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Hardware-In-the-Loop Simulation of an Attitude Control with Switching Actuators for SUAV

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Abstract—— **The attitude control law for fixed-wing small unmanned aircraft proposed in this paper is constructed based on two phases of a flight: stable flight and maneuvering flight. In the maneuvering flight, the aircraft deflects the main control surfaces (ailerons and elevator), whereas on the stable flight only the trim tabs are deflected. The switch between the two flights is done when the aircraft enters a zone in which the difference between the aircraft's attitude and the reference value that the airplane needs to reach is less than a predetermined value. The control laws are implemented on an on-board computer and are validated though Hardware-In-the-Loop (HIL) simulations, between the hardware and the flight simulator X-Plane, which simulates the unmanned aircraft dynamics, sensors, and actuators. The results presented prove that this implementation can reduce the rise time and the overshoot, compared with traditional implementations.**

I. INTRODUCTION

SINCE an American high-school student named Walter Good built and flew a radio-controlled model airplane, in 1935, this type of aircraft has been used in a wide range of applications [1]. They can be used on missions that are totally or partially autonomous [2]. To accomplish autonomous missions such as fumigation, surveillance, and vehicle tracking, it is essential to have a reliable attitude control, which is one of the most important areas of study and research on Small Unmanned Aerial Vehicles (SUAVs).

This paper presents a methodology to control the roll and pitch angles of SUAVs using two physical surfaces of an airplane: the main surfaces (aileron and elevator) and the secondary surfaces (trim tabs). The main idea is to divide the flight in two phases, and accordingly to the actual flight phase, to generate commands for each control surface.

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In addition to the attitude control proposed, another focus of this paper is to demonstrate that it is possible to test and verify ideas to modify traditional flight control loops, in a fast and easy way, using appropriate tools, including flight simulators and Hardware-In-the-Loop (HIL) simulations.

Neither the gains tuning nor the aircraft's dynamic's equations are presented here, because the paper focuses on the explanation of how to achieve advantages of the proposed control. Gain tuning details for the architecture presented can be found at [3]. SUAV dynamic's equation can be found at [4].

The paper is organized as follows. The next section describes the control surfaces used for the implementation presented in this work. Section 3 introduces the flight simulator X-Plane and the characteristics of the SUAV model used during the simulations. The fourth section details the proposed attitude control. The implementation of Hardware-In-the-Loop and the communication system are explained in Section 5. Section 6 presents the results obtained. The conclusion discusses the validity of proposed modifications, based on the results obtained, as well as the research that still needs to be done in this project.

II. CONTROL SURFACES

The control of an aircraft can be achieved by causing variations in the lift and the drag forces. These variations in these forces can be produced by deflecting the control surfaces. As the control surfaces are located at some distance from the center of gravity of the aircraft, the forces created by deflection cause moments related to the aircraft's center of gravity [5]. Figure 1 shows the moments caused by the deflection of the control surfaces and the axes of the aircraft.

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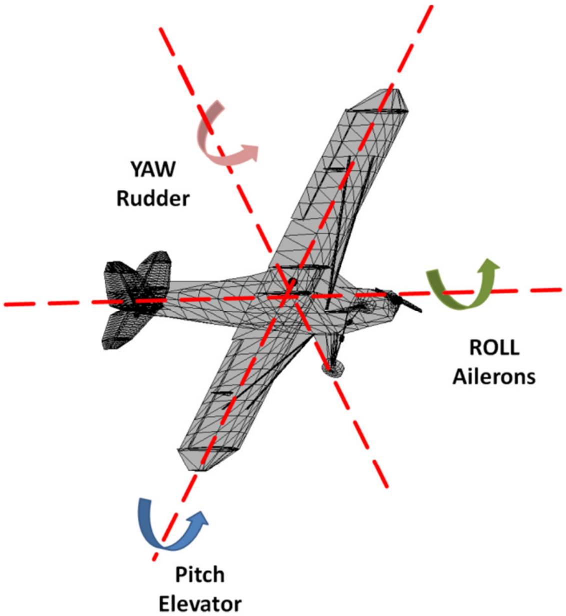

Fig. 1. Moments

The roll angle is controlled by deflecting surfaces located on the wings of the aircraft, called ailerons, while the pitch angle is controlled by the control surface located on the horizontal stabilizer of the aircraft elevator.

To keep the aircraft in a straight and level flight, the control surfaces must deflect only a small amount [6]. Each main control surface has small surfaces called trim tabs. These mini surfaces are used to produce the same effect as the major surfaces, but in minor proportions [7]. There are trim tabs for the ailerons, located in ailerons, and trim tabs for elevator, located in the elevator. Figure 2 illustrates an aileron and an aileron trim tab, built on a wing.

In this work, the aileron and the elevator are called "main control surfaces", whereas the trim tabs are called "secondary control surfaces". The term "control surface" is used generically for main and secondary control surfaces.

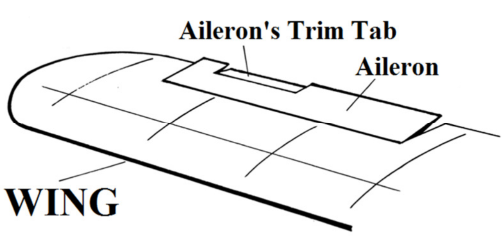

Fig. 2. Control Surface

Due to their small size and complexity, small unmanned aircraft ordinarily do not have independent trim tabs. The same physical control surface is usually used as main and secondary control surface. The primary difference between surfaces is the range that one can be deflected. A command of a main control surface deflects the moving surface on a major scale, and a command of a trim tab deflects the same surface on a scale equivalent to fixed percentage of the major scale.

Assuming $\delta_{aileron}$ is the command to deflect the moving surface that integrates the functions of aileron and aileron trim, Figure 3 illustrates the surface and aileron trim tab in three positions:

- Neutral Position:

  Aileron command (δ_a) and aileron trim tab command (δt_a) are null ($\delta_{aileron} = \delta_a = \delta t_a = 0$);

- Aileron trim tab maximum position ($\delta t_{a\ \max}$):

  Aileron trim tab command is maximum ($\delta_{aileron} = \delta t_{a\ \max}$);
- Aileron maximum position ($\delta_{a\ \max}$):

  Aileron command is maximum ($\delta_{aileron} = \delta_{a\ \max}$);

III. X-PLANE

X-Plane is used in this work to provide navigation data from the SUAV and to simulate its dynamics. It is a commercially flight simulator developed by Laminar Research, that can be installed on computers running Linux, Mac OS, or Windows operating system. Smaller versions are available for installation in mobile devices, tablets, and smartphones that use Android or iOS operating system.

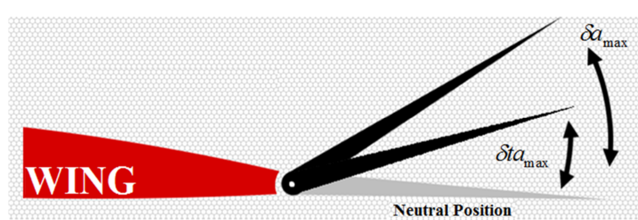

Fig. 3. Control Surfaces

X-Plane's aircraft are extremely accurate enabling a simulation with a high degree of similarity to an actual flight. According to the manufacturer, X-Plane is not a game, but an engineering tool that can be used to predict the flying qualities of fixed-wing or rotary aircraft [8]. The accuracy of the X-Plane makes it a useful tool to predict and test the performance of an aircraft and its characteristics. Moreover, it is the only simulator approved by the Federal Aviation Administration (FAA) for training of pilots. [9]

The library of X-Plane already has a wide variety of models, but you can create your own model, as done in this work, through the Plane Maker. Using the flight simulator, a SUAV was created based on the physical characteristics of a Piper J3 Cub 1/6 scale.

- Wingspan: 1.800 mm [71.0 in];
- Wing Area: 45.0 dm2 [698 sq in];
- Weight: 2500 g [5.5 lbs];
- Length: 1.200 mm [47 in];
- Brushless electric motor 540 W [0.72 hp];
- Maximum payload: 2.5 kg [5.5 lb];
- Cruising speed: 54 km/h [14 m/s; 30 knots];
- Cruising altitude over ground: 300 m [1000 ft].

Through Plane Maker, it was possible to configure the control surfaces of the small airplane to deflect in the range between -15° and +15°, with 0° the neutral position. The X-Plane allows the user to send commands to control the main control surfaces of the aircraft (selecting "joystick ail/elev/rudd" field on the X-Plane Input/Output Data), and at the same time to send commands to control the trim tabs of the aircraft (selecting "trim/flaps/spoiler" field on the X-Plane Input/Output Data). However, if the aircraft selected does not has a physical trim tab, as our SUAV, X-Plane will treat the command of trim as a command of main surfaces, but it will deflect the main surfaces only 10% of the nominal range. So we used this feature of X-Plane to implement the proposed control.

Hence, the maximum deflection that the surface can achieve with a trim tab command is ±1.5°, whereas if a maximum command of a main control surface is applied, the surface is deflect by ±15°. If both control surface and trim tab command is applied at the same time the surface will be deflected by the sum of both, which is an advantage that will be explored on next section.

Fig. 4. X-Plane's Model

Figure 1 illustrates the SUAV's airframe and Figure 4 illustrates the final painted version of the aircraft.

IV. Attitude Control

In this section, the two phases of a flight considered for the attitude control proposed in this work are introduced, and then the control loop is presented.

A. *Stable Flight*

On the first flight of an unmanned aircraft, it needs to be "trimmed", i.e the trim tabs should be adjusted to allow a straight and level flight (roll angle and pitch near zero degrees), here called a stable flight. Once the aircraft is trimmed, this process is not repeated.

The attitude control in a stable flight, as proposed here, works as if a new trim setting is done for every reference angle, and not only when the reference angles are close to zero, as in a manual flight.

During this stage of flight, only the trim tabs are used to control the airplane, as presented in the attitude control loop, Figure 5. A proportional-derivative controller and an incremental control were used to generate the output signal applied on the SUAV's trim tabs. This control loop, using proportional and derivatives gains, is explained in [4,5,6]. How the incremental control performs as an integral controller is demonstrated in [10].

The concept of attitude control in a Stable Flight is not limited just to maintaining the aircraft's pitch and roll angles close to zero, but to ensure that the aircraft starts to change its altitude or makes a turn only with the actions of trim tabs, whenever the aircraft's attitude is near the reference.

Obviously more time will be required to achieve the goal than when applying a command directly on the main control surfaces. However, our results demonstrate that using only the trim tabs substantially reduced the overshoot and almost eliminated the steady-state error.

B. Maneuvering Flight

Traditional control loops are designed to command the main control surfaces of an SUAV. We use this same idea to control the aircraft when a big variation in its attitude is needed, called Maneuvering Flight.

The attitude control during flight manoeuver is triggered when the difference between the reference angle and the current angle of the aircraft is greater than a predetermined value. On this control, the control surfaces (ailerons and elevator) are actuated, demanding less time for the aircraft to reach the reference, which decreases rising and settling times. It should be noted that although the same proportional-derivative control structure of the stable flight is utilized, the gains are totally independent on the loop gain of the attitude control in a stable flight [3].

C. Attitude Control

The attitude control proposed in this work consists of mixing the stable flight attitude control and the maneuvering flight attitude control, meaning that both trim tabs and control surfaces are used to control the attitude of the aircraft, according to Figure 5.

The operation of this control system is established as follows: first, the error is calculated (err_α), between the reference angle (α_{ref}) and the current angle ($\alpha_{current}$) of the aircraft as in

$$err_\alpha = \alpha_{ref} - \alpha_{current} \qquad (1)$$

If this error is smaller than a fixed value, called the maximum error (err_{max}), it is not necessary to make huge changes in attitude to reach the reference angle. Thus, only the attitude control in a stable flight is activated, meaning that only commands to trim tabs (δ_{tsup}) will be sent, and the main control surfaces will be set at the neutral position (Triggers P2),

$$If\ err_\alpha < err_{max}\ then\ \delta_{sup} = 0 \qquad (2)$$

If the difference (err_α) between the reference angle and the current angle of the aircraft is greater than the predetermined value (greater than err_{max}), the aircraft needs to perform a big maneuver to achieve the reference angle. Therefore, the attitude control of flight maneuver is triggered as soon as the main surfaces are deflected (Triggers P1). This loop control remains active until the error is less than the predetermined value, as shown in the equations 3 and 4.

$$If\ \ err_\alpha > err_{max}\ \ \text{then}\ \delta_{sup} = \Delta\,\delta_{sup} + \delta_{sup\ current} \qquad (3)$$

$$\Delta\,\delta_{sup} = (err_\alpha \times \mathrm{Kp_{sup}}) - (\mathrm{d}\alpha/dt \times \mathrm{Kd_{sup}}) \qquad (4)$$

Where:

$\mathrm{Kp_{sup}}$	is the direct gain for the maneuvering flight;
$\mathrm{Kd_{sup}}$	is the indirect gain for the maneuvering flight;
α	is the angle to be controlled (pitch or roll);
$\mathrm{d}\alpha/dt$	is the angle rate on the navigation coordinates system.
$\delta_{sup\ \mathrm{current}}$	is the current value applied on the surfaces (elevator or ailerons)
δ_{sup}	is the command to be applied on the SUAV's surface (elevator or ailerons)

At this time, the automatic attitude control will disable the control loop of maneuver in flight, which holds the main control surfaces back to the neutral position, or zero degrees (Triggers P2) via the main control surface command (δ_{sup}). In this situation, only the stable flight control will be engaged.

The stabilized flight control will cause the aircraft to reach the reference angle, and when achieved, it will ensure the aircraft maintains the desired attitude, deflecting the trim tab as in (5) and (6).

The stable flight control loop is always engaged in order to guarantee continuous and smooth movement of the aircraft when attitude control in a maneuvering flight is trigged off.

$$\delta_{tsup} = \Delta\,\delta_{tsup} + \delta_{tsup\ current} \qquad (5)$$

$$\Delta\,\delta t_{sup} = (err_\alpha \times \mathrm{Kp_{tsup}}) - (\mathrm{d}\alpha/dt \times \mathrm{Kd_{tsup}}) \qquad (6)$$

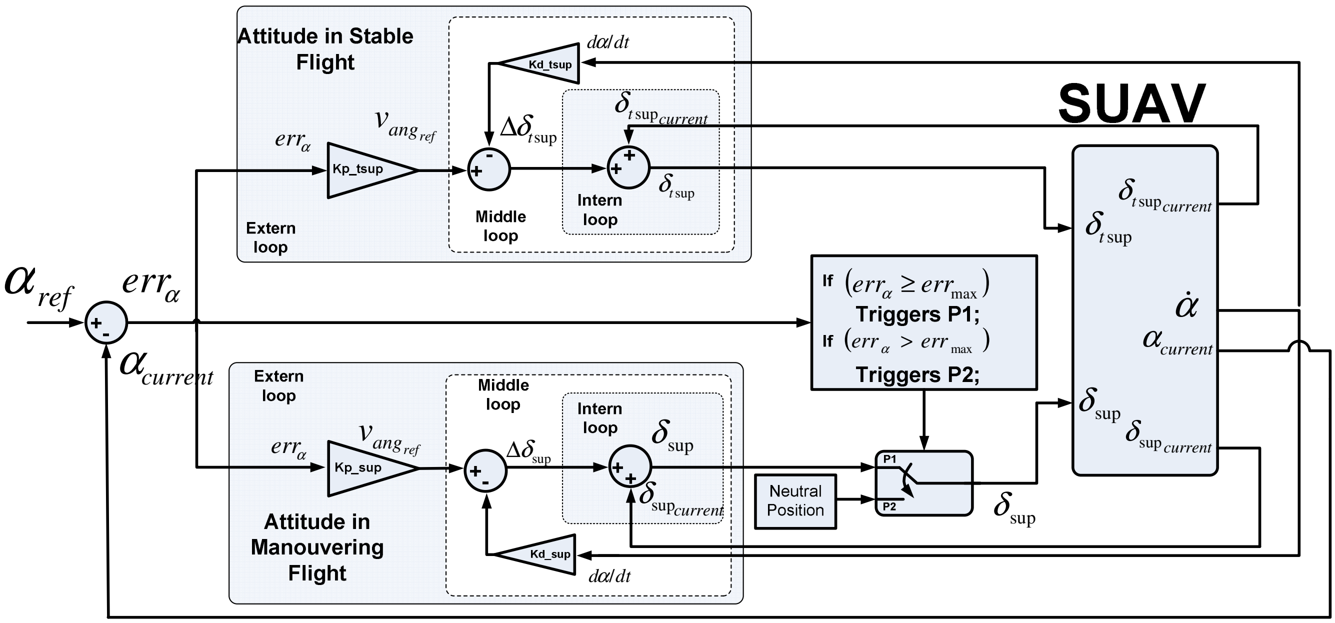

Fig. 5. Generic architecture of attitude control loop

Where:

Kp_{tsup}	is the direct gain for the stable flight;
Kd_{tsup}	is the indirect gain for the stable flight;
$\delta t_{sup\ current}$	is the current value applied on the trim tab surfaces (elevator or aileron trim tabs)
δ_{sup}	is the command to be applied on the SUAV's trim tab surface (elevator or aileron trim tabs)

Deactivating the attitude control in a stable flight when the maneuvering flight loop is engaged impacts the performance of the airplane. If attitude control in a maneuvering flight is disabled and the flight control stabilization is activated, the aircraft will have both trim tabs as the only control surfaces acting and they will be in the neutral position. Thus, the trim tabs will depart from the neutral position, and the automatic control has to interact to calculate the command that needs to be sent to the trim tabs.

As a consequence, the airplane will take considerable time to reach the reference angle. Because the deflection of the main control surfaces causes a greater effect on the aircraft, if compared with the trim tabs, practically when both controls are engaged, no effect is noted by the deflection of the trim tabs.

However, if both controls are engaged when the maneuvering flight loop is triggered off, the trim tab will already be in a position that helps the reference angle to be reached quickly.

V. Hardware-in-the-loop Implementation

HIL simulation consists basically of the attitude control running on a dedicated hardware, which reads the status of the aircraft simulated by the X-Plane, and sends commands from the control surfaces to the flight simulator, which also simulates the SUAV's dynamics.

The attitude control implementation was done using two ARM Cortex M3 microcontrollers manufactured by Texas Instruments. The attitude laws described were implemented in one microcontroller, which communicates with X-Plane through a wired serial port. The other microcontroller was used to receive data wirelessly from the attitude control, simulating a ground station. Both firmwares were written in C Language. These two features allow easy upgrade of the hardware, if required in the future.

The microcontroller responsible for the attitude control receives the attitude rate angles, the attitude angles, and the actual position of the main and secondary surfaces. It also calculates the new position to be applied on the surface based on the control laws, sends commands back to X-Plane, and finally updates the simulated ground station (second microcontroller).

Once X-Plane receives the command data from the attitude control, it sets the values on the aircraft control surface, simulates its dynamic, and sends the new attitude values to the microcontroller, closing the loop.

D. *Communication between systems*

X-plane provides a native channel of communication through its Ethernet port using UDP (User Datagram Protocol), by sending and receiving data over the computer's network interface card. UDP is the standard communication protocol for gaming and video conferencing. It is a fast way to communicate, but without a guarantee of receiving data. UDP does not have control structures, such as timeouts, retransmissions, flow control, and acknowledgments.

In order to avoid using Ethernet protocols, which minimize the size of the code generated, a plug-in (written in C# Language) was developed to establish the communication between the serial port from the microcontroller and the UDP port from X-Plane.

The implementation is presented on Figure 6, where the plug-in translates the UDP packets from X-Plane to serial packets for the microcontroller. More details about this Hardware-In-the-Loop implementation and the adjustment of the gains can be found at [3].

VI. RESULTS

In order to highlight the optimization using both trim tabs and control surface, we present one simulation using only control surfaces, one using only trim tabs, and finally one using both surfaces, for each angle control.

As mentioned earlier, in the maneuvering flight, we use only the main control surfaces: ailerons and elevator. By having larger deflection, these surfaces cause an aggressive response of the aircraft, as perceived in Figure 7, which illustrates the roll response to a step input.

The dashed line represents the reference applied, whereas the aircraft's response is represented by the solid line.

Figure 8 presents the pitch angle response using only the elevator. In the simulations where only one surface is deflected, the system works as a normal control loop, as stated in [5].

Figure 9 shows the roll response when the roll angle control is done only by the aileron trim tabs. Due to the characteristics of the secondary control surface, they cause a slow response of the aircraft. The pitch angle simulation is shown in Figure 10, using the elevator trim tabs.

The response using the main control surfaces have a rise time lower than responses of the loops using only trim tabs, as presented in Table 1 and 2. However, the stable flight response does not present a visible overshoot. After this initial analysis, we proposed the control loop in Figure 5, which takes advantage of the fast response of maneuvering flight loop, and does not overshoot after being switched to the stable flight loop.

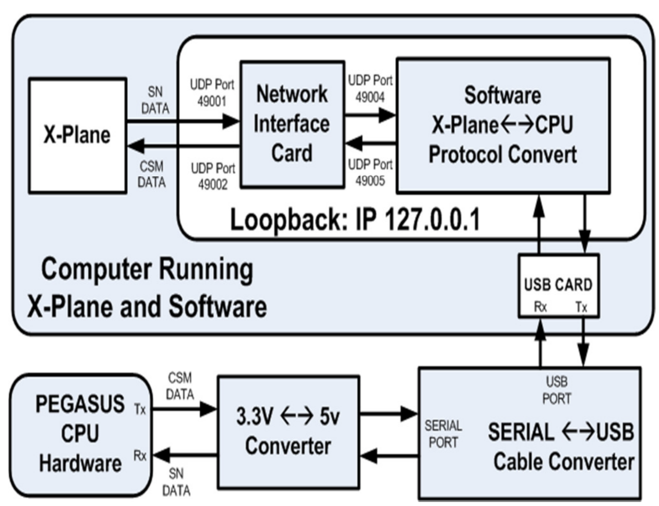

Fig. 6. Hardware-In-the-Loop Architecture

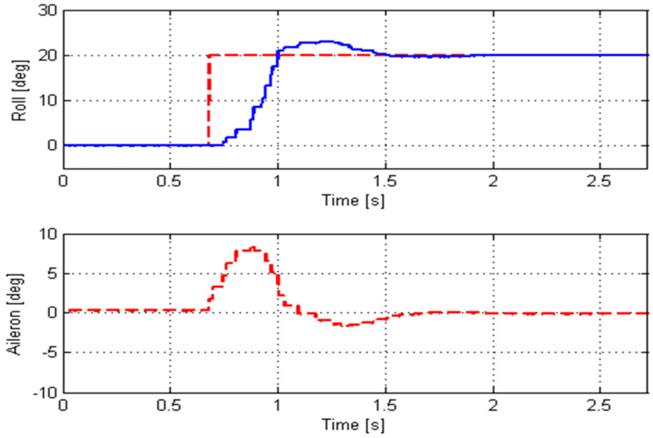

Fig. 7. Roll angle response only with ailerons

Using the control loop shown in Figure 5, the results obtained are presented in Figure 11 for the roll angle and 12 for the pitch angle.

The autopilot system switches between the two flights modes when the difference between the reference angle and the current angle is less than three degrees.

Table 1 – Roll Response

ROLL	Ailerons	Ailerons' Trim Tabs	Both Surfaces
Rise Time (s)	0.1930	0.7250	0.1333
Overshoot (%)	14.650	0.3500	0.2000
Settling Time (s)	1.0878	1.3071	0.8142
Steady-state error(°	-0.0279	- 0.0169	-0.0058

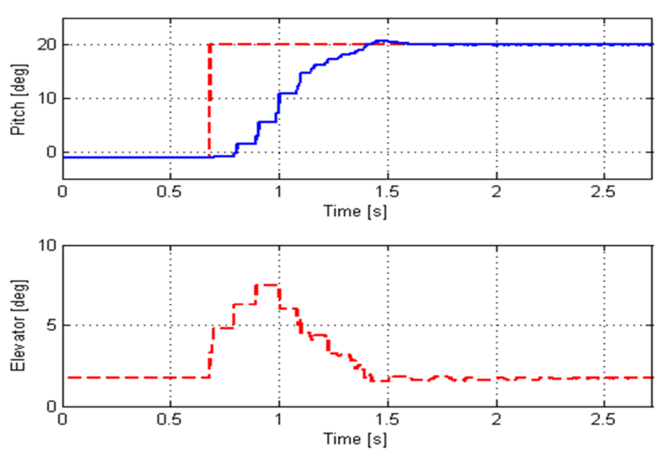

Fig. 8. Pitch angle response only with elevator

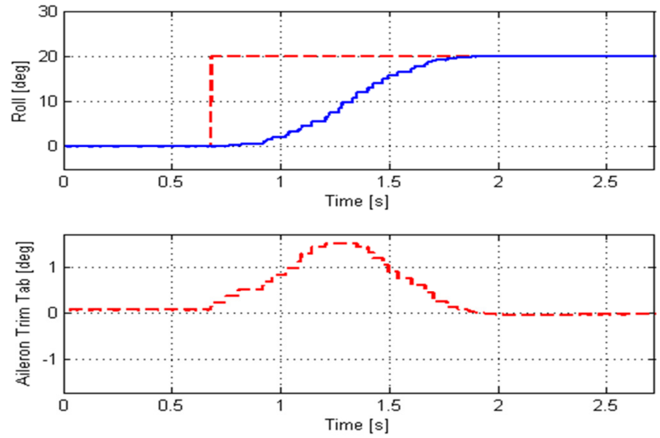

Fig. 9. Roll angle response only with aileron trim tab

It is possible to note, as in the pitch angle response, the operation of the proposed loop. The automatic control deflects both control surfaces, while the difference between the reference angle and the current angle of the aircraft is greater than the predetermined value, three degrees in this simulation.

Table 2 – Pitch Response

PITCH	Elevator	Elevator Trim Tabs	Both Surfaces
Rise Time (s)	0.4335	0.8523	0.3751
Overshoot (%)	3.5000	0.0021	0.0005
Settling Time (s)	0.9209	1.7294	0.9041
Steady-state error(°)	-0.0133	-0.0108	- 0.0067

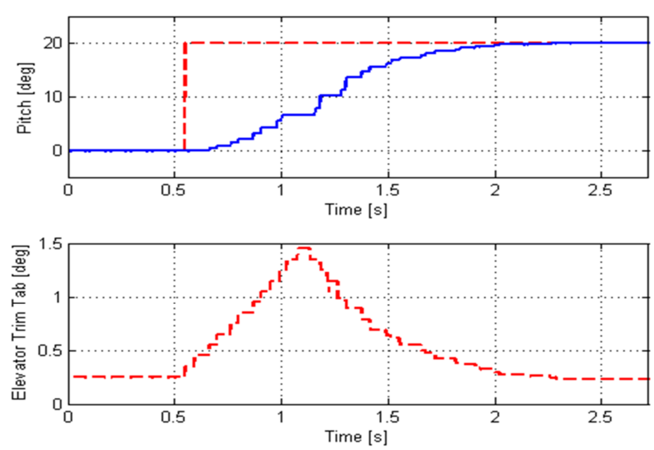

Fig. 10. Pitch angle response only with elevator trim tab

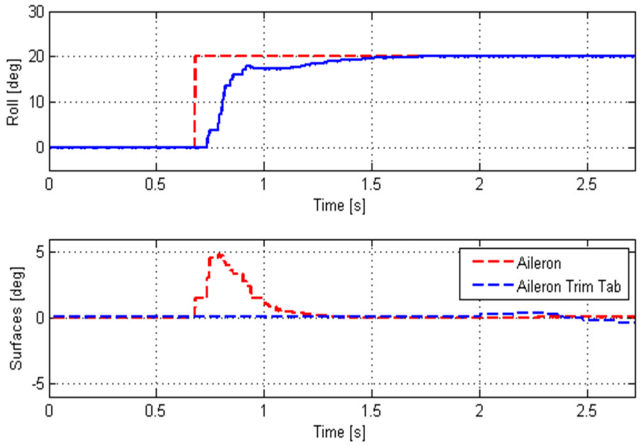

Fig. 11. Roll angle response with both surfaces

When the difference is less than this value, the main control surfaces, ailerons and elevator, receive commands to stay fixed at neutral position and only the trim tabs are deflected.

Table 1 and 2 present the performance characteristics of the simulated attitude loops.

VII. Conclusion and Future Work

With the presented control, it is possible to take advantage of the best properties of each control loop, which are low rise time in maneuvering flight loop and no overshoot and steady-state error near zero from stable flight loop.

In [10] the authors implemented an incremental control which already leads to a steady-state near zero. Even though, the proposed implementation presented here contributes to eliminate the error as seen on the results.

Another way of expressing the proposed control is by adopting the following idea: when the switching between the loops occurs (the maneuvering flight control loop is disengaged), a new situation for the stable flight control loop is presented, and then the SUAV only needs to reach three more degrees instead of the first 20 degrees of the reference. As trim tabs were already being deflected, they do not have a time delay to leave the neutral position, making the aircraft's movements smoother.

The HIL simulation used to test the automatic control behavior proved to be an easy and fast way of verify new ideas about control loops without having to determine the aircraft's equations of motion.

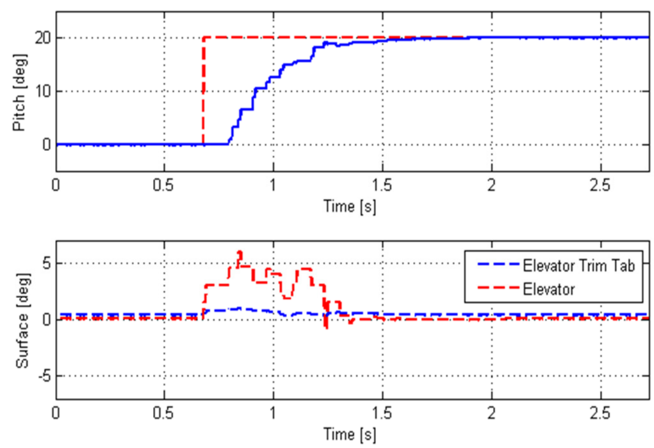

Fig. 12. Pitch angle response with both surfaces

Although in this paper only a customized SUAV model was used, X-Plane's library has many other aircraft models that could have been used to verify the control.

The proposed architecture improved the attitude control of the SUAV, as presented in the results. A study to be done in the sequence is verify how the aircraft behaves if it is exposed to disturbances like lateral wind or turbulences.

Because the main idea of switching the actuators in different phases of flight was successfully implemented for the Piper 1/6 Scale, future research will focus on verifying the idea on other X-Plane models. Then the equations of motion will be used to set limitation parameters and tune the controllers. One item of immediate future work includes creating a HIL platform to also verify altitude, heading, and airspeed controls and guidance algorithms using the proposed control.

Acknowledgments

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