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Target capture and station keeping of fixed speed vehicles without self-location information

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ABSTRACT

Target capture and station keeping problems for an autonomous vehicle agent have been studied in the literature for the cases where the position of the agent can be measured. Station keeping refers to moving the agent to a target whose distances are predefined from a set of beacons that can be stations or other agents. Here we study the target capture and station keeping problems for a nonholonomic vehicle agent that does not know its location and can measure only distances to the target (to the beacons for station keeping). This sensing limitation corresponds to consideration of unavailability of GPS and odometry in practical UAV settings. For each of the target capture and station keeping problems, we propose a control algorithm that uses only agent-target (agent-beacon for station keeping) range and range rate information. We show the stability and convergence properties of our control algorithms. We verified the performance of our control algorithms by simulations and real time experiments on a ground robot. Our algorithms captured the target in finite time in the experiments. Therefore, our algorithms are efficient in scenarios where GPS is unavailable or target identification by vision algorithms is unreliable but continuous agent-target range measurements are available.

1. Introduction

Target capture, which is also referred to as target docking or target pursuit, is the problem of reaching a target by a mobile autonomous vehicle. This problem has been studied in a collection of recent works, see for example [5,11], and the references therein. The autonomous vehicle A in the target capture problem can be a mobile ground robot or an unmanned aerial vehicle (UAV) trying to reach a target T. Usually, the target T is a sensor that emits a certain form of signal which can be used by a suitable sensor mounted on A to measure distance. The case where the positions of A and T are both known in the global coordinate frame is the standard target tracking problem and can be solved in various ways. However, these solutions cannot be applied when A can sense the distance to T only but not the (relative) position. Thus, one needs to either utilize the derivative of the distance measurements or estimate the target location on-line to achieve the target capture objective.

For example, [6] derives a continuous-time adaptive localization algorithm to localize T by assuming that mobile agent A's own position in global frame and its distance to the target T at each time instant are available. This algorithm is established to be robust to slow persistent drifts of T and guarantees perfect estimation in case of persistence of excitation (PE) of the motion trajectory of A with respect to T. Further, [8] derives a least-squares (LS) based estimation algorithm to achieve the same objective, with further extension of the design to be used with time-of-flight (TOF) sensors. Ref. [10] presents results on the sensor/beacon placement, which guarantee practical localization of sensors by using the source signals of a network of beacons.

A further problem involving adaptive localization is adaptive target pursuit, capture, or tracking. Ref. [11] proposes an adaptive control strategy based on [6] that achieves the target capture task while localizing the target at the same time. Target pursuit and circumnavigation around a target has been studied in some other recent works as well, including [5,7,18,22]. In [5], the authors derive an algorithm that steers a nonholonomic vehicle, by controlling only its angular velocity, to a source to which the vehicle cannot measure its distance, but receives a signal from the source in the form of an unknown function of the distance. Employing extremum seeking and averaging techniques, circumnavigation around the target is achieved in that work. The localization algorithm of [6] and a motion control law are combined in [22] for the same objective, assuming that the range measurement to the target and the vehicle's own position in a reference frame can be

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measured. Circumnavigation is studied in [7] as well, with the assumption of bearing angle measurement to the target instead of the range measurement.

Here we propose a control algorithm to solve the aforementioned target capture problem when the self-position measurement is not available to the mobile agent. We assume that the vehicle can sense the vehicle-target distance measurements only, i.e., the vehicle does not utilize any other sensor such as GPS, inertial measurement unit (IMU), or camera in the target capture control algorithm. In Section 2, we examine the target capture problem for a nonholonomic vehicle by using a switching-based control law inspired by the control approach described in [3,4,16]. The switching between the control rules is based on the range measurement and the range rate signal. We first present the control law for a general case where the range measurement and its time derivative are available. In Section 3, we study the stability and convergence properties of the proposed control algorithm. In Section 4, we discuss the case of unavailability of range rate information and the use of observer to compensate this case.

Further, in Section 5, we study the station keeping of nonholonomic vehicles, which steers an autonomous vehicle A towards a target location T, which is not known by the vehicle explicitly, but defined by its pre-defined distances to a set of stationary vehicles/sensors $S_1, \ldots, S_N$, which are known by A. This problem has been considered in some works including [1,2,9] and has applications in formation acquisition and maintaining of autonomous multi-agent (vehicle/robot) systems as well as wireless network based target localization and tracking. Assuming that $T - S_i$ distances are predefined and that A can sense its distances to S_i, we modify the control law in Section 2 such that A minimizes the difference between $T - S_i$ and $A - S_i$ distances to accomplish the station keeping task asymptotically.

A preliminary version of this work was presented in [14] where switching control algorithms were proposed for the target capture and station keeping problems without real-time implementation. Here, we modify the target capture control algorithm of [14], demonstrating complete stability and convergence analysis, and propose two novel control algorithms for the station keeping problems as well. Since [3,4,16,22] consider the circumnavigation problem, the methodology of this paper greatly differs from [3,4,16,22] in that our purpose is to steer the vehicle to a close vicinity of the target in contrast to circumnavigation problem where the vehicle is desired to orbit around the target with a relatively bigger radius. Furthermore, the angular control law in our algorithm is bounded similar to [19].

We demonstrate the performance of the proposed control algorithms via simulations and experimental tests on a nonholonomic mobile ground robot in Sections 6 and 7. Section 8 presents the conclusions and future directions of the work.

2. Target capture problem and control design

In this section, we formally define the target capture problem and present our proposed control law to solve this problem for a mobile nonholonomic vehicle, assuming that the range and range-rate measurements are available to the vehicle.

2.1. Problem definition

Consider a nonholonomic vehicle A with the dynamics

$$[\dot{x}_A, \dot{y}_A]^\top = v[\cos(\theta), \sin(\theta)]^\top, \quad \dot{\theta} = \omega, \tag{1}$$

where $p_A(t) \triangleq [x_A(t), y_A(t)]^\top \in \Re^2$ and $\theta(t) \in (-\pi, \pi]$ are the unknown position vector and heading angle of the vehicle in the global coordinate frame, and $u(t) \triangleq [v(t), \omega(t)]^\top \in \Re^2$ is the control input of the vehicle with $0 \le v \le \bar{v}$ and $-\bar{\omega} \le \omega \le \bar{\omega}$, with $\bar{v}, \bar{\omega}$ being the maximum linear and angular speeds of the vehicle, respectively. Consider also a target T with unknown constant position $p_T \triangleq [x_T, y_T]^\top \in \Re^2$. We denote the distance between A and T by

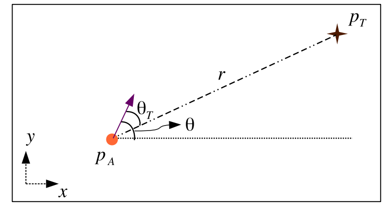

Fig. 1. Illustration of the vehicle-target configuration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

$$r(t) \triangleq \| p_A(t) - p_T \|. \tag{2}$$

This configuration is illustrated in Fig. 1. Another representation of the dynamics (1) uses a time-varying coordinate system centered at A, and the unknown angle $\theta_T \in (-\pi, \pi]$ from the vector $p_T - p_A$ to the current heading of A [3]:

$$\dot{r}(t) = -v(t)\cos(\theta_T(t)), \tag{3}$$

$$\dot{\theta}_T(t) = \omega(t) + \frac{1}{r(t)} v(t) \sin(\theta_T(t)). \tag{4}$$

We focus on driving the nonholonomic vehicle A to the ϵ_r-neighborhood $\mathcal{B}_{\epsilon_r}(p_T) \triangleq \left\{ p \in \Re^2 \;|\; \|p - p_T\| \le \epsilon_r \right\}$ of the target T, where ϵ_r is a pre-defined small threshold constant, and stop the vehicle in this region.

Problem 1. Consider a nonholonomic vehicle A with motion dynamics (1). Given the range measurement $r(t)$ in (2) and its time derivative $\dot{r}(t)$, find a control law $u(t) = [v(t), \omega(t)]^\top$ so that A converges to the ϵ_r neighborhood $\mathcal{B}_{\epsilon_r}(p_T)$ of T in finite time.

A similar problem is considered in [5] in the context of extremum seeking, carrying expense of added sinusoid search signals. Here we follow a more direct approach similar to that of [3,16] for the target capture problem.

2.2. Control law

In this subsection, we derive the base control law we propose, assuming that range-rate $\dot{r}(t)$ is perfectly available for measurement. In Section 4, we discuss implementation without having $\dot{r}$ information directly. Inspired by the circumnavigation control design in [3,16], we propose the control law

$$u = [v, \omega]^\top, \tag{5}$$

$$v(t) = \begin{cases} \bar{v}, & \text{if } r(t) > \epsilon_r \\ 0, & \text{otherwise,} \end{cases} \tag{6}$$

$$\omega(t) = \begin{cases} \left((\operatorname{sgn}(\dot{r}(t)) + 1)c + \dfrac{(1+\alpha)\bar{v}}{r(t)} \right) \sigma\left(\dfrac{-\dot{r}(t)}{\bar{v}} \right), & \text{if } r(t) > \epsilon_r \\ 0, & \text{otherwise,} \end{cases} \tag{7}$$

$$\sigma(x) = \begin{cases} 1, & \text{if} \quad x \le \sqrt{1-\gamma} \\ \frac{1-x^2}{\gamma}, & \text{if} \quad \sqrt{1-\gamma} < x < 1 \\ 0, & \text{if} \quad x \ge 1 \end{cases} \tag{8}$$

where, for $r(t) \ge \epsilon_r$, $\sigma(-\dot{r}/\bar{v}) = \sigma(\cos(\theta_T))$ is a function that regulates the angle θ_T, $\bar{v}$ is the pre-specified maximum linear speed, and $0 < \gamma < 1$, $c > 0$, and $\alpha > 0$ are design parameters. The plot of