CACSD TOOL FOR SIMULATION AND PERFORMANCE OF MULTI-RATE SAMPLED-DATA SYSTEMS

Yolanda Cerezo[a], Ignacio López[b], Alfredo Cuesta [c], Luis Grau[d]

[a] Universidad Francisco de Vitoria. Madrid. Spain.
[b,d] Universidad Nacional de Educación a Distancia. Spain.
[c] Felipe II College, Universidad Complutense de Madrid. Spain

[a] y.cerezo.prof@ufv.es, [b] ilopez@scc.uned.es, [c] acuesta@cesfelipesegundo.com , [d] lgrau@scc.uned.es

ABSTRACT
In this work a CACSD tool named MRPIDLAB is presented. The tool is devoted to the analysis and tuning of PID controllers working on a general multirate sampled data system, where different variables are sampled at different rates. The tool allows testing different scenarios including not only time constrains in the sampling rate but also delays in every channel. Also, since a multi-rate PID (MRPID) regulator, with 3 extra degrees of freedom which are the internal action rates, is obtained a new general tuning method is implemented. Such a method is a multi-objective optimisation in which up to four performance requirements might be imposed.

An illustrative example is given to show the utilization of the developed analysis tool and to demonstrate the usefulness of the proposed multirate PID control and its tune.

Keywords: Multi-Rate control, Digital control, PID tuning, CACSD tools

1. INTRODUCTION

Multirate (MR) Digital Control Systems are those in which more than one variable is updated at different rate (Velez and Salt 2000). Multirate Digital Control is a research field of great interest, since it can be applied to many different practical situations, both to improve the system performance and to deal with situations which are inherently multirate (Cuenca 2004). The two main fields of application are motion control, from the seminal works of Araki to the most recent ones by Gu Tomizuka or Chen (Gu and Tomizuka 2000; Tomizuka 2004; Mizumoto 2007), and network based control either on a field-bus or even on internet (Sala 2005; Casanova et al. 2006; Salt et al. 2006; Yang and Yang 2007).

On the other hand, PID controller is still the most widely used in industrial processes (Aström and Hägglund 2000; González, López, Morilla and Pastor 2003). In general, its parameters are tuned to achieve a requested evolution in the controlled variable for changes either in the reference or in the load (Aström and Hägglund 2005). In a well designed control system, features of both sensors and actuators should agree with the dynamics of the system to be controlled. Despite of that, it could happen that the measure is not always available at one particular instant specified by the controller, the actuator input can not or should not be modified in certain circumstances or the evolution of the control signal is not adequate for the actuator. Moreover, the controller also imposes its own constraints. However, using a discrete controller has the advantages of obtaining the same responses of a continuous one if the sampling is fast enough but also provides new control strategies impossible to achieve in the continuous domain (López, Dormido and Morilla 1994).

Since the controller is the element that makes the system output to follow the reference satisfying different specifications at a time, it would be desirable not to impose an excessive number of constraints but still being versatile enough to adapt well to the constraints imposed by other elements in the system. To this end, this work extends to the multirate case the classic structure of a sampled control system with PID controller. It also describes the structure of a multirate sampled-data control system, which uses a discrete multirate PID controller. In this system, different periods are used to take samples from the process output, reconstruct the control signal and calculate the control actions, with the only constrain of these being constant but not necessarily equal one to another. The performance of the system is described from a discrete point of view.

A CACSD tool developed for Matlab is presented. Previous works in CACSD tools for MR control systems can be found in (Velez and Salt 2000; Albertos et al. 2003; Cuesta, Grau and Lopez 2006). The contributions of the tool here presented are the implementation of the MRPID controller, in its different configurations (interactive and non interactive form), via a graphical user interface (GUI). The use of an optimization algorithm, particularly using heuristic methods, constitutes a global tool to the design and tuning of multirate PID controllers for a wide range of control engineering applications.

On the other hand the tool is flexible enough to allow testing the effect on the performance of different factors like load disturbances, noise measurements, saturation in the actuators not only in the MR case but also in Single-Rate and even continuous systems

This paper is organised as follows. The next section describes the control systems and the different working modes than can be set. In section III the tool is presented. The tuning method is proposed in section IV. An example is given in section V in order to clarify the use of tool and the benefits of MR control in some cases. Finally the conclusions are given.

2. DESCRIPTION OF THE CONTROL SYSTEM

Fig. 1 shows the structure of the control system. It is a typical sampled control loop (Franklin, Powell and Workman 1994), where both load perturbations d(t) and a noise in the measure n(t) have been included. Note that period T_y, used for taking samples of the control variable and period T_u, used to modify the controlled variable can be different. In the sequel, this system will be called *multirate* system when $T_y \neq T_u$, or *single-rate* system when $T_y = T_u$. Note that the latter is only a particular case of the former.

Following with the same figure, some other signals are present: variable to control y(t), discrete signal of the variable to control $y^* = y(k_y T_y)$ (obtained at period T_y), discrete reference signal $r^* = r(k_y T_y)$, discrete error signal $e^* = e(k_y T_y) = r^* - y^*$, discrete control signal $u^* = u(k_u T_u)$ (obtained at period T_u), continuous control signal u(t) (obtained from u* using a holder H at period T_u).

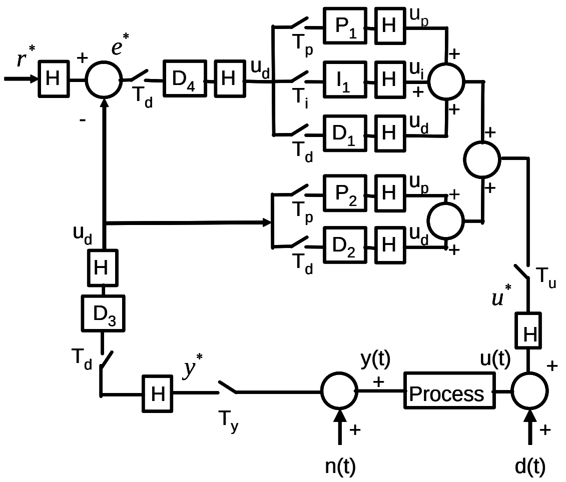

Figure 1: General structure of the multirate PID into a control system.

Taking the classical multirate structure as a starting point, this work proposes its generalization through the introduction of new structures for the controller, multirate PID, in which the proportional P, integral I and derivative D control actions are obtained with periods T_p, T_i and T_d, respectively (which are allowed to be different and independent to each other). H blocks that also appear in this figure are holders that allow the generation of signals of period whilst the last value of its input remains constant between successive samples. T_h can be chosen as the minimum significant number among all periods of the global system. This allows considering any value for the periods with such precision. Note that the digital sum can be obtained, since all periods are multiples of T_h. In what follows, this controller will be called *Multirate PID Controller*. The input of the controller is the error signal e*, which is held at period T_h to generate signal $e(k_h T_h)$. Each of these actions are calculated at those periods and outputs $u_p(k_p T_p)$, $u_i(k_i T_i)$ and $u_d(k_d T_d)$ are obtained and, again, held in order to obtain the sum of all of them, obtain $u(k_h T_h)$ and subsequently sample at period T_u to get the controller output u*.

From the general structure presented and based on different relationships between periods (as proposed in the structure) some operating modes can be defined:

Mode 1. Cuasi-continuous: $T = T_r = T_y = T_u = T_p = T_i = T_d$, with T small enough to design the controller in the continuous domain. This technique is known as Digital Redesign and it is widely applied.

Mode 2. Single-rate: $T = T_r = T_y = T_u = T_p = T_i = T_d$, with T greater than in Mode 1 so that a direct digital design must be chosen.

Mode 3. Single-rate process with multirate controller: $T = T_r = T_y = T_u = m_p T_p = m_i T_i = m_d T_d$.

Mode 4. Multirate process with single-rate controller: $T_r = T_y \neq T_u$, $T_p = T_i = T_d$.

Mode 5. Multirate process with multirate controller: $T_r = T_y \neq T_u$, T_p, T_i, T_d such that at least one of them is different from the rest.

A general framework is now considered in order to deal with different multirate controllers, such as PID, PI-D, I-PD, both interactive and non interactive. Based on each type of controller, only the three corresponding actions will be considered:

1. non interactive PID, with P_1, I_1, D_1.
2. non interactive PI-D, with P_1, I_1, D_2.
3. non interactive I-PD, with P_2, I_1, D_2.
4. interactive PID, with P_1, I_1, D_4.
5. interactive PI-D, with P_1, I_1, D_3.
6. non interactive I-PD, with P_2, I_1, D_3.

The model of the MRPID, of the process and of the control loop are then implemented as algorithms into the MRPIDLAB. Although there are modelling techniques that provide theoretical results for MRPIDs (Salt and Albertos 2005; Cuesta, Grau, López, 2007) they impose simple ratios between the error rate and the control rate. In this sense the numerical model proposed here is better than these because it allows any ratio.

3. SIMULATION TOOL

Both the simulations presented in this work and the tunings have been obtained using a CACSD tool named

MRPIDLAB and developed by the authors for Matlab. It consists of two interfaces shown in Fig. 2: The input interface (above) and the General Tuning Method (GTM) (below).

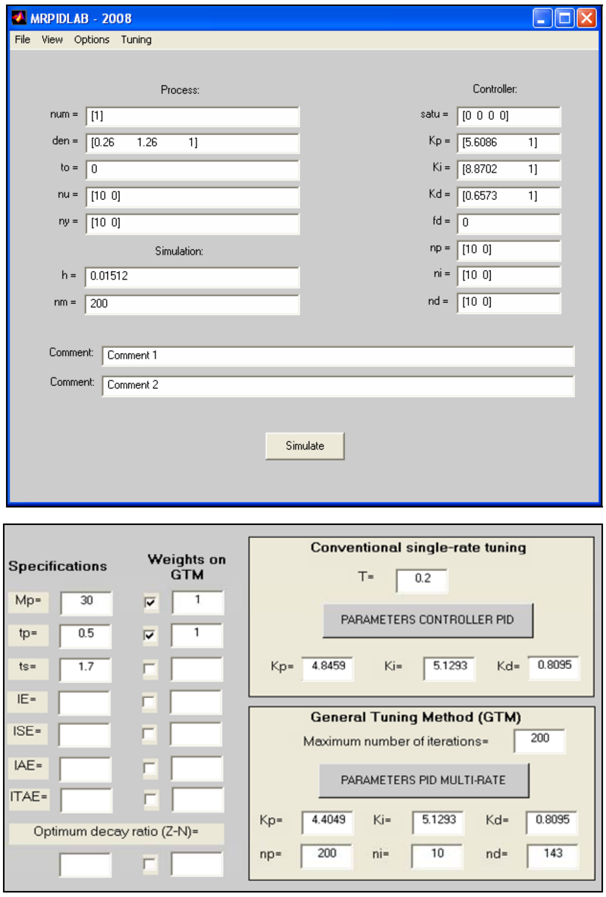

Figure 2: Input interface (above) and the GTM interface (below)

3.1. Input interface

Here, the controls are distributed in four sections: Simulation, Process, Controller and Comments.

- *Simulation*, which allows to introduce the simulation period h (T_h or one of its integer submultiples) and the number of samples to calculate nm. T_h can be chosen as the minimum significant number among all periods of the global system. This allows considering any value for the periods with such precision.
- *Process*, which allows to introduce the process model (linear system with time delay, *num*, *den* and t_0), periods $T_y=n_y h$, $T_u=n_u h$ and delays associated to y* and u*.
- *Controller*, which allows to introduce saturations for the control signal u(t) and the output y(t), as well as control parameters (K_p, K_i, K_d), the algorithm applicable to each action, the factor of the derivative filter f_d, periods $T_p=n_p h$, $T_i=n_i h$, $T_d=n_d h$, and delays associated to the different actions.
- *Comments*, lines for comments associated to the simulation.

In the lower part of the window a ‘Simulate’ button runs a simulation with the data introduced.

There are also four different menu options:

- *File (open, save* and *exit)*, which allows to save in a file all variables associated to an experience, or open a file of such type, and exit the application.
- *View (all, output, error, control, proportional, integral, derivative, measure, actuator* and *delete)*, which allows to see the different signals obtained through the simulation and to delete all but the last simulation.
- *Options (controller-type, load, noise* and *anti-windup)*, allows to among controllers PID, PI-D or I-PD, interactive or not, and introduce perturbations in load, noise in measure and anti-windup methods.
- *Tuning (frequency and time)*. Depending on the specifications, it allows to do a pre-tuning and a fine fit for the final tuning, by means of numerical optimization and using heuristics algorithm.

MRPIDLAB proves to be a powerful tool especially in the controller design stage because it provides an environment in which different uncertainties and time scenarios, especially multi-rate situations, can be included, obtaining more realistic simulations.

3.2. GTM Interface

GTM interface is launched when tuning is requested. Up to four different specifications can be set: Maximum percentage overshoot (M_p) and the time it occurs (t_p), settling time (t_s) and one of the performance criteria among IE, ISE, IAE or ITAE. Alternatively also the decay ratio can be set. To its right the weights for each specification must be fixed.

The upper box to the right of the interface is necessary to find the parameters of a single-rate PID controller that satisfies or gets the best control action given the specifications. This is the starting point for the optimisation (box below-right) for tuning the real multi-rate controller, implemented in the tool and summarised in the next section

4. GENERAL TUNING METHOD

Although the main goal of this paper is to present the MRPIDLAB, it is necessary to show briefly the general tuning method (GTM) implemented in order to demonstrate the benefits of the tool and the MRPID controller. A more exhaustive description may be found in (Lopez and Cerezo 2007). The most relevant feature of the GTM highlighted in this section is the fact that PID parameters and inner rates are obtained ad hoc using an offline numerical optimization via a heuristic algorithm, simulated annealing (Rutenbar 1989), when classical design methods can not be directly applied or when they lead to a poor performance. As starting point for the optimisation, a solution considering a conventional, single-rate is selected. Thus, the GTM consists of the following steps:

1. Consider a set of specifications with fixed values.
2. Select as period T the maximum of the periods found in the loop.
3. Apply a classical tuning method which allows obtaining control parameters for the single-rate system at period T.
4. Using control parameters obtained in Step 3, minimize a cost function (1) in such a way that specifications can be obtained for the multirate case.

In the last step, from all the obtained parameters, re-tune of K_p, K_i y K_d and/or periods T_p, T_i and T_d is possible through minimizations of a cost function J

$$J(K_p, K_i, K_d, T_p, T_i, T_d) = \sum_{i=1}^{m} \beta_i J_i \quad (1)$$

Since the global control goal may also depend on many different goals, sometimes even contradictory one to another, the relevance of each one can be expressed by weights $\beta_i \in \Re$ with $0 \le \beta_i \le 1$. Besides, any of the goal functions J_i of (1) are:

$$J_i(K_p, K_i, K_d, T_p, T_i, T_d) = \left| \frac{f_s - f_e}{f_e} \right| \quad (2)$$

being f_e the expected value and f_s the value obtained in the simulation.

As a last remark, this is a local optimization process that generally leads to satisfactory results, but it can not guarantee that the optimal global solution will be achieved.

5. EXAMPLE

This example shows just a bit of the potential that both MRPID controllers and the developed tool have.

In the sequel we will consider a performance requirement is an overshoot M_p=30% at t_p=0.5 seconds and a settling time t_s(2%)<1.7 seconds. The control loop is as follows: the error is measured every T_y=0.2 seconds and the control action is updated every T_u=0.143 seconds, the controller used is a PID with parallel structure and the process model is:

$$G_m(s) = \frac{1}{(0.25s+1)(s+1)} \quad (3)$$

Four different cases have been tested. The first one considers the problem from the classical discrete single-rate (SR) control theory and imposes a single period T=max(0.2, 0.143)=0.2. With respect to T_h its value is considered in all the experiments equal to 0.001 as imposed by all periods of the global system. Then the real MR problem is dealt with in three different ways: MR-I uses the tuning parameters obtained under the assumption of a single period T, MR-II uses new parameters now considering the multi-rate situation from the beginning, and finally MR-III provides new parameters considering also inner multi-rate. Results have been shown in Tables 1 and 2. In the sequel we give a detailed explanation of the tests.

Table 1: Tuning experiments

Sampling scheme					
Case	T_y	T_u	T_p	T_i	T_d
SR	0.2	0.2	0.2	0.2	0.2
MR-I, MR-II	0.2	0.143	0.2	0.2	0.2
MR-III	0.2	0.143	0.2	0.01	0.143

Table 2: Tuning experiments

Parameters of the controller			
Case	K_c	K_i	K_d
SR, MR-I	4.8459	5.1293	0.8095
MR-II	2.0426	2.9418	1.0559
MR-III	4.4049	5.1806	0.7934

The first one (SR) consists of selecting a sampling period T at which a conventional single-rate tuning is done. Thus considering T=max(T_y,T_u)=0.2, applying pole assignment methods and finally minimising the cost function (4) we obtain the controller parameters K_c, K_i, K_d shown in Table 2.

$$J = \beta_1 \left| \frac{M_{ps} - M_{pe}}{M_{pe}} \right| + \beta_2 \left| \frac{t_{ps} - t_{pe}}{t_{pe}} \right| + \beta_3 \left| \frac{t_{ss} - t_{se}}{t_{se}} \right| \quad (4)$$

However, if the controller is tuned with such parameters, when considering the real multi-rate situation and T_u drops to 0.143 sec. (MR-I) the performance is degraded. The response of the process and the control action for both SR and MR-I are shown in Fig. 3 and 4 respectively.

Remark 1. SR satisfies the requirements but not the sampling constrains while MR-I satisfies the sampling constrains but, since it uses the same parameters than SR, does not satisfies the requirements. Hence, SR tuning method is not valid when the goal is to tune the controller for MR situations.

The second test (MR-II) minimise (4) again, but now considering the real MR situation from the beginning, with T_r=T_y=T_p=T_i=T_d=0.2 and T_u=0.143. Once the tune is done, Fig. 5 and 6 show the response and the control action with the new results versus the MR-I ones.

Remark 2. The requirements on M_p and t_p are satisfied but not on t_s. Then it would be necessary to have new degrees of freedom in order to make more flexible the controller and thus attain the objective.

In the last test (MR-III) inner multi-rate is added to the controller so that any control action works with different period to another. Thus, having T_p=0.2, T_i=0.01 and T_d=0.143 new parameters are found (see

Table 2). Response and control action are shown in Fig. 7 and 8.

Remark 3. Requirements are now fully satisfied.

Remark 4. It was not possible to do it in any of the former tests. Just when every basic control action took different rates the global control action was able to do it.

This is the most relevant result of this batch of tests and justifies the use of the MRPID considering the inner rates as extra degrees of freedom.

Remark 5. Both the tuning method and the simulations are implemented in MRPIDLAB, under a Graphical User Interface that simplify the use.

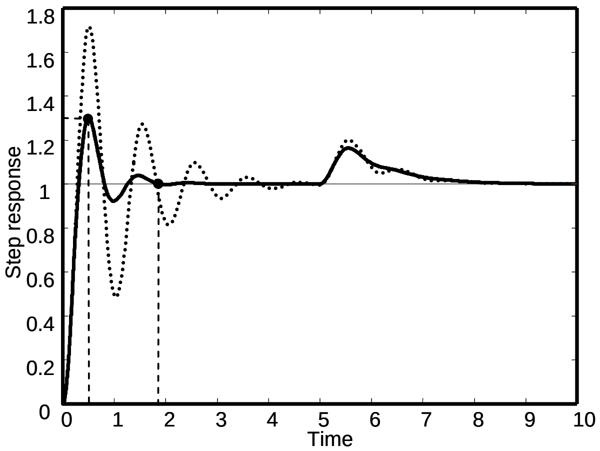

Figure 3: System response for SR (solid) and MR-I (dashed).

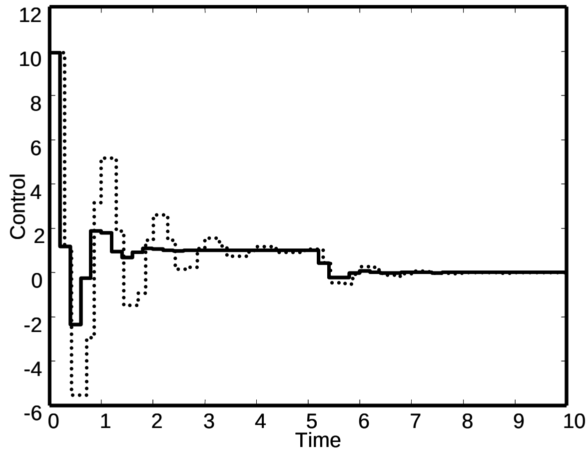

Figure 4: Control action for SR (solid) and MR-I (dashed).

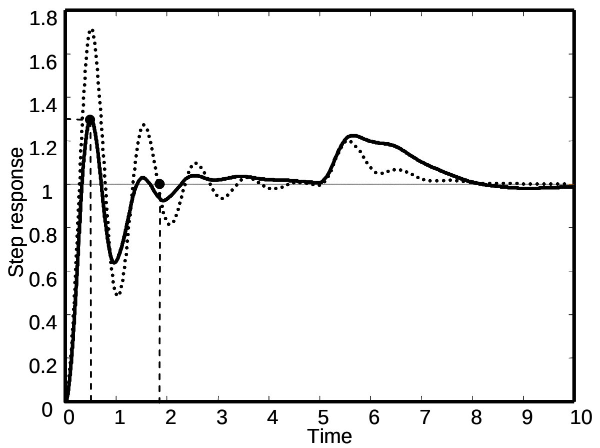

Figure 5: System response with MR-I (dashed) and MR-II (solid).

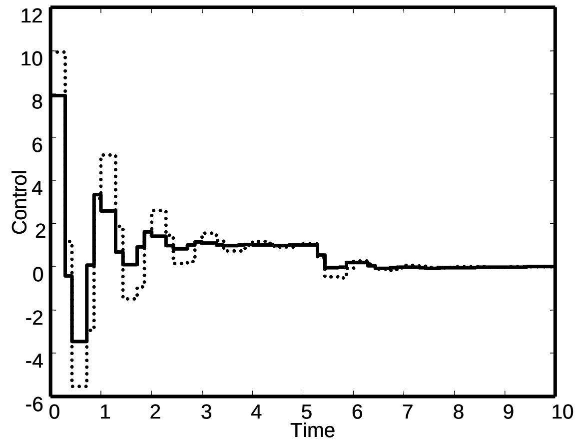

Figure 6: Control action with MR-I (dashed) and MR-II (solid).

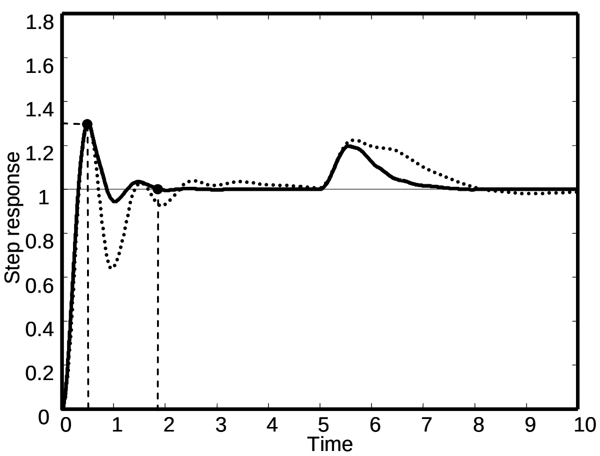

Figure 7: System response with MR-II (dashed) and MR-III (solid).

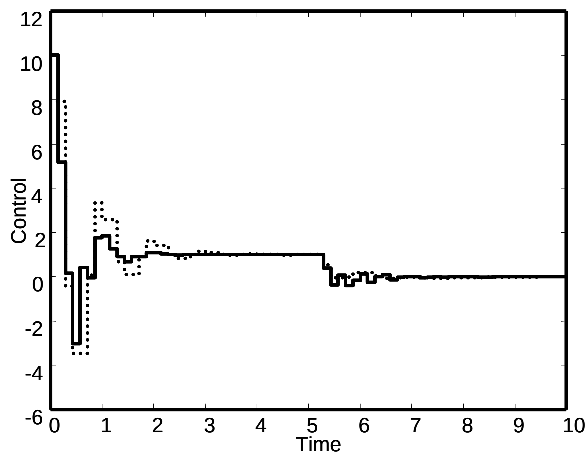

Figure 8: Control action with MR-II (dashed) and MR-III (solid).

6. CONCLUSIONS

The contribution of this paper is to present a new Matlab™, MRPIDLAB. The goal of this tool is twofold: design and simulation. With respect to the former, it takes into account both conventional and non-conventional discrete PID controllers (and continuous when the sampling period is high enough). It is remarkable that non-conventional systems are closer to real problems and that the designing procedure is a multi-objective optimisation. Hence the controller obtained proves a better performance than the single-rate approximation.

On the other hand, the tool serves a simulation environment in which any sampling rate can be set in any variable, different PID configurations can be tested, and saturations, load disturbances, noise measurements and delays can be included.

Finally it is remarkable that the use of MRPID together with the GMT may improve considerably the performance and satisfy the requirements there where conventional PID or tuning methods do not.

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