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Dynamic Transfer among Alternative Controllers

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Abstract. Advanced control strategies and modern consulting provide new challenges for the classical problem of bumpless transfer. It can, for example, be necessary to transfer between an only approximately known existing analogue controller and a new digital or adaptive controller without accessing any states. Transfer ought to be bi-directional and not presuppose steady state, so that an immediate back-transfer is possible if the new controller should drive the plant unstable. In this paper we present a scheme that meets these requirements. By casting the problem of bi-directional transfer into an associated control problem, systematic analysis and design procedures from systems theory can be applied. The paper includes laboratory and industrial applications.

Key Words. Bumpless Transfer, Industrial control.

1. INTRODUCTION

1.1 Motivation

The issue of avoiding process upsets during transfer among alternative controllers, also called bumpless transfer, was one of the imminent questions addressed by early control theory. It is therefore not surprising that there is a large number of reported schemes in the literature and it is tempting to consider the problem solved.

In this paper, however, we draw attention to the fact that there is a new role for bumpless transfer in modern consulting. In particular, we consider the scenario where there is an *existing* industrial control loop and a newly designed controller is to be *temporarily* installed and tested during normal plant operation. The existing regulator could, for example, be an analogue PI controller and the new regulator might be a high-order digital controller designed by criterion optimisation.

This scenario has certain implications for a suitable bumpless transfer strategy:

- It should be bi-directional, that is, it should be possible to swap the new controller both in and out of the existing loop to conduct temporary performance analysis.
- It should require minimal plant modifications in order to make testing of new designs as convenient and feasible as possible; in particular, it should not presuppose the existing controller to be in observer or velocity form and it should not require explicit manipulation of the controller states. This would be difficult or impossible if the existing design is analogue.
- It should not require steady state operation, since the new controller might, inadvertently, drive the loop unstable and require immediate back-transfer to the original controller in spite of wild transients.
- It should be sufficiently robust to handle inaccurately known controllers which, rather surprisingly, is a common problem in existing industrial processes.
- It should be able to transfer between analog and digital, fixed and adaptive, or low- and high-order controllers.

To meet these objectives, the basic idea of our proposal is to treat the idle, or latent, controller itself as a dynamic system and force its output to track the active controller with help of a tracking loop. This recasts bumpless transfer into an associated tracking problem to which systematic analysis and design theory may be applied.

1.2 Review of Previous Work

The majority of early investigations are controller, implementation and problem specific. Typical assumptions include a PID controller architecture, particular analogue or digital hardware, and the explicit objective to switch between manual and automatic control, frequently presupposing steady state.

More recent research efforts are characterised by increasingly general and theoretically founded frameworks. They are usually concerned with the effects of various nonlinearities operating on the controller output (Fig. 1.1), which allows a unified treatment of windup and bumpless transfer. Beside the survey paper by Hanus (1988), we also mention the following three approaches.

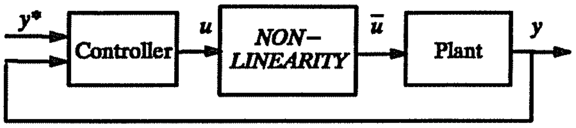

Fig. 1.1: Common Framework for analysing windup and bumpless transfer

In the notation of Fig. 1.1, the observer based approach suggested in Åström and Wittenmark (1984) relies on an explicit observer to assure convergence of the controller output u to the actual system input $\bar{u}$. If the nonlinearity is a saturation, this strategy avoids integral windup. By considering a time varying saturation in which both upper and lower limits are set to the current value of a manual or alternative control signal, bumpless transfer is achieved.

The conditioning technique (Hanus 1980, Hanus et al 1987) is based on a back calculation that translates limitations on the system input $\bar{u}$ to limitations on the reference signal y^*; implicitly, these limitations then define a domain of achievable reference signals. By projecting the actual reference into the achievable domain, anti–windup and bumpless transfer is achieved.

Finally, the general framework described in Campo et al (1989) includes both of the above and other methods, including the one proposed in this paper, as special cases. It provides an excellent formalism for comparison and stability analysis of various alternatives. It is, however, not immediate how to exploit this framework for actual synthesis.

2. ROBUST BI–DIRECTIONAL TRANSFER

2.1 *Bumpless Transfer as Control Problem*

For the sake of clarity, the following discussion considers transfer among two SISO, one degree of freedom controllers. Extensions to two degree of freedom and MIMO controllers, as well as transfer among n alternative controllers, are straight forward.

Consider the diagram of Fig. 2.1, where

$$G = \frac{B(s)}{A(s)} \tag{2.1}$$

is a plant currently controlled by the active controller C_A.

The bold lines show the active closed loop

$$y = \frac{C_A\, G}{1 + C_A\, G}\, y^* \tag{2.2}$$

and the regular lines make up an additional feedback loop governed by

$$u_L = \frac{T_L C_L F_L}{1 + T_L C_L} u_A + \frac{C_L}{1 + T_L C_L}\,(y^* - y) \tag{2.3}$$

Clearly, (2.3) describes the configuration of Fig. 2.2, where the latent controller C_L takes the role of a plant whose output u_L is forced to track the active control signal u_A by means of the two degree of freedom controller $(T_L\,,\, F_L)$.

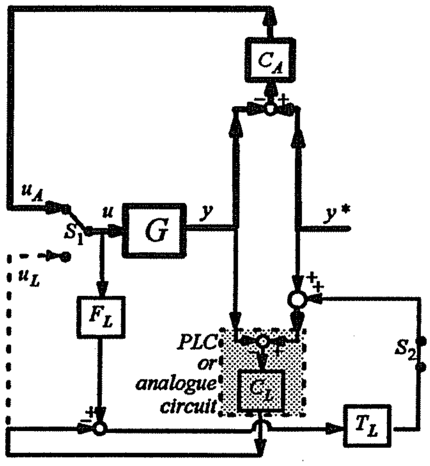

Fig. 2.1: Half of the bumpless circuit diagram. The plant is controlled by the active controller C_A, and the latent controller C_L is forced to track the active signal u_A by the tracking controllers. If the switches are activated, control is bumplessly transferred to C_L. Complementing the diagram with the symmetrical other half, allows bi–directional transfer.

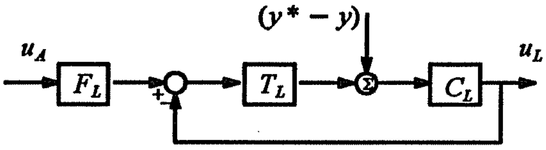

Fig. 2.2: Tracking loop with latent control u_L tracking the active control u_A. The plant control error acts as disturbance.

The control problem associated with bumpless transfer, then, is the design of the compensators (T_L, F_L) to guarantee a certain tracking bandwidth in spite of noise and controller uncertainty. Within this bandwidth, the controller outputs track each other and robust transfer is therefore achieved. Clearly, transfer becomes bi–directional by adding a symmetrical second tracking loop to the configuration. Note that transfer is achieved without accessing any of the controller states. The only signals required are the control signal, the plant output, and the possibility to add a signal into the setpoint. Observe that the tracking signal is added into the setpoint, which is available, rather than into or after the summation junction between y^* and y, which might be implemented in an analogue circuit or programmed into a PLC.

2.2 *Relation to Previous Work*

Compared to the observer based technique of Åström and Wittenmark (1984), the proposed scheme does not presuppose the existing controller to be in a particular form.

The conditioning technique of Hanus (1980) also manipulates the reference signal to for tracking, but the required signal is computed from exact knowledge of the controllers, whereas our scheme utilises feedback to achieve robust tracking in spite of noise and controller uncertainty.

Uram (1971) proposed a special case of our scheme in which $T_L = k/s$ for all controllers, a choice sometimes implemented in industrial loops and termed 'high gain conventional anti–windup' in Campo et al (1989). For simple controllers, such as the PI controller mentioned below, this is certainly a feasible choice. The advantage of our generalisation, however, is that it provides additional degrees of freedom in more complex situations that involve trade–offs between tracking bandwidth, control saturations, limitations due to the given sampling rate and uncertainty.

2.3 *Issues of Tracking Controller Design*

In principle, tracking controllers can be designed by any method desired. There are, however, a few issues that must be kept in mind, notably the fact that the "plant" of the tracking loop, that is the latent controller, will usually be open–loop unstable due to an integrator and it will frequently also contain saturations; see, e.g., Goodwin et al (1993) for the design of internal model controllers for systems with saturating actuators.

The following expressions are useful for the most common industrial case, namely the one where the existing controller is of PI type:

$$C_L = \frac{Ps + I}{s} . \qquad (2.4)$$

In that case, a tracking controller consisting of a PI controller in series with a low–pass filter suffices:

$$T_L = \frac{a_1 s + a_0}{(\beta_1 s + \beta_0) s} , \qquad (2.5)$$

with feedforward filter

$$F_L = \frac{\omega_n^2}{P a_1 s^2 + (P a_0 + I a_1) s + a_0 I} \qquad (2.6)$$

where

$$a_1 = \frac{1}{I} \left[(\gamma - \frac{P}{I}) \, \omega_n^2 + 2\zeta\omega_n \right] , \qquad (2.7)$$

$$a_0 = \frac{\omega_n^2}{I} , \quad \beta_1 = \gamma , \qquad (2.8)$$

$$\beta_0 = 2\zeta\omega_n\gamma + 1 - P a_1 \qquad (2.9)$$

yields a closed loop of

$$u_L = \frac{\omega_n^2 \, u_A \; + \; (Ps + I)(\beta_1 s + \beta_0) s \, e}{(s^2 + 2\zeta\omega_n s + \omega_n^2) \, (\gamma s + 1)} , \qquad (2.10)$$

where $e = (y^* - y)$ is the plant control error. Hence, given the PI controller (2.4), equations (2.5)–(2.10) allow convenient tuning of the tracking bandwidth and relative damping by means of γ and ζ. Note, that it was necessary for the tracking controller (2.5) to contain an integrator in order to reject the plant control error from the tracking loop; alternatively, one could also use feedforward from e, but this is usually rather implementation dependent and might not be worth the effort.

3. APPLICATIONS

3.1 *Laboratory Scale Application*

In this section we present a laboratory scale application to demonstrate bumpless transfer during transients and fast recovery after closed loop instability. The process is a 500kW diesel generator that was simulated on an analogue simulator with a transfer function given approximately by

$$G = \frac{356}{s^2 + 18.1 s + 356} \; \frac{15.9}{s^2 + 16.1 s + 7.3} \qquad (1.1)$$

where the first transfer function models the actuating servo and the second transfer function models the diesel generator. A controller given approximately by

$$C_1 = \frac{0.22 s^2 + 2.22 s + 1}{0.22 s^2 + 1.33 s} \qquad (1.2)$$

was also implemented on the analogue simulator. Then the alternative controller

$$C_2 = \frac{14.4 s + 1.6}{s} \qquad (1.3)$$

together with the proposed bi–directional transfer scheme, was configured on the implementation platform UNAC (Godfrey et al 1992). Note that C_2 is deliberately designed to drive the closed loop unstable. Fig. 3.1 shows the closed loop step response as control is transferred from the stable to the unstable compensator and back. The closed loop is immediately stabilised

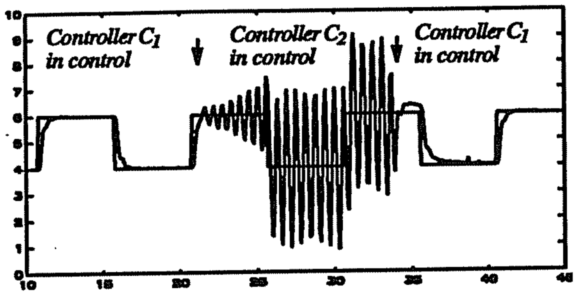

Fig. 3.1: Transfer between closed loop stable & unstable controller

once C_1 is back in control, because the unstable control signal generated by C_2 is merely a reference signal to the tracking loop of C_1; therefore the states of C_1 are not wound up when transfer occurs and the loop is stabilised with the dynamics generated by C_1.

This example demonstrates the safety that the proposed scheme adds to the test of newly designed controllers: if they should, inadvertently, cause unacceptable oscillations, an immediate back transfer is possible. The extended period in unstable operation in Fig. 3.1 is merely for demonstration purposes.

3.2 *Industrial Application*

In this section we demonstrate an industrial application in which a newly designed controller, implemented on the UNAC system (Godfrey et al 1992), was transferred to a continuous bloom caster; the details of the trial are given in Graebe et al (1992). The application required the digital control of a valve to regulate the level of molten steel in a mould. The existing controller, only approximately known, produced the oscillations seen in the middle of Fig. 3.2B. The cause of these unwanted oscillations was determined to be slip–stick friction in the valve and a newly designed controller including dither was to be tested during normal operation. Fig. 3.2A shows the two control signals tracking each other, while Fig. 3.2B shows the graceful transfer between the existing and the newly designed compensators.

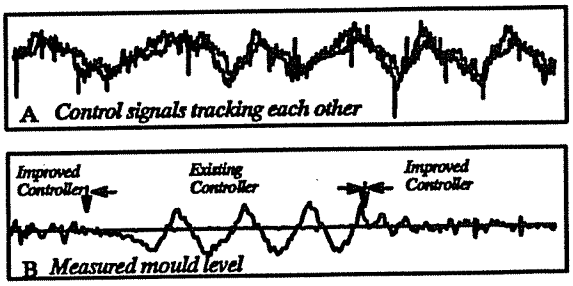

Fig. 3.2: Industrial application of bi–directional transfer

This example demonstrates a situation in which a newly designed controller is to be swapped temporarily and on–line against the existing controller which is only approximately known, not in observer form and inherently not in steady state. The safety and convenience of the proposed scheme helps to convince plant operators to approve of such trials.

4. CONCLUSIONS

Modern consulting has generated new challenges for the classical problem of bumpless transfer. In particular, we have highlighted the need for bi–directional robust transfer among analogue and digital controllers without accessing their states or presupposing steady state. We have shown that this can be achieved by considering the latent controller to be, itself, a dynamical system that is controlled by a tracking controller. The tracking loop uses the active control input to the plant as a reference signal that the latent controller is forced to track. This recasts the problem of bumpless transfer into a control problem to which systematic design theory can be applied. A simulation example confirmed that the method can indeed achieve fast recovery from a loop that has accidentally turned unstable, and an industrial application further shows the practical utility. Since development of this scheme, its convenience and safety improvement has become a key feature of several industrial projects.

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