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Fuzzy Logic Techniques for Intelligent Spacecraft Control Systems

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ABSTRACT

As technology allows the growth in size and performance of spacecrafts their control systems are continuously redesigned and perfection to achieve improvements in accuracy and stabilization. A clear line in research is the improvement in the design and development of sensors and actuators to became smaller, more precise and cheap. The research line in intelligent control leads to the development of new control strategies based on new ideas and principles.

The paper discusses the synthesis of guidelines to establish techniques to design and develop a fuzzy logic based intelligent spacecraft control system. This fuzzy controller is a knowledge based controller that performs the close loop operations autonomously either by supervising or replacing the conventional algorithms. It allows the representation of uncertainties of the plant, the treatment of nonlinearities and the generation of smooth control actions.

The fuzzy controller can be optimized to meet a prescribed constraint criterion. Using an experienced spacecraft controller (manual) or with the use of computer optimization tools (automatic) it is possible to find the best fuzzy sets of the controller membership functions or the best rule data base representing its knowledge.

1. INTRODUCTION

A spacecraft control system is the component part of a spacecraft in charge of measuring its position and attitude and producing guidance and rotation commands. It contains several blocks (figure 1): the navigation block calculates the actual state of the vehicle; the guidance part calculates the future state of the spacecraft to achieve the desired trajectory and the control part calculates the desired control torques to achieve this trajectory.

The objectives are to maintain the vehicle within a prescribed orbit and attitude having fuel consumption and maneuver time minimized.

The main control requirements of a spacecraft are formulated as a deviation from conditions of regular motion. In principle this control problem could be solved in the framework of classical linear control: first defining the plant math model, second generating the laws to control it and then analyzing the robustness in conditions of abnormal operation. The reality is that the motion equations are nonlinear [10], the performance of sensors and actuators is not totally perfect and the size of the spacecraft produces elastic modes neglected in the mathematical model of the plant. In most occasions low and high frequencies appear with very low damping. Bode diagrams and phase plots are insufficient to forecast totally the plant behaviour in all circumstances and approximation in the discretization process must be done carefully.

2. CURRENT TECHNIQUES

This section presents a short review of the current techniques used in space control. There are several types of platforms for developing a spacecraft control system. They are classified depending on the selection of the control architecture [4]: centralized, decentralized or hierarchical. In the centralized approach all sensors provide data to the controller which on time provokes the functioning of the actuators. This model is lacking of fault tolerant features but the global control delivers performance. In the decentralized model the controller is a group of several small controllers connecting different sensors with actuators. Here fault tolerant behavior is achieved but global coordination is difficult. The hierarchical solution is a mixture of the previous two having a coordination loop over several closed loops which control every part of the plant. In this case the design is more complex but the final system is robust to non standard situations.

Among the modern control theories developed until the present day for spacecraft systems the more widely used are the following ones:

- Multivariable robust control. Used in system with several inputs and outputs that are cross-coupled. The closed loop systems include a part for decoupling of the variables. The control engineer's goal is to stabilize the system along a series of values (a parameter). Two variants are applied in space-
craft control. \( H^\infty \) techniques and Bayesian identification techniques. Nearly every spacecraft uses this technique nowadays (science satellites like SOHO, FIRST, SILEX or telecommunications satellites like TELECOM2, HISPA SAT, ARTEMIS, etc).

- **Predictive control.** It is based on the production of two models of the system: reference and predictive. The control engineer produces a mathematical reference model of the plant. At every instant the system generates some predictive models which lead to a specific end condition. Out of all these possible solutions only one will satisfy the restriction of fuel consumption and minimum time maneuver. The optimal model is applied as a control input to the present configuration. The complete process is repeated at regular intervals. The goal of this control is the increase in robustness and elimination of tracking errors. This control is typical of the high pointing accuracy satellites used in scientific explorations (GOMOS, SOHO).

- **LQ (Linear Quadratic) techniques.** The plant is assumed to be linear. It is described in the state space form. The control engineer creates a quadratic function using the inputs of the system. The problem is to minimize this quadratic function with respect to the control inputs subject to linear system constraints. This solution is well applied to satellites in equilibrium that must remain in equilibrium. This control is used in combination with the previous two.

- **Modal control.** The control engineer specifies the response time, bandwidth, damping ratio, etc. of the plant. The poles of the closed loop systems regulate the performance of the controller. The position of the poles in the Z plane modes are selected to fulfill a specific criterion of convergence. This is the case of most geostationary satellites. It is easy to apply and can be extended to more complicated models. This technique is the preamble to the applications of more deep analysis for nonlinearities.

### 3. FUZZY LOGIC IN SPACECRAFT CONTROL

The techniques shown in the previous section use the experience of the control engineer helped by computer design control, simulations tools and computer verification models. To apply these techniques the plant must be well understood and its reactions known in nearly all circumstances.

Can fuzzy logic be applied efficiently to spacecraft control systems? or, Is it just a good alternative to PID controllers? Can it compete with classical models? Fuzzy logic has shown to be specially suitable in occasions when the plant is not static but changes with time (or differs slightly among very similar systems) or when the characteristics of the plant are not totally known or understood at the time when the controller was designed or when the control actions and goals were not precisely defined. Fuzzy logic has been proven to be adequate to solve control problems not in the best way but just in a suitable way within the required limits and giving satisfactorily performance.

The configuration of most spacecrafts contain the following characteristics:

- The spacecraft is not a rigid body anymore but an object with multiple moving appendages.
- The final mass is not known with total precision until the complete spacecraft is finished and filled up with fuel (e.g. time close to the launch); so the control system must be designed with certain tolerances.
- A satellite thruster system can never be perfectly aligned. At the beginning of the life of the satellite every maneuver has to be carefully calibrated.
- Once in station keeping, the movement of the solar arrays provoke structural flexures to the spacecraft dynamics. As a consequence structural resonances can occur disturbing the attitude.
- In most occasions when thrusters are fired (reorbit or station keeping) the satellite experiences parasitic torques along all axis different from the one containing the fired device.
- As time passes the fuel consumption varies the total mass of the satellite and therefore the centre of gravity changes.
- The matrix of inertia is not diagonal: there are cross products of inertia.

In all the previous situations there is a significant degree of fuzziness.

Figure 2 shows a diagram of blocks of a typical fuzzy controller.

![Fuzzy Controller Diagram](image-url)

The Fuzzy Logic system represents an intelligent knowledge based controller which consists of a data base of rules and the definitions of the fuzzy sets [6], [7], [1], [3]. The plant state is normalized to be able to be fuzzificated into the appropriate fuzzy sets. The inference engine fires the rules using the membership functions over the fuzzy sets and produces a result that has to be defuzzificated. Finally the output is denormalized in order to be applicable to the control action required.

Depending on the type of problem there are basically two ways to apply fuzzy logic to spacecraft control: direct control and supervisory control. In both cases the control is called expert because it incorporates knowledge.
from an expert that cannot be embedded during the design of the mathematical model.

If fuzzy logic is applied to direct control (figure 3) the fuzzy controller will replace the conventional one completely. In this case the controller replaces the role of the process operator solving the problem to produce a smooth control action in the proximities of the set point. This control reduces the errors in the process output and prevents from exceeding some predetermined value by means of adjusting the control output. In this case a typical rule of the data base looks like

\[
\text{if something happens with a state variable} \\
\text{then produce control output}
\]

If fuzzy logic is applied to supervisory control (figure 4) the controller acts as a supervisor of the classic control loops. The supervisor determines when and which of the classic elements will work selecting the appropriate parameters for them. Here the controller replaces the role of the control engineer tuning parameters for all the classic elements included in the complete design. The rule data base contains two kinds of rules [8]: context rules (to derive properties of close loop control from open loop) and tuning rules (to change parameters adapting them to different necessities). In this case a typical context rule of the data base looks like

\[
\text{if open loop process is } X \\
\text{then close loop is } Y
\]

and a typical tuning rule looks like

\[
\text{if something happens with a control variable} \\
\text{then change parameter in block } Z
\]

Basiclly both types of control can be applied to spacecraft systems. Direct control is more appropriate to the centralized and decentralized types of satellite control architectures (section 2) whereas supervisory control fits perfectly in the case of a hierarchical architecture.

4. CONTROLLER CONSTRUCTION

During several years the fuzzy logic community has developed several techniques to construct fuzzy controllers. These techniques have some commonalities. Grouped and analyzed together they form the core of a design guide for fuzzy control engineering.

Controller Design

The steps involved in the construction of the intelligent controller can be depicted as shown in figure 5 [12], [2].

Prior to any involvement in the design the control engineer should study the physical problem to determine which characteristics should be considered. This part is also common to the crisp approach. At this stage it is necessary to choose the type of control architecture more suitable for the problem. Several factors have to be considered: the type of satellite (science, telecommunications, Earth observation), type of orbit (circular, elliptic), etc.

The definition of input and output variables. The input variables are the sensor measurements (positions, velocities, yaw, pitch, roll, etc.). For a system with thrusters the output variables are the firing of a particular thruster (thrust position and time of fire) and the attitude angles and rates. For a system with momentum wheels the output variables can be the angular velocity of wheel rotation or the deflection angle for a gimbaled momentum
wheel control system. If the system includes solar arrays another output variable will be the deflection angle of the flaps to force the solar sailing navigation (GEO orbits).

Universe of discourse. The next step is the definition of the universe of discourse for all variables. For angles the universe of discourse stretches from \(-\pi/2, \pi/2\). For angle rates the universe of discourse stretches between 0 and a maximum value governed by the actuators limits. For distances, velocities, etc. and their rates the universes of discourse belong to [min. value, max. value].

Knowledge acquisition. An efficient method to acquire and capture the knowledge of an experienced spacecraft controller is very important. This knowledge will form the rules data base which will contain the type of control to realize. The first method for knowledge acquisition is the interview with the expert. He/she will tell the control engineer how many rules are sufficient. Normally no more than two variables are considered in the antecedent of every rule. Together with the interview of the spacecraft controller the knowledge should be reinforced with computer simulations. But this requires parametric studies with very large Monte Carlo type analysis which are not always available. An alternative is to use the high fidelity real-time fly simulators of a human pilot mind.

Compilation of the rules data base. The rules data base forms the kernel of the knowledge based controller [20]. Depending of the type of fuzzy control (direct or supervisory) the construction of the rules data base is significantly different. In the case of direct control the knowledge based controller implements the closed loop control actions substituting completely the operator. The data base rules are grouped depending on the control action they generate: for the transitional movement there must be rules for controlling azimuth, rules for controlling elevation and rules for controlling distances and velocities; for the rotational movement there must be rules for controlling pitch, rules for controlling roll and rules for controlling yaw. In the case of supervisory control the fuzzy device must schedule the functioning of the classic control blocks. The rules data base contains context rules and tuning rules. With the context rules the fuzzy controller classifies the satellite flying type environment. With the tuning rules the fuzzy device changes loop gains, delays, constants, etc. Thanks to the tuning rules the data base will incorporate an experience which can only be realized in the corresponding analytic model by means of manual operations.

The election of the Inference Engine. The inference engine is needed to fire the rules. There are several methods to program the engine. One of the most popular is the Mandani's Min-Max mechanism; normally the AND operator is chosen as the minimum of two weight antecedents instead of its multiplication. For fast processing the defuzzification strategy used is often the centre of gravity computation. In general, the inference engine can be an approximate reasoning kernel based on already proposed systems. There are several free packages as well as commercial ones.

Verification with simulations. The power of the simulations can be used to verify the convergence and stability of the controller. A fast prototype must simulate the plant and the controller as well. Most of the available packages provide with graphical tools to visualize the results of the simulations. An example of pseudocode for the verification of the functioning of a fuzzy system for spacecraft control using simulations could be as follows:

```python
initialize all;
create rules for the rules data base;
step = 1;
big_loop
    draw positions & velocities;
spacecraft kinematics;
spacecraft attitude dynamics;
sensor measurements;
store everything for drawing;
Fuzzy_control_computations;
if final_condition_reached then out
else step = step+1;
end big_loop;
```

Optimization. The knowledge of a spacecraft controller can be captured to generate the rules data base or to determine the overlapping of the fuzzy sets. A priori it is difficult to evaluate if the control output produced is optimal or not. To optimize the rules data base or the fuzzy sets used by the membership functions two approaches can be followed: manual optimization using the common sense and human experience or automatic tuning (using adaptive fuzzy control or genetic algorithms tools). In general a simple heuristic approach of overlapping 25% the membership functions does not produce a priori the best solution [11]. That is, changing the shape of the membership function changes the performance of the controller. A genetic algorithm tool or similar can help to solve this optimization problem but it will be hard to include such a system in a real time environment.

Controller Implementation

Coding, testing and flying. The physical implementation of the controller requires to write source code that will be inserted in the RAM (and sometimes in a ROM) of the flying processor. There are several tools that allow code generation from a fuzzy shell. In most of the cases a cross compilation from C, FORTRAN or Ada code into the microcontroller machine code will be required. Once the code is generated it must be tested. This can easily be done with simulators (preliminary test environment) or in a full integration test environment on ground with real actuators and effectors.

The final system will be mounted in the attitude and orbit control subsystem of the vehicle [21], [5]. It will determine the actual state of the spacecraft and it will generate torques to execute maneuvers to guide and position the spacecraft. Once in the final orbit the close loop operations of the intelligent controller are performed in an autonomous way replacing the usual control algorithms. The intelligent controller must substitute the guidance and control parts. The goal is to produce smooth control actions to avoid disturbance torques reaching any final orbit and attitude as soon as possible.

5. APPLICATIONS and EXAMPLES

A good example of the applicability of fuzzy logic for an intelligent control is the maintenance of the spacecraft within a determined region of space (figure 6).
docking of an active servicing spacecraft into a big passive space station rotating around the Earth (figure 7). In this problem the active chaser produces smooth control actions in the proximity of the passive target and during the structural latching to avoid disturbance torques in the final assembly orbit [13].

In this case another supervisory control could be applicable. The reason is that fuzzy logic is very well suited to guide the servicing vehicle during the rendezvous phases. For the fine docking and structural latching operations the fuzzy device could command a typical PID type control block.

Finally, the problem of the very high pointing accuracy for scientific satellites (figure 8) should be mentioned. The demand for accuracy in pointing maneuvers (< 0.001°) has increased during this decade and it is expected to further increase in the future.

This can be the case for an automatic station keeping within a prescribed orbital window of a geostationary satellite. The satellite has to be maintained within an imaginary cube of approximate 120 square kilometers by 40, 50 meters width. Due to several perturbing forces (Sun, Moon, Earth triaxiality) the satellite dance inside the cube exhibiting a periodic movement.

From time to time the satellite has to be moved back to its original position. These operations are done regularly from ground with the help of the localization campaigns and maneuver calibrations. A fuzzy logic based intelligent control system could measure its position, velocity, etc. and compute the type, amount and duration of thruster firing to reallocate itself back to the right orbit. In this case a supervisory control would be more appropriate.

Another example of applicability of fuzzy intelligent control is the problem of the rendezvous and docking operations of two spacecrafts [9], [15].

Typically the satellite is pointed to several targets in several slots of time [19], [18], [16], [17], [14]. These operations are commanded from ground using operational procedures executed by spacecraft controllers. Again, a fuzzy logic based intelligent control system could measure its position and orientation in space with respect to the target and compute the torques to repoint the satellite.

In this case a direct control type could activate the reaction control wheels of a three-axis stabilized satellite for achieving a smooth very fine pointing accuracy.

6. CONCLUSIONS

From the experience of several decades and a tremendous effort employed in the optimization of a variety of control systems the engineers know that a poor identification of the plant produces good results in the robustness of the system.

Fuzzy logic deals with uncertainty in the identification of the system model. Fuzzy logic emulates the behavior of human operators for complex control tasks. A fuzzy logic
controller embedded in a guidance, navigation and control system of a spacecraft can realize autonomously the close loop operations helping or replacing the conventional crisp control algorithms.

Fuzzy and crisp logic will coexist in the near future to develop a new generation of spacecraft control systems of high quality, more flexible, cheaper and intelligent.

REFERENCES


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