Fault Detection for a Temperature Control System using PID Controller Based on Artificial Immune Systems

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Abstract- An Artificial-Immune-System (AIS) based anomaly detection system applied to a PID-based Temperature Control System (TCS) is presented. At normal working, the environment temperature is controlled by PID Control System in a LabVIEW™ platform. As the TCS is composed of sensors, PID circuitry and PWM actuator, faults in these devices can cause abnormal disturbances. An AIS-based algorithm, namely, the Negative Selection Algorithm (NSA), is the base of the proposed anomaly detection system. The NSA verifies abnormal system conditions based on the normal system conditions and it was used to verify abnormal (or faulty) system conditions of the PID controller responses. Experimental results show that the proposed system is effective in order to detect anomaly.

I. Introduction

A simple control method is the Proportional-Integral-Derivative (PID) one, which are still used in industrial process automation to control variables like pressure, level, speed, etc. However, since the actual PID controllers are composed of components as sensors, electronic and electrical actuators, electronic e mechanical parts, and so on, which for your turn are subjected to failures, than it is important to develop methods to verify if the controller is faulty or not. This importance came from the fact that a faulty controller can cause stop or damages in the process, or mainly in the people operating it.

On other context, a natural system that may be used as a model for error detectors is the biological immune one which is a complex system with several mechanisms for defense against pathogenic organisms. The primary purpose of immune systems is to recognize all cells within the body and categorize those cells as body's own cell (self) or foreign cell (nonself). Such a recognition process is known as self-nonself discrimination [1]. After discrimination, the nonself cells are further categorized in order to induce an appropriate type of defensive mechanism [2]. With the ability to detect nonself cells, immune systems seem to be an adequate source of inspiration to development of algorithms for early detection of anomalous behavior in systems [3]. Artificial systems coming from immune systems are called Artificial Immune Systems (AIS) and they are being considered one of the most promising nature-inspired techniques used for novelty detection systems [1]. One of the most important algorithms from AIS and the main tool for self-nonself discrimination is the Negative Selection Algorithm (NSA) for its great ability in early detection of faults [1].

In this paper, it is presented a PID-based temperature control system which an automatic and on-line NSA is used to verify if it is in a faulty or in a normal condition. Experimental results show that the proposed NSA is effective.

II. Control System

In short, an automatic control system is a dynamic system, which as time evolves, behaves in a certain prescribed way without human interference. Control theory deals with the analysis and synthesis of control systems. Generally, these systems are composed of sensors, controllers and actuators. Every component in a control system can be subject to faults (material fatigue, lacking of maintenance, wrong specification, etc.). A simple control method is the Proportional-Integral-Derivative (PID).

A. PID Control

A typical structure of a PID control system is shown in Fig.1, which the error signal *e(t)* is used to generate the proportional, integral, and derivative actions according with the following expression:

$$u(t) = Kp\left[e(t) + \frac{1}{Ti}\int_0^t e(t)dt + Td\frac{de(t)}{dt}\right] \qquad (1)$$

where *u(t)* is the control signal, *e(t) = r(t) − y(t)*, *r(t)* is the desired state signal or reference signal, and *y(t)* is feedback signal or measured state signal [2].

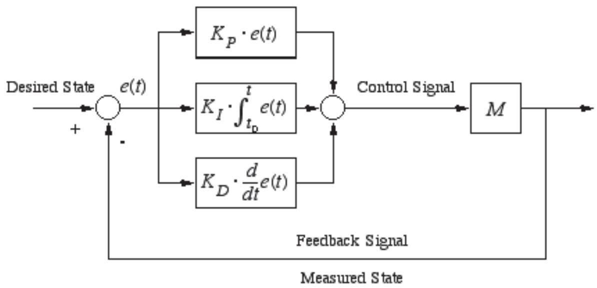

Figure 1. Block Diagram of a PID Control System.

III. Immune System overview

The nature of biological immune systems prevents humans from being infected by pathogens that cause diseases. Without a functional immune system, even minor infections can be fatal. A typical immune system provides two kinds of defending functions, namely innate immunity and adaptive immunity. The innate immunity is determined by the genes that a person inherits from her parents, whereas the adaptive immunity is adaptively formed when some pathogens cannot be effectively destroyed by the system's innate immunity [4]. There are two main types of mechanisms of defense: the innate and the acquired (or adaptative). When the organism is invaded by a strange agent, the innate system is the first one to be operated and in many cases, this answer protects for you only the organism. When the first step is insufficient, the adaptive system is operated. Since this action is more specific, the answer becomes more efficient [5]. Humoral immunity, also known as antibody mediated immunity, protects the body from bacterial infections using B-cells to generate antibodies and helper T-cells to activate the production of antibodies. Centralized learning occurs in the thymus, the initial destination of immature T-cells that have developed from stem cells in the bone marrow. The learning process ensures that an immune response can only be initiated against cells not belonging to the body. Self-cells or proteins circulate through the thymus and are exposed to the immature T-cells. If any binding or matching between receptors on a T-cell and a self-cell occur then the immature T-cell is destroyed. This process is known as programmed cell death. The process is essentially a negative selection. The matured T-cells are then distributed throughout the body into lymph nodes by the lymphatic system to take part in a distributed detection process [5].

IV. Negative Selection Algorithm

As described in previous section, the negative selection process is carried out in order to mature T-cells for recognizing pathogenic organisms (body's non-self cells) and not recognizing body's self cells. During T-cell maturation, receptors are made by a random genetic rearrangement process which eliminates T-cells that react against self-proteins. In this way, only T-cells that do not match any self-protein are allowed to leave the Thymus [2]. These matured T-cells then circulate throughout the body to perform immunological functions to protect it against pathogenic organisms [1].

Based on this process, Forrest et al. [6] proposed the Negative-Selection Algorithm (NSA) for change detection. In general, this algorithm generates detectors randomly, eliminating the ones that detect self, so that the remaining detectors can detect nonselves with high probability. The NSA is composed of three phases summarized as follows:

- **Definition of the self data**. In this phase, is defined as self a data that need to be protected or monitored. These data can be a collection of vectors $R = \{R_1, \ldots, R_n\}$, where R_i is a vector of length L with elements from a finite or infinite field. Each of these vectors is called a self-vector.

- **Detector generation phase**. Generate candidate detectors randomly and verify if they match any self-vector in *R* (according to a specified matching rule, see below). If a match is found, the candidate is rejected. Otherwise, it is accepted as detector. This process is repeated until a desired number of detectors are generated forming the set of detectors. This phase is illustrated in Fig. 2(a).

- **Monitoring phase**. Monitor *R* for changes by continually matching the detectors against vectors of *R* (here, susceptible of change). If any detector ever matches, then a change occurred, because the detectors are designed not to match any of the original vectors in *R*, as illustrated in Fig. 2(b).

(a) (b)

Figure 2. (a) First phase of the NSA (Detector generation phase). (b) Second phase of the NSA (monitoring).

B. Matching rules

In negative-selection algorithm, criterion of matching are necessary since a perfect match between two vectors of equal length means that at each location in the vectors, the symbols are identical. In this case, the matching is completely specific, so a detector will match only a single self-vector. So that detectors could match several vectors, i.e., to increase the capability of detecting, a partial-matching rule is used [7].

Two main partial matching rules are the **r-contiguou**s matching rule and the **r-hamming** matching rule. Both the r-contiguous matching rule and the r-hamming matching rule are controlled by the threshold parameter r. The higher the value of r, the more specific the match is. A consequence of using a partial matching rule is that there is a tradeoff between the value of r and the number of necessary detectors to detect nonself vectors [7].

The **r-contiguous matching rule** was proposed by Forrest *et al.* [6]. It consists in looking for r contiguous matches between symbols in corresponding positions. Suppose that two vectors *x*, which can be a self-vector, and *y*, which can be a detector, so, for example, if *x* and *y* assume the values in Fig. 3, then *x* and *y* match for all $r \leq 5$.

x: 1 1 0 0 ***1 0 1 0 1*** *0 1 1 1*
y: 0 0 1 0 ***1 0 1 0 0*** *1 1 0 1*

Figure 3. A match under the r-contiguous matching rule, with vectors of length $L = 13$ consisting of symbols from the binary alphabet with the matching constraint $r = 5$. The vectors *x* and *y* in the above example match for all $r \leq 5$.

The **r-hamming matching rule** is based on Hamming distance and consists in looking for r matches between symbols in corresponding positions (not necessary contiguous). An example based on r-hamming matching rule is shown in Fig. 4, and *x* and *y* match for all $r \leq 9$.

x: 1 1 0 ***0 1 0 1 0*** *1 0* ***1*** *1* ***1 0 1*** *0*
y: 0 0 1 ***0 1 0 1 0*** *0 1* ***1*** *0* ***1 0 1*** *1*

Figure 4. The vectors *x* and *y* in the above example match for all $r \leq 9$.

Consider real values, the r-contiguous and the r-hamming matching rules can be based on the parameter δ, called discrepancy. For example, suppose $\delta = 0.5$ and the values of *x* and *y* shown in Fig. 5, the difference between correspondent values of *x* and *y* that are smaller than δ are marked as 1 and otherwise 0, forming the vector *z*. In this way,

- x and y match for all $r \leq 5$ considering the r-contiguous matching rule, and
- x and y match for all $r \leq 6$ considering the r- hamming matching rule.

x:	*2.1*	*3.9*	*5.6*	*8.2*	***3.7***	***8.1***	***5.6***	***9.7***	***0.9***	*2.7*	*2.0*	***3.3***	*1.4*
y:	*4.5*	*1.2*	*3.2*	*2.6*	***3.4***	***7.8***	***5.6***	***9.8***	***1.1***	*5.6*	*7.6*	***2.9***	*7.6*
z:	*0*	*0*	*0*	*0*	***1***	***1***	***1***	***1***	***1***	*0*	*0*	***1***	*0*

Figure 5. Considering real values, x and y match for all $r \leq 5$ considering the r-contiguous matching rule, and x and y match if for all $r \leq 6$ considering the r- hamming matching rule.

V. Temperature Control System

In this section, it is presented a simple implemented temperature control system that is used to validate the proposed immune-based PID controller capable to detect abnormal conditions. In short, the system is composed of heater resistor (10Ω/5W), which the temperature is to be controlled, an LM35 temperature sensor with adequate filter circuit, a PWM circuit as actuator in order to heat the resistor, an Arduino-based prototyping platform, and a bluetooth module, which is responsible for communication with a control interface designed in LabVIEW™. In Fig. 6, it is shown the implemented system.

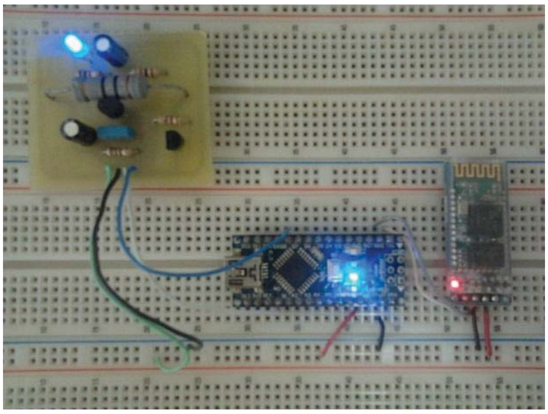

Figure 6. Implemented Temperature Control System.

The PID control algorithm was embedded into the Arduino-based prototyping platform which acquires the measured signal from LM35, calculate the error according to the desired state signal or setpoint defined in the LabVIEW-based control interface, and generate the PWM control signal to the actuator. The control interface, seen in Fig. 7, has a chart that shows the heater resistor temperature at the setpoint (defined by user) and a thermometer graph to indicate the actual temperature in the resistor. The setpoint can be varied between 20°C and 70°C.

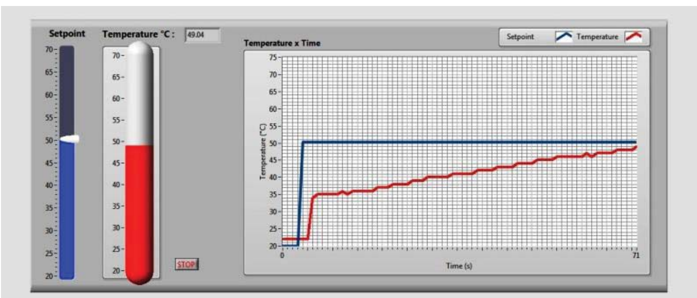

Figure 3. The implemented control interface.

The NSA was implemented in the LabVIEW environment, considered as self-vector, a set of n acquired temperature values (time window), where, n is the number of consecutive acquitions. In this way, considering normal condition, it is obtained a large collection of time windows, *i.e.*, self-vectors, and are applied in the

detector generation phase of NSA. It is done off-line, that is, not in the implemented LabVIEW environment.

The NSA **monitoring phase** runs in the implemented LabVIEW environment and, in this case, the system is subject to faults, the detectors generated previously are used to monitor the occurrence of abnormal conditions.

VI. Experiments

In this section, it is shown a description of the experiments carried out and the experimental results.

A. Experiment 1: Normal operation

This experiment aims to check the action of PID controller when the setpoint value is 50°C and the response temperature curve, shown in Fig. 8 (a), is considering the normal operation of the system.

B. Experiment 2: Abnormal operation

With the intention of assess the efficiency of the immune NSA-based PID controller, it was injected some faults in the system, namely: open circuit, full PWM signal and zero PWM signal. The response curve with the injected faults can be seen in Fig. 8 (b).

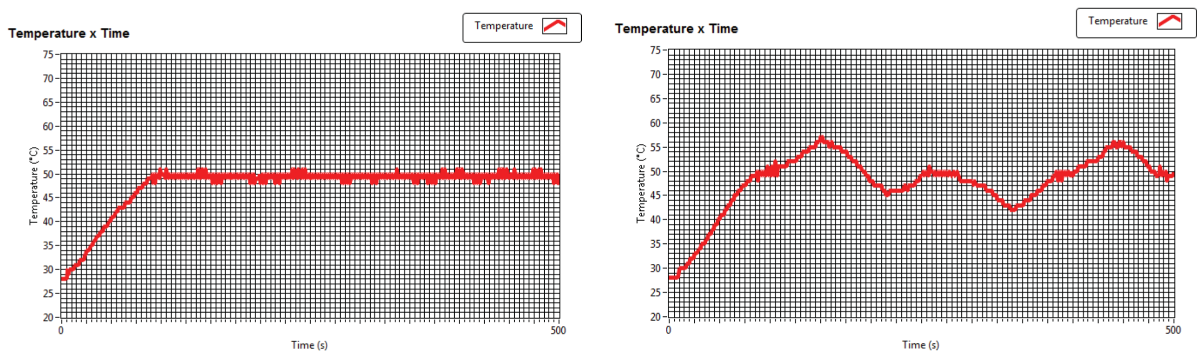

Figure 4. (a) Normal temperature curve. (b) Abnormal temperature curve.

VII. Experimental Results

In Fig. 9, it is shown two curves: the green one is the normal system operation (setpoint at 50°C) and the blue one the curve with injected faults.

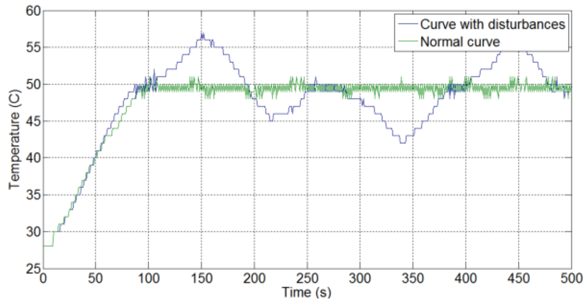

Figure 9. Temperature curves of the system (normal and faulty).

In order to assess the efficiency of the NSA, in the Fig. 10, a faulty system response (the green curve) is automatic monitored and, as a result, the number of active detectors can be observed as the blue values in the figure. For example, if 50 detectors are active, it means that 50 detector was capable of detecting the corresponding time window. The used rule was the r-hamming one with the following parameters: r = 4, N_d (number of detectors) = 100, criterion = r-hamming and number of points (time) equal to 400. Considering r-contiguous matching rule, the experimental results were similar.

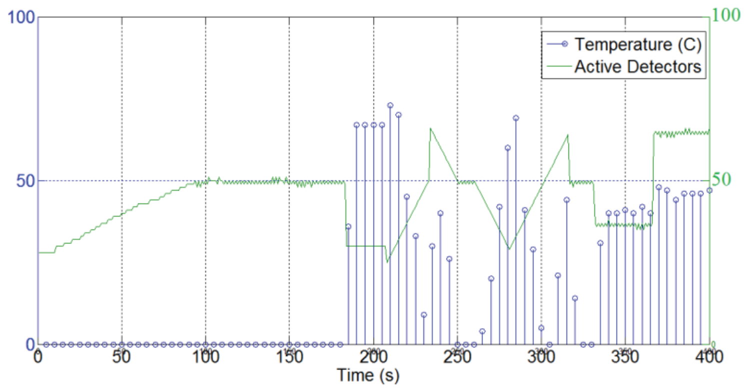

Figure 10. Active detectors.

In order to show that the proposed NSA do not detect normal condition, a normal curve was applied to it and, as shows in Fig.11, any detector was active.

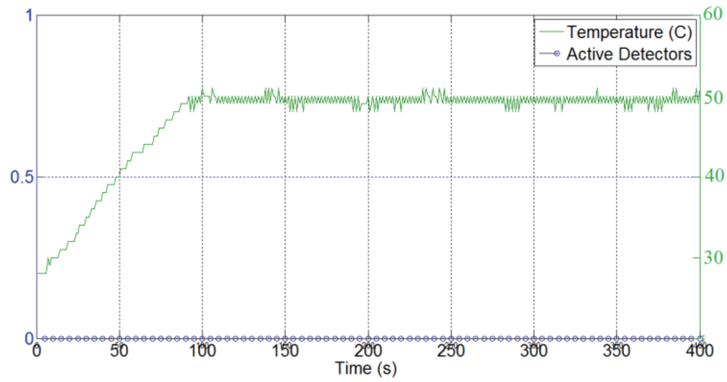

Figure 11. False positive detection

IX. Conclusions

The objective of this work was check the efficiency of an algorithm (NSA) that is able identifier same faults inserted in a temperature control system using PID controller. The NSA requires reasonable work effort during the generation detectors phase and a low-effort on the monitoring phase, showing that it turns to be adequate method to detect abnormal condition in system control. Also, the experimental results shows that the detection capability is very effective.

X. References

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