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Research Article

Pole-placement Predictive Functional Control for over-damped systems with real poles

J.A. Rossiter [a,*], R. Haber [b], K. Zabet [b]

[a] Department of Automatic Control and Systems Engineering, University of Sheffield, S1 3JD, UK
[b] University of Applied Science Cologne, Department of Plant and Process Engineering, D-50679 Kln, Betzdorfer Str. 2, Germany

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ABSTRACT

This paper gives new insight and design proposals for Predictive Functional Control (PFC) algorithms. Common practice and indeed a requirement of PFC is to select a coincidence horizon greater than one for high-order systems and for the link between the design parameters and the desired dynamic to be weak. Here the proposal is to use parallel first-order models to form an independent prediction model and show that with these it is possible both to use a coincidence horizon of one and moreover to obtain precisely the desired closed-loop dynamics. It is shown through analysis that the use of a coincidence horizon of one greatly simplifies coding, tuning, constraint handling and implementation. The paper derives the key results for high-order and non-minimum phase processes and also demonstrates the flexibility and potential industrial utility of the proposal.

1. Introduction

Predictive functional Control (PFC) has been very successful in industry (e.g. [1,2]) and yet surprisingly received very little interest in the academic literature [3,10,11,15]. A likely reason for this is that researchers in predictive control have focussed on proofs of issues such as guarantees of stability [6,18] and feasibility, robust stability [4], parametric methods [7] and more recently robust feasibility in the presence of bounded disturbances [9]. It should be noted that PFC techniques are much simpler to code and implement than conventional predictive control methods [3,8,15] and thus PFC is best viewed as an alternative to PID or other low level control law where the cost per control law is necessarily small but nevertheless one may desire attributes such as systematic constraint handling. PFC allows systematic as opposed to ad hoc constraint handling and thus is often preferred to PID approaches for scenarios where constraint handling is challenging. Clearly comparisons with conventional predictive control such as Dynamic Matrix Control are not appropriate as those, by definition, can give better performance, but of course at much higher cost.

A main selling point of PFC is that the design is done by choosing a target behaviour (equivalently closed-loop pole/time constant). If there is a strong link between the user choice and the behaviour that results, this is an intuitive and easy design technique, as compared to say PID. Moreover, PFC has a critical advantage over PID approaches, that is, constraint handling can be embedded systematically and with minimum coding/computation. However, the literature has given little attention to theoretical a priori guarantees of stability, feasibility or robustness for PFC; of course some results do exist [12,17] and industrial users always do practical assessments. This paper seeks to redress the balance slightly by demonstrating some useful new theoretical results for PFC which also extend the efficacy of tuning of the approach.

1.1. Background on PFC

A conventional PFC has two tuning parameters: the position of the coincidence point in the future (the coincidence horizon) and the desired settling time $t_{95\%}$, also called TRBF. It is implicitly assumed that the closed-loop response will become approximately first-order with the target settling time, although in fact this can only be assured if the coincidence horizon is one.

For higher-order aperiodic processes it is common to recommend the coincidence point to be near to the inflection point of the process step response [11], which is the place of maximum

* Corresponding author.
E-mail addresses: j.a.rossiter@sheffield.ac.uk (J.A. Rossiter), robert.haber@fh-koeln.de (R. Haber).

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value of the impulse response. The idea is based on the fact that at this point, the manipulated variable change has maximum effect. However, in such a case the actual settling time will often not match the desired settling time t_{95} so tuning becomes more challenging as the direct link between designer choice and effect is lost. One reason is that in case of higher-order processes, the closed-loop response will not approximate a first-order response closely and hence the relation to the settling time is not straightforward [16].

1.2. Paper contributions

This paper will propose an alternative way to tune PFC for systems with real poles. It will be shown that within the proposed PFC design, the closed-loop poles can be selected as free parameters and this is a major advance on conventional PFC where only the slowest closed-loop pole is selected by defining the settling time and even that requires some trial and error and has no guarantee of what is achievable. It is interesting to note that the proposed method, in the unconstrained case, has some equivalence with pole placement design, but a critical point is that it is still based on prediction and allows systematic constraint handling which is not the case for pole-placement designs! It is also noteworthy that the proposed PFC method works with a coincidence horizon of just one, which is contrary to the conventional advice with classical PFC and also enables a significant reduction in computing complexity.

Section 2 gives some background on PFC concepts, a conventional law and demonstrates the tuning challenges. Section 3 introduces the proposed pole placement PFC approach for second-order systems along with some analysis of the properties. Section 4 then generalises the approach to higher-order models and emphasises the additional degrees of freedom which enable more flexible tuning. The paper finishes with numerous examples which demonstrate the attributes of the proposed algorithm and how these compare with conventional PFC.

2. Background information on PFC

2.1. Target behaviour

PFC is based on the assumption that it is realistic to achieve closed-loop behaviour close to a first-order system with a delay τ (or h samples), time constant T_r and unit gain, for example:

$$r^*(s)=\frac{e^{-s\tau}}{T_r s+1}r(s);\quad r^*(z)=\frac{z^{-h}(1-\lambda)}{1-\lambda z^{-1}}r(z) \tag{1}$$

where $r(s)$ and $r^*(s)$ are Laplace representations of the reference signal and reference trajectory respectively and $r(z)$ and $r^*(z)$ corresponding to z-transform representations. In the following the reference signal is taken to be a step of amplitude r. A typical desired step response, with no delay, is plotted in Fig. 1 where the pole is set at $\lambda=0.8$ and the sample period is $T=1$. Equivalently, industrial users use the notation of target closed-loop response time (CLTR), that is about 3 time constants, where $\lambda=e^{-T/T_r}$ with T being the sample period and $T_r=CLTR/3$.

2.2. Coincidence point and degrees of freedom

Assuming the desired closed-loop behaviour is 'known' (as illustrated in Fig. 1), then the objective is for output predictions $y_p(k+i|k)$ (the predicted value of y_p at sample $k+i$ with prediction made at sample k) to follow this target exactly. Assuming a non-zero initial condition of $y_p(k)$, a first-order response with a known asymptotic value r and decay rate λ can be written down explicitly as follows:

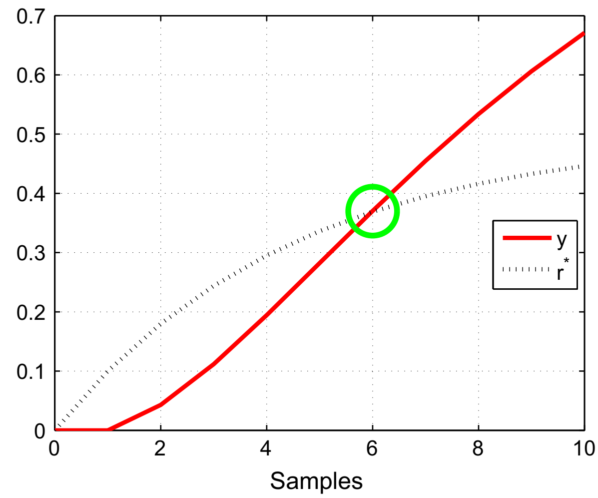

Fig. 1. Target step response $r^*(z)$ with pole of 0.8 and illustration of coincidence with output prediction y at a coincidence horizon of 6.

$$y_p(k+i|k)=r-[r-y_p(k)]\lambda^i;\quad i>0 \tag{2}$$

PFC is not able to make all future predicted output values satisfy (2) and so instead chooses a single sample instant in the future, the so-called coincidence horizon n_y, and ensures that the output prediction matches the target response (2) at that point only (as illustrated in Fig. 1 for $n_y=5$). Consequently the PFC law reduces to (conceptually), enforcing the single equality:

$$y_p(k+n_y|k)=r-[r-y_p(k)]\lambda^{n_y} \tag{3}$$

In order to manipulate the predictions, some degrees of freedom (d.o.f.) are needed and these are conventionally the values of the future inputs, $u(k), u(k+1), \ldots$. Within PFC, the coding and computation requirements are deliberately very simple and thus, the predicted future input is taken to be a constant, that is:

$$u(k)=u(k+1|k)=u(k+2|k)=\cdots \tag{4}$$

Thus the only d.o.f. is the proposed value $u(k)$.

Remark 1. The target behaviour (2) and control law requirement (3) can be coded by inspection. Where the system has a delay 'h', the target behaviour should be modified slightly to:

$$y_p(k+n_y+h|k)=r-[r-y_p(k+h|k)]\lambda^{n_y-h}.$$

The reader will note that both output terms are based on values h samples further ahead.

A potential weakness of PFC is the simplicity of control law (3). The user needs to be sure that matching a single point implies the rest of the response is also closely matched to the target behaviour. It has been shown [11,16] that this is the case for first-order systems only. Hence this paper proposes a modified PFC algorithm, such that the result can be extended to some higher-order systems where common understanding is that the best value for n_y can only be found by trial and error (and indeed that assumes a good choice exists). It is notable that for non-minimum phase systems it is intuitively obvious that n_y must be greater than the time of the inverse response part but how much greater is not obvious. This paper shows how such a requirement can be avoided thus enabling more systematic tuning.

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