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GENO-FUZZY CONTROL OF SPACECRAFT AUTOMATIC SERVICING

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Abstract. Spacecraft servicing comprises the tasks of assembly, resupply, repair and maintenance of in-orbit manufactured space parts. Automatic servicing relies on intelligent fly control systems to perform fast, soft, and precise docking operations. This paper proposes the use of a fuzzy logic guidance and navigation system mounted on an active chaser vehicle, which wants to dock with a big passive space station on orbit around the Earth. It produces smooth control actions in the proximity of the target, and during the docking to avoid disturbance torques in the final assembly orbit. A genetic algorithms tool is used to optimize the controller reducing docking time, and fuel consumption. It performs the optimization by finding the best fuzzy sets, and membership functions of the controller.

Keywords. Fuzzy control, Genetic algorithms, Spacecraft autonomy.

1. INTRODUCTION

Nowadays, the main space programs like the American space Shuttle, or the Russian MIR station incorporate some sort of semi-autonomous controllers to realize docking operations. In the future, big systems like the International Space Station will require an average of tenths of flights a year to perform in orbit servicing. In this scenario, full autonomous rendezvous and docking operations will permit to reduce mission time and operational costs, and increase human productivity.

The proposed case study is the autonomous assembly of a servicing spacecraft with a space station, on orbit around the Earth. The servicing spacecraft (called the **chaser**) is small in comparison with the space station (called the **target**). The spacecraft chaser is the active element, and mounts a control system which allows autonomous active servicing. This spacecraft control system has sensors to measure its position and orientation in space. It calculates the actual state of the vehicle, and computes the desired control actions to maintain or achieve a determined position and orientation. The space-

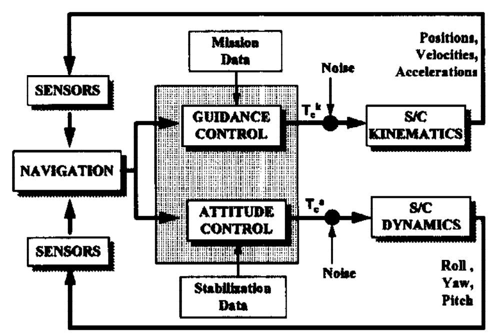

Fig. 1. Control Loop of a chaser

craft target is the passive element during the operations. It has also sensors to measure, at any time during the maneuvers, the distance and orientation with respect to the chaser. However, it does not perform any maneuver.

The paper discusses the use of a genetic algorithm (GA) tool to optimize the implementation of a fuzzy logic controller, mounted in the chaser. The system determines the actual state of both vehicles, and generates torques to execute maneuvers to establish the structural assembly in orbit. This allows a fast and soft docking with the target.

2. AUTONOMOUS SERVICING

The space station is orbiting around the Earth at a height of about 300 to 400 km (Wohlke 1992). The chaser carries an autonomous fuzzy logic based control system. Figure 1 shows the chaser control system. 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; the control part calculates the desired control torques to achieve this trajectory (Georgiou *et al.* 1991, Champetier *et al.* 1991).

The target has the necessary mechanical-electrical elements for the docking of the chaser. The docking operations are realized using a reference coordinate system called Local Vertical, Local Horizontal (LVLH). That is: +X (roll) in the direction of target flight, +Z (yaw) in the direction of center of Earth, and +Y (pitch) orthogonal to these two. The chaser is approaching the target using the V-bar technique, where the docking axis is along the velocity vector of the space station, and against its radial velocity.

The rendezvous is completed in several phases: homing, final approach, docking, and structural latching. The homing phase starts with the target presence acquisition by a large range sensor (normally a S-band radar), mounted in the chaser. This phase comprises the chaser-target distances in the range of 100 to 1 km. The final approach phase comprises the close up of the chaser from -1 Km to -1 m. During this phase a short range sensor (camera) localizes a specific mark in the target (Ho and McClamroch 1993). The docking phase starts approximately at -1 m from the target, and ends just a few centimeters from it, before the latching. A set of sensors for very close rate measurements, mounted in the chaser docking side allow the fine docking. Four latches mounted clockwise to the close up sensors will fit into four handles, that close when the proximity operations are finished.

2.1 *Translation Motion in Circular Orbit*

The translational motion of a spacecraft system in a low circular orbit can be described using the Clohessy-Wiltshire-Hill equations. Those are linear differential equations with time constant coefficients, which describe the movement of two small masses in a circular orbit around a third big object. They were programmed in the rendezvous guidance computer used in the Gemini mission (1962), and still provide short-range maneuver computation for the Shuttle. This equations have as input the initial position and velocity of the chaser. The output is the position and velocity of the chaser after a time interval. To apply these equations, the two rotating bodies must have a small mass in comparison to the non-rotating body. The position and velocity of the chaser are given in this LVLH reference system.

$$\ddot{\boldsymbol{r}}_2 - \ddot{\boldsymbol{r}}_1 = \frac{\mu}{r_1^3}\left[\boldsymbol{r}_1 - \frac{r_1^3}{r_2^3}\boldsymbol{r}_2\right] + \boldsymbol{f} \qquad (1)$$

where r_1, r_2 are the distances of target and chaser from the Earth center, μ is the product $G * M_{earth}$ and $\boldsymbol{f}$ is the perturbing force. This equation linearized in the LVLH system gives:

$$\begin{aligned} \ddot{x} - 2\omega\dot{z} &= f_x \\ \ddot{y} + \omega^2 y &= f_y \\ \ddot{z} + 2\omega\dot{x} - 3\omega^2 z &= f_z \end{aligned} \qquad (2)$$

where ω is the coordinate frame's angular velocity with respect to an inertial frame. These equations are not solvable in general but in some special cases it is possible to derive an analytical solution.

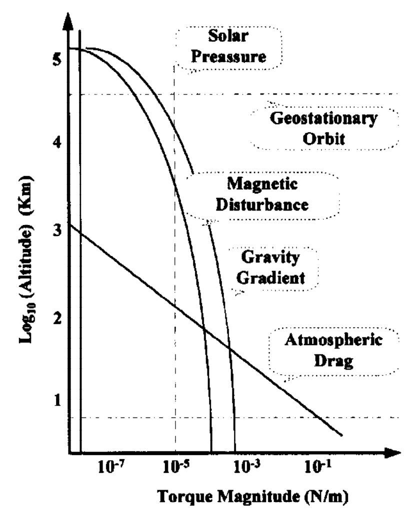

Fig. 2. Perturbing forces to a spacecraft

For a rendezvous of this type, the force $\boldsymbol{f}$ is the atmospheric drag. Other forces, like the Earth magnetic field disturbances, solar pressure, or cosmic dust can be easily neglected (figure 2). Even the atmospheric drag decreases to zero when talking of distances between chaser and target of about decimeters. At the end of the final approach, and during the docking and structural latching phases this force can be neglected.

The solution to equations 2 is as follows:

$$\begin{bmatrix} x \\ y \\ z \\ \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 6\omega - 6S & \frac{4S}{\omega} - 3t & 0 & \frac{2}{\omega}(1-C) \\ 0 & C & 0 & 0 & \frac{S}{\omega} & 0 \\ 0 & 0 & 4-3C & -\frac{2}{\omega}(1-C) & 0 & \frac{S}{\omega} \\ 0 & 0 & 6\omega(1-C) & 4C-3 & 0 & 2S \\ 0 & -S\omega & 0 & 0 & C & 0 \\ 0 & 0 & 3S\omega & -2S & 0 & C \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \\ z_0 \\ \dot{x}_0 \\ \dot{y}_0 \\ \dot{z}_0 \end{bmatrix} \quad (3)$$

where $S = sin\omega * t$, and $C = cos\omega * t$ for simplicity. Knowing the initial position $[x_0, y_0, z_0]$, and the initial velocity $[\dot{x}_0, \dot{y}_0, \dot{z}_0]$ it is possible to calculate the final position $[x, y, z]$, and the final velocity $[\dot{x}, \dot{y}, \dot{z}]$, after a time t.

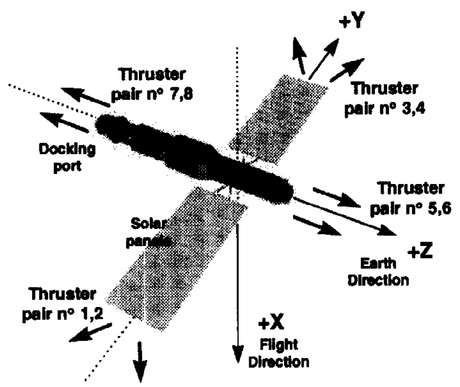

Fig. 3. Thrusters position in chaser

The translation of the servicing vehicles is realized by means of thrust impulses. The thruster system of the servicing vehicle consists of 8 pairs localized at four surfaces as shown in figure 3. Pairs (5,6) will impulse the satellite in the $-X$ direction and pairs (7,8) in $+X$ direction, etc.

2.2 *Rotational Motion*

The attitude control of both chaser and target is three axis stabilized, although during the operations the station attitude is constant (Fehse 1985). The attitude control of the servicing vehicle is performed with a double gimbaled bias momentum wheel (figure 4). The Euler equation governing the movement is:

$$\boldsymbol{F}_d|_{S'} = \left[\frac{d\boldsymbol{h}}{dt}\right]_S + \boldsymbol{W}_{SS'} \times \boldsymbol{h}_S \quad (4)$$

where S' is a fixed reference system with origin in the center of satellite mass, and S is a reference system with the same origin that rotates with the satellite. S' and S are defined as the LVLH system. $\boldsymbol{F}_d$ is any disturbance force (atmospheric drag, thruster misalignment, etc). $\boldsymbol{W}_{SS'}$ is the angular velocity of S respect to S', and $\boldsymbol{h}$ is the total angular momentum of the spacecraft ($\boldsymbol{h}_{chaser}$ body + $\boldsymbol{h}_\omega$ gimbaled wheel).

Pitch (θ) equation is simple and decoupled from yaw (ϕ) and roll (ψ) assuming a symmetric satellite but yaw and roll equations are coupled.

$$\begin{aligned} F_{dy(pitch)} &= I_y\ddot{\theta} + \dot{h}_y \\ F_{dx(roll)} &= I_x\ddot{\phi} + \omega_{SS'}hw\phi + hw\dot{\psi} + \dot{h}_x - \omega_{SS'}h_z \quad (5) \\ F_{dz(yaw)} &= I_z\ddot{\psi} + \omega_{SS'}hw\psi - hw\dot{\phi} + \dot{h}_z - \omega_{SS'}h_x \end{aligned}$$

where I_x, I_y, I_z are the principal moments of inertia of the chaser. The chaser control torques $(\dot{h}_x, \dot{h}_y, \dot{h}_z)$ are produced through the wheel gimbal defections δ and γ.

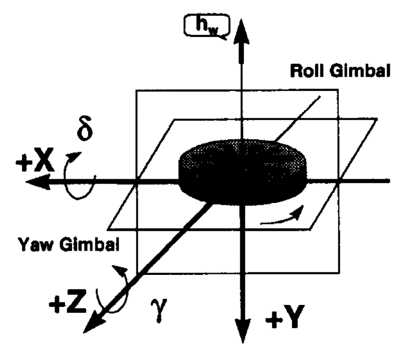

Fig. 4. Double gimbaled momentum wheel deflections

3. GENO-FUZZY CONTROL

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 (Daley and Gill 1985, Daley and Gill 1987, Brown 1994). The next steps are followed to construct the geno-fuzzy controller (Karr *et al.* 1990):

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 (Berenj *et al.* 1993). At this stage, it is necessary to choose the type of control architecture most 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. For the translation movement of the chaser, the input variables of the FC system are azimuth, elevation, range and its derivatives. These quantities are defined with respect to a coordinate system

(LVLH), centered in the docking port of the space station. Like this, the azimuth (a) is defined as the angle formed by the X axis and the Line of Sight (LOS), between the center of gravity of chaser and docking port of the station (figure 5).

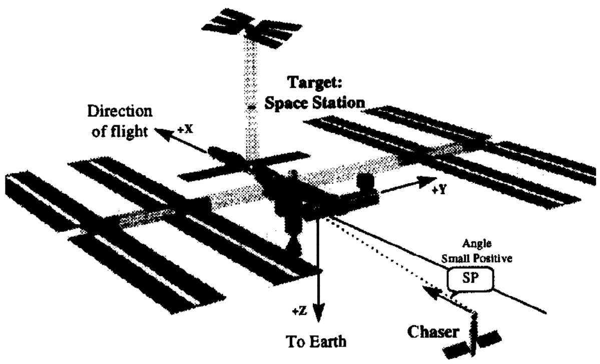

Fig. 5. Fuzzy sets definition

Similarly, this is done with azimuth rate ($\dot{a}$), elevation (e), elevation rate ($\dot{e}$), range (r) and range rate ($\dot{r}$). For the rotational part, the input variables are defined with respect to a coordinate system with origin in the center of gravity of the chaser as defined in figure 3. These will be pitch (θ), pitch rate ($\dot{\theta}$), roll (ϕ), roll rate ($\dot{\phi}$), yaw (ψ) and yaw rate ($\dot{\psi}$). The output variables will be the firing time (f_t), position of fired thruster (P_T), yaw deflection (δ) and roll deflection (γ) of the gimbaled control wheel.

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 each of the actuators limits, etc. The fuzzy sets for each variable are defined as follows: for azimuth, azimuth rate, elevation, elevation rate, range rate, roll, pitch, yaw, and its derivatives, the fuzzy sets are Small Negative (SN), Small Positive (SP), Large Negative (LN), and Large Positive (LP). For range, the possible fuzzy sets are Small (S), and Large (L), as no more distinctions are needed.

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 be implemented. 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:

- The control of each axis is carried out in an independent manner: firings in Z direction control azimuth and firings in Y direction control elevation.
- The firings over each axis are calculated taking into account angles and its derivatives.
- The control in azimuth and elevation is not symmetric; due to the Clohessy-Wiltshire-Hill equations firings in X direction will 'elevate' the chaser in its path towards the target. It is necessary to realize compensation firings in the +Z direction. However, the control in elevation is symmetric with respect to the +X axis.
- In addition the tendency of human controllers is to make azimuth and elevation equal to 0° during the final approach phase (typically at -10 or -20 m of the target) to be able to reduce control workload and focus on fine range rate control. This scheme complies with an intuitive proportional navigation guidance towards the point of starting axis translation.
- With respect to the amount and size of the firings they depend proportionally on the distance: different firing strategies must be followed depending on the distance to the target. During docking the firings are frequent with very small size.

Compilation of the rules data base. The rules data base forms the kernel of the knowledge based controller (Tso and Fung 1994). The data base rules are grouped depending on the control action they generate: for the translational movement of the chaser, the data base contains 16 rules for azimuth, and azimuth rate (in-plane motion), 16 rules for elevation, and elevation rate (out-of-plane motion), and 8 rules for range and range rate. For the rotational movement of the chaser, the rules data base contains 16 rules for pitch and pitch rate, 16 rules for yaw and yaw rate, and 16 rules for roll and roll rate.

4. OPTIMIZATION WITH GAS

The GAs tool can act over the membership functions definition or over the rules data base set up. The tool provides three kind of operators: Reproduction, Crossover, and Mutation. The reproduction operator generates new strings based in a random probability factor. The crossover operator mixes two strings based on another probability factor. The mutation operator changes part of a string based on a third probability factor. The application of the three operators is done in a programming loop. The loop ends at the time when a cost function reaches its maximum (or minimum). The method used in the codification is the concatenated, mapped, unsigned binary coding method: given the limits of the fuzzy sets, and an initial population of strings, the tool generates randomly strings for each of the limits. These strings are then *concatenated* to form the representation of the membership functions. This representation is based on the formula:

$$C = C_{min} + \frac{Binrep}{2^M - 1} \times (C_{max} - C_{min}) \qquad (6)$$

where $Binrep$ is the binary representation of a string, M is the maximum number of generations, and C_{max} and C_{min} are the representation of the concatenations of the first and last possible solutions. Using this method there is a correlation between the string length and the state variables.

Once the solutions are concatenated, the tool generates an initial population of N strings. In this moment a computer loop will start applying the three operators: First the reproduction; for this operator and with the probability of reproduction, the tool assigns to each string a range of values in the interval [0,100]; then it produces a random number per string in the same range [0,100], and finally it forces reproduction, in case the random number is in the range corresponding to the string. The next operator is the crossover; this subroutine is in charge of mixing two strings in a random way using a predetermined probability factor. The last operator is mutation; this operator changes 1 bit randomly in one string using the mutation probability factor. Finally, the tool analyses the merit of each solution looking for the end in the computer loop. To evaluate the merit, it is necessary to look into the physics of the problem to define an optimization constraint; then to define several initial condition cases, and calculate the constraint function for a particular set of membership functions and these initial condition cases; finally the minimum (maximum) of this computation must be determined. In the case study the cost function is a special solution of the Clohessy-Wiltshire-Hill equations, in which the known values are positions, velocities, and angles, and the value to compute is the time to dock (t).

5. SIMULATIONS

Simulations where used to verify the convergence and stability of the controller before the real application. Simulations were developed on a PC compatible Pentium 100 MHz portable type computer. The core of the simulations and the physics environment was written in MATLAB 4.0®, for Microsoft Windows^{TM}. The code for the fuzzy controller was written using FISMAT, the Fuzzy Inference Systems toolbox for MATLAB developed by Prof. Zadeh.

The fuzzy inference engine with approximate reasoning was implemented using Mamdani's Min-Max mechanism. The AND operator was chosen as the minimum of two weight antecedents, instead of its multiplication. For fast processing, the defuzzification strategy used was the center of gravity computation. The GAs tool was codified by the authors, and applied to optimize the fuzzy sets and the membership functions. Figure 6 shows several simulation runs. In the plane XZ the servicing vehicle starts its travel in different initial positions: $X = -50\ m$ and $Z = 10, 20, 30, 40\ m$. In the plane XY the servicing vehicle starts its travel in positions $Y = 20, 40$. The case of $Y = 20$ corresponds to

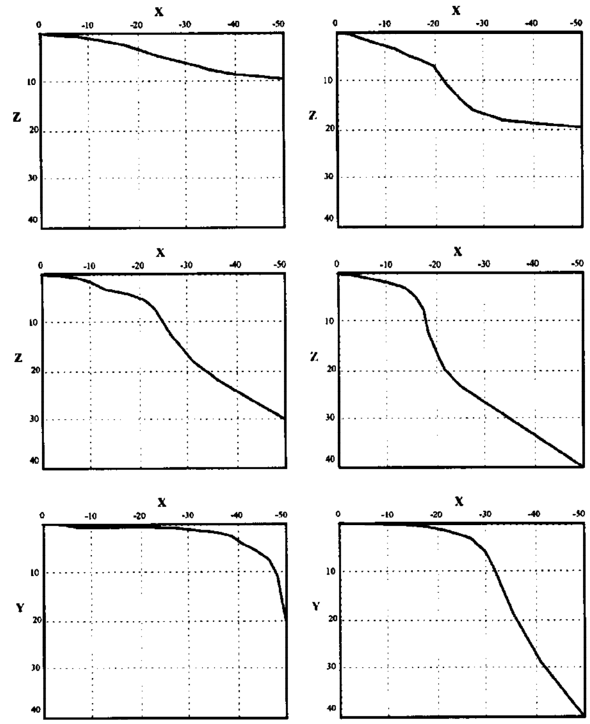

Fig. 6. Simulations run for docking

the simulations in plane XZ when $Z = 10, 30$. The case of $Y = 40$ corresponds to the simulations in plane XZ when $Z = 20, 40$. These simulation runs show the driving of a soft docking when $X < 20$ which corresponds to the human piloting of a translation along axis during the last part of the flight. The motion in the plane XY tries to rapidly reduce the value of Y. The control of each axis is carried out independently. The genetic algorithm tool performs off-line optimizing the membership functions of the fuzzy controller. It contains subroutines for each of the operators.

The genetic algorithm for the optimization of the fuzzy controller used the following parameters: the population size was 500 strings, the maximum number of generations was 50, the different probability factors for each operator were: probability of crossover, $P_C = 0.8$, and probability of mutation, $P_M = 0.01$. Figure 7 shows a combination of several simulation runs when the GA is applied to optimize the docking time, and the number of firings. The chaser was initially located in the coordinates (-40,0,30), behind the target at -40 m. The GAs tool ends the optimization in generation 50. The graph shows fuzzy control of generation numbers 10 (the longest path), 20, 30, and 50 (the shortest path). The docking time decreases from 10 to 5 minutes. For the generation series, from 0 to 10 the number of firings was more than 5. For the generation series, from 11 to 40 the number of firing decreased to 3. Finally, with the biggest number of generations

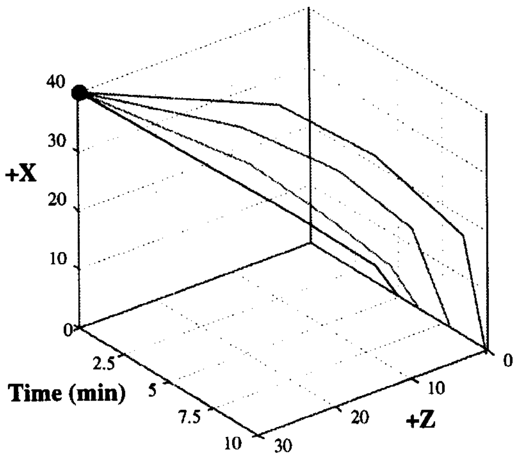

Fig. 7. Docking times of 4 generations

(supposed to be the optimal solution), the number of firings decreased to 2.

6. CONCLUSIONS

This article presented a method for the design of a geno-fuzzy controller for a small spacecraft with a servicing mission to a big space station, rotating around the Earth. The docking of the servicing spacecraft must be fast, precise, and soft enough to decrease mission time, and fuel consumption. This will allow for future missions to increase the amount of space traffic to and from Earth into space.

Fuzzy logic emulates the behavior of human operators for complex control tasks like in the case of the piloting of the servicing spacecraft. Fuzzy logic deals with uncertainty in the identification of the chaser controller model. A fuzzy logic controller embedded in a guidance, navigation, and control system of a spacecraft can realize close loop operations, helping or replacing the conventional crisp control algorithms. The rule data base of the fuzzy controller can be constructed with the help of an expert spacecraft pilot, and can be reinforced and verified with the help of simulators.

The reduction in fuel consumption is of vital importance to reduce the cost of the mission (less fuel implies less weight and therefore less cost). The rendezvous and docking time must be as little as possible to allow the increase in productivity in the space exploitation. A genetic algorithm tool can be used to optimize the controller for a particular mission. Knowing the initial parameters for the docking mission it is possible to calculate the best path to minimize such parameters. The tool performs off-line giving a global solution that is implemented in the fuzzy controller. In order to use the optimization in real-time, fast processing advanced computer systems must be carefully analyzed.

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