Conceptual Model Development for a Knowledge Base of PID Controllers Tuning in Closed Loop

José Luis Calvo-Rolle[1], Héctor Quintián-Pardo[1], Antonio Couce Casanova[1]
and Héctor Alaiz-Moreton[2]
[1]*University of Coruña*
[2]*University of León*
Spain

1. Introduction

In the area of control engineering work must be constant to obtain new methods of regulation, to alleviate the deficiencies in the already existing ones, or to find alternative improvements to the ones used previously. This huge demand of control applications is due to the wide range of possibilities developed to this day.

Regardless of this increasing rhythm of discovery of different possibilities, it has been impossible at this moment to oust relatively popular techniques, as can be the 'traditional' PID control. Since the discovery of this type of regulators by Nicholas Minorsky Mindell (2004) Bennett (1984) in 1922 to this day, many works have been carried out about this controller. In this period of time there was an initial stage, in which the resolution of the problem was done analogically and in it the advances were not as remarkable as have been since the introduction of the computer, which allows to implement the known structure of direct digital control Auslander et al. (1978), illustrated in figure 1.

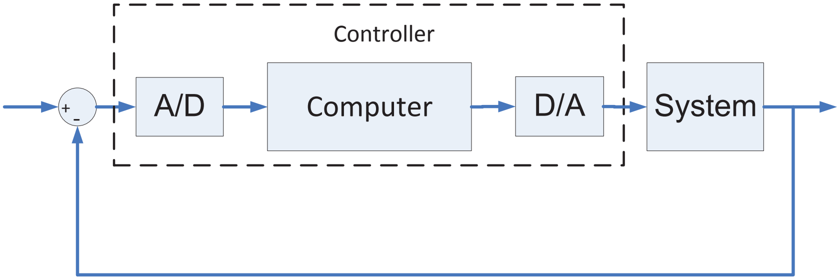

Fig. 1. Structure of direct digital control

Since then, regulators have passed from being implemented in an analogous way to develop its control algorithm digitally, by signal digital processors. As well as carrying out the classic PID control in digital form, its development based on computer allows adding features to the regulator with difficulty could have been obtained analogically.

We must say that there exist usual control techniques for the processes in any area, in which innovations have been introduced. But nevertheless, the vast majority of these techniques in their implementation employ PID traditional controllers, although in an improved way, increasing the percentage of use around 95% Astrom & Hagglund (2006). Its use is still very high due to various reasons like: robustness, reliability, relative simplicity, fault, etc.

The great problem of the PID control is the adjustment of the parameters that it incorporates. Above all in its conventional topology Astrom & Hagglund (2006) Feng & Tan (1998), as a consequence of the investigations carried out in the area, many contributions have been made by specialists, existing among them many methods to obtain the parameters that define this regulator, achieved through different ways, and working conditions of the plant to control. It must be highlighted that the methods developed to obtain the terms, which in occasions are empiric, are always directed to optimize defined specifications; the negative thing is that frequently when some specifications are improved others get worse.

It is necessary to highlight that empirical methods have been the first to be discovered and they are often the ones first learnt in the training of technicians for this discipline. In this sense the parameters obtained in this way through the application of formulas of different authors, are a starting point of adjustment of the regulator, being necessary, normally, a later fine adjustment by trial and error.

Regardless of what has been said, in practice there is a wide variety of regulators working in the industry with an adjustment far from what can be considered optimum Astrom & Hagglund (2006). This fact is originated among other reasons due to a lack of adjustment techniques by the users.

This fact creates the necessity to use intelligent systems, due to the demand of a better performance and resolution of complex problems both for men as well as for the machines. Gradually time restrictions imposed in the decision making are stronger and the knowledge has turned out to be an important strategic resource to help the people handling the information, with the complexity that this involves. In the industry world, intelligent systems are used in the optimization of processes and systems related with control, diagnosis and repair of problems. One of the techniques employed nowadays are knowledge based systems, which are one of the streams of artificial intelligence.

The development of knowledge based systems is very useful for certain knowledge domains, and also indispensable in others. Some of the most important advantages offered by knowledge based systems are the following:

- Permanence: Unlike a human expert, a knowledge based system does not grow old, and so it does not suffer loss of faculties with the pass of time.
- Duplication: Once a knowledge based system is programmed we can duplicate it countless times, which reduces the costs.
- Fastness: A knowledge based system can obtain information from a data base and can make numeric calculations quicker than any human being.
- Low cost: Although the initial cost can be high, thanks to the duplication capacity the final cost is low.
- Dangerous environments: A knowledge based system can work in dangerous or harmful environments for the human being.

- Reliability: A knowledge based system is not affected by external conditions, as a human being is (tiredness, pressure, etc).
- Reasoning explanation: It helps justify the exits in the case of problematic or critical domain. This quality can be used to train not qualified personnel in the area of the application.

Up to now the existing knowledge based systems for resolution of control systems have reduced features Pang (1991) Wilson (2005) Zhou & Li (2005) Epshtein (2000) Pang et al. (1994) Pang (1993), summarizing, in application of the method known as "Gain Schedulling" Astrom & Wittenmark (1989a), which is based in programming the profits of the regulator with reference to the states variables of the process. For the cases in which the number of control capacities have increased, the knowledge based system, is applicable to specific problems. There is the possibility to implement knowledge based systems programming them in the devices, but without taking advantage of the existing specific tools of Knowledge Engineering Calvo-Rolle & Corchado (n.d.) Calvo-Rolle (2007).

According to what has been said, the development of a PID conceptual model is described in this document to obtain the parameters of a PID regulator with the empirical adjustment method in a closed loop; feasible in the great majority of cases in which such method is applicable. The model has been developed for six groups of different expressions with highly satisfactory results, and of course expandable to more following the same methodology.

The present document is structured starting with a brief introduction of PID regulator topology employed, along with the traditional technique of which the conceptual method is derived, an explanation of the proposed method that is divided in three parts: In the first part the tests done to representative systems are explained, in the second part how the rules have been obtained and in the third one how the knowledge has been organized. Concluding with the validation of the proposed technique.

2. PID controller

There are multiple forms of representation of PID regulator, but perhaps the most extended and studied one is the one given by equation 1.

$$u(t) = K\left[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}\right] \tag{1}$$

where u is the control variable and e is the error of control given by $e = y_{SP} - y$ (difference between the specified reference by the entry and exit measured of the process). Therefore, the control variable is the sum of three different terms: P which is proportional to the error, I which is proportional to the integral of the error and D which is proportional to the derivative of the error (expression 2). The parameters of the controller are: the proportional gain K, the integral time T_i and the derivative time T_d. If the function transfer of the controller is obtained and a representation of the complex variable is done, the form is the one illustrated in expression 2.

$$G_C(s) = \frac{U(s)}{E(s)} = K\left(1 + \frac{1}{T_i \cdot s} + T_d \cdot s\right) \tag{2}$$

There are several ways for the representation of a PID regulator, but for the implementation of the PID regulator used, defined in the previous formula and more commonly known as the

Standard format Astrom & Hagglund (2006) Feng & Tan (1998), shown in the form of blocks in figure 2.

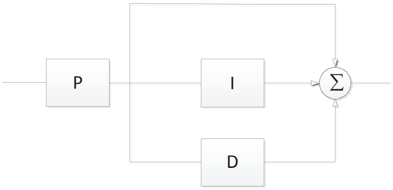

Fig. 2. PID regulator in standard topology

The industrial processes whose normal function is not adequate for certain applications are infinite. This problem, in many cases, is solved through the employment of this regulator, with which defined specifications are obtained in the control of processes leading to optimum values for what was being done. The adjustment of this controller is carried out varying the proportional gain and the integral and derivative times.

3. Empirical adjustment in closed loop of PID regulators

It is true that this day there are analytical methodologies to obtain the parameters of a PID regulator, in order to achieve improved one or various specifications. From a chronological point of view, the empirical procedures were born before the obtaining of the parameters, and currently they are still used for various reasons: the parameters are obtained in an empiric way, they are simple techniques, a given characteristic is optimized, good results are obtained in many cases, there is usually always a rule for the case that is trying to be controlled, etc.

3.1 Steps to obtain the parameters

The empiric techniques are based on the following steps:

1. Experimental establishment of certain characteristics of the response of the process that can be carried out with the plant working either in open or closed loop.
2. Application of formulas depending on the data previously obtained, to get the parameters of the regulator, with the aim that the operation of the plant with the controller is within certain desired specifications.

3.2 Measurement of the characteristics of the response of the process

In the first of the steps listed above for obtaining the PID controller parameters, the goal is to measure the characteristics of the responses of the process, it can be done in different ways, obtaining identical results in theory, although with small variations feasible in reality.

3.2.1 Sustained oscillation method

A fundamental method in the tuning of PID controllers is a closed loop method proposed by Ziegler and Nichols in 1942, whose best-known name is "the method of sustained oscillation".

It is an algorithm based on the frequency response of the process. The features to determine are:

- Critical proportional gain (K_c).- It is the gain of a proportional controller only, which causes the system to be oscillatory (critically stable).
- Sustained oscillation period (T_c).- It is the period of oscillation is achieved with the critical gain.

The procedure for obtaining these data is described below:

1. Closed loop system is located with a regulator that is only proportional (figure 3).

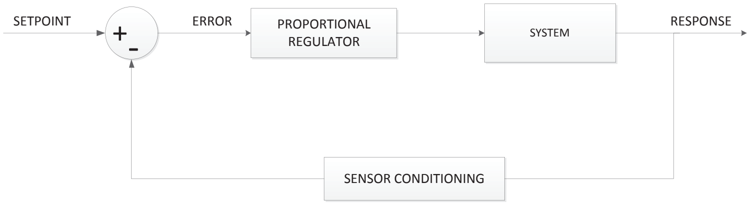

Fig. 3. System regulated with a proportional controller

2. Set any value of the proportional gain of the regulator and cause abrupt changes in the set point, then watching as the system response.
3. Increasing or decreasing the proportional gain of the regulator as necessary (if the system response is stabilized at a value, increase and if the output takes values without periodicity, decrease) until the system oscillates with constant amplitude and frequency as in figure 4. At that moment, writing down the value of the proportional gain applied to the regulator to achieve this state, this value corresponds to the gain of the system Kc, and also measure the period of oscillation of the output in these conditions, which is the period of sustained oscillation system T_c.

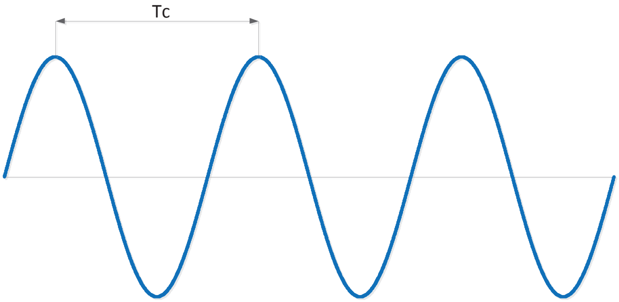

Fig. 4. Shape of the output in sustained oscillation state.

3.2.2 Relay-feedback method

The above method for obtaining parameters in closed loop of a regulator is a method that cannot be often used, since what is actually being done by increasing the proportional gain is to bring the system to a border zone of stability (oscillation), so that is possible to pass to the unstable region with relative ease. Sometimes without taking the system to instability, and just placing it in an area of sustained oscillation, the system is in a prohibited area, which could not operate by what might happen in the plant to be controlled. Therefore the application of this technique is only valid in certain specific cases where it can be passed to the oscillation or instability without major consequences.

An alternative way to locate the empirical critical gain (K_c) and the sustained oscillation period (T_c) of the system is by using the Relay method (Relay Feedback) developed by Aström and Hägglud, which is to bring the system to state of oscillation with the addition of a relay as shown in figure 5.

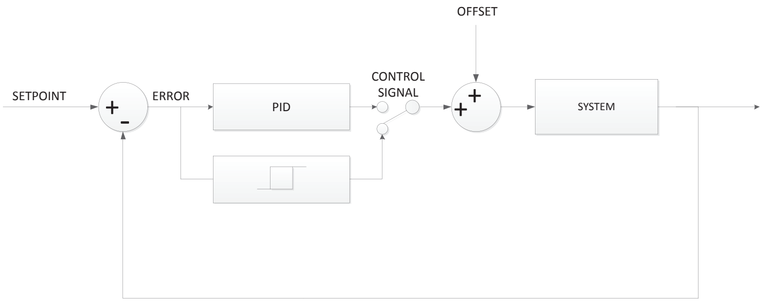

Fig. 5. Scheme for implementation of Relay-Feedback

The period of this achieved oscillation is approximately the same value as the sustained oscillation period T_c. In the experiment it is convenient to use a relay with hysteresis whose characteristics are shown in figure 6, an amplitude d and a window width of hysteresis h.

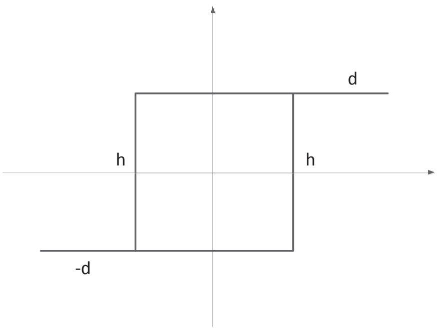

Fig. 6. Relay hysteresis used in the Relay-Feedback

Once the assembly, proceed as follows to obtain the mentioned parameters:

1. Bring the process to a steady state mode with the system regulated by PID controller, with any parameters that allow to achieve the aforementioned state. The values of the control signal (controller output) and the process output in the above conditions shall be recorded.
2. Then, control is closed with the relay instead of the PID controller. As a set point, the value read from the process output in the previous step is given. The value of the control signal taken in the previous section needed to bring the process in steady state is introduced into the entry shown in Figure 5 as Offset.
3. The process is put into operation with the indications made int the previous section, and wait for the output becomes periodic (in practice it can be considered to have achieved this state when the maximum value of the output repeats the same value in at least two periods in a row).
4. Two parameters must be recorded as shown in Figure 7, where T_c is the period of sustained oscillation.

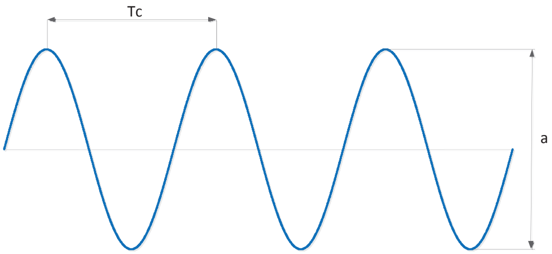

Fig. 7. System output with Relay-Feedback

5. The critical gain of the process is determined by the expression 3.

$$K_c = \frac{4d}{\pi\sqrt{a^2 - h^2}} \tag{3}$$

The Relay Feedback has the advantage that the adjustment can be made on the setpoint and can be carried out at any time. However, it has the disadvantage that, for the tuning process must overcome several occasions the setpoint and can be cases in which this is inadvisable because of the damage that can caused in the process.

3.2.3 Measurement of the characteristics of the response of the process from frecuency response example of bode diagrams

As previously indicated, the method of adjustment in closed loop is applicable to all those systems whose root locus cuts with the imaginary axis. In other words, occurs when increasing a proportional gain can bring the plant into a state of oscillation and subsequent instability.

This has an immediate translation in the field frequency on the Bode curves (figure 8), and consists of increasing the gain commented, causing a rise in the curve of modules to match

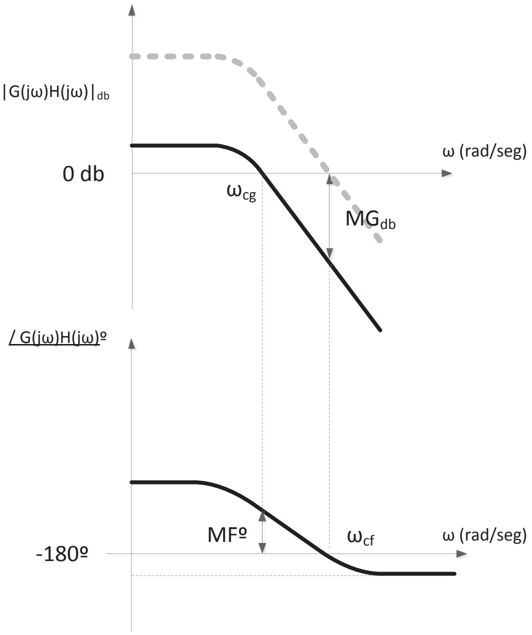

Fig. 8. Effect on Bode curves by increasing the proportional gain

the gain crossover frequency to the phase crossover frequency, state in which the system is oscillating (oscillates at the gain crossover frequency or phase crossover frequency with period T_c). The value of the gain that must be introduced to reach this state is the gain margin expressed in units (critical gain K_c).

This method is applicable in systems in which to practice a frequency analysis is possible. The parameters to introduce in the expressions of the terms of the controller can be seen on the results.

3.3 Parameters calculation through application of formulas

Once the characteristics of the response of the process have been measured and know what specification wants to be optimized, the following is to apply formulas developed to fulfill the description sought, bearing in mind the scopes of application for which they were obtained. The application range for the case of empiric adjustment in a closed loop comes defined usually by the product of the critical gain K_c and the process gain k.

Different authors propose expressions, depending on the characteristics of the response measured, for the achievement of the parameters of the regulator. It must be highlighted that there are multiple expressions given that work in an adequate way in certain cases for which they were developed. It is frequent also that the manufacturers of controllers deduce their own expressions that work satisfactorily above all with the products that they manufacture and especially for those applications to which are destined. It must be highlighted that there are no general equations that always work well, because of this, it will be necessary to select the expressions that best adjust in each specific case to the control intended.

In this study, the most known and usual Ziegler (1942) Astrom & HÃd'gglund (1995) McCormack & Godfrey (1998) Tyreus & Luyben (1992) that are employed in the achievement of the parameters of the PID regulators have been compiled, even though the methodology followed can be used for any case. In table 1 the different expressions used in the present study are shown, together with the scope of application in each case Astrom & Wittenmark (1989b).

Method	K_p	T_i	T_d	Application range
Ziegler-Nichols	$0.6 \cdot K_c$	$0.5 \cdot T_c$	$0.125 \cdot T_c$	$2 < k \cdot K_c < 20$
Ziegler-Nichols modified (little overshoot)	$0.33 \cdot K_c$	$\frac{T_c}{2}$	$\frac{T_c}{3}$	$2 < k \cdot K_c < 20$
Ziegler-Nichols modified (without overshoot)	$0.2 \cdot K_c$	T_c	$\frac{T_c}{3}$	$2 < k \cdot K_c < 20$
Tyreus-Luyben	$0.45 \cdot K_c$	$2.2 \cdot T_c$	$\frac{T_c}{6.3}$	$2 < k \cdot K_c < 20$

Table 1. Expressions of parameters of authors and scopes of application

4. Design rules of PID regulators in closed loop

In the first part of this section a sweep at the different expressions of achievement of parameters of the PID regulator previously mentioned is made, in which the systems are controlled with this type of regulator, with the aim of obtaining some generic design rules, or in their case particular rules for certain types of systems.

Due to the general character of the rules it will be necessary to use significant systems for this. In this aspect it has been opted to use a known source in this scope, which is the Benchmark of systems to control PID developed by Ästrom y Hägglund Astrom (2000). In this source a collection of systems is presented which: are usually employed in the testing of PID controllers. These systems are based in countless sources of importance and also the immense majority of the existing systems adapt to some of those included in this source.

4.1 Benchmark systems to which closed loop empiric adjustment is not applicable

There are a set of systems included in the Benchmarking to which the empiric adjustment in closed loop is not applicable. If for instance there is a system whose transfer function is the expression 4, which deals with a system of first order.

$$G(s) = \frac{1}{s+1} \tag{4}$$

The root locus for this transfer function is shown in figure 9, where one can see that does not cut the imaginary axis, and therefore cannot get the setting parameters of the PID closed-loop for this case.

If there is a system with a transfer function as the one in the expression 5, which is an unstable system, when introducing a step type input, will not be able to apply this method to regulate it.

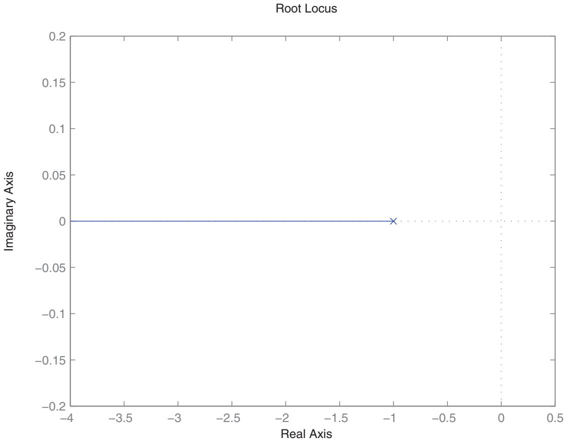

Fig. 9. Root locus for 1st order system with pole at -1

$$G(s) = \frac{1}{s^2 - 1} \tag{5}$$

Another possibility within the contemplated functions in the Benchmark is the systems that possess a function like the one in expression 6.

$$G(s) = \frac{1}{(s+1)^2} \tag{6}$$

The root locus in this case is shown in figure 10, where one can see that it does not cut the imaginary axis, and therefore cannot get the setting parameters of the PID controller for this case either.

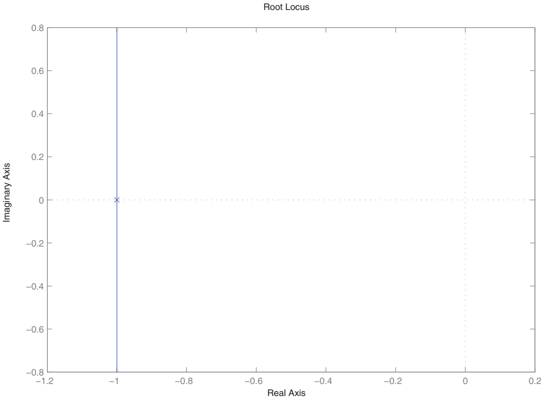

Fig. 10. Root locus for a system with two poles at -1

4.2 Benchmark systems to which empiric adjustment in closed loop is applicable

Apart from the types of systems found in some of the examples in the previous section, the rest can be regulated by a controller PID applying the empiric adjustment in closed loop to obtain its parameters. If there is a transfer function like the one in expression 7, and whose root locus is the one of figure 11, it will be possible to adjust the PID controller in closed loop.

$$G(s) = \frac{1}{(s+1)^3} \tag{7}$$

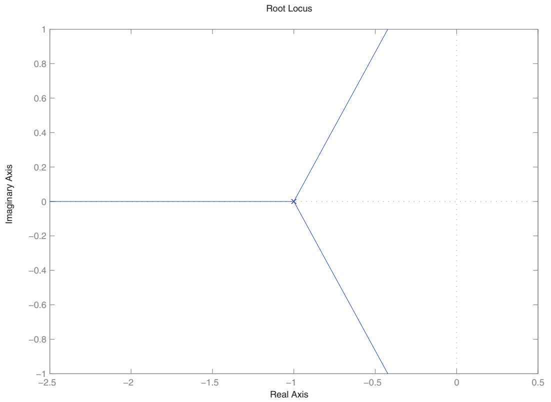

Fig. 11. Root locus for a system with three poles at -1

The response characteristics of the process in closed loop are determined obtaining values of k = 1, K_c = 8.0011, T_c = 3.6274. The range of application is given by the product k x K_c taking a value in this case 8.0011, which, as indicated in table 1 applies to the four methods outlined.

4.3 Analysis of the methods applied to obtain the rules

Having measured the response characteristics of the system, regulating it with the different expressions in the case study proceeds, extracting significant specifications like: response time, peak time, overshoot and settle time.

All the tests will be carried out on all the systems proposed by Ästrom in Benchmark in which they are applicable, to check the results and be able to extract conclusions from which rules will be obtained. If system of the expression 7 is regulated, the results obtained are illustrated in figure 12.

5. PID controller conceptual modeling

The conceptual model of a domain consists of the organization as strict as possible of the knowledge from the perspective of the human brain. In this sense for the domain that is being dealt with in this case study, a general summarized model is proposed and shown in figure 13.

As can be observed it is divided in three blocks:

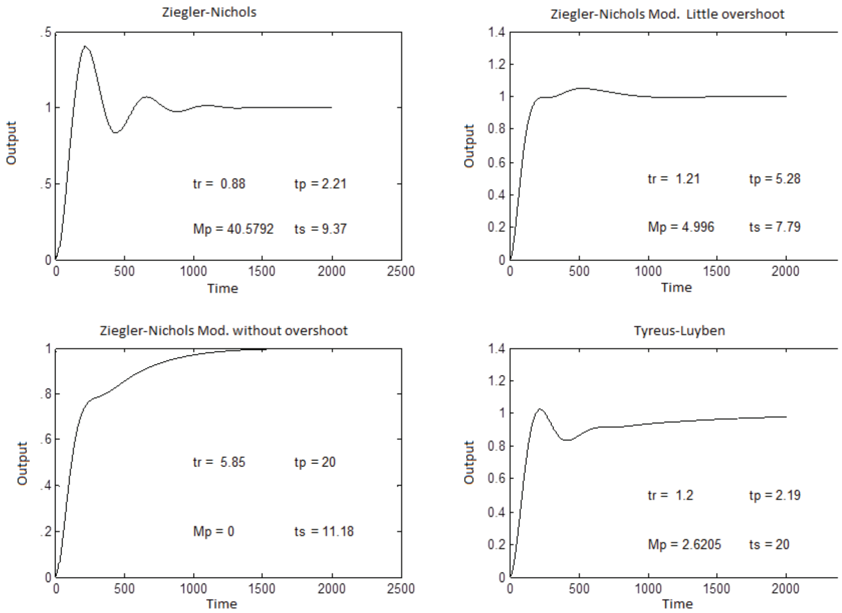

Fig. 12. Response of the system regulated by the expressions of Ziegler-Nichols (initial and modified) and Tyreus-Luyben

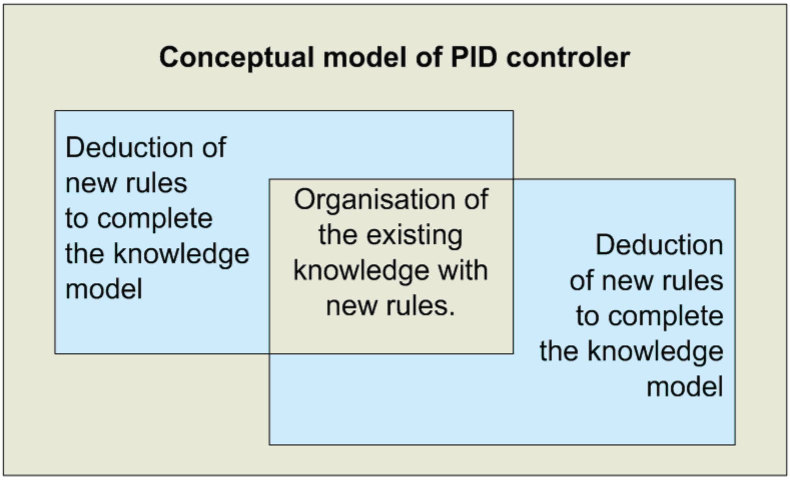

Fig. 13. General schema summarized from the conceptual model of empiric adjustment of PID regulators in closed loop

- Organization of the existing rules: In this block the aim is to organise the existing rules of the types of expressions, scopes of application range, change criteria in the load disturbance or follow up of the setpoint control criterion, etc.

- Organization of existing knowledge with new rules: This block is the meeting point between the other two, and it aims to organise the existing knowledge in an adequate way for which it will be necessary to create new rules.
- Deduction of new rules to complete the knowledge model: In this part it has been detected the necessity to deduce new rules to make a complete knowledge model, from the system itself and the desired specifications, to the final derivation of the parameters of the controller in a reasoned way.

5.1 General diagram of knowledge in the closed loop

In accordance with the steps deducted by the elaboration of the conceptual model, a general diagram of the knowledge for the adjustment of PID controllers in closed loop shown in figure 14 is obtained.

Following the above a more detailed description of the knowledge schema is done, in different figures with their corresponding explanation. It starts with the corresponding part in the top right corner of the general diagram, detailed in figure 15.

In this first part it checks whether the system can be brought to the sustained oscillation by any existing methods. On one hand are the methods of sustained oscillation, and the frequentials methods with Bode as an example, and on the another hand is the method of Relay-Feedback. This is because in some systems empirical adjustment parameters in closed loop can be deducted by the latter procedure in a more feasible, for example, processes in which the transfer function is unknown, it is more viable its use that any of the other two. After selecting the method, in all cases checks if it have been able to achieve sustained oscillation. If the answer is negative in the case of Relay-Feedback is concluded that no empirical adjustment will be applied in closed loop system. If it is negative in the case of sustained oscillation or frequential methods, the user is given the possibility to check if is achieved by the method of Relay-Feedback, if that is not desired, it also concludes that it is not possible to apply empirical adjustment in closed loop system.

If by any method sustained oscillation is reached, it may be possible to adjust the PID closed loop. To check it first calculates the parameters k, K_c and T_c, and then checks if the product k x K_c is within the range of application of expressions.

In figure 16 (continuation of figure 15) check that the measured parameters are within range, if the answer is affirmative then Benchmark systems that do not meet the range are discarded, and the scheme ends in the rule rg. 6. Otherwise, it requires the user to specify if he/she wishes to apply the expressions, although not being within the range. Otherwise, it requires the user to specify whether the terms are applied, although not being within the range. If the answer is negative adjustment in closed loop cannot be done. If the answer is affirmative, a group with generic characteristics to which the system belongs will be determined depending on the product k x K_c. For this, it first checks whether its value is infinite. If not, the scheme applies the rule rg.5, if it were, have to check whether the system is unstable because it can happen that it has a pole at the origin, and in this case, the product is infinite. If the system is unstable and the product is infinite, rule rg.5.1 will be applied and, if unstable, it is concluded that the adjustment in closed loop cannot be used.

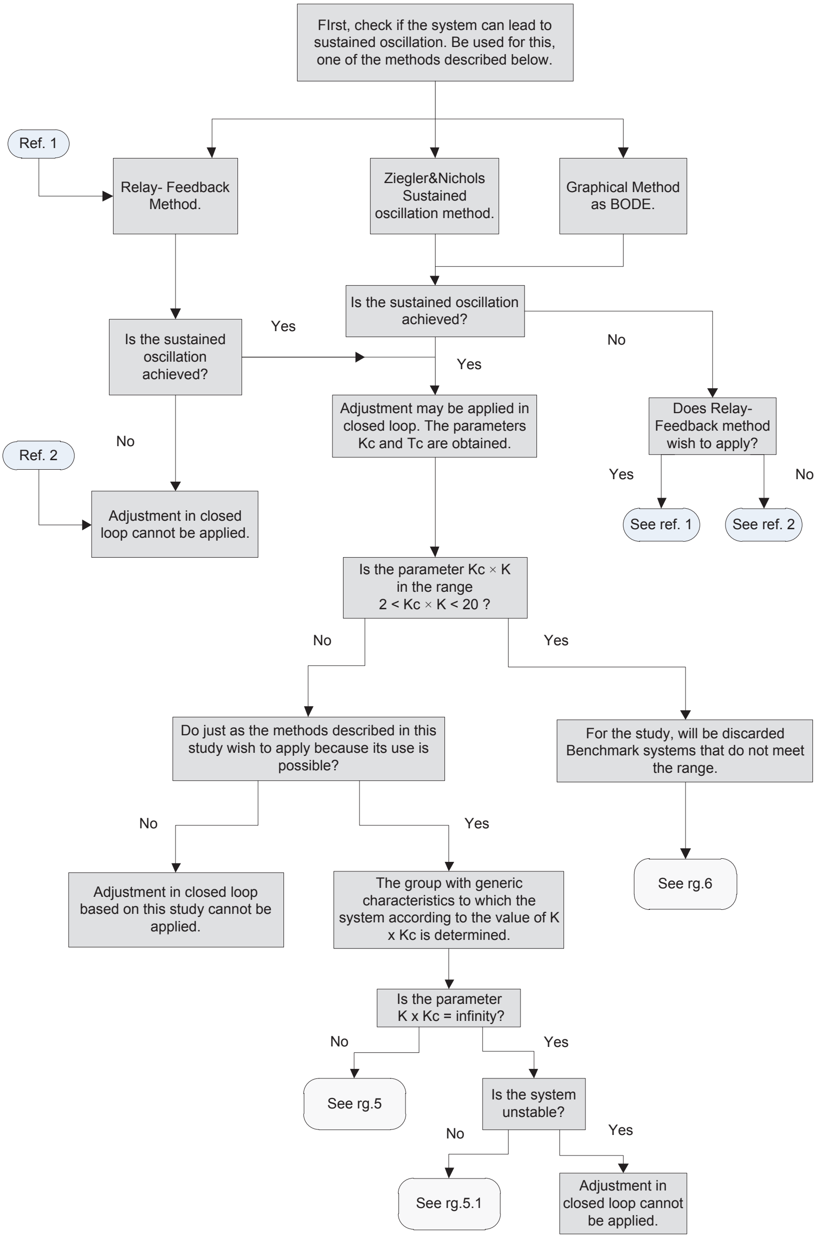

Fig. 14. General diagram of knowledge for closed loop empirical tuning of PID controllers

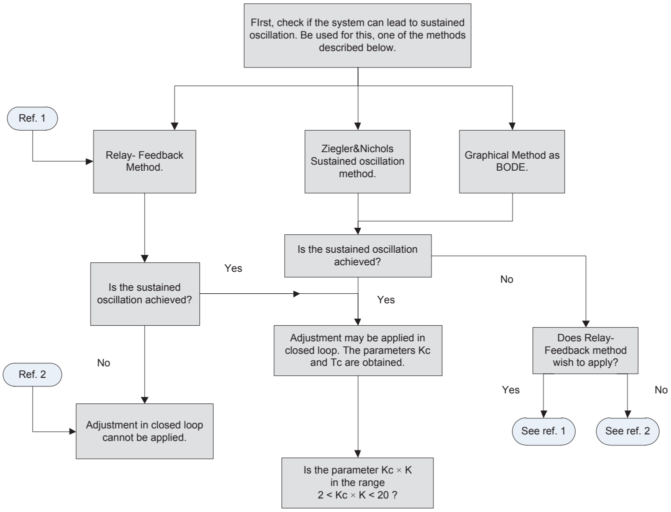

Fig. 15. Area 1 of the diagram

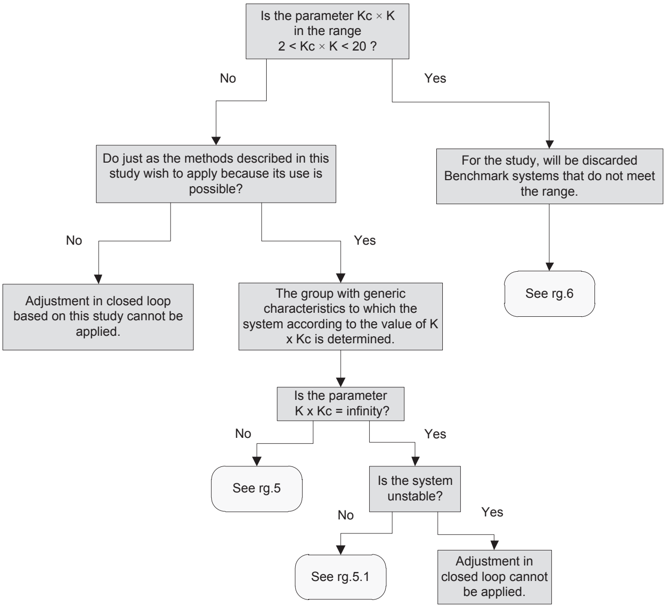

Fig. 16. Area 2 of the diagram

5.2 Deduction of rules to complete the knowledge model

As has been commented in the general summarized schema of knowledge, it is necessary to draw new rules to complete the knowledge model: In this part the need to do a model of complete knowledge model has been detected, from the system itself and the specifications desired, up to the final obtaining of the parameters of the controller. In this sense two examples are shown in which the two possibilities of deduction of the rules are clarified.

5.2.1 Deduction of the rules rg.5

This rule as shown in figure 16, is applied in the worst case, where the product k x K_c is not within the application range of expressions.

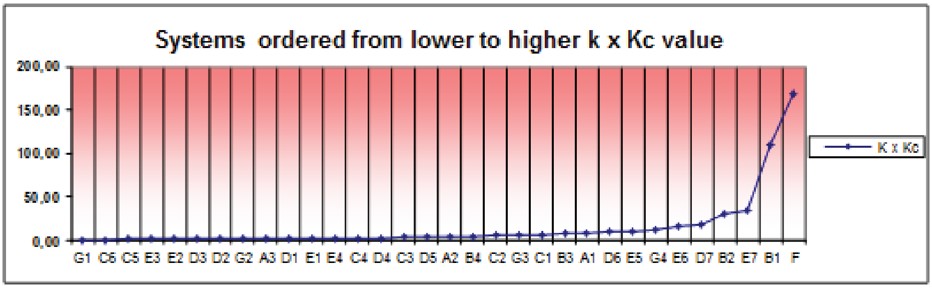

Fig. 17. Systems of Benchmark ordered from lower to higher k x K_c value

In order to create the groups with generic characteristics, different systems are sorted from lowest to highest value of the ratio k x K_c (figure 17 and table 2). In this case is done in a table (table 3) as it intends to have generic groups in all specifications.

In the table the values of the specification in each case have been indicated, alongside the expressions for obtaining the parameters used to improve this specification. Next, a division in groups is made in which the systems with groups of equal expressions are concentrated. Having this in mind, for instance systems G1 to A1, with the condition that $0 < L/T \leq 8.0011$, and establish the following rules:

- To minimize T_r, apply the method Ziegler&Nichols.
- To minimize T_s, apply the method Ziegler&Nichols.
- For the lowest percentage of M_p, apply the method of Ziegler&Nichols modified (without overshoot).
- To minimize Tp, apply again the method Ziegler&Nichols.

Table 3 shows that there are several exceptions which correspond to areas of the range where would be the systems G2, A1 and C6 of Benchmark. If the values obtained in the specifications after applying the above rules are checked, concludes that in the case of A1 and G2, the difference is very small. For the C6 system, these value differences are greater and the rule would not be entirely valid, but it is the only exception and therefore is generalized, despite making a small mistake.

System	k x K_c
G1	0.44
C6	0.5
C5	1.1429
E3	1.5377
E2	1.6422
D3	1.7071
D2	1.7972
G2	1.8812
A3	1.884
D1	1.9052
E1	1.9052
E4	1.9317
C4	2
D4	2
C3	3.2
D5	3.8891
A2	4
B4	4
C2	5
G3	5.24
C1	6.1585
B3	6.7510
A1	8.0011
D6	8.8672
E5	9.7963
G4	11.2414
E6	16.818
D7	17.5578
B2	30.2375
E7	35.1592
B1	110.1
F	167.7135

Table 2. Values of the parameters K x K_c of each system

6. Validation

A validation of the conceptual model proposed is carried out. This will not be done on the cases in which the transfer function is known, and it is exactly adapted to one of the systems referred in the Benchmark, but it will be carried out on the worst case, when the transfer function is not known or if it is known and it does not adapt to any of the systems.

The validation is done on 9 systems not contemplated in the Benchmark and it is checked for each one of the specifications that the model has been developed. There are a total of 36 checking cases, in which the results shown in table 4 are obtained.

Therefore it is considered that the model proposed has a satisfactory functioning, and that overall, the results are the following:

SYSTEM	T_r	T_s	M_p	T_p
G1	24.45 (Z&N)	48.18 (Z&N)	0 (Z&N s M_p)	131.21 (Z&N)
C6	0.44 (Z&N p M_p)	48.95 (Z&N)	0 (Z&N s M_p)	2.81 (Z&N p M_p)
C5	7.92 (Z&N)	19.03 (Z&N)	0 (Z&N s M_p)	110 (Z&N)
E3	0.76 (Z&N)	7.25 (Z&N)	0 (Z&N s M_p)	2.02 (Z&N)
E2	0.72 (Z&N)	6.79 (Z&N)	0 (Z&N s M_p)	1.94 (Z&N)
D3	0.74 (Z&N)	6.53 (Z&N)	0 (Z&N s M_p)	1.99 (Z&N)
D2	0.77 (Z&N)	5.58 (Z&N)	0 (Z&N s M_p)	2.04 (Z&N)
G2	1.05 (Z&N)	9.29 (Z&N p M_p)	0 (Z&N s M_p)	4.71 (Z&N)
A3	4.01 (Z&N)	32.75 (Z&N)	0 (Z&N s M_p)	9.75 (Z&N)
D1	0.84 (Z&N)	5.42 (Z&N)	0 (Z&N s M_p)	2.21 (Z&N)
E1	0.84 (Z&N)	5.42 (Z&N)	0 (Z&N s M_p)	2.21 (Z&N)
E4	0.85 (Z&N)	7.56 (Z&N)	0 (Z&N s M_p)	2.25 (Z&N)
C4	1.32 (Z&N)	8.51 (Z&N)	0 (Z&N s M_p)	3.79 (Z&N)
D4	0.8 (Z&N)	7.25 (Z&N)	0 (Z&N s M_p)	2.13 (Z&N)
C3	1.14 (Z&N)	7.39 (Z&N)	0 (Z&N s M_p)	3.31 (Z&N)
D5	0.77 (Z&N)	6.17 (Z&N)	0 (Z&N s M_p)	2.39 (Z&N)
A2	1.62 (Z&N)	11.76 (Z&N)	0 (Z&N s M_p)	3.94 (Z&N)
B4	1.62 (Z&N)	11.76 (Z&N)	0 (Z&N s M_p)	3.94 (Z&N)
C2	1.02 (Z&N)	8.69 (Z&N)	0 (Z&N s M_p)	2.76 (Z&N)
G3	0.34 (Z&N)	2.88 (Z&N)	0 (Z&N s M_p)	0.78 (Z&N)
C1	0.96 (Z&N)	8.27 (Z&N)	0 (Z&N s M_p)	2.5 (Z&N)
B3	0.52 (Z&N)	4.47 (Z&N)	0 (Z&N s M_p)	1.37 (Z&N)
A1	0.88 (Z&N)	7.79 (Z&N p M_p)	0 (Z&N s M_p)	2.19 (T&L)
D6	0.71 (Z&N)	7.98 (Z&N)	0 (T&L)	2.46 (Z&N)
E5	0.84 (Z&N)	8.95 (Z&N s M_p)	0.31574 (Z&N s M_p)	2.59 (Z&N)
G4	0.16 (Z&N)	1.46 (Z&N)	0 (T&L)	0.4 (Z&N)
E6	1.52 (Z&N)	19.92 (Z&N s M_p)	3.4625 (Z&N s M_p)	4.77 (Z&N)
D7	0.67 (Z&N)	3.98 (T&L)	1.7451 (T&L)	2.46 (Z&N)
B2	0.12 (Z&N)	0.9 (T&L)	10.062 (Z&N s M_p)	0.34 (Z&N)
E7	2.05 (Z&N)	19.75 (T&L)	14.3172 (Z&N s M_p)	6.34 (Z&N)
B1	0.04 (Z&N)	0.33 (T&L)	20.9154 (Z&N s M_p)	0.12 (Z&N)
F	0.13 (Z&N)	1.29 (T&L)	13.2937 (Z&N s M_p)	0.36 (Z&N)

Table 3. Groups rg.5 for changes in the load

- The scores are $36/36 = 100\%$
- The misses are $0/36 = 0\%$

Comment	Number	Percent overall experiments
The expression indicated by the rule coincides with the one that has to actually be used.	30 *cases*	83.4%
The expression indicated by the rule does not coincide with the one that has to actually be used, but the deviation is very small.	6 *cases*	16.6%
The expressions indicated by the rule makes the system unstable	0 *cases*	0%
The expressions indicated by the rule does not coincide with the one that has actually to be used so the deviation is considerable.	0 *case*	0%

Table 4. Results of the validation

7. Conclusions

The task of selection of the adjustment expression to be used has been solved with the proposed technique in the present paper, thus through the follow up of the rules procedure the adjustment expressions can be selected for the case disposed and also choose among them if more than one is applicable.

Having selected the expression or expressions to obtain the parameters, the calculation of these is carried out following the procedure for the case that has been chosen previously in a structured way. And so the possible paths to be followed are solved with rules, including those to reach a balance between specifications that do not improve in one same path.

When carrying out the conceptual modeling two relevant contributions have been obtained. First, clarity has been added in various stages of the adjustment of a PID. Second, some contradictions have been manifested between different expressions that have been solved with it.

The procedure in real plants whose function transfer is different to the ones mentioned in the Benchmark, has been validated for the more restrictive cases of the deduced rules. The results obtained and presented in the corresponding section to validating satisfy the initial objectives when verifying the functioning of the rules in the plants used.

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PID Controller Design Approaches - Theory, Tuning and Application to Frontier Areas

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First placed on the market in 1939, the design of PID controllers remains a challenging area that requires new approaches to solving PID tuning problems while capturing the effects of noise and process variations. The augmented complexity of modern applications concerning areas like automotive applications, microsystems technology, pneumatic mechanisms, dc motors, industry processes, require controllers that incorporate into their design important characteristics of the systems. These characteristics include but are not limited to: model uncertainties, system's nonlinearities, time delays, disturbance rejection requirements and performance criteria. The scope of this book is to propose different PID controllers designs for numerous modern technology applications in order to cover the needs of an audience including researchers, scholars and professionals who are interested in advances in PID controllers and related topics.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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InTech China
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中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821