

A Bio-knowledge based method to prevent control system instability

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Abstract—This study presents a novel bio-inspired method, based on gain scheduling, for the calculation of Proportional-Integral-Derivative (PID) controller parameters that will prevent system instability. The aim is to prevent a transition to control system instability due to undesirable controller parameters that may be introduced manually by an operator. Each significant operation point in the system is firstly identified. Then, a solid stability structure is calculated, using transfer functions, in order to program a bio-inspired model by using an artificial neural network. The novel method is empirically verified under working conditions in a liquid-level laboratory plant.

Keywords- *bio-inspired models, artificial neural networks, knowledge-based system, industrial applications, robust stability*

I. INTRODUCTION

Continuous research is necessary in the field of process engineering to arrive at new methods of regulation, in order to improve current designs [1]. The demand for system control applications is driven by the increasingly numerous ranges of possibilities [2-4] [5-8] that are nowadays under development or in use.

Despite the rapid development of novel methods for regulation processes, better alternatives to popular techniques, such as the “conventional” Proportional-Integral-Derivative (PID) controller, have yet to be found. Many aspects of PID have been examined, ever since the first theoretical analysis of a PID controller by Nicholas Minorsky [9] in 1922.

Numerous innovations have been introduced to control systems for processes in almost all fields [10, 11]. Interesting examples are those based on artificial intelligence methods, [5-8, 12]. Nevertheless, the vast majority, as many as 90% [13], of control loop systems use PID controllers. Nowadays, conventional PID is often applied for different reasons such as ruggedness, reliability, simplicity, error tolerance, and so on [14].

When dealing with non-linear systems, certain specifications have to be equal in all areas of operation. The regulator will therefore require different parameters for each area.

These problems can be reduced by using self-regulating and adaptive PID controllers [15, 16]. It should be noted, however, that their implementation can be expensive and specific to the type of process that it is meant to regulate,

which further complicates any general theory on PID controllers.

Many of the drawbacks resulting from self-regulating and adaptive PID controllers are alleviated using the well-known Gain Scheduling method [17, 18]. This method is easier to implement, and normally achieves highly satisfactory results. The concept of Gain Scheduling began in the early 90s [19] and is now considered part of the family of adaptive controllers [15].

Significant system variables that define the point of operation have to be selected in order to implement Gain Scheduling. It is then necessary to choose several regions throughout the entire operating range of the plant, in which behaviour is linear. The controller parameters are then fixed which provide similar specifications for the operating range of the plant.

Although, there is no systematic procedure for these tasks; the first step often begins with the easily measured variables. The second step is more complicated, as it is necessary to choose operation points throughout the entire range of plant operations. The system may be stable for controller parameters that are deduced, but it may not be stable between the selected points. There is no simple solution to this situation, which is usually broken down into constituent parts. This is the reason why the subject has been studied by researchers [20, 21] and why it is necessary to create a Knowledge Base System (KBS) [22-27].

The Gain Scheduling method selects the correct controller parameters, although operators often adjust the parameter values with the aim of improving plant specifications. At times, the parameters they assign can cause instability. The novel bio-inspired method proposed in this paper is intended to prevent instability. Artificial neural networks are proposed as a means of overcoming the problem [28-30]. Essentially this method decides whether PID parameters programmed by human operators are valid and, whenever the plant enters an unstable zone due to parameter combinations, the method restores a more stable combination for the operation point in question.

This paper starts with a brief introduction to PID controller topology in Section 2. Section 3 introduces the novel bio-inspired controller topology, and Section 4 goes on to explain the stability/instability solid structure concept. A case study based on a non-linear process, used to demonstrate the proposed method, is described in Section 5.

Finally, the conclusions and future lines of work are presented in Section 6.

II. PID CONTROLLER TOPOLOGY

There are multiple ways to represent PID controllers, but perhaps the most widely used is given in equation 1, (commonly known as the standard format) [13, 14].

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

Where ‘ u ’ is the control variable and ‘ e ’ is the control error given by ‘ $e = SP - y$ ’ (difference between ‘ SP ’, the reference specified by the input and ‘ y ’, the measurement unit specified by the output). The other terms are the tuning controller parameters: proportional gain ‘ K ’, integral gain ‘ T_i ’ and derivate gain ‘ T_d ’.

III. A NOVEL BIO-INSPIRED CONTROLLER TOPOLOGY

System dynamics change with process operation conditions. Changes in a dynamic process may, for instance, be caused by well-known nonlinearities inherent in the system. It is possible to modify the control parameters, by monitoring their operating conditions and establishing rules. The methodology comprises the following steps: first of all, Gain Scheduling is applied, then the behaviour of the plant is analyzed at different points of interest, and, finally, rules are established to program gains in the controller. It would then be possible to obtain certain specifications which remain constant throughout the whole range of operation. In the proposed method, it is possible to change the PID parameter values to improve the operating conditions, but the possibility of undesirable parameter combinations must be prevented. This idea is schematically represented in Figure 1.

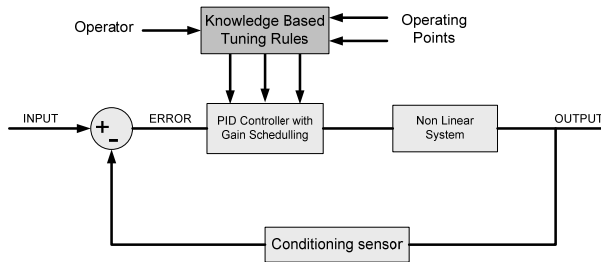


Figure 1. Gain Scheduling with proposed topology.

The idea of Gain Scheduling is to obtain the PID parameters when given the operating points. In this case, a new input has been added, with which the operator can modify the other parameters taken from knowledge based tuning rules. Figure 2 shows a basic diagram of the suggested structure for the method in which PID parameters may be adjusted by the operator. If the input causes system instability, the proposed topology can commute parameters and program the controller to maintain it within the dynamic range of the plant.

There is an artificial MLP-type neural network [31] in the proposed system, which must be trained to detect the existence of stable parameter combinations. In case of instability, the system will revert back to stable values according to the operating work point that was initially programmed.

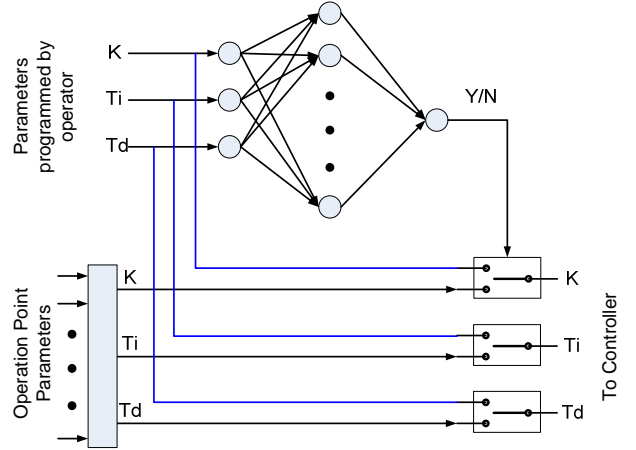


Figure 2. Multi-Layer Perceptron Neural Network architecture.

IV. STABILITY SOLID STRUCTURES CONCEPT

In order to apply a Multi-Layer Perceptron (MLP) network, an interesting and informative data set must be chosen.

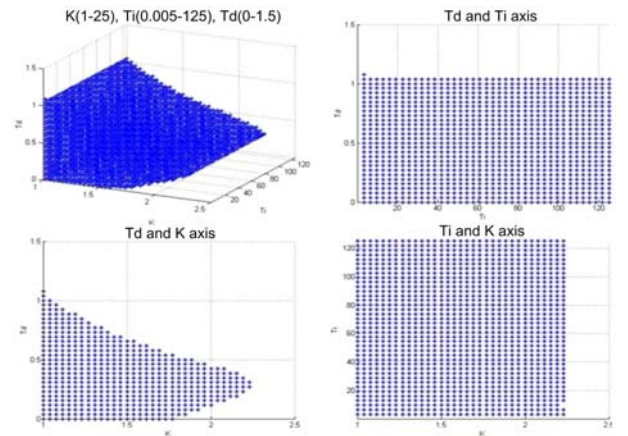


Figure 3. Example of a solid stability structure.

To that end, solid stability and instability structures were applied, in order to delimit both states in absolute terms. These structures are defined by PID controller parameters along with its stability/instability (both states do not coexist) points that have to be placed into three axes of a three-dimensional graphic. Abundant literature exists on robust stability problems that describe this concept [32-34]. Figure 3 shows an example of a solid stability structure: a 3-dimensional graph (the three parameters of the controller K ,

Ti and Td) with the corresponding 2-dimensional views. The volume that is represented in the 3-dimensional graph consists of parameter combinations of the controller for a stable system. If the structure was unstable, then the volume consists of the parametric controller combinations for an unstable system.

V. A CASE STUDY: EMPIRICAL VERIFICATION OF THE PROPOSED METHOD

An empirical verification of the proposed novel method was performed on a small pilot plant (figure 4) in which the tank level is controlled by adjusting the following parameters: $q_i(t)$ is the input flow, $q_o(t)$ is the output flow, $h(t)$ is the tank liquid level, A is the tank base area, $SP(t)$ is the set point for the level, G_r is the controller, $n(t)$ is the measure level in the tank, $u(t)$ is the signal control to operate the valve, K_v and K_b are constants relating to features of the valve and the level sensor respectively.

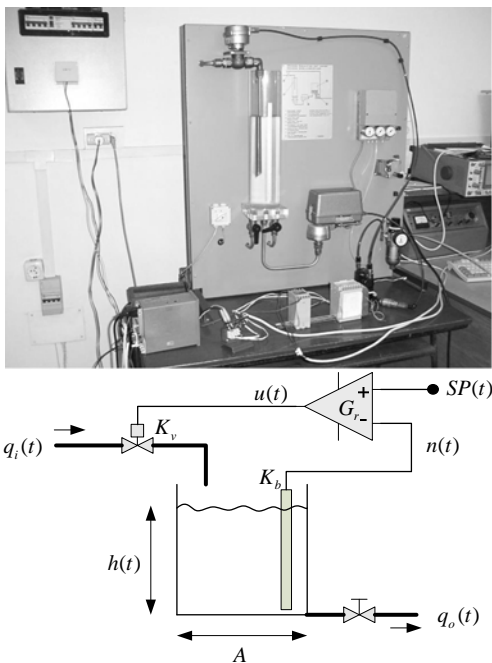


Figure 4. Photograph and scheme of the real plant.

The real plant used for these experiments consists of a tank, fed at the top by a proportional valve (Fig.4), which will be controlled to maintain a constant water level while emptying through an output restriction.

The regulator is a virtual controller that takes signals from the plant through a data acquisition card, which are fed into the Simulink Matlab software. As a set point signal, the plant receives the required water level and adjusts the proportional valve to regulate the input flow into the tank.

A. System operation conditions which define a Knowledge Base System (KBS)

The operation conditions of the system are infinite; certain values must therefore be chosen. Coherent estimates

are necessary to achieve good results and it makes no sense to obtain parameters for multiple cases. One approach is to choose a reasonable amount of equidistant values and observe the parametrical changes in each case. An opportunity arises to define new intermediate values if there are substantial changes from one value to another.

Certain characteristics of the tank will not vary such as its base area. In this case the only term that defines the operation conditions or gains adjustment rules of the controller is the level of the tank. It should be highlighted that that certain aspects may arise under field conditions, such as changes in pressure, noisier communications, dirty system components, distance between control and actuators or sensors. Taking into account the pilot plant and the value ranges that can taken by the level of the tank, ten different operating conditions (ranges) were established: (0%-10%), (10%-20%), ..., (90%-100%). As will be seen in the final results, the chosen range of tank filling values will be sufficient to cover the entire operating range of the system.

B. Obtaining the controller parameters for each operation point

A hysteresis block could be selected to obtain the regulator parameters of the different working points, in parallel with the PID controller, before applying the Relay Feedback method.

The Relay Feedback method is an alternative to the Ziegler-Nichols closed loop [35-37], for the empirical location of the critical gain (K_c) and the period of sustained oscillation (T_c) of the system. The method, developed by Aström and Hägglud [15, 38], fixed the system in its oscillation state. Its implementation scheme is shown in Figure 5. The Relay Feedback has the advantage that an adjustment can be made to the set point at any time.

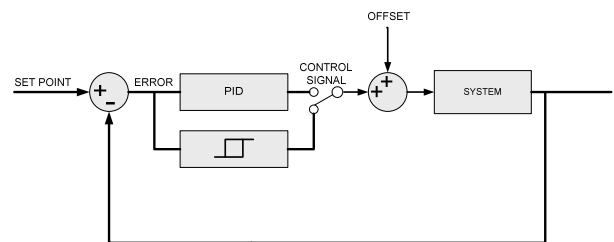


Figure 5. Diagram of Relay-Feedback with relay and PID controller option.

This system oscillation has a period with approximately the same value as the period in the Ziegler-Nichols method. A relay with hysteresis centered on the zero value with an amplitude d and a hysteresis window width of h is recommended for the general method.

C. Procedures carried out

1) *Obtaining certain parameters: T_c and K_c :* As this particular case study is working with a relatively slow system, there is no need to implement the hysteresis cycle mentioned in the above explanation of the Relay Feedback with a window. Instead, a simple comparator is enough ($h=0$)

and $d=0.5$). The offset for this case is not necessary because it would be zero. When the system is in operation and sufficient time has elapsed, oscillation is stabilized and periodic. It is then necessary to pay attention to the final zone, and with the expressions for the Relay Feedback method, the extracted parameters are T_c and K_c .

2) *Obtaining the initial PID controller parameters.* With the parameters that have been obtained in the previous step, it is possible to get the controller parameters to apply direct formulas, thereby achieving the three terms of the regulator: (K , T_i and T_d). In this system, they will have to be obtained from load disturbance criterion, after which the Ziegler-Nichols closed loop method is applied [37].

3) *Controller fine tuning.* Were the results unsatisfactory, subsequent manual fine-tuning may occasionally be needed after having obtained the parameters with the relay feedback method. This is a delicate adjustment which should not at any point saturate the output controller. A compromise has to be found, without the proportional component (K) being excessive, that would cause a rapid response in the output and little overoscillation, which would apparently be ideal. However, under these conditions the proportional valve will be in a state of constant flux, which will lead to its deterioration within a short period of time. As a conclusion, it is necessary to search for gradual outputs, without saturation or sudden changes. Parameter obtaining for each case: Taking into account all the aspects commented on above, the criteria for the fine-tuned controller parameters in each case are minimum overoscillation and maximum speed for the restrictions presented in the preceding paragraphs. Accordingly, this leads to the parameters shown in Table I.

TABLE I. TABLE TYPE STYLES

| Level | K | T _i | T _d |
|------------|-----|----------------|----------------|
| 0% - 10% | 3.2 | 22 | 3.1 |
| 10% - 20% | 3.0 | 27 | 3.9 |
| 20% - 30% | 2.8 | 30 | 4.3 |
| 30% - 40% | 2.5 | 33 | 4.6 |
| 40% - 50% | 2.1 | 35 | 4.8 |
| 50% - 60% | 2.0 | 36 | 5.1 |
| 60% - 70% | 1.9 | 39 | 5.2 |
| 70% - 80% | 1.6 | 40 | 5.3 |
| 80% - 90% | 1.1 | 41 | 5.4 |
| 90% - 100% | 1.0 | 41 | 5.4 |

4) *Neural Network implementation.* A different Multi-Layer Perceptron (MLP) [28] network was applied for each operation condition range in this research, in order to detect parameter values that lead to system instability. Firstly, it was necessary to obtain the transfer function for each operating point under consideration. To do so, the system identification was obtained at each point by applying an ARX (Auto-Regressive models with eXogenous inputs) method [39] using the Matlab Identification Toolbox. Other identification methods used were AR (AutoRegressive

model) and ARMAX (AutoRegressive Moving Average model with eXogenous inputs model) but the best results were achieved with ARX for the plant used in the experiment (table II shows the Fit between the real plant and the model, and the final prediction error that provides a measure of model quality).

TABLE II. COMPARISON OF IDENTIFICATION METHOD PARAMETERS (FIT AND FINAL PREDICTION ERROR)

| Transfer function range | AR | | ARX | | ARMAX | |
|-------------------------|--------|---------|--------|---------|--------|---------|
| | Fit(%) | FPE | Fit(%) | FPE | Fit(%) | FPE |
| 0% - 10% | 52.1 | > 10e-6 | 70.1 | < 10e-6 | 65.3 | < 10e-6 |
| 10% - 20% | 55.3 | > 10e-6 | 73.2 | < 10e-6 | 69.0 | < 10e-6 |
| 20% - 30% | 56.0 | > 10e-6 | 75.6 | < 10e-6 | 72.1 | < 10e-6 |
| 30% - 40% | 55.1 | > 10e-6 | 75.8 | < 10e-6 | 75.5 | < 10e-6 |
| 40% - 50% | 56.8 | > 10e-6 | 76.2 | < 10e-6 | 75.8 | < 10e-6 |
| 50% - 60% | 56.0 | > 10e-6 | 78.1 | < 10e-6 | 76.1 | < 10e-6 |
| 60% - 70% | 54.1 | > 10e-6 | 78.0 | < 10e-6 | 76.5 | < 10e-6 |
| 70% - 80% | 56.1 | > 10e-6 | 78.2 | < 10e-6 | 76.0 | < 10e-6 |
| 80% - 90% | 56.2 | > 10e-6 | 78.8 | < 10e-6 | 75.7 | < 10e-6 |
| 90% - 100% | 55.8 | > 10e-6 | 72.4 | < 10e-6 | 72.3 | < 10e-6 |

Stability structures were then obtained, and the Neural Network architecture was trained with those same points. A neural network was obtained for all operating points. The number of neurons in its intermediate layer fluctuated between 6 and 8. The structure was adopted after rigorous testing with different numbers of neurons in the hidden layer (tests were conducted with 4 to 9 neurons in the intermediate layer) for every neural network.

The activation transfer functions of the hidden layer are hyperbolic tangent types. Other activation functions were probed, although the best results for each operation point in all the ANNs were achieved with the hyperbolic tangent function (table III). In the output layer, a hard limit transfer function was applied to indicate whether the parameters programmed by human operator are valid or whether it is necessary to apply corresponding stored parameters to the operation point.

TABLE III. COMPARISON BETWEEN ARTIFICIAL NEURAL NETWORK ACTIVATION TRANSFER FUNCTIONS (LINEAR TRANSFER FUNCTION, LOG-SIGMOID TRANSFER FUNCTION, TAN-SIGMOID TRANSFER FUNCTION) IN HIDDEN LAYER (BEST ERROR AND NUMBER OF NEURONS IN MIDDLE LAYER)

| ANN range | linear | | logsig | | tansig | |
|------------|--------|--------|--------|--------|--------|--------|
| | Err(%) | No Ne. | Err(%) | No Ne. | Err(%) | No Ne. |
| 0% - 10% | 21 | 7 | 10 | 7 | 3 | 7 |
| 10% - 20% | 19 | 8 | 11 | 7 | 0 | 6 |
| 20% - 30% | 25 | 8 | 13 | 7 | 0 | 6 |
| 30% - 40% | 26 | 7 | 15 | 7 | 0 | 8 |
| 40% - 50% | 24 | 8 | 12 | 8 | 0 | 7 |
| 50% - 60% | 18 | 8 | 13 | 7 | 0 | 7 |
| 60% - 70% | 26 | 8 | 11 | 8 | 0 | 7 |
| 70% - 80% | 29 | 7 | 16 | 8 | 1 | 7 |
| 80% - 90% | 35 | 7 | 14 | 8 | 0 | 8 |
| 90% - 100% | 25 | 8 | 12 | 7 | 0 | 8 |

Once this configuration had been selected, the different characteristics of the training carried out with back-propagation learning were set. The training steps were fixed

at ranges of 400 to 700 epochs, with an average error of below 1% at the end of the training. The MLPs were trained off-line, although their performance was verified on line.

VI. METHOD ASSEMBLY AND RESULTS VERIFICATION

The method was run in the Matlab/Simulink environment. A National Instruments data acquisition card (model USB-6008 12-bit 10 KS /s Multifunction I/O) was chosen for operations at the plant. This card is automatically recognized by Matlab/Simulink. The diagram of the process is implemented in Simulink (Figure 6).

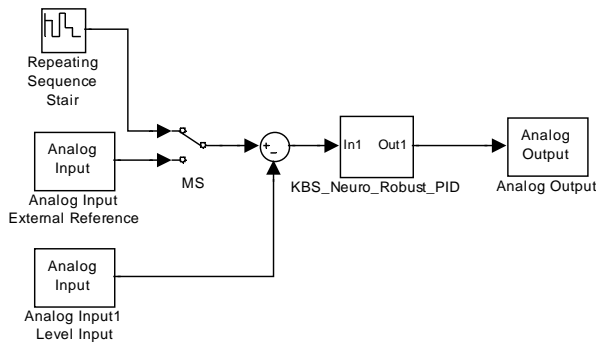


Figure 6. System implemented in Simulink.

There are two ways of fixing the set point for the laboratory tests on the plant: the first is to generate a sequence of repeating values; the second is to set its value using an external voltage (Analog Input block diagram). One of the two options has to be chosen.

The reading of the liquid level in the tank is performed by an ultrasonic level sensor with a continuous analogue output of between 0 and 10 volts. It is connected to one of the inputs of the data acquisition card in differential mode (Analog Input1). The next step is to develop the previously described controller; creating the output diagram blocks in Simulink (figure 7).

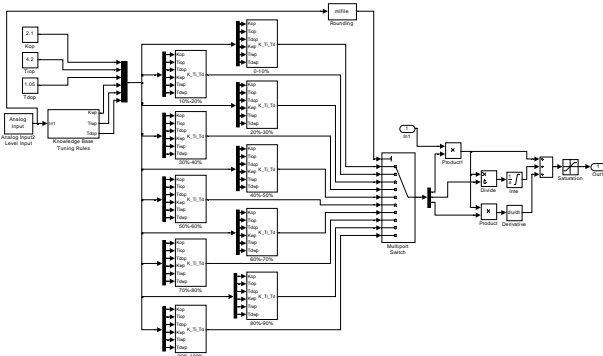


Figure 7. Implementation of the controller.

Figure 7 shows the implementation of a PID controller the parameters for which are the outputs of the multiport switch. Its inputs depend on the tank level read by the level sensor through analog input 2 on the data acquisition card

and the parameters that are manually programmed by the operator. There are 10 blocks (Range Blocks) in the above diagram (Fig. 7), one for each range level (i.e. 10% to 20%). Their internal layout is shown in figure 8, where additionally, inside each Range Block there is a further block (Subsystem2) that contains the scheme on the right, which is the topology of figure 2 implemented in Simulink (Matlab).

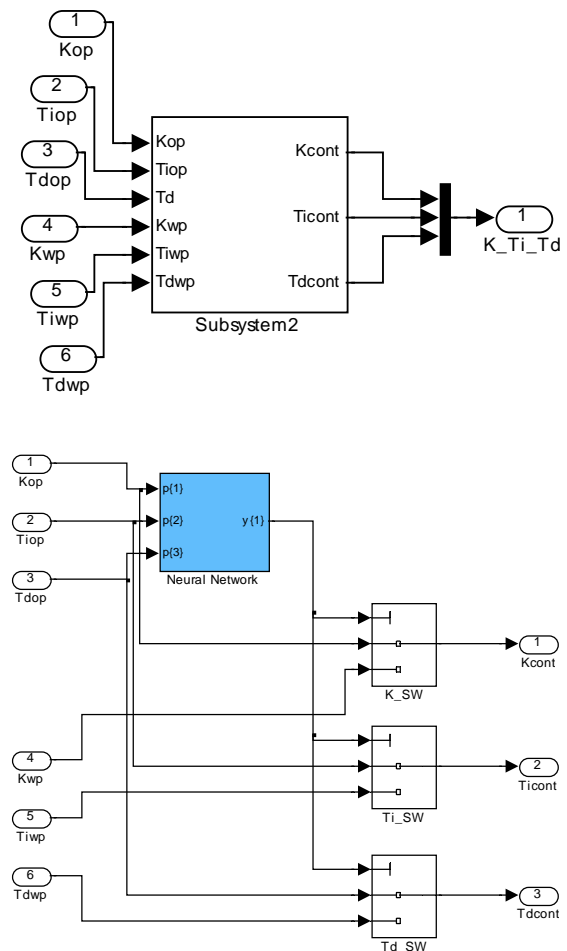


Figure 8. Range Block internal scheme and Subsystem2 contents.

The pins In1 and Out1 (Fig 7) are the KBS_Neuro_Robust_PID block pins in figure 5, which send a control signal to one of the analog outputs of the data acquisition card, to take direct action on the proportional valve.

In this way, the Controller will select the most appropriate parameters for the work point which it is running. When an operator modifies the parameters, they are evaluated by the system and if there is a risk of system instability, the parameter are automatically replaced by other more appropriate ones for the operation of the work point, in such a way that they guarantee system stability. Thus achieved present it as improvement of other control

techniques: gain scheduling and robust control. The first has a fixed dynamic, then operator can't change it. Second can change dynamic but don't assure optimal responses, and with non-linear systems is very difficult task maintain similar specifications in all operation range. The improvement is added to other techniques with the aim to leak failures in system control that have been probed.

VII. CONCLUSIONS

A new method for a bio-inspired control system is presented in this study that retains the advantages offered by the conventional PID system on which it is based, as well as the possibility of applying it to non-linear systems while maintaining invariable specifications throughout the operational range. Moreover, it is set up to ensure that manual modifications to the controller parameters made by an operator to input particular specifications, for whatever reason, will at no time lead to control system instability.

The novel proposal in this research is an option to take into account in non-linear systems that function throughout the range of operation, and that can be divided into zones with linear behaviour in which the control of the PID regulator is feasible. It is therefore an alternative to different types of self-adjusting controllers. It should be stressed that the solution is not easy to implement but the work involved is greatly simplified with today's programmable controllers and existing computing tools.

Multiple tests of the proposed bio-inspired method on the laboratory plant which involved tests on the different work points yielded satisfactory results. The system is robust when an operator introduces dangerous parameter combinations in order to change operating specifications. The system component prevents system instability and restores the programmed safety combination for the relevant operation point. It has to be said that the technique functioned very satisfactorily, considering the size of the tank which fills up and empties very rapidly. The temporal specifications are also very similar at all points of operation after different changes made to the level of the liquid, a very important fact in the case of operation with no modifications made to the parameters.

Future work along the same lines responds to a series of challenges. The first proposal is to apply the new method to a real industrial plant in which possesses the data and experience for which it was conceived. Possible case studies would be the control loops used in distillation columns at refineries or electricity generating stations. It is often the case that the advanced control centres in these sectors leave experienced operators with a certain degree of control to vary control parameters and in consequence specifications. Other future work will apply the method to make a system more robust not only against possible instability, but also against undesired specifications. Work will therefore continue on introducing greater stability into structures so that the project is within the range of values for a particular specification.

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