Student name: Karol Herta
Student number: 079099561
Supervisor: Dr. Damian Giaouris
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Literature review

‘Plug and control’: adaptive PID controller for industrial applications

University of Newcastle upon Tyne
School of Electrical, Electronic and Computer Engineering

Abstract — This literature review gives an overview of the PID control system analysis, technology and design methods with the focus on a practical implementation. The controversial but highly productive derivative action proves itself to be implementable despite sensor noise and long time delays within a plant. A need for a four-parameter-design with an additional filter constant parameter arises within this context. A selection of the four-parameter-tuning methods gives a fundamental base for a possible future controller design. Furthermore, the well-known performance limiting windup phenomenon is here exposed and some remedies techniques are discussed. It is shown, that an extension of the typical controller to a two-degree-of-freedom architecture may results in an improved set-point following performance. Finally, a general overview of the existing adaptive control methods used within the PID control scheme and their practical implementation problems are given to the reader. The superiority of the relatively new ‘plug and control’ self-tuning method, with respect to the well-known and widely used in industrial applications auto-tuning method, is demonstrated. After the recapitulation of the reviewed design methods, a number of ideas toward the design of a new ‘plug and control’ adaptive PID controller for a wide range of industrial application are introduced.

I. Introduction

MORE then 90% of the controllers implemented in industrial applications are based on the well-know proportional-integral-derivative (PID) control concept [1]. Between 1970 and 2002, around 64 patents on PID tuning have been registered and this just in the United States. Analytic methods, heuristic methods, frequency methods, optimisation methods, adaptive methods and various combinations of these tuning and model identification methods can be found in the literature. The overwhelming number of the existing techniques makes the selection for a particular application fairly challenging. Even if some of the methods show a good performance in theory, they might face some problems in real applications. Therefore, the design of a controller muss not just consider the process disturbance rejection and good set-point following performance but also the sensor noise, actuator signal limitation and process model uncertainties.

The aim of this literature review is to analyze the major problems arising form the practical implementation of a PID controller, dispose the available techniques to eliminate or reduce these problems and to point out possible design methods based on the most recent research and knowledge. In the summery of this literature review a possible future design of a ‘plug and control’ PID controller for a wide range of industrial application is proposed and briefly described.

II. Literature Review

A. Derivative Filter

The derivative action of a PID controller has the advantage of compensating the phase lag caused by the integral action, thus it helps improving the system stability and assists maximizing the integral gain for a better performance. It also contributes to a faster loop recovery after the occurrence of a load disturbance [2]. The derivative action, however, is rarely used in practical cases. In general, about 80% of all the PID controllers employed in the industry [2], and in the case of the pulp and paper industry even 97% [3], has the derivative action switched off. The scepticism of applying the third controller action arises from the fear of amplify the sensor noise and thus of destroying the actuator. De facto, the use of the derivative action makes the implementation of a low-pass filter in the control loop essential. Typically, the filter factor is not considered in the tuning procedure of the PID gains and is added afterwards into the design. But this may have a disastrous impact on the stability margin [4]. In [3] it has been shown that the derivative filter constant does influence the complete design. Therefore, the authors claim that the PID design is in fact a four-parameter design and the derivative filter constant is an integral part of it. The filter types used within the integrated design greatly diverge in the literature; firs- and higher-order derivative filters and also output filters has been proposed. A comparison of those filters shows the superiority of the first order output filter [5].

Different viewpoint concerning the use of the derivative action in plants with considerable time delays has been mention in [4]. The common opinion of not applying a derivative action in this kind of plants has been refuted. As shown in [4] and [6] the derivative action does offer a significant improvement to the controller performance, the improvement however, become less significant as the ratio of process's time delay and effective time constant increases.

B. Integrator Windup

The integrator windup is in practice one of the well-known phenomenon which can significantly limit the performance of a PID controller. This undesirable effect is caused by the actuator physical min-max signal limitation, which in fact causes the control signal to saturate [2], [7]. If a set-point change is applied and the controller faces the saturation, the control error decreases slower then under ideal conditions and thus leads the integral part to an excessive rise. The over proportional raised integral term can cause large overshoots and long settling times. According to [2] the low frequency oscillations caused by the integrator windup may even lead to instability. The saturation problem is of concern mainly in the case of set-point changes and process start-up and rarely in the case of load disturbances [5].

Probably the most simplistic and intuitive way to avoid the integrator windup is to prevent the control signal to saturate by smoothing the set-point change or by detuning the controller. The preventive limiting of the control signal however, degenerates the performance, leads to a sluggish step response, and thus is generally not recommended [2], [5]. A new modified anti-windup scheme based on conditional integration and back-calculation has been proposed in [7]. The conditional integration avoids the integral windup stopping the integral term in predefined conditions and the back-calculation recalculate the integral term in the case of control signal saturation. If applied separately, the performance of this methods can be affected by a considerable large dead time of the process and an additional tuning parameter may be required in case of different normalized dead times. The proposed modified technique overcomes these drawbacks and due to its simplicity can be efficiently implemented in any industrial controllers. Another promising anti-windup technique can be applied in a PID controller with an automatic reset configuration architecture, and this without an additional design effort [2], [5]. In this implementation the saturation function of the actuator is simply added in the reset path of the controller and can de facto be a nonlinear function. This implies that a possible actuator dead zone can also be considered and implemented in the controller design.

The comparison of different anti-windup methods based on simulation and experimental results shows that every considered method indeed does improve the performance, but no particular method is superior for all considered cases. The modified anti-windup scheme based on conditional integration and back-calculation however, is less sensitive to diverse process models [5].

C. Set-point Weighting

PID gains tuning methods face in practice difficulties when different control specifications have to be met. A controller tuned for an excellent load disturbance rejection shows generally a poor set-point following performance. If however, both specifications are of concern in a given application, a two-degree-of-freedom controller should be implemented [6]. The great advantage of the two-degree-of-freedom controller arises from its ability to treat the stability and performance problems separately. It consists of a feedforward and a feedback action, where the aim of the feedforward action is to improve the set-point change response and that of the feedback to assure stability and a good disturbance rejection. The controller is based on the well-known and widely used in the industry ISA[1]-PID control law

$$u = K_p \left(br - y + \frac{1}{sT_i}\left(r - y\right) + \frac{sT_d}{1 + sT_d / N}\left(cr - y\right) \right) \tag{1}$$

where r, y, and u are the reference, process output and control signals, K_p, T_i, and T_d are the PID gain, integral, and derivative time constants and N is the filter parameter. The parameters b and c are the set-point weights which aims to improve the set-point following performance. The weights b and c appear fortunately only in the feedforward action, thus the feedback can be tuned as usual. Moreover, the method applied to tune the feedforward action is independent from the feedback tuning method [8]. According to [6] a controller should be in general tuned for robustness and load disturbance first, the set-point following issue have to be addressed

[1] Instrumentation, Systems, and Automation Society (ISA), formerly the Instrument of Society of America, is a non-profit organisation that helps professionals to solve difficult technical problems

afterwards with the two-degree-of freedom architecture. But the two-degree-of-freedom controller has been seldom implemented in industrial application because of its additional tuning effort. A simple tuning method for the gains b and c has been therefore proposed in [8] as a solution to this problem. The proposed method can be implemented into an already existing controller and, as already mentioned, it will not affect the former tuning of the feedback action. In [9] the two-degree-of-freedom controllers with fixed set-point weights, as for example in [8], have been criticized. A far better performance can be achieved by applying a fuzzy set-point weighting technique. In this method, the value of the set-point weight b is continually updated during the transient response of the system. The set-point weight c has been set to zero, which can be normally done in the case of an abrupt set-point change [6]. The fuzzy rules for the fuzzy set-point weighting technique are based on the well-known Macvicar-Whelan matrix.

The comparison of different set-point weighting tuning rules shown in [9] implies the superiority of the fuzzy based approach in case of saturated control variable. If no saturation is present, it is very difficult to improve the Integral of the Absolute Error (IAE) value of an optimal tuned controller. The proposed tuning rule shows smaller overshoot, decreased rise time, and surprisingly an improved load disturbance rejection.

D. Tuning Methods

The Ziegler-Nichols (Z-N) tuning methods proposed in 1942 by John G. Ziegler and Nathaniel B. Nichols are probably the best known methods and are still frequently used in many industrial PID control systems. Hitherto proposed tuning rules can not replace the Z-N methods in terms of their familiarity and simplicity to use [1]. The Z-N rules give in general a satisfactory load disturbance rejection; the resulting oscillatory response however, is not acceptable in many systems [10].

Following the statement in [3] that the PID design is a truly four-parameter-design, only those tuning methods that include the fourth parameter, namely the derivative filter constant, will be considered in this literature review. A selection of the available tuning methods including the fourth parameter has been given in [3] and [5]. The best known method is the Internal Model Control (IMC), which is based on cancellation of the stable plant poles by the controller zeros. The method shows a good set-point following performance but a poor load disturbance rejection [10]. The IMC and its modifications, as for example the Skogestad IMC (SIMC) tuning rule, has been compared with the Kristiansson and Lennartson tuning rules KLκ150 and KLT63 in [4]. The KLκ150 and KLT63 rules, which also include the derivative filter, give in general a better

IAE value. In contrary to these methods, the IMC technique rarely results in optimal performance. The term *optimal controller*, as used in the context of Kristiansson and Lennartson tuning rules, refers to a controller with good mid-frequency robustness (damping) and the best possible trade off between output performance and control activity [11]. In other words, the controller performs a good process disturbance rejection without an excessive control action. The two tuning rules given by Kristiansson and Lennartson are based on the same concept but different plant information; the KLκ150 is based on the information obtained from a relay experiment involving hysteresis and KLT63 on a simple step response.

The probably best nominal process disturbance rejection performance of all existing tuning methods has the Åström and Hägglund method [3]. This technique, called M-constrained Integral Gain Optimization (MIGO), is based on the maximization of the integral gain [6]. Åström and Hägglund themselves emphasize that it is not possible to find a simple optimal tuning rule for processes with relative time delay bigger then 0.5; a more sophisticated and accurate process model is of great advantage in this case. An Approximate MIGO (AMIGO) tuning rule is proposed in this context. It is a conservative robust tuning rule that works well for a wide range of processes, however, with a lower performance as in the optimal case where an accurate higher order process model is given. The tuning method as such does not include the filter design, however, a pre-designed filter is considered in the tuning procedure. The proposed filter is an output filter, which as mentioned in Section *A*, is superior to the derivative one.

E. Adaptive Control Concepts

The main idea of the adaptive control is to automatically adjust the parameters of a fixed-structure controller based on the recent and future process information. The adaptive control concepts can be roughly subdivided into the model-reference adaptive control (MRAS), self-tuning control, dual control and iterative control. The self-tuning technique, however, has proved itself to have the most impact on the industrial control applications. Self-tuning can be interpreted as an automation of the off-line tuning executed by an operator. The automation is achieved by an on-line process model identification followed by the control parameter design. A self-tuning controller that adopts itself continuously results in a sophisticated controller structure and thus should be used only for truly non-linear, time varying plants [12]. In cases where a continuous adaptation is not required, an on-demand self-tuning controller should be applied. The on-demand tuning, also known as auto-tuning, has been implemented in many software based controllers, as for example in the Siemens Step7 PLC library [13], and in numerous hardware based controller [1]. The auto-tuners however, have the disadvantage of time consuming model identification procedure in case of plants with long time constants [15]. Moreover, during the on-line model identification process, the controller may bring an output which is not acceptable by the plant. This problem can be solved with a 'plug and control' controller, which performs the model identification during the normal operating conditions and thus does not influence the operation of the process [13], [15].

F. Real-time System Identification

A problem arising form the adoption of a self-tuning method in a real control application is the system identification. The system identification can be subdivided into two major techniques, namely into the excitation and the non-excitation one [1]. The prior technique is based on time- or frequency domain methods, such as the step or relay excitation [14]. Nearly all regulators available on the market accommodate these methods in the auto-tuning mechanism [15]. Paradoxically, the non-excitation method is more appropriate in the industry because it does not disturb the controlled application, as the model identification is performed during the normal system operation as for example the process start-up or any other set-point changes [1]. The idea of 'plug and control' controllers is based on the non-excitation method as can be deduced from the Section *E*. The identification procedure itself is commonly based on the well-known least-squares method [15]. A noise insensitive model can be easily obtained using this method be firstly identifying a higher order system and than reducing it into a required lower order one. In a truly time varying systems a so called forgetting factor is recommended [12]. It modifies the identification algorithm so that the identified model is more based on the recent date and therefore on the more valid ones.

III. Conclusions

The design of an adaptive PID controller for industrial applications muss not only consider the tuning and model identification algorithms, but also the performance limiting aspects arising from practical implementation. In many applications for example, the derivative action of the PID controller is switched off because of the sensor noise amplification problem. The derivative action though, improves the overall performance and thus should be not switch off. The high-frequency problem can be tackle with a filter, which in turn makes the PID controller design a truly four-parameter-design. De facto, this has a colossal consequence on the tuning method selection procedure. Even though a numerous tuning methods exist, many of them will not show an optimal performance in practical cases because of their limitation to a three-parameter-design.

In this context, two tuning methods, namely the Kristiansson-Lennartson and the Åström-Hägglund method, have shown their superiority. They include the fourth parameter in their design and show an overall good process disturbance rejection and robustness. Moreover, to improve the set-point following performance, the typical controller can be extended to two-degree-of-freedom architecture. Fuzzy set-point weighting technique proved itself to be a good tuning method for the additional parameters arising from the new architecture. An additional performance limiting aspect, and in some cases even an instability causing problem, is the well-known integrator windup phenomenon. None of the investigated anti-windup methods show their superiority; some of them however, may be preferable in particular cases.

The primary problem of adaptive control is the system model identification. The majority of the existing on-demand self-tuning PID controllers use excitation methods to identify the plant. The additional excitation signal may however, disturb the normal plant operation, what in fact makes the adaptive method not always applicable. The relatively new and not yet widely implemented in industrial application 'plug and control' self-tuning method uses a non-excitation technique, which do not influence the plant in any way. The plant information is obtained during the normal controller operation and is then used to identify the model, typically using modified least-squares methods.

The author strongly believes that a bottom-up approach for a new design of a universal 'plug and control' controller for a wide range of industrial applications is the most appropriate approach. The best possible outcome will be achieved targeting the best possible performance and not fixing the performance criteria prior the design. Future work on the new controller design in this project will firstly include a comparison of the two in this literature review proposed tuning methods; such a comparison could not been found in any literature. The chosen method will be then applied to the PID controller and then the design will be gradually expanded with a fuzzy set-point weighting and a chosen anti-windup method. The non-excitation plant identification technique used in the prior 'plug and control' designs will be expanded; not only the set-point changes during the normal plant operation but also the process disturbances will be used to identify the plant model. The design in its different stages will be tested on a test batch proposed in [6]. The batch includes 134 different processes, which are representative for a wide range of plants meet in process control.

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