FUZZY LOGIC FOR SPACECRAFT CONTROL: AN EUROPEAN APPROACH

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ABSTRACT

As technology allows the growth in size and performance of spacecraft 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 goal of the paper is to describe the undergoing European projects to develop and achieve a fuzzy logic based technology for the control of a spacecraft. In the search for an easy, efficient, cost-effective control design and development technique, fuzzy logic seems to provide a method of reducing system complexity while increasing control performance.

First, the article analyses which the current techniques in spacecraft control systems. The emphasis is put on the analyses and design of spacecraft control systems due to its complexity.

Second, the article discusses in detail if fuzzy logic can be applied to spacecraft control systems and how can this be done easyly and efficiently. Two different techniques are detailed: direct control and supervisory control. The advantage and disadvantages of each of them are carefully described.

Next, the paper details the available systems in Europe at this moment. The focus is centered around the efforts made by ESA to build three different models of spacecraft control systems based on fuzzy logic: 3-axis stabilized spacecraft model, rendezvous and docking model, and re-entry model.

After that, the paper concludes with the efforts to develop a proprietary technology to cover the existing gap in Europe. Fuzzy Logic may lead the path to new fast, robust, extensible, upgradable, and much cheaper spacecraft control systems.

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 and predicts its immediate future state to achieve the desired trajectory (guidance); and the control part calculates the desired control torques to achieve this trajectory and attitude.

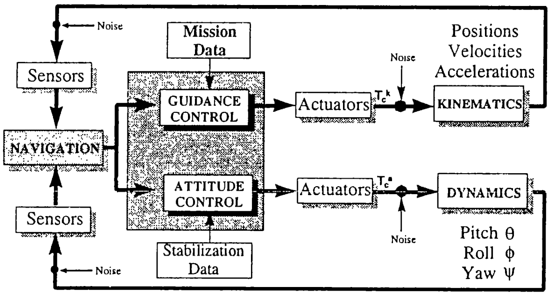

Fig. 1. Control Loop of a Spacecraft

The objectives are to maintain the vehicle within a prescribed orbit and attitude respecting the given mission constraints (fuel consumption and maneuver time minimized, heat load, etc).

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 [11], 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

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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 spacecraft control: H^∞ techniques and Bayesian identification techniques.
- 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 a particular restriction. 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.
- 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. 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.

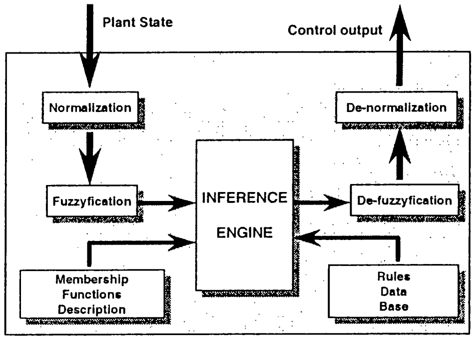

Fig. 2. Fuzzy Controller Diagram

The configuration of most spacecraft 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 (re-orbit 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.

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 [7], [8], [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.

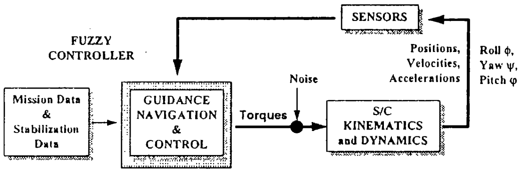

Fig. 3. Direct Fuzzy Control

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.

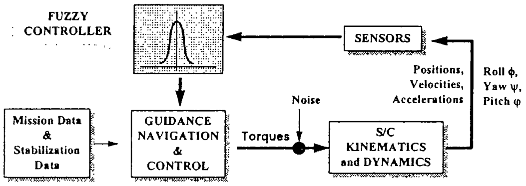

Fig. 4. Supervisory Fuzzy Control

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

if something happens with a state variable
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 [9]: 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

if open loop process is X
then close loop is Y

and a typical tuning rule looks like

if something happens with a control variable
then change parameter in block Z

Basically, 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 commonalties. Grouped and analyzed together they form the core of a design guide for fuzzy control engineering.

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

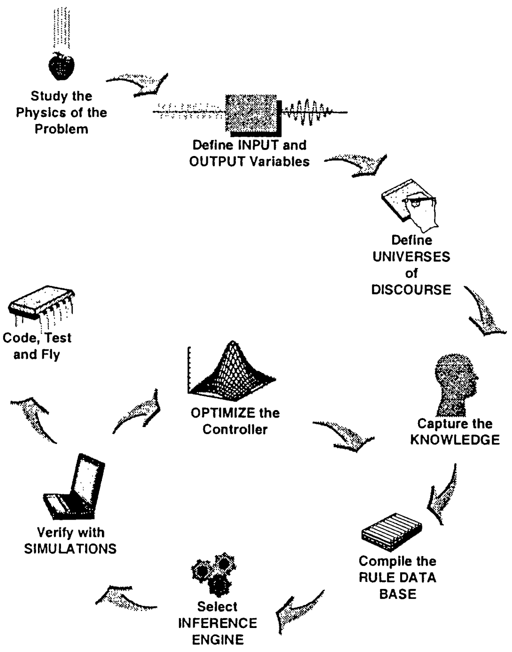

Fig. 5. Fuzzy Controller Design Spiral

Study the physics of the problem. 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, etc.

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 (e.g.) $[-\pi/2, \pi/2]$. For angle rates the universe of discourse stretches between (e.g.) 0 and a maximum value governed by the actuators limits. For distances, velocities, etc. and their rates the universes of discourse belong to a particular interval.

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.

Compilation of the rules data base. The rules data base form 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 close loop control actions substituting completely the operator. The data base rules are grouped depending on the control action they generate. 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 Mamdani'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.

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.

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 for example).

Coding, testing and flying. The physical implementation of the controller requires to write source code that will be inserted in the computer memory of the flying processor. 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 autonomously way replacing the usual control algorithms.

5. APPLICATIONS IN EUROPE

The European Space Agency is currently undertaking studies in the applicability of the fuzzy logic control techniques to spacecraft control.

Utilising the research made by the Technical University in Delft (The Netherlands), ESA is on the way to construct spacecraft simulators which incorporate fuzzy logic techniques in their guidance, navigation, and control systems.

Three different projects demonstrate the feasibility of the fuzzy logic control for spacecraft applications:

- 3-axis stabilised satellite control.
- Rendezvous and docking control between a re-supply vehicle and a space station.
- The Earth atmospheric re-entry of a rescue vehicle which carries astronauts from an orbiting space station back to Earth.

In all cases, the control system is based on fuzzy logic, capturing the knowledge of experienced spacecraft pilots or ground operators. This knowledge is represented as a set of rules and the definitions of the fuzzy sets. The control system shall determine the present state of both vehicles, and shall generate torques to execute the maneuvers that will lead to the desired orbit and attitude.

3-axis Stabilized Satellite Control

The three-axis stabilized spacecraft case is representative of an ESA typical scientific, Earth observation, or telecommunication satellite mission. The target of this development is the ESA Infrared Space Observatory ISO. The fuzzy control for ISO shall verify the advantages of this type of control in high pointing accuracy maneuvres (figure 6).

The demand for accuracy in pointing maneuvers has increased during this decade and it is expected to further increase in the future.

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.

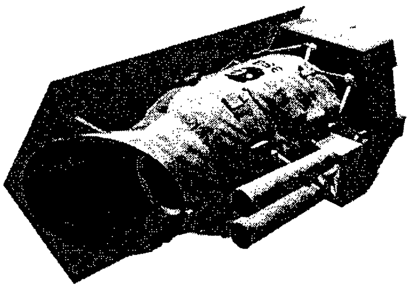

Fig. 6. The Infrared Space Observatory

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. ISO had to be able to maneuver smoothly from one celestial source to the next, and then maintain accurate pointing on that target. The spacecraft was capable of pointing at any region of the sky that satisfies certain stray-light constraints. The slew speed between sights was set at 7 degrees/min in order to optimize observation time, and the duration of each observation could range from a few seconds to up to 10 h, depending on the type of source.

In this case, a direct control type could activate the reaction control wheels and the thruster system of the satellite achieving a smooth, very fine pointing accuracy. The control effort should be minimum, having the constraints to keep fuel comsumption and slewing time as a minimum.

Rendezvous and Docking Control

The second case of applicability of fuzzy intelligent control is the problem of the rendezvous and docking operations of two spacecrafts [10], [15]. The target of the investigation is here the ESA's re-supply vehicle for the International Space Station (the Automatic Transfer Vehicle ATV) [6].

As one of the European contributions to the future International Space Station (ISS), the European Space Agency is developing the Automatic Transfer Vehicle (see figure 7). ATV is an unmanned, Ariane-5 launched vehicle that will perform regular reboost and refuelling and payload supply and removal to the ISS. Other missions of ATV will comprise payload supply and payload removal from the ISS.

The ATV project was approved in October 1995 by the Council of the European Space Agency. ATV will be launched for the first time from Kourou (French Guiana) in February 2003.

ATV is basically a cylindrical shaped spacecraft containing a cargo module pressurized or un-pressurized, a docking port, and a propulsion module. ATV will dock to the service module of the Russian segment of the ISS.

The ATV rendezvous and docking mission is equivalent to the problem of the rendezvous and docking of an active servicing spacecraft into a big passive space station rotating around the Earth. 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, a supervisory control could be applicable. The reason is that fuzzy logic may be 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.

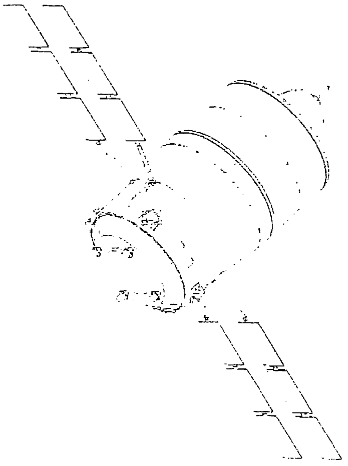

Fig. 7. The Automatic Transfer Vehicle

Atmospheric re-entry of a lifting body

The third study case is a lifting body winged type vehicle for atmospheric Earth re-entry and landing. The target of this development is the ESA-NASA Crew Rescue Vehicle (CRV).

The CRV (depicted in figure 8) is a spacecraft attached to the International Space Station which will serve as a re-entry vehicle for astronauts on-board. The CRV will departure from its docking port of ISS and will reach a particular landing site.

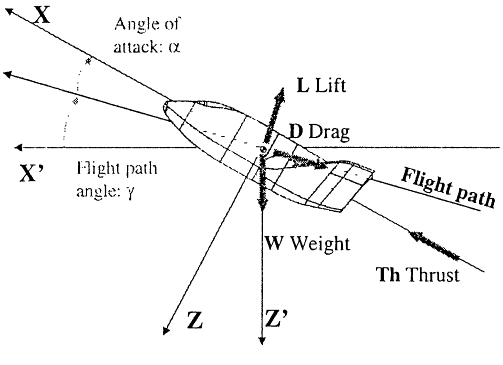

Fig. 8. The ESA-NASA Crew Rescue Vehicle

The short flight (around 40 minutes) of the CRV is catalogued in three basic phases: the de-orbiting, the re-entry, and the landing. For each of the phases, the craft behaves differently. This fact makes the flight dynamics rather complex and engineering demanding. The critical control problem is the stabilization of the spacecraft axis, and its velocity vector.

Fuzzy logic in the guidance, navigation, and control unit of the CRV shall be able to cope with a huge variety of control regimes, performances, and constraints during the complex flight of the vehicle.

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.

ESA is underway to build up three fuzzy logic based spacecraft control simulators for three different types of missions: a classic 3-axis estabilized satellite mission (ISO), a rendezvous and docking (ATV) and a lifting body re-entry vehicle (CRV). These shall prove the capability and adequacy of fuzzy logic in the area of spacecraft control, leading the way to new cheaper, faster, better control system for space vehicles.

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.

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