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PID controller tuning for unstable processes using a multi-objective optimisation design procedure

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Abstract: Multi-objective optimisation techniques have shown to be a useful tool for controller tuning applications. Such techniques are useful when: 1) it is difficult to find a controller with a desirable trade-off between conflictive objectives; or 2) it is valuable to extract an additional knowledge from the process by analysing trade-off among possible controllers. In this work, we propose a multi-objective optimisation design procedure for unstable process, using PID controllers. The provided examples show the usability of the procedure for this kind of process, sometimes difficult to control; comparison with existing tuning rule methods provide promising results for this tuning procedure.

Keywords: PID controller tuning, multi-objective optimisation, evolutionary algorithms.

1. INTRODUCTION

Proportional - Integral - Derivative (PID) controllers remain as reliable and practical control solutions for several industrial processes (Åström and Hägglund, 2001). One of the main advantages of PID controllers is their ease of implementation as well as their tuning, giving a good trade-off between simplicity and cost to implement (Stewart and Samad, 2011). Owing to this, research for new tuning techniques is an ongoing research topic (Åström and Hägglund, 2005). Current research points to guarantee reasonable stability margins as well as a good overall performance for a wide variety of processes.

New tuning techniques are being focused on the fulfilment of several objectives and requirements, sometimes in conflict among them (Ang et al., 2005; Li et al., 2006). Some tuning procedures are based on optimisation statements (Ge et al., 2002; Toscano, 2005; Åström et al., 1998; Panagopoulos et al., 2002; Rajinikanth and Latha, 2012) and some cases they are solved by means of evolutionary algorithms (Reynoso-Meza et al., 2013b). Recently Multi-objective Optimisation (MOO) techniques have shown to be a valuable tool for controller tuning applications (Reynoso-Meza et al., 2014b,a). They enable the designer or decision maker (DM) having a close embedment into the tuning process since it is possible to take into account each design objective individually; they also enable comparing design alternatives (*i.e.* different controllers), in order to select a tuning fulfilling the expected trade-off among conflicting objectives.

As identified in Arrieta et al. (2011), efforts are particularly concentrated in open loop stable systems; nevertheless some critical processes as continuous stirred tank reactors and bioreactors, common in chemical processing units and biological processes, are unstable open loop systems. Several works have been focused on PID-like controllers tuning for such processes; nevertheless, efforts to merge multi-objective optimisation techniques have been not yet applied for such instances.

In this paper, a simple multi-objective problem statement is defined for unstable first order plus dead time (UFOPDT) processes and compared with existing tuning rules. The remainder of this paper is as follows: firstly in Section 2 it is presented a brief background on PID control tuning, UFOPDT process and multi-objective optimisation. Afterwards, a MOO procedure for is presented in Section 3 and it is compared and validated in Section 4. Finally, some concluding remarks are given.

2. BACKGROUND

In order to describe the tuning approach of this paper, some preliminaries in control tuning, unstable open loop process and EMO are required. They are provided below.

2.1 Background on PID controller tuning and unstable process

A basic control loop is depicted in Figure 1. It comprises transfer functions $P(s)$ and $C(s)$ of a process and a controller respectively. The major aim of this control loop

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is to keep the desired output $Y(s)$ of the process $P(s)$ in the desired reference $R(s)$.

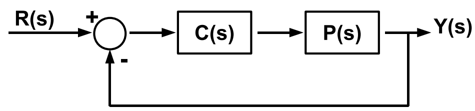

Fig. 1. Basic control loop.

For this work, process $P(s)$ in figure 1 represents a UFOPDT process:

$$P(s) = \frac{K}{Ts-1}e^{-Ls} \tag{1}$$

where K is the process gain; T the time constant and L the time lag of the system. Equation (2) shows the transfer function of the selected structure of the PID controller:

$$C(s) = k_p\left(1 + \frac{1}{T_I \cdot s} + T_D \cdot s\right) \tag{2}$$

where k_p is the proportional gain, T_I the integral time (s), T_D the derivative time (s); this controller will send a control signal to the process, according with the error $E(s) = R(s) - Y(s)$.

The control problem consists in selecting proportional, integral and derivative gains (k_p, $k_I = \frac{k_p}{T_I}$ and $k_D = k_p \cdot T_D$ respectively) for the PID controller $C(s)$, in order to achieve a desirable performance of the process $P(s)$ in the control loop as well as robust stability margins. Conflictive objectives may appear, when seeking for a desirable trade-off between performance and robustness; for this reason, EMO techniques could be appealing for PID controller tuning.

2.2 Multi-objective optimisation statement

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

$$\min_{\boldsymbol{\theta}} \boldsymbol{J}(\boldsymbol{\theta}) = [J_1(\boldsymbol{\theta}), \ldots, J_m(\boldsymbol{\theta})] \tag{3}$$

subject to:

$$\boldsymbol{K}(\boldsymbol{\theta}) \leq 0 \tag{4}$$

$$\boldsymbol{L}(\boldsymbol{\theta}) = 0 \tag{5}$$

$$\underline{\theta_i} \leq \theta_i \leq \overline{\theta_i}, i = [1, \ldots, n] \tag{6}$$

where $\boldsymbol{\theta} = [\theta_1, \theta_2, \ldots, \theta_n]$ is defined as the decision vector with $\dim(\boldsymbol{\theta}) = n$; $\boldsymbol{J}(\boldsymbol{\theta})$ as the objective vector and $\boldsymbol{K}(\boldsymbol{\theta})$, $\boldsymbol{L}(\boldsymbol{\theta})$ as the inequality and equality constraint vectors respectively; $\underline{\theta_i}, \overline{\theta_i}$ are the lower and the upper bounds in the decision space.

It has been noticed that there is not a single solution in MOPs, because there is not generally a better solution in all the objectives. Therefore, a set of solutions, the Pareto set, is defined. Each solution in the Pareto set defines an objective vector in the Pareto front. All the solutions in the Pareto front are a set of Pareto optimal and non-dominated solutions:

- Pareto optimality (Miettinen, 1998): An objective vector $\boldsymbol{J}(\boldsymbol{\theta}^1)$ is Pareto optimal if there is not another objective vector $\boldsymbol{J}(\boldsymbol{\theta}^2)$ such that $J_i(\boldsymbol{\theta}^2) \leq J_i(\boldsymbol{\theta}^1)$ for all $i \in [1, 2, \ldots, m]$ and $J_j(\boldsymbol{\theta}^2) < J_j(\boldsymbol{\theta}^1)$ for at least one j, $j \in [1, 2, \ldots, m]$.
- Dominance (Coello and Lamont, 2004): An objective vector $\boldsymbol{J}(\boldsymbol{\theta}^1)$ is dominated by another objective vector $\boldsymbol{J}(\boldsymbol{\theta}^2)$ iff $J_i(\boldsymbol{\theta}^2) \leq J_i(\boldsymbol{\theta}^1)$ for all $i \in [1, 2, \ldots, m]$ and $J_j(\boldsymbol{\theta}^2) < J_j(\boldsymbol{\theta}^1)$ for at least one j, $j \in [1, 2, \ldots, m]$. This is denoted as $\boldsymbol{J(\theta_2)} \preceq \boldsymbol{J(\theta_1)}$.

To successfully implement the multi-objective optimisation approach, three fundamental steps are required: the MOP definition, the multi-objective optimisation (MOO) process and the multi-criteria decision making (MCDM) stage. This integral and holistic process will be denoted hereafter as a multi-objective optimisation design (MOOD) procedure.

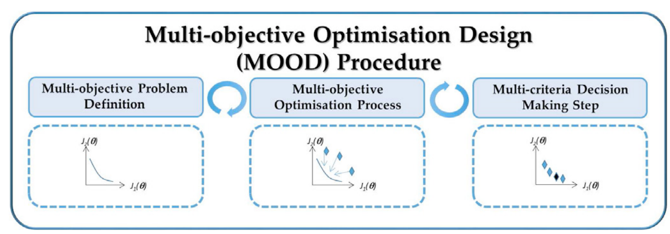

Fig. 2. Multi-objective optimisation design (MOOD) procedure.

Next, this MOOD procedure will be used in order to find suitable PID parameters for UFOPDT processes.

3. MOOD PROCEDURE FOR UNSTABLE SYSTEMS

As commented before, for a successful implementation of the MOOD procedure, the following steps should be carried out: the MOP definition, the optimisation process and the MCDM stage. All of them will be clarified within the PID controller tuning for a UFOPDT framework.

3.1 Multi-objective problem definition

Within this context, the decision variables for the optimisation statement are $\boldsymbol{\theta} = [k_p, T_I, T_D]$. A total of three design objectives will be stated: one related to performance and two related with robustness. In the first case, the settling time $St[s]$ for a step response will be used; in the latter case, the inverse [2] of gain and phase margins, Gm Pm respectively. It is possible to incorporate more design objectives, nevertheless this would lead to which is known as a many-objectives optimisation instance (Ishibuchi et al., 2008). Such instances represent a particular challenge for MOO algorithms, since convergence and spreading capabilities are usually in conflict. This instance will be addressed in a future work, and we will focus on this paper in a multi-objective problem with 3 design objectives.

[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.

[2] in order to use an overall minimisation problem statement.