Automatica 65 (2016) 76–89

Contents lists available at ScienceDirect

Automatica

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

# Range-only based circumnavigation of a group of moving targets by a non-holonomic mobile robot[☆]

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ARTICLE INFO

*Article history:*
Received 6 November 2014
Received in revised form
21 October 2015
Accepted 4 November 2015
Available online 7 December 2015

*Keywords:*
Robot navigation
Mobile robots
Sensor based control
Circumnavigation of multiple targets

ABSTRACT

We consider a single planar non-holonomic Dubins-car like robot traveling with a constant and given longitudinal speed and controlled by the angular velocity, which is upper limited in absolute value. There also is a group of moving targets in the plane. The robot measures only the relative distances to the targets and cannot distinguish among them. A sliding mode control law is proposed that drives the root mean square distance to the targets to a pre-specified value. This law is justified by a non-local convergence result, along with description of the domain of convergence. Specifically, we first disclose requirements to the averaged characteristics of the group's motion, which should be necessarily met in order for the constant-speed robot with a limited turning capacity be able to maintain the desired root mean square distance to the group. Then we show that under slight and partly unavoidable enhancements of these necessary conditions, the proposed controller does drive this distance to the desired value and ensures its stable maintenance afterwards provided that the controller is properly tuned. Recommendations on its tuning are also provided. The convergence and performance of the control law are confirmed by computer simulations.



## 1. Introduction

Recent decades have witnessed a proliferation in robotics research aimed at improvement of situational awareness, on one hand, and minimization of security risks, on the other hand, in an automated fashion. The problem of single/multiple target encirclement by using a mobile robotic platform lies at the crossroads to these two objectives. The involved navigation task consists of approaching the targets and then following them in a reasonably close range. In the case of a single target, a standard requirement is to escort it at a pre-specified distance. Since the pursuer typically moves faster than the target, this results in continuously encircling the target and gives rise to the term *circumnavigation*. Among the multiple-target scenarios, this name is supported by those, substantial but not overwhelming, where all or a bulk of the targets should be enclosed with the path of the pursuer.

Circumnavigation is of interest for, e.g., military (Beard, McLain, Goodrich, & Anderson, 2002) and civilian (Kumar et al., 2001) surveillance and intelligence, getting situational awareness before coming to a closer contact, guarding the perimeter of an area, protection of VIP objects, entrapment of threatful objects, objects inspection, retrieval and fusion of data from/about spatially distributed sensors/spots, and improving connectivity of multihop communication in robotic networks (Zavlanos, Egerstedt, & Pappas, 2011).

Recently, designs of controllers for robotic circumnavigation have gained much interest. Most of works assume access to the full (typically relative) coordinates of the target/targets; see e.g., Ceccarelli, DiMarco, Garulli, and Giannitrapani (2008), Kim and Sugie (2007), Kim, Harab, and Hori (2010), Marshall, Broucke, and Francis (2006), Oh et al. (2013), Sepulchre, Paley, and Leonard (2008), Shames, Fidan, and Anderson (2011), Summers, Akella, and Mears (2009), Tang and Özgüner (2005), Tang, Shinzaki, Lowe, and Clark (2014), Wang and Gu (2012) and Zhou and Roumeliotis (2011) and literature therein. However measurement of the full relative position may require costly and complex sensing hardware and/or extended signal processing, undesirable whenever poor

☆ This work was supported by the Russian Science Foundation (RSF, Proj. No 14-21-00041) and the Saint Petersburg State University, and the Australian Research Council (DP130103898). The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Dimos V. Dimarogonas under the direction of Editor Ian R. Petersen.

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http://dx.doi.org/10.1016/j.automatica.2015.11.032
0005-1098/

payload, energy, and computational capacities are a real concern, like e.g., for miniature mobile robots (Scaramuzza, Achtelik, Doitsidis, & Friedrich, 2014). Also, many common technologies of determining such a position use active sensing, which may be undesirable for stealth or energy saving reasons. Meanwhile, global positioning data is not viable in harsh environments (Scaramuzza et al., 2014), like underwater, indoor, urban, etc., where the signals from a common source of such data – a Global Navigation Satellite System – may be shadowed, jammed, spoofed or otherwise corrupted due to the weakness of these signals, which makes them vulnerable to accidental or intentional interference.

There is a substantial body of recent research on navigation and guidance algorithms based on incomplete positional data (Arora, Dutta, & Bapat, 2004; Gadre & Stilwell, 2004; Matveev, Teimoori, & Savkin, 2011c), like range- or bearing-only data, or the strength of a signal that decays away from the target, like an infrared, acoustic, or electromagnetic signal emitted by the target; see, e.g., Cochran and Krstic (2009), Matveev, Teimoori, and Savkin (2011a,b) and Zhang, Arnold, Ghods, Siranosian, and Krstic (2007). Regarding circumnavigation, the papers (Deghat, Shames, Anderson, & Yu, 2014; Deghat, Xia, Anderson1, & Hong, 2014; Fidan, Dasgupta, & Anderson, 2012; Shames, Dasgupta, Fidan, & Anderson, 2012) handle single (Deghat, Shames et al., 2014; Fidan et al., 2012; Shames et al., 2012) and multiple (Deghat, Xia et al., 2014) targets and a fully actuated mobile robot with simple integrator kinematics and unconstrained control input, that has access to its full position in a reference frame where every target is either steady or slowly drifts. Only the relative distance to Fidan et al. (2012) and Shames et al. (2012) or bearing of Deghat, Shames et al. (2014) and Deghat, Xia et al. (2014) every target is measured. The algorithms ensure circumnavigating a single target and enclosing multiple targets with a pre-defined margin. This is achieved perfectly if the target/targets is/are steady, and with an error proportional to the rate of their drift otherwise. An extension of these results on a Dubins-car like robot with unconstrained control input and bearing-only data about a single target is offered in Deghat et al. (2012). If global positioning data is not available, the aforesaid full robot's position can be acquired by using dead reckoning methods, which however suffer from accumulation of integration errors, especially in face of long durations typical for circumnavigation missions.

For just the same Dubins-car type robot, Cao, Muse, Casbeer, and Kingston (2013) offer a control law that ensures circumnavigating a steady target based on access to only the relative distance to the target and its rate. Meanwhile, unconstrained control input, like in Cao et al. (2013) and Deghat et al. (2012), means the Dubins car is capable of making arbitrarily sharp turns and can be viewed as approximately holonomic. In Matveev et al. (2011c), a non-holonomic Dubins-car type robot with a priori limited control range and a single unknowingly maneuvering Dubins-car type target are considered. By assuming measurements of only the relative distance to the target and access to the rate at which this reading evolves over time (via e.g., numerical differentiation), a sliding mode controller based on ideas of equiangular navigation (Teimoori & Savkin, 2010) was proposed and justified: it was proved that it ensures perfectly circumnavigating the moving target at exactly the pre-specified distance.

Thus the theory of circumnavigating multiple targets on the basis of range-only measurements lies in uncharted territory. This paper aims at filling this gap by extending the approach of Matveev et al. (2011c) on multiple targets, while retaining theoretically perfect achievement of the control objective and realistic robot's model, i.e., its non-holonomy, under-actuation, and a priori limited control range.

Specifically, we consider a Dubins-car type robot. It travels in a plane over curves of bounded curvatures and is controlled by the angular velocity upper limited in absolute value. There also are unknowingly maneuvering targets, which are not necessarily slow, unlike (Deghat et al., 2012; Deghat, Shames et al., 2014; Deghat, Xia et al., 2014; Fidan et al., 2012; Shames et al., 2012). They are anonymous, i.e., carry no identity which permits the robot to distinguish between them. The robot has access only to the relative distance measurements, which can be acquired in a "stealth mode" via processing the strengths of signals emitted from the targets. The objective is to drive the mean square root distance to the targets to a pre-specified value and to subsequently follow them with maintaining this value.

This objective does not directly demand to necessarily enclose multiple targets. This has a good fit to scenarios where it is required to achieve only closeness to the targets, no matter from which side, like in missions of surveillance and intelligence, data retrieval and fusion, improving connectivity of multihop multiagent communication, etc. Then the use of the mean square distance establishes a trade-off among the contradictory goals of being simultaneously close to many spatially distant locations. As compared with consecutively visiting close proximities of the targets, this option permits us to reasonably handle kinematically inhomogeneous groups in which targets may temporarily move faster than the pursuer so that the group's mean speed remains within the robot's capacity. In this regard, we systematically deal with only averaged characteristics of the group.

For missions like protection/entrapment of VIP/threatful moving objects, the notion of "group" should be defined prior to formal problem setup since it is unrealistic to, e.g., encircle unboundedly diverging targets. In this paper, "group" is defined as a set of targets whose mean positional scatter is bounded over time. We also accept that enclosure of only a reasonable "bulk of the group" may be sufficient. Moreover, this may prevent performance degradation due to deviation of the pursuer from this bulk because of intentional or occasional escape of a few targets far away, which e.g., holds if the distance to the nearest target or the distance to the group centroid minus the distance to the farthest target (Deghat, Xia et al., 2014) is used. Meanwhile, the mean distance metric does ensure enclosure of the entire group if its desired value is chosen large enough compared with the group's positional scatter.

In this paper, we extend the sliding mode control law from Matveev et al. (2011c) to the case of multiple targets, which are not constrained by nonholonomy, like in Matveev et al. (2011c). Our objective is to demonstrate that the proposed law is nearly exhaustive: it solves the problem almost whenever it is solvable. To this end, we start with revealing the level of conformity between the maneuvering capacity of the robot and the challenge imposed by the mobile group, which is necessary for the mission to be feasible. Then we show that under slight enhancement of these necessary conditions, the problem is solved by the proposed controller. This is justified by means of a mathematically rigorous non-local convergence result, which is accompanied by recommendations on the controller tuning. They are given in closed form, up to estimation of the sensitivity of a certain closed-form function $f$, which is a measure of variability in the values of $f$ caused by changes of one of its arguments. This estimation typically comes to routine calculus exercises and direct numerical analysis. Though these are elementary, their particulars and exactness may depend on the available knowledge about the targets' motion. So we illustrate transformation of the above recommendations into a closed form for two particular case studies. Convergence and performance of the proposed controller are confirmed by computer simulations. The multiple target scenario, the need to work with averaged characteristics of the overall group, and the lack of nonholonomy in targets makes the analysis completely different from that in Matveev et al. (2011c).

The body of the paper is organized as follows. Section 1 introduces the robot's model and problem setup. Section 3 offers