TOWARDS INTELLIGENCE IN EMBEDDED PID CONTROLLERS

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ABSTRACT

Controllers that possess a higher degree of automation than standard controllers are known as expert or intelligent controllers. This paper describes the development of a low-cost micro-controller based commercial PID controller with a modest level of heuristics combined with logic to provide one-button autotuning, and the ability to flag troublesome plant dynamics which require more sophisticated control algorithms.

KEY WORDS

embedded controllers, relay auto tuners, intelligent control, frequency response identification, pathological plants

1 The need for intelligent control

The motivation for this work to modify a simple low-cost industrial controller to provide auto tuning capability with some intelligence. Intelligence in this context defined as a controller with some of the characteristics listed in [1] as that desirable in an expert controller and the reason is quite simple. The market for this controller is for process control applications in small manufacturing industries where the users are unlikely to have much appreciation of controller tuning. Even with competent staff, [2] has found that not only are the majority of the control loops badly tuned, just over 30% are operate in manual. Hence this controller attempts to provide one-button tuning.

Of course no controller tuning scheme is a panacea to all plants so this research has taken a much more modest approach. Rather than try to tune everything, the controller tries to identify what plants are within an acceptable set, and label the others as 'pathological', and refuse to tune them. This may seem unreasonable, but we believe that it is in the best interests of the operating engineers.

Lee and co workers reported in [3] an expert-based system tuning scheme similar to that proposed in this work. However the framework required, calculations performed, and the substantial hardware requirement mean that their application is really only suitable for a large distributed control system.

The outline of the paper is as follows. The low-cost industrial PID controller and the prototyping environment are introduced in section 2. Section 3 highlights the draw-backs of auto-tuning derived from a single relay experi-

ment. Strategies suitable for simple embedded systems to address these flaws using a second relay experiment are introduced in section 4. The performance is illustrated in section 4.2. Finally some conclusions are presented in section 5.

1.1 A pathological challenge

In a recent general article by the author highlighting the advantages of relay-based tuning, [4], a followup article, [5], laid down a challenge: could relay based tuning adequately deal with a pathological turbine control problem where the governing dynamics are

$$G_5(s) = \frac{0.2(1-s)}{(s+2)(s+0.01)} e^{-2s}$$
(1)

which both exhibits an inverse response and a large span of time constants.

Table 1 lists a further collection of illustrative plants, some of which have been adapted from the collection intended for control benchmarking by Åström and co workers given in [6].

Table 1. A collection of dynamic plants used for testing the PID controller, adapted from [6]. Sample time $T_s = 0.1$ s.

Plants used for Testing	
$G_1 = \frac{2e^{-2s}}{(3s+1)(2s+1)}$	$G_2 = \frac{0.4e^{-0.2s}}{(2s+1)(1.5s+1)}$
$G_3 = \frac{2.5}{(2s+1)^5}$	$G_4 = \frac{0.5e^{-0.1s}}{(s+1)^5}$
$G_5 = \frac{0.2(1-s)e^{-2s}}{(s+2)(s+0.01)}$	

2 The industrial PID Controller and prototyping environment

A low cost embedded PID controller manufactured by Texmate, [7], is shown in Fig. 1. It is based on an 8051 microprocessor and contains 6 independent simple PID controllers, programmable logic functionality, and an interpreted Basic-like macro language. It is this language that was used to extend the PID functionality of the intelligent controller described in this article. The controller is intended for process control applications and operates at a fixed sample rate of 10Hz.



(a) Front panel of the controller



(b) The rear panel showing the analogue and serial signals.

Figure 1. The 8051 based Tiger 380 controller from Texmate.

A parallel project described in [8] improved the basic PID control functionality by providing the provision for a two-degree of freedom controller, methods to improve the discrete implementation of the derivative action, protection against integral windup, [9], and derivative kick. Improvements were also made to how the supervising executive interacts with the controller including bumpless transfer and bumpless parameter changes when adjusting tuning constants.

In the prototyping environment for this application, the various plants (such as those listed in Table 1) are simulated in an external computer fitted with a data acquisition card. This makes it easy to rapidly test a wide range of dynamics, but still subject the controller to a realistic environment such as measurement noise, quantisation errors, controller jitter etc.

Clearly it is impractical to implement a full expert system on such modest hardware as employed in the controller in Fig. 1, but it is possible to implement a scaled down and simplified collection of heuristics for controller tuning.

Flaws of simple relay-based autotuning 3

Relay based autotuning, [10] is a simple, popular and reasonably safe scheme that uses a relay under feedback with amplitude u_m to establish for a given plant the ultimate gain, k_{180} , and oscillation frequency based on the observed output amplitude y_m and frequency. The ultimate gain is given by

$$k_{180} = \frac{1}{|G(i\omega_{180})|} \approx \frac{4u_m}{\pi y_m}$$
(2)

where the ultimate frequency, ω_{180} , is simply the observed frequency. Consequently from this single point on the Nyquist diagram, appropriate PID constants can be derived using the classic Ziegler-Nichols table or the plethora of slight variants thereof such as suggested in [11, p318].

Fig. 2 shows that the 'one-button' tuning-on-demand single relay experiment works as advertised for the well behaved plants from Table 1, and while delivers an adequate controlled response for more challenging plants, exhibits excessive input action partly due to the derivative term.



(b) Time t > 700 seconds showing plants G_4 to G_1

Figure 2. Demonstrating the one-button tuning for plants G_1 through G_4 . At various times the plant is swapped (unbeknown to the controller), and at various other times the relay tuning is initiated. In all cases the relay update algorithm terminates automatically.

However for some plants the simple relay experiment can deliver misleading results. For example the results shown in Fig. 3 for the pathological plant Eqn. 1 under relay feedback indicate immediately that something is amiss. In fact this ugly, un-sinusoidal response is an indication that the plant does not have sufficient low pass filter characteristics, the ultimate gain and frequency estimates will be poor leading to suspect closed loop performance (as subsequently verified in Fig. 6.) While these shortcomings have been investigated at length, (see for example [12, 13]), many of the proposed solution strategies are overly complex or unsuitable for simple embedded systems.



Figure 3. Plant Eqn. 1 under relay feedback. An estimate of the deadtime is given by the difference between $\max(y_m)$ and the last relay switch.

Clearly what is required is some intelligence in the supervisory tuning algorithm based on simple heuristics advising if the plant is suitable for PI or PID control or if a more sophisticated control scheme is required. Candidates such as lambda or IMC tuning, [14], necessitates a process model, but to establish a model, we need additional frequency response points.

4 Two-point frequency response based tuning schemes

There are two favoured simple techniques to stimulate the plant to operate at frequencies other than ω_{180} . One is to cascade a known dynamic element such as an integrator with the unknown plant, and the other is to employ a relay with hysteresis, refer Fig. 4. This application employs the cascaded integrator option and includes an adaptive relay gain in an attempt to try and maintain a reasonable signal to noise ratio over the frequency range of interest. Further details of the adaption scheme are given in [8].

The two relay experiments deliver the four parameters $k_{180}, \omega_{90}, k_{90}, \omega_{90}$ where

$$|G(j\omega_{180})| = \frac{1}{k_{180}} \quad \text{when } \arg(G(i\omega_{180})) = -180^{\circ}$$
$$|G(j\omega_{90})| = \frac{1}{k_{90}} \quad \text{when } \arg(G(i\omega_{90})) = -90^{\circ}$$

from which it is possible to derive first and second order models. However running the relay experiment twice (to generate the two operating points), and the solution of the subsequent nonlinear regression incurs a significant increase in operational complexity, especially when implemented autonomously on simple hardware.



Figure 4. Reconstructing the frequency response of $G_1(s)$ using (a) multiple relay experiments with varying levels of hysteresis, (\Box) , and (b) cascading an integrator, (\triangle) .

The gain of a first order plant model

$$G_1(s) = \frac{K_p}{\tau s + 1} e^{-Ls} \tag{3}$$

is given by

$$K_p = \sqrt{\frac{\omega_{180}^2 - \omega_{90}^2}{k_{90}^2 w_1^2 - k_{180}^2 w_2^2}} \tag{4}$$

from which the time constant and time delay are given by the following, possibly contradictory, alternatives

$$\tau = \frac{1}{\omega_{180}} \sqrt{k_{180}^2 K_p^2 - 1} = \frac{1}{\omega_{90}} \sqrt{k_{90}^2 K_p^2 - 1}$$
(5)
$$L = \frac{1}{\omega_{180}} \left[-\pi + \tan^{-1} \left(\omega_{180} \tau \right) \right] = \frac{1}{\omega_{90}} \left[\frac{-\pi}{2} + \tan^{-1} \left(\omega_{90} \tau \right) \right]$$
(6)

In many practical cases the operators may have partial prior process dynamic knowledge such as the open loop gain. In addition an estimate of the time delay is given by the difference between the "critical" time and the time at the last relay switch, (refer Fig. 3). Combining all this information with the alternatives given in Eqn. 5 and Eqn. 6 will almost certainly lead to contradictions, and it is these contradictions that dictate the suitability of using Eqn. 3 for model based control.

A further drawback of first order models is that while they are easy to fit, they often lead to poor controllers since they do not capture the smooth 'S' curve that is common in most industrial responses, and the limited parameterisation means that some behaviour is not well addressed. With just one extra parameter, we can use second order models with time delay as shown as G_2 in Fig. 5 which rectify many of the above problems, and with the inclusion of yet another parameter we can capture the inverse response of G.



Figure 5. Possible models to fit to an inverse response system. Note that the first order model has the largest time delay.

4.1 Higher order models

Computation schemes to derive second order models in the form of

$$\hat{G}_2(s) = \frac{K_p}{as^2 + bs + 1} e^{-Ls}$$
(7)

are derived in [3] (but with some errors) and are computationally exacting. However simplifications and approximations are possible in the restricted case where the phase lag introduced by the relay and relay plus integrator are -180° and -90° respectively.

In this case the time delay is obtained by solving the nonlinear equation

$$\frac{\sin(L\omega_{180})}{\cos(L\omega_{90})} = \frac{\omega_{180}k_{90}}{\omega_{90}k_{180}} \tag{8}$$

for L. One way to obtain a reasonable starting estimate for any numerical scheme to tackle Eqn. 8 is to approximate $\sin(L\omega_{180})/\cos(L\omega_{90})$ with $\tan(L\bar{\omega})$ where $\bar{\omega}$ is the average of ω_{180} and ω_{90} . This gives an estimate of the delay as

$$L \approx \frac{2 \tan^{-1} \left(\omega_{180} k_{90} / (\omega_{90} k_{180}) \right)}{\omega_{180} + \omega_{90}} \tag{9}$$

Once L is known, either from Eqn. 8 or from schemes assuming first order system such as Eqn. 6, the remaining parameters K_p , a and b in Eqn. 7 can be calculated explicitly.

$$K_p = \frac{\omega_{180}^2 - \omega_{90}^2}{\omega_{90}^2 k_{180} \cos(\omega_{180}L) - \omega_{180}^2 k_{90} \sin(\omega_{90}L)}$$
(10)

$$a = \frac{k_{180}\cos(\omega_{180}L) - k_{90}\sin(\omega_{90}L)}{\omega_{90}^2 k_{180}\cos(\omega_{180}L) - \omega_{180}^2 k_{90}\sin(\omega_{90}L)}$$
(11)
$$k_{180}\sin(\omega_{180}L) \left(\omega_{190}^2 - \omega_{20}^2\right)$$

$$b = \frac{\omega_{180} \cos(\omega_{180}L) \cos(\omega_{180}L)}{\omega_{180} (\omega_{90}^2 k_{180} \cos(\omega_{180}L) - \omega_{180}^2 k_{90} \sin(\omega_{90}L))}$$
(12)

Finally we can extend the model described by Eqn. 7 to include possible non-minimum phase behaviour

$$\hat{G}_{2b}(s) = \frac{K_p(cs+1)}{as^2 + bs + 1} e^{-Ls}$$
(13)

Provided we know the gain K_p *a priori*, and solve again a scalar nonlinear expression for *L*, the remaining coefficients are given by solving the over-constrained system

$$\begin{bmatrix} -\omega_{180}^2 & 0 & \omega_{180} K_p k_{180} \sin(L\omega_{180}) \\ 0 & \omega_{180} & \omega_{180} K_p k_{180} \cos(L\omega_{180}) \\ -\omega_{90}^2 & 0 & -\omega_{90} K_p k_{90} \cos(L\omega_{90}) \\ 0 & \omega_{90} & \omega_{90} K_p k_{90} \sin(L\omega_{90}) \end{bmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix}$$
$$= \begin{pmatrix} -K_p k_{180} \cos(L\omega_{180}) - 1 \\ K_p k_{180} \sin(L\omega_{180}) \\ -K_p k_{90} \sin(L\omega_{90}) - 1 \\ -K_p k_{90} \cos(L\omega_{90}) \end{pmatrix}$$
(14)

Again it is possible to analytically invert the matrix in Eqn. 14, and while the expressions for the parameters are somewhat tedious, they are now in a form suitable for implementation in an embedded system. Furthermore as opposed to the two-point schemes with arbitrary frequencies, this solution procedure for all parameters excepting L is explicit and avoids vector matrix calculations.

4.2 Heuristics

Irrespective of the structure chosen, it is possible to compute simple model characteristics such as the dominant normalized deadtime, τ^* , and normalized gain, κ ,

$$\tau^* = \frac{L}{\tau + L}, \quad \kappa = \frac{|G(i\omega_{180})|}{G(0)}$$
 (15)

which can be used as heuristics to select appropriate tuning decisions such as proposed by [3] or [15]. For example $\tau^* > 0.6$ indicates delay dominance where a deadtime compensator is required, while $\kappa > 0.5$ indicate a lack of sufficient low pass behaviour leading to poor estimates of k_{180}, ω_{180} from the relay experiment. Plants that satisfy either condition can be considered pathological.

Summarising, we have four options (in increasing level of complexity). We could:

- 1. just rely on the basic relay experiment to deliver the ultimate gain and frequency and use that in combination with ZN tuning rules, or
- 2. assuming we know *apriori* the plant gain, we can fit a first order model with 2 parameters, or
- 3. undertake a second relay experiment with an integrator in series allowing us to validate the first-order model, Eqn. 3, or fit a second order model, Eqn. 7, or
- 4. assuming again we know the plant gain, fit a more general second order model, Eqn. 13, that includes inverse responses.

Options (2)–(4) deliver a transfer function model allowing a much more assured controller design approach and deliver some indicators of model uncertainty. The cost in options (3), and particularly (4) is the requirement to solve a delicate nonlinear expression for L that, in most cases, has multiple solutions.

An example of the procedure for the pathological plant of Eqn. 1 is given in Fig. 6 which compares the experimentally derived frequency response from the two-point relay experiment with the true plant. In this case the heuristics rejected all the plant models bar Eqn. 13 which was subsequently used to design an IMC controller.



(a) Frequency response of models \hat{G}_2 (-·), and \hat{G}_{2b} (--), compared to the true plant, Eqn. 1 (solid). The \Box , \triangle indicate the estimated points from the relay experiment.



(b) Ziegler-Nichols (dashed) and IMC (solid) tuning based on a model derived from two relay based experiments.

Figure 6. The frequency based model identification via relay-experiment and subsequent closed loop control of plant Eqn. 1.

4.3 Sensitivity and multiple solutions

Note that the experimentally derived frequency response points on the Bode diagram in Fig. 6(a) are very slightly off despite the lack of structural model/plant mismatch. As it turns out, this error is sufficiently small so that the consequent IMC control is adequate. However it is difficult to establish a reasonable heuristic that defines 'small' in this context.

A further possible problem that is not evident in Fig. 6 is that the algorithm for both $G_2(s)$ and G_{2b} require the solution of a non-convex nonlinear equation for the time delay L. The numerical difficulty of this expression is illustrated by the multiple roots of the curve in Fig. 7(a) which plots the residual as a function of time delay L. Unless the starting estimate is close to the true value of L = 2, it is quite likely that the routine will converge to a spurious root such as $L \approx 4.2$. Such a model (labeled spurious in Fig. 7(b)) does not in fact exhibit an inverse response.



(a) The residual of the nonlinear expression for L. Note that the true value is L = 2, but spurious roots occur at $L \approx 4.2$.



(b) Nyquist plots for the true model, $G_5(s)$, Eqn. 1, the fitted $G_{2b}(s)$ and a model fitted with an estimate of L near the spurious root of 4.2.

Figure 7. Plant under consideration is Eqn. 1.

This is in fact one of the more benign results. For some roots the fitted system is unstable (violating the basic assumption of the relay identification scheme), or worse, converge to a negative value. Note that starting from the estimate of L derived from a lower order model, say a first order model, or even an approximation similar to Eqn. 9 is in fact ill advised because for low order models, L is typically over estimated (refer Fig. 5) encouraging the numerical routine to select the spurious root.

5 Conclusions

While a fully intelligent expert controller requires considerably more hardware than an embedded 8051 microprocessor, it is possible to construct a robust industrial PID controller with single button auto-tuning. The auto-tuner will, if required, establish the frequency response at phase lags of -180° and -90° and identify plant models up to second order with possible non-minimum behaviour. Then depending on possible, *a priori* process knowledge, heuristics derived from the model characteristics, and the magnitude of the discrepancies in the solution to the overdetermined equations of fit, a model structure is proposed, or the system is deemed 'pathological' and flagged as such. IMC tuning is employed if relevant, or modified ZN type lookup rules if only the ultimate gain and frequency is established.

The performance of the controller is demonstrated experimentally for a variety of benchmark plants including a challenging turbine control problem. The latter indicates that under optimal conditions, the controller delivers good results, but the identification phase is extremely sensitive, and small errors or a poor initial estimate of the deadtime can render the problem pathological.

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