A Supervisory Loop to Remedy Actuator Saturation: Immune Approach

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***Abstract*— This paper describes the actuator saturation problem and its solution. Actuator saturation is one the practical problem in control of various systems. Even it might cause instability. In this article we describe different problems that are caused by saturation. After that a method is proposed to remedy the effect of it. In the proposed method this problem is solved by decreasing the band width of the controller. In order to accomplish this, a supervisory control is employed which uses artificial immune algorithm to adjust the proper forward path gain and then we compare the result with fuzzy supervisor. As you will see immune supervisor has better result in compare with fuzzy model. Recently, the biological immune system arouses researchers' interest since it has several useful mechanisms which can be used for information processing. In this paper, an improved artificial immune algorithm is presented which is used in the design approach of a supervisory loop.**

Keywords- supervisory loop; flexible joint robots (FJR); artificial immune systems; immune feedback principle.

I. INTRODUCTION

Actuator saturation has been considered by the control community from early achievements of control engineering. During 50's and 60's at the beginning era of optimal control, researchers have been working on saturation, introducing bang-bang control methods. Over the last decade the control research community has shown a new interest in the study of the effects of saturation on the performance of systems. In fact it can be said that in the past, researchers were encountered a drawback identified as actuator saturation and developed methods to avoid it; while now, researchers develop methods to achieve a desirable performance in the presence of actuator saturation seen as a limitation.

There are three problems which caused by saturation actuator: wind up, instability and changing the direction of control. Wind up problem happen in controllers which have integrator (PI, PID).

A common classical remedy for systems with bounded control is to reduce the bandwidth of the control system such that saturation seldom occurs. This is a trivial weak solution because even for small commands and disturbances, the possible performance of the system is degraded. This idea (reduction in bandwidth by reduction in the closed loop gain) is practical and "easy", so this motivates some researchers to propose an "adaptive" reduction in bandwidth consistent with the actuation levels [8]. The "adaptation" process is done under supervision of a supervisory loop, and as proposed in [8] is accomplished through complex computations which practically seems not to be implementable.

In recent years much attention has been focused on Artificial Immune System (AIS) [1], which have already been demonstrated its robustness and flexibility against dynamically changing world. The biological immune system has various features such as immunological memory, immunological tolerance, pattern recognition, and so on. Recent studies on immunology have clarified that the biological immune system does not just detect and eliminate the non-self materials, rather plays important roles to maintain its own system against dynamically changing environments. Therefore, the AIS which imitate the biological immune system would be expected to provide a new methodology suitable for dynamic problem. In 1974, Jerne first proposed a theory of immune particular network [2]. The hypothesis was that the immune system maintains an idiotypic network of interconnected B-cells for antigen recognition. These cells both stimulate and suppress each other in certain ways that lead to the stabilization of the network.

In literatures [3, 4], new kinds of feedback controller based on adjustment law of T-cells are proposed and employed to adaptive learning of neural network. Based on the biological immune feedback regulation strategy, an immune supervisory loop is proposed in this article.

This paper is organized as follows: the next section describes the saturation problem; section II is devoted to description of new method, section III presents some simulation results and finally, the last section consist of some conclusion results.

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II. SUPERVISORY LOOP

G(s) system with a feed back loop controls the system by K(s) controller. Figure (1) shows this closed loop system.

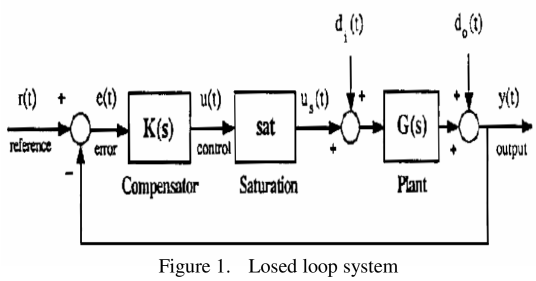

Figure 1. Losed loop system

Without loss of generality we can assume that u (t) of the control vector has a saturation limit of 1. In other words the saturation function can be defined as follows:

$$sat(u(t))=\begin{cases} 1 & 1 \le u(t) \\ u(t) & -1 \le u(t) \le 1 \\ -1 & u(t) \le -1 \end{cases}$$

Suppose that controller is designed to have a good performance in absence of saturation. In presence of saturation most of the desirable performances are missed. Performance problems in this situation are two types: 1) Inevitable limitations such as slow responses, undesirable transitions, etc. 2) Removable problems such as instability, bad steady state performance, etc. The goal in considering saturation at design step is to decrease or remove the latter. To reach this aim we put a suitable gain in forward path of closed loop system. This method decreases the bandwidth when the system is experiencing saturation and in normal conditions the effect of error governor is diminished. This configuration reduces the amplitude of the control effort.

III. IMMUNE ALGORITHM

A. *Biological immunity*

The biological immune system is a robust, complex, adaptive system that defends the body from foreign pathogens. It is able to categorize all cells (or molecules) within the body as self-cells or non-self cells. It does this with the help of a distributed task force that has the intelligence to take action from a local and also a global perspective using its network of chemical messengers for communication. There are two major branches of the immune system. The innate immune system is an unchanging mechanism that detects and destroys certain invading organisms, whilst the adaptive immune system responds to previously unknown foreign cells and builds a response to them that can remain in the body over a long period of time.

The immune system is governed by local interactions among immune cells and antigens. Two of the most important cells in this process are white blood cells, called T-cells, and B-cells. Both of these originate in the bone marrow, but

T-cells pass on to the thymus to mature, before they circulate the body in the blood and lymphatic vessels. The T-cells are of three types; T helper cells which are essential to the activation of B-cells, Killer T-cells which bind to foreign invaders and inject poisonous chemicals into them causing their destruction, and suppressor T-cells which inhibit the action of other immune cells thus preventing allergic reactions and autoimmune diseases. B-cells are responsible for the production and secretion of antibodies, which are specific proteins that bind to the antigen. Each B-cell can only produce one particular antibody. The antigen is found on the surface of the invading organism and the binding of an antibody to the antigen is a signal to destroy the invading cell.

B. *Feedback principle of immune system*

In an immune system, there is a feedback mechanism that enables human survival in face of infection and disease. Figure (2) presents the principle of feedback mechanism. The basic cells that are involved in the process are antigens Ag, antibodies Ab, B-cells B, helper T-cells T_h and suppressor T-cells T_S [5]. We know that antigens are recognized by Antigen Presenting Cell, when they invade into organisms, then, the message is sent to T-cells. After receiving the message, B-cells will be stimulated by T-cells and create antibodies immediately to eliminate the antigen. When the number of antigens is increasing, the number of T_h cells will increase and the human body can create more B-cells to protect itself. Along with the decrease of antigens, the amount of T_S cells in the body would increase and the number of B-cells would reduce accordingly.

After a period of time, the immune system inclines to balance. As mentioned above, the T_S cells have the function of restraining the T_h cells and B-cells. For the invasion of the antigen, the B-cells are activated and restrained by the T_S cells. Therefore, the consistency of the kth generation B-cells can be given by [6]:

$$B(k)=T_h(k)-T_s(k) \quad (1)$$

$$T_h(k)=k_1\,\mu(k) \quad (2)$$

$$T_s(k)=k_2\,[f(\Delta B(k))]\,\mu(k) \quad (3)$$

where μ (k) is the consistency of antigen at the kth generation; K_1 is the helper gene of T_h; K_2 is the suppressor gene of T_S; ΔB (k) is the change of B-cell's consistency, $f(x)$ is a nonlinear function that represents the interaction between antibody and antigen. We can extract the relationship formula about the consistency of B-cells and antigen from equation 1 to 3. It is demonstrated as follows:

$$B(k)=k_1\,[1-\gamma\, f(\Delta B(k))]\,\mu(k) \quad (4)$$

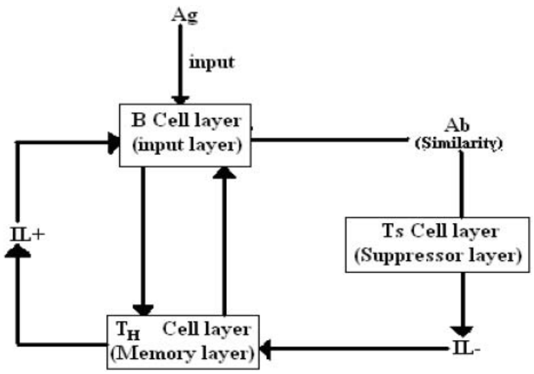

Figure 2. Immune response

C. Immune P Cntroller

The principal function of an appropriate immune response lies in ensuring the stability of the immune system and simultaneously responding to the antigen invasion fast, because all the antigens attacking the biological body have to be omitted. On the other hand, a high antibody consistency harms the body and should be controlled. Therefore, the general aim of the immune system is to minimize the injury of the biological body. In the dynamic regulation of a control system, it is requested that deviation should be suppressed to ensure the system stability, which is actually consistent with the aim of immune system.

If we assume the amount of antigen $\mu\,(k)$ as error $e\,(k)$, total stimulation that is accepted by B-cells is the input control $u\,(k)$. And then the law of feedback control can be showed as follows:

$$U_{IC}\,(k)=K[1-\propto(1-f\,[\Delta u(k)])]\ e\,(k) \qquad (5)$$
$$=K_{IC}\ e\,(k)$$

while $K[1-\propto(1-f\,[\Delta u(k)])]=K_{IC}$ is the proportional gain of immune controller. $f(x)$ is a nonlinear function of $\Delta u(k)$.

According to the antigen consistency's effect on antibody in immune response, we choose nonlinear function as T-cells regulating function. It is defined as follows:

$$f\,(x)=1-\frac{2}{1+\exp\,(-ax)} \qquad (6)$$

where $-1 < f\,(x) < 1$ and the value of (a) determines the region of action of variable x. The output of Immune controller can be computed as follows:

$$U_{IC}\,(k)=K\,[1-\propto(1-\frac{2}{1+\exp\,(-ax)})]\ e\,(k) \qquad (7)$$
$$=K_{IC}\ e\,(k)$$

IV. SIMULATIONS

In this section, we provide a computer simulation to demonstrate the performance of flexible joint robot (FJR) in presence of saturation and immune supervisory loop.

Consider the single link flexible joint manipulator introduced in [7] and illustrated in figure 2, with ordinary nominal values of m=1, I=1, J=1, L=1, g=9.8, k=100.In this section we considered a flexible joint robot with its controller. This controller consists of a composite structure, with a PD controller on the fast dynamics and a PID controller on slow dynamics [8].

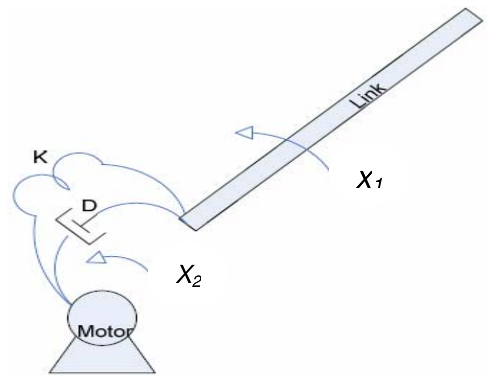

Figure 3. Flexible joint robot with single degree of freedom

If saturation block is added to the original model of system (figure 4), instability will occur. The instable output is shown in figure 5.

The proposed method has two steps, first the compensator is designed without considering any saturation limit, then a time varying scalar gain $0<k(t)\leq 1$ is added which modifies error and is adjusted via a supervisory loop figure (6). Variable (k(t)) is designed by fuzzy method in figure (7) and with artificial immune algorithm in figure (11). Figures (10 & 14) demonstrate changes of this variable during the control process in these methods.

These methods decrease the bandwidth when the system is experiencing saturation. This configuration reduces the amplitude of the control effort as is done by saturation itself. As you see in figures (8 & 12) immune supervisor has better performance in compare with fuzzy one. Immune supervisor made the simulation result more better than fuzzy method, in addition, in immune supervisor k(t) changes in a lower than fuzzy one. Figures (9, 13) show the tracking error response of the supervised system.

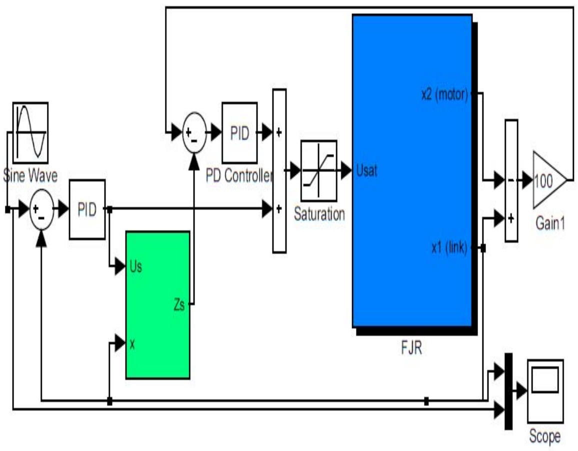

Figure 4. *Closed loop system with composite controller without supervisory loop*

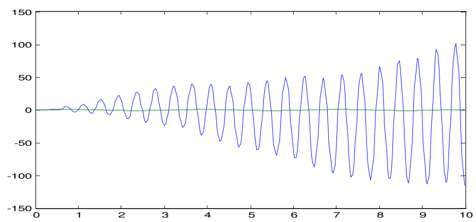

Figure 5. Tracking response of system with saturation

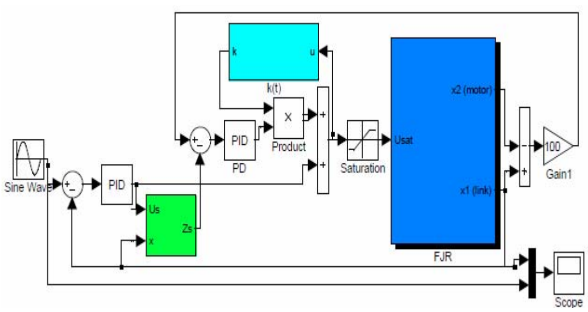

Figure 6. *Closed loop system with supervisory loop*

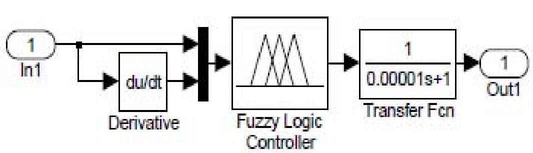

Figure 7. *k(t) subsystem description(fuzzy method)*

Fuzzy controllers are capable of approach arbitrary nonlinear function. Fuzzy controller that we employ here consists of two inputs and one out put. The two input variables are |u(x)| (the output of saturation block) and its variation $\dot{u}(x)$ apart, output variable is the k (t).fuzzy sets named: small, near, over for input variable u(x) and negative (Neg), zero, positive (pos) for $\dot{u}(x)$. Output variable in the paper named as follows: small(S), very small (VS), large (L) and one.

These servile functions above are defined in the whole area $(-\infty, +\infty)$.

Consequently these rules used for fuzzy control:

1-if |u(x)| is near to one and $\dot{u}(x)$ is positive (pos) then k (t) is large (L).

2-if |u(x)|≥1 and $\dot{u}(x)$ is negative (Neg) then k(t) is small (S).

3-If |u(x)|≥1 and $\dot{u}(x)$ is zero then k(t) is very small (VS).

4- If |u(x)|≥1 and $\dot{u}(x)$ is positive (pos) then k(t) is very small (VS).

5-in other conditions k(t)=1.

Fuzzy control bases at simulating human thinking way, which solves well the controlled object problem such as nonlinear, large delay, large inertia, fluctuant parameter, without accurate description of controlled model, so it is widely used in all kinds of controlled system. Fuzzy controller could approach to any linear or nonlinear functions; meanwhile, it is also an effective way to construct nonlinear function.

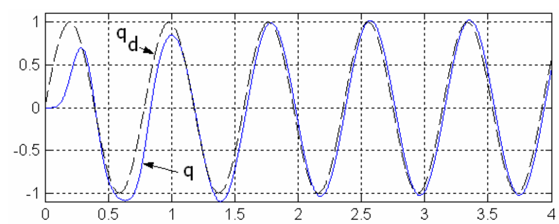

Figure 8. *Tracking response*

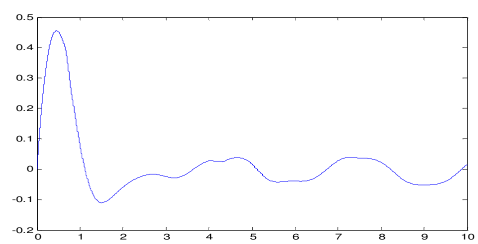

Figure 9. *Error of tracking response*

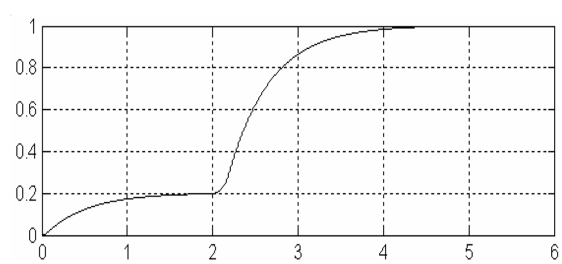

Figure 10. *The value of k (t)*

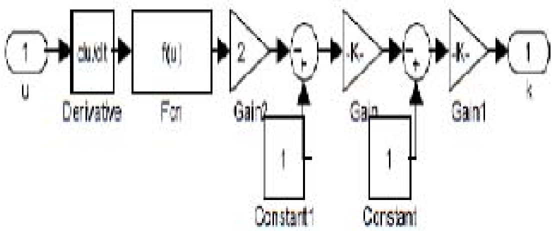

Figure 11. *k(t) subsystem description(immune method)*

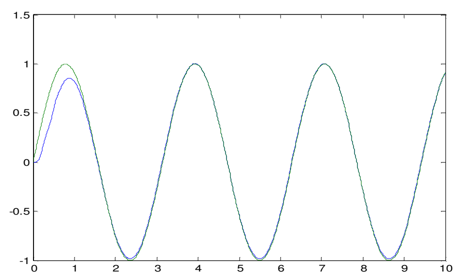

Figure 12. *Tracking response*

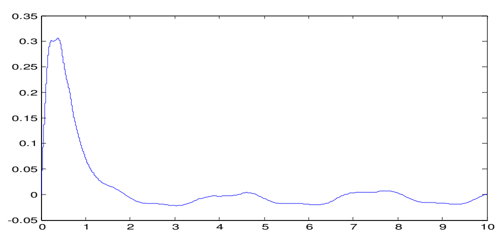

Figure 13. Error of tracking response

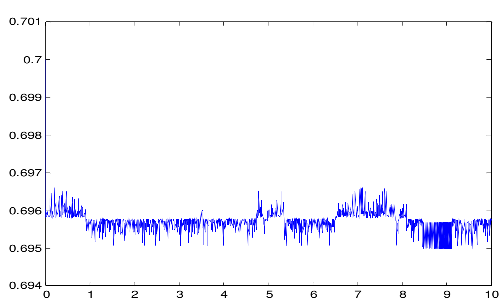

Figure 14. :The value of k (t)

V. CONCLUSION

In this article we introduced the actuator saturation problem and in order to remedy the instability caused by actuator bounds, a supervisory loop is proposed. It is shown that fuzzy and immune supervisors make it possible to reduce the saturation level in the control input, without great loss in performance. The supervisor will affect the signals before the controller so affecting the controller states dislike the saturation block which placed after the controller. Also we saw that immune supervisor has much more better performance than fuzzy supervisor.

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