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Brief paper

Robot navigation for monitoring unsteady environmental boundaries without field gradient estimation☆

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ABSTRACT

A non-holonomic Dubins-car like robot should detect, locate, and track the boundary of an a priori unknown dynamic environmental scalar field. The field is measured by an on-board sensor in a point-wise fashion at the robot's location. The focus is on unsteady boundaries that arbitrarily evolve over time, and, e.g., may change shapes and sizes. We present a sliding mode control method for localizing and tracking such boundaries: the robot is steered to the boundary and circulates in its close proximity afterwards. The proposed control algorithm does not require estimation of the spatial gradient of the field and is non-demanding with respect to both computation and motion. Its mathematically rigorous justification is provided. The effectiveness of the proposed guidance law is confirmed by computer simulations and experiments with a real wheeled robot.

1. Introduction

Recent environmental disasters, e.g., the deep horizon oil spill in Mexican Gulf in 2010 and the Fukushima Daiichi nuclear disaster in 2011, have highlighted the need for effective tools capable of timely detecting and monitoring dynamic environmental boundaries. This is of interest not only for tracking oil spills (Clark & Fierro, 2007) and localization of radioactive contamination, but also in many other missions, such as tracking forest fires (Casbeer et al., 2006) or contaminant clouds (White, Tsourdos, Ashokoraj, Subchan, & Zbikowski, 2005) or harmful algae blooms (Pettersson, Durand, Johannessen, & Pozdnyakov, 2012), exploration of sea temperature and salinity or hazardous weather conditions, etc. Such missions are devoted to localization of a spatially distributed phenomenon whose boundary can typically be defined as the level set (isoline) where a certain scalar field (e.g., the radiation level or the concentration of a pollutant) assumes a critical value.

This paper is focused on the case where data about an a priori unknown field are acquired through immediate contact of a sensor with the sensed entity, like radiation, transparent gas, etc., which occurs in a point-wise fashion. Static sensor networks typically require high both deployment density and computational/communication loads to provide a good accuracy of observation (Nowak & Mitra, 2003). More effective use of sensors is achieved in mobile networks thanks to their capacity of autonomously concentrating on the boundary of interest. However to derive this benefit, the mobile sensor should be equipped with a motion control system by which it can detect, localize, move to, and then track this boundary.

Designs of such systems have gained much interest recently; see, e.g., Chang, Wu, Webster, Weissburg, and Zhang (2013), Hsieh, Loizou, and Kumar (2007), Marthaler and Bertozzi (2003), Srinivasan, Ramamritham, and Kulkarni (2008), Zhang and Leonard (2010) and literature therein. Many methods assume access to spatial derivatives of the field, including networked contour estimation (Bertozzi, Kemp, & Marthaler, 2004; Marthaler & Bertozzi, 2003; Srinivasan et al., 2008), centralized controllers stemming from the "snake" algorithms in image segmentation (Bertozzi et al., 2004; Marthaler & Bertozzi, 2003), potential-based approach (Hsieh et al., 2007), gradient and Hessian estimation in multi-sensor scenarios (Fabbiano, Canudas de Wit, & Garin, 2014; Zhang & Leonard, 2010), local access directly to the boundary, including its tangent and curvature (Susca, Bullo, & Martinez, 2008), access

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to the flow velocity in a somewhat allied problem of tracking coherent structures in flows (Michini, Hsieh, Forgoston, & Schwartz, 2014), etc. However, spatial derivatives are often not directly measured. Meanwhile, their estimation from the field values needs gathering sensors into a tight flock near the examined point and needs data exchange among the sensors, whereas efficient observation of the boundary, conversely, coheres with distribution of the sensors over it, and data exchange may be degraded or even infeasible in some circumstances. Finally, sensor-based derivative estimators are prone to noise amplification, and their implementation is an intricate problem in practical setting (Ahnert, 2007). This carries a threat of performance degradation, puts strong extra burden on controller tuning, and may drastically increase the overall computational load (Ahnert, 2007). A load of these troubles can be alleviated through a reliable finite-parametric model of the field (Porat & Nehorai, 1996), which however is often not available so that the field is treated as "generic".

This paper is concerned with the gradient-free approach intended to handle a single mobile sensor with a point-wise access to only the value of a generic field; see e.g., Andersson (2007), Barat and Rendas (2003), Casbeer et al. (2006), Kemp, Bertozzi, and Marthaler (2004) and literature therein. Switches between two (Joshi, Ashley, Huang, & Bertozzi, 2009; Zhipu & Bertozzi, 2007) or more (Barat & Rendas, 2003) pre-specified steering angles depending on the current field value were advocated in Barat and Rendas (2003), Joshi et al. (2009), and Zhipu and Bertozzi (2007). Such methods result in jagged trajectories and rely in effect on systematic sideways maneuvers for data collection, which gives rise to concerns about waste of resources. An algorithm based on segmentation of infrared images of the forest fire was offered in Casbeer et al. (2006). These works rely, more or less, on heuristics, giving no rigorous guarantees of success. A local convergence was proved in Baronov and Baillieul (2007) for the proposed PD controller, a Dubins-car like vehicle with an unlimited control range, and a radial harmonic field. A non-local convergence result was obtained in Matveev, Teimoori, and Savkin (2012) for a generic smooth field and a Dubins-car like vehicle with an a priori limited control range in order to rigorously justify the proposed sliding-mode control law.

By and large, the previous "gradient-free" research was confined to steady fields and environmental boundaries. However, they are almost never steady in the real world due to dispersion, advection, transport by wind, drift by water current, etc. Meanwhile, the theory of tracking dynamic level sets lies in the uncharted territory. This paper is aimed at filling this gap.

Specifically, it develops the sliding mode method set forth in Matveev et al. (2012) for steady fields that disentangles boundary tracking from the above intricacies related to gradient estimation and sideways fluctuations. Dynamic field and boundary bring a series of extra challenges. For example, feasibility of tracking a steady isoline by a non-holonomic Dubins car via a limited steering control depends on only the match between the turning capacity of the car and the curvature of the isoline. In the case of a dynamic isoline, its kinematics crucially affects this very feasibility, to say nothing about capability of a particular control law to cope with the isoline displacements, rotations, and deformations and about recommendations on its tuning. In this paper, we provide a better insight into these "kinematics" issues. Based on this background, we show that the ideas from Matveev et al. (2012) not only remain viable for generic dynamic fields but are also featured by a certain exhaustiveness: the examined control law solves the problem under conditions close to necessary ones provided that it is properly tuned. Moreover, specific recommendations on its tuning are offered.

To these ends, the paper discloses relevant characteristics of dynamic fields and establishes conditions necessary for the vehicle to be capable of tracking the dynamic isoline. Then we prove that whenever slight enhancements of these conditions hold, the proposed controller solves the problem for a fairly generic field and an under-actuated non-holonomic Dubins-car type mobile robot. This is done by means of a mathematically rigorous non-local convergence result, which contains recommendations on the controller tuning. Theoretical results are confirmed by extensive computer simulations and experiments with a real wheeled robot.

The topical shift to dynamic fields means incorporating the issue of navigation of a mobile robot towards an unknowingly maneuvering target and further escorting it with a desired margin (given by the field value) on the basis of a single measurement that decays away from the target, like the strength of an acoustic or electromagnetic signal. Such navigation is of interest in many areas (Arora, Dutta & Bapat, 2004; Gadre & Stilwell, 2004; Matveev, Teimoori, & Savkin, 2011); it carries a potential to reduce the hardware complexity and cost and to improve target pursuit reliability. To the best of our knowledge, rigorous analysis of such a navigation law was offered in Matveev et al. (2011) for only a very special case of the field—the distance to a moving Dubins-like car. However the results of Matveev et al. (2011) are not applicable to more general dynamic fields.

2. System description and problem setup

A planar mobile robot travels with a constant speed v and is controlled by the time-varying angular velocity u limited by a given constant $\overline{u}$. The plane hosts an unknown and time-varying scalar field $D(t, \boldsymbol{r}) \in \mathbb{R}$. Here $\boldsymbol{r} := (x, y)^\top$ is the vector of the absolute Cartesian coordinates x, y in the plane $\mathbb{R}^2$. The objective is to steer the robot to the level curve (isoline) $D(t, \boldsymbol{r}) = d_0$ where the field assumes a given value d_0 and to ensure that the robot remains on this curve afterwards, circulating along it. The on-board control system has access to the field value $d(t) := D(t, x, y)$ at the robot's current location $x = x(t), y = y(t)$ and to the rate $\dot{d}(t)$ at which this measurement evolves over time t. However, neither the partial derivative D_t', nor D_x', nor D_y' is accessible.

The kinematic model of the robot is as follows:

$$\begin{array}{lll} \dot{x} = v\cos\theta, & \dot{\theta} = u, & x(0) = x_{\text{in}} \\ \dot{y} = v\sin\theta, & |u| \le \overline{u}, & y(0) = y_{\text{in}}, \end{array} \quad \theta(0) = \theta_{\text{in}}, \tag{1}$$

where θ gives the robot orientation. A controller should be designed such that $D[t, x(t), y(t)] \to d_0$ as $t \to \infty$.

In this paper, we examine two navigation laws, each corresponding to a certain sign in the following expression:

$$u(t) = \pm \mathbf{sgn}\,\{\dot{d}(t) + \chi[d(t) - d_0]\}\overline{u}, \tag{2}$$

where $\mathbf{sgn}\, a$ is the sign of a ($\mathbf{sgn}\, 0 := 0$) and

$$\chi(p) := \begin{cases} \gamma p & \text{if } |p| \le \delta, \\ \mathbf{sgn}\,(p)\mu & \text{otherwise,} \end{cases} \qquad \mu := \gamma\delta \tag{3}$$

is a linear function with saturation, whereas $\gamma > 0$ and $\delta > 0$ are design parameters. Access to $\dot{d}$ may be acquired via, e.g., numerical differentiation. As will be shown, the choice of sign in $\pm$ predestines whether the desired isoline is ultimately traced counterclockwise or clockwise.

For the discontinuous controller (2), the desired dynamics (Utkin, 1992) is given by $\dot{d}(t) = -\chi[d(t) - d_0]$. Since it is unrealistic to desire large $\dot{d}$, saturation is a reasonable option.

3. Necessary conditions and assumptions

To judge the feasibility of the control objective and to tune the controller, we introduce the following characteristics of the dynamic field $D(\cdot)$:

$\nabla D = (\partial D/\partial x, \partial D/\partial y)^\top$—the spatial gradient;
$I_t(\eta) := \{\boldsymbol{r} : D(t, \boldsymbol{r}) = \eta\}$—the spatial η-isoline;