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# *Fuzzy Tuner for a Satellite Large Angle Maneuvering Control*

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**Abstract:**

***This paper presents an Expert controller for a three axes large angle satellite reorientation maneuvers. The controller is a conventional PD controller with a fuzzy auto tuner that uses the quaternion and angular velocities error on each axis to make the proper control action according to these errors based on fuzzy rule tables derived from our experience. The controller will use the errors to adjust the PD control action properly to minimize the attitude errors and speed up reaching the desired attitude in a suitable time and with a well behaved manner.***

**منظم مضبب للسيطرة على قمر صناعي في حال المناورة بزاوية كبيرة**

**الخلاصة**

***هذا البحث يقدم مسيطر خبير للسيطرة على قمر صناعي بثلاث إحداثيات بحالة المناورة بزاوية كبيرة. هذا المسيطر هو من النوع التناسبي التفاضلي (Proportional Derivative PD) ويستخدم منظم مضبب آلي. سوف نستخدم في هذا البحث أخطاء السرعة الزاوية والرباعيات (quaternion) في كل إحداثي لإعطاء تصرف مسيطر مناسب للسيطرة على القمر الصناعي. هذا التصرف سيكون مبني على أساس جدول قوانين مضبب مشتق من خلال خبرتنا. المسيطر سوف يستخدم الأخطاء لكي يعدل معالم المسيطر التناسبي التفاضلي بصورة مناسبة لكي يقلل من أخطاء الموقف ويسرع عملية الوصول إلى الموقف المطلوب بصورة مرضية.***

## 1 -Introduction:

During their mission in space, spacecrafts need to acquire a certain position in space to maintain their required tasks. Thus many methods were introduced to this problem such that the spacecraft takes its orientation in space correctly.

The theory of optimal control is widely used in this field [1,2,3] but with no general performance index that is every investigator takes the problem from his point of view through selecting his own performance index.

Other methods use adaptive control theory such as Model Reference Adaptive Control (MRAC) [4], variable structure control [5], sliding mode controller [6], but all of these methods suffer from the complexity of the computation specially if we know the dynamical representation of the spacecraft is highly non linear.

The method of fuzzy logic control is widely applied in many fields and proved to be good and robust with a near optimal response [7]. The fuzzy controller does not need any mathematical representation to the system since it uses the human reasoning and looks to any system as a black box, and only uses a number of IF-THEN rules to describe there control action [8].

In this paper the method of fuzzy logic control is used to perform a PD like control action to control the satellite to acquire its orientation in space through the use of quaternion feedback as a source of error.

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**2-Satellite Dynamical & kinematics equations:**

The rotational motion of a rigid body in free space may be described as:

$$I_1.\dot{\omega}_1 = (I_2 - I_3).\omega_2.\omega_3 + T_1 \quad (1.a)$$

$$I_2.\dot{\omega}_2 = (I_3 - I_1).\omega_1.\omega_3 + T_2 \quad (1.b)$$

$$I_3.\dot{\omega}_3 = (I_1 - I_2).\omega_1.\omega_2 + T_3 \quad (1.c)$$

Where $\omega_i$ is the angular velocity, $I_i$ is the moment of inertia of the spacecraft at $i^{th}$ axis, $T_i$ is the control torque.[9,10]. These equations are known as the dynamic of the spacecraft, while the kinematics of spacecraft, which describe its orientation, is given by:

$$\dot{q}_1 = \tfrac{1}{2}(\omega_1.q_4 - \omega_2.q_3 + \omega_3.q_2) \quad (2.a)$$

$$\dot{q}_2 = \tfrac{1}{2}(\omega_1.q_3 + \omega_2.q_4 - \omega_3.q_1) \quad (2.a)$$

$$\dot{q}_3 = \tfrac{1}{2}(-\omega_1.q_2 + \omega_2.q_1 + \omega_3.q_4) \quad (2.a)$$

$$\dot{q}_4 = \tfrac{1}{2}(-\omega_1.q_1 - \omega_2.q_2 - \omega_3.q_3) \quad (2.a)$$

The quaternion feedback error may be obtained from the following matrix equation [11]:

$$\begin{bmatrix} q_{e1} \\ q_{e2} \\ q_{e3} \\ q_{e4} \end{bmatrix} = \begin{bmatrix} q_{c4} & q_{c3} & -q_{c2} & -q_{c1} \\ -q_{c3} & q_{c4} & q_{c1} & -q_{c2} \\ q_{c2} & -q_{c1} & q_{c4} & -q_{c3} \\ q_{c1} & q_{c2} & q_{c3} & q_{c4} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \quad (3)$$

Where $q_c$ is the command quaternion and $q_e$ is the quaternion error.

For a special case at which the spacecraft is needed to be aligned toward the earth the commanded quaternion is given by:

$$\begin{bmatrix} q_{c1} \\ q_{c2} \\ q_{c3} \\ q_{c4} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad (4)$$

Thus equation (3) will be:

$$\begin{bmatrix} q_{e1} \\ q_{e2} \\ q_{e3} \\ q_{e4} \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \quad (5)$$

**3-Fuzzy Controller Design Algorithm:**

Fuzzy logic control provides a formal methodology for representing manipulating and implementing a human's heuristic knowledge about how to control a system. Basically it is an artificial decision-maker that operates in a closed loop system in real time. It gathers plant output data, compares it to reference input and then decides what the plant input should be to ensure that the performance objective will be met.

Designing a fuzzy logic controller consist of four components. Fuzzification, fuzzy rule base, fuzzy inference engine, and defuzzification. The fuzzification process converts the real input (usually error and change of error) to fuzzy universe of discourse to produce corresponding fuzzy inputs. These inputs are fed into the fuzzy inference engine, where certain fuzzy rules coming from the fuzzy rule base are triggered according to the fuzzy input variables. These triggered rules produce the output variable which in turn is defuzzified by the defuzzifier to the real world universe of discourse and the o/p is used as the plant input [8].

**4-FLC Application To The Attitude Control Problem:**

The used fuzzy logic controller consists of two fuzzy algorithms that simulate the control action of proportional and derivative parts of a PD controller with two rule tables shown in table (1). Where NB for negative big, NS for negative small, Z for zero, PS for positive small and PB for positive big, CE for change of error, and E is the error.

***Table (1.a). The Fuzzy Rule Table*** **(Kd)**

| E | NCB | NCS | ZC | PCS | PCB |
|---|---|---|---|---|---|
| NEB | Z | NS | NS | NB | NB |
| NES | PS | Z | Z | NS | NB |
| ZE | PS | Z | Z | Z | NS |
| PES | PB | PS | PS | Z | NS |
| PEB | PB | PB | PS | PS | Z |

***Table (1.b). The Fuzzy Rule Table*** **(Kp)**

| E \ CE | NCB | NCS | ZC | PCS | PCB |
|---|---|---|---|---|---|
| NEB | PB | PB | PS | PS | PS |
| NES | PB | PB | PB | PS | PS |
| ZE | Z | PB | PS | PB | Z |
| PES | Z | PB | PB | PB | PB |
| PEB | Z | Z | Z | PB | PB |

The fuzzy rules were derived by our experience through the observation of the control action with proportional term alone then with derivative term alone along with the transient and steady state response and were checked for many different linear systems to improve there action on the controlled response by improving the rule tables for tuning the proportional & derivative control actions.
The table is read as:

**IF (E is NB) and (CE is NB) THEN (Kp ACTION is PB) and (Kd ACTION is Z)**

Where E is the error signal=input (desired)-output (measured) CE is the change of error, Kp is the proportional control action and Kd is the derivative control action.
It is noted that the first table contains negative values for the derivative control action and that is right because the control action may be positive, negative, or zero.
The fuzzy inference engine is built using the minimum operation rules of fuzzy application. The fuzzy outputs inferred by the whole rule base is the union of the components inferred by each of the individual rules.
The bell shaped function (Gaussian distribution) is used to give the membership function to the error, change of error and the output of each controller. This function is given by:

$$\mu(x) = \exp\left(-\tfrac{1}{2}.((m-x)/\sigma)^2\right) \qquad (6)$$

Where m is the center of the membership function (mean), σ is the width of the membership function (standard deviation) and x is the input variable. This function is shown in fig (1).

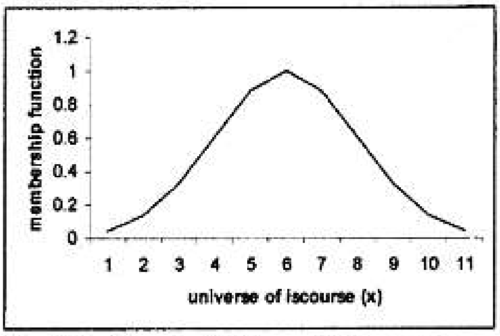



***Fig.(1). The Bell Shaped Function***

For the defuzzification process, the center of gravity method is used and is given by:

$$U = \frac{\sum_{i=0}^{N} \mu(u_i).u_i}{\sum_{i=0}^{N} \mu(u_i)} \qquad (7)$$

Where N is the number of the used interval (in this work it was chosen to be 21), $\mu_i$ is the degree of membership of every output variable corresponding to each error, change of error pair. U is the crisp o/p of the controller, thus a general block diagram of a PD like fuzzy controller is shown in fig (2)

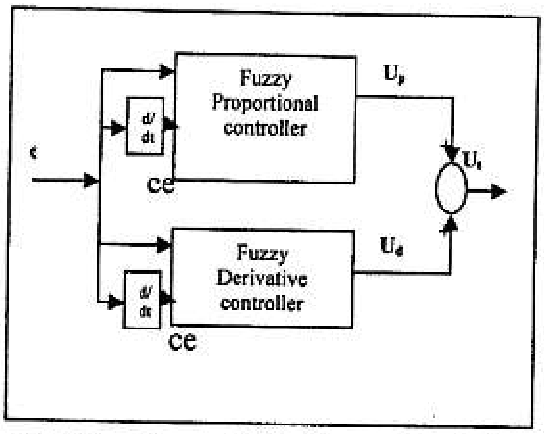



*Fig.(2). Fuzzy PD Controller Block diagram.*

For the purpose of controlling a rigid body satellite, it is worth to note that the effective error comes from the angular velocities and the quaternion. Both errors are effected by only three inputs (one for each angular velocity and quaternion pair)*, thus the control algorithm should encounter these two values to produce one control action in one direction, hence a general block diagram is shown in fig (3) which is used in large angle mode. In this block diagram the fuzzy PD controller is the same as that shown in fig (2). $g_\omega$ and $g_q$ are scales that are used to give a reasonable action, which is fed to the satellite.

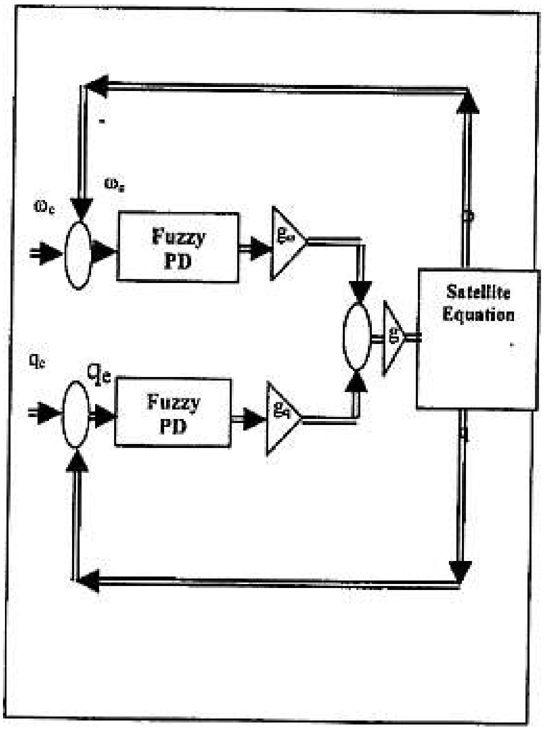



*Fig.(3). Attitude Control System Block Diagram.*

**5-Simulation And Results:**

The fuzzy PD like Controller described earlier was applied to the rigid body satellite given by equation (1) with the parameters shown in table (2):

*Table (2). The Initial Parameters Used in the Simulation*

| | | | |
|---|---|---|---|
| $g$ | $g_\omega$ | $g_q$ | |
| 20 | 400 | 20 | |
| $I_1$ $Kg.m^2/sec^2$ | $I_2$ $Kg.m^2/sec^2$ | $I_3$ $Kg.m^2/sec^2$ | |
| 10000 | 9000 | 12000 | |
| $\omega_1$ rad/sec | $\omega_2$ rad/sec | $\omega_3$ rad/sec | |
| 0.006942 | 0.008307 | 0.002235 | |
| $q_1$ | $q_2$ | $q_3$ | $q_4$ |
| 0.668 | 0.679 | 0.14 | 0.255 |

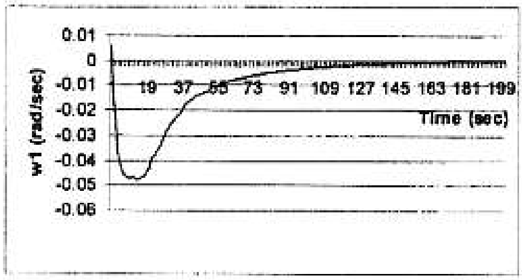
The angular velocities are shown in fig (4) where the body rates change from initial value until reaching the desired value (0 rad/sec) within 99sec for $\omega_3$ with maximum divergence from desired

*Note that $q_i$, (i=1,2,3), is a vector quantity along the x, y, and z direction, while $q_4$ is a scalar quantity.

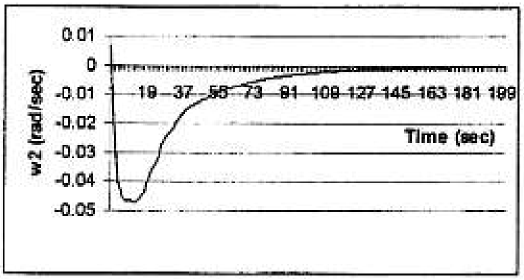
value about –0.005 rad/sec and about 143 second settling time for both $\omega_1$ & $\omega_2$ with a maximum divergence about –0.048 rad/sec .

Note that the response is decreasing with a little non smooth behavior which can be improved by increasing number of fuzzy sets to include medium with positive and negative values to decrease the gap between big and small fuzzy sets to make the behavior smoother.

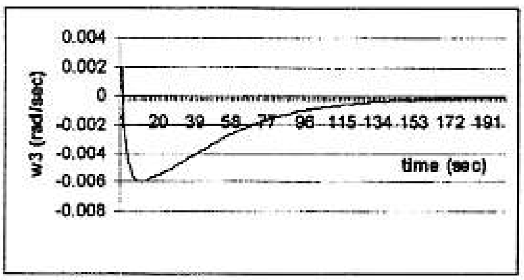
The spacecraft quaternion, which are shown in fig (5), approach the desired value in smooth well behaved manner at a time approach 164 sec for q1, q2 and 145 sec for q3 while q4 acquires steady state error after 100 sec and settles within this value to the end of simulation time.




*(4.a) $\omega_1$ vs. Time.*

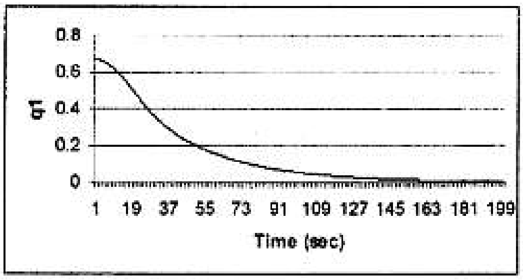



*(4.b) $\omega_2$ vs. Time.*

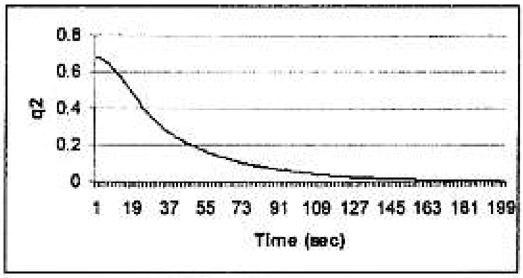



*(4.c) $\omega_3$ vs. Time.*

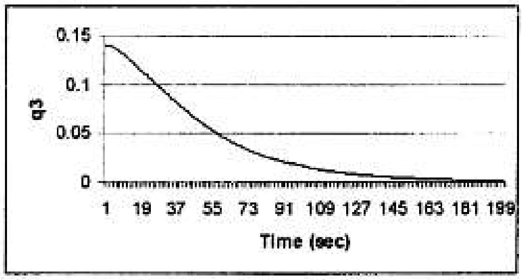
***Fig(4). The Angular Velocities.***



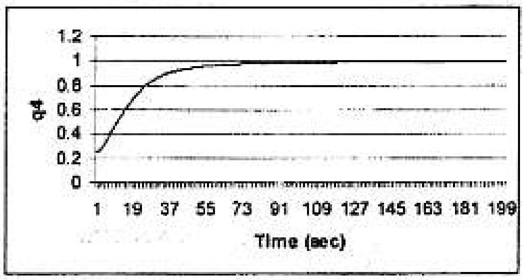

*(5.a) $q_1$ vs. Time.*




*(5.b) $q_2$ vs. Time.*




*(5.c) $q_3$ vs. Time.*




*(5.d) $q_4$ vs. Time.*

***Fig.(5). Quaternion.***

## 6- Conclusion:

The conclusion derived from this simulation can be recognized from the acceptable well performance of the system in approaching the desired attitude (as shown in fig's (4) & (5)), while as we can see that we have a simple control algorithm which does not require the system mathematical model, and it does not need complicated mathematical calculations to produce its action. It is also noted that the acceptable computation time is suitable for real time control.

On the other hand it is seen that we need six fuzzy like PD controllers to achieve our task (one for the angular velocity on each axis and one for the quaternion associated with that axis) which is a drawback in this design. But it is reasonable if we note that other conventional control algorithms use two control actions within there design and sum them to produce one control action. Another drawback is that if a sudden and a big change in the satellite dynamics or disturbance in the input or the output of the satellite happened, then the fuzzy like PD controller will not act smoothly since these changes are not encountered in the rule table. Again such changes may happen in other conventional control design and it is also encountered in the control algorithm.

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