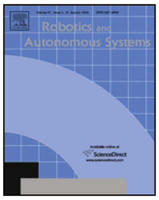
Robotics and Autonomous Systems 58 (2010) 203–215

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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



Equiangular navigation and guidance of a wheeled mobile robot based on range-only measurements[☆]

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ARTICLE INFO

Article history:
Received 6 February 2009
Received in revised form
11 August 2009
Accepted 9 September 2009
Available online 18 September 2009

Keywords:
Wheeled robots
Guidance
Navigation
Range-only measurements

ABSTRACT

We consider the problems of a wheeled mobile robot navigation and guidance towards an unknown stationary or maneuvering target using range-only measurements. We propose and study several methods for navigation and guidance termed Equiangular Navigation Guidance (ENG) laws. We give mathematically rigorous analysis of the proposed guidance laws. The performance is confirmed with computer simulations and experiments with ActivMedia Pioneer 3-DX wheeled robots.

1. Introduction

Navigation and guidance of mobile robots towards steady or moving objects (targets) is one of the most important areas of robotics that has attracted a lot of attention in recent decades (see e.g. [1–3] and references therein). However, in most of existing methods, both the line-of-sight angle (bearing) and the relative distance (range) are assumed to be available for navigation and guidance algorithms. There is also a relatively large body of research on navigation and guidance with bearings-only measurements [4,5]. Most of these methods suffer from the line-of-sight problem and fail to find a solution if the target is behind an obstacle. Furthermore, several approaches can be found in literature which mainly use the range measurements to localize the robot while generating a local map of the environment in order to avoid obstacles and navigate towards a known target [6–9]. In contrast, few results on navigation and guidance towards an unknown target using range-only measurements have been published.

The problem of range-based localization or navigation is motivated by its employment in various wireless network related applications, unmanned underwater vehicles, surveillance and emergency services [10–12]. In these applications the only available information from the target is the line-of-sight (LOS) range, i.e. the imaginary straight line which starts at the vehicle's reference point and is directed towards the goal reference point. The range can be obtained by measuring the time-of-flight of an acoustic pulse [11] or estimated using the strength of the received signal transmitted by the target [10]. Range-only guidance problems may appear as an effort to reduce the cost of active target tracking or in robust tracking in highly noisy environment where angle measurements are often missing especially in naval applications (see e.g. [13]). Such problems become more important with the growing use of mobile robots for deployment and localization of wireless nodes in sensor networks [14,15] or for localization of various small devices [16]. Using wireless sensor nodes equipped with ultra-wideband radios, the range information can be obtained to even blocked targets. Having obtained the LOS range, a general algorithm is required whereby the robot can navigate towards the target.

There is a huge body of literature on the problem of robot navigation towards a maneuvering target. One of the first strategies in pursuing a moving target for indoor applications, given a complete map of environment and a pursuer with omni-directional field of view, presented by Guibas et al. [17]. With discretizing a polygonal environment based on visibility boundaries and searching the resulting information, their algorithm generates a path that guarantees capture. Using priori knowledge from the map and particle filtering, Liao et al. [18] proposed strategies for tracking a mobile target and coordinating a team of robots equipped with range-only sensors. A number of algorithms presented by [19] for tracking a non-adversarial target in a known cluttered environment using multiple robots. In order to simplify the problem, these algorithms discretize a polygonal map of the environment into convex cells to

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[☆] This work was supported by the Australian Research Council.

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doi:10.1016/j.robot.2009.09.004

form an undirected graph. While communicating with each other, each robot plans for its next path towards the target using the latest range information from it. Hollinger et al. [20] presented another framework for tracking a moving target in a cluttered environment with a priori known floor plan using range measurements from radio nodes. None of these approaches provides a general algorithm which generates the heading or the robot direction using the range information.

In this paper, we consider the problem of range-only navigation of a wheeled robot towards an unknown target. We propose several similar guidance algorithms for approaching and following both steady and moving targets with range-only measurements. With constant robot linear velocity, we use the robot-target range variation as a measure for the angle at which the robot approaches the target. The proposed guidance methods have the property that the trajectory of the controlled robot is close to a certain curve called an equiangular spiral. Therefore, we call the proposed algorithms Equiangular Navigation Guidance (ENG) laws. We give a theoretical analysis of the proposed ENG laws with a mathematically rigorous proof of their performance. Furthermore, we present a mathematically rigorous analysis of robustness of the proposed method to measurement noise. The applicability and performance of the proposed method is also confirmed by computer simulations and robotic experiments with ActivMedia Pioneer 3-DX wheeled robots. The proposed navigation strategy can be combined with a local obstacle avoidance technique which leads to a reliable and fast long-range navigation [21]. We consider the case of wheeled mobile robots, however, the obtained results are obviously applicable to many other mechanical systems which under certain assumptions have similar governing differential equations [1,3,22,2]. A potential application could be a wheelchair or a wheeled robot approaching on the press of a single button or small autonomous underwater vehicles (AUVs) moving towards the mother-ship using a single transponder [11]. In these applications, the conventional navigation systems are prohibited due to cost and volume constraints.

The reminder of the paper is organized as follows. Problem description and models of the controlled wheeled robot and the target are introduced in Section 2. Section 3 introduces our navigation and guidance laws and gives their mathematically rigorous analysis. Computer simulation results are given in Section 4. Section 5 describes experiments with ActivMedia Pioneer 3-DX wheeled robots for both steady and moving targets. Finally, brief conclusions and possible directions for future research are presented in Section 6.

2. Problem description

Let us consider a three-wheeled, non-holonomic mobile robot of Dubins car type [23], which moves in a horizontal plane. In a two-dimensional space, the position of the robot can be represented by a triplet $P_R = (X_R, Y_R, \theta_R)$ where (X_R, Y_R) is the location of the middle of the wheelbase and θ_R is the heading angle measured counterclockwise from the global x-axis. Let V_R be the linear velocity and ω_R the angular velocity of mobile robot. A rolling-without-slippage model is assumed for the robot. The kinematics model is classically given by:

$$\begin{aligned}\dot{X}_R(t) &= V_R(t)\cos(\theta_R(t))\\ \dot{Y}_R(t) &= V_R(t)\sin(\theta_R(t))\\ \dot{\theta}_R(t) &= \omega_R(t)\end{aligned}\tag{2.1}$$

with $U(t) = [V_R(t)\ \omega_R(t)]^{\mathrm{T}}$ as the control vector of the mobile robot, $U(t) \in [0, V_{\max}] \times [-\omega_{\max}\ \omega_{\max}]$ with $V_{\max}, \omega_{\max} > 0$. The Eqs. (2.1) may also describe the kinematics of tactical missiles, space robots or UAVs; see e.g. [24,25,22].

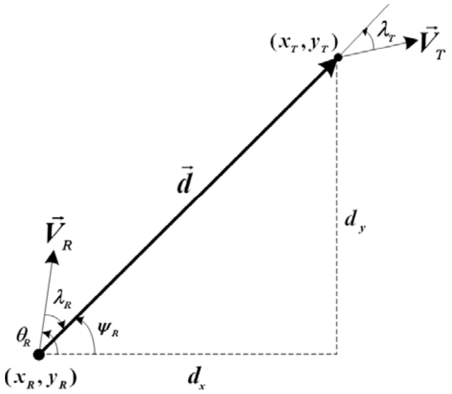

Fig. 1. Robot position and orientation with respect to target.

The target may be stationary or moving in any direction with velocity $V_T(t)$. We assume that the robot and the target are moving on a smooth horizontal surface and in an obstacle-free environment. The only available information about the target is the relative distance between the robot and the target. No information about target motion model is available. In particular, the target may be another nonholonomic mobile robot with its position and orientation (X_T, Y_T, θ_T) and the same kinematic equation (2.1). We assume that the robot maximum linear speed is greater than the target maximum linear speed. It is obvious that if this assumption does not hold then for any guidance law there exists a target motion such that

$$|X_T(t) - X_R(t)| + |Y_T(t) - Y_R(t)| \to \infty$$

as $t \to \infty$. On the other hand, it should be pointed out that the target may be more maneuvering than the robot, for example, the target may have a smaller minimum turning radius than the controlled robot.

Given the robot position and orientation with respect to the target position in the polar coordinate system, we define LOS-range d and the angle between the front-direction and the target direction λ as shown in Fig. 1:

$$\begin{aligned}d &= \sqrt{d_X^2 + d_Y^2}\\ \lambda_R &= \psi_R - \theta_R\\ \lambda_T &= \psi_R - \theta_T,\end{aligned}\tag{2.2}$$

where θ_R and θ_T are the robot and target heading angles, respectively, and ψ_R is the line-of-sight angle and $|\lambda_R| \leq \pi$, $|\lambda_T| \leq \pi$. In Fig. 1, $\vec{V}_R(t)$ is the robot velocity vector, $\vec{V}_T(t)$ is the target velocity vector, $\vec{d}(t)$ is the vector from the robot to the target, $d(t) := |\vec{d}(t)|$ is the range to the target. The robot-target motion is expressed by

$$\dot{d} = -V_R\cos(\lambda_R) + V_T\cos(\lambda_T)\tag{2.3a}$$

$$\dot{\lambda}_R = -\omega_R + \frac{V_R}{d}\sin(\lambda_R) - \frac{V_T}{d}\sin(\lambda_T).\tag{2.3b}$$

Note that the kinematic Eq. (2.3) are only valid for non-zero values of the LOS-range, since λ_R is undefined for $d = 0$.

The objective is to design a guidance law that uses only measurements of the relative distance $d(t)$ between the robot and the target and allows the robot to approach a stationery or follow a maneuvering target as close as possible.

3. Equiangular Navigation Guidance (ENG) laws

We assume that the distance $d(t)$ to the target and its derivative $\dot{d}(t)$ are both available to the robot's controller. Furthermore, we