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Multiplexed extremum seeking for calibration of spark timing in a CNG-fuelled engine[☆]

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ABSTRACT

The compositional variability of many alternative fuels, coupled with fuel agnostic behaviour like engine ageing and vehicle-to-vehicle differences, leads to the desire for some form of online calibration in order to optimise fuel efficiency. This has led to the incorporation of extremum seeking techniques within the field in order to continually fine tune engine performance. These typically address steady state engine performance and are characterised by slow convergence times, hindering their deployment in typical dynamic driving scenarios. To address this potential shortcoming, in this paper a novel multiplexed extremum seeking scheme is proposed to track a time-varying extremum caused by a measurable disturbance. It consists of multiple extremum seeking agents that are individually activated based on the disturbance. The multiplexed approach accommodates the rigorous practical stability results of the "traditional" extremum seeking approaches, but offers improved results in dynamic scenarios. The proposed approach is implemented both in simulation and experimentally on a compressed natural gas (CNG) engine operating over a drive cycle. The experimental results show that under proper tuning, the proposed controller can improve the engine fuel efficiency for unknown natural gas compositions without requiring gas composition sensing at little additional calibration effort.

1. Introduction

The optimal inputs to an automotive engine depend on engine speed and load, normally defining the engine operating point. In a typical driving scenario the operating point varies constantly, requiring fast adjustments of engine inputs. Within a production Engine Control Unit (ECU), a feedforward approach is taken to adjust the engine inputs quickly. In this quasi-steady state approach, optimal engine inputs are calibrated during steady-state operation and stored in lookup table formats for a finite number of engine operating points. In the lookup tables, the optimal inputs are parametrised against the engine speed and load values. Engine inputs are then determined by employing interpolation methods for all possible operating points (Guzzella & Onder, 2009).

Unlike gasoline and diesel, most of the alternative fuels such as natural gas, bio-gas, and gasoline-ethanol blends can be delivered with different compositions. For example in the case of natural gas, the composition varies based of its geographic source of extraction and occasional modifications made by the local gas distributer companies (Ly, 2002). Fuel composition affects combustion properties such as stoichiometric air-fuel ratio, energy content, burn rate, and knock resistance. Therefore, the optimal engine inputs can vary as a result of the variation in the fuel composition (Kakaee, Paykani, & Ghajar, 2014; Min, Bang, Kim, Chung, & Park, 2002). Subsequently the quasi-steady state approach will deliver suboptimal performance when the fuel composition changes from the one used for calibration. Hence, a means of online adjustment is needed to account for the composition variation in alternative fuels. Crucially, for the adaptation to be effective, it must evolve at a faster time-scale than the operating point variations.

Extremum Seeking (ES) is a class of adaptive control methods that is used for online steady-state optimisation of unknown dynamical systems. Most of the ES presented in the literature are based on estimating the gradient of the static steady-state input–output map and using that estimation to shift input towards the extremum of the function. Therefore a large number of ES implementations can be classified according to the gradient estimation method used in the approach. In the so called black-box ES approach, the correlation of the input

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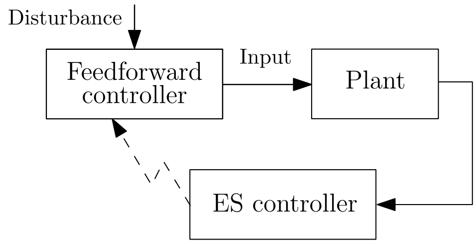

Fig. 1. The proposed adaptive approach.

perturbation signal to the resulting deviation in the plant output is used for gradient estimation (Krstić & Wang, 2000); while in the grey-box (or model-based) approach it is derived by exploiting the known structure of the input–output mapping which has some uncertain parameters (Guay & Zhang, 2003; Nesić, Mohammadi, & Manzie, 2012; Sharafi, Moase, & Manzie, 2015). In the latter approach a parameter estimator is employed to estimate the input–output mapping. In another approach to ES, nonlinear programming methods can be used in a sampled-data fashion to implement ES controller regardless of the smoothness of the mapping (Teel & Popović, 2001).

ES was applied in a range of automotive application even before the theoretical results had been developed. Draper and Li (1951) identified the benefits of these approaches in the engine calibration process. In Wellstead and Scotson (1990), ES was used to generate optimal spark timing with respect to fuel efficiency despite engine wear and part-to-part variation caused by production tolerance. Later, ES techniques based on nonlinear programming was applied to facilitate the calibration of multiple engine inputs (Popović, Janković, Magner, & Teel, 2006).

More recently, the widespread of alternative fuels has revived interests in ES within the automotive research community. ES has been proposed for tuning the spark timing in flex-fuel (Hellstrom, Lee, Jiang, Stefanopoulou, & Yilmaz, 2013) and CNG (Mohammadi, Manzie, & Nesic, 2014; Sharafi et al., 2014) engines. However, due to the slow convergence properties of the current ES schemes, only set-point calibration has been considered in the previous works. This suits the application of ES in stationary power plants where engine operating condition does not vary for sufficiently long periods of time. In dynamic scenarios where steady state operation is not typical (as is the case in normal driving), rapid changes in the optimal combination of inputs often render these approaches inadequate.

The non-stationary input–output behaviour of the engine in the presence of load and speed variations creates a time-varying ES scenario (Hellstrom et al., 2013). In fact, this scenario is relevant and reported in many other energy systems such as: Maximum Power Point Tracking (MPPT) for a wind turbine in the presence of wind speed variation (Ghaffari, Krstic, & Seshagiri, 2014) and MPPT for a fuel-cell in the presence of load variation (Chang & Moura; Zhong, Huo, Zhu, Cao, & Ren, 2008). In all these applications the presence of an exogenous disturbance can vary the locus of the extremum point.

The inability of conventional ES approaches to handle these type of problems has motivated recent developments. The inclusion of an inner-loop dynamic controller was proposed in Ghaffari et al. (2014) to compensate for a time-varying extremum. The approach was successfully implemented for wind turbine tracking, but requires convergence rates faster than the time varying dynamics. In the same vein, ES algorithms based on high frequency dither are presented for Hammerstein plants in Moase and Manzie (2012) and Sharafi et al. (2015) and for input-affine systems in Scheinker and Krstić (2013, 2014). With the similar objective of improving ES transient performance but in a sampled-data setting, Poveda and Teel (2015) proposes an event-based method. All these techniques also implicitly require the ES to evolve faster than the time-varying phenomena in the plant, and may be sensitive to high frequency noise.

To address a wider range of applications, an adaptive feedforward approach was developed in Marinkov, de Jager, and Steinbuch (2014) for static plants when the exogenous input signal is measurable. In this scheme the unknown mapping between the exogenous disturbance and the extremum input is continuously identified and incorporated in a feedforward controller. While only a static map was considered in Marinkov et al. (2014), crucially it does not require the exogenous input to be periodic.

Building on the work in Marinkov et al. (2014), this paper introduces a novel multiplexed ES approach for dynamical plants subject to measurable exogenous disturbance. It combines the quasi-steady state feedforward approach with the adaptation provided by a ES algorithm. This approach is depicted in Fig. 1. The multiplexed extremum seeker has an intuitive structure in that it consists of a set of individual extremum seekers, each of which are activated only when the exogenous input falls within a unique specified range. This introduces an inevitable tradeoff since there are competing objectives in the selection of the activation ranges for the individual extremum seeking agents — i.e. smaller ranges lead to better approximation accuracy but can compromise convergence rates and (eventually) stability. Unlike the related results in Ghaffari et al. (2014), Moase and Manzie (2012) and Scheinker and Krstić (2013), the proposed method does not explicitly rely on the ES dynamics being faster than the exogenous disturbance, enabling potential application in a wider range of practical problems.

It is noted that the approach taken in Marinkov et al. (2014) shares some similarities in scope with the proposed multiplexed ES. However, Marinkov et al. (2014) only considers static plants and stability issues are largely ignored. Particularly, the adaptive method in Marinkov et al. (2014) naturally requires the disturbance signal to satisfy a “persistency of excitation” condition. This may lead to a very restrictive assumption on the typically unknown exogenous input. Experimental demonstrations of the proposed method on a CNG engine highlight the promise of the proposed approach, particularly in the absence of this restrictive assumption.

Mathematical preliminaries

A continuous function $\alpha : [0, a) \to \mathbb{R}_{\geq 0}$ is said to be class $\mathcal{K}$ if it is nondecreasing and $\alpha(0) = 0$. $\alpha(\cdot)$ is class $\mathcal{K}_\infty$ if it is class $\mathcal{K}$ and $\lim_{r\to\infty}\alpha(r) = \infty$. A function $\sigma : \mathbb{R}_{\geq 0} \to \mathbb{R}_{\geq 0}$ is said to be class $\mathcal{L}$ if it is decreasing and $\lim_{t\to\infty}\sigma(t) = 0$. A function $\beta : [0, a) \times \mathbb{R}_{\geq 0} \to \mathbb{R}_{\geq 0}$ is said to be class $\mathcal{KL}$ if it is class $\mathcal{K}$ with respect to the first argument and class $\mathcal{L}$ with respect to its second argument. Denote the $\mathcal{L}_2$ norm of a vector by $\|\cdot\|$. $\mathcal{L}_\infty$ norm of a signal vector is denoted by $\|\cdot\|_{t_0}$ and defined as $\sup_{t_0\leq t\leq\infty}\|\cdot\|$. Similarly for any $t \geq t_0$, $\|\cdot\|_{t_0}^t$ denotes $\sup_{t_0\leq t\leq t}\|\cdot\|$.

2. Multiplexed extremum seeking scheme

Most ES design approaches consider optimising the steady-state output of a plant with stationary input–output behaviour. However this is not applicable to the large class of systems that exhibit a time-varying steady state input–output mapping caused by exogenous input disturbances. External disturbances can affect the steady state performance of the plant, which ultimately may change the location of the extremum. If the map between the exogenous input and the extremum point is well defined, ideally a controller is required to estimate that map instead of estimating just one extremum point.

The concept of multiplexed ES is illustrated in Fig. 2. Let $w(t) \in \Gamma \subset \mathbb{R}^1$ denote the exogenous disturbance signal and $u^*(w)$ the unique extremum input of the input–output mapping for any fixed w. In order to estimate $u^*(\cdot)$, it is approximated in a piecewise constant fashion. To that end the domain of $w(t)$, Γ, is divided into a total number of M subregions Γ_i in which $u^*(\cdot)$ is assumed constant. Subsequently, independent ES controllers can be assigned at each subregion, between the grid points to shift the plant input to $u^*(w)$. Here, it is worthwhile to mention the following: