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Evolutionary multi-objective optimisation with preferences for multivariable PI controller tuning

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ABSTRACT

Multi-objective optimisation design procedures have shown to be a valuable tool for control engineers. They enable the designer having a close embedment of the tuning process for a wide variety of applications. In such procedures, evolutionary multi-objective optimisation has been extensively used for PI and PID controller tuning; one reason for this is due to their flexibility to include mechanisms in order to enhance convergence and diversity. Although its usability, when dealing with multi-variable processes, the resulting Pareto front approximation might not be useful, due to the number of design objectives stated. That is, a vast region of the objective space might be impractical or useless *a priori*, due to the strong degradation in some of the design objectives. In this paper preference handling techniques are incorporated into the optimisation process, seeking to improve the pertinency of the approximated Pareto front for multi-variable PI controller tuning. That is, the inclusion of preferences into the optimisation process, in order to seek actively for a pertinent Pareto front approximation. With such approach, it is possible to tune a multi-variable PI controller, fulfilling several design objectives, using previous knowledge from the designer on the expected trade-off performance. This is validated with a well-known benchmark example in multi-variable control. Control tests show the usefulness of the proposed approach when compared with other tuning techniques.

1. Introduction

Intelligent control is a subfield of control systems engineering of growing interest among researchers (Ruano, 2005; Ruano et al., 2014). Nowadays, the most accepted definition for intelligent control comprises using one or several tools from computational intelligence and soft computing for control engineering purposes. Such tools range from neural networks, fuzzy logic systems and evolutionary algorithms (Albertos, 2007; Ruano, 2007; Tzafestas, 2007) to rule-based and knowledge-based systems (Liao, 2005). Such techniques have shown to be useful in complex instances in control systems engineering (Ruano, 2005).

One of the fundamental tasks in intelligent control is the controller tuning problem (Jiménez et al., 2015; Mishra, Kumar, & Rana, 2015; Ponce, Ponce, Bastida, & Molina, 2015; Sabzi, Humberson, Abudu, & King, 2016). Such problem consists in finding suitable values for the tuneable parameters of a given control structure. With such parameters it is expected to fulfil some desired closed-loop specifications for a given process. Although there are several control structures, the PI-PID controller remains as a reliable and practical control solution for several industrial processes (Åström & Hägglund, 2001). One of the main advantages of PI-PID controllers is their ease of implementation, giving a good trade-off between simplicity and cost to implement (Stewart, Samad, Samad, & Annaswamy, 2011; Tan, Liu, Fang, & Chen, 2004). Owing to this, seeking for new tuning techniques is an ongoing research topic (Åström & Hägglund, 2005); current research points to guarantee reasonable stability margins as well as a good overall performance for a wide variety of processes (Vilanova & Alfaro, 2011).

New tuning techniques are being focused on the fulfilment of several objectives and requirements, sometimes in conflict among them (Ang, Chong, & Li, 2005; Li & Ang, 2006). Some tuning procedures are based on optimisation statements (Åström, Panagopoulos, & Hägglund, 1998; Ge, Chiu, & Wang, 2002; Panagopoulos, Åström, & Hägglund, 2002; Sanchez & Vilanova, 2013; Toscano, 2005) and in some cases they are solved by means of stochastic optimisers. A recently popular approach consists on using

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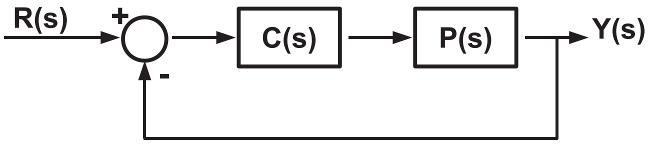

Fig. 1. Basic control loop.

Evolutionary Multi-objective Optimisation (EMO) for PI-PID controller tuning for single input, single output (SISO) and multiple input, multiple output (MIMO) processes (Reynoso-Meza, Blasco, Sanchis, & Martínez, 2013b).

In EMO, a simultaneous optimisation approach is used in order to seek for a Pareto set approximation. This Pareto set comprises several solutions, where all they are Pareto-optimal, *i.e.* there is not a solution better than another in all the objectives, but a different trade-off between conflictive objectives. In order to approximate this Pareto set, Multi-Objective Evolutionary Algorithms (MOEAs) are used. Selecting or coding a MOEA is just a part of the overall process; from a practical point of view a multi-criteria decision making (MCDM) stage is required by the decision maker (DM or simply, the designer) in order to select a controller from the approximated Pareto front. Therefore, a Multi-objective Optimisation Design (MOOD) procedure for controller tuning is needed, where the multi-objective problem (MOP) definition, the optimisation process and the MCDM stage are integrated. This procedure has shown to be a valuable tool for control engineers (Reynoso-Meza et al., 2013b; Reynoso-Meza, Sanchis, Blasco, & Martínez, 2014c); it may enable the designer to have a close embedment with the tuning process; with them it is possible to take into account each design objective individually; it also enables the design alternative comparison, to select a controller fulfilling the expected trade-off among conflictive objectives.

This MOOD procedure has been used with success in PI-PID tuning for MIMO processes (Herreros, Baeyens, & Perán, 2002; Hung, Shu, Ho, Hwang, & Ho, 2008; Reynoso-Meza, Sanchis, Blasco, & Herrero, 2012; Xue, Li, & Gao, 2010; Zhao, Iruthayarajan, Baskar, & Suganthan, 2011). As noticed in Reynoso-Meza et al. (2014c), mechanisms to improve convergence, diversity and constraint handling have been included in MOEA for this purpose; the following step seems to be related with improving pertinency of solutions by means of the statement of designer's preferences. These mechanisms will enable the algorithm to approximate a Pareto front with pertinent solutions in the search process; furthermore, they could facilitate the DM's task of analysing and selecting a design alternative (Coello, 2000). This feature has not been widely exploited and could be helpful to solve efficiently many-objective optimisation instances (Ishibuchi, Tsukamoto, & Nojima, 2008) for multi-variable PI controller tuning. In such instances, each control loop and the overall system must fulfil several performance specifications.

The aim of this paper is twofold. On the one hand, stating a general *MOP/EMO* definition to deal efficiently with MIMO processes using designer's preferences; despite the fact that every process is different and the designer would prefer stating its own meaningful objectives, a general procedure could be valuable, where a pertinent Pareto front is provided for the further analysis in the MCDM stage. On the other hand, comparing preference handling techniques for EMO and evaluate their performance for PI controller tuning in MIMO processes. In both cases, this paper follow the assumption that the DM has already decided to use a MOOD procedure for controller tuning and the desired objectives have been selected.

The remainder of this paper is as follows: in Section 2 a basic background on multivariable PI control, EMO and preference handling will be provided; in Section 3 a *MOP/EMO* procedure for multivariable PI controller tuning will be stated; Section 4 will be dedicated to solve a benchmark set-up based on the Wood and Berry distillation column (Berry, 1973; Wood & Berry, 1973); Finally, some concluding remarks are given.

2. Background

Some notions on multivariable PI control, multi-objective optimisation, and preferences handling are required. They are provided below.

2.1. Background on multivariable PI controller tuning

A basic control loop is depicted in Fig. 1. It comprises transfer functions $P(s)$ and $C(s)$ of a process and a controller respectively. The objective of this control loop is to keep the desired output $Y(s)$ of the process $P(s)$ in the desired reference $R(s)$.

In the case of a $N \times N$ MIMO process, $P(s)$ is composed of several sub-processes P_{ij} with $i, j \in \{1, \ldots, N\}$ and it has the following structure:

$$P(s) = \begin{bmatrix} P_{11}(s) & \ldots & P_{1N}(s) \\ \vdots & \ddots & \vdots \\ P_{N1}(s) & \ldots & P_{NN}(s) \end{bmatrix} \tag{1}$$

The complexity of a process like this is mainly due to its coupling effects between inputs and outputs. There are several alternatives to control a MIMO system, and the selection of one technique over another depends on the desired balance between complexity and tradeoff between design specifications. PI controllers are simple but successful solutions, and their performance can be improved with complementary techniques (Åström & Hägglund, 2005); because of this, they are used in this work. The decoupled PI controller $C(s)$ has N SISO PI controllers:

$$C(s) = \begin{bmatrix} C_1(s) & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & C_N(s) \end{bmatrix} \tag{2}$$

Eq. (3) shows the transfer function of the selected structure of the PI controller:

$$C_i(s) = k_p\left(1 + \frac{1}{T_i s}\right) \tag{3}$$

where $i \in \{1, \ldots, N\}$, k_p is the proportional gain, T_i the integral time (s). The control problem consists in selecting proper gains k_p and $k_i = \frac{k_p}{T_i}$ for each one of the PI controllers $C_i(s)$ in order to achieve a desirable performance of the process $P(s)$ in the control loop as well as robust stability margins. This control problem is well known and it has been addressed with several techniques. Given the coupling effects among sub-processes $P_{ij}(s)$, conflictive objectives may appear, at least related with the performance of each individual control loop. For this reason, EMO techniques could be appealing for PI controller tuning.

2.2. Multi-objective optimisation statement

As referred in (Miettinen, 1998), a MOP with m objectives,[1] can be stated as follows:

$$\min_{\boldsymbol{\theta}} \boldsymbol{J}(\theta) = [J_1(\boldsymbol{\theta}), \ldots, J_m(\boldsymbol{\theta})] \tag{4}$$

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[1] A maximisation problem can be converted to a minimisation problem. For each of the objectives that have to be maximised, the transformation: $\max J_i(\boldsymbol{\theta}) = -\min(-J_i(\boldsymbol{\theta}))$ could be applied.