbf{x}_i)\mathbf{f}(\mathbf{x}_i)\boldsymbol{\Theta} - \mathbf{L}(\mathbf{x}_i)\mathbf{f}(\mathbf{x}_i)\mathbf{m}_i. \tag{10}$$

Equation (10) describes the fast processes in the internal contour of tuning the coefficients that are stable at $\mathbf{L}(\mathbf{x}_i)\mathbf{f}(\mathbf{x}_i) < 0$. In this case, the matrix function $\mathbf{L}(\mathbf{x}_i)$ may have the form $\mathbf{L}(\mathbf{x}_i) = -\mathbf{f}^\top(\mathbf{x}_i)$. In a steady (for the fast contour) regime, we have $d\boldsymbol{\Theta}_i/d\tau = 0$, then

$$\boldsymbol{\Theta}_i = \mathbf{m}_i(\tau). \tag{11}$$

Thus, the law of tuning of the controller parameters takes the form

$$\dot{\boldsymbol{\Theta}}_i = \mu^{-1}\mathbf{f}^\top(\mathbf{x}_i)(\mathbf{F}(\mathbf{x}_i) - \dot{\mathbf{x}}_i). \tag{12}$$

The presence of noise in determining the vector of state in the navigation system of the robots, which is based on using GPS data or machine vision images, requires the use of differentiating blocks with filtration for calculating the derivatives in Eq. (12). The basis of these blocks may be the structure of the dynamic system, which retains the stability properties with an unbounded amplification factor [18].

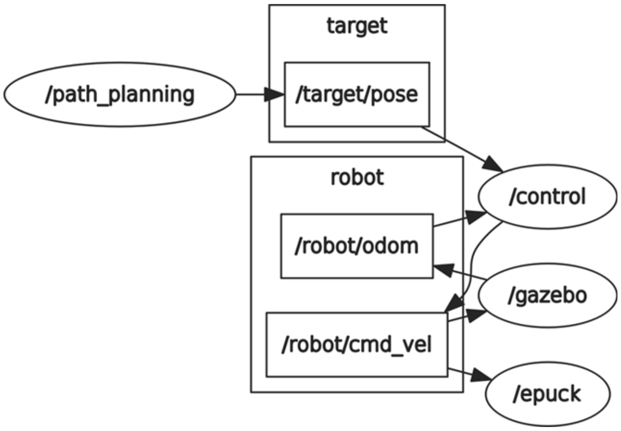

Fig. 1. Structure of the ROS-based control system.

CONTROL SYSTEM

The system for control of each robot was created on the ROS basis, which is a modern and actively developed system with an open-source code for control of robotic devices [19]. It includes a large set of ready libraries and program modules, as well as a universal mechanism of communication between them, which allows one to design complex program assemblies. The developed control system includes a set of independent programs interacting with each other via messages. The system structure for each ith robot is shown in Fig. 1. The programs are marked by ovals, and the messages are marked by rectangular frames. The arrows show the message transfer direction.

The system includes the following programs:

— path planning (/path_planning);
— modeling of robot motion, Gazebo simulator (/gazebo);
— control law implementation (/control);
— driver forming control commands for the robot (/epuck).

The mechanism of operation of this system is characterized by asynchronous transfer of messages between the above-mentioned programs based on the publish/subscribe principle [20]. The coordinates of the next point $\mathbf{x}_{ri}$ for each robot are calculated in the /path_planning module depending on the current position of the leader on the trajectory and specified arrangement of robots with respect to the leader. These data are published in the system and are used in the /control module, where the control vector is calculated by Eqs. (3), (6), and (12) at each step and the /robot/cmd_vel message is published. Based on the commands of velocities, the Gazebo simulator calculates the robot position at each time instant.

The developed software is used both for simulations and for control of actual robots [21]. In the latter case, drivers forming motor control commands are actuated instead of simulators. These drivers are individual codes receiving /robot/cmd_vel messages in the ROS system and transforming them to signals with pulsed width modulation of motor drivers or setting commands for the lower level control system. The data on the coordinates and angles of orientation of each robot are received from the machine vision system with the use of the ar_track_alvar module from the ROS system processing frames taken by the video camera fixed at the top. If robots are used outdoors, information about the coordinates can be obtained from the navigation system, which unites signals from different sources.

Thus, a control method and software for the ROS-based control of a group of robots are developed. Integration with the Gazebo simulator makes it possible to simulate various situations and to study the quality of system operation.

NUMERICAL EXPERIMENT

To study the properties of the proposed control algorithm, as well as stability issues, and to solve the proposed problem, we performed a series of numerical experiments using the developed software with different values of the input parameters; the path was defined as a sinusoid or a piecewise-linear trajectory, whereas the components of the disturbance vector $\mathbf{m}_i(t)$ had the form of harmonic signals with constant amplitude

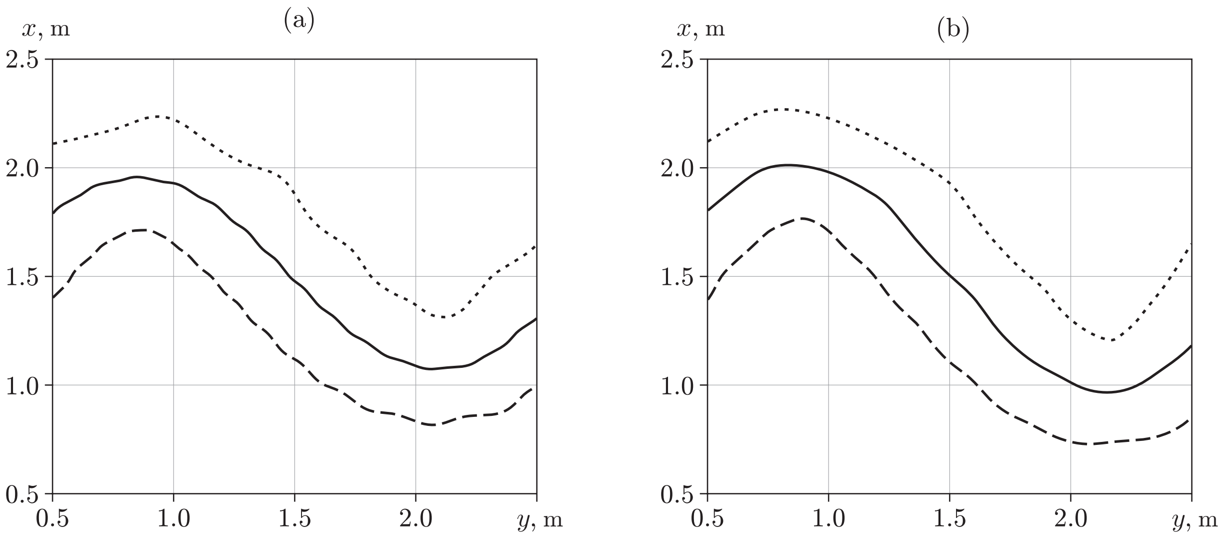

Fig. 2. Trajectories of motion of a group of robots in the absence (a) and in the presence (b) of the tuned parameter $\mathbf{\Theta}_i$ in the control law.

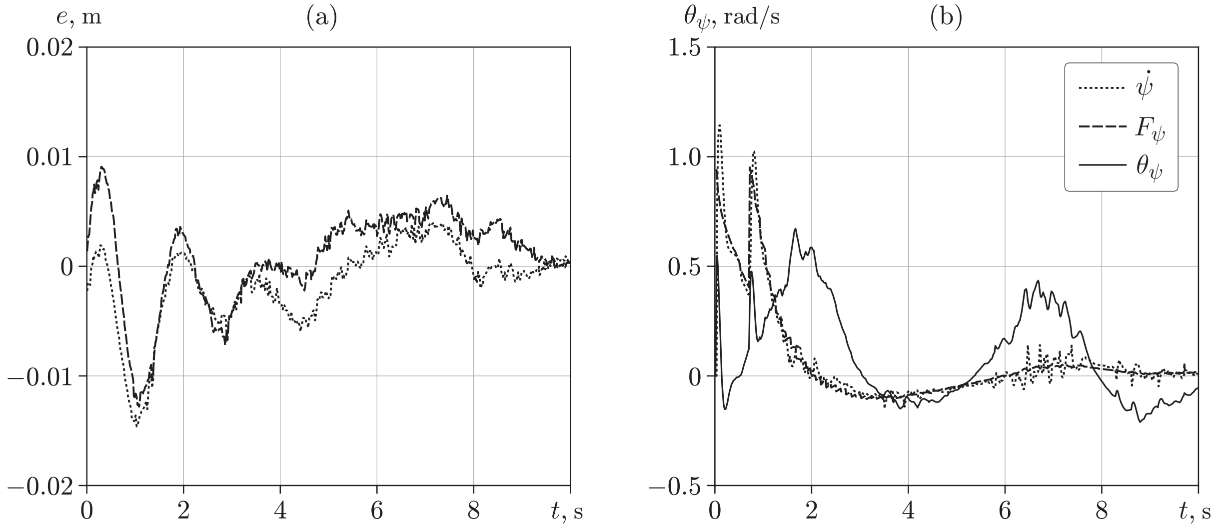

Fig. 3. Motion parameters: (a) deviations (e) of the robots from prescribed positions with respect to the leader; (b) comparison of real and desired values of the higher derivatives of the angle of approach and the change in the tuned parameter of the controller.

and frequency. The influence of the presence and absence of the parameter $\mathbf{\Theta}_i$ in the control law (6) on the robot deviation from a specified path was checked. The following parameters of the control algorithm were used in the present experiments:

$$A = \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 1.5 \end{bmatrix}; \qquad \mu = 0.05. \tag{13}$$

The results of modeling a group consisting of three robots moving in column under harmonic disturbances are shown in Fig. 2.

The analysis of system operation in the presence of the contour of correction of the desired position of each robot (Fig. 3) revealed a possibility of coordinated motion of a group of robots transporting certain cargo over a prescribed trajectory while maintaining a specified configuration of the group within 5%, as was demonstrated in numerical experiments with a required distance between the robots equal to 0.2 m.

The absolute deviation of the robots from the prescribed trajectories was within 0.01 m. In the absence of the correction contour, the deviation of the robots from the desired trajectory was 0.05 m. The character of the processes and the numerical values of deviations from the prescribed position in the case of modeling the motion along piecewise-linear trajectories in the steady regime were qualitatively identical to those in the case illustrated in Fig. 3. The possibility of adaptive tuning provides desired dynamic characteristics of the control channels, which significantly decreases the influence of the considered disturbances on the trajectories of motion of each robot and on the magnitude of their deviation from the required position with respect to the leader of the group.

Thus, the control system ensures the motion of the robots along a required trajectory under conditions of disturbances, and the fact that Eq. (6) contains the parameter $\boldsymbol{\Theta}_i$ varied in accordance with Eq. (12) reduces the deviation from the prescribed path down to 0.01 m.

CONCLUSIONS

A method for control of a group of robots moving in column over a programmed trajectory in the case of imposed disturbances and dynamic characteristics that are not known in advance is proposed. The use of an internal fast correction contour compensates for the action of disturbances and provides necessary dynamic characteristics of control channels for each robot in the group, which reduces the deviation of the robots from specified positions with respect to the leader in the case of their joint motion along a prescribed trajectory. A ROS-based structure of the control system for a group of robots is presented, which allows the user to separate the control functions between individual codes and to change the functionalilty of the system by means of combining various modules, including simulations, navigation, terrain mapping, and machine vision. Numerical experiments demonstrated that the error of maintaining a prescribed configuration of the group is smaller than 5% for the disturbance type considered in the study.

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