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Research article

# Set-point manipulation approach towards online performance improvement in existing process control loops

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## ARTICLE INFO

## Article history:

Received 26 July 2016

Received in revised form

26 April 2017

Accepted 1 July 2017

## Keywords:

Set-point manipulation

Closed architectural controller

Integral windup

Gain scheduling

Distributed control system

PID

## ABSTRACT

The majority of current industrial process control systems are based on PID control. However, in many of these systems, once the initial setup has been carried out, it is difficult to implement subsequent continuous improvements on the control performance without shutting down the production and disarming the overall system to retrofit alternative controllers. These measures to integrate additional instruments for allowing such flexibility incur heavy costs in terms of time and resources. In this paper, we propose an approach towards achieving the control adaptations which cannot be achieved easily with an existing closed-architectural system. The approach leverages on a set-point manipulation mechanism which allows a virtual modification of the closed-architectural system. In this way, process performance of existing plants can be continuously improved without the need to continuously alter the existing closed loop system. The implementation of the proposed configuration is illustrated with respect to a PID controller although the framework proposed is amenable to higher order controller as well. Simulation examples and experimental results are furnished to show the motivation for such an approach and the improved performance achievable with the proposed approach.

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## 1. Introduction

Proportional-Integral-Derivative (PID) control is generally a popular form of control for applications with modest control specifications and they can be found in a wide and diverse range of applications such as, but not limited to, process control, automotive, flight control, and factory automation. PID controllers can be combined with logic, sequential machines, selectors, and function blocks to build complicated automation systems such as those used for energy production, transportation, and manufacturing. On top of that, many sophisticated control strategies, such as model predictive control, are also organized hierarchically based on PID control. The main reasons for its success are its simple structure, which is easy to be understood by the engineers, and reliability under practical conditions, which ensures consistent performance compared to other advanced and complex controllers. It has remained true that PID controllers are by far the most dominating form of controllers in use today, comprising more than 90% of industrial controllers. [1].

Driven by its simplicity and popularity, PID control has been the de-facto industrial standard for many years. Automation

equipment and instruments are often provided together with built-in PID control in proprietary and closed architectural forms so that the users and customers do not have to deal with them separately. Furthermore, majority of process control loops have been implemented as PID feedback control systems. These closed-loop systems often restrict the users to input fixed control gains and the reference signals. Modification of control strategy in these closed-loop systems for process improvement typically requires physical alterations such as controller replacements and additional instrument installations, which are not desired or even viable for process plants in continuous production. Two examples of such scenarios arising would be 1) the need to bundle additional anti-windup mechanism for the integral control action and 2) the flexibility to adapt control gains on the fly when faced with process parameter changes or incorporating of additional processes into existing plants.

Among the twos, integral windup commonly occurs due to control input limitation and saturation nonlinearity of the physical systems. When windup steps in, the performance of the closed-loop system significantly deteriorates yielding a larger overshoot, slower settling time and lower stability [2–5]. Thus, anti-integral-windup mechanisms (AIWM) are necessary to counter this phenomenon. Built-in PID controllers and existing process plants may or may not have an AIWM provided. When they are not equipped with an AIWM, anti-windup can be mediated with a low integral control gain. Even if they are equipped with AIWM, there are

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different types of AIWMs and each strives in a specific situation. Thus, the AIWM provided may not be always suitable for the actual application and changes to the AIWM configuration parameters have to be done continuously to retain it, or an alternate one has to be employed, which cannot be easily done with a closed framework.

Control gains need to be adapted to changes in dynamics of the plant to achieve acceptable performance, and such changes are inevitable with a time varying or nonlinear plant. This is often done through a gain scheduling table, for cases when the changes are predictable, and via a general adaptive control, when the changes are not as structured [6,7]. Either case will warrant changes to the control gains synchronously with the dynamic changes in the plant. Additionally, recent proposed control strategies such as [8–10] can significantly improve control performance. However, these are difficult to achieve in a closed-setup in which the initial system design allows only fixed gains to be assigned.

These scenarios are cumbersome to handle in a closed-loop control system without shutting down the production and disarming the overall system to retrofit alternative controllers. Moreover, these measures to integrate additional instruments for allowing such flexibility incurs heavy costs in terms of time and resources. In this paper, we propose an approach towards achieving the control adaptations which cannot be achieved easily with an existing closed-architectural system. The approach leverages on a set-point manipulation mechanism in which the system is designed such that a virtual modification of the existing closed-architectural system becomes feasible. In this way, process performance of existing plants can be continuously improved without the need to continuously alter the existing closed loop systems. Moreover, there are other potential applications as well for this approach, such as realizing a high order controller, a signal processing filter, or fuzzy logic controller [11] on top of the existing closed-loop control.

Next section of this paper focuses on reviewing different types of AIWMs, followed by a detailed illustration of the proposed approach. The configurations to integrate different types of AIWMs as well as to incorporate gain scheduling system through the proposed approach are demonstrated afterwards. Simulation results of these configurations on closed-architectural control systems are furnished to show the effectiveness of the proposed approach. A real-time implementation of the approach on a distributed water-tank system is provided as well to demonstrate its wide range of applicability.

## 2. Review of anti-integral-windup mechanisms

Many AIWMs have been introduced in the literature and majority of them can be categorized into three different kinds: conditional integration, back tracking calculation, and limited integrator schemes [12]. In conditional integration schemes [13–15], the integral action is suspended and only the PD control is activated when control input is saturated. In back tracking calculation schemes [2,16–19], the difference between the saturated and unsaturated control input signals is used to generate a feedback signal to moderate the integrator's output. In limited integrator schemes [20], the integrator value is limited with a high-gain dead zone to ensure operation in the linear range.

Limited integrator schemes are not commonly used, especially in built-in controllers, as they are not amenable to general usage [21]. Back tracking calculation and, especially, conditional integration schemes are more commonly found in these built-in controllers. But even under the commonly used conditional integration schemes, there are four main types.

- 1) Type A: the integral term is limited to a predefined value.
- 2) Type B: The integration is stopped when the error is greater than a predefined threshold.
- 3) Type C: The integration is stopped when the control variable saturates.
- 4) Type D: The integration is stopped when the control variable saturates and the control error and the control variable have the same sign.

As there is no single AIWM which fits all situations, the mechanism provided in a built-in controller may not be suitable for the actual process. Replacing one with another more suitable mechanism is then required and this is not a simple task in a closed-form control system. Even if the mechanism is suitable for the nominal plant, process model variation can happen either due to process modification or due to nonlinearities and disturbances occurring over time. As a result, parameters such as the predefined value, the threshold, and the maximum output allowable need to be updated continuously on the fly.

## 3. Proposed configuration and approach

Consider a general closed-loop control system in Fig. 1, using a built-in controller  $G_C = G_{C1}G_{C2}$  (shown in the dotted box) to control the process  $G_P$ . The symbols ( $r$ ,  $w$  and  $y$ ) represent the set-point, the disturbance and the process variable respectively. Off-the-shelf controllers often are bundled both the controller  $G_C$  and process  $G_P$  together as single entities. The controller will typically receive as user inputs the set-point ( $r$ ) and a set of fixed control gains.

In Fig. 1, the closed-loop transfer function between  $y$  and  $r$  is given by (1) and the closed-loop transfer function between  $y$  and  $w$  is given by (2)

$$G_{yr} = \frac{G_{C1}G_{C2}G_P}{1+G_{C1}G_{C2}G_P} \quad (1)$$

$$G_{yw} = \frac{G_P}{1+G_C G_P} \quad (2)$$

To allow control adaptation in closed architectural control system, a new control configuration is proposed as shown in Fig. 2.

The part of the controller in the dotted box can be thought as a set-point manipulator transforming the original set-point  $r$  into a new one  $\bar{r}$  for the controller  $G_{C1}$  which directly manipulates the process. The closed-loop transfer functions between  $y$  and inputs ( $r$  and  $w$ ) can be shown to be

$$G_{yr} = \frac{G_{C1}G_P(\bar{G}_C+1)}{1+G_{C1}G_P(\bar{G}_C+1)} \quad (3)$$

and

$$G_{yw} = \frac{G_P}{1+G_C G_P} \quad (4)$$

Thus, it can be observed that the proposed control configuration in Fig. 2 is equivalent to the closed-architectural control of Fig. 1 in terms of the closed-loop relationships only if (5) is valid.

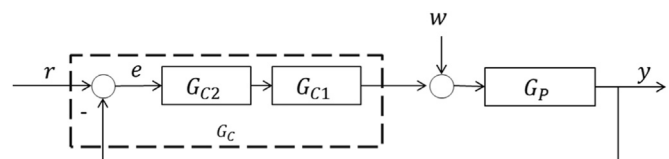


Fig. 1. Block diagram of closed-loop control system with built-in controller.

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