Engineering xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Robotics—Article

Control of Velocity-Constrained Stepper Motor-Driven Hilare Robot for Waypoint Navigation

Robins Mathew, Somashekhar S. Hiremath *

Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

A R T I C L E I N F O

Article history:
Received 26 June 2017
Revised 11 February 2018
Accepted 12 July 2018
Available online xxxx

Keywords:
Trajectory tracking
Adaptive control
Waypoint navigation
Hilare robot
Particle swarm optimization
Probabilistic road map

A B S T R A C T

Finding an optimal trajectory from an initial point to a final point through closely packed obstacles, and controlling a Hilare robot through this trajectory, are challenging tasks. To serve this purpose, path planners and trajectory-tracking controllers are usually included in a control loop. This paper highlights the implementation of a trajectory-tracking controller on a stepper motor-driven Hilare robot, with a trajectory that is described as a set of waypoints. The controller was designed to handle discrete waypoints with directional discontinuity and to consider different constraints on the actuator velocity. The control parameters were tuned with the help of multi-objective particle swarm optimization to minimize the average cross-track error and average linear velocity error of the mobile robot when tracking a predefined trajectory. Experiments were conducted to control the mobile robot from a start position to a destination position along a trajectory described by the waypoints. Experimental results for tracking the trajectory generated by a path planner and the trajectory specified by a user are also demonstrated. Experiments conducted on the mobile robot validate the effectiveness of the proposed strategy for tracking different types of trajectories.

1. Introduction

The application of mobile robots, and particularly wheeled mobile robots (WMRs), is exponentially increasing in today's fast-growing market. These robots play a major role in many sectors, with their applications ranging from service robots to military robots. The Hilare robot is one type of robot among WMRs with a number of applications, primarily in indoor environments. Fig. 1 provides a schematic diagram of a Hilare robot. This type of mobile robot has two independently actuated wheels mounted on either side of the body in such a way that the central axis of wheels coincides with each other, and has one or more passive wheels to balance the robot [1]. The ease of design, ease of manufacturing, and ease of predicting the dynamics for this type of mobile robot make it a simple, suitable, and economic choice among the different ground contact mobile robots that are currently available [2].

The motion of a Hilare robot is controlled by controlling the velocities of the independent right and left wheels. When the wheels roll on the contact surface without lateral slip, non-holonomic behavior is induced in the robot motion. In the inverse kinematics of the mobile robot, this non-holonomic behavior appears as a constraint on the robot velocity that cannot be transformed into a position constraint [3]. Although the robot cannot move sideways, it can reach any desired position and orientation in the workspace by taking a complex trajectory. Since the robot cannot move sideways, finding an optimal trajectory from an initial point to a final point through closely packed obstacles, and controlling the robot through this trajectory, are challenging tasks. To serve this purpose, path planners and trajectory-tracking controllers are usually included in a control loop. The same tasks would be much easier if the mobile robot had the ability to move sideways.

A trajectory-tracking controller is the lowest level in a layered control architecture, and is essential for the motion control of any mobile robot. The main objective of the trajectory-tracking controller is to reduce the cross-track error [4]. Over the years, many approaches have been developed for the control of the Hilare robot [5]. The simplest approach to control the motion of this mobile robot is to use motion primitives, such as straight motion and in-place turning. A suitable combination of these primitives is used to control the robot through the predefined trajectory

---

* Corresponding author.
E-mail address: somashekhar@iitm.ac.in (S.S. Hiremath).

https://doi.org/10.1016/j.eng.2018.07.013

Please cite this article in press as: Mathew R, Hiremath SS. Control of Velocity-Constrained Stepper Motor-Driven Hilare Robot for Waypoint Navigation. Eng (2018), https://doi.org/10.1016/j.eng.2018.07.013

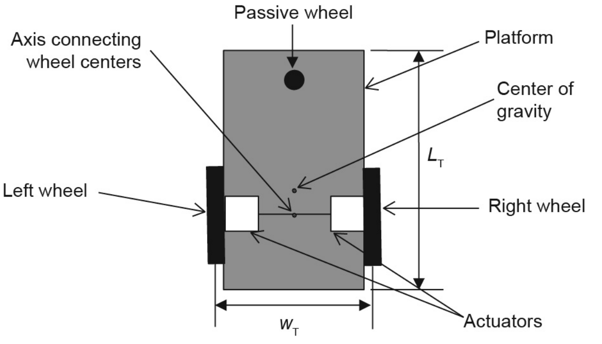

Fig. 1. Schematic diagram of a Hilare robot. L_T: length of the platform; w_T: width of wheel track.

[6,7]. However, this strategy may cause unwanted jerks and oscillations that affect the smoothness of the motion and the stability. Research on path-tracking controllers for a car-like robot [8] has shown that the stability of the controller is affected also by look-ahead distance. That work also suggests that a large look-ahead distance will result in cutting corners. According to the literature, other control methods such as adaptive control, the back-stepping method, artificial neural networks, fuzzy control, biologically inspired methods, potential field-based control, and so forth have been evolved over time for the smooth and stable tracking control of mobile robots [9–11]. Of these methods, a well-established method to control a mobile robot is a stable tracking controller, as proposed by Kanayama et al. [12]. This method is applicable to all types of autonomous mobile robots. The controller works such that the position and orientation error of the mobile robot with respect to a reference trajectory is reduced. The literature shows that this method can be modified further to develop smooth tracking controllers [13–15].

A reference trajectory for the controller can be obtained from the operator or from a path-planning algorithm. In general, path planning comes before the trajectory-tracking controller in the control hierarchy, and is very important in mobile robot navigation. Different approaches have been proposed, with different levels of complexity, accuracy, and applicability, for planning a feasible path for mobile robots [16]. Geometric path-planning algorithms [17], rapidly-exploring random trees (RRTs) [18], and probabilistic road maps (PRMs) [19] are some of the algorithms that can provide a reference trajectory to the tracking controller. A PRM is a well-known technique for planning an admissible path for a non-holonomic mobile robot. A PRM-based path planner can find the trajectory that must be followed by the mobile robot in order to reach the destination and to avoid the various obstacles.

Although many control methods have been developed for trajectory-tracking control, few efforts have been made to study a controller that is implemented in a layered control architecture in which the output of a path planner acts as an input to the controller. The available literature also lacks an explanation of the implementation of these controllers in Hilare robots with stepper motor-driven wheels. The current paper focuses on addressing these gaps in the literature. We propose a control strategy that can guide a mobile robot along a reference trajectory that is specified as a set of discontinuous waypoints through which the mobile robot must move in order to reach the destination. Parameter optimization has been carried out to minimize the average cross-track error and average linear velocity error of the mobile robot.

The paper is organized as follows: Section 2 presents the kinematic model and controller design. Section 3 presents the simulation and optimization of control parameters. Experimentation is presented in Section 4, and conclusions and future work are detailed in Section 5.

2. Kinematic model and controller design

Consider a Hilare robot, as shown in Fig. 2, located on a two-dimensional surface for which a global coordinate system (inertial frame (X_I, Y_I)) is defined. The robot has three degrees of freedom on the surface. The posture (P_i) of the mobile robot at any given instant i constitutes the position (x_i, y_i) of the mobile robot and its heading angle (θ_i) (Eq. (1)). Here x_i and y_i are the inertial frame intercepts of the center of the axis connecting the actuated wheels. The direction perpendicular to the axis connecting the center of the actuated wheels is considered to be the heading direction of the mobile robot—that is, the X axis of the local frame connected to the mobile robot. The heading angle (θ_i) of the mobile robot is the angle between the X_I axis of the inertial frame and X axis of the local frame. Thus, in further calculations, the mobile robot is assumed to be a point body located at the center of the axis connecting the actuated wheels. The locus of the points (x_i, y_i) over time is considered to be the trajectory being tracked by the mobile robot.

$$P_i = \begin{bmatrix} x_i \\ y_i \\ \theta_i \end{bmatrix} \tag{1}$$

In the present study, the trajectory to be tracked by the mobile robot is specified as a path connecting the waypoints from a start position (P_{w0} (x_{w0}, y_{w0})) to a destination position (P_{wn} (x_{wn}, y_{wn})) through a set of discontinuous waypoints (P_{wk} (x_{wk}, y_{wk})). Here, k is an integer between zero and the total number of waypoints (n) and w stands for waypoint. The linear and angular velocities of the mobile robot are given by v_i and ω_i, respectively. The rate of change in the posture ($\dot{P}_i$) of the mobile robot with respect to the linear velocity (v_i) and angular velocity (ω_i) of the robot can be resolved into the horizontal velocity component ($\dot{x}_i$), vertical velocity component ($\dot{y}_i$), and angular velocity components ($\dot{\theta}_i$) (Eq. (2)).

$$\dot{P}_i = \begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{\theta}_i \end{bmatrix} = \begin{bmatrix} \cos\theta_i & 0 \\ \sin\theta_i & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_i \\ \omega_i \end{bmatrix} \tag{2}$$

To calculate the linear velocity and angular velocity, the right and the left wheels of the mobile robot are considered to be rotating at angular velocities of ω_{1i} and ω_{2i}, respectively. The linear velocity of the mobile robot due to the rotation of these wheels can be calculated by combining the individual wheel velocities, as shown in Fig. 3(a); the angular velocity can be calculated as shown in Fig. 3(b).

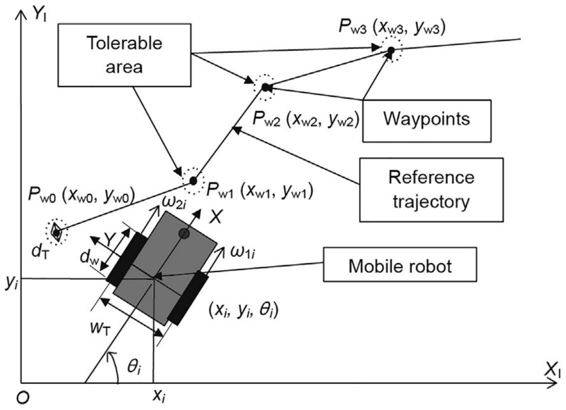

Fig. 2. Hilare robot tracking waypoints. P_i (x_i, y_i, θ_i): posture of the mobile robot; d_T: accepted transition distance; d_w: wheel diameter; ω_i: angular velocity.

Please cite this article in press as: Mathew R, Hiremath SS. Control of Velocity-Constrained Stepper Motor-Driven Hilare Robot for Waypoint Navigation. Eng (2018), https://doi.org/10.1016/j.eng.2018.07.013