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A DIFFERENT APPROACH TO ROBUST AUTOMATIC CONTROL FOR AIRPLANES

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ABSTRACT

Current automatic control system uses linear mathematical models to validate automatic flight control for airplanes. Gain scheduling, non linearity and improved feedback through simulation are also introduced. Very computers operate the actuators in order to keep the airplane on the right path, in the current trim and with the proper safety margin. Some engineers are testing fuzzy control logic to control airplanes and UAVs (Unmanned Aerial Vehicles). The result is brilliant, since very simple controllers are able to fulfill the specification with little "knowledge" about the airplane performances. This means that fuzzy controllers are very robust since they are able to operate with much degraded aerodynamics or with reduced thrust. However no one was able to validate the airplane/fuzzy controller with a mathematical proof. So it is not sure that it will works in any condition. By the way the same happens for the airplane/human pilot model. So a mathematical proof is still required also for this later solution. On the other side, very accurate, time based non linear mathematical models are available for flight simulation. These models are used in several fields ranging from development to training. In recent years computers that can run these accurate models in fractions of seconds were marketed at very low prices. The idea introduced in this paper is to run an accurate mathematical model on some of these fast autopilot computer in order to optimize the sequence of commands to be inputted to the FBW system of the airplane in order to keep the path in the safest way possible. For this purpose it is necessary to have enough computing power to calculate this best solution at a rate compatible to a correct control of the airplane. In this paper we will demonstrate that these computing resources are already available and it is predictable that the computing speed of future years will allow running even more sophisticated simulators. The question may be: why use more complicated systems when current control system fulfills satisfactorily the same task in a cheaper and more reliable way? The answers are several. At first it is a matter of robustness, what happens if the yaw damper fails or the actuator of the left ailerons is unable to fulfill its task or the tail is ripped off? In this case standard systems are not able to take the airplane to the ground safely even if it is indeed possible to control the airplane by a coordinate action of the remaining control surfaces. Optimization means that it is possible to reduce the stress on structures in order to improve aircraft life, to find the control sequence that assure the mean fuel consumption or to prefer the shortest time possible to reach the required trim on the right path. In other words it is more flexible. It is also possible to monitor aircraft performance in order to evaluate external or internal disturbances. Air turbulences, wind gusts may be controlled in order to optimize structural integrity or passenger comfort. Internal disturbances, as defective functioning of components or controls, occasional failure of sensors may be diagnosed, in some cases corrected in other simply reported after landing. The reliability improvement is not the latest benefit. As a rule of the thumb more electronics or more components means less reliability with the exception of redundancy and this is the case of this paper.

Keywords: automatic control; airplane control.

INTRODUCTION

Some years ago a research activity called "Nuvolari fuzzy" [1] was performed by this author with other researchers and engineers. The research was aimed to calculate the best lap time for an F1 racing car given a certain track. The problem is well known to specialist and is still subjected to intensive research. In fact it is necessary to find out the best combination of tires, aerodynamics, springs, dampers, etc. in order to obtain the fastest lap for a certain car. Even the engine tuning may be optimized in order to increase performances. The possibility to individuate this best solution before track tests is precious. However another requirement should be fulfilled: the drivability and stability of the car, that should be easy to drive and sincere in response to commands. In other word the best solution should be feasible to be driven by a human pilot with a feasible sequence of commands.

In the "Nuvolari Fuzzy" project, a fuzzy model of the human pilot and a lumped mass model of an F1 racing car were used. The optimization operated with an elitarian combined genetic algorithm [2, 3, 4] that optimized the fuzzy pilot on a specific car and on a certain track. The fuzzy controller that simulated the pilot had several parameters that resemble pilot's driving style [5-10]. These parameters were optimized by a specialized genetic algorithm that found the best pilot for a certain portion of the track. The process was repeated from the starting position to the end of the track until a record lap time, or a set of best lap times can be found. It was then possible to vary aerodynamics, springs… until the best regulations for the car could be found.

The main limit to the "Nuvolari Fuzzy" project was the difficulty to find or to measure correct values for the many parameters that were included in the F1 racing car dynamic simulator. In other words the difficulties were

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centered in the accuracy of the simulator of the car itself. With a correct simulation the best lap was slightly slower than the best lap of the human champion since the fuzzy pilots were not champions, but was acceptable for a very good human pilot.

It is then possible to transfer this experience to build an optimized control for an airplane. In fact an accurate simulator of the airplane is already available and the main defect of the “Nuvolari fuzzy” optimizer is overcome.

THE PRINCIPLES

The optimized controller

Modern airliners can be programmed for the entire flight. As the pilot carries out the rotation the automatic flight control system can be activated. This system is composed by a Flight Computer and the Automatic Pilot. The Flight Computer is programmed during preflight operations. During the flight the Flight Computer transfers the data to the Automatic Pilot in order to keep the airplane on the planned path. If everything works properly the airplane automatic control ends with the auto land procedure.

In Flight by Wire (FBW) [11, 12, 14] airplanes the Automatic Pilots controls the FBW computers.

The optimized control system proposed in this paper can work in several different ways. The simplest way is to substitute the Automatic Pilot with the optimizer of fuzzy pilot. The best fuzzy pilot can then pilot the airplane for the time-step chosen. For this optimization the Genetic Algorithm (GA) [15] may be used. In more detail the procedure works as follows.

The Flight computers input to the optimizer the correct future path. The control sequence to be inputted to the controls is then calculated by a generation of Fuzzy Pilots. These fuzzy pilots work with the aircraft simulator in order to keep the airplane on the planned path. The performances of these fuzzy pilots are then ordered with the criteria chosen. For example, acceptable criteria may be: lowest fuel consumption, minimum error, minimum stress on structures… or a combination of these criteria. For this purpose an objective function is implemented.

The crossover is then performed and a new generation of fuzzy pilots tests their performances. This process is repeated until the required optimization level is obtained. Usually 4 generations are sufficient. The best fuzzy pilots then control the airplane. The whole optimization process should be performed with the frequency necessary to obtain a correct control of the airplane. Normally this frequency is around 50 Hz.

An optimum configuration for the optimization may be the following: 10 CPUs for the calculation and four CPUs for the refereeing. The 10 CPUs may work in parallel for each generation while the CPUs for the refereeing evaluate the objective function and control the crossover process. For the optimization, two times redundancy is sufficient for the required reliability.

In this case the improvement over the existing control system is only the possibility to satisfy an arbitrary optimization function.

The diagnostic system

In order to improve the performances of the system diagnostics may be performed on what happened in the previous step. Given a control sequence a foreseen path can be calculated by the airplane simulator, this path can be compared with the true airplane path and errors can be evaluated. These errors can be due to several different causes: external and internal.

The air is not a homogeneous mean and turbulences are common. Wind gusts may occur. It is possible to implement a simplified model of the air to individuate this type of disturbance.

Instruments may be inaccurate; FBW systems use redundancy also on sensors in order to obtain the required reliability, a simple program can diagnose inaccuracy of sensors.

Control surface control may be inaccurate; also in this case it is possible to try detection.

Engine thrust may be different or unequal and also in this case diagnostic may work.

Main failures may be present: failures of yaw dampers, air control surface actuators or main damages to structures may be present.

In this case the diagnostic system can correct these failures by modifying simulator parameters and try to keep the airplane under control.

For the diagnostic system the same 10 CPUs of the optimizer can be used if they are fast enough to run diagnostics and optimization, or a parallel CPU system may be used if diagnostics are too sophisticated.

FBW overdrive

In the case of main failures FBW may be inadequate to control the airplane. In fact in case of important failures different control strategies may be necessary. In these cases the optimization can find a pilot able to control the damaged aircraft in order to keep the plane under control.

The fuzzy pilot

Before introducing the fuzzy pilot simulator, it is opportune to introduce the way in which the flying path is introduced. The data for the path from the FCS (Flight Control System) is two vectors (current velocity and future velocity), or for optimizer/aircraft performance control (old vector and current vector). If a mountain or an obstacle is present the flight path is checked for minimum altitude requirement. The "ideal" path is always represented by a cubic Hermite spline. In our case, the fuzzy pilot will try to follow this path at his best, ending it with the right velocity vector. The right velocity final vector is to be optimized, not the path. Other factors taken into account for the optimization are maximum g-level and fuel consumption. The arithmetic mean of final position, velocity vector and fuel consumption is calculated. If the maximum g-level is surpassed the pilot is discarded from the population as unfit. A local reference system is defined. The origin is in the last arrival point. The y-z plane passes through the final velocity vector and is parallel to the gravity vector. The z (vertical) axis is directed upward. The x-y is orthogonal to the gravity vector (horizontal). The cubic Hermite path is projected onto the x-y (horizontal) and y-z (vertical) plane. Two paths are then individuated: the horizontal and the vertical path. If the aircraft position is projected on this two planes, it is possible to calculate and horizontal (lateral) distance and a vertical one. Ideally, the horizontal distance requires side-stick, while the vertical distance requires throttle control and push-pull action on the stick. Of course it is not true since constant velocity turns requires velocity-throttle compensation.

The knowledge base of the fuzzy pilot

The fuzzy pilot controls the aircraft through four output variables: throttle position, two stick angles and pedal position. These four output variables are controlled separately.

The input variables are also four: vertical and lateral distance (d_h, d_l) from the current position to the final position, lateral distance and the two components of difference of speed (Δv_h, Δv_l). By the way the distance controls also the integration step of the simulator. The velocity membership function is depicted in Figure-3. For Δv_l, the input value v is in inverse proportion to the Δv_l. The higher Δv_l the lower v_l. v_l is then rendered non dimensional and inputted as a percentage value. If the ratio is high, the velocity is low; if the ratio is low the velocity is high. For v_h, gravity should be taken into account. The first rule of the controller is the following: the throttle should be increased if the distance is high and the velocity is low. An example of throttle position is shown in 1. The second output membership function is the stick speed. It depends from two variables: the distance from path center line and the curvature radius. The distance membership functions have been thickened in order to improve the correction ratio, as the car is closer to track margins. The second fuzzy rule of the fuzzy pilot is the following: it is necessary to increment angular stick velocity as the distance from centerline increases and the curvature radius diminishes. Stick velocity output membership functions are depicted in Figure-7.

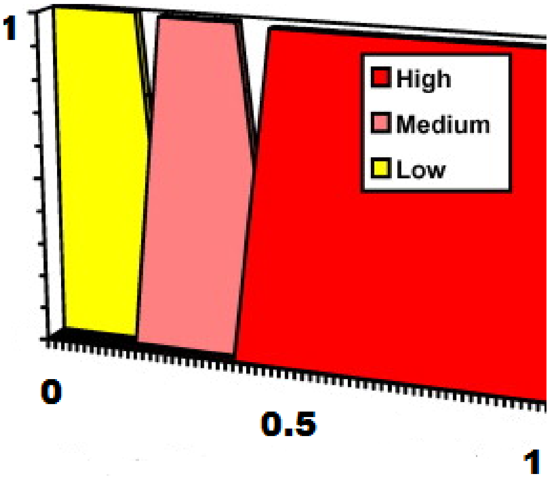

Figure-1. Distance membership function.

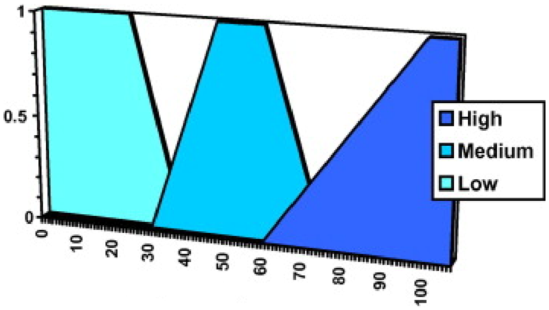

Figure-2. Speed membership function.

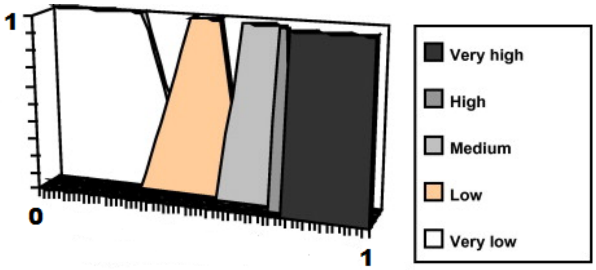

Figure-3. Throttle membership function.

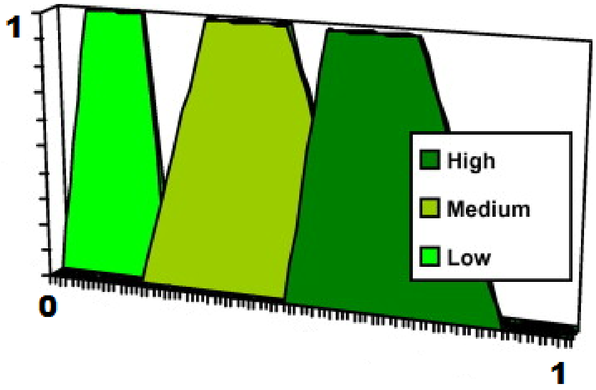

Figure-4. Distance membership functions.

The initial population

Every fuzzy controller (pilot) is defined by three controllers (throttle position, yaw lateral speed, yaw vertical speed). The different individuals are differentiated by the input and output membership functions. Each pilot is then coded by the genes relative to the input/output membership functions and by the gain constants. These constants amplify the response of the pilot and correspond to the aggressiveness of the pilot. Each pilot is then defined by 349 real numbers. Ten reasonable pilots are defined as an initial population. The number of ten is given by a compromise between convergence speed and quality of results. The reasonable pilots are defined by a set of pilots that are able to take the aircraft near the final position in most conditions. A stochastic choice of the initial genes would have put on the car a set of poor pilots very far away from an acceptable level.

The fitness function

The fitness function is defined as follows (1).

$$fitness = \frac{\Delta\left|v_x^2 + v_y^2 + v_z^2\right| + \sqrt{d_x^2 + d_y^2 + d_z^2} + \Delta v_x^2 + \Delta v_y^2 + \Delta v_z^2}{5} \quad (1)$$

This fitness function works since the insufficient pilots are automatically discarded. Excessive errors in position put the pilot to the unfit position and he will not be part of the new generation. For example, if the error exceeds the half the size of the airspace assigned by the controller and by the safety rules the pilot is out. A g limit is defined and it should not be exceeded.

The genetic operators

In this Genetic Algorithm (GA) two modified operators that will operate only on some genes with a selective crossover procedure assist the "standard" GA operators. The standard crossover operator makes the media of all the real genes of the parents and obtains a son with the multiple crossover approach. The additional factors that control the crossover and the generation of a new population are the crossover probability (0–100) and the crossover points (c_p=1–5). No mutation is considered. These numbers can be given as input to the GA and control the convergence ratio and quality of the solution as it will. In fact when the probability is 100 all the individuals can be coupled. When its value is 80 only the first 8 individuals can be coupled, when it is 20 only two of the individuals can be coupled. The coupling is stochastic and the best ranking individuals have more probability to be coupled than the others. The influence of the parameter point is different from the standard crossover and for the modified crossover. The value of points indicates the number of points where the crossover takes place (c_p =1⇒1 point, c_p =2⇒2 points, c_p 3⇒3 points). If c_p=4 it means that also the gain constants are interested by the crossover. The standard crossover does not influence the ranges of the input variables. The best individual takes part to the crossover but is inherited by the following generation without being subject to crossover. This is the well known elitarian version of the GA. The modified crossover works in the same way of the "standard" crossover but operates on the output membership functions, it has assigned the parameter c_p =5 in the input mask.

The GA optimization

The combined-elitarian GA algorithm calculates the ranking of the population, the maximum ($f_{\max}$), the minimum ($f_{\min}$) and the media (f_{medium}) of the fitness. These three values are fundamental for the selection of the operators. Given the {*f*max, *fmin, fmedium*} of the preceding (i-1) generation and the same values of the current (i) generation, only the traditional operators are used, cp= {1-3}:

$$f_{\max}^{i-1} \times 1.05 \le f_{\max}^{i} \; OR \; f_{medium}^{i-1} \times 1.05 \le f_{medium}^{i} \; OR \; f_{\min}^{i-1} \times 1.05 \le f_{\min}^{i} \quad (2)$$

Only the combined operator's cp= {4-5} are used when:

$$f_{\max}^{i-1} \times 1.01 \ge f_{\max}^{i} \; OR \; f_{medium}^{i-1} \times 1.01 \ge f_{medium}^{i} \; OR \; f_{\min}^{i-1} \times 1.01 \ge f_{\min}^{i} \quad (3)$$

Adimensional distance and velocity

The fuzzy pilot works by directly controlling the throttle and the stick. If the target is easy, low altitude gain, low speed gain, almost leveled flight, small corrections are needed. So the membership functions were put in percent. The conversion of the fuzzy pilot to the real inputs to the simulator is amplified or reduced by a fixed entity.

If we have a Mach 1 aircraft at 100 FL (Flight Level), the velocity scale can be the difference between the minim velocity ($v_{\min}=v_{\text{stall}}$*1.1) and the maximum one. So the scale factor can be calculated as follows:

$$V_{scale} = \frac{|\Delta v|}{v_{\max} - v_{\min}} \quad (4)$$

For the distance two different factors may be considered:

$$dv_{scale} = \frac{\Delta d_{v\_current}}{|\Delta d_v|} \quad (5)$$

$$dl_{scale} = \frac{\Delta d_{l\_current}}{|\Delta d_l|} \quad (6)$$

For the throttle the maximum vertical velocity v_H should be used

$$Throttle_{scale} = \frac{\Delta v_z + \dfrac{d_z}{|v_i - v_f|}}{\dfrac{d}{|v_H|}} \quad (7)$$

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Simulator as a tool for testing the fbw optimization

A flight simulator of the FNPT II type was developed since 1996. It enables the simulation of systems operating directly on the aircraft such as the FBW systems. It is characterized by an open multi-computer multi-tasking architecture. A server is responsible equations of motion integrations, data acquisition and TCP/IP protocol handling. Three other PCs display the instruments to the PF (Pilot Flying) and to PNF (Pilot not flying) (Figure-5). Finally, a fourth computer system is dedicated to the visual. There is also a supervisor station with its own computer for the instructor.

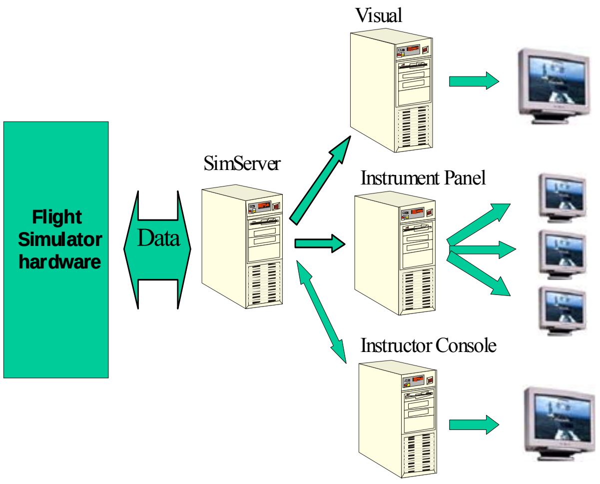

Figure-5. Flight simulator HW architecture.

The visual system and the equation integrator are implemented in C ++ with direct tpc/ip connection between the two computer systems.

Tests

The tests were performed on a normal flight of an airliner from Milan to Rome. The model is the one of a Cessna Citation X.

The parameters that were manually tuned for optimum result were the probability and the number of points for crossover and mutation. The flight was divided into 3,600 steps of about 1s each. This means that every second the optimizer changes the fuzzy pilot. This is far from acceptable for take-off and landing. However it was the maximum reasonable with our computers.

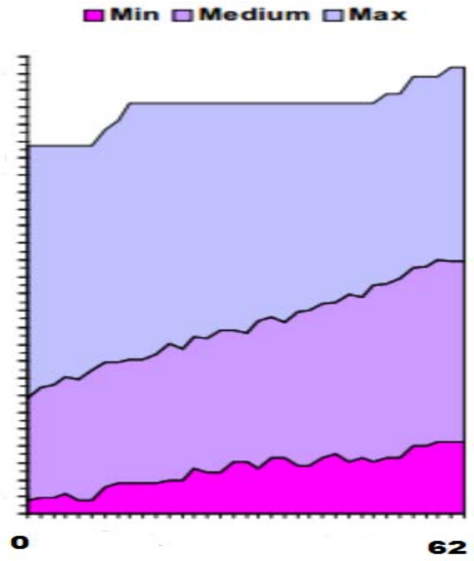

Figure-6. Typical GA result, step time 1s, climb.

The results of a typical GA optimization step during the climb are depicted in Figure-6. Convergence was reached after 62 generations. For optimum result c_p is set to 4.

Initial population is 10 individuals. The average number of "pilots" discarded per generation is 63. On our simulator, even with disturbances introduced as gust of wind and sudden air density variation the fuzzy pilot behaves well.

CONCLUSIONS

The proposed procedure works very well in term of performances, with very good fuzzy pilots selected. The fuzzy pilot selected by the GA were tested in difficult conditions and proved to be very robust pilots. However, the computer time required for the optimization process far exceeds the requirements. Even with a 14 computer parallel arrangement reasonable computer times cannot be reached. It is perfectly possible that this technique will prove to be feasible for the next generation of autopilots, but for the current one it is far out of reach.

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Symbols

Symbol	Denomination	Unit
c_p	GA parameter	-
f	Fitness function value	
$d_{l,h}$	lateral, vertical distance for the optimization	m
$\Delta v_{l,h}$	Lateral, vertical component of Differential speed	m/s
$v_{x,y,z}$	Velocity components	m/s
$d_{x,y,z}$	Distance components	m/s
v_{scale}	Scale factor for the velocity	m/s
v_{max}	Max speed of aircraft for altitude and weight	m/s
v_{min}	Min speed of aircraft for altitude and weight	m/s
dv_{scale}	Scale factor for the vertical distance	-
dl_{scale}	Scale factor for the lateral distance	-
$Throttle_{scale}$	Throttle factor for the lateral distance	-
Δv_z	Vertical component of differential speed	m/s
v_i	Initial speed magnitude	m/s
v_f	Final speed magnitude	m/s
V_H	Maximum vertical speed	m/s