Automatica 94 (2018) 63–71

Contents lists available at ScienceDirect

Automatica

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

Brief paper

Fault-tolerant iterative learning control for mobile robots non-repetitive trajectory tracking with output constraints[☆]

Xu Jin

The Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, 270 Ferst Drive, Atlanta, GA, 30332-0150, United States

ARTICLE INFO

Article history:
Received 3 July 2017
Received in revised form 30 December 2017
Accepted 11 March 2018

Keywords:
Iterative learning control
Non-repetitive trajectory tracking
Mobile robots
Barrier Lyapunov functions
Actuator faults

ABSTRACT

In this brief, we develop a novel iterative learning control (ILC) algorithm to deal with trajectory tracking problems for a class of unicycle-type mobile robots with two actuated wheels that are subject to actuator faults. Unlike most of the ILC literature that requires identical reference trajectories over the iteration domain, the desired trajectories in this work can be iteration dependent, and the initial position of the robot in each iteration can also be random. The mass and inertia property of the robot and wheels can be unknown and iteration dependent. Barrier Lyapunov functions are used in the analysis to guarantee satisfaction of constraint requirements, feasibility of the controller, and prescribed tracking performance. We show that under the proposed algorithm, the distance and angle tracking errors can uniformly converge to an arbitrarily small positive constant and zero, respectively, over the iteration domain, beyond a small initial time interval in each iteration. A numerical simulation is presented in the end to demonstrate the efficacy of the proposed algorithm.

1. Introduction

Iterative learning control (ILC) is well known to be effective in handling repetitive control processes (Xu, 2011). There have been many applications of ILC in industrial systems such as robotics, traffic control, high-speed trains, chemical plants, to name just a few (Bristow, Tharayil, & Alleyne, 2006; Ji, Hou, & Zhang, 2016; Li, Ren, & Xu, 2016; Mezghani et al., 2002). ILC can take advantage of the repetitiveness in the system dynamics and/or tasks, so that to improve the tracking performance asymptotically or exponentially over the iteration domain.

The study of unicycle-type mobile robots with two actuated wheels has received great attention in both research and industry communities during the past decade (Chan, Stol, & Halkyard, 2013; Do, 2008; Wang, Huang, & Wen, 2017; Xu, Guo, & Lee, 2014). This type of robot is simple in structure and design, and easy to maneuver due to the ability to turn at the spot (Chan et al., 2013). With two inputs (control torque vector) and three outputs (position and orientation), it often serves as a benchmark example for the study of nonholonomic systems (Wang et al., 2017). Among different classes of problems associated with such mobile robots, the trajectory tracking problem is an interesting and important one, which has potential applications in search and rescue missions, robotic delivery systems, to name just a few.

It is worth noting that most works in the trajectory tracking literature for autonomous agents, including mobile robots, consider the operation over an infinite time horizon (Chan et al., 2013; Do, 2008; Hu, Du, & Sun, 2017; Park, Yoo, Park, & Choi, 2010; Wang et al., 2017; Xu et al., 2014; Zhang & Zhang, 2014). In some applications, however, the duration of operation is limited in each round, and the tasks have to be performed many times over an iteration domain. For example, in robots search and rescue missions, due to the capacity of the batteries, the robots have to be brought back after some time, and deployed again after the charging is completed. Note that in each iteration, the desired system trajectories can be different in practice, due to changes in the environment or tasks. The control algorithms in the aforementioned literature which work over an infinite time horizon may not be suitable for such scenarios, since convergence to the desired trajectories may not be achieved in the limited time range for each iteration. Therefore, it is important to design ILC algorithms to take both the time and iteration domain into consideration. To the best of our knowledge, there have been no works so far in the ILC literature that deal with nonlinear mobile robots trajectory tracking. How to develop ILC algorithms for non-repetitive trajectory tracking problems for mobile robots, while taking the actuator faults with unknown mass and inertia of the robot into consideration, is an important research topic yet to be discussed.

[☆] The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Angelo Alessandri under the direction of Editor Thomas Parisini.

E-mail address: xu.jin@gatech.edu.

https://doi.org/10.1016/j.automatica.2018.04.011

Another important consideration in addressing trajectory tracking problems for mobile robots is about the constraint requirements. In reality, we often require some system variables or their tracking errors to remain in certain sets, to ensure the feasibility of the control design, to guarantee prescribed tracking performance, or to avoid undesirable consequences (Arabi & Yucelen, 2018; He, Chen, & Yin, 2016; Jin & Xu, 2013; Li, Tong, & Li, 2014; Li, Tong, Liu, & Feng, 2017; Liu, Lu, Li, & Tong, 2017; Liu & Tong, 2017; Tee, Ge, & Tay, 2009; Tong, Sui, & Li, 2015; Xu & Jin, 2013; Zhang, Huang, Xie, & Zhu, 2017; Zhang & Yang, 2017). For example, if the distance tracking error between the robot and the desired trajectory is too large in a search task, the target area may not be reached. If the angle tracking error between the robot and the desired trajectory is beyond certain range, some instruments that require accurate pointing may not work effectively. Despite being an important and practical problem, such issues related to constraint requirements have not yet been considered in the ILC literature for trajectory tracking problems of mobile robots, which is another main motivation for this work.

In this brief, we present a novel ILC algorithm for the trajectory tracking problems for a class of unicycle-type robots with two actuated wheels that are subject to actuator faults. We show that under this newly proposed ILC algorithm, the distance and angle tracking errors will uniformly converge to an arbitrarily small positive constant and zero, respectively, over the iteration domain, beyond a small initial time interval in each operation, while the constraint requirements on the distance and angle tracking errors will not be violated. The main contribution is summarized as follows:

(i) A novel ILC algorithm is presented to deal with trajectory tracking problems for a class of unicycle-type mobile robots. In particular, unlike most of the ILC literature that requires identical reference trajectories over the iteration domain, the desired trajectories in this work can be iteration dependent, and the initial position of the robot in each iteration can be random.

(ii) Unlike most of the ILC literature that assume the system dynamics and uncertainties are iteration invariant, in this work the mass and inertia property of the robot and wheels can be unknown and iteration varying, which means that different payloads can be carried in each iteration according to mission specific tasks, and the wheels can be replaced in different iterations.

(iii) Barrier Lyapunov functions are used in the analysis to guarantee satisfaction of constraint requirements, feasibility of the controller, and prescribed tracking performance, which is also the first in the ILC literature.

(iv) Time and iteration dependent actuator faults and constraint requirements can be effectively dealt with by the proposed algorithm.

2. Problem formulation

Consider the unicycle-type mobile robots with two wheels described as (Do, 2008; Wang et al., 2017)

$$\dot{\eta}_k(t) = J_k(\eta_k(t))\omega_k(t),$$
$$M_k\dot{\omega}_k(t) + C_k(\dot{\eta}_k(t))\omega_k(t) + D_k(\eta_k(t))\omega_k(t) = \tau_k^{\mathrm{F}}(t), \tag{1}$$

where $k = 1, 2, \ldots$ is the iteration index, $t \in [0, T]$ is the operation time, with T being the during of operation in each iteration. $\eta_k(t) = [x_k(t), y_k(t), \psi_k(t)]^{\mathrm{T}} \in \mathbb{R}^3$ represents the position $(x_k(t), y_k(t))$ and orientation $\psi_k(t)$ of the mobile robot, with $(\cdot)^{\mathrm{T}}$ being the transpose of a vector. $\omega_k(t) = [\omega_{1,k}(t), \omega_{2,k}(t)]^{\mathrm{T}} \in \mathbb{R}^2$ represents the angular velocities of the wheels on the left and right. $M_k \in \mathbb{R}^{2\times2}$ is the

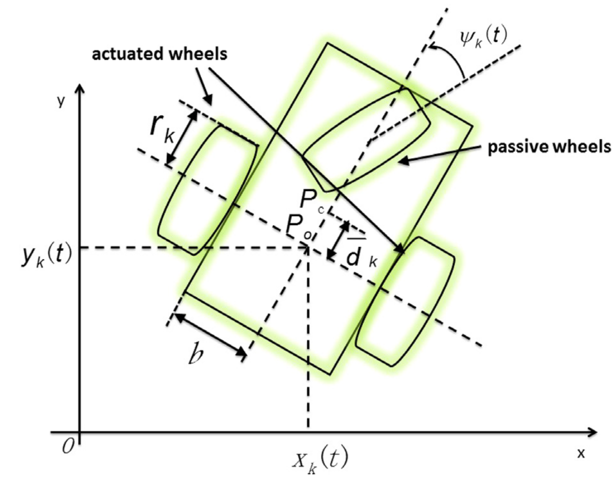

Fig. 1. Configuration of a two-wheeled mobile robot.

symmetric, positive definite inertia matrix. $C_k(\dot{\eta}_k(t)) \in \mathbb{R}^{2\times2}$ is the centripetal and coriolis matrix, and $D_k(\eta_k(t)) \in \mathbb{R}^{2\times2}$ represents the surface friction. $J_k(\eta_k(t)) \in \mathbb{R}^{2\times2}$, M_k, $C_k(\dot{\eta}_k(t))$ and $D_k(\eta_k(t))$ are defined as

$$J_k(\eta_k(t)) = \frac{r_k}{2}\begin{bmatrix} \cos(\psi_k(t)) & \cos(\psi_k(t)) \\ \sin(\psi_k(t)) & \sin(\psi_k(t)) \\ \dfrac{1}{b} & -\dfrac{1}{b} \end{bmatrix},$$

$$M_k = \begin{bmatrix} m_{1,k} & m_{2,k} \\ m_{2,k} & m_{1,k} \end{bmatrix}, \quad C_k(\dot{\eta}_k(t)) = \begin{bmatrix} 0 & c_k\dot{\psi}_k(t) \\ -c_k\dot{\psi}_k(t) & 0 \end{bmatrix},$$

$$D_k(\eta_k(t)) = \begin{bmatrix} d_{1,k}(\eta_k(t)) & 0 \\ 0 & d_{2,k}(\eta_k(t)) \end{bmatrix},$$

the parameters are defined as $m_{1,k} = 0.25b^{-2}r_k^2(m_kb^2 + I_k) + I_{w,k}$, $m_{2,k} = 0.25b^{-2}r_k^2(m_kb^2 - I_k)$, $m_k = m_{c,k} + 2m_{w,k}$, $I_k = m_{c,k}\bar{d}_k^2 + 2m_{w,k}b^2 + I_{c,k} + 2I_{m,k}$, $c_k = 0.5b^{-1}r_k^2m_{c,k}\bar{d}_k$, where $b \in \mathbb{R}$ is the half width of the robot, $r_k \in \mathbb{R}$ is the radius of the wheel. $m_{c,k} \in \mathbb{R}$ and $m_{w,k} \in \mathbb{R}$ are the masses of the body and the wheel of the robot at the kth iteration, respectively. $\bar{d}_k \in \mathbb{R}$ is the distance between the center of the mass of the mobile robot (point P_c in Fig. 1) and the middle point between the left and right wheels (point P_o in Fig. 1). $I_{c,k} \in \mathbb{R}$ is the moment of inertia of the body about the vertical axis through P_c. $I_{w,k} \in \mathbb{R}$ is the moment of the wheel with a motor about the wheel axis. $I_{m,k} \in \mathbb{R}$ is the moment of the wheel with a motor about the diameter. Only b and r_k are required to be measured, all other parameters, namely c_k, $m_{c,k}$, $m_{w,k}$, $I_{c,k}$, $I_{w,k}$, and $I_{m,k}$ can be unknown, and r_k, c_k, $m_{c,k}$, $m_{w,k}$, $I_{c,k}$, $I_{w,k}$, and $I_{m,k}$ can be iteration dependent. $d_{1,k}(\eta_k(t)) \in \mathbb{R}$ and $d_{2,k}(\eta_k(t)) \in \mathbb{R}$ can be state dependent. $\tau_k^{\mathrm{F}}(t) \in \mathbb{R}^2$ is the control input torque that is subject to actuator faults (Jin, 2016, 2018; Tong, Huo, & Li, 2014), where the superscript "F" stands for "faulty":

$$\tau_k^{\mathrm{F}}(t) = \rho_k(t)\tau_k(t) + \varphi_k(t), \tag{2}$$

where $\tau_k(t) \in \mathbb{R}^2$ is the uncorrupted control design, $\rho_k(t) \in \mathbb{R}^{2\times2}$ represents the multiplicative actuator faults, and $\varphi_k(t) \in \mathbb{R}^2$ represents the additive actuator faults, both of which can be iteration and time varying. If $\rho_k(t) \equiv I_{2\times2}$ and $\varphi_k(t) \equiv [0, 0]^{\mathrm{T}}$ at iteration k, where $I_{2\times2}$ is the two-by-two identity matrix, the robot is said to be healthy or free from actuator faults.

The basic geometric structure for a mobile robot's trajectory tracking can be seen in Fig. 2. Perfect tracking of the trajectory is achieved, when the robot (represented in solid lines) coincides with the imagined leader robot (represented in dashed lines).