GENETIC ALGORITHMS FOR FUZZY CONTROL OF AUTOMATIC DOCKING WITH A SPACE STATION

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ABSTRACT

The spacecraft guidance and control community is engaged in the task to achieve continuous improvements in accuracy. There are two ways to realize this: the improvement in the design and development of sensors and actuators, or the development of new control strategies based on new ideas and principles. The autonomous assembly of two spacecraft in orbit requires intelligent control systems for soft and precise docking operations. We propose the study of a fuzzy logic guidance and navigation system, mounted in a chaser vehicle. This Fuzzy Controller (FC) is a knowledge based controller, that performs the closed loop operations autonomously. It produces smooth control actions in the proximity of the target, and during the docking to avoid disturbance torque in the final assembly orbit. We study the use of Genetic Algorithms (GAs) to perform the optimization of the fuzzy controller by finding the best fuzzy sets of the membership functions, to optimize docking time and fuel consumption.

1. Introduction

Spacecraft servicing comprises assembly, re-supply, repair and maintenance of in-orbit manufactured space parts. Big space programs like the Russian MIR station, the American space Shuttle, or the future International Space Station require such techniques. Autonomous servicing relays in intelligent control systems to perform soft docking operations, allowing to decrease mission time and operational cost, and increase human productivity. Usually, the spacecraft chaser plays an active role mounting a control system which allows autonomous active servicing. The spacecraft control system measures its position and orientation in space. It calculates the actual state of the vehicle, and computes the desired control forces to maintain or achieve a determined position and orientation. The spacecraft target is the passive element during the operations.

The paper discusses the use of GAs to optimize the implementation of a fuzzy Logic controller mounted in the chaser. The system determines the actual state of both vehicles, and generates torque to execute maneuvers to establish the structural assembly in orbit. The knowledge of the fuzzy controller consists of a data base of rules and the definitions of the fuzzy sets. The knowledge of an experienced spacecraft controller is captured into a set of rules forming the rules data base. The proposed GAs tool performs the optimization of the fuzzy membership functions, allowing the achievement of the minimization of time and fuel consumption during the maneuvers. We present here, a new way to compute efficiently the fitness function of the proposed GA.

2. Mission Design

The particular case study is the soft docking of a small active chaser servicing vehicle, into a big passive target space station. The space station is orbiting around the Earth at a height of about 400 km [8]. The chaser carries an autonomous fuzzy logic based control system. The target has the necessary mechanical-electrical elements for the docking of the chaser (figure 1).

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 the radial velocity of the station.

Both, the servicing vehicle and the station are permanently three axis stabilized during the maneuvers. Typical rendezvous operations [3] to approach the servicing vehicle to the station, start at - 100 km far from the station.

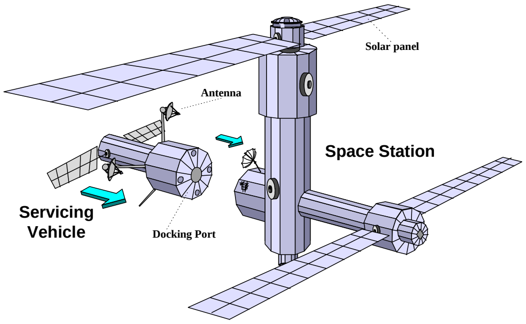

Fig. 1: Servicing vehicle docking to a space station

The final approach phase comprises the close up of the chaser from -1 Km to -1 m. During this time, a short range sensor (camera) mounted in the servicing vehicle localizes a specific mark in the target [4]. In addition, the chaser can mount other type of sensors, that redound the measurements for backup purposes (laser and radar, etc). 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.

3. The Physics of the System

The translation 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. These 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.

$$\ddot{\mathbf{r}}_{\mathbf{2}} - \ddot{\mathbf{r}}_{\mathbf{1}} = \frac{\mu}{\mathbf{r}_{\mathbf{1}}^{\mathbf{3}}}\left[\mathbf{r}_{\mathbf{1}} - \frac{\mathbf{r}_{\mathbf{1}}^{\mathbf{3}}}{\mathbf{r}_{\mathbf{2}}^{\mathbf{3}}}\mathbf{r}_{\mathbf{2}}\right] + \mathbf{f} \qquad (1)$$

where r_1, r_2 are the distances of target and chaser from the Earth center, μ is the product $G * M_{earth}$ and $\mathbf{f}$ 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.

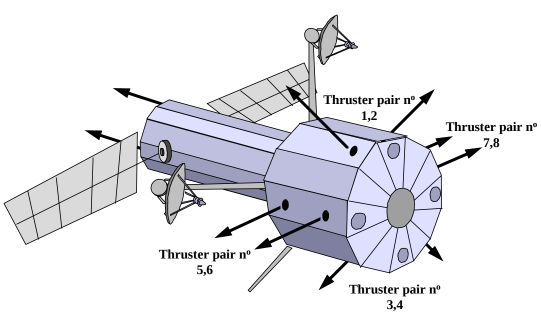

Fig. 2: Thrust location in chaser

For a rendezvous of this type, the force $\mathbf{f}$, is the combination of the atmospheric drag, and Earth magnetic field disturbances. Both forces can be easily neglected when talking of distances between chaser and target of about decimeters.

The translation of both vehicles is realized by means of thrust impulses. During the docking maneuvers, the space station is maintained passive. The thrusters system of the servicing vehicle consists of eighth pairs, localized at four surfaces, as shown in figure 2. Pairs (5,6) will impulse the satellite in the $-X$ direction, and pairs (7,8) in $+X$ direction, etc. The attitude control of both, chaser and target, is three axis stabilized, although during the operations the station attitude is constant. The control of the servicing vehicle is performed with a double gimbaled, bias momentum wheel. The corresponding Euler equations are:

$$\mathbf{F_d}|_{\mathbf{S'}} = \left[\frac{\mathbf{dh}}{\mathbf{dt}}\right]_{\mathbf{S}} + \mathbf{W}_{\mathbf{SS'}} \times \mathbf{h}_{\mathbf{S}} \qquad (3)$$

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. $\mathbf{F_d}$ is any disturbance force (atmospheric drag, thrusters misalignment, etc). $\mathbf{W}_{\mathbf{SS'}}$ is the angular velocity of S respect to $S^{'}$, and $\mathbf{h}$ is the total angular momentum of the spacecraft (body + gimbaled wheel). Pitch equation is simple and decoupled from yaw and roll, assuming a symmetric satellite, but yaw and roll equations are coupled.

$$\begin{aligned} F_{dy(pitch)} &= I_y\ddot{\theta} + \dot{h}_y \\ F_{dx(roll)} &= I_x\ddot{\phi} + \omega_{SS'} h_W \phi + h_W \dot{\psi} + \dot{h}_x - \omega_{SS'} h_z \\ F_{dz(yaw)} &= I_z\ddot{\psi} + \omega_{SS'} h_W \psi - h_W \dot{\phi} + \dot{h}_z - \omega_{SS'} h_x \end{aligned} \tag{4}$$

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

4. Genetic Fuzzy Control

Figure 3 shows the proposed Guidance, Navigation and Control System (GNC). The navigation block calculates the actual state of both spacecraft, and their relative measurements. The guidance and control (G&C) system contains a fuzzy logic controller, which reads the state of the chaser, and calculates the control torque to achieve the desired trajectory. In addition, the fuzzy controller counts with the support of a genetic algorithm tool. The proposed GAs tool is shown in figure 4. The GAs tool provides three kind of operators: Reproduction, Crossover and Mutation. The tool works in an off-line environment (not in real-time), performing the optimization of the fuzzy controller membership functions. The rules are captured from the experience of a spacecraft controller.

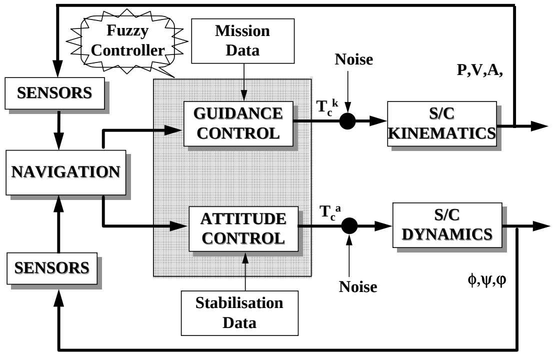

Fig. 3: GNC system with Fuzzy Controller

Thanks to this data base, the FC will incorporate an experience which can only be realized in the corresponding analytic model by means of manual operations [2]. The expert defines the way to determine the state of the target-chaser system, and the way to use the thrust commands for each situation. The inference engine can be an approximate reasoning kernel based on already proposed systems [6].

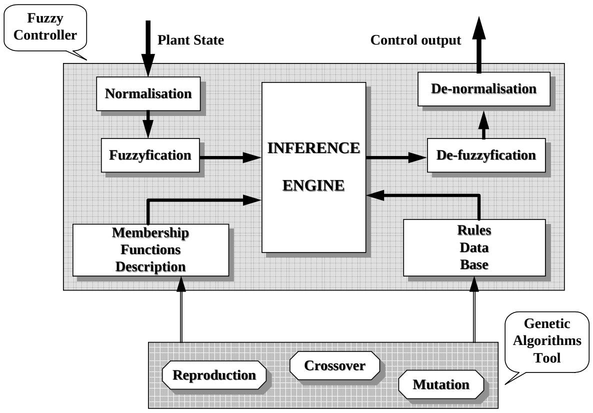

Fig. 4: Controller with GAs optimization system

For the translation movement of the chaser, the input variables of the FC system will be azimuth a, elevation e, azimuth rate $\dot{a}$, elevation rate $\dot{e}$, range r, and range rate $\dot{r}$. For the rotational part, the input variables 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 amount of firing time f_t, and the position of fired thruster P_T. The universes of discourse of these variables are as follows:

$$\begin{gathered} a, e, \phi, \psi, \theta \in [-\pi/2, \pi/2]\ (in\ rad), \\ \dot{a}, \dot{e} \in [-2, 2]\ (in\ ^o/sec), \\ r \in [0, R_{max}]\ (in\ Km), \dot{r} \in [-10, 10]\ (in\ m/sec), \\ \dot{\phi}, \dot{\psi}, \dot{\theta} \in [-0.5, 0.5]\ (in\ ^o/sec), \\ Burn \in [-10, 10]\ (in\ dcm/sec) \end{gathered}$$

The fuzzy sets for each variable are defined like this: for azimuth, azimuth rate, elevation, elevation rate, and range rate the fuzzy sets are Small Negative (SN), Small Positive (SP), Large Negative (LN), and Large Positive (LP) (figure 5). For range the possible fuzzy sets are Small (S) and Large (L), as no more distinctions are needed. For roll, pitch, yaw, and its derivatives the fuzzy sets are Small Negative (SN), Small Positive (SP), Large Negative (LN), and Large Positive (LP).

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 of movement, 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, human controllers try to

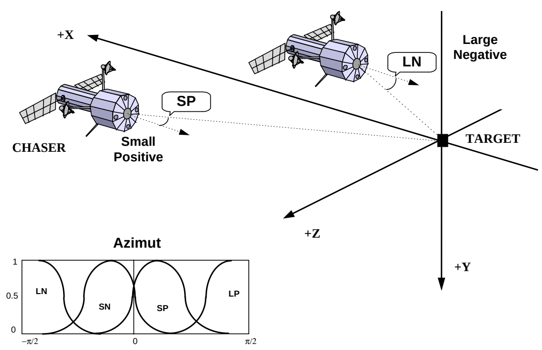

Fig. 5: Fuzzy Rule Data Base compilation

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 comply with an intuitive proportional navigation guidance towards the point of starting axis translation. 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.

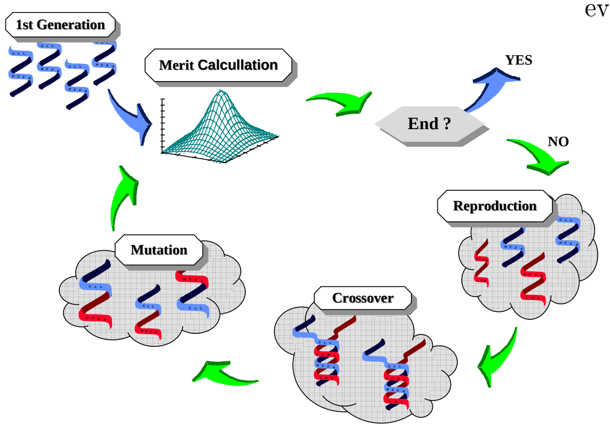

Fig. 6: GAs optimization tool operating

This knowledge produces the rules data base (figure 5). For the translation 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.

A simple heuristic approach of overlapping 25% the membership functions does not produce a priori, the best solution for the soft docking [5]. Changing the shape of the membership function, changes the performance of the controller. The GAs tool solve this optimization problem [7]. The tool starts codifying all the possible solutions. 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 (figure 6). The next step is to calculate the merit of each string to determine if at least, one of them have achieved the desired optimization goal. If it is not the case, the tool applies the first operation: *reproduction*. This operator generates new strings based in a probability factor, related with the merit computed previously. The next step is the application of the *crossover* operator: it mixes two strings based on it own associated probability factor. Finally, the tool applies the *mutation* operator, based in a third probability factor. The loop ends at the time to calculate again the merit of the set of strings, altered through the operators.

In order to setup the GAs environment, several parameters have to be defined: the population size (500 strings), the maximum number of generations (50), the different probability factors for each operators ($P_C = 0.8$, probability of crossover and $P_M = 0.01$, probability of mutation), and the merit evaluation.

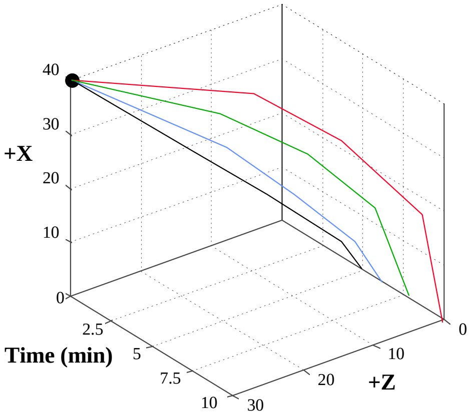

Fig. 7: Docking times of 4 generations

Here the novel idea is to choose a simple, but effective way to evaluate the merit of each string solution: 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).

Figure 7 shows a combination of several simulations run. 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).

Simulations were developed on a PC compatible 486/66DX2 portable type computer. The code was written in MATLAB 4.0®, for Microsoft Windows^{TM}. The fuzzy inference engine, with approximate reasoning was implemented using FISMAT, the Fuzzy Inference Systems toolboox for MATLAB developed by Prof. Zadeh. The GAs tool was codified by the authors, and applied to optimize the FISMAT functions.

The result of these simulations are then compared, with pilot models for the Shuttle proximity operations [1]. These piloting techniques for docking with stations contemplate soft and secure docking. In long range distances between the chaser and the target, the human pilot realizes a faster control than the geno-fuzzy system. The number of firings is reduced and the fuel consumption is low. In short range distances between the chaser and the target the geno-fuzzy controller delivers more performance than the pilot model. The values of the azimuth and elevation decrease rapidly keeping the number of firings low.

5. Conclusions

Automatic servicing to a space station allows to decrease the cost of the operations, and the mission time drastically. With the use of intelligent automatic systems, the docking operations will be simplified, increasing the number of servicing missions per year.

A fuzzy logic controller embedded in a guidance, navigation, and control system of a spacecraft can realize autonomously the closed loop operations, replacing the conventional crisp control algorithms.

The rules data base can be constructed with the help of an expert spacecraft controller, based on already existing piloting techniques. For short range distances, between chaser and target, human control produces a lot of small firings. This high number of firings causes drastic changes in azimuth and elevation, making difficult and imprecise the translation along axis. The membership functions of the fuzzy system can be optimized for a particular mission, using a genetic algorithm tool. This allows to reduce the number of firings. The value of azimuth and elevation goes smoothly to 0, during the translation along axis, and the fuel consumption is minimized.

Further studies are being conducted to optimize the rules data base as well, where even more performance is expected.

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