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Give us PID controllers and we can control the world ⋆

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Abstract: The aim of this paper is to emphasize the importance of PID control for our society in general and for the control engineering community in particular. To this end, we first equate the relevance of PID controllers with other inventions in history to remark how PID control has contributed to revolutionizing our world as the main ambassador of the automatic control field. Afterwards, the PID control resilience is provided by showing a brief historical evolution to realize its timely adaptation, and how nowadays it is much more than just the three terms; P, I, and D. Moreover, it is summarized how PID control has been demonstrated to be equivalent to other optimal control solutions and how the recurrent comparison with Model Predictive Control (MPC) is not necessary at all, as both control algorithms should be considered as complementary approaches. Finally, encouragements and suggestions are summarized to continue working on PID control topics.

Keywords: PID control, history, classical control, control engineering.

1. INTRODUCTION

The evolution of our society has been marked by excellent scientific and engineering inventions throughout history, such as the electricity by Benjamin Franklin, the steam engine by James Watt, the first plane by Wright brothers, the phone by Alexander Bell,..., only to mention a few of them (Challoner, 2022). Inventions have had a tremendous impact in improving our quality of life, contributing to better communications, transport, health care systems, industry, etc. In the end, most well-known inventions are recognized by people because of their tangible impacts in society. However, there are many other hidden inventions that are very well known in the scientific world, but which are transparent for our society because they have not had a visible impact. This is the case of the automatic control field, called *The Hidden Technology* by Prof. Karl Johan Åström (Åström, 1999). He emphasizes that the core of automatic control, feedback, although hidden, is present everywhere, and we can find successful examples of applications along the history in economics, biology, medicine, energy generation and transmission, engineering, manufacturing, communication, process control, transportation, and entertainment (Bennett, 1996; Bernstein, 2002; Åström and Murray, 2021).

The development of the automatic control field during the last hundred years has been impressive, and nowadays there is an enormous variety of control algorithms available, ranging from the simpler feedback control solution based on an on-off controller, passing thorough nonlinear predictive control approaches based on first-principle models, to those algorithms using artificial intelligence methods. Many of these control algorithms are discovered to solve particular problems and are typically replaced with the time when new solutions appear. However, this is not the case for the Proportional-Integral-Derivative (PID) controller. It is really impressive to see how, in addition to all these advances, PID control is still considered as the reference control algorithm for most control problems in industry, academy and society. It was proposed for the first time in 1922 by Nicolas Minorsky as part of an automatic ship steering for the US Navy (Minorsky, 1922). Since then, it has been used initially in the process control industry and afterwards used as a solution to most control problems worldwide. Even today, it is not only the most widely used control algorithm in industry, covering more than 90 % of industrial control solutions, but it is also considered the control algorithm taken as a model to teach feedback control fundamentals in all universities and technical colleges; and it is a universally recognized automatic solution that can be found in home devices and utilities such as smartphones, car cruise control, ovens, microwave ovens, drones, air conditioning systems, heating systems, electrical bikes, segways, electrical hoverboards, elevators, etc. (Vilanova and Visioli, 2012).

Thus, in the same manner as we can assert that feedback is the heart of the automatic control field, we can also affirm that PID control is its perfect ambassador, as it has been the pragmatic and realistic feedback realization transferred into our society. PID is today everywhere and has contributed to improve our lives and transform the

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world (industrial revolution, telecommunications, process automation, energy-based systems, home electronics, etc.). For that reason, in the same way that the Greek philosopher Archimedes once said, “Give me a firm place to stand and a lever, and I can move the Earth”, we can stand that “Give us PID controllers and we can control the world”.

The previous statement could seem too excessive, but if we analyze it with perspective, observe the wide application of PID control for any type of processes, and see how powerful PID control has been to deal with all kind of real problems related to stabilization, performance improvement, cost reductions, safety behaviors, and disturbance attenuation, among many others; it is not excessive at all.

PID control has been considered an obsolete control solution by many researchers in the control engineering community in recent decades. However, one could wonder why it is still used everywhere in spite of new appearing control solutions, why it is always considered as the reference controller to be improved by any new proposal of novel control algorithms, or why it is considered as the main block in other more complex control approaches as those based on cascade control, multivariable control, hierarchical control, adaptive control, or ratio control (Hägglund and Guzmán, 2018). The main reason is that PID control has evolved since its origin in 1922 and is currently not just a control algorithm based on three terms; P, I, and D, as many researchers indicate. Now, it includes many other capabilities to deal with signal filtering, bumpless transfer, feedforward control, anti-windup, and switching modes, which has made it easier to adapt to new control problems while at the same time keeping its algorithmic simplicity (Åström and Hägglund, 2006). PID control perfectly agrees with the pure definition of *resilience*, which is the process and outcome of successfully adapting to difficult or new challenging situations.

Moreover, compared to other optimal control algorithms, it has been shown to be very close to optimal solutions despite its simple control structure (Soltesz and Cervin, 2018; Larsson and Hägglund, 2011; da Silva et al., 2020). In this sense, PID has traditionally been compared to MPC algorithms, when, however, they should be considered complementary control algorithms as part of a hierarchical control approach (Åström and Hägglund, 2001; Skogestad, 2023). MPC cannot compete with PID in low-level control problems, and, conversely, a single PID cannot compete with MPC to deal with large complex problems. Another important advantage of PID control is related to operational aspects and the interaction with operators, since it makes the connection and disconnection of control loops easier when, for instance, maintenance tasks arise in the process industry. Figure 1 shows a funny drawing by Brian Douglas that actually describes how, over time and after acquiring new knowledge, control engineers value the relevance and power of PID control.

The previous summary reveals the motivation for this paper. As we did in this introductory section, we first recall the importance of PID control in improving real problems around the world in academia, industry, and society. We strongly believe that reinforcing this information is useful not only for the control engineering community in general but also, particularly, for new generations of

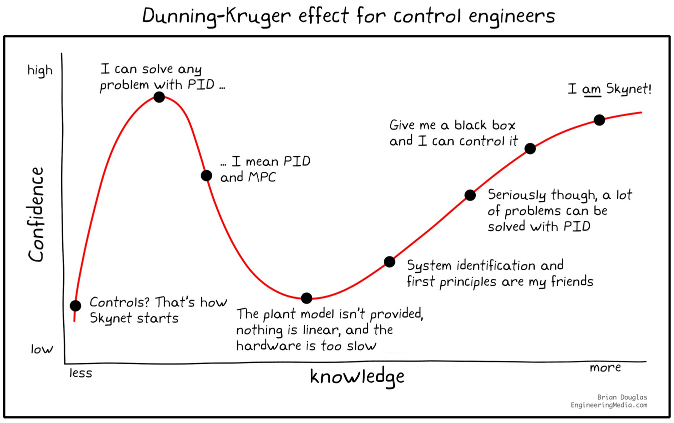

Fig. 1. PID control consideration based on knowledge as part of the Dunning-Kruger effect for control engineers drawing by Brian Douglas (https://engineeringmedia.com).

control engineers. Then, in the next sections of the paper, we will briefly summarize the PID control history and how, thanks to its resilience, nowadays is much more than just a three-term controller. Afterwards, operational aspects, optimal capabilities, and the never-ending story of PID versus MPC will be discussed. Finally, future research directions on PID control topics are suggested.

2. BRIEF HISTORY

The history of PID control is actually a very long journey, which was very well summarized in previous publications (Bennett, 2001; Åström and Hägglund, 2006). This section tries only to remark on some of the important milestones in PID history.

Examples of control with proportional and integral action can be found in applications such as steam engines, wind mills, and different water level systems several centuries ago (Bissell, 2009). However, these control functions were not considered as separate controllers, but were seen as natural parts of the rest of the constructions.

The first time the three PID control terms were combined dates from 1922 in the work developed by Nicolas Minorsky for the design of an automatic ship steering for the US Navy (Minorsky, 1922). However, this work was practically unnoticed by the community until Harold Hazen cited it in his book in 1934 (Hazen, 1934). Since then, PID has attracted the attention of researchers and practitioners, and it is still the dominating controller, not only in the process control industry, but it is considered the standard feedback controller in most other control applications as well.

Among the different advances in PID control, the development of new tuning methods has ruled the main research lines in the evolution of PID controllers (Somefun et al., 2021). The first published tuning rules were proposed by Albert Callander and co-authors, who proposed visual charts to allow tuning of PI and PID controllers for a range of processes with delay (Callender et al., 1936; Hartree et al., 1937). However, the probably first and most well-known tuning rule was developed by Ziegler and Nichols in (Ziegler and Nichols, 1942). Approximately a decade later, Coon proposed new tuning rules thanks to advances in the frequency response approach (Coon, 1956b,a). Afterwards, the more remarkable tuning contribution was at the end of the 1960's with the Lambda method proposed by (Dahlin et al., 1968). Then, the original Lambda ideas were exploited and extended under the Internal Model Control (IMC) framework in (Rivera et al., 1986; Morari and Zafiriou, 1989). After that, many other tuning rules have been proposed in the literature, (O'Dwyer, 2009), but only a few of them have been demonstrated to provide really relevant advances, such as AMIGO (Åström and Hägglund, 2004) or SIMC (Skogestad, 2003) tuning rules as a generalization of the original Ziegler-Nichols and Lambda (IMC) tuning methods, respectively. In the late eighties, automatic tuning procedures for PID controllers were developed and simplified the tuning procedure for these controllers.

On the other hand, research has also been performed to formulate new fuzzy, adaptive, or robust PID control algorithms. However, two particular milestones can be considered as some of the most important contributions with remarkable practical application, namely, the antiwindup control schemes and the set-point weighting approach. For example, the back-calculation control scheme proposed in (Fertik and Ross, 1967) to deal with integral windup problems was a very important contribution. In the same way, the set-point weighting control algorithm proposed in (Araki, 1984a,b) provides the PID controller with the advantages of a two-degree-of-freedom control scheme, i.e., decoupling the setpoint tracking and the disturbance rejection problems by using only one single control algorithm. These two improvements on the basic PID control algorithm are clear examples of how the PID controller today is much more than just three terms, such as described in the next section.

Notice that as commented above, the PID history is really extensive. For more detailed information, see Bennett (2001); Åström and Hägglund (2006); Vilanova and Visioli (2012).

3. PID EVOLUTION: MORE THAN THE THREE TERMS

As summarized previously, PID controllers have been produced for about hundred years. During the first half of this period, they were analog, pneumatic, mechanical, or electrical. At the end of the seventies, computer-based controllers appeared, and nowadays almost all PID controllers are implemented as software components in PLC or DCS systems.

The basic structure of the PID controller is

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)\, d\tau + T_d\frac{de(t)}{dt}\right) \qquad (1)$$

where u is the controller output and $e = r - y$ is the control error, i.e. the difference between setpoint r and process output y. The controller parameters are the proportional gain K, integral time T_i, and derivative time T_d. This controller structure is named ideal or standard PID form, but parallel and interactive forms can also be considered (Åström and Hägglund, 2006).

Equation (1) describes more or less the function of the earlier analog implementations. However, the PID controllers used nowadays include much more. A PID controller implemented in modern DCS systems should for instance have functions for bumpless mode switches between manual and automatic mode, bumpless transfer at parameter changes, antiwindup, signal filtering, feedforward control, and possibility to go over from control mode to tracking mode, where the controller output is tracking an external signal. Advanced implementations have also automatic tuning, continuous adaptation, gain scheduling, and functions for performance monitoring. See e.g. Hägglund and Åström (1991), Åström and Hägglund (2006) and Visioli (2006). A reflection that can be made is that these functions are seldom found in controllers that are called more advanced than PID.

Another feature of the PID controller is that it is a powerful building block to obtain more advanced multivariable control architectures. Those architectures are based on, for instance, feedforward control, cascade control, ratio control, midrange control, split-range control, control with selectors, and decoupling of coupled processes. These architectures, based on the PID controller as a building block, are the architectures that are used today to control almost all process control plants. They have often been developed over many years by many clever engineers with ad hoc solutions. Then, when new plants are to be installed, it is common practice to copy architectures from older similar plants, being in many cases not published or available in the literature. In fact, this issue opens many possibilities for research on the PID control field, as will be discussed later (Skogestad, 2023).

Many of the previous features have been collected in the new standard published by the International Society of Automation in (ISA, 2023), where it is recognized that the new standard PID control law is not the common control algorithm described by Equation (1), but it also includes most of the control configurations and capabilities described in this section.

4. OPERATIONAL ASPECTS

This section highlights another important advantage of the PID controller, which is related to the operational situations occurring in real facilities. There are situations where the PID controller is running in automatic mode without any interrupt, without any need for interaction with operators or other surrounding functions in the control system. However, in more advanced applications, such as in process control plants, there are needs for such interactions.

There is normally a need to be able to switch the controller between manual and automatic mode, for instance during equipment maintenance, start up or shut down. The dynamics of the process section that is controlled often varies over time because of equipment degradation or equipment replacements. In these cases, the controller should be retuned. These interactions with operators can be performed relatively easy in PID controllers. One can switch between manual and automatic mode, and one can modify the controller parameters, everything without introducing any bumps in the control signal. What is important is that the personnel at the plants know how to perform these interactions, and most of them understand the relations between the controller parameters and the control behaviour, i.e. they know how to tune the controller to obtain the desired control performance.

On the other hand, the PID controllers are normally not isolated in a single control loop, but part of a larger multivariable control architecture. In these cases, there is a need for interaction between the controllers and surrounding functions. These interactions are performed by sending analog and boolean signals to and from the different controllers. The PID controllers are well prepared for such interactions, and in this way providing the possibilities for cascade control, feedforward control, control with selectors, switching between control and tracking of external signals, etc. Also here the users of the PID controllers know how to enable these functions.

Except for simple isolated control applications, it is crucial that the controllers enable efficient interaction between both users and other control functions. PID controllers have this property, and the interaction can often be performed by personnel at the plants. Other controllers often lack several of these properties (as MPC as will be discussed in next sections), and if not, they must often be enabled by consultants outside the plant.

5. THE PID CONTROLLER IS ALMOST OPTIMAL

Many researchers have seen the simplicity of the PID controller as a serious limitation in the sense that optimal solutions cannot be achieved. This is perhaps relevant for many complex problems, but solving optimization control problems is normally not the aim of using PID controllers. Nevertheless, PID controllers have been demonstrated to provide near optimal solutions for many cases, as described in this section.

In Soltesz and Cervin (2018), the performance of the PID controller with a second-order low-pass filter was compared with linear controllers with arbitrarily high order using Q, or Youla, parametrization. The comparison was made using a test batch of 124 stable processes with dynamics relevant for process control given in Åström and Hägglund (2006). The performance criterion was IAE at step load disturbances, and reasonable robustness constraints were applied. The investigation showed that the relative IAE improvement when using the higher-order controller never exceeded 50 % in the considered process batch. It was also interesting to note that the Bode plots of the two controllers were very similar. They were almost identical at low frequencies with the -1 slope caused by integral action. At mid and high frequencies, the higher-order controller had only slightly higher gain and phase advance. A similar investigation with similar results was made in Larsson and Hägglund (2011), with a test batch that contained not only stable but also integrating processes.

Ingimundarson and Hägglund (2002), Normey-Rico and Guzmán (2013), Grimholt and Skogestad (2018), and da Silva et al. (2020) compared the PID controller with dead-time compensating controllers. If no robustness constraints are imposed and the process model is accurate, the dead-time compensating controllers can outperform the PID controller in cases of long dead times. However, the investigations showed that with reasonable robustness constraints, including a relevant delay margin, the PID controller will provide better results than the dead-time compensators in most cases.

In summary, if reasonable robustness requirements are posed on the controller, the PID controller is close to optimal for most linear processes of arbitrary order, being these robustness capabilities another reason of its permanent use in process industry.

6. THE NEVER ENDING STORY: PID VS MPC

In the previous sections we have pointed out that the PID controller is close to optimal as long as control of linear processes is considered. It is also superior to other controllers in terms of interaction with users and surrounding features. Despite this, the PID controller has been questioned ever since computers began to be used for control.

In the seventies and eighties, there was a large focus on adaptive control in academia. It was believed that adaptive controllers, with a higher degree than the PID controller, should replace the PID controllers. These adaptive controllers turned out to be very unrobust and the possibilities to interact with the adaptive controllers were limited. The use of adaptive control in industry is rare today.

In the nineties, fuzzy controllers were suggested to replace the PID controller. A feature was said to be that it had no controller parameters to set. On the other hand, there were some membership functions to determine. The fuzzy controller is seldom used today.

During the last decades, the most common competitor to the PID controller is the MPC controller, and this comparison is today a permanent discussion at conferences and meetings in the academic world. Nevertheless, here the comparison is more complicated. One can compare the PID controller and the MPC controller at the single-loop level. However, the MPC controller is mainly suitable for higher-level multivariable control, and a comparison should in this case be made with the decentralized classical control structures that are based on PID controllers.

6.1 Single-loop case

In the single-loop case, the PID controller is close to optimal and it has much better interaction properties than the MPC controller. On the other hand, the MPC controller has abilities to handle nonlinearities more efficiently than the PID controller, and for single-loop control problems with severe nonlinearities the MPC controller may be a good choice. However, for the majority of single-loop control problems the PID controller is still the best option.

Another demonstration of the advantage of the PID controller is given by the following example. Consider a single control loop for just a first-order process where it is desired to achieve a specific closed-loop time constant, indifferently for the setpoint tracking or regulation control problem. This can be handled easily by a PID controller using some of the different tuning methods in the literature where the closed-loop time constant is specified, such as the Lambda method or the SIMC method (Skogestad, 2003). However, this is not easily done for the MPC, as systematic closed-loop tuning is still an open problem in MPC, and only heuristic rules or trial-and-error solutions are available (Rossiter, 2017).

Another simple example for the single-loop case is disturbances rejection using feedforward. In (Pawlowski et al., 2012), it was demonstrated that an MPC algorithm is not capable of rejecting disturbances even in cases of perfect modeling cancellation and with perfect knowledge of future disturbances. The classical tuning of the MPC controller including feedforward capabilities must be modified to make the disturbance rejection effective, still at the prise of losing robustness properties. However, this problem can be solved easily by the combination of a PID controller and a feedforward compensator, where the performance is dramatically improved with respect to the MPC for measurable disturbances. Notice also that even when disturbances are measurable, its use is not trivial in MPC, as the development of observers is required to be considered as part of the basic MPC control law.

6.2 Higher control level

The MPC controller has been shown to work well at higher control levels in many cases. A main advantage is the possibility to handle difficult nonlinear aspects. One should note that also in these applications the PID controllers are normally used at lower levels. However, the architectures developed during many years that are based on pure PID controllers are still found to be most efficient, mainly because of their superior interaction capabilities as discussed in Section 4 (Åström and Hägglund, 2001).

Suppose for instance that a sensor is to be replaced by a new one with other dynamic properties, e.g. another signal range. It is desired to make this shift without interrupting the production. In the PID case, the operators switch the controller to manual mode, and perhaps also some other controllers that are affected by the sensor shift. When the new sensor has been installed, the controller is retuned because of the changed process dynamics. Finally, all controllers are switched to automatic mode again. The whole procedure is handled by the staff working in the plant. In the MPC case, it is hard to switch parts of the plant to manual mode while keeping the rest of the control running. Retuning of the MPC means updating the corresponding process model, a task that often has to be done by consultants, and not by operators on site. This type of simple maintenance task is very common in process control plants, and it illustrates the difference in interaction capability between classical control and MPC control.

In the same way as for the previous examples, one could look for other situations where MPC performs better than PID, like cases of large multivariable processes with strong interactions and constraints. Nevertheless, and as pointed out above, MPC and PID should not be competitors but complementary solutions to exploit the advantages of each control algorithm according to a top–down control approach. Thus, MPC should be used as a supervisory control algorithm focused on the process optimization and system coordination objectives, and provide optimal set-points to PID controllers in charge of the plant-level control problems. The key point of this solution is the design of an adequate time scale separation of the control layers, in such a way that MPC and PID take care of the slow and fast process dynamics, respectively (Skogestad, 2023).

7. FUTURE DIRECTIONS

When we think about future research topics for PID control, this is typically associated with the development of new PID tuning methods. Nevertheless, PID tuning has received too much attention in the academy over many years, and it is really difficult to come up with new tuning ideas. There are, however, many open problems related with PID control and its combination with anti-windup control schemes, selectors, feedforward control, mid-range control, cascade control, etc. Many of these control approaches, where PID controllers are used as the main control blocks, are working in industry following ad hoc configurations, and there is a lack of theory to demonstrate, justify, or even improve the performance of these control solutions.

These ideas have recently been claimed in Skogestad (2023), where a list of research topics on classical control solutions based on PID controllers is proposed. We share the request of Prof. Skogestad in that work, where he encourages the control engineering community to devote research on these topics and develop theory for these classical regulatory control solutions. We also fully agree with his statement: "Simple control solutions are easier to implement, understand, tune (and retune) and change", since this summarizes the main advantages and capabilities of the PID control discussed in this paper, and they are also the main reasons why PID is widely used worldwide.

8. CONCLUSIONS

The aim of this paper is to emphasize the relevance of PID control for our society in general and for the control engineering community in particular. It was discussed that PID control can be considered by far one of the most impactful inventions in science and engineering in history, where its importance was unnoticed in many cases for being implemented as a hidden technology. PID control is perhaps the only control technique continuously studied for more than a century. So, after a hundred years of contributions, we strongly support the idea that PID control can be established as the ambassador of the automatic control field.

Particularly, in the single-loop case, it has been demonstrated that the PID controller has properties that mean it will be the best and most used controller also in the future for almost all control applications. At higher control levels, there are nowadays more advanced control structures, like the MPC controller, that provide optimal setpoints to the lower control levels that continue to be based on PID controllers. It is sometimes argued that these optimization-based controllers should replace the PID controllers also at the lower control levels. This paper has pointed out the reasons why this should not happen.

Another goal of the paper is to encourage more research in the PID control area, an area that is used in industry and will continue to be so.

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