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Reducing energy costs by optimizing controller tuning

Aidan O'Dwyer
Dublin Institute of Technology, aidan.odwyer@dit.ie

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Aidan O'Dwyer
School of Control Systems and Electrical Engineering, Dublin Institute of Technology, Ireland.

Abstract

The proportional integral derivative (PID) controller is the most dominant form of automatic controller in industrial use today. With this technique, it is necessary to adjust the controller parameters according to the nature of the process. This tailoring of controller to process is known as *controller tuning*. Controller tuning is easily and effectively performed using *tuning rules* (i.e. formulae for controller tuning, based on process information). Such tuning rules allow the easy set up of controllers to achieve optimum performance at commissioning. Importantly, they allow ease of re-commissioning if the characteristics of the process change. The paper outlines the results of recent work in the collation of industry-relevant PI and PID controller tuning rules, which may be applied to a variety of applications with the aim of reducing energy costs. The control of a pilot scale heating, ventilation and air-conditioning (HVAC) plant is detailed as a case study.

1. Introduction

PI and PID controllers have been at the heart of control engineering practice for seven decades. Historically, the first tuning rule for setting up controller parameters was defined in 1934 for the design of a proportional-derivative (PD) controller for a process exactly modelled by an integrator plus delay (IPD) model [1]. Subsequently, tuning rules were defined for PI and PID controllers, assuming the process was exactly modelled by a first order lag plus delay (FOLPD) model [2] or a pure delay model [2], [3].

In general, at commissioning, the PID controller is installed and tuned. However, surveys indicating the state of industrial practice report sobering results. For example, in the testing of thousands of control loops, it has been found that 65% of loops operating in automatic mode produce less variance in manual than in automatic (i.e. the automatic controllers are poorly tuned) [4]. In another interesting study of 150,000 control loops at over 250 industrial sites around the globe, it was shown that 68% of all controllers had unacceptable performance; even the best sites has only 70% of all controllers performing acceptably, while the worst site had 15% of all controllers performing acceptably [5]. Process performance deteriorates when the controller is poorly tuned; this deterioration may be reflected, for example, in increases in energy costs and environmental emissions. The net effect will be an increase in operating costs and a reduction in overall competitiveness.

Thus, there is strong evidence that PI and PID controllers remain poorly understood and, in particular, poorly tuned in many applications. This is surprising, as very many tuning rules exist to allow the specification of the controller parameters. Tuning rules have the advantage of ease of calculation of the controller parameters (when compared to more analytical controller design methods), on the one hand; on the other hand, the use of tuning rules is a good alternative to trial and error tuning. It is clear that the many controller tuning rules proposed in the literature are not having an impact on industrial practice. One reason is that the tuning rules are not very accessible, being scattered throughout the control literature; in addition, the notation used is not unified.

It is timely, therefore, to outline the results of recent work done in the collation of tuning rules, using a unified notation, for continuous-time PI and PID control of single-input, single-output (SISO) processes [6], [7]. Such rules may be specified for processes either without or with a time-delay (dead-time) term. Firstly, a brief summary of how good control can result in a reduction in energy costs is provided. Then, examples of the range of PI and PID controller structures proposed in the literature, together with process models used to define the controller tuning rules, are provided. Subsequently, a case study of the control of a pilot scale HVAC plant is detailed. Finally, conclusions to the paper are drawn. An outline of the tuning rules for setting up PI and PID controllers, for a variety of process models, is available in a recent paper [8]; detailed tuning rule formulae are also available [6,7].

2. Reducing energy costs with good control

The Carbon Trust (www.carbontrust.co.uk) has an excellent series of companion guides, good practice guides and general information reports that consider this topic in detail. On their website, the Carbon Trust declare their role to be "to help the UK move to a low carbon economy by helping business and the public sector reduce carbon emissions now and capture the commercial opportunities of low carbon technologies". In Ireland, Sustainable Energy Ireland (SEI) has a broadly similar mandate.

The Carbon Trust documents make the following points:

1. Improved control (in general) results in energy savings, safety improvements, better environmental performance, consistent product quality, minimises raw materials wastage and reduces manufacturing costs [5], [9], [10]. Typically, good control can reduce raw material and energy costs by between 2% and 6%, with a payback period (for the investment) of less than 12 months [5], [9], [10]; examples from the steel industry and oil refining are outlined [5]. The important point is also made that control is almost the only technology where major enhancements can be made between shutdowns [5].
2. Regarding energy efficiency specifically, the point is made that excessive comfort margins, due to poor control, are major causes of excessive energy consumption; good control can reduce comfort margins and thus reduce energy consumption by 5-15% [5], [9], [10], [12]. In another comment, it is stated that applying modern computing and control techniques can reduce energy costs by at least 10% [13].
3. Good controller tuning is an important component of improved energy efficiency. A table giving priorities for control projects, from an energy saving point of view, is available [5]. Properly tuning controllers is the second most important priority in this table; implementing good controller tuning has nil capital cost and a payback period of hours.

General information reports, how-to guides and case studies illustrating energy efficiency possibilities, using automatic control, are also available. These reports cover:

- Replacing manual control by automatic control [14];
- Using final control elements such as variable speed drives or valves, in control loops [15-21];
- Using advanced sensors and transmitters in control loops [22-23];
- Applying advanced control concepts, such as ratio control [24-25], adaptive and self-tuning control [26-28], expert systems [29-31], model predictive control [32-33], data mining [34-35] and genetic algorithms [36];
- Building services applications [37-38].

Finally, an energy wizard (an interactive energy efficiency guide) is available at http://www.actionenergy.org.uk/energywizard/. One menu on the energy wizard is labelled "Savings via Process Control"; different applications in the chemical industry and in the food and drink industries are considered.

3. Controller architecture and process modeling

A practical difficulty with PID control technology is a lack of industrial standards, which has resulted in a wide variety of PID controller architectures. Seven different structures for the PI controller and forty-six different structures for the PID controller have been identified. Controller manufacturers vary in their choice of architecture; controller tuning that works well on one architecture may work poorly on another. Full details are given in [6], [7]; considering the PID controller, the most common architectures is the 'ideal' PID controller (Figure 1), given by

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{1}$$

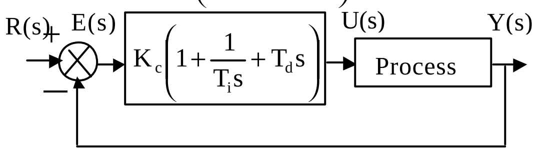


Figure 1. Ideal PID controller in a unity feedback block diagram representation. 276 tuning rules have been identified for this controller structure.

The most dominant PI controller architecture is the 'ideal' PI controller, given by

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s}\right) \tag{2}$$

The wide variety of controller architectures is mirrored by the wide variety of ways in which processes with time delay may be modeled. The most common model is the stable FOLPD model, given by

$$G_m(s) = \frac{K_m e^{-s\tau_m}}{1+sT_m} \tag{3}$$

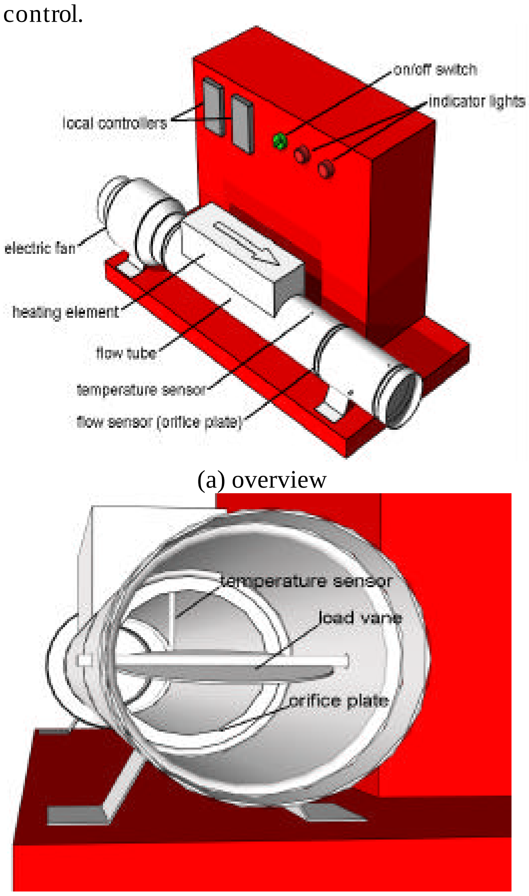
Some 82% of the PI controller tuning rules identified have been defined for the ideal PI controller structure, with 42% of tuning rules based on a FOLPD process model. The range of PID controller variations has lead to a less homogenous situation than for the PI controller; 40% of tuning rules identified have been defined for the ideal PID controller structure, with 37% of PID tuning rules based on a FOLPD process model [7].

Of course, the modeling strategy used influences the value of the model parameters, which, in turn, affect the controller values determined from the tuning rules. Forty-one modeling strategies have been detailed to determine the parameters of the FOLPD process model, for example. Space does not permit a full discussion of this issue; further details are provided in [6], [7].

4. Case study

This section details the control of a pilot scale laboratory heating and ventilation system (VVS-400 product, Instrutek Ltd., Norway). The system is represented in 2x2 multi-input, multi-output (MIMO) form. A process reaction curve identification technique was used to model (in FOLPD form) the flow process and temperature process portions of the system, over a range of operating conditions. Tests revealed that both processes were continuously non-linear. A "gain scheduler" with static decoupling was designed, using look-up tables, to continuously interpolate for the most suitable PI/PID controller settings and decoupler gains.

A three dimensional diagram of the pilot scale heating and ventilation system is shown in Figure 2. An electric fan is located at one end of the tube and blows air over a heating element. The air exits to the surroundings at the other end of the tube. An orifice plate is situated just before the exit (see close up of inside the tube). The differential pressure across the orifice is used to determine the flow rate. A platinum resistance temperature sensor is positioned inside the tube. A load vane provides a method of restricting the airflow at the tube exit. The power supply and other electrical components of the rig are inside the housing. Two independent local controllers for the flow and temperature processes, that have PI/PID and auto-tuning functions, are provided. It is possible to connect directly to the fan and the heating element so that the processes may be controlled via a PC. Not shown are two flick switches that can be used to switch out the local controllers in favour of PC control.



(a) overview

(b) end elevation view

Figure 2: Instrutek VVS-400 laboratory heating and ventilation rig

A static characteristic curve for both the flow and temperature process reveals the non-linearity of both processes. The flow process curve (Figure 3) shows that limits exist on its maximum and minimum operating region. At flows less than 15% of maximum fan voltage setting, very little change in output occurs for a change in input. This is effectively a dead-band region of the flow. The maximum flow rate obtainable is 75%. The figure also shows that the slope of the characteristic curve is greater at high inputs, implying high process model gain at high inputs. The temperature process has an infinite number of characteristic curves, as process behaviour depends on the infinite number of possible flow rates. Characteristic curves at three flow rates were determined (Figure 4). It is clear that the higher the flow rate, the lower the maximum temperature achievable. This is sensible from an intuitive point of view as the cooling effect of the airflow would be greater at high flow rates. At high temperature inputs, each curve tended to level off or saturate; the maximum temperature obtainable is limited by the maximu m power output of the element. Each curve has a lower limit consistent with the ambient room temperature.

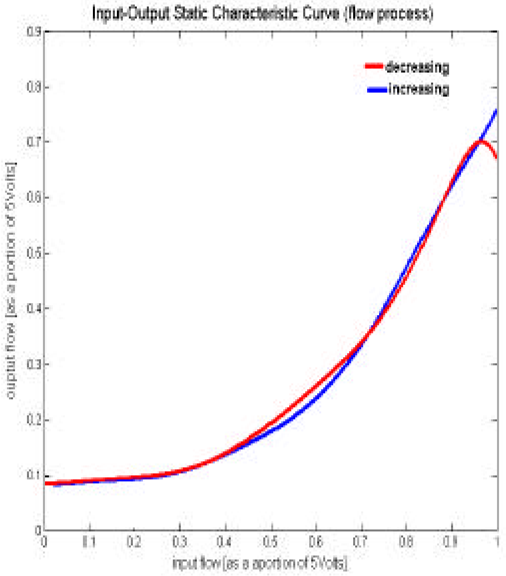


Figure 3: Flow process characteristic curve

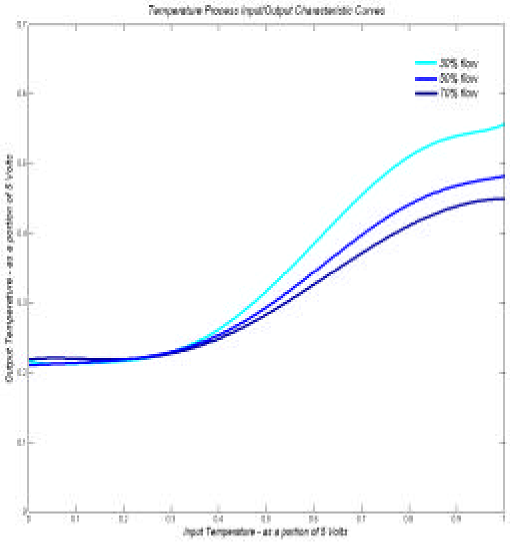


Figure 4: Temperature process characteristic curve

Due to the non-linearity, process models were determined, from the open loop step response of both the flow process and the temperature process, at three operating points for the flow process, and nine operating points for the temperature process (three heater settings at three flow settings). Process modelling, and the decoupling of interacting effects, are treated further in the poster.

PI and PID controllers were chosen to control the processes because of the relatively low time delay to time constant ratio revealed by the identification tests and also because of their wide use in industry and relatively simple implementation. Suitable tuning rules were chosen for these controllers, based on minimising the integral of absolute error (IAE) performance criterion, for both servo and regulator applications [6], [7]. The controllers were specified for each operating point. Closed loop response tests were carried out at particular operating conditions. As examples, servo and regulator performance, when a PI controller is used, for the "medium" flow condition, and separately for the "medium" and "low" temperature condition, at a 30% (low) flow condition, are provided in Figures 5 and 6, respectively (see end of paper). Satisfactory performance is observed. Subsequently, a gain scheduler with static decoupling was designed, using look-up tables; this is outlined in the poster.

5. Conclusions

Control academics and practitioners remain interested in the use of PI and PID controllers. PID controller tuning rules can be directly implemented in a variety of applications i.e. the hardware already exists, but it needs to be optimised. The outcome is directly measurable in reduced energy costs. This paper references work carried out in tuning rule development, further details of which are available [6],[7]. The most startling statistic to emerge from the detailed work is the quantity of tuning rules identified to date; 443 PI tuning rules and 691 PID tuning rules, a total of 1134 separate rules. Recent years have seen an acceleration in the accumulation of tuning rules. In general, there is a lack of comparative analysis regarding the performance and robustness of closed loop systems compensated with controllers whose parameters are chosen using the tuning rules; associated with this is the lack of benchmark processes, at least until recently [39]. In addition, much work remains to be done in the evaluation of controllers designed using tuning rules in a wide variety of practical applications. The main priority for future research in the area should be a critical analysis of available tuning rules, rather than the proposal of further tuning rules.

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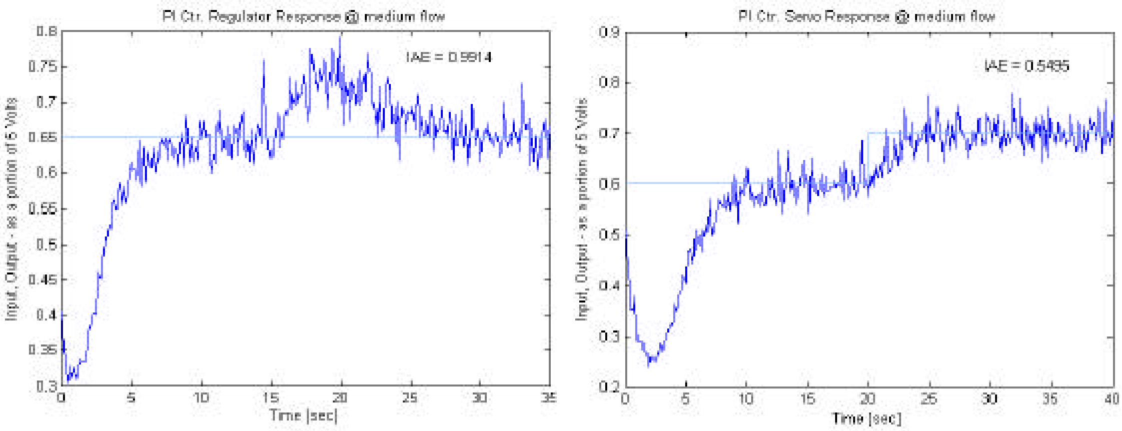

Figure 5: Responses – flow system

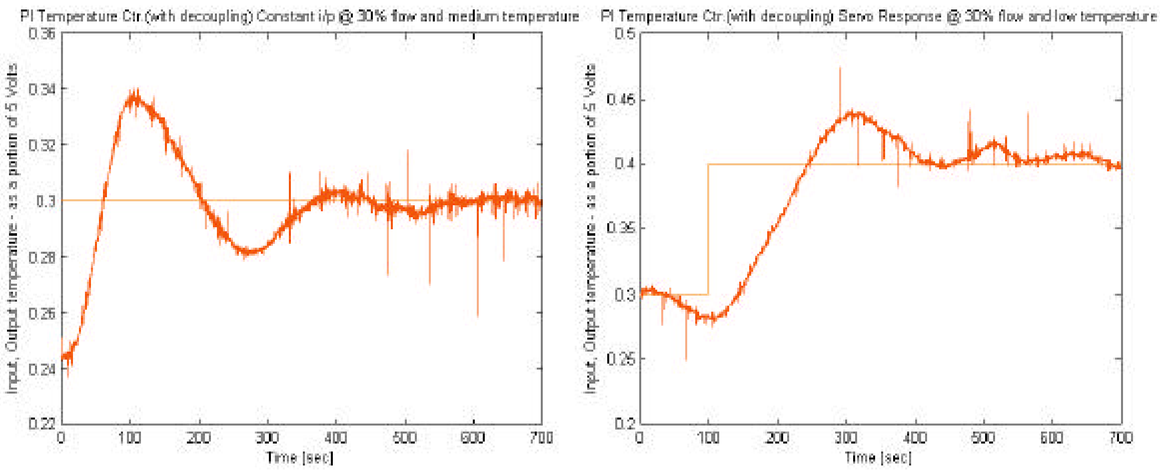

Figure 6: Responses – temperature system (with decoupling)