DEVELOPMENT AND EVALUATION OF STRATEGIES FOR PILOTING ASSISTANCE FOR LIGHT AIRCRAFT

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Abstract

The objective of this work is to develop and study several facilitated airplane strategies to be used in light aircrafts in order to make the flight more intuitive, improving the learning time and the flight safety. A flight simulator will be implemented to test the studied strategies with various users having different piloting skills. For each strategy it will be given a score considering the user´s feeling as well as his capability tofollow a predetermined path.

1 Introduction

Recently, the growth of the market of small aircraftshas shown a popularization of the so called light aircrafts [1]. Most of the time, those airplanes are personal airplanes used for leisure and short travels. While in general aviation most pilots are professional pilots, personal airplanes pilots are usually the owners of them and most of the time are inexperienced pilots. This fact decreases the flight safety especially in situations that demand attention and a higher level of piloting effort such as piloting, navigating and communicating with ground stations simultaneously.

To solve this issue researches are being conducted to develop facilitated airplanes systems for light aircrafts, based in fly-by-wire systems [2], in order to make the flight safer by reducing the piloting effort and so making it easier.

This work will study several facilitated airplane strategies to permit longitudinal control of the airplane based directly in its trajectory instead of its attitude. For so, automatic controllers strategies have been chosen based in reference variables directly linked to the airplane longitudinal movement.

The specific objectives of this work are:

- Design and implementation of a longitudinal flight simulator in order to test the proposed strategies.
- Evaluate the suitability of the proposed strategies through flight simulations involving people with different piloting skills and knowledge.

First, a dynamic model of the aircraft chosen for the flight simulator, the CB-10 “Triatlhon” [3], will be presented. The computational implementation of the flight simulator and the definition of the studied strategies as well as their adjustment within the simulator will be presented next. At last, the used evaluation methodology and the most important results obtained will be exposed.

2 Airplane Dynamic Model

Fig.1 presents the dynamic model of the simulator airplane. The CB-10 “Triatlhon” was chosen because it is a light aircraft that in the near future will become a base for flight tests and facilitated flight systems researches conducted by the Centre for Aeronautical

Studies of the Federal University of Minas Gerais.

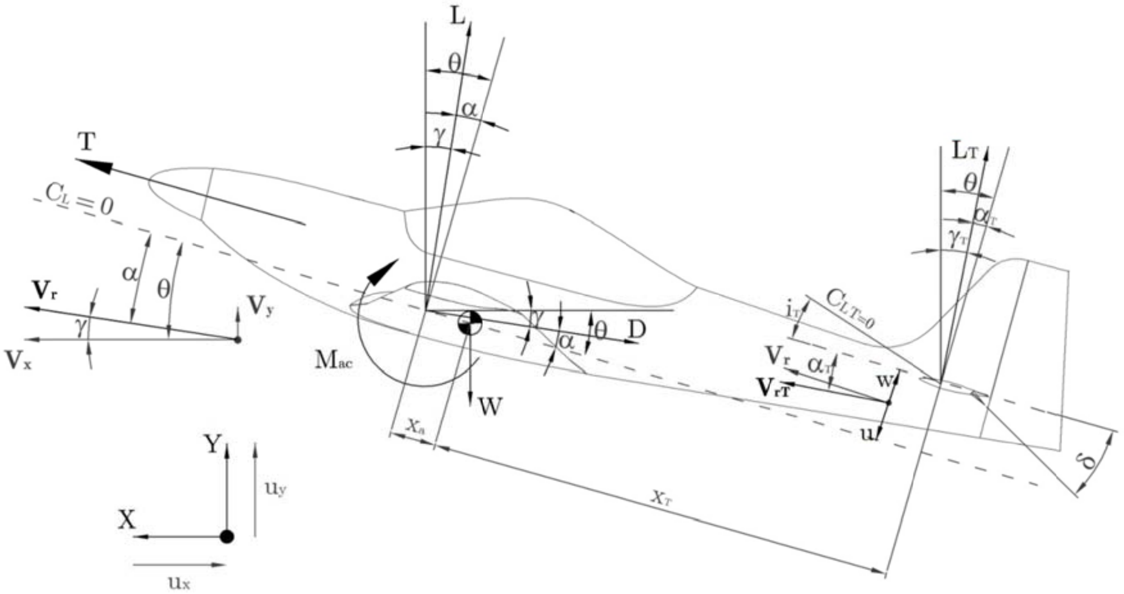

Fig. 1. Dynamic Model

Based on reference [4], the airplane equations of motion will be presented. The model features three degrees of freedom: i) the displacement along the x axis, ii) the displacement along the y axis and iii) the longitudinal rotation over the z axis. Therefore, there are six state variables for the considered model described as follows:

$$\begin{aligned} x_1 &= x \\ x_2 &= y \\ x_3 &= \theta \\ x_4 &= \dot{x} = V_x \\ x_5 &= \dot{y} = V_y \\ x_6 &= \dot{\theta} = V_\theta = q \end{aligned} \tag{1}$$

They can also be written as:

$$\begin{aligned} \dot{x}_1 &= x_4 \\ \dot{x}_2 &= x_5 \\ \dot{x}_3 &= x_6 \\ \dot{x}_4 &= \frac{1}{m}\begin{bmatrix} -L\cdot\sin\gamma - D\cdot\cos\gamma - \\ L_T\cdot\sin\gamma_t + T_{(Pp)}\cdot\cos\theta \end{bmatrix} \\ \dot{x}_5 &= \frac{1}{m}\begin{bmatrix} L\cdot\cos\gamma - D\cdot\sin\gamma + \\ L_T\cdot\cos\gamma_t + T_{(Pp)}\cdot\sin\theta - W \end{bmatrix} \\ \dot{x}_6 &= \frac{1}{J}\begin{bmatrix} L\cdot x_A\cdot\cos\alpha + D\cdot x_A\cdot\sin\alpha - \\ L_T\cdot x_{T.}\cos\alpha_T + M \end{bmatrix} \end{aligned} \tag{2}$$

Where:

$$\begin{aligned} L &= \tfrac{1}{2}\cdot\rho_{(x_2)}\cdot V_R^2\cdot S_w\cdot C_{L(\alpha)} \\ D &= \tfrac{1}{2}\cdot\rho_{(x_2)}\cdot V_R^2\cdot S_w\cdot C_{D(\alpha)} \\ M &= \tfrac{1}{2}\cdot\rho_{(x_2)}\cdot V_R^2\cdot S_w\cdot\bar{\bar{c}}\cdot C_{M(\alpha)} \\ T &= C_t\cdot\rho\cdot n^2.D^4 \\ L_T &= \tfrac{1}{2}\,\rho_{(x_2)} S_T\, C_{LT(\alpha_T;\delta)} V_{RT}^2 \\ V_R &= \sqrt{\left(x_4+u_x\right)^2+\left(x_5-u_y\right)^2} \\ \gamma &= \operatorname{arctg}\left[\left(V_y-u_y\right)/\left(V_x+u_x\right)\right] \\ \alpha &= \theta-\gamma \\ V_{TT} &= \left(x_4+u_x\right)\cos x_3+\left(x_5-u_y\right)\operatorname{sen} x_3 \\ V_{NT} &= \left(x_4+u_x\right)\operatorname{sen} x_3-\left(x_5-u_y\right)\cos x_3+u-w \\ V_{RT} &= \sqrt{V_{TT}{}^2+V_{RT}{}^2} \\ u &= x_6\cdot x_T \\ w &= \alpha\frac{d\varepsilon}{d\alpha}V_R \\ \alpha_T &= \operatorname{atg}\left(V_{NT}/V_{TT}\right) \\ \gamma_T &= x_3-\alpha_T \\ C_{LT} &= \left[\left(\alpha_T+i_t\right)\cdot a_1\right]+\left[\delta\cdot a_2\right] \end{aligned} \tag{3}$$

The thrust generated by the engine considering the propeller efficiency was calculated as in reference [5], making it possible to obtain a table relating the propeller thrust coefficient, the aircraft speed, the percentage of engine power and the engine rotation.

The presented state model has two control variables, the elevator deflection δ directly related to the horizontal tail lift and the engine power percentage Pp. Thus, these are the two control variables that will be used in the simulator.

3 Flight Simulator Implementation

The simulator was implemented using the numerical software Matlab® through the Simulink® interface. The toolbox AeroSim® was used to communicate with the flight simlulator FlightGear that was used as a graphical interface.

The integration envolving the Matlab® software with the FlightGear graphical interface provides a better interaction with the user compared to the graphic response of the simulator.

The AeroSim® toolbox has several useful tools which were used to design the simulator instruments panel. Basic instruments usually present in light airplanes were chosen, and also some others to measure variables related to the longitudinal movement such as: the attack angle, the pitch angle, the velocities angle and the load factor as shown in Fig. 2.

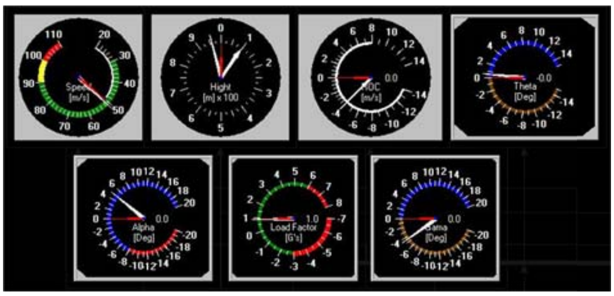

Fig. 2. Instruments Panel

Two pointers were used in each instrument due to the fact that the studied strategies are based in reference values of the longitudinal movement related variables. One pointer (the white one) shows the instantaneous variable value while the other (the red one) shows the reference value that the variable is heading to.

4 Facilitated Flight Strategies

As it was shown before, the dynamic model of the airplane has two control variables: δ and Pp. In a conventional airplane those variables are set directly by the pilot trough the stick and the throttle in order to control the attitude of the airplane. Fig. 3 presents a simplified scheme of a conventional airplane longitudinal control.

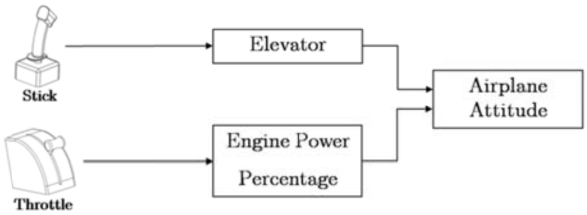

Fig. 3. Conventional Control System

Applying pre-established control laws using electronic mechanisms to manage the command-attitude-trajectory interface, it will be possible for the pilot to control directly the airplane trajectory as the airplane automatic control system performs all the necessary calculations.

The facilitated flight strategies are programmed in controllers with feedback from the commands reference output values. In that way, through the pre-established control laws, it is possible to determine the best configuration for the airplane in order to fly the desired path Fig. 4.

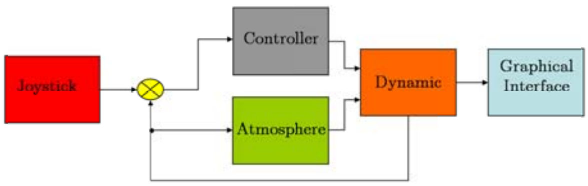

Fig. 4. Facilitated Flight Strategies Implementation

Because of that, instead of controlling directly the engine power percentage and the elevator's angle through the throttle and the stick, the pilot will control two other variables related to the airplane longitudinal movement. The automatic controller will then calculate the necessary power and elevator's angle in order to reach the values specified by the pilot for the new controlled variables.

Thus it is necessary to select variables related to the airplane longitudinal movement that are propitious to be implemented in the facilitated flight strategies. These are the chosen candidates:

- Speed [V];
- Altitude [h];
- Rate of climb [ROC];
- Pitch angle [θ];
- Angle described by the horizontal and vertical speeds [γ]

Each combination of the above variables taken two by two will define a strategy to be used. Table 1 summarizes the chosen strategies for this work. The reference columns represent the variables to be set by the pilot while the actuation columns show the variables that will be modified by actuating the elevator or by changing the engine power in order to achieve the set points provided by the pilot.

Table 1 – Implemented Strategies

Estrategy	Reference		Actuation	
	Stick	Throttle	Elevator	Engine
01	h	v	V	h
02	h	v	H	v
03	ROC	v	V	ROC
04	ROC	v	ROC	v
05	θ	v	V	θ
06	θ	v	θ	v
07	γ	v	V	γ
08	γ	v	γ	v

Although it seems more natural that the power throttle should control the airplane speed while the stick should control the other chosen variable, this restriction will not be imposed. Along this work the strategies that use the engine power to modify the airplane speed will be called direct strategies while the ones that use the elevator for the same purpose will be called crossed strategies.

Having defined all the strategies to be used it is necessary to implement controllers to provide the automatic control of the reference variables for each strategy. In this work it will be used proportional, integrative, derivative (PID) controllers.

The next step consists in implementing the controllers into each strategy. The set points chosen by the pilot for the controlled variables are compared to their actual values and the error is applied to the controller input. The PID will then use the elevator or the engine power (depending on the strategy) in order to make the error be equal to zero. A bloc diagram of the implementation is provided by Fig. 5. As each strategy acts into two variables, the PID actuated by the stick will be called PID 1 and the other, actuated by the throttle, PID 2.

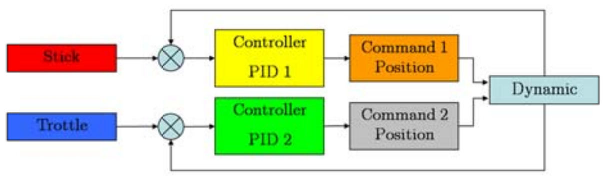

Fig. 5. Implementation of the PID into the Strategies

All the above definitions are required to adjust the gain values of each strategy PIDs. Particular effort must be made in order to achieve a similar response characteristic for each strategy. It must be noted that the objective of this work is not to develop optimum controllers but to compare the studied strategies. Thus it is important that the gains adjustment do not interfere in the evaluation process.

The controller's adjustment will be divided in three steps:

- Initial gain values selection.
- Definition of a characteristic response from the controllers with feedback (objective function).

- Adjustment of the controllers gains in order to achieve the characteristic response defined.

The indirect method of Ziegler Nichols [6] was used to determine the initial gain values in order to feature typical characteristics of a PID controller, stable, damped and with no steady error.

Next, performance indexes related to the response with feedback must be elaborated and studied. The response must be stable, with a short stabilization time and with no steady error. An objective function will be created for that purpose as a function of the desired performance indexes.

Last, using optimization algorithms, the controllers' gains must be refined so that the system response achieves the expected indexes. As shown before, each strategy will have two different control variables. It is important to note that the optimization of each variable's PID (PID 1 and PID 2) must be performed considering the other variable's PID optimization since one influences the other performance.

5 Tests

First of all, a reference trajectory was defined after studying the simulated airplane performance in order to represent a high performance flight. The trajectory consists in a series of patches corresponding to leveled flight, climbing and diving. All over the trajectory the airplane speed and position can be computed for further analysis. Fig. 6 presents the predefined flight trajectory.

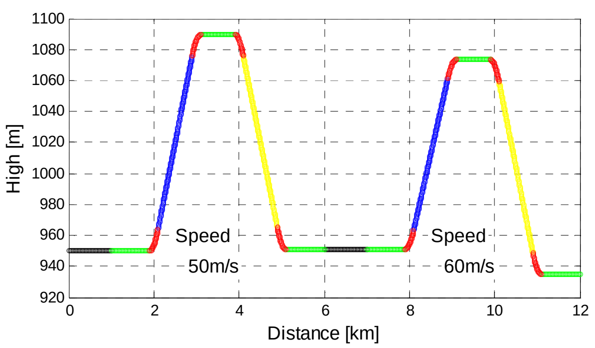

Fig. 6. Reference Trajectory

For a better identification of the reference trajectory, circles to be flown through by the user have been implemented in the FlightGear interface. Each part of the trajectory is identified by a different color so the user can easily know where he is flying.

Fig. 7 features a screenshot of the simulator graphic interface with the reference circles implemented. Obviously, it would be no need of these circles if the strategies were supposed to be implemented in a real airplane.

Fig. 7. Simulator's Graphic Interface Screenshot

The quality of each strategy was measured by the capability of the user to stick to the reference trajectory and reference speed. Each user was asked to fly with each of the eight strategies and with no strategy at all in a random order. The strategies, including the no strategy condition, were then evaluated in a subjective and an objective ways.

The subjective evaluation was conducted using the Cooper-Harper scale [7]. That scale is widely used to classify an airplane's control qualities, 1 representing good control qualities with no improvements required and, 10 representing an incontrollable airplane. Each user, after each flight, was asked to give a score to the flown strategy based on his feeling and comfort following the Cooper-Harper scale. The desired performance is reached when the user is able to control the airplane following the established path, without physical and mental efforts. The acceptable performance is when minor non continuous efforts are required for the same purpose.

The objective evaluation was conducted by computing all the flight, the altitude and speed instant errors calculated as follows:

$$|\text{Speed Error}| = |V_{\text{flight}} - V_{\text{reference}}| \tag{4}$$

$$|\text{Hight Error}| = |h_{\text{flight}} - h_{\text{reference}}| \tag{5}$$

The total errors, called accumulated errors, were then calculated by integrating the instant errors all along the simulated flight.

$$|\text{Speed Acumulated Error}| = \int_{x=0}^{x=final} (\text{Speed Error}) \cdot dx \tag{6}$$

$$|\text{Hight Acumulated Error}| = \int_{x=0}^{x=final} (\text{Hight Error}) \cdot dx \tag{7}$$

According to that error formulation, the error represents how much the user flown out of the reference trajectory and speed. Two by-pass patches were added at the beginning of the flight and at the transition speed in order to give the user some time to trim the airplane and get familiarized with the controls.

5 Results

5.1 Subjective Evaluation

The strategies were tested by thirty four users and Table 2 presents the mean score given to each strategy following the Cooper-Harper scale as well as the standard deviation (S. D.).

As can be noted from Table 2, seven of the eight studied strategies, according to users' opinion, showed an improvement in flight quality compared to the no strategy condition. Strategy 5 (Crossed, Reference: Speed and Pitch Angle) was the only that did not presented an improvement.

It must be noted that the mean score for the no strategy condition was 7.4, which according to the Cooper-Harper scale corresponds to: "A control system that can not ensure a suitable performance with a tolerable amount of work. An improvement is mandatory. The systems features serious deficiencies" (most users did not have piloting experience).

Table 2 – Strategies score (subjective)

		Reference (Speed and Altitude)		Reference (Speed and Rate of Climb)		Reference (Speed and Pitch Angle)		Reference (Speed and Speeds Angle)	
	No strategy	Str. 1 (Crossed)	Str. 2 (Direct)	Str. 3 (Crossed)	Str. 4 (Direct)	Str. 5 (Crossed)	Str. 6 (Direct)	Str. 7 (Crossed)	Str. 8 (Direct)
Mean	7.4	7.2	3.2	4.3	2.5	7.7	3.4	3.4	2.2
S. D.	2.0	2.4	1.8	19	1.4	1.7	1.5	1.5	1.3

According to the users, strategies 4 (Direct, Reference: Speed and Rate of Climb) and 8 (Direct, Reference: Speed and Speeds Angle) achieved the best improvement to flight quality with a score inferior to 3. In the Cooper-Harper scale that corresponds to: "Satisfactory. No improvements needed. Negligible deficiencies". It was classified between reasonable and good.

It is also interesting to note that among all strategies the direct ones presented a better score than the crossed ones. Only strategy 8 that scored 2.2 for the direct mode (good) had a crossed mode that was rated below 4 (still in the no improvement needed category). However, it is necessary to keep in mind that those results are only representative for a flight trajectory with characteristics similar to the studied one.

5.2 Objective Evaluation

Fig. 8 features the mean cumulated error referring to the flown flight altitude difference relatively to the reference trajectory. The accumulated error was normalized using the no strategy condition as a reference. Strategy 1 (Crossed, Reference: Speed and Altitude) presented a worsening of 60% relative to the no strategy condition and achieved the worst performance of all strategies. In the other hand strategy 8 (Direct, Reference: Speed and Speeds Angle) presented an improvement of almost 80%, achieving the best performance of all strategies.

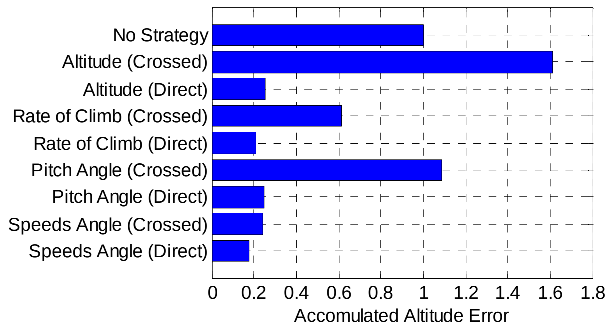

Fig. 8. Mean Accumulated Error for Speed (normalized)

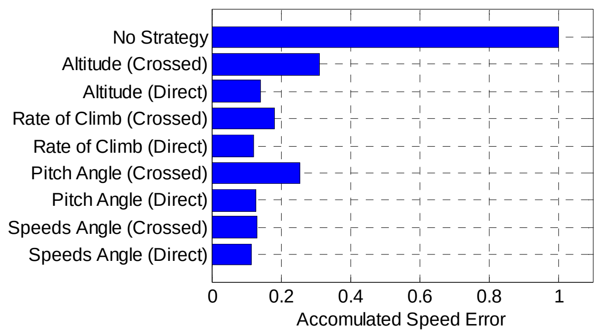

Fig. 9. Mean Accumulated Error for Altitude (normalized)

Fig. 9 features the mean cumulated error referring to the flown flight speed difference relative to the reference speed. It is interesting to note that all strategies, even crossed ones, achieved an improvement of more than 60% regarding the no strategy condition. Again the direct strategies obtained a better score than the crossed ones. All direct strategies achieved more than 80% of improvement. Once more, strategy 8 (Direct, Reference: Speed and Speeds Angle) was the best rated strategy.

Following, a short analysis comparing the best strategies (4 and 8) to the no strategy condition will be performed.

5.3 Flown Trajectory Analysis

Fig. 10 presents users trying to fly following the reference trajectory with no facilitated flight strategies. Whereas they were flying through the indicated black lines the error was not computed. It was considered a transition region as mentioned earlier in this article.

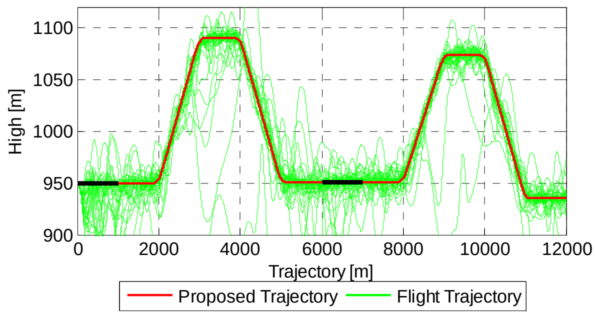

Fig. 10. No Strategy – Proposed and Flown Trajectories

The results concerning strategies 4 and 8 are shown in Fig. 11 and Fig. 12. The improvements are outstanding. The strategies clearly facilitated the trajectory control by making it possible for the users to stick close to the reference trajectory.

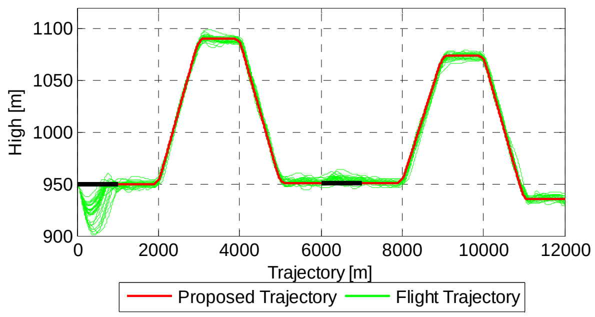

Fig. 11. Strategy 4 – Proposed and Flown Trajectories

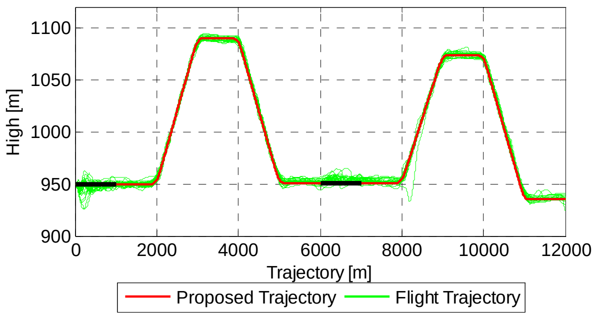

Fig. 12. . Strategy 4 – Proposed and Flown Trajectories

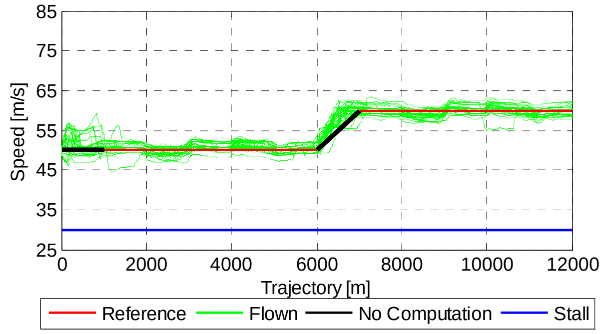

Fig. 14. Strategy 4 – Proposed and Flown Speeds

5.4 Flown Flight Speed Analysis

Fig. 13 features the flown flight speed with no piloting assistance strategies and the reference flight speed. It is important to note that some users had great difficulties controlling the flight speed and even let it decrease below the stall angle compromising the flight safety.

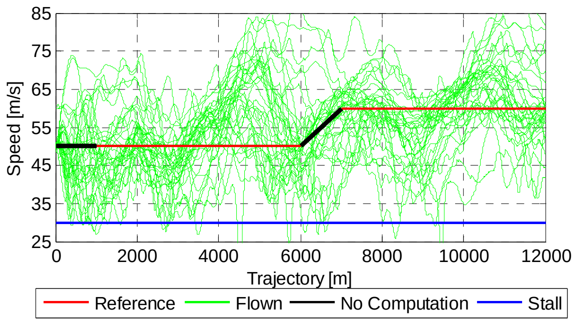

Fig. 13. No Strategy – Proposed and Flown Speeds

Fig. 14 and Fig. 15 show the flown flight speed for the assisted flights using strategies 4 and 8.

Once again the assisted flights performed much better than the non assisted flight. Especially, no user let the airplane stall, which characterizes a safety improvement.

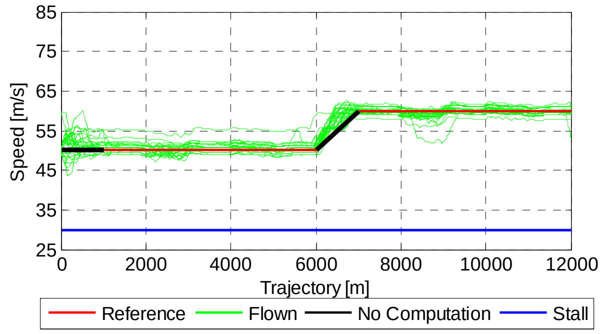

Fig. 15. Strategy 8 – Proposed and Flown Speeds

5.5 Experienced Users and no Experienced Users Comparison

A comparison regarding the experienced and no experienced users' flights can help validating the hypothesis that the assisted flight strategies improve the airplane flight qualities. As an example, two of the users will be compared: An experienced pilot and a user with no piloting skills and non aeronautical knowledge.

Fig. 16 presents a comparison of the flown trajectory of the two compared users. As expected the experienced pilot stuck closer to the predetermined trajectory while the other user did not performed so well, particularly at the first climbing path.

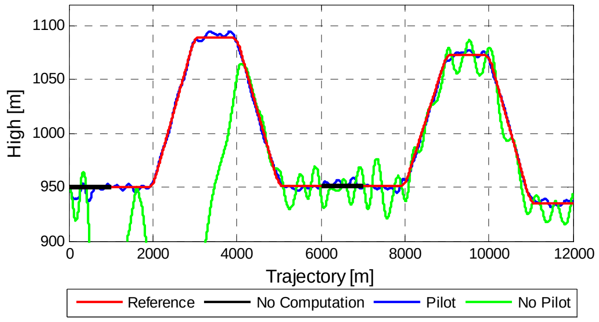

Fig. 16. Trajectory Comparison – No Flight Assistance

Fig. 17 features a comparison of the same users flying with the control strategy 8. It is clearly seen that both users had a much closer performance. It can also be noted that the experienced pilot did not lose any performance using the assisted flight strategy.

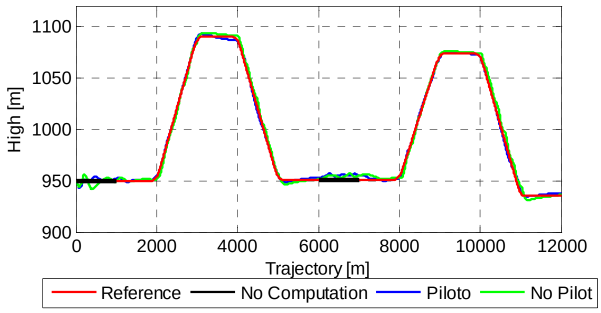

Fig. 17. Trajectory Comparison – Strategy 8

The same analysis was performed for the flown flight speed. Fig. 18 shows that both users had some issues controlling the flight speed but specially the inexperienced user. Fig. 19 shows the compared users flying with assisted flight strategy 8. Both users controlled the flight speed much easier and achieved a comparable performance.

The comparisons analysis suggest that the implementation of facilitated flight strategies can bridge the gap between experienced and inexperienced pilots.

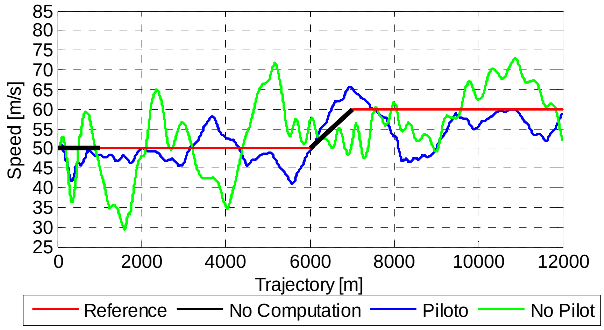

Fig. 18. Flight Speed No Flight Assistance

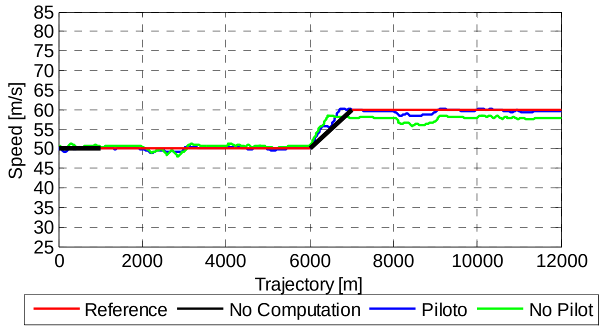

Fig. 19. Flight Speed Comparison Strategy 8

5 Conclusion

Along this work, assisted flight strategies were developed and studied based on the airplane trajectory control instead of the usual airplane attitude control. The studied strategies were evaluated by thirty four users having different flight skill and aeronautical knowledge. The evaluation was carried out using a flight simulator developed and implemented for that specific purpose.

Eight assisted longitudinal flight strategies were evaluated having as reference variables: altitude, rate of climb, pitch angle and speeds angle. For each chosen combination of those reference variables there were proposed two modes: the direct mode (speed variation controlled by the engine power percentage) and the crossed mode (speed variation controlled by the elevators deflection).

For all combinations the direct modes achieved better performance than the crossed modes. In some cases crossed strategies induced a worst performance comparing to the no strategy condition. That can be seen for instance in Fig. 8 where strategies 1 (Crossed, Reference: Speed and Altitude) and 5 (Crossed, Reference: Speed and Pitch Angle) clearly were over performed by the no strategy condition.

Strategy 8 (Direct, Reference: Speed and Speeds Angle) was the most performing strategy for this work. According to the users' opinion that strategy achieved a score of 2.2 in the Cooper Harper's scale and was classified as: "Satisfactory. No improvements needed. Negligible deficiencies. Desired Performance Achieved with no Pilot Efforts". Strategy 4 was the second more performing strategy scoring 3 in the Cooper Harper scale and classified as: "Satisfactory. No improvements needed. Unpleasant deficiencies. Desired Performance Achieved with minimum pilot efforts". Strategies 8 and 4 are thus good candidates to be implemented in flight assistance systems.

Last, a comparison between an experienced pilot and an inexperienced user with no flight skills showed that their performance could be brought to the same level using assisted flight strategies.

References

[1] Finotti J. *Jet Sets – NASA's plan to revolutionize how Floridians fly in the future* – Florida Trend – The Magazine of Florida Business – SATS, 2002

[2] Tomczyk A. *Proposal of the experimental simulation method for handling qualities evaluation* Department of Avionics and Control Systems, Faculty of Mechanical Engineering and Aeronautics, Rzeszo´w University of Technology, Rzeszo´w, Poland; Aircraft Engineering and Aerospace Technology: An International Journal, 2008.

[3] Barros C P. *Uma metodologia para o desenvolvimento de projeto de aeronaves leves subsônicas* – Universidade Federal de Minas Gerais – Escola de Engenharia – Programa de Pós-Graduação em Engenharia Mecânica, 2001.

[4] Oliveira P H I A. *Otimização de trajetórias de vôo de distância em planadores* - Tese de Doutorado em Engenharia Mecânica - Universidade Federal de Minas Gerais, UFMG, Brasil, 2004.

[5] Hartman E P. Biermann D. *The aerodynamic characteristics of full-scale propellers having 2, 3, and 4 blades of Clark y and R.A.F. 6 airfoil sections.* NACA Report N 640, 1938

[6] Ogata K. *Engenharia de Controle Moderno*, Quarta Edição, Segunda Reimpressão. Editora Pearson Prentice Hall, 2006.

[7] Harper R P JR. *Handling qualities and pilot evaluation*, (Calspan Corp., Buffalo, NY) & Cooper, G. E., (G. E.Cooper Associates, Saratoga), CA Journal of Guidance, Control, and Dynamics 0731-5090 vol.9 no.5 (515-529), 1986

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