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Brief paper

Stable genetic adaptive controllers for multivariable systems using a two-degree-of-freedom topology

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ABSTRACT

This paper introduces an adaptive reference tracking controller based on the online genetic estimation of the parameters of the system. The main novelty of the paper relies on the fact that the stability of the genetic adaptive scheme is analytically proved and not simply validated by means of simulation as it is customary in the literature. The resulting set-up is flexible enough to be integrated within a great variety of genetic estimation algorithms, which can in many cases outperform traditional estimation procedures. The goal is achieved by using a certain two-degree-of-freedom (2-DOF) based implementation of the control law in which the reference tracking property is separated from the closed-loop stability. Within this framework, the here-presented procedure for the genetic controller synthesis just affects two time-varying pre-filter blocks that do not compromise the closed-loop stability under weak conditions. In this manner, the power and versatility of genetic algorithms can be safely used to achieve tracking performance disregarding stability, which is delegated to a static feedback controller designed on the basis of robust control theory.

1. Introduction

Genetic algorithms (GAs) have been revealed as powerful tools for solving a wide variety of problems since their introduction by Holland in 1975. Basically, they act as optimization tools able to tackle complex problems which are practically intractable from an alternative (analytical) point of view. Several areas in Science and Engineering such as Economics, Structural Design, Network Design, Game Theory and Operations Research, to cite a few of them, have benefited from the use of GAs (Moyne et al. 1995). Moreover, GAs have also found application in the area of automatic control systems design (Jamshidi et al., 2002). In this context the controller is formulated to have a set of parameters, which the GA tries to optimize according to the closed-loop performance associated with each set of candidate values. GA-based approaches to controller design can be condensed into three major categories:

(1) The first one consists of integrating GAs with fuzzy or neuro-fuzzy controllers with the aim of improving (or decreasing) the set of rules necessary to design the fuzzy subsystem (see, for instance, Seng et al., 1999; Lee and Zak, 2002; Chen and Rine Training, 1998).
(2) The second one consists of using the GA in the offline optimization of the controller or observer composing the closed-loop, (Pereira and Pinto, 2005). There are several works covering this topic, including the observer design (Moyne et al., 1995), state feedback control laws (Moore et al., 2001; Zuo, 1995), PID control (Pereira and Pinto, 2005; Kristinsson and Dumont, 1992) and $\mathcal{H}_\infty$ optimization (Jamshidi et al., 2002).
(3) Finally, the third approach employs GAs to determine the (time-varying) controller online. This approach fits well into the adaptive control framework.

There are several works pointing out the advantages of using GAs in the online estimation of the controller parameters (Marra and Walcott, 1996; Kristinsson and Dumont, 1992; Lennon and Passino, 1999; Kumon et al., 2003). Reported advantages include the fast convergence to adequate controller parameters (Lennon and Passino, 1999; Ibeas and de la Sen, 2006), direct identification of poles and zeros instead of plant coefficients and improved robustness properties with respect to traditional recursive estimation schemes (Kristinsson and Dumont ,1992; Lennon and Passino, 1999; Hidalgo et al., 1999). The conclusion of these works is that GAs are powerful tools to be included within the adaptive control framework.

Nevertheless, most of these works (even the most recent ones) do not tackle explicitly the stability issue in their development (Lennon and Passino, 1999). The main reason for this relies on the

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fact that the heuristic nature of GAs makes it difficult to predict their evolution, which basically obeys probabilistic rules. Hence, works covering the adaptive control of systems using GAs do not usually include the stability analysis of the resulting closed-loop but just a validation, through simulation or experimental work, of their applicability in practice (Kristinsson and Dumont, 1992; Lennon and Passino, 1999). Furthermore, those exploring the stability issue usually include a number of probabilistic-type hypotheses on the parameter evolution in order to guarantee the closed-loop stability (see, for instance, Marra and Walcott, 1996).

In this paper, a two-degree-of-freedom (2-DOF) scheme to implement reference tracking adaptive controllers based on GAs is proposed. The main feature of the suggested approach is that it benefits from the genetic *estimation* of good properties for tracking performance without affecting closed-loop stability. This is proved under weak, feasible conditions on the GA parameters evolution. This benefit is obtained by implementing the control law according to a 2-DOF topology appearing in Soroka and Shaked (1986) and Kuroiwa and Kimura (2003). As it will be seen, this scenario stability is mainly guaranteed by an internal and fixed feedback controller whereas the tracking performance is attained by virtue of online readjustment of the genetic compensator blocks. In summary, the idea is to delegate stability to the internal compensator, due to which it will be shown to be weakly influenced by the evolution of the genetic population. This way, GAs can be safely exploited for reference tracking purposes.

The paper is organised as follows: Section 2 introduces the problem formulation and main objectives. In Section 3, the genetic design of the controller is commented. Section 4 states the stability properties of the resulting closed-loop system. Section 5 is devoted to simulation examples while some concluding remarks end the paper.

2. Problem formulation

We consider the problem of controlling a general LTI continuous-time system with m inputs and p outputs described by an irreducible Left Matrix Fraction Description:

$$\mathbf{G}(s) = \mathbf{N}^{-1}(s)\mathbf{M}(s) \tag{1}$$

where $\mathbf{M}(s) \in \mathbb{R}^{p\times m}$ and $\mathbf{N}(s) \in \mathbb{R}^{p\times p}$ are (matrix) polynomials in the Laplace variable s with unknown (matrix) coefficients and satisfying the following assumption.

Assumption 1. Upper-bounds for the plant (matrix) polynomial degrees are known:

$$\deg \mathbf{N}(s) \le \overline{n}, \quad \deg \mathbf{M}(s) \le \overline{m}$$

with $\overline{n} \ge \overline{m} \ge 0$ known.

Thus, we are considering the nominal model affected by parametric uncertainty. In particular, no unmodelled dynamics are taken into account. In the particular SISO case, (1) reduces to the scalar transfer function representation.

Since nowadays it is very common to control a continuous-time process using a discrete-time controller, we will consider a discrete model of the plant in order to synthesize a discrete-time controller. Therefore, the design procedure proposed in this paper will apply to both discretized continuous systems and to purely discrete ones just avoiding the previous discretization step. This set-up is preferable to the original continuous-time one in order to incorporate into the theoretical framework the way in which control systems are commonly implemented in practice.

2.1. Discrete plant model

A discrete-time Left Matrix Fraction Description of (1) is obtained using a zero order hold (*ZOH*) with sampling period T_s according to

$$\begin{aligned}\mathbf{H}(z) &= Z\left[\frac{1-e^{-sT_s}}{s}\mathbf{G}(s)\right] = (1-z^{-1})\mathcal{Z}\left[\frac{1}{s}\mathbf{G}(s)\right] \\ &= (1-z^{-1})\mathcal{Z}\left[\frac{1}{s}\mathbf{N}^{-1}(s)\mathbf{M}(s)\right] \\ &= (1-z^{-1})\mathbf{D}_\mathbf{p}'^{-1}(z^{-1})\mathbf{N}_\mathbf{p}'(z^{-1}) = \mathbf{D}_\mathbf{p}^{-1}(z)\mathbf{N}_\mathbf{p}(z) = \mathbf{N}_\mathbf{p}^\mathbf{r}(z)(\mathbf{D}_\mathbf{p}^\mathbf{r})^{-1}(z)\end{aligned} \tag{2}$$

with

$$\mathbf{N}_\mathbf{p}(z^{-1}) = \mathbf{B_1}z^{-1} + \ldots + \mathbf{B}_{\overline{m}}z^{-\overline{m}}$$
$$\mathbf{D}_\mathbf{p}(z^{-1}) = \mathbf{I}_{p\times p} + \mathbf{A_1}z^{-1} + \ldots + \mathbf{A}_{\overline{n}}z^{-\overline{n}}$$

where $\mathcal{Z}$ denotes the *zeta*-transform and $z^{-1} \leftrightarrow q^{-1}$ (while $z \leftrightarrow q$) is equivalent to the one sampling period backward operator (one sample period ahead operator). The pair $\mathbf{N}_\mathbf{p}^\mathbf{r}(z)$, $\mathbf{D}_\mathbf{p}^\mathbf{r}(z)$ constitute a Right Matrix Fraction Description and it will be used later. Moreover, upon Assumption 1, the following degree relations regarding the discrete plant (2) hold:

$$\deg \mathbf{D_p}(z) \le \overline{n}, \quad \deg \mathbf{N_p}(z) \le \overline{m} \tag{3}$$

since a *ZOH* has been used to obtain the corresponding discrete-time model (Bilbao-Guillerna et al., 2005). The knowledge of these orders allows specifying the size of the chromosomes in the GA formulation. Hence, the original problem is reformulated into the control of a discrete-time linear system with parametric uncertainty. Since the plant parameters are unknown, a genetic estimation algorithm will be used to estimate the value of the (matrix) polynomials $\mathbf{N_p}(z)$, $\mathbf{D_p}(z)$, converting them into time-varying and denoted $\hat{\mathbf{N}}_{\mathbf{p}k}(z)$, $\hat{\mathbf{D}}_{\mathbf{p}k}(z)$. The GA will be used to obtain such estimated (matrix) polynomials in such a way that its use within an online adaptive control scheme results into an asymptotically stable closed-loop system. As commented in Section 1, GA utilization within an adaptive controller usually lacks stability considerations. In the sequel, a concrete implementation of a 2-DOF control law allows linking the advantages of the genetic estimation along with conventional LTI closed-loop stability analysis under weak conditions on the evolution of the genetic population. This is the main contribution of the paper.

3. Controller design procedure

This section describes the control scheme proposed to assess the stability within a genetic adaptive estimation framework. The plant in (1) will be considered, assuming parametric uncertainty, through its discrete-time counterpart (2). Firstly, the basic topology of the control scheme is introduced in the following section.

3.1. Two degree of freedom (2-DOF) control law implementation

In this section we concentrate on the basic 2-DOF control law implementation introduced in Soroka and Shaked (1986) and Kuroiwa and Kimura (2003) and displayed in Fig. 1 for convenience.

Given a general two-parameter LTI compensator, different realizations are possible. As pointed out in Kwok and Davison (2007) not all of them possess the same properties. The above topology is adequate to be used within the genetic algorithm context. Let us see why: within this configuration, the (matrix) transfer function from the reference $\mathbf{r}_k$ to the output $\mathbf{y}_k$ is