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Probabilistic self-tuning approaches for enhancing performance of autonomous vehicles in changing terrains

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ABSTRACT

Motion controllers usually require a tuning stage to ensure an acceptable performance of the vehicle during operation in challenging scenarios. However, such tuning stage is a time consuming process for the programmer and often is based on intuition or heuristic approaches. In addition, once tuned, the vehicle performance varies according to the nature of the terrain. In this work, we study the use of well-known probabilistic techniques for self-tuning trajectory tracking controllers for service units based on the idea of saving both vehicle's resources and human labour force time. The proposed strategies are based on Monte Carlo and Bayesian approaches to find the best set of gains to tune the controller both off-line and on-line, thus enhancing the controller performance in the presence of changing terrains. The approaches are implemented and validated on a skid-steer mini-loader vehicle usually used for mining purposes. Implementation details and both simulation and empirical results are included in this work, showing that when using our approaches, effort can be saved up to 30% and tracking errors reduced up to 75%.

1. Introduction

Motion controllers in mobile robots are widely used in industrial applications such as agricultural or mining processes. A path or trajectory is previously defined according to the task, the environment, terrain and vehicle restrictions and time constraints. However, in industrial processes, errors in tracking procedures, caused by inefficient manoeuvring, terrain changes or perturbations in the control actions, have direct financial consequences in the resource management of the vehicle.

In precision agriculture, there are automated tasks such as harvesting, seeding, grow monitoring and chemical treatments, in which service units (i.e. an automated agricultural machinery) follow a predefined path while performing the agricultural task (Hu et al., 2014; Dong et al., 2013; Tanigaki et al., 2008; Yin et al., 2013) using a trajectory tracking controller. For example, in Fang et al. (2005), a path tracking controller is used for automated monitoring of the grove; in Dong et al. (2011), a path tracking approach is implemented on a service unit able to seed and harvest following an optimized 2D path; whereas in Eaton et al. (2010) a similar approach is proposed but for a 3D modelling of the environment taking into consideration the terrain slopes and constraints. On the other hand, the mining industry also requires accurate tracking controllers, such as in the case shown in Altafini (1999) and Fan et al. (2010), where a mining truck has to follow a predefined path from the loading point in the open sky mine, to the processing line.

When implementing trajectory tracking controllers in automated mobile machinery, despite the applications mentioned above, tracking errors and the performance of the controller play crucial roles in the efficiency associated with the task being executed by the machinery and the resource management of the system (Blazic, 2011; Howard et al., 2009). For example, in agricultural and mining applications, tracking errors are associated with more drastic control commands which could lead to actuator saturation problems and the corresponding decrease in performance of the controller, which also represents an increase in the resource consumption of the system (Howard et al., 2009; Blazic, 2011; Bibuli et al., 2012). In the mining industry or in urban applications, trajectory tracking errors could lead to catastrophic loss of both human lives and production.

Trajectory tracking controllers are usually designed according to the tracking errors and a set of adjustable constant gains, as shown in Kanayama et al. (1991), Bibuli et al. (2012), Morro et al. (2011), Kim and Kim (2011), and Morin and Samson (2009). Such a set of gains

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allows for a better tuning of the controller in order to improve its performance. The gains are defined within certain ranges in which the stability of the controller and convergence to zero of the error are guaranteed, as it is shown in Kanayama et al. (1991), Morin and Samson (2009), Kwon and Chwa (2012), and Cowlagi and Tsiotras (2012). Nevertheless, the values adopted by the constant gains are set before starting the control process and are not usually adjusted during operation. Thus, changes in the terrain or disturbances that the mobile robot might suffer, although absorbed by the controller, might imply an excessive waste of energy until the system is fully recovered and the robot is able to track the predefined path or trajectory. A clear example is when the robot has to track a path that is not kinematically compatible with the mobile robot's model as shown in Cheein and Scaglia (2014), Morro et al. (2011), and Sun et al. (2009) (and the references therein).

The set of gains associated with a controller is usually determined according to a previously defined design criteria, such as energy optimization, as shown in Blazic (2011). However, the task of finding the appropriate gains is a time consuming one for the scientist and the engineer. Thus, to mitigate the latter problem, several approaches have been proposed to find the optimal gains for different controllers, such as the case of the PID, in which Karaboga and Kalinli (1996), Lieslehto (2001), and Kim et al. (2001) use heuristic techniques. Fuzzy logic approaches, machine learning approaches and artificial neural networks Meza et al. (2009), Hong et al. (1992), Lee et al. (2003), Xiao and Wang (2011), and Shukla et al. (2015), are commonly used for self-tuning of the mentioned gains, for a wide variety of controllers. However, it is to be noted that gains are determined prior to the execution of the control process and not during the robot navigation Al-Araji et al. (2011).

The main goal of this work is to study and evaluate the use of well-known probabilistic techniques to on-line setting of optimal gains in motion controllers, regardless the controller formulation. Thus, the proposed techniques are aimed at ensuring low energy consumption when traversing through different terrains and to avoid the dependence with the programmer tuning skills. The approaches are based on optimizing the tracking error and the controller's performance, as previously defined by the authors in Blazic (2011) and Cheein and Scaglia (2014). Additionally, the presented approaches are able to find the best set of gains within the bounds in which they are defined while minimizing the tracking error and maximizing the controller performance, as well as avoiding actuator saturation problems by programming. The proposed methodology is tested on three different tracking controllers previously published in the literature, two of them obtained through Lyapunov and Vector Oriented Field theory, and one of them via an algebraic approach. The controllers were implemented on a vehicle automated for mining applications. As recommended by Roth and Batavia (2002), the path used to test our approaches was a square-shaped path in different terrain characteristics. An empirical analysis is included showing both the improvements in the controller performance and in the tracking errors when using our approaches. In addition, in our work we do not face robust, stochastic or adaptive control strategies that will overcome our goal (Lua et al., 2008; Martin et al., 2013; Fang et al., 2006; Bayar et al., 2016). Instead, we explore and test the possibility of using probability as an external tool to the motion controller formulation that the manufacturer, scientist, programmer or engineer could use to fulfil performance requirements in real-time, without designing new motion controllers.

2. Problem statement

Let $X \subseteq \mathbb{R}^n$ and $U \subseteq \mathbb{R}^m$ respectively be the state and control input spaces of the mobile robot, and let the dynamics of the robot be defined by the following system, which is assumed to be controllable:

$$\dot{x}(t) = f(x(t), u(t)), \quad x(0) = x_{init} \tag{1}$$

where $x(t) \in X, u(t) \in U$, for all $t, x_{init} \in X$, and f is a vector of continuously differentiable functions of its variables. Additionally let $\mathcal{X}$ denote the set of all essentially bounded functions $x : [0, T] \to X$ as *state space trajectories*, and $\mathcal{U}$ denote the set of all essentially bounded functions $u : [0, T] \to U$ as *control trajectories*, with $T \in \mathbb{R}_{>0}$ the final time. A trajectory of the robot under input u is defined as $\varphi_u = (x, u, T)$, and a reference trajectory under a reference input u^* is a trajectory $\varphi^*_{u^*} = (x^*, u^*, T)$. A trajectory tracking controller $u(t) = \mathbf{g}(x, x^*; K)$ is a control law that ensures that $\|x^* - x\| \to 0$ as $u \to u^*$ and K is the set of adequately adjusted tuning parameters. The problem is to find K such that the controller is a tracking controller and minimizes a cost functional $J : \mathcal{X} \times \mathcal{U} \to \int_0^T \|x^* - x\| dt < M \in \mathbb{R}$ for some constant and finite value M.

The set of tuning parameters K not only plays a crucial role in the system stability, but also in the controller performance, in the tracking or following errors and finally, in the energy management as will be shown later, since the vehicle might traverse different terrain conditions, or face trajectory kinematic challenges. However, choosing K is usually a manually handled task and depends on the designer intuition and tuning becomes, in some cases, an extenuating task often repeated when using different robots. Therefore, the twofold main aim of this work is:

- To avoid manually setting K. When embedding controllers, finding the best K for implementation is a time consuming task for the researcher or the programmer and K might vary according to the characteristics of the vehicle and the terrain.
- To automatically find the best K that would enhance the performance of the controller. Since the performance of the controller as presented in Blazic (2011) is a direct metric of the kinetic energy of the vehicle, K should be chosen in such a way that should optimize the resource management of the vehicle.

This paper is concerned with parameter tuning of path or trajectory tracking controllers where each controller parametrisation K can be depicted with a point in parameter space $\mathcal{K} \subseteq \mathbb{R}^d$, where d is the number of parameters that are tuned. The approach is based on fixed-gain controllers that exist in the literature and whose stability has already been proven for a fixed set of gains that satisfy certain conditions. The latter can be formally represented with a subset $\mathcal{K}_s$, which is often referred to as the stability region of the parameter space $\mathcal{K}$. Controller tuning during operation makes the approach adaptive in its nature. It is well known that adaptation of parameters presents a potential threat to the stability of the system. Unmodelled dynamics, disturbances, measurement errors, time-varying dynamics, etc., that are also present in practical applications of mobile robotic systems, compromise systestability even in the case of fixed-gain controllers. Their effect is that the stability region of the idealised case $\mathcal{K}_s$ usually shrinks, which means that the controller should be designed with some stability margin to maintain stability in the presence of these undesired phenomena. The case treated in this work is not so problematic from stability point of view due to the fact that the parameters are only allowed to change within the part of parameter space where each fixed-gain controller guarantees system stability. This means that the most usual path to instability through parameter drift is not possible. There is, however, the potential risk of destabilising the system through a quick change of controller gains, whose effect is to shrink the stability region even further. But this phenomenon can be prevented by stopping the adaptation when