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A switching formation strategy for obstacle avoidance of a multi-robot system based on robot priority model

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ABSTRACT

This paper describes a switching formation strategy for multi-robots with velocity constraints to avoid and cross obstacles. In the strategy, a leader robot plans a safe path using the geometric obstacle avoidance control method (GOACM). By calculating new desired distances and bearing angles with the leader robot, the follower robots switch into a safe formation. With considering collision avoidance, a novel robot priority model, based on the desired distance and bearing angle between the leader and follower robots, is designed during the obstacle avoidance process. The adaptive tracking control algorithm guarantees that the trajectory and velocity tracking errors converge to zero. To demonstrate the validity of the proposed methods, simulation and experiment results present that multi-robots effectively form and switch formation avoiding obstacles without collisions.

1. Introduction

A multi-robot system can perform collaborative tasks in manufacturing, surveillance, and space exploration. The multi-robot formation control problem stands out because the robots can efficiently accomplish cooperative tasks by forming and maintaining some formations. There are three proposed classical formation control approaches: behavior-based approach [1], virtual structure approach [2], and leader-follower approach [3]. Based on [4], the formation control issues include assignment of feasible formations, moving into formation, maintenance of formation, and switching between formations. This paper focuses on solving these problems for mobile robots within a cluttered environment, based on leader–follower formation approach.

In order to complete cooperative tasks, a novel priority model is designed for each robot. According to the priority model, the system assigns tasks to the robots. The leader robot has the highest priority. The follower robot's priority is based on the desired distance and desired bearing angle with the leader robot. This paper will describe the coordination of priority model and switching formation strategy in detail in Section 3.

Obstacle avoidance is a challenging task in mobile robot control systems. Artificial potential field method, in [5] and [6], is a well-known method for obstacle avoidance, due to its mathematical simplicity. The basic concept of this method is to fill a working environment with an artificial potential field, where the robot is attracted by the goal and repulsed by an obstacle [5]. However, besides the stability problem, this method also suffers from a local minimal problem because it is difficult for the robot to identify the repulse force. In addition, the artificial potential field method is used for each robot to avoid obstacles in multiple robot systems, the collision problem between robots is ignored. Mixed-integer linear programming [7] is used to plan a safe path. However, the NP-hard problem results in the complex computation. The null-space-based behavioral control in $\mathbb{R}^2$ for obstacle avoidance is suggested in [8], where a control task is defined to keep the robot heading aligned with the vector field orientation. This is applied for each robot to avoid obstacles, without considering the collision avoidance problem. According to this paper, a switching formation strategy for a multi-robot system is proposed. A geometric obstacle avoidance control method is proposed for the leader robot to calculate its waypoint. Follower robots switch into the obstacle avoidance formation with the leader robot. There are three advantages of switching formation strategy for a multi-robot system to avoid obstacles: (1) when avoiding obstacles, robots are collision free. (2) In the switching formation strategy, since the desired distance between the leader robot and the follower robot may not change, multi-robots can efficiently reform the predefined formation after avoiding obstacles. (3) Due to simple equations of the switching formation strategy, it is easy to apply the strategy in the experiment.

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There are several methods used to control robots' motion, such as adaptive control [9], EKF [10], and optimal feedback control [11]. Adaptive control algorithm is widely used in order to decrease uncertainties in the system [12]. The trajectory tracking problem is widely solved using the kinematic model of a mobile robot [13], where 'perfect velocity' tracking is to generate the actual velocity control inputs. However, since it is difficult for the dynamics of the robot to produce the perfect velocity as the kinematic controller [14], the torque inputs are used [15]. An adaptive tracking control algorithm is presented with the integration of an adaptive kinematic controller and a torque controller, based on [12,13].

2. Robot models

2.1. Mobile robot with two actuated wheels model

As shown in Fig. 1, robot R_i (i is the robot's identifier, $i=1,2,\ldots,n$) consists of a passive wheel and two actuated wheels to achieve the motion and orientation. The radius of both of the actuated wheels is r_i. The distance between the two actuated wheels is denoted by $2b_i$. The mass center of the mobile robot is located at M_i, and O_i is located in the middle point between the right and left driving wheels. The distance between M_i and O_i is denoted by d_i. o,x,y is an inertial Cartesian, and $\{O_i,X,Y\}$ is the local coordinate system fixed to the robot. The configuration of robot R_i can be $q_i=[x_i,y_i,\theta_i,\phi_{ir},\phi_{il}]^T$ in an inertial Cartesian frame, where (x_i,y_i) are the coordinates of O_i, θ_i is the heading angle of the mobile robot, and ϕ_{ir}, ϕ_{il} are the angles of the right and left driving wheels.

Based on [15], there are three constraints. Firstly, O_i moves in the direction of the axis of symmetry. Secondly and thirdly, the wheels must roll without slipping

$$\dot{y}_i\cos\theta_i-\dot{x}_i\sin\theta_i=0 \tag{1}$$

$$\dot{x}_i\cos\theta_i+\dot{y}_i\sin\theta_i+b_i\dot{\theta}_i=r_i\dot{\phi}_{ir} \tag{2}$$

$$\dot{x}_i\cos\theta_i+\dot{y}_i\sin\theta_i-b_i\dot{\theta}_i=r_i\dot{\phi}_{il} \tag{3}$$

The three constraints can be rewritten in the form of

$$A(q_i)\dot{q}_i=0 \tag{4}$$

where

$$A(q_i)=\begin{bmatrix}\sin\theta_i & -\cos\theta_i & 0 & 0 & 0\\ \cos\theta_i & \sin\theta_i & b_i & -r_i & 0\\ \cos\theta_i & \sin\theta_i & -b_i & 0 & -r_i\end{bmatrix}.$$

Define $\nu_i=(\nu_{i1},\nu_{i2})^T$ as the angular velocities of the right and left wheels of robot R_i. Based on [15], the model of the nonholonomic mobile robot can be written as follows:

$$\dot{q}_i=S(q_i)\nu_i(t) \tag{5}$$

$$\overline{M}(q_i)\dot{\nu}_i+\overline{V}(q_i,\dot{q}_i)\nu_i+\overline{\tau}_{id}=\overline{B}\tau_i \tag{6}$$

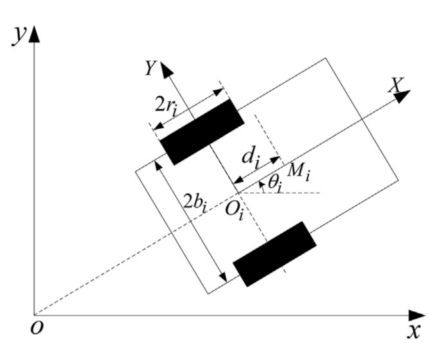

Fig. 1. Two-wheels nonholonomic mobile robot model.

where

$$S(q_i)=\begin{bmatrix}\frac{r_i}{2}\cos\theta_i & \frac{r_i}{2}\cos\theta_i\\ \frac{r_i}{2}\sin\theta_i & \frac{r_i}{2}\sin\theta_i\\ r_i/2b_i & -r_i/2b_i\\ 1 & 0\\ 0 & 1\end{bmatrix},$$

$$\overline{M}=\left(\frac{r_i}{2b_i}\right)^2\begin{bmatrix}(m_ib_i^2+I_i)+I_{iw} & (m_ib_i^2-I_i)\\ (m_ib_i^2-I_i) & (m_ib_i^2+I_i)+I_{iw}\end{bmatrix},$$

$$\overline{V}=\begin{bmatrix}0 & \frac{r_i^2}{2b_i}m_{ic}d_i\dot{\theta}_i\\ -\frac{r_i^2}{2b_i}m_{ic}d_i\dot{\theta}_i & 0\end{bmatrix},\quad \overline{B}=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix},\quad m_i=m_{ic}+2m_{iw},$$

and

$$I_i=m_{ic}d_i^2+2m_{iw}b_i^2+I_{ic}+2I_{iw}.$$

$\tau_i=(\tau_{i1},\tau_{i2})^T$ is the torque applied on the right and left wheels of robot R_i. m_{ic} and m_{iw} are the mass of the body and wheel with a motor. I_{ic}, I_{iw}, and I_{im} are the moment of inertia of the body about the vertical axis through M_i, the wheel with a motor about the wheel axis, and the wheel with a motor about the wheel diameter, respectively. $\overline{\tau}_{id}$ is the bounded unknown disturbances of robot R_i including unstructured and unmodeled dynamics.

Property 1. *$\overline{M}(q_i)$ is symmetric and positive definite.*

Property 2. *$(\dot{\overline{M}}-2\overline{V})$ is skew symmetric.*

Assumption 1. The bounded disturbances $\overline{\tau}_{id}$ satisfies $\|\overline{\tau}_{id}\|\le c_{i0}+c_{i1}\|\nu_i\|$, with positive constants c_{i0} and c_{i1} [12].

2.2. Leader–follower formation model

For n robots, robot R_1 is assigned to be the leader robot, which determines each follower robot's motion. Let R_1 and $R_i(i=2,3,\ldots,n)$ be the leader robot and the follower robot, respectively. l_{i1} is defined as the desired distance between R_1 and R_{iw}. β_{i1} is the desired bearing angle from the orientation of the follower robot to the axis connecting R_1 and R_{iw}. The formation control model is as Fig. 2. The waypoint posture $q_{iw}=(x_{iw},y_{iw},\theta_{iw})^T$ of follower robot R_i are denoted as

$$\begin{bmatrix}x_{iw}(t)\\ y_{iw}(t)\end{bmatrix}=\begin{bmatrix}x_1(t)-l_{i1}\cos(\beta_{i1}+\theta_1(t))\\ y_1(t)-l_{i1}\sin(\beta_{i1}+\theta_1(t))\end{bmatrix} \tag{7}$$

$$\theta_{iw}(t)=a\tan2((y_{iw}(t)-y_i(t-1)),(x_{iw}(t)-x_i(t-1))) \tag{8}$$

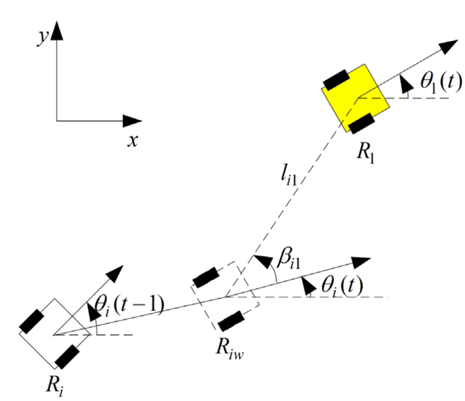

Fig. 2. The leader–follower formation control model.