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IMPLEMENTATION OF A WASHOUT FILTER USED IN STEWART PLATFORM

Rodrigo Cristian Lemes
Instituto Federal de São Paulo (IFSP) campus São Carlos. Rodovia Washington Luís, km 235 prédio AT-6 - Salas 136, - Bairro Monjolinho CEP 13.565-905 - São Carlos – SP.
lemes@ifsp.edu.br

Fabio Toledo Bonemer De Salvi
Mateus Moreira de Souza
Ricardo Afonso Angélico
Caio Augusto Zagria Barbosa
Eduardo Morgado Belo
Escola de Engenharia de São Carlos (EESC) – USP. Avenida João Dagnone, nº 1100 - Jardim Santa Angelina. CEP 13563-120 - São Carlos – SP.
fabiodesalvi@usp.br; mateusmoreiradesouza@yahoo.com.br; ricardoangelico@gmail.com; caio.augusto.barbosa@usp.br; belo@sc.usp.br.

Ricardo Breganon
Instituto Federal do Paraná, Av. Dr. Tito, s/n, Jardim Panorama, Jacarezinho – PR.
ricardo.breganon@ifpr.edu.br

Abstract. *The aim of this work is to implement the filter called Classic Washout, which creates sensations of movement, for application in a movable Stewart platform. This washout filter is intended to recreate the sensations of movement caused by changes of acceleration, lateral and rotational that an aircraft can provide, due to changes in attitudes caused by external factors, and those caused by the pilot's command. A complete dynamic model of an aircraft was implemented using Matlab/Simulink and its initial flight conditions in order to obtain data as linear accelerations and angular velocities of this aircraft. These signals are then filtered by washout filter and inserted in the inverse kinematics of the movable platform, which will condition the correct movements of the actuators according to the motion sensations created by the aircraft. Experiments were performed in Stewart platform, varying linear acceleration and the angular velocities for checking and validation of the washout filter, as well as the mathematical modeling of the entire system. Results indicate the efficiency of the washout filter, and the necessity to properly estimate the natural frequency values of the damping coefficient filters, since they are determined by trial and error through work experience reported by the pilot in the simulator.*

Keywords: *Stewart Platform, Classical Washout Filter, Flight Simulator.*

1. INTRODUCTION

Stewart Platforms are composed of two platforms connected by six parallel linear actuators and the relative position between the two platforms can be changed by extending or retracting the actuators. This type of structure allows placed on the movable platform device can be moved in six degrees of freedom. These are the three linear translatory movements X, Y, Z (longitudinal, lateral and vertical), and the three movements of rotations φ, θ, ψ (roll, pitch and yaw). The evolution of platforms Stewart emerges from the need to create flight simulators increasingly sophisticated, they are used in pilot and crew training, and are used in the design and evaluation of aircraft control and embedded systems.

The use of flight simulation in research has extended considerably in the last 40 years, as equipment improvements have become available. As this growth continues, there are many issues that are being debated regarding the use of simulation for experimental research and development. One of the major issues surrounding human factors flight simulation research involves determining what level of simulator fidelity is necessary to provide satisfactory experimental results. (Rehmann, 1995)

In a very simplistic manner the overall structure of the movement of a flight simulator system can be understood in a way that when the pilot responds to motion sensations and the task given by training, represents the inputs for the dynamic model of the aircraft which will have as output this model, the linear and angular acceleration. Then, due to the limitations of the displacement movement mechanism, the linear and angular acceleration of the aircraft is filtered by the filter washout. The trajectories generated by the filter are the reference inputs of the motion controller. The controller drives the movement mechanism with the appropriate control signals and receives signals from sensors mounted on the engine as feedback signals.

The aim of this work is to implement the filter called Classic Washout, which creates sensations of movement, for application in a movable Stewart platform and for this, a complete dynamic modeling of an aircraft shall be implemented using Matlab/Simulink as well as their initial flight conditions to obtain data such as linear and angular accelerations of this aircraft. These signals are then and inserted in the inverse kinematics of the movable platform, which will correct a condition of movement of the actuators according to the motion sensations created by the aircraft.

2. THE STEWART PLATFORM

A Stewart platform designed in the Aerospace Control Laboratory of the *Escola de Engenharia de São Carlos – USP* was utilized in this work. Fig. 2(a) shows the Stewart platform utilized. It has six electromechanical actuators that are utilized to control the position and attitude of the movable platform. To measure the variation of the actuators' lengths encoders in the shaft of the actuators' engines were utilized to measure the number of rotations of the engine, and then a calibration curve was applied to obtain each actuator variation length. The acquisition, transmitting, and processing system dSPACE was utilized in combination with the speed controller drive RoboClaw 2 to send signal of voltage in the range of 10 V to -10 V to the actuators' engines.

3. THE WASHOUT FILTER

The motion cueing algorithm so called as washout filter is a transformation that transforms the motion from actual vehicles to simulators. The purpose of the washout filter is to reproduce the angular rates and forces that a pilot would feel if the simulation was real, using a 6 DOF Stewart Platform (SP), which has limited workspace. In order to do this the filter's inputs are the linear accelerations and angular rates at the rider's head, since that is where the human vestibular system is located. Such input is then reproduced, in the most realistic way, on the rider's head by moving the platform in which the model is mounted. Its major function is to "wash out" unnecessary signals and pull the position of the simulator back to its neutral position. Some minor functions which followed after the washout filter are designed to increase the efficiency of the platform workspace. The senseless maneuver is developed to moves the platform toward its original position beyond the threshold of human perception. (Chen and Fu, 2010).

Many different schemes of washout filter have been proposed in the last three decades. Classical washout filter was the first kind that has been developed by Reid and Naron, shown in Fig.1, which is composed of linear low-pass filters and high-pass filters and is featured by its simplicity and ease of adjustment. The filter parameters used in the version with the most favorable pilot comments are given in table 1. (Nahon and Reid, 1990)

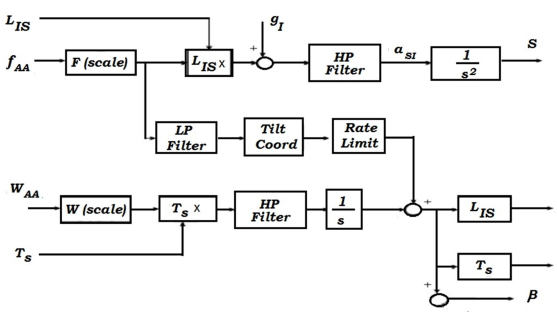


Figure 01: Classical washout algorithm. (Reid and Nahon, 1985)

Table 01: Classical washout filter characteristics. (Nahon and Reid, 1990)

Filter	Order	Wn	ζ
x translation high-pass	2	2.5	1.0
y and z translational high-pass	2	4.0	1.0
All rotational high-pass	1	1.0	-
x translational low-pass	2	5.0	1.0
y translational low-pass	2	8.0	1.0

The inputs to the algorithm are the aircraft translational specific forces $f_{AA} = [f^x_{AA}\ f^y_{AA}\ f^z_{AA}]^T$ and angular velocities $W_{AA} = [p_{AA}\ q_{AA}\ r_{AA}]^T$ while the outputs is the simulator displacements *S* and *B*. Before filtering the input channels are scaled and limited at 10 m/s^2, then transformed to the inertial reference frame by transformation matrices L_{IS} and T_S. Both matrices depend on the actual state of the simulator and are continuously updated. After that, g is added to the specific forces to create the inertial frame accelerations. The inertial accelerations are high-pass filtered at the first section called High-Frequency Translation Motions in order to remove the large displacement low-frequency motions. (See table 1 to the values of the second-order high-pass filter of the form in the equation 1). Finally, twice integrating the filtered accelerations, one obtains the translational displacement *S* to the simulator.

The aircraft translational specific forces f_{AA} are also sent to a second section called Tilt-Coordination which are low-pass filtered in order to remove the large displacement high-frequency motions and then subjected to tilt coordination to transform the translational motions into rotational motion. (See table 1 to the values of the second-order low-pass filter of the form in the equation 2). These signals are then limited to 3 deg/s to keep the tilt rate and acceleration motions below the human perception thresholds, so that only the gravity component of the tilt angle can be detected. (KO, 2012)

A third section called High-Frequency Rotational Motions, are first scaled and limited to 34.4 deg/s, transformed into Euler rates using the matrix T_S and then are high-pass filtered to yield the high-frequency component of simulator angular motion. (See table 1 to the values of the first-order high-pass filter of the form in the equation 3). The values of natural frequency "w_n" and damping coefficient "ζ" from Table 1, are determined and selected from a sets values tuned by trial and error through experiments reported by the flight simulator pilot relative to a set of maneuvers.

$$S_{x,y,z} = S^2/(s^2 + 2\zeta\omega_n s + \omega_n^2) \tag{1}$$

$$\beta tilt_{\phi,\Theta} = \omega_n/(s^2 + 2\zeta\omega_n s + \omega_n^2) \tag{2}$$

$$\beta_{\phi,\Theta,\psi} = S/(s + \omega_n) \tag{3}$$

The motion inputs f_{AA} and W_{AA} are scaled and limited to reduce the amplitude of the motions to be simulated. The scale factor adopted on all inputs are 0.5.

4. THE INVERSE KINEMATICS

The inverse kinematics presented in this study to the platform is based on (Breganon, *et all* 2013). Once defined the desired position and attitude of the Stewart platform from the dynamic and washout filter, the length of the six actuators can be obtained utilizing the inverse kinematics of the platform. Joints of actuators are known for a given platform, and their relative positions can be written in relation to the center of each platform in two coordinate systems shown in Fig. 2. The base platform coordinate system utilizes the center of the base platform F as origin, the xf-axis pointing between joints with actuators 1 and 6, zf-axis is perpendicular with the platform plane, and yf-axis completes the right hand rule. The movable platform coordinate system center M and its axis xm, ym, and zm are defined in a similar way. The positions of joints of the base and movable platforms in its coordinate systems are represented in Eq. (4) and (5), respectively.

$$\{F_i\}^F = \{F_{i1} \quad F_{i2} \quad 0\}^T, i = 1,2,\ldots,6 \tag{04}$$

$$\{M_i\}^M = \{M_{i1} \quad M_{i2} \quad 0\}^T, i = 1,2,\ldots,6 \tag{05}$$

The transformation matrix [T^{MF}] to obtain coordinates from movable coordinate system to base coordinate system can be obtained utilizing three rotations in sequence. The first rotation is applied in xm-axis until ym-axis is parallel to the base platform plane; this angle of rotation φ is known as roll angle. Then it is applied a rotation in the ym-axis until the movable platform is parallel to the base platform; the pitch angle θ is obtained. And the last rotation is applied in the zm-axis generating the yaw angle ψ. The transformation matrix is show in Eq. (6).

$$[T^{MF}] = \begin{bmatrix} C\psi C\theta & C\psi S\theta S\phi - C\phi S\psi & C\psi C\phi S\theta + S\psi S\phi \\ C\theta S\psi & C\psi C\phi + S\psi S\theta S\phi & C\phi S\psi S\theta - C\psi S\phi \\ -S\theta & C\theta S\phi & C\theta C\phi \end{bmatrix} \tag{06}$$

Where, C = Cosine (.) and S = Sine (.)

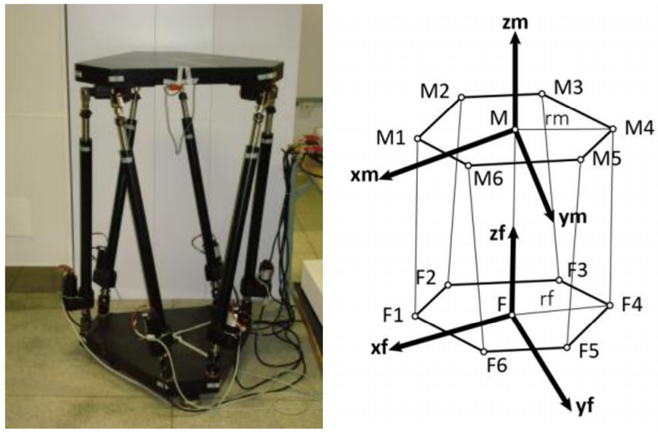
The position of the movable platform can be written in the base platform system as shown in Eq.(7) and the length vectors V_i of the six actuators can be obtained utilizing Eq.(8).

$$\{M\}^F = \{x \quad y \quad z\}^T \tag{07}$$

$$\{V_i\}^F = \{V_{i1} \quad V_{i2} \quad V_{i3}\}^T = \{M\} + [T^{MF}] * \{M_i\} - \{F_i\}, i = 1,2,\ldots,6 \tag{08}$$

The actuator's length l_i is the module of the vector $\{V_i\}$ as shown in Eq.(9).

$$l_i = \left(V_{i1}^2 + V_{i2}^2 + V_{i3}^2\right)^{0.5}, i = 1,2,\ldots,6 \tag{09}$$



(a) (b)

Figure 02: (a) The The Stewart platform of the Aerospace Control Laboratory. (b) Base and Movable platforms coordinate systems. (Breganon, *et all.,* 2013)

Flight dynamics focuses on the behavior of vehicles in flight and the causal factors that influence the motions exhibited in response to atmospheric disturbances or pilot inputs.

5. EXPERIMENT SETUP

In order to investigate the application of the washout filter for application on a Stewart platform, it is necessary to implement the dynamics of an aircraft where the data of linear and angular accelerations may be provided and recreated. The flight dynamics focuses on the behavior of vehicles in flight and the causal factors that influence the motions exhibited in response to atmospheric disturbances or pilot inputs.

The experimental setup for simulating a complete aircrafts dynamic model was implemented using Matlab/Simulink and its initial flight conditions in order to obtain data as linear accelerations and angular velocities of the aircraft. These signals are then filtered by washout filter and inserted in the inverse kinematics of the movable platform, which will condition the correct movements of the actuators according to the motion sensations created by the aircraft. See Fig. 03.

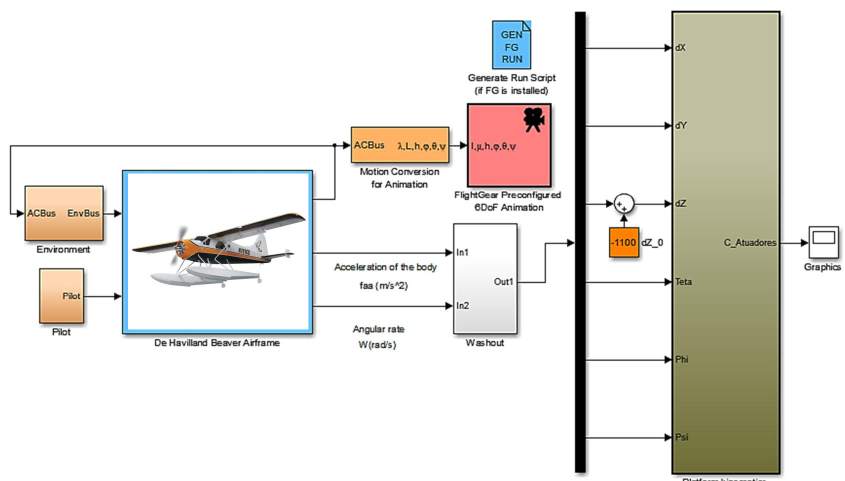
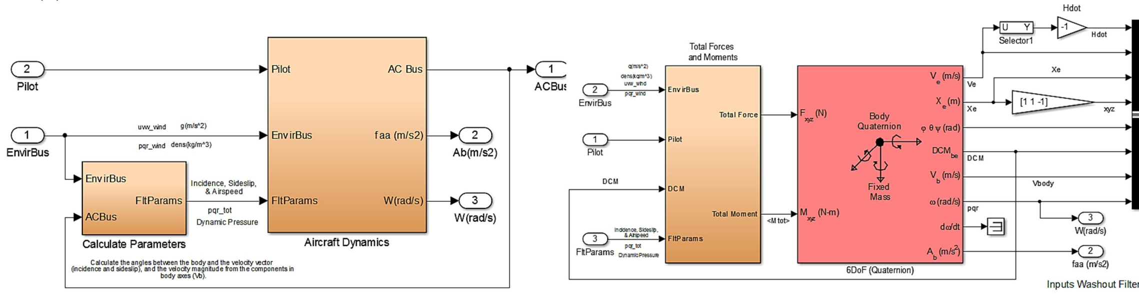


Figure 03: Experimental Setup.

A complete dynamic model of an aircraft was implemented using Matlab/Simulink and its initial flight conditions in order to obtain data as linear accelerations and angular velocities of this aircraft. These signals are then filtered by washout filter and inserted in the inverse kinematics of the movable platform, which will condition the correct movements of the actuators according to the motion sensations created by the aircraft.

Pilot control signals are sent to the block containing the dynamics of the aircraft, along with the simulation parameters of external factors and flight environments, such as, wind models, atmosphere model, gravity model, dynamics pressure, incidence, sideslip and airspeed. This environment datas are transformed into aerodynamic coefficients and engine coefficients in order to get the total forces and moments. This aircrafts forces and moments signals are sent to the block of six-degrees-of-freedom equations of motion with respect to body axes. See Fig. 04 (a) and (b).



(a) (b)

Figure 4: (a) De Havilland Beaver Airframe block parameters. (b) The Aircraft Dynamics block parameters.

Finally, from the 6DOF Quaternion block Fig. 4(b), linear accelerations given in (m/s^2) and angular velocities (rad/s) of this aircraft are sending to the washout filter and Drive position and attitude values to a FlightGear Flight Simulator vehicle given values for longitude, latitude, altitude, roll, pitch, and yaw respectively.

6. IMAGE GENERATORS

The open source and free alternative image generator is FLIGHTGEAR (FG). FG is jointly developed by many flying enthusiast around the world and it is given free of charge. The source code is also available for download and licensed under GNU General Public License v2. FG allows anyone to study and modify the source code so that it can be used with other third party applications. FG provides complete world scenery despite the quality of the image is not as good as the one provided by commercial IG. On top of that, FG can be customized to show an out-of-window view for a preset view angle. This means by using multiple FG computers, multiple views provides a 180-degree out-of-cockpit view. Another advantage of using FG is that it accepts external input via TCP/IP.

The external input in this case is a UDP broadcast from MATLAB. With multiple FG computers, the display of the 180-degree out-of-cockpit view can be done easily with a continuous broadcast from the MATLAB computer. (Nusyirwan, 2011)

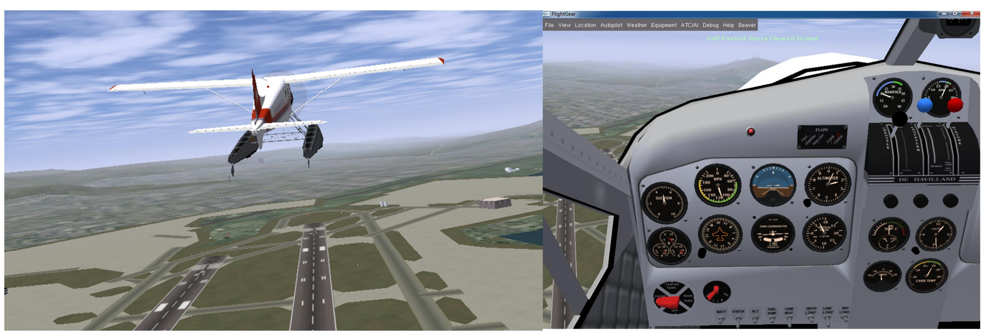


Figure 5: Flightgear open source and free alternative image generator.

7. RESULTS

To prove the classical washout filter efficiency in simulating movements of sensations, experiments were conducted performing maneuvers such as pitch, yaw and roll of an aircraft in flight to a certain attitude and initial speed. A joystick was used as a command input configured to perform the experimental maneuvers in order to make the experimental procedure as realistic as possible.

An initial approach is related with the throttle plane. We know that when we increase or suddenly decrease the acceleration of a body, we feel the actions of the acceleration acting on our sensory vestibule, responsible for creating in our mind the effects of the body's speed changes. Figure 6 illustrates the throttle behavior created by the pilot moving of the state minimum acceleration 0 at full throttle in 1. As a consequence of the action caused by the pilot to position the throttle at maximum acceleration position, the fig. 7 illustrates the behavior of linear acceleration (m/s^2) in the x-axis plane as a function of time (s).

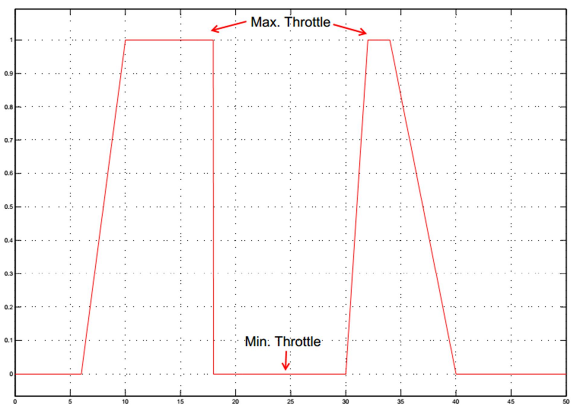


Figure 6. Throttle behavior created by the pilot.

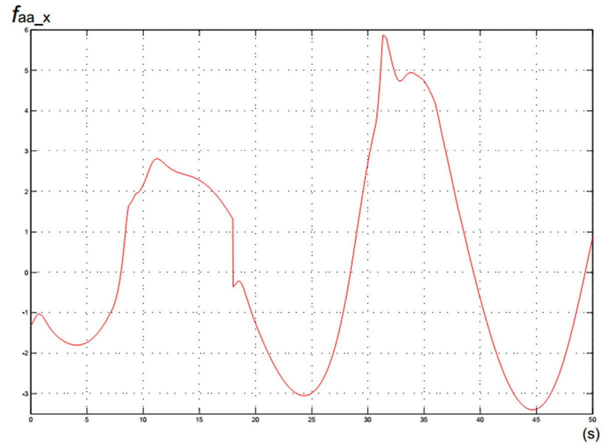
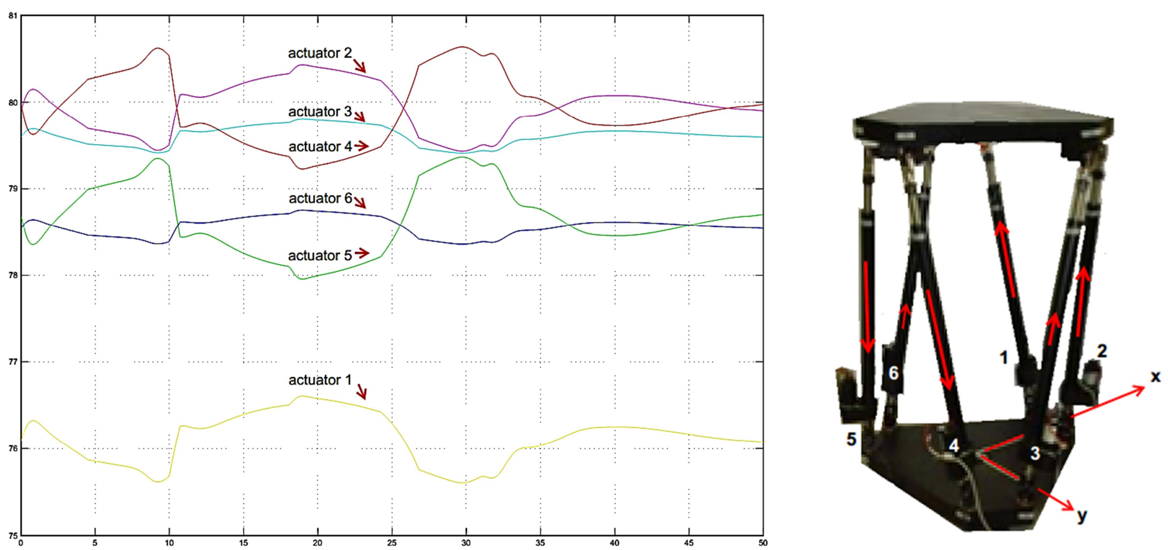


Figure 7. Linear acceleration in the x-axis plane as a function of time

Figure 8(a) and Figure 8(b) shows the behavior of actuators with linear displacement in centimeters, according to the linear acceleration in the x-axis is created by the sudden change of acceleration imposed on the aircraft. When the pilot moves all the throttle to the maximum acceleration, it is intuitive know, that the pilot will feel a force as if being pushed against the seat. This sense of acceleration is recreated by tilting the platform in a positive pitch angle, which will reproduce the felt acceleration force imposed by the pilot.

From Fig. 8(a) we may note through the movement of the platform actuators, moving in a positive pitch angle in t~10s, where actuators 1 and 2 extend relatively greater than the actuators 3 and 6, while the actuators 4 and 5 retracts. In t~18s, we note the platform moving at negative pitch angle due to slowdown caused by the pilot. All this is made possible by the action of washout filter.



(a) (b)

Figure 8. (a) Movement of the platform actuators caused by the change acceleration of the aircraft. (b) Representation of the actuators motions with increasing acceleration in the x axis.

To verify the operation of classical washout filter, a motion simulation in steady decline of an aircraft in flight for a few seconds was carried out, in order to analyze the behavior of the accelerations involved in this procedure. Fig. 9 shows the loss of the aircraft altitude as well as Fig. 10 shows the attitude angles of roll (φ) pitch (θ) and yaw (ψ), developed by simulating.

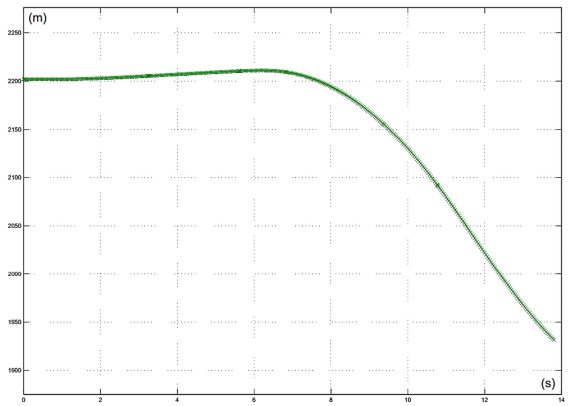


Figure 9. Downward movement of the aircraft simulation.

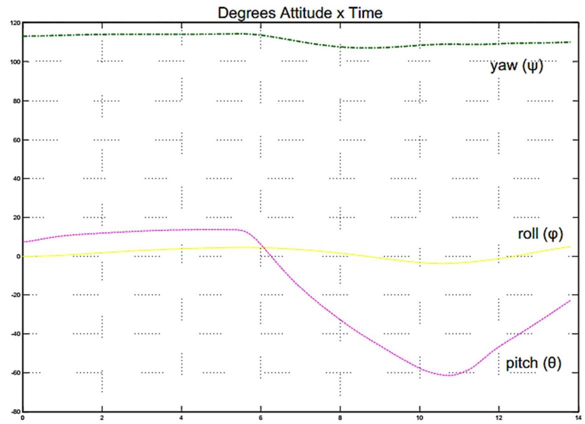


Figure 10. Attitude angles of roll (φ) pitch (θ) and yaw (ψ), developed by simulating downward movement.

As a result of downward movement, in addition to linear accelerations generated by the aircraft, the angular velocities occur around the axes of motion. For this case, an angular velocity W_{aa}_y is outstandingly larger than the other axes, as shown in Fig. 11.

The Fig. 12, shows the behavior of actuators where the signal of the acceleration and angular velocity are sent to the washout filter, that send the right signals to the kinematics to calculate the linear movement of each actuator to simulate the Stewart platform. One can see in Fig.12 that the platform produces the motion to lower the nose of the airplane in a more sudden movement initially and tends to recover according to the angular velocity Waa_y tends to be constant or equal to 0 from Fig.11.

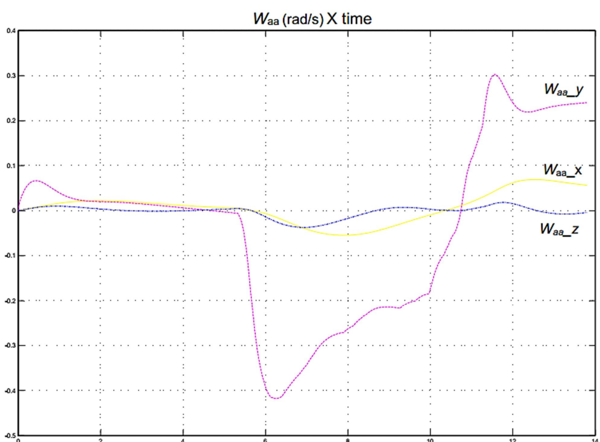


Figure 11.Angular velocity as a result of downward movement.

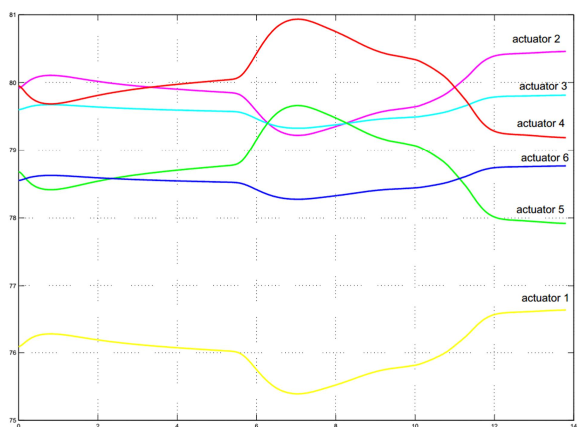


Figure 12. Movement of the platform actuators caused by the change angular velocity.

Another important question to be verified in this paper is the search for understanding the use of Washout filter and its features. It can be seen from Fig. 13 an “Fx_” signal containing high frequency and low frequency were sent to the high-pass filter sets of first-order high-pass filter called rotation channel, to a second-order high pass filter called translation channel, and to a low-pass filter sets called tilt Coordination. All the characteristics were according to set by Tab. 1.

Figure 13 shows clearly the action and function of these filters to simulate movements, where we can clearly notice the high pass filter action in let pass only the high frequency signals such as those seen by the state change signal and the signal peaks from Fx_. It can also clearly see the low pass filter in action when filtering high frequency signals and maintain and attenuate low-frequency signals.

The values of natural frequency “w_n” and damping coefficient “ζ” from Tab. 1, are determined and selected from a sets values tuned by trial and error through experiments reported by the flight simulator pilot relative to a set of maneuvers, and it was used as parameters for experimental trials of this paper.

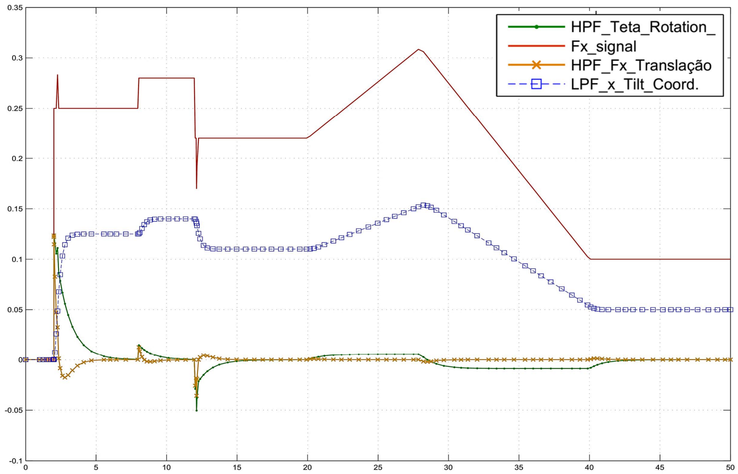


Figure 13. Classical Washout filter in action with the characteristics were according to set by Table 1.

Figure 14 and Figure 15, shows the behavior from the change values of the mathematical model used in the channel translational movement algorithm. In Figure 14, the value of the numerator of equation 1 was changed from 1 to 0.5 and 2. It shows that a greater numerator increases the signal amplitude, making the movements of the platform to more aggressive pilot commands, while in Fig. 15 a higher value for the natural frequency "W_n" becomes faster response to command and lower ranges of motion.

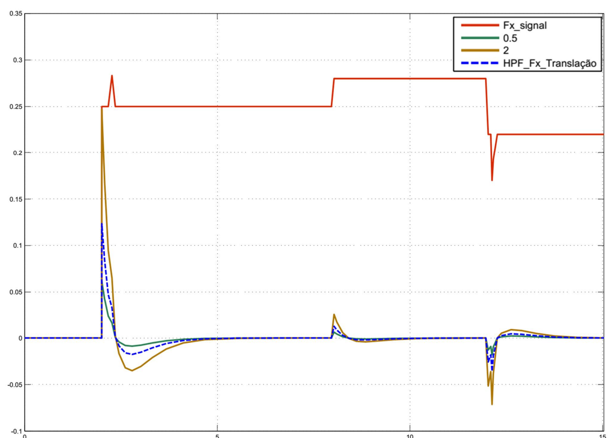


Figure 14. Changes in the numerator's equation of the second order high-pass Washout filter translational channel.

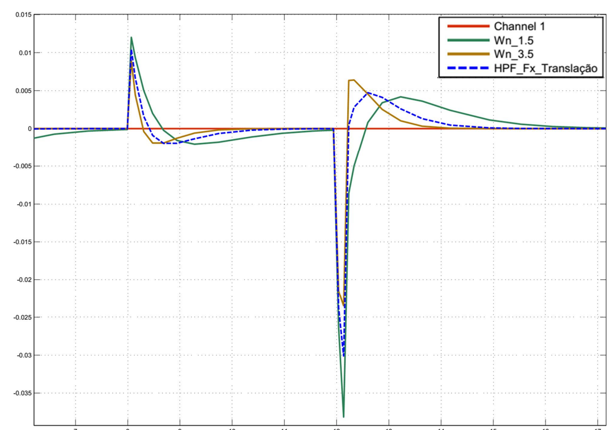


Figure 15. Chances the values of natural frequency "Wn" of the second order high-pass Washout filter translational channel.

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