Genetic Rules to Tune Proportional + Derivative Controllers for Integrative Processes with Time Delays

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Abstract

The controller tuning rules proposed by Ziegler & Nichols and their later modifications have been of huge success in the industry due to their simple application and reliability. The acceptance of this technique is based on the proposition of a set of heuristic rules for tuning the controller requiring information obtained from process measurements. The rules involving mathematical models for tuning had not been of the same success because the mathematical model is not available in most cases nor the qualified staff to develop this kind of designs. The intention of the presented article is to follow the approach proposed by Ziegler & Nichols to analyze integrating systems, maintaining the objective of providing a set of tuning rules obtained from the input and output signals. The difference with the previously proposed approach which uses human experience to develop the set of rules, is the use of evolutionary algorithms for synthesizing the tuning rules.

1. Introduction

The automated control techniques have been greatly improved through years of research and application, however the PID control structure is the most broadly used for industrial applications. An opinion survey performed among industry participants and academic control specialists shows that the PID controller is the second most important contribution to control practice after the microprocessor in the 20th century [1]. The PID strategy has a long trajectory in history: in military applications during The American Civil War [2], the complex development of the first pneumatic PID controllers and the initial rejection toward these [3]. Currently many authors refer that 70% to 90% of the control implemented in industry are PID control loops.

The first pneumatic PID controller sold in industry was the Stabilog from Faxboro in 1939 leveraging on this effort Taylor developed the Fulscope [4]. Before this controllers were developed the most part of control design was implemented “ON-OFF” with some simple pneumatic devices and electro mechanic relays. The PID controller represented a huge challenge for the operators at the time it became commercially available, this probably was the main reason for the lack of success of these controllers at first. In response to the little commercial enthusiasm for this controllers Foxboro printed out bulletins explaining simple and clearly the operation of a device of this nature. Taylor answered entrusting two of the company engineers: Ziegler and Nichols, with the developing of a simple tuning strategy which should be easy to follow by the instruments and operation technicians. They responded in 1942 and 1946 publishing their very well known heuristic tuning rules for open loop systems and closed loop respectively.

The success of the rules proposed by Ziegler and Nichols is due mainly to the fact that they only require knowing the input and output signals from the process in study this is why these rules are still being used. Even now is hard to expect that each operator has good knowledge of complex variables and differential equations in addition to having the mathematical model.
of each system. Currently there are PID manufacturers that have as operation principle the rules proposed by Ziegler and Nichols [5].

The Ziegler Nichols strategy however can just be used with asymptotically stable systems. The Ziegler Nichols open loop method [6] requires the stabilization of the system after a period of time from a step input, the closed loop system on the other side, needs of a stable limit cycle [7]. The tuning techniques for unstable integrating processes required by definition of the total or partial knowledge about the process model and behavior as shown in [8,9]. However if this process data is not available or not enough these tuning techniques are not appropriate.

If the priority is to keep the core approach of the Ziegler Nichols rules, the ideal procedure should be to use some key measurements from the process time response, this may result highly risky with unstable industrial processes, feasible however for integrating industrial systems if the right safety margins are defined.

2. PID Controller

The ISA framework is the most broadly used PID structure in industry.

\[
u(t) = K_i \left( e(t) + \frac{1}{T_1} \int_0^t e(\tau)d\tau + T_d \frac{de(t)}{dt} \right)
\]

This structure is also known as text book algorithm [15], it is defined in association with the Zigler-Nichols rules. A number of the PID tuning techniques for unstable or integrating systems use the equation (1) as a design basis. Due to the dynamic nature of the integrating systems, the most appropriate control structure is a P+D controller. A block diagram of this class of controller is presented in figure 1.

\[
G_{IC}(s) = \frac{(T_d s + 1)K_p G(s)}{1 + (T_d s + 1)K_p G(s)}
\]

Considering that the proposed process includes an integrating dynamic, the process positively adds its behavior to the P+D dynamic for controlling purposes. The proposal stated in the herein presented paper is oriented to practical applications, the following discrete approximation of the P+D controller will be considered further on.

\[
u(k) = K_p \left( e(k) + T_d \left( e(k) - e(k-1) \right) \right)
\]

3. Evolutionary Algorithms

Evolutionary algorithms are techniques with a resemblance of artificial intelligence based upon the natural selection theory. Genetic algorithms are probably the most known and broadly used evolutionary algorithm.

In the natural evolution process, the best fitted individuals have the biggest chances for reproduction, which is essentially important for the survival capability of each individual. With the new generations, the new population have bigger chances to inherit the characteristics of their fittest ancestors. From the outside point of view it may seem that the individuals change their structure through time in order to adapt to the environment. But the fact is the survival of the fittest.

Through an evolutionary process nature finds answers. Evolutionary algorithms emulate such process, building a virtual environment that is the question itself and allowing the evolution of individuals which form the answer (please refer to figure 2).
4. Genetic PID controller

In recent years control applications have leveraged on the optimization capability of the genetic algorithms. As far as PID controllers, the genetic algorithms are used for control optimization in particularly demanding conditions, as an example [13].

The basic idea in genetic PID is the definition of a chromosome [14] with the PID controller gains in the genetic information (please refer to figure 3).

![Figure 3. Gain chromosome](image)

Each chromosome is tested and evaluated. The individuals with higher than the average attributes will have greater chances for reproduction. The set of gains that allow a better performance of the controller will have greater chances to inherit their genetic profile. Please refer to [11, 12] for details on the genetic PID structure.

5. Visioli rules

Visioli leveraged on the optimization capability of the genetic algorithms to replace the contribution of an expert generating tuning tables heuristically for PID controllers.

In [10] Visioli presents a variety of tuning tables for first order unstable integrating systems under several error minimization criteria.

Presented in table 1 there are the optimization criteria for the minimization of the integral of the squared error (ISE) for first order integrating systems following the equation

\[ G(s) = \frac{K}{s} e^{-Ls} \]  

Where integrating gain is represented by \( K \) while the transport delay in the system is represented by \( L \).

The main disadvantage of this method is that a transfer function in the form (4) is required, this means an extra identification protocol.

| Table 1. Visioli tuning rules for integrating systems, ISE criteria. |
|------------------------|------|
| PID parameter | ISE  |
| \( K_p \) | 1.03/KL |
| \( T_i \) | - |
| \( T_d \) | 0.49L |

6. Method Post-optimization

The technique developed by Visioli had been reviewed and used for tuning of several processes. In order to perform verification and trials 30 integrating process had been programmed with a gain range from 0.001 to 1000, with translation delays comprehended between 0.01 to 9 time units. The rules used by Visioli can be understood as an algorithm as follows:

\[ K_p = \text{parameter1}/(K^*L) \]  

\[ T_d = \text{parameter2}*L \]  

The parameters 1 and 2 are the ones optimized by the genetic algorithm used by Visioli. For the development of the fitness function (F.F.) [13], we use the Integral of Absolute Error (IAE) defined by

\[ IAE = \sum_{i=0}^{n} |e(kT_e)| \]  

of an independent genetic algorithm used for the post-optimization of (5) and (6) for the previously defined set of 30 plants. Such evolutionary process is presented in figure 4.

![Figure 4. Evolutionary process of the post-optimization](image)
important to state that the new table is more appropriate for the plants included in the optimization process however if the following process is considered

\[ G(s) = \frac{0.0506}{s} e^{-0.6s} \]  

(8)

which is presented as a testing plant in [10] and if we use the table 2, we obtain the results presented in figure 5. When we review the results for the equation 8, we can observe an IAE value of 230.91 for the original Visioli method, and 165.36 for the improved visioli method.

**Table 2: Post-optimization for Visioli tuning rules for integrating systems, IAE criteria.**

<table>
<thead>
<tr>
<th>PID parameter</th>
<th>IAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kp</td>
<td>0.5992/KL</td>
</tr>
<tr>
<td>Ti</td>
<td>-</td>
</tr>
<tr>
<td>Td</td>
<td>2.1883L</td>
</tr>
</tbody>
</table>

It is important to notice that (8) is tested as a process sampled at 10Hz and was not included in the set of 30 processes used for optimization of the genetic algorithm, by this we can state an acceptable extrapolation capability.

**Figure 5. Control for (8) using tables 1 and 2.**

### 7. Time response based rules

As initially stated, the main objective is to define a set of rules for tuning integrating process without requiring the mathematical model following the equation (4).

It is essential to avoid using parameters that may only be obtained from an identification process in addition to proposing a simple interpretation and use of the rules by the operator. The parameters selected considering the above mentioned can be measured directly from the time response like the slope for the open loop response (M) and the translation delay (L).

In order to obtain the Kp and Td gains for tuning the plant an adequate representation of the slope and the translation delay are required in the genetic algorithm. A modification to the representation used by Visioli is used in the present research.

The last step for obtaining the rules is to perform the genetic optimization process considering a defined set of plants. The fitness function considers the IAE criteria.

The proposed criteria, independent of the mathematical model parameters but dependent on the system time response are presented in table 3.

**Table 3: Tuning rules based on time response for integrating systems, IAE criteria.**

<table>
<thead>
<tr>
<th>PID parameter</th>
<th>IAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kp</td>
<td>0.0747/M</td>
</tr>
<tr>
<td>Ti</td>
<td>-</td>
</tr>
<tr>
<td>Td</td>
<td>0.015*L</td>
</tr>
</tbody>
</table>

Because this table was obtained using an unitary step excitation, it is important to say that when the amplitude of the input signal u (Δu) is different to the unit, M must be calculated as \( M_{new} = M/\Delta u \)

The most demanding stage of the testing process in this research are the tests related with the process that are not included in the genetic optimization. It is very important to mention that table 3 has a better performance with systems with small time delays. Some results associated with this table are presented bellow.

Considering the following integrating process:

\[ G(s) = \frac{0.654}{s} e^{-10s} \]  

(9)

This system with a unit step input will present a integrating response with a slope near 10, the time delay can be measured directly from the time response, as the time the system takes to respond to the applied input. The resulting control for (9) sampled at 10Hz is presented in figure 6 the tables 1 and 3 are also used in
this results. The IAE for Visioli method was 378.73 and for the proposed method the IAE was 333.88.

With the intention of establishing a reference mark for the obtained results, we introduce another method for tuning controllers for integrative systems. Poulin and Pomerlau proposed a method that gives the possibility to handle at the same time the allowable maximum peak overshoot and the minimum phase and amplitude margins [16]. For the process defined by the equation 8, the figure 7 is presented.

A special class of integrative systems is represented by the form:

\[ G(s) = \frac{Ke^{-Ls}}{s(s + a)} \]  

(10)

This form is not contemplated by Visioli. Poulin and Pomerlau present a method that consists on the analysis of the open loop frequency response of the process in series with the controller. The controller parameters are adjusted to satisfy the specification on the maximum peak resonance (Mr) of the closed loop system [9]. The basic idea of the tuning method is to find the controller parameters that minimize the distance between the open-loop transfer function and a specified contour corresponding to the desired maximum peak resonance Mr.

Considering the form (10), we propose the table 4.

**Table 4: Tuning rules based on time response for integrating systems, IAE criteria.**

<table>
<thead>
<tr>
<th>PID parameter</th>
<th>IAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_p )</td>
<td>0.067/M</td>
</tr>
<tr>
<td>( T_i )</td>
<td>-</td>
</tr>
<tr>
<td>( T_d )</td>
<td>0.019*L</td>
</tr>
</tbody>
</table>

If now we suppose the system

\[ G(s) = \frac{e^{-0.2s}}{s(s + 1)} \]  

(11)

In the figure 8 a comparison is presented among the control applied to (11), when the tuning methods are the Poulin and the proposed in the table 4 for systems with the shape (10).

To prove the rules with a practical example an integrative process type was selected: the control of angular position of a D.C. motor which includes a mechanical reduction of speed. Using the step response, a model was identified only with comparative ends. Starting from the slope \( (M_{new}=0.006077) \) and the delay \( (L=0.9\text{sec.}) \) the table 3 was applied, to obtain the controller gains. The control of the motor was...
carried out with a P+D analogical controller implemented with operational amplifiers, using the obtained gains. In the figure 9 a comparison of the control is presented in simulation and the practice.

![Figure 9](image)

**Figure 9.** a) Position Control in simulation b) Practical position control

### 8. Conclusions

The results reported in the presented article are preliminary and are a stage of the research with the main objective of obtaining set of rules like the ones purposed by Ziegler Nichols for integrating systems and some types of unstable systems. The results documented so far are positive. The main idea of this research is to define a set of tuning rules for integrating systems generated with data that can be directly measured from the time response. The approach of obtaining this set of rules leveraging in evolutionary algorithms has a value by itself because is not a very explored way with great potential of results for control applications in the mid term.

### 9. References


