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An extremum-seeking control approach for constrained robotic motion tasks

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ABSTRACT

In this paper, we propose two adaptive control schemes for multiple-input systems for execution of robot end-effector movements in the presence of parametric system uncertainties. The design of these schemes is based on Model Reference Adaptive Control (MRAC) while the adaptation of the controller parameters is achieved by Extremum Seeking Control (ESC). The two control schemes, which are called Multiple-Input ESC–MRAC and Multiple-Input Adaptive-Dynamic-Inversion ESC–MRAC, are suitable for linear and nonlinear systems respectively. Lyapunov and averaging analysis shows that the proposed schemes achieve practical asymptotic reference state tracking. The proposed methods are evaluated in simulations and in a real-world robotic experiment.

1. Introduction

Robots are often required to perform constrained motion tasks inside unknown and deformable environments such as while engraving an object's surface or writing on a soft material. In such cases, uncertainty about the end-effector and the environment makes the execution of these tasks a challenge since the robot should efficiently compensate for this uncertainty to accurately execute a desired motion path. In addition, during movement inside deformable environments, motion dynamics between different directions are physically coupled and this coupling is non-negligible and has to be taken into account for proper system modeling and control. An illustration of an example engraving task where this dynamic coupling occurs, is shown in Fig. 1. In order to deal with uncertain systems, adaptive control is a suitable approach to follow since it is specially tailored to accommodate uncertainties. In this paper, we propose two task-space adaptive control schemes for the execution of multi-directional robot end-effector movements inside unknown and deformable environments where the task uncertainty and the physical coupling between different directions of movement are taken into account. Our task-space control approach could be then combined with any inverse-kinematics algorithm for motion of manipulators (Falco and Natale, 2011).

In recent robotic research, significant effort has been devoted to learning of control skills from demonstrated data or combining control approaches with learning-by-demonstration for execution of various motion tasks. In Lee, Ott, and Nakamura (2009), motion primitives are learned by demonstration and combined with impedance control to perform physical contact tasks. In Mitrovic, Klanke, and Vijayakumar (2010), dynamic models are learned and combined with a Linear Quadratic Regulator for performing constrained motion tasks by assuming, however, knowledge of the system dynamics. A composite adaptive control scheme is developed in Nakanishi, Farrell, and Schaal (2002) based on locally weighted regression for state tracking of single-input single-output systems. In Hirche and Lee (2012), following learning of a task-space force control policy from multiple task demonstrations, generalization of this policy to new motions is proposed by combining regression learning with Taylor-like polynomial approximation while, in Koropouli, Lee, and Hirche (2011), regression learning of force patterns from single demonstrations is proposed for performance of constrained motion tasks inside deformable environments. In addition, in Schmidts, Lee, and Peer (2011) learning of motion and force regulation skills from multiple demonstrations is proposed for object grasping. However, such approaches depend on the demonstrated data and their ability to deal with uncertainty is obviously rather limited. Another family of works employs reinforcement learning to iteratively accomplish a

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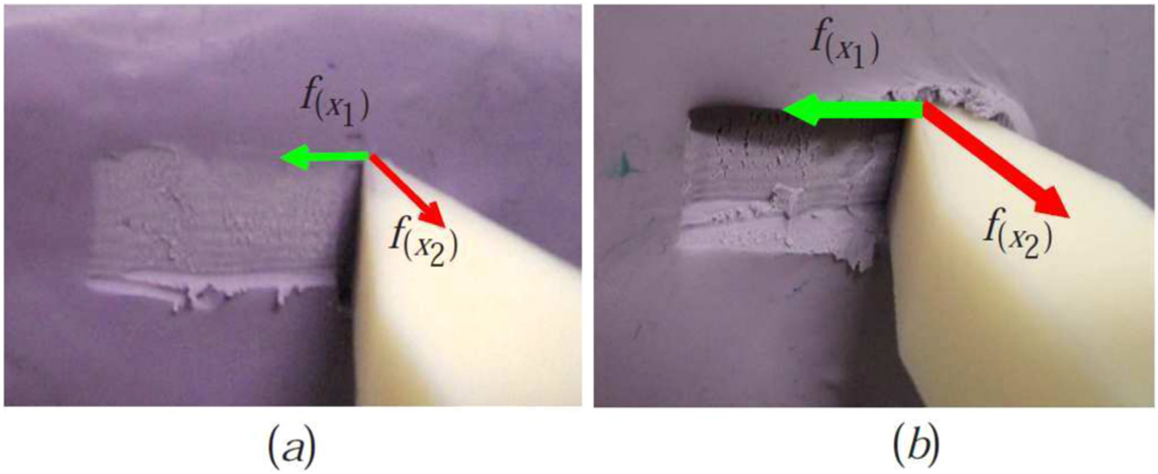

Fig. 1. An example of a constrained robotic motion task in deformable environment; engraving is realized at different depths inside a plasticine object. Different environmental disturbance $\{f_{(x_1)}, f_{(x_2)}\}$ is experienced in each case due to the changing manipulating mass. Engraving in a (a) low depth, (b) high depth.

motion task while optimizing task performance (Buchli, Stulp, Theodorou, and Schaal, 2011; Peters and Schaal, 2008). However, during manipulation of deformable environments, a motion task has to be successfully accomplished in a single execution in contrast to reinforcement learning which requires multiple trials and causes, in this way, non-desired cumulative deformation of the environment.

Apart from learning-based approaches, adaptive control approaches have also been employed in robotic tasks. In Cheah, Liu, and Slotine (2006), adaptive Jacobian control of robot manipulators with kinematic and dynamic uncertainties is accomplished while in Yao (1997) existing adaptive robust control schemes are implemented and evaluated in tracking control of manipulators. Model Reference Adaptive Control (MRAC) is employed in Garus (2007) for motion control of an underwater robotic vehicle and in Tzafestas, Stavrakakis, and Zagorianos (1988) for control of a six degrees-of-freedom robotic manipulator whose dynamics are simulated by a Newton-Euler model.

Among existing adaptive control approaches, MRAC stands out as one of the most well-established and widely used approaches (Astrom and Wittenmark, 2008; Narendra and Annaswamy, 2005). MRAC assumes that a reference model exists, which expresses the desired response of a system to a reference signal, and ensures that the system follows the reference model. The use of reference models dates back to the foundation of aircraft control and, since then, MRAC has been widely used in multiple applications (Garus, 2007; Guo, Liu, and Tao, 2009; Reddy, Kota, and Chandrasekhar, 1991; Tzafestas et al., 1988). Recent work on MRAC has been realized in Guo et al. (2009), Poorya (2013), Haghi and Ariyur (2013), and Haghi and Ariyur (2011). In Guo et al. (2009), a multiple-input multiple-output MRAC approach is proposed for output tracking by using state feedback. Although MRAC is an appealing approach which is widely employed for tracking, it depends strictly on the system model. To avoid this strict dependence on the system dynamics, combination of Extremum Seeking Control (ESC) with MRAC is proposed in Poorya (2013) for state tracking of Single-Input Single-Output (SISO) systems. ESC is a model-free optimization scheme (Ariyur and Krstić, 2003; Zhang and Ordonez, 2012) and has been employed in various engineering applications such as in formation flight control (Binetti, Ariyur, Krstić, and Bernelli, 2002) and tuning of PID controllers (Killingsworth and Krstić, 2006). ESC aims at tracking the minimum or maximum (extremum) of the performance function of a system. The ability to express the ideal behavior of a system in terms of a reference model, as in MRAC, is beneficial because the reference model serves in the design of the control law of the system and can regulate its transient behavior (Narendra and Annaswamy, 2005; Poorya, 2013). However, MRAC imposes certain matching conditions between the system and its reference model and these conditions may not always be able to be established, which, in turn, makes MRAC inapplicable. In addition, as it is earlier discussed, MRAC is strictly model-dependent and mainly refers to systems with parametric uncertainty. By combining MRAC with ESC, model-free parameter adaptation is achieved, which can offer certain robustness to non-parametric uncertainties as well compared to single MRAC. In Haghi and Ariyur (2013), an ESC–MRAC approach for output tracking of nonlinear MIMO systems is proposed by performing feedback linearization and the initial problem is converted into output tracking of multiple SISO systems and solved by employing the method proposed in Poorya (2013). The method in Haghi and Ariyur (2013) assumes that the control input can be expressed in a specific linear parameterized form while each SISO system optimizes an individual cost function which solely depends on this system's output.

Our present work focuses on the development of an adaptive control approach for reference state tracking of multiple-input systems. This approach refers to both linear and nonlinear systems which involve parametric uncertainty. The goal is that the system's states track some reference states by optimizing a global state cost criterion for the task. The proposed approach is motivated by the scenario of our robotic application where an end-effector is required to make a specific motion in multiple directions of a workspace. To solve the state-tracking problem we combine MRAC with ESC similar to Poorya (2013). MRAC addresses linear systems and in order to address nonlinear systems as well, we combine MRAC with Adaptive Dynamic Inversion (ADI). According to ADI, the parametrically uncertain nonlinearities of the system are taken into account in the control design and its unknown weighting parameters adapt in real-time to compensate for the relative uncertainty. The design of the proposed control laws is based on MRAC while adaptation of the controller parameters is achieved by ESC.

The principal goal of the work of this paper is to solve the state tracking problem for an end-effector with uncertain properties, which interacts with an uncertain environment. Therefore, apart from proposing an adaptive control approach for reference state tracking, we also focus on demonstrating how this approach works in simulations and how it can be used in real-world robotic tasks to improve robot tracking performance in the presence of parametric system uncertainties. In particular, the contributions of this