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I. Abstract

Telban and Cardullo [1] have developed and successfully implemented the non-linear optimal motion cueing algorithm at the Visual Motion Simulator (VMS) at the NASA Langley Research Center in 2005. The latest version of the non-linear algorithm performed filtering of motion cues in all degrees-of-freedom except for pitch and roll. This manuscript describes the development and implementation of the non-linear optimal motion cueing algorithm for the pitch and roll degrees of freedom. Presented results indicate improved cues in the specified channels as compared to the original design.

To further advance motion cueing in general, this manuscript describes modifications to the existing algorithm, which allow for filtering at the location of the pilot's head as opposed to the centroid of the motion platform. The rational for such modification to the curing algorithms is that the location of the pilot's vestibular system must be taken into account as opposed to the off-set of the centroid of the cockpit relative to the center of rotation alone. Results provided in this report suggest improved performance of the motion cueing algorithm.

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II. Contents

II. List of Tables

II. List of Figures

III. Nomenclature

In order to be consistent with the original non-linear optimal algorithms developed report by Telban and Cardullo [1], similar nomenclature was adopted in the current report.

Symbols

$\mathbf{a}$	acceleration $\mathbf{a} = \begin{bmatrix} a_x & a_y & a_z \end{bmatrix}^{\mathbf{T}}$
$\mathbf{A}_\mathrm{j}$	coordinates of the upper bearing block of the j-th actuator
$\mathbf{B}_\mathrm{j}$	coordinates of the lower bearing block of the j-th actuator
A, B, C, D, H	matrices of the state-space model of a control system
$\mathbf{A}'$	system matrix of the standard form optimal control system
$d, e, \delta, \gamma, \lambda$	NASA adaptive algorithm washout parameters
E	objective function or energy norm for neurocomputing approach
e	pilot sensation error
Fr	reference frame
f	specific force
$\hat{f}$	sensed specific force
G_O, G_S	gain sensitivities in the otolith and semicircular canals models
g	acceleration due to gravity
J	system cost function
K	state feedback gain matrix
l_j	length of the j-th motion platform actuator
$\mathbf{L}_\mathrm{SI}$	transformation matrix from simulator into inertial frame

$\mathbf{P}$	solution of the algebraic Riccati equation
$\mathbf{Q}$, $\mathbf{R}$, $\mathbf{R}_d$	weighting matrices in a cost function (tracking form)
$\mathbf{Q}_2$	weighting matrix for nonlinear algorithm control law
$\mathbf{R}_1', \mathbf{R}_2, \mathbf{R}_{12}$	weighting matrices in a cost function (standard form)
$\mathbf{R}$	radius vector
s	Laplace variable
$\mathbf{T}_S$	transformation matrix from angular velocity to Euler angle rates
T_0, T_1, T_2, T_3, T_4	coefficients in the semicircular canal sensation model
$\mathbf{u}$	input to a control system
$\mathbf{u}'$	input to the standard form optimal control system
$\mathbf{v}$	error output of neurocomputing solver
$\mathbf{w}$	white noise
$\mathbf{W(s)}$	optimal algorithm transfer function matrix
$\mathbf{x}$	system state vector
$\mathbf{y}$	desired state space system output
$\mathbf{z}$	excitatory input signal for neurocomputing system
α	prescribed degree of nonlinearity for nonlinear algorithm
$\boldsymbol{\beta}$	Euler angles $\boldsymbol{\beta} = \begin{bmatrix} \phi & \theta & \psi \end{bmatrix}^{\mathbf{T}}$
$\boldsymbol{\delta}$	pilot control input vector
γ	filtered white noise break frequency
μ	learning parameter for neurocomputing solver
τ	time constants in the semicircular and otolith sensation models
ρ	density of the otoconial membrane

$\boldsymbol{\omega}$	angular velocity about the body frame $\boldsymbol{\omega} = \begin{bmatrix} p & q & r \end{bmatrix}^{\mathbf{T}}$
$\hat{\boldsymbol{\omega}}$	sensed angular velocity

Subscripts

Subscripts indicate to what the main symbol is related.

$(\ )_{\mathrm{A}}$	aircraft
$(\ )_{\mathrm{CG}}$	center of gravity of aircraft
$(\ )_{\mathrm{d}}$	simulator states included in the cost function
$(\ )_{\mathrm{e}}$	sensation or perceptual error
$(\ )_{\mathrm{I}}$	inertial reference frame
$(\ )_{\mathrm{j}}$	j-th actuator of the motion platform
$(\ )_{\mathrm{n}}$	white noise input states
$(\ )_{\mathrm{OTO}}$	otolith model
$(\ )_{\mathrm{PS}}$	pilot station
$(\ )_{\mathrm{PA}}$	pilot in the aircraft
$(\ )_{\mathrm{S}}$	simulator
$(\ )_{\mathrm{SCC}}$	semicircular canals sensation model
$(\ )_{\mathrm{ST}}$	simulator tilt coordination channel
$(\ )_{\mathrm{VEST}}$	human vestibular system
$(\ )_{\mathrm{VIS}}$	human visual system
$(\ )_{\mathrm{x,y,z}}$	x, y, or z component
$(\ )_{\alpha}$	relates to system with nonlinearity

Superscripts

Superscripts indicate which reference frame the main symbol is in

$(\ )^A$	in aircraft reference frame Fr_A
$(\ )^I$	in inertial reference frame Fr_I
$(\ )^S$	in simulator reference frame Fr_S

1. Introduction

This report documents the modifications to the NASA Non-Linear Optimal Motion Cueing Algorithm. The report consists of two major parts.

The first part describes modifications to the non-linear optimal algorithm, which are needed in order to perform filtering at the pilot station location as opposed to the original design of the algorithm where filtering was done at the centroid of the motion platform of the simulator. The essence of such a modification is in shifting the origin of the simulator attached reference frame from the centroid of the motion platform to wherever the location of the pilot station is. It could be the pilot’s head or pilot’s abdomen for instance. The new algorithm evaluation is also presented.

The second part of the report describes the development of the non-linear optimal filters for the additional two rotational degrees of freedom such as pitch and roll. In the original design of the algorithm only scaling and limiting was implemented for these rotational degrees of freedom. Note, that for the yaw channel the nonlinear washout filter was successfully implemented by Telban and Cardullo [1]. This report also delivers the FORTRAN code necessary for successful implementation of these algorithms on the NASA Langley Visual Motion Simulator (VMS).

It is assumed that the reader is familiar with the original work on development of the non-linear optimal algorithm performed by Telban and Cardullo [1]. For that reason some of the sections of the report are relatively concise.

2. Background

Figure 2.1 illustrates the basic vehicle simulator structure. As one can see, the motion cueing algorithm plays an essential part in the entire simulator architecture. The prime objective of any motion cueing algorithm is to provide a human operator with an array of cues, which will evoke behavior consistent with that in the real aircraft. It is obvious that due to some physical limitations none of the existing ground simulators are capable of delivering that 100%. Hence, motion cueing algorithms are designed to “trick” a person into believing that he/she is experiencing cues similar to those in a real flight. The latest innovation in this area is the non-linear optimal algorithm designed by Robert Telban and Frank Cardullo [1]. This chapter is dedicated to describing basic concepts of the non-linear washout algorithm. However, for better understanding of the non-linear algorithm, the description of the linear optimal algorithm is given first. Some mathematical aspects of on-line implementation are addressed in this chapter along with the description of the human perceptual models utilized in the non-linear as well as lineal optimal algorithms.

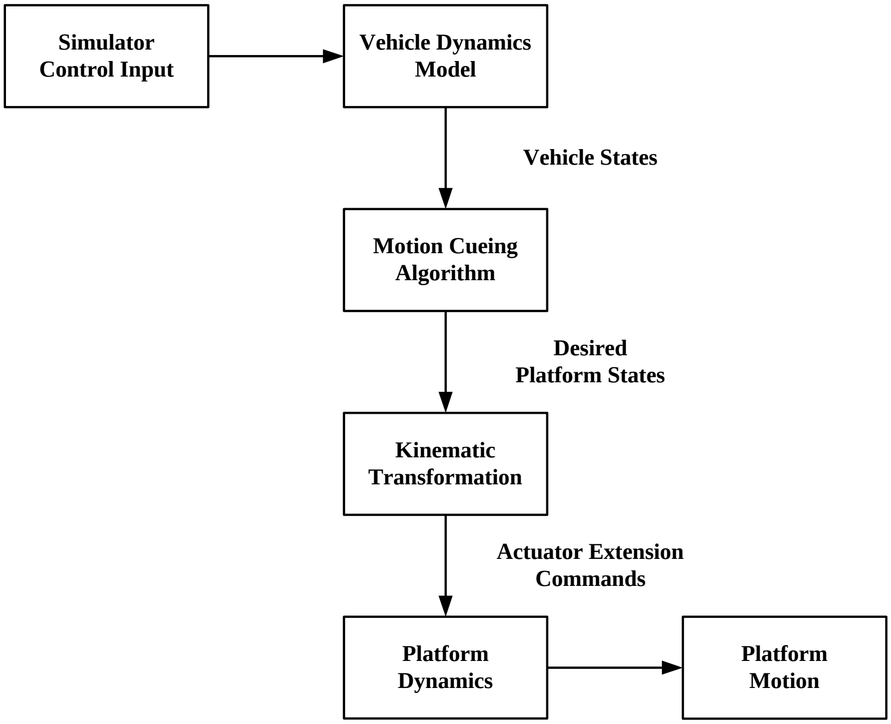


Figure 2.1. Vehicle simulator structure. Adopted from Telban and Cardullo [1]

2.1. Simulator geometry and reference frames

There are four reference frames involved in algorithm design: aircraft center of gravity reference frame (RF), Fr_{CG}, aircraft RF, Fr_A, simulator RF, Fr_S, and the inertial RF, Fr_I. Figure 2.2 illustrates these RFs as they are oriented in space and with respect to each other. It can be seen that Fr_{CG} has its origin in the center of gravity of the aircraft. Fr_S is attached to the centroid of the upper motion platform of the simulator. Zs is directed downward and perpendicular to the plane of the motion platform. Xs is looking forward, whereas Ys is pointing toward the pilot's right hand side. Fr_A is associated with the similar point in the aircraft cockpit as Fr_S on the simulator platform. All three RFs are parallel to each other. The inertial RF Fr_I is attached to the simulator motion system base. Fr_I is oriented in such a way that Z_I is parallel to gravity vector and Y_I pointing to the right with respect to the simulator operator.

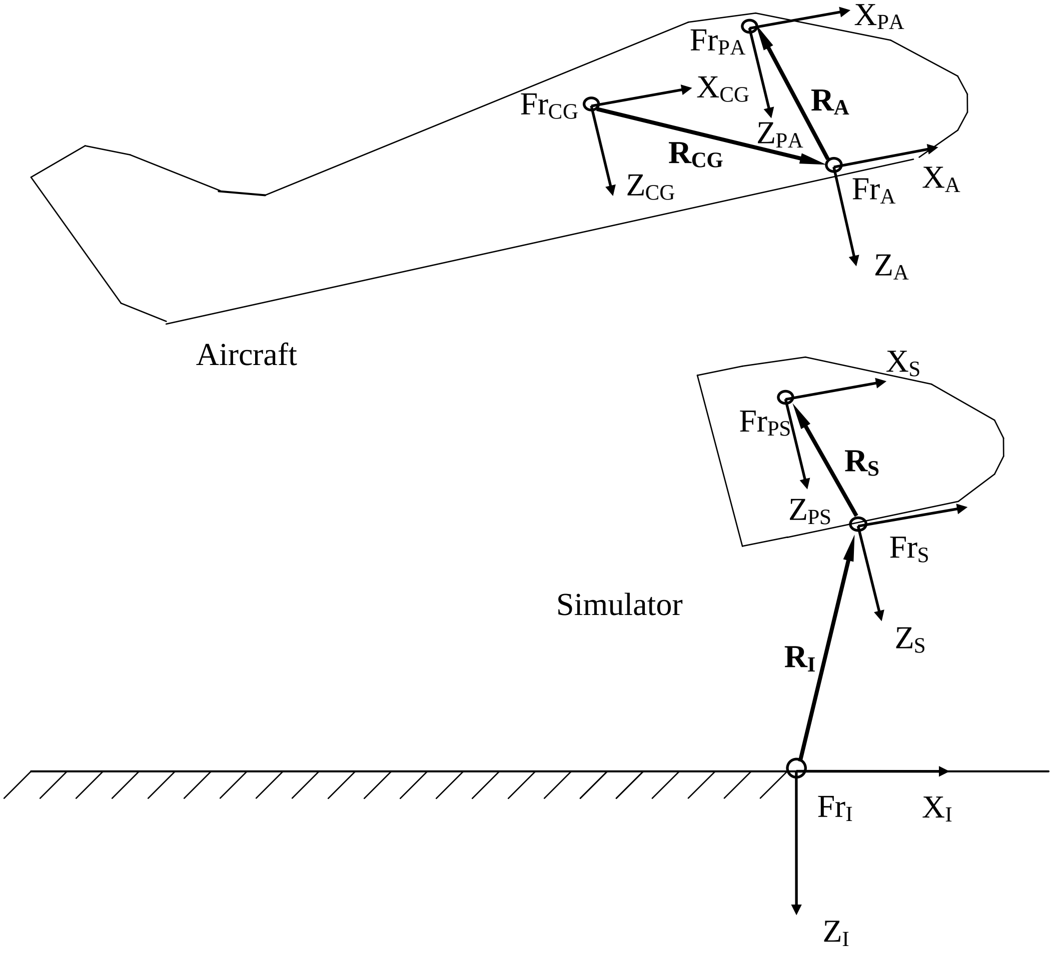


Figure 2.2. Reference frames used in the algorithm and their mutual orientation. Adopted from Telban and Cardullo [1]

The NASA Langley VMS motion system is a six degrees of freedom synergistic type device. The geometry of this motion system is shown in Figure 2.3.

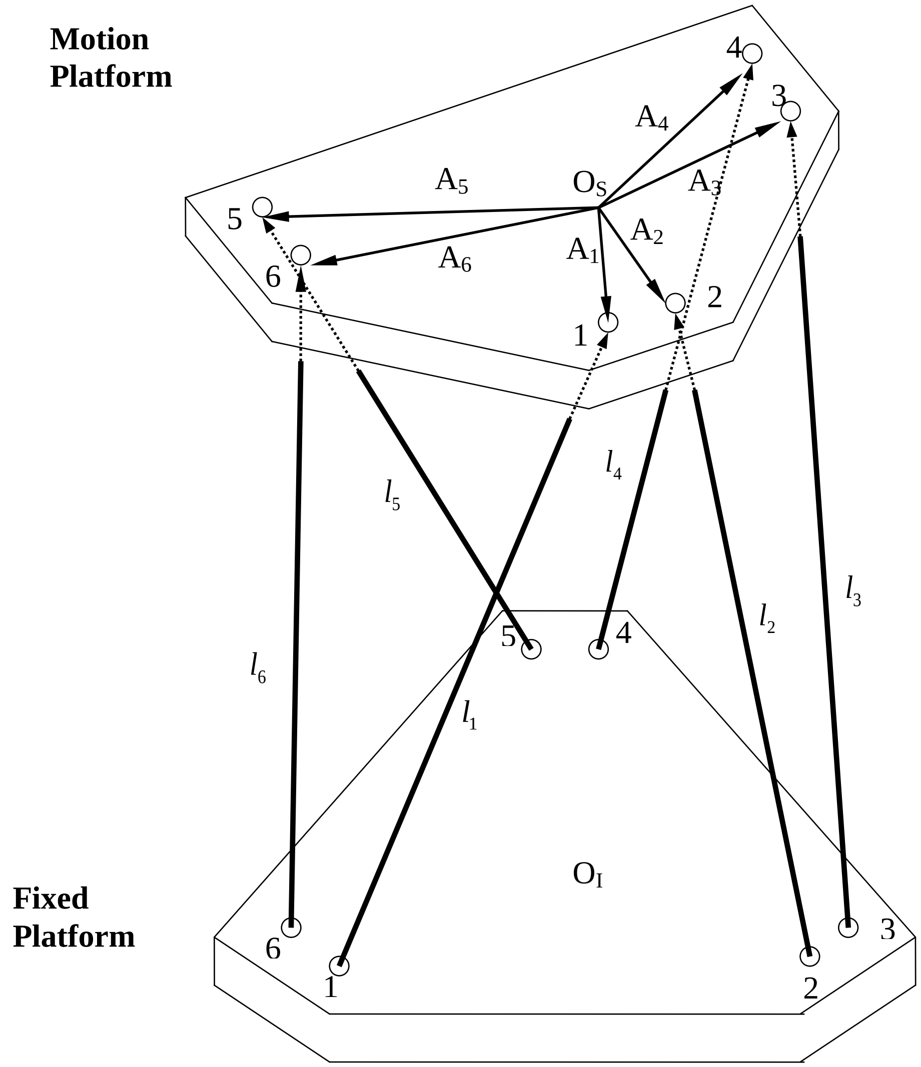


Figure 2.3. VMS motion system geometry. Adapted from Telban and Cardullo [1]

2.2. Human perceptual system models

Another characteristic of this motion cueing algorithm is that it incorporates a model of the human vestibular system, with the new semicircular canal and otoliths models. A new integrated visual-vestibular perception model is also involved in the design. Note that the models of semicircular canals, otoliths and visual-vestibular interaction constitute the perceptual model of a pilot. Figure 2.6 illustrates how such a model falls into the entire concept of washout filters.

2.2.1. Semicircular canals

The semicircular canals are responsible for sensing angular motion. For the implementation into the linear optimal as well as nonlinear optimal algorithms the following mathematical model of the semicircular canals was presented [1]:

$$\frac{\phi_c(s)}{\alpha(s)} = K_{SCC}\left[\frac{\tau_a s}{(1+\tau_a s)}\right]\left[\frac{(1+\tau_L s)}{(1+\tau_1 s)(1+\tau_2 s)}\right], \tag{2.1}$$

where $\phi_c(s)$ is the deflection of the cupula (a leaf-like structure in the semicircular canals, which deflects if the head is accelerated or decelerated) and $\alpha(s)$ is the stimulus acceleration. This model takes into account both the semicircular canal dynamics and neural transduction dynamics. For implementation into the linear optimal and non-linear optimal cueing algorithms, angular velocity is employed as a stimulus, requiring the following transfer function:

$$\frac{\hat{\omega}(s)}{\omega(s)} = 5.73\frac{80s}{(1+80s)}\frac{(1+0.06s)}{(1+5.73s)(1+0.005s)}, \tag{2.2}$$

where $\omega(s)$ and $\hat{\omega}(s)$ are stimulus and sensed angular velocities respectively.

Note that for the online implementation of the algorithm, a reduced form of the transfer function was used, which is given in equation (2.3)

$$\frac{\hat{\omega}(s)}{\omega(s)} = 5.73\frac{80s}{(1+80s)(1+5.73s)}, \tag{2.3}$$

2.2.2. Otoliths

The otolith organs are the elements of the vestibular system that provide linear motion sensation in humans and mammals. These organs are responsive to specific force, responding to both linear acceleration and tilting of the head with respect to the gravity vector. Telban and Cardullo [1] proposed the following otolith model, which provides the relationship between the sensed response and the specific force stimulus:

$$\frac{\hat{f}}{f} = K_{OTO} \frac{(\tau_L s + 1)}{(\tau_1 s + 1)(\tau_2 s + 1)}, \tag{2.4}$$

where K_{OTO} = 0.4, τ_1 = 5 sec, τ_2 = 0.016 sec, and τ_L = 10 sec. For implementation into the motion cueing algorithms, Eq. 2.4 can be rewritten as

$$\frac{\hat{f}}{f} = K'_{OTO} \frac{(s + A_0)}{(s + B_0)(s + B_1)}, \tag{2.5}$$

where $A_0 = 1/\tau_L$, $B_0 = 1/\tau_1$, $B_1 = 1/\tau_2$, and $K'_{OTO} = K_{OTO}\tau_1\tau_2 / \tau_L$.

2.2.3. Human Vestibular model

The following section illustrates how the otolith and semicircular canals models are integrated together for further utilization in the nonlinear optimal washout algorithm. According to the formulation of the non-linear washout algorithm, which will be presented in the last section of this chapter, the human perceives the signal **u,** comprised of both the angular velocity and translational accelerations:

$$u = \begin{bmatrix} \dot{\theta} \\ a_x \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}. \tag{2.6}$$

The semicircular canal model (Eq. (2.2)) can be rewritten in a more formal way:

$$\hat{\dot{\theta}} = \frac{G_{SCC}\tau_1\tau_a s^2\left(1+\tau_L s\right)}{\left(1+\tau_a s\right)\left(1+\tau_1 s\right)\left(1+\tau_2 s\right)} u_1, \tag{2.7}$$

where values for semicircular canals time constants τ_1, τ_2, τ_a, and τ_L are given in Eq. 2.2, and G_{SCC} is the angular velocity threshold that scales the response to threshold units. Eq. 2.7, in turn, can be rewritten as

$$\hat{\dot{\theta}} = \frac{T_4 s^3 + T_3 s^2}{s^3 + T_2 s^2 + T_1 s + T_0} u_1, \tag{2.8}$$

where:

$$T_0 = \frac{1}{\tau_a\tau_1\tau_2},\ T_1 = \frac{\tau_a + \tau_1 + \tau_2}{\tau_a\tau_1\tau_2},\ T_2 = \frac{\tau_1\tau_2 + \tau_a\left(\tau_1 + \tau_2\right)}{\tau_a\tau_1\tau_2},\ T_3 = G_{SCC}/\tau_2,\ \text{and}\ T_4 = G_{SCC}\tau_L/\tau_2,$$

and can be defined in state space notation as

$$\begin{aligned} \dot{\mathbf{x}}_{\mathbf{SCC}} &= \mathbf{A}_{\mathbf{SCC}}\mathbf{x}_{\mathbf{SCC}} + \mathbf{B}_{\mathbf{SCC}}\mathbf{u} \\ \hat{\dot{\theta}} &= \mathbf{C}_{\mathbf{SCC}}\mathbf{x}_{\mathbf{SCC}} + \mathbf{D}_{\mathbf{SCC}}\mathbf{u}, \end{aligned} \tag{2.9}$$

which in observer canonical form is,

$$\mathbf{A}_{\mathbf{SCC}} = \begin{bmatrix} -T_2 & 1 & 0 \\ -T_1 & 0 & 1 \\ -T_0 & 0 & 0 \end{bmatrix},\ \mathbf{B}_{\mathbf{SCC}} = \begin{bmatrix} T_3 - T_2T_4 & 0 \\ -T_1T_4 & 0 \\ -T_0T_4 & 0 \end{bmatrix},\ \mathbf{C}_{\mathbf{SCC}} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix},\ \text{and}\ \mathbf{D}_{\mathbf{SCC}} = \begin{bmatrix} T_4 & 0 \end{bmatrix}.$$

On the other hand, the otolith model (Eq. 2.4) can be redefined in a state space notion as:

$$\begin{aligned} \dot{\mathbf{x}}_{\mathbf{OTO}} &= \mathbf{A}_{\mathbf{OTO}}\mathbf{x}_{\mathbf{OTO}} + \mathbf{B}_{\mathbf{OTO}}\mathbf{u} \\ \hat{f}_x &= \mathbf{C}_{\mathbf{OTO}}\mathbf{x}_{\mathbf{OTO}} + \mathbf{D}_{\mathbf{OTO}}\mathbf{u}, \end{aligned} \tag{2.10}$$

where $\mathbf{x}_{\mathbf{OTO}}$ are the otoliths states, and

$$\mathbf{A}_{\mathbf{OTO}} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -b & -a & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -b & -a \end{bmatrix},\ \mathbf{B}_{\mathbf{OTO}} = \begin{bmatrix} c & 0 \\ d - ac & 0 \\ e & 0 \\ 0 & f \\ 0 & h - af \end{bmatrix},$$

$$\mathbf{C}_{\mathbf{OTO}} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 \end{bmatrix}, \qquad \mathbf{D}_{\mathbf{OTO}} = \begin{bmatrix} -G_{OTO}K'_{OTO}R_{Sz} & 0 \end{bmatrix}.$$

The representations in Eq. 2.9 and 2.10 can be combined to form a single representation for the human vestibular model:

$$\begin{aligned}\dot{\mathbf{x}}_V &= \mathbf{A}_V\mathbf{x}_V + \mathbf{B}_V\mathbf{u} \\ \hat{\mathbf{y}}_V &= \mathbf{C}_V\mathbf{x}_V + \mathbf{D}_V\mathbf{u},\end{aligned} \tag{2.11}$$

where $\mathbf{x}_V$ and $\hat{\mathbf{y}}_V$ are, respectively, the combined states and sensed responses, and $\mathbf{A}_V$, $\mathbf{B}_V$, $\mathbf{C}_V$, and $\mathbf{D}_V$ represent the vestibular models as one set of state equations:

$$\mathbf{A}_V = \begin{bmatrix} \mathbf{A}_{SCC} & \mathbf{0} \\ \mathbf{0} & \mathbf{A}_{OTO} \end{bmatrix},\ \mathbf{B}_V = \begin{bmatrix} \mathbf{B}_{SCC} \\ \mathbf{B}_{OTO} \end{bmatrix},\ \mathbf{C}_V = \begin{bmatrix} \mathbf{C}_{SCC} & \mathbf{0} \\ \mathbf{0} & \mathbf{C}_{OTO} \end{bmatrix},\ \mathbf{D}_V = \begin{bmatrix} \mathbf{D}_{SCC} \\ \mathbf{D}_{OTO} \end{bmatrix}.$$

2.3. Linear Optimal Algorithm formulation

Before getting to the description of the non-linear optimal washout algorithm, some background information on the linear optimal algorithm is presented. Note that both algorithms are designed based on the same principles and concepts. The major differences are in real-time implementation of washout filters.

Figure 2.4 contains the block diagram of the linear optimal algorithm structure.

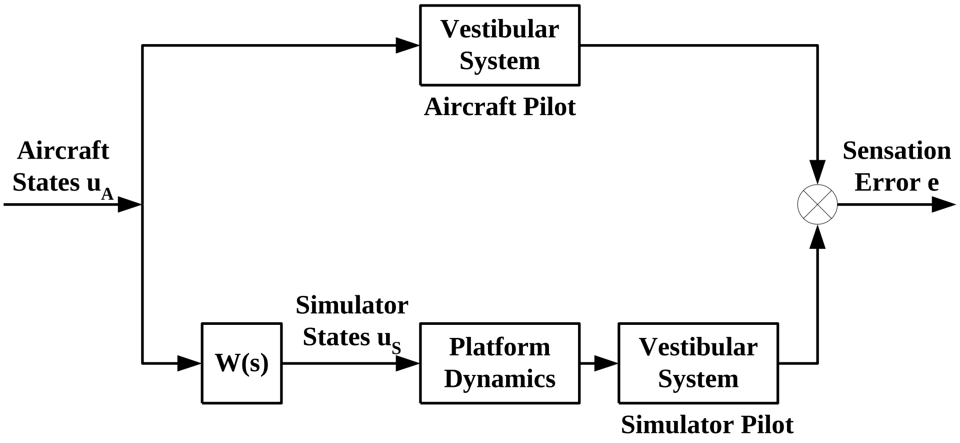


Figure 2.4. Linear Optimal Algorithm Structure. Adopted from Telban and Cardullo [1]

Since the entire purpose of the washout filters is to minimize the sensation error, the transfer function matrix **W(s)**, which relates the desired simulator motion input to the aircraft input, is to be determined. In other words the elements of **W(s)** are the coefficients of the washout filter. The linear optimal algorithm generates the desired transfer functions **W(s)** by solving the Riccati equation by an off-line program, which are then implemented on-line. Figure 2.5 illustrates how the linear optimal washout filters are implemented on-line.

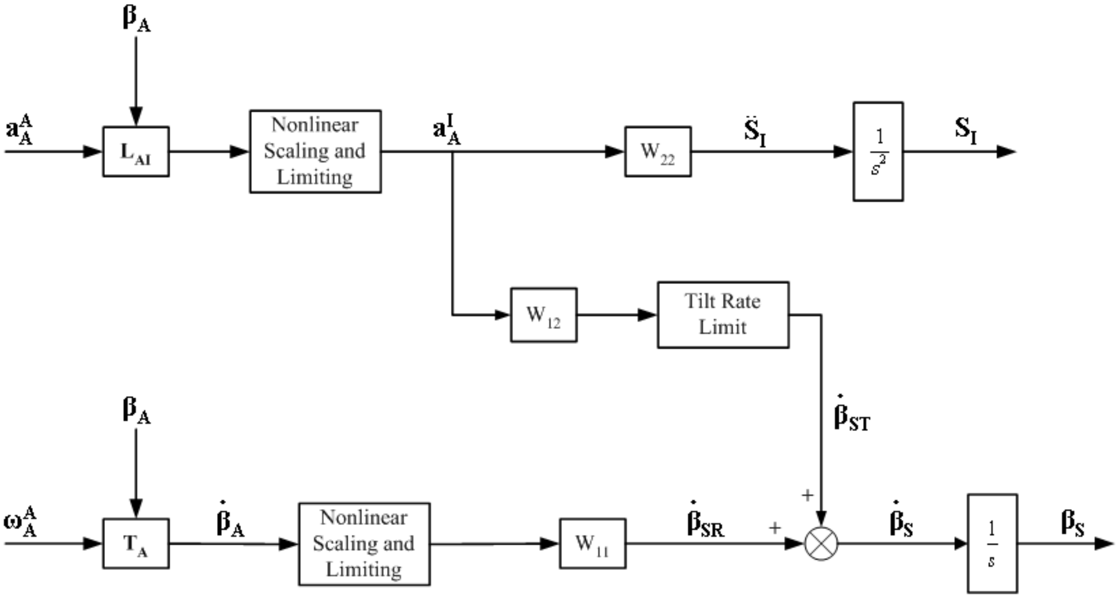


Figure 2.5. Optimal Algorithm Implementation for Longitudinal Mode. Adopted from Telban and Cardullo [1]

2.4. Non-linear Optimal Algorithm

The non-linear optimal algorithm is formulated in a similar fashion to that of the linear optimal algorithm, except for the differences in computing the matrix **W(s)**. The structure of the algorithm is shown in Figure 2.6.

As can be seen the solution to the Riccati equation, which was obtained offline in the linear optimal algorithm, is now implemented in real time, resulting in the necessary matrix for computing the desired non-linear optimal filters.

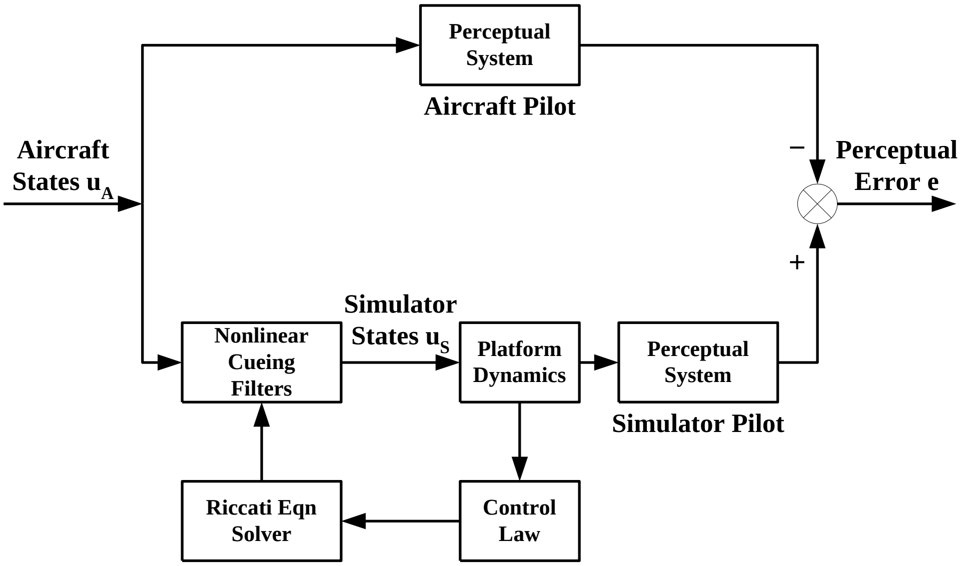


Figure 2.6. Non-linear Optimal Cueing Algorithm Structure. Adopted from Telban and Cardullo [1]

Figure 2.7 illustrates how the non-linear washout filter is formulated for the longitudinal mode.

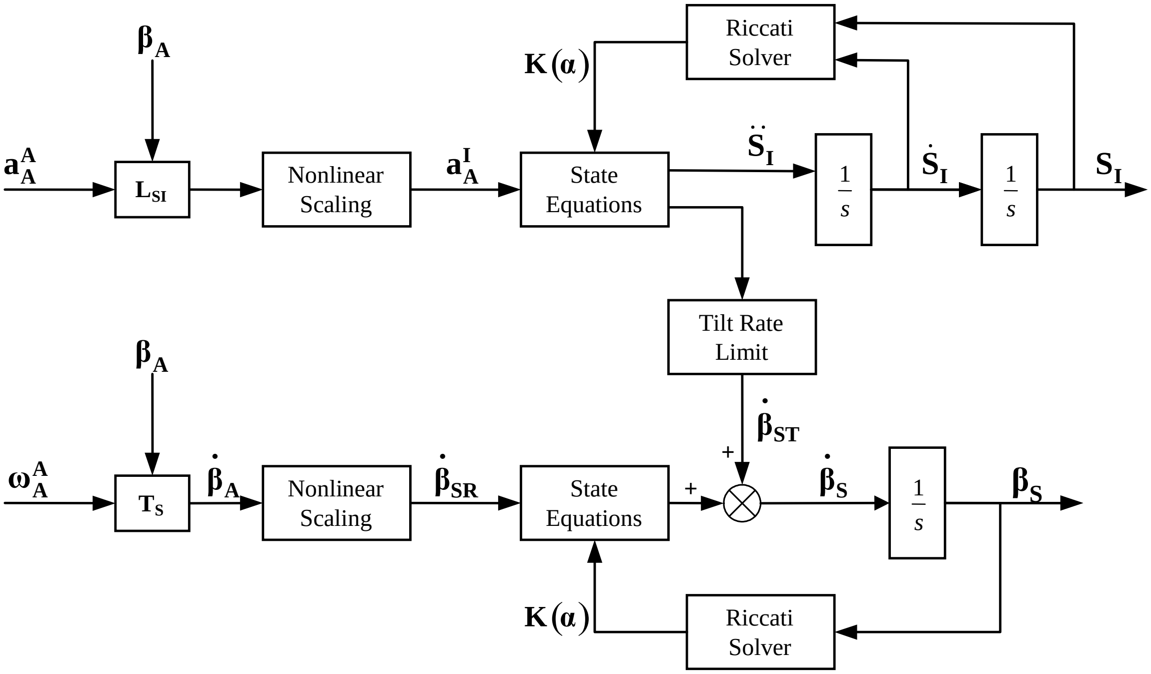


Figure 2.7. Nonlinear optimal algorithm implementation. Longitudinal mode. Adopted from Telban and Cardullo [1]

There are two separate filtering channels for translational and rotational degrees of freedom with the cross-feed path providing tilt coordination cues.

The aircraft acceleration is first transformed from the simulator attached RF to the inertial RF. The signal is then passed through the non-linear scaling and limiting block. The resulting signal then becomes an input to the “State Equations” block, from which the simulator translational acceleration is produced. This acceleration is integrated twice to produce the simulator translational position command S_I. Signals S_I and $\dot{S}_I$ form a feedback loop and serve as inputs to the “Riccati Solver” block. The solution to the Riccati equation is the matrix **K(α),** which is fed back to “State Equations” block.

The aircraft angular velocity ω_A^A is transformed to the Euler angular rate ($\dot{\beta}_A$). Next it is limited and scaled. A separate set of State equations is employed along with the Riccati solver. The resulting signal is β_S - the simulator angular position command. For the previous on-line implementation, however, the case of a unity-gain pitch (and roll) filter was implemented. Hence, Figure 2.7 can be redrawn as it is shown in Figure 2.8.

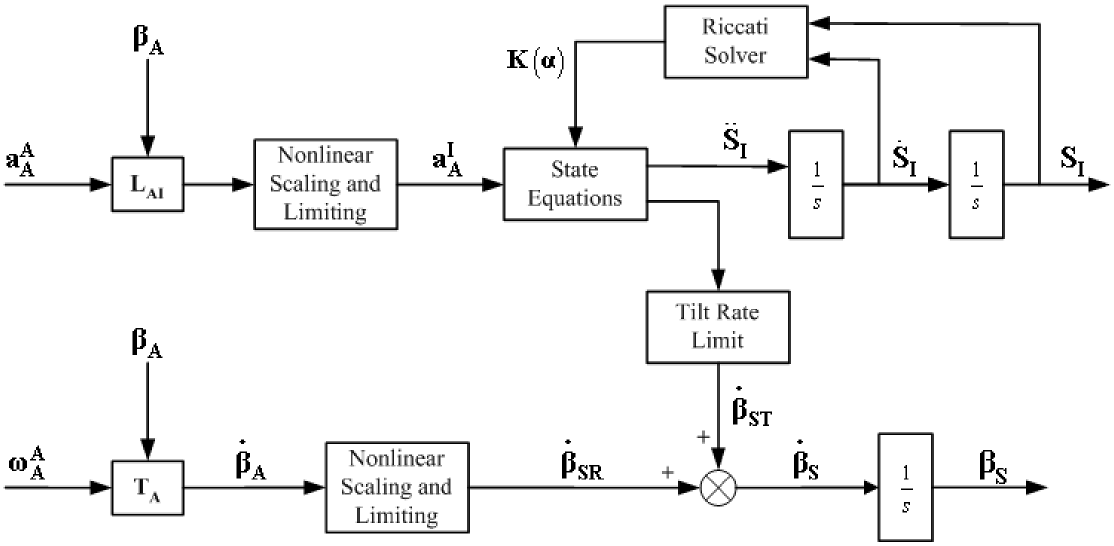


Figure 2.8. Nonlinear Algorithm Implementation with Unity-Gain Pitch Filter. Adopted from Telban and Cardullo [1].

The simulator translational S_I and angular β_S position commands are then transformed from degrees-of-freedom space to simulator actuator space. Actuator commands are then generated to achieve the desired simulator platform motion.

As one might already be aware, solving the Riccati equation in real time is a computationally challenging task. Conventionally a Newton-Raphson technique is utilized for that purpose. The main drawback is that it involves a matrix inversion, which can result in singular solutions for ill-conditioned systems. The non-linear optimal algorithm uses the structured neural network to solve the Riccati equation in real time. The main advantage of the neural computing approach over the Newton-Raphson is speed due to the fact that neither matrix inversion nor computation of the Jacobian matrix as a Kronecker product is required. Moreover, the problem of having a singular solution eliminates itself, since no matrix inversion is involved.

3. Development of transformation equations for cues determined at pilot's station

3.1. Modifications of the original nonlinear optimal algorithm

Before continuing with this section of the report a new terminology shall be introduced. Pilot's Station (PS) is the point in the simulator cockpit where washout filters are applied. In the original design of the non-linear optimal algorithm filtering was applied at the origin of the simulator reference frame F_{rs}. This report proposes modification to the original non-linear algorithm, which position the PS at the location of the pilot's head. The rational here is such that filtering must be performed at the location of the pilot's vestibular apparatus.

3.1.1. Filtering at Pilot's Station.

According to the theory of washout filter development the location where the actual "filtering" is being performed is associated with the location of the origin of the simulator reference frame. As has been previously mentioned, in the original design of the algorithm the location of the origin of the simulator attached RF is at the centroid of the upper motion platform. Hence the essence of applying non-linear washout filters at the PS location as opposed to the centroid of the upper joint bearings of the motion platform is, in fact, the shift of the simulator related reference frame Fr_S from the motion platform to wherever the PS is located. The given shift vector R_{SS} (Figure 3.1) has the following coordinates in Fr_S : [0.0254, -0.653, -2.1946] (unique to the NASA Langley Visual Motion Simulator, VMS). The vectors A_{iS} connect the origin of the PS to each platform attach point. B_{jS} vectors will change as well. These vectors are different from the original implementation and are computed by means of a simple coordinate transformation. Table 3.1 contains coordinates of A_{iS} vectors before and after the transformation.

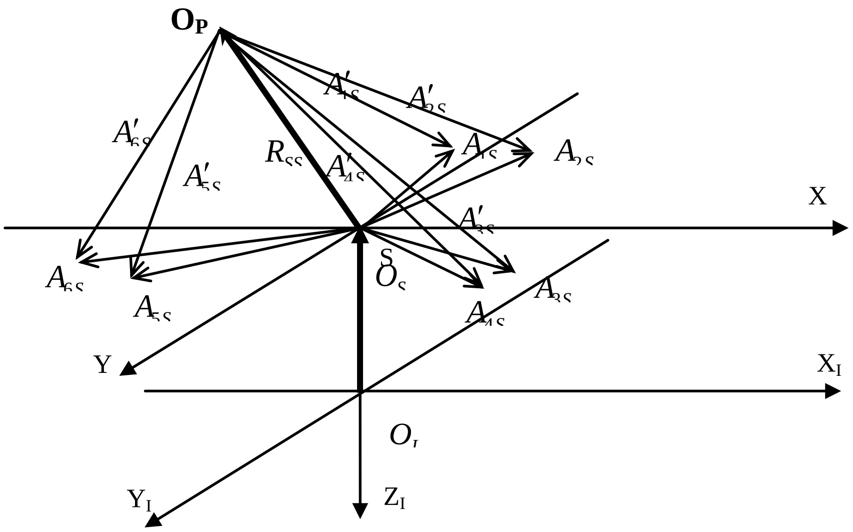


Figure 3.1. Geometrical interpretation of the Fr_S reference frame shift from O_S (centroid of the upper motion platform) to O_{PS} (pilot station)

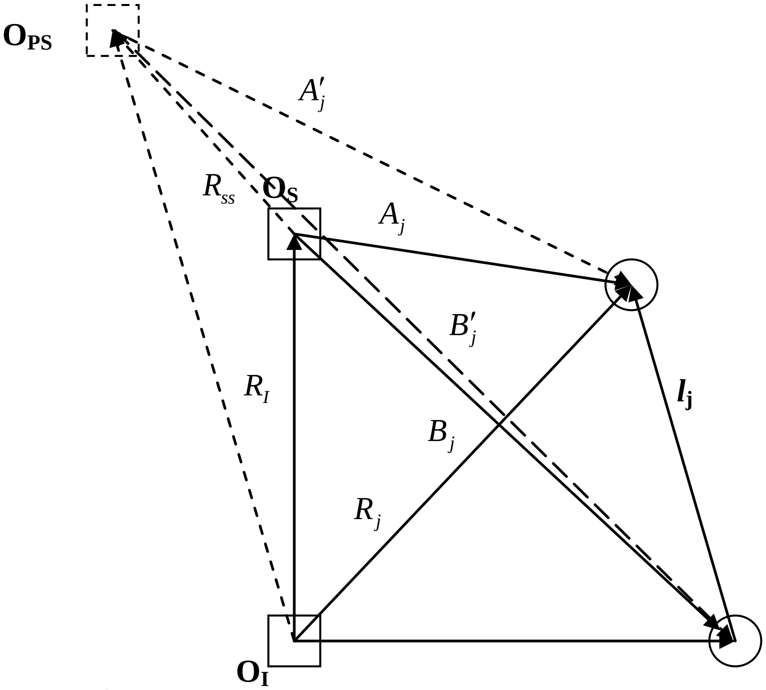


Figure 3.2. Vectors of the j-th actuator

Figure 3.2 demonstrates the relative location of the upper and lower ball joint bearings of the *j-th* actuator of the simulator. It is quite obvious that when the location of the Fr_S origin is shifted from O_S to O_{PS}, R_I and A_j (along with B_j) are changed accordingly.

Table 3.1. Upper and Lower ball joints coordinates

Original		*Modified*	
Vector	*coordinates*	*Vector*	*coordinates*
A_1	[2.1117179, 0.0762, 0.0]	A_1'	[2.0863179, 0.7112, 2.1946]
A_2	[2.1117179, –0.0762, 0.0]	A_2'	[2.0863179, 0.5588, 2.1946]
A_3	[-0.98986594, –1.8669, 0.0]	A_3'	[-1.01526594, –1.2319, 2.1946]
A_4	[-1.12184942, –1.7907, 0.0]	A_4'	[-1.14724942, –1.1557, 2.1946]
A_5	[-1.12184942, 1.7907, 0.0]	A_5'	[-1.14724942, 2.4257, 2.1946]
A_6	[-0.98986594, 1.8669, 0.0]	A_6'	[-1.01526594, 2.5019, 2.1946]
B_1	[1.5021, 1.9812, 2.5806]	B_1'	[1.4767, 2.6162, 4.77524]
B_2	[1.5021, -1.9812, 2.5806]	B_2'	[1.4767, -1.3462, 4.77524]
B_3	[0.9647, -2.2914, 2.5806]	B_3'	[0.9898, -1.6564, 4.77524]
B_4	[-2.4668, -0.3102, 2.5806]	B_4'	[-2.4922,0.3247, 4.77524]
B_5	[-2.4668, 0.3102, 2.5806]	B_5'	[-2.4922, 0.9452, 4.77524]
B_6	[0.9647, 2.9214, 2.5806]	B_6'	[0.9393, 2.9264, 4.77524]

The reader should be aware that the data presented above are applicable solely to the VMS facility at NASA Langley.

3.1.2. Variable flow

According to the code available in the original NASA report by Telban and Cardullo [1] it is clear that the accelerations used as inputs to the non-linear washout filters are computed at the origin of the Fr_A, i.e. at the centroid of the upper motion platform. The specific forces at the PS are then calculated utilizing the knowledge of the simulator cockpit geometry. Therefore, the variable flow (accelerations in particular) can be presented in a form of the following block diagram (Figure 3.3).

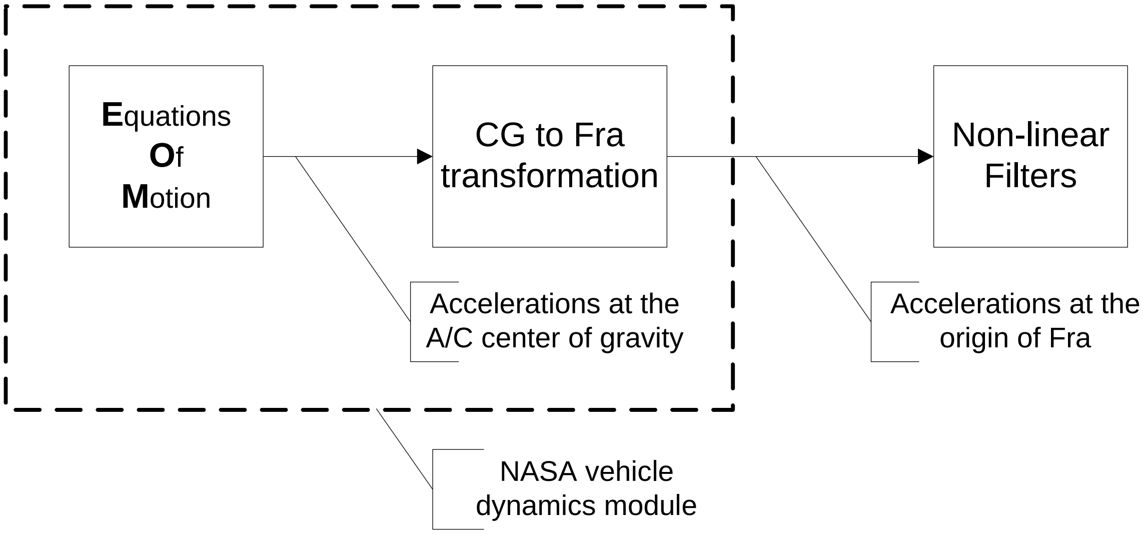

Equations
Of
Motion
CG to Fra transformation
Non-linear Filters
Accelerations at the A/C center of gravity
Accelerations at the origin of Fra
NASA vehicle dynamics module

Figure 3.3. Variables (accelerations) flow

The following is a summary of changes to the original design of the algorithm that had been done in order to perform filtering at the PS.

- An auxiliary block had been introduced into the block diagram of the online implementation of the original non-linear washout filter. This block calculates the a/c acceleration at the location of the pilot's station in the aircraft reference frame (Fr_A). The modified version of the online implementation block diagram is given in Figure 3.4. The geometrical location of the PS in the VMS cockpit is known and defined by the vector $R_{SS} = [0.0254, -0.653, -2.1946]$ in meters.
- Vectors, connecting the origin of the Fr_S and the joints of the upper motion platform had been recalculated, taking into account the shift of Fr_S from its former location at the centroid of the cockpit/upper motion platform to the new location at the pilot's head (see section 3.1.1.).

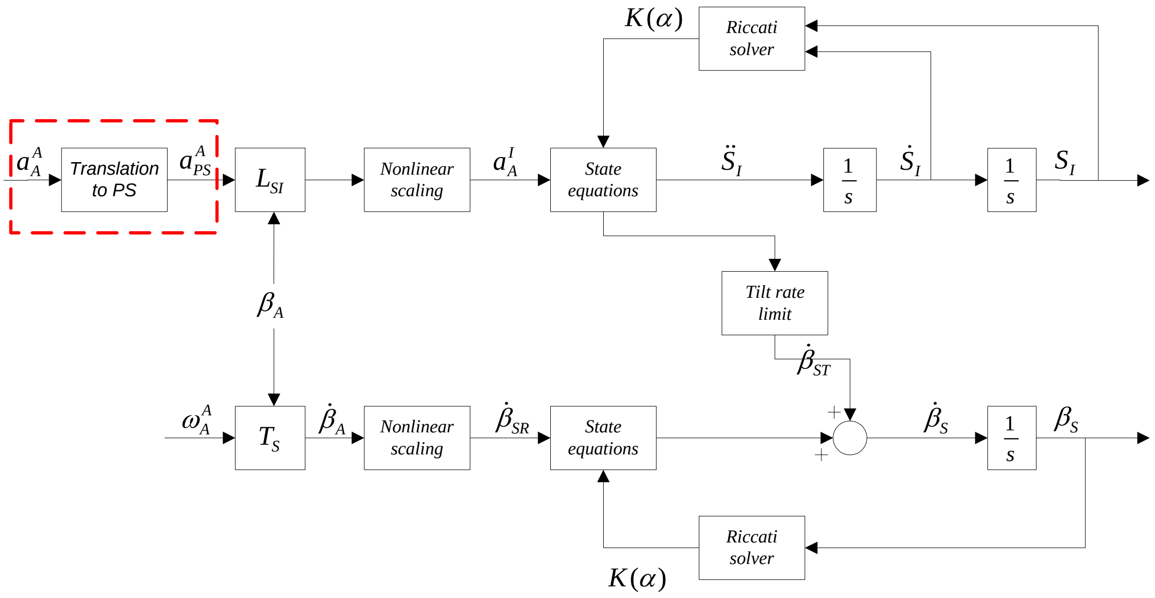


Figure 3.4. The modified version of the online implementation of the nonlinear washout filter (longitudinal channel)

3.1.3. Equations

The following are the equations for computing translational accelerations at the pilot station which are implemented in the "*Translation to PS*" block, in Figure 3.4.

$$\begin{aligned}
a_{xPS}^{\;A} &= a_{x\;A}^{\;A} - R_{ssx}(q^2+r^2) + R_{ssy}(pq-\dot r) + R_{ssz}(pr+\dot q)\\
a_{yPS}^{\;A} &= a_{y\;A}^{\;A} + R_{ssx}(pq+\dot r) - R_{ssy}(p^2+r^2) + R_{ssz}(qr-\dot p) \qquad (3.1)\\
a_{zPS}^{\;A} &= a_{z\;A}^{\;A} + R_{ssx}(pr-\dot q) + R_{ssy}(qr+\dot p) - R_{ssz}(p^2+q^2)
\end{aligned}$$

where $a_{PS}^A = [a_{xPS}^{\;A}, a_{yPS}^{\;A}, a_{zPS}^{\;A}]$, $a_A^A = [a_{xA}^{\;A}, a_{yA}^{\;A}, a_{zA}^{\;A}]$, $R_{ss} = [R_{ssx}, R_{ssy}, R_{ssz}]$, $\omega_A^A = [p, r, q]$, and $\dot\omega_A^A = [\dot p, \dot q, \dot r]$ respectively.

3.2. New algorithm evaluation

This section of the report presents the evaluation of the modified non-linear optimal washout algorithm. The evaluation is done in a form of a comparative analysis against the original non-linear optimal algorithm. Comparison is performed for 6 degrees of freedom (3 translational and 3 rotational) and is followed by a discussion.

Table 3.2 contains information on the degree of freedom and the corresponding type and characteristic of the input signal. In each case, the inputs are the accelerations m/s^2 for the translational and rad/s^2 for rotational degrees of freedom) measured at the aircraft centroid.

Table 3.2. Characteristics of the input signal for each degree of freedom

Degree of freedom	Input	Characteristics
Longitudinal (x-channel)	Ramp to step	Peak magnitude: 1 m/s^2 Slope: 3 m/s^2/s
Lateral (y-channel)	Half sine	Peak magnitude: 3 m/s^2 Duration: 5 s
Vertical (z-channel)	Pulse	Peak magnitude: 1 m/s^2 Duration: 10 s
Pitch	Pulse doublet	Magnitude: 0.1 rad/s^2 Duration: 5 s
Roll	Pulse doublet	Magnitude: 0.1 rad/s^2 Duration: 5 s
Yaw	Pulse doublet	Magnitude: 0.1 rad/s^2 Duration: 5 s

Appendix B contains a set of plots for each degree of freedom. Each set consists of the following graphs:

- Actuator extensions (6)
- Aircraft and Simulator Sensed Specific Force (3)
- Aircraft and Simulator Sensed Angular Rate (3)
- Platform Velocity in Inertial Coordinates (3)
- Desired and Actual Platform Displacement (3)
- Specific Force at Aircraft Pilot Head (3)
- Specific Force at Simulator Pilot Head (3)
- Aircraft Angular Rate (3)
- Platform Angular Rate (3)
- Aircraft Angular Position (3)
- Desired and Actual Platform Angular Position (3)
- Aircraft Acceleration at MB Centroid (3)

- Platform Acceleration at MB Centroid (3)

3.3. Discussions

In this section the discussion of the peculiarities of the motion platform behavior associated with applying of the washout filter at the PS will be presented. For that purpose the yaw channel was chosen. Figure 3.5 illustrates how the nonlinear filter for the yaw channel was implemented online.

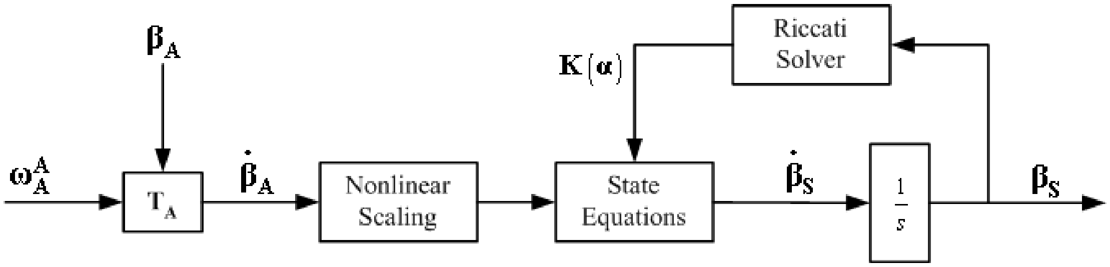


Figure 3.5. Nonlinear Algorithm Implementation for Yaw Mode

The characteristic feature of the yaw channel is that when excited there is no gravity alignment issue, which is associated with the longitudinal or lateral channel. In other words, there is no need to tilt the motion platform to produce the sustained acceleration cues.

The original nonlinear washout algorithm developed by Telban and Cardullo [1] did a very good job in simulating cues, inherent to a pure yaw motion of the aircraft. However, when the filtering is performed at the PS a few differences (compared to the original algorithm) in the behavior of the platform can be observed. For example, Figure 3.6 contains graphs for the aircraft and platform accelerations at the motion platform centroid.

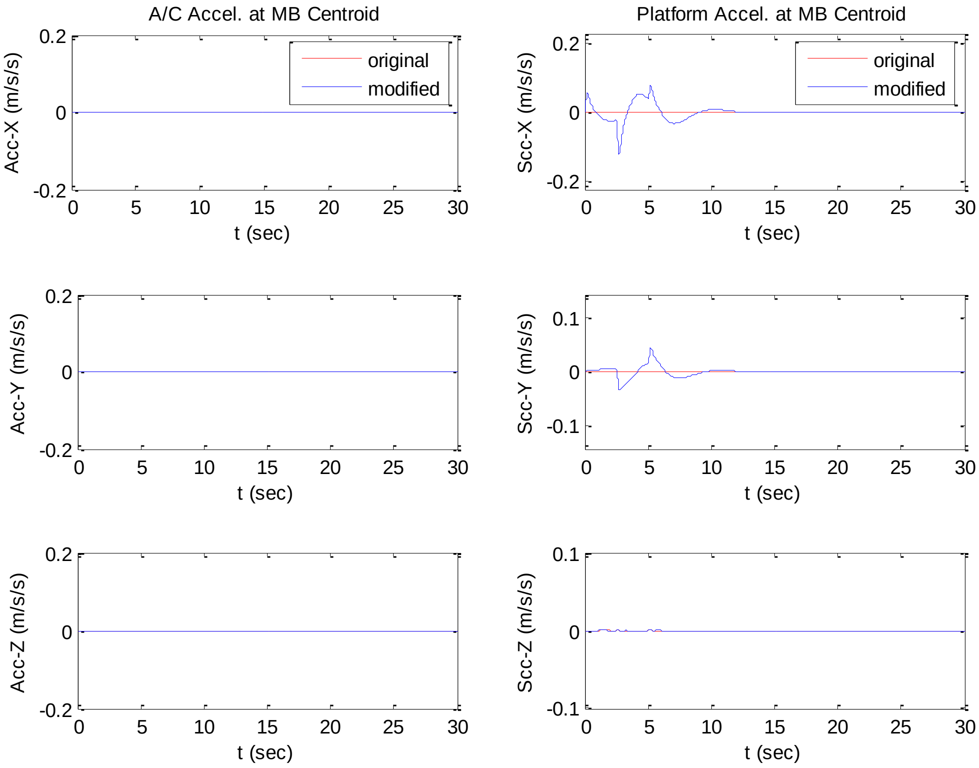


Figure 3.6. Aircraft and Platform accelerations at the centroid of the motion platform

It can easily be seen that accelerations in the X and Y channels are nonzero when filtering is done at the PS. If one looks at the physics of the yaw motion of the platform, it is possible to reason the presence of those accelerations. Figure 3.7 illustrates the geometry of the motion platform if observed from the top (Figure 3.1 if observed from the top). The Z axis of the Fr_A is aimed away from the reader and is perpendicular to the drawing, given that the origin of the Fr_A is placed at the centroid of the motion platform. Vector OA represents the XY component of the vector R_{ss}.

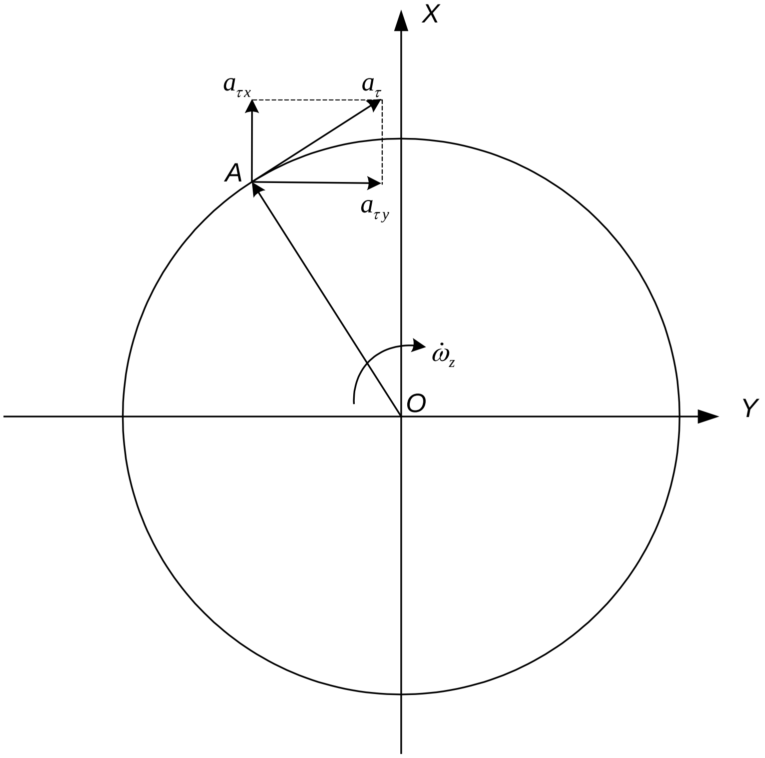


Figure 3.7. The XY plane of the F_{r_a}, when being placed at the centroid of the motion platform

Consider the clockwise rotation of the platform with the angular velocity $\dot{\omega}_z$. At point “A” this motion will result in the tangential acceleration a_τ. In Fr_A vector a_t has components $a_{\tau x}$ and $a_{\tau y}$. If filtering is performed at the PS, then accelerations $a_{\tau x}$ and $a_{\tau y}$ automatically form inputs to the translational and lateral channels of the washout algorithm. Which, in turn, results in the sway and surge motion of the platform (Figure 3.8).

One should also note that accelerations and angular rates resulting from this minor surge and sway motion of the platform is either on or below the perceptual threshold. Moreover, the modified algorithm resulted in better (closer to the aircraft) reproduction of the specific force (Figure 3.9).

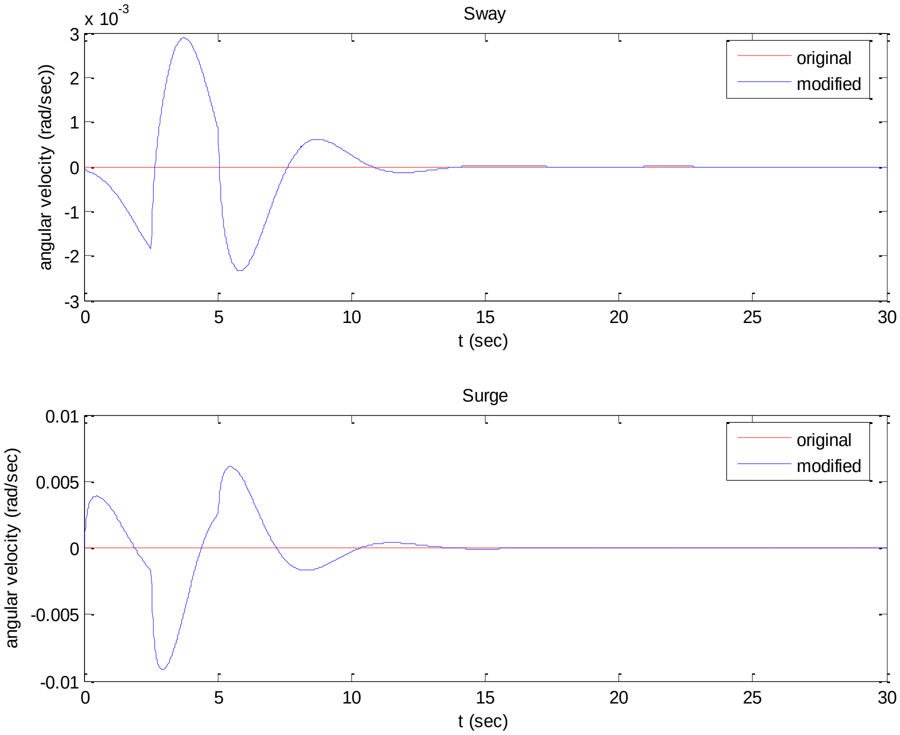


Figure 3.8. Tilt angular velocities for sway and surge channels

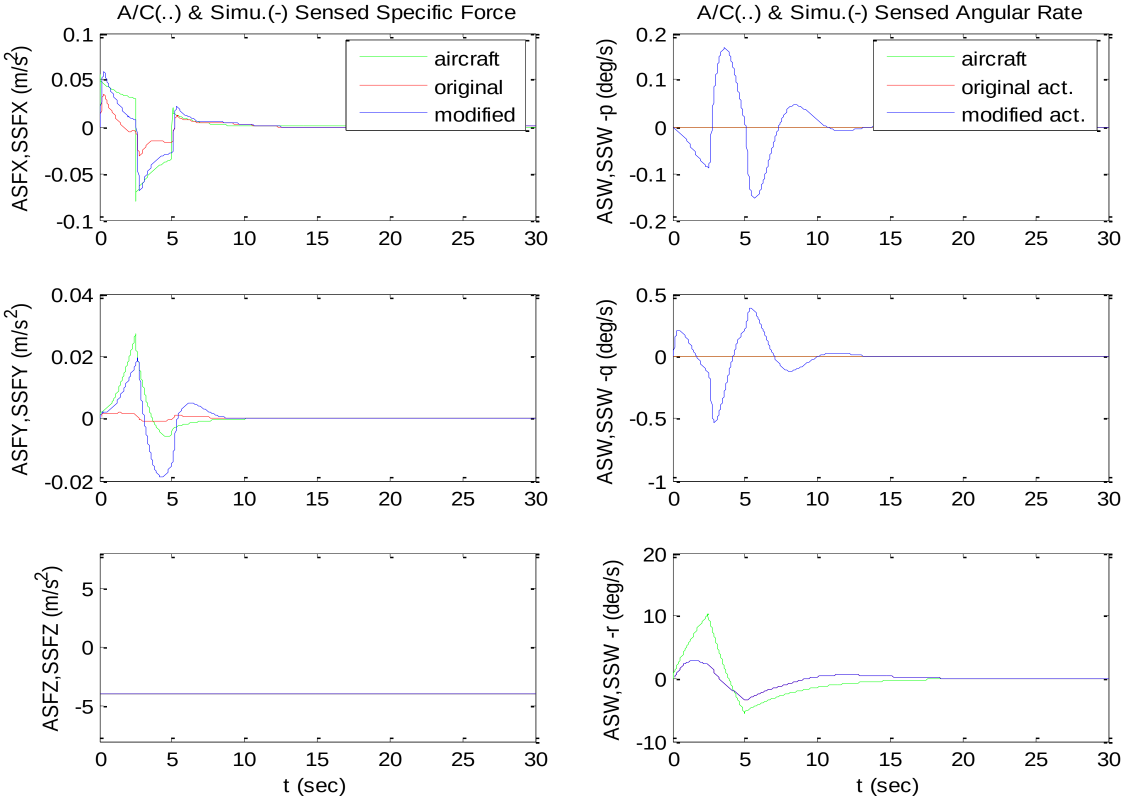


Figure 3.9. Aircraft and Simulator sensed Specific Forces and Angular Rates

4. Design and Development of Nonlinear Optimal Filters for Two Rotational Degrees of Freedom

4.1. Problem description

According to the original design of the nonlinear algorithm, filtering in the channels of the rotational degrees of freedom, such as pitch and roll, was confined to limiting and scaling only. The major task of this part of the project is to develop nonlinear filters for two rotational degrees of freedom: pitch and roll.

4.2. Algorithm development

4.2.1. Pitch

The derivation process is similar to that performed by Telban [1] when designing the nonlinear filter for the yaw channel.

The semicircular canals model described in a form of a transfer function is given in Eq. (4.1), which is the reduced form of the semicircular model cited in Eq. (2.7). One can refer to the original report by Telban [1] for a detailed explanation on how such reduction was made. It is worth mentioning, however, that the simplified formula cuts down the computational burden substantially, which is essential for real time applications.

$$\hat{\dot{\theta}} = \frac{G_{SCC} s^2}{s^2 + T_1 s + T_0} u, \tag{4.1}$$

where $\hat{\dot{\theta}}$ is the sensed angular velocity, G_{SCC} is the angular velocity threshold gain, which scales the response to the threshold units, and T_1 and T_0 relate to the semicircular canals time constants.

In state space form this model constitutes the state equations:

$$\begin{aligned} \dot{x}_{SCC} &= A_{SCC} x_{SCC} + B_{SCC} u \\ \dot{\theta} &= C_{SCC} x_{SCC} + D_{SCC} u \end{aligned}, \tag{4.2}$$

where $A_{SCC} = \begin{bmatrix} -T_1 & 1 \\ T_0 & 0 \end{bmatrix}$, $B_{SCC} = \begin{bmatrix} -G_{SCC} T_1 & 0 \\ -G_{SCC} T_0 & 0 \end{bmatrix}$, $C_{SCC} = \begin{bmatrix} 1 & 0 \end{bmatrix}$, $D_{SCC} = \begin{bmatrix} G_{SCC} & 0 \end{bmatrix}$.

The additional state due to optokinetic influence must be added to these equations:

$\hat{\dot{\theta}}_{OK} = \dfrac{T_2}{s+T_2}\hat{\dot{\theta}}_e$, where $\hat{\dot{\theta}}_e = \hat{\dot{\theta}}_A - \hat{\dot{\theta}}_S$, and T_2 relates to the time constant τ_{OK},

The state equations become then:

$$\begin{aligned} \dot{x}_{SCC} &= A_{SCC}x_{SCC} + B_{SCC}u \\ \dot{\theta}_{PE} &= C_{SCC}x_{SCC} + D_{SCC}u \end{aligned}, \tag{4.3}$$

where

$$A_{SCC} = \begin{bmatrix} -T_1 & 1 & 0 \\ -T_0 & 0 & 0 \\ -T_2 & 0 & -T_2 \end{bmatrix},\ B_{SCC} = \begin{bmatrix} -G_{SCC}T_1 & 0 \\ -G_{SCC}T_0 & 0 \\ -G_{SCC}T_2 & 0 \end{bmatrix},\ C_{SCC} = \begin{bmatrix} 1 & 0 & 1 \end{bmatrix},\ D_{SCC} = \begin{bmatrix} G_{SCC} & 0 \end{bmatrix}.$$

The ultimate set of state equation should include the otolith model as well. In the case of pure pitch, however, the human otoliths are not engaged. Hence the final version of the state equation set will be as follows:

$$\begin{aligned} \dot{x}_V &= A_V x_V + B_V u \\ y_{PE} &= C_V x_V + D_V u \end{aligned}, \tag{4.4}$$

where x_V, and y_{PE} are, respectively, the combined states and perceived responses, whereas matrices

$$A_V = A_{SCC}, B_V = B_{SCC}, C_V = C_{SCC}, D_V = D_{SCC}$$

The next step is to add additional motion platform states x_d and filtered white noise x_n.

$$\dot{x}_d = A_d x_d + B_d u_s\ , \tag{4.5}$$

where $x_d = \begin{bmatrix} \int \theta dt & \theta \end{bmatrix}$, and $A_d = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$ and $B_d = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

In turn, the aircraft input can be expressed as a filtered white noise:

$$\begin{aligned} \dot{x}_n &= -\gamma x_n + \gamma w \\ u_A &= x_n \end{aligned}, \tag{4.6}$$

where γ is the break frequency for a given degree of freedom

The state equations given in Eq. 4.4, 4.5, and 4.6 can be combined to form the desired system equation

$$\begin{aligned} \dot{x} &= Ax + Bu_s + Hw \\ y &= \begin{bmatrix} e & x_d \end{bmatrix} = Cx + Du_s \end{aligned}, \tag{4.7}$$

with

$$A_{SCC} = \begin{bmatrix} A_v & 0 & -B_v \\ 0 & A_d & 0 \\ 0 & 0 & -\gamma \end{bmatrix}, B = \begin{bmatrix} B_v \\ B_d \\ 0 \end{bmatrix}, H = \begin{bmatrix} 0 \\ 0 \\ \gamma \end{bmatrix}, C = \begin{bmatrix} C_v & 0 & -D_v \\ 0 & I & 0 \end{bmatrix}, D = \begin{bmatrix} D_v \\ 0 \end{bmatrix},$$

where *y* is the desired output, and $x = \begin{bmatrix} x_e & x_d & x_n \end{bmatrix}^T$ represents the combined states.

The standard optimal control form is then applied to form a cost function *J*, which is later enhanced by the additional term $e^{2\alpha t}$ [2], where "α" is a scalar representing a minimum degree of stability in the closed loop system, α >0.

$$J' = E\left\{\int_{t_0}^{t_1} e^{2\alpha t}\left(\mathbf{x}^{\mathbf{T}}\mathbf{R}_1'\mathbf{x} + \mathbf{u}'^{\mathbf{T}}\mathbf{R}_2\mathbf{u}'\right)dt\right\}, \tag{4.8}$$

where $\mathbf{R}_1'$ is positive definite and $\mathbf{R}_2$ is positive semi-definite.

The cost function constrains both the sensation error and the motion platform states.

The essence of the washout algorithm is to compute the simulator control input so that the given cost function is minimized. The solution is sought in the following form:

$$\mathbf{u}_{\mathrm{S}} = -\mathbf{K}(\alpha)\mathbf{x}, \tag{4.9}$$

where K(α) is the feedback matrix, which depends upon the solution to the algebraic Riccati equation. For the sake of brevity however, the author will omit the derivation of the solution and will get down to the on-line implementation of the algorithm, the block diagram of which is given in Figure 4.1. It is worth mentioning that the variable α is set to depend upon the motion platform states: $\alpha = \mathbf{x}_{\mathbf{d}}^{\mathbf{T}}\mathbf{Q}_2\mathbf{x}_{\mathbf{d}}$.

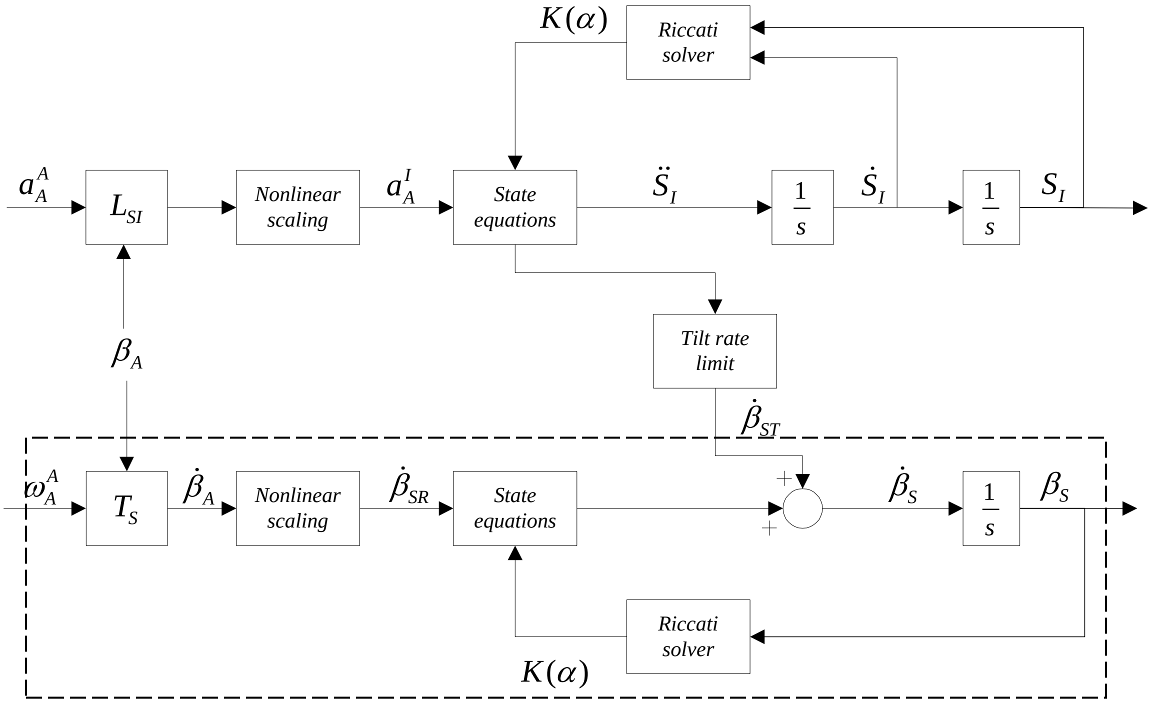


Figure 4.1. Nonlinear Algorithm implementation for longitudinal mode. The dotted box in this figure encompasses the pitch channel. Adopted from Telban and Cardullo [1]

4.2.2. Roll

For the roll channel, the filter development is analogous to the pitch channel. The sensed rotational motion $\hat{\dot{\theta}}$ in Eq. 4.1 is replaced by $\hat{\dot{\phi}}$. The remaining development is identical in form to Eqs. 4.2 to 4.9, resulting in a matrix of fifth-order transfer functions **W(s)** for the lateral mode. The on-line implementation of this mode is identical to Figure 4.1.

4.2.3. Modifications to the on-line implementation code

This section contains block diagrams and flowcharts of the nonlinear washout algorithm augmented by the non-linear filters for pitch and roll channels. The format of presentation is similar to that used by Telban and Cardullo [1].

The flowchart for the augmented nonlinear algorithm subroutine NEWOPT4 is shown in Figure 4.2. The RESET/HOLD modes and transformation subroutines are identical to the optimal algorithm discussed in the preceding section

Two new subroutines, NFILP and NFILQ, accomplish the task of solving the Riccati equation in real time for the pitch and roll mode. The feedback matrices and updated motion states for each mode are then computed in the subroutine STATE4, which was also modified to accommodate new filters for pitch and roll. The subroutine INTEG4, which computes the desired simulator displacements and attitudes, taking into account the tilt coordination limits had to be modified as well. Appropriate flowcharts are given later in the text. Note that STATE4 has to be computed six times as opposed to four times in the original design.

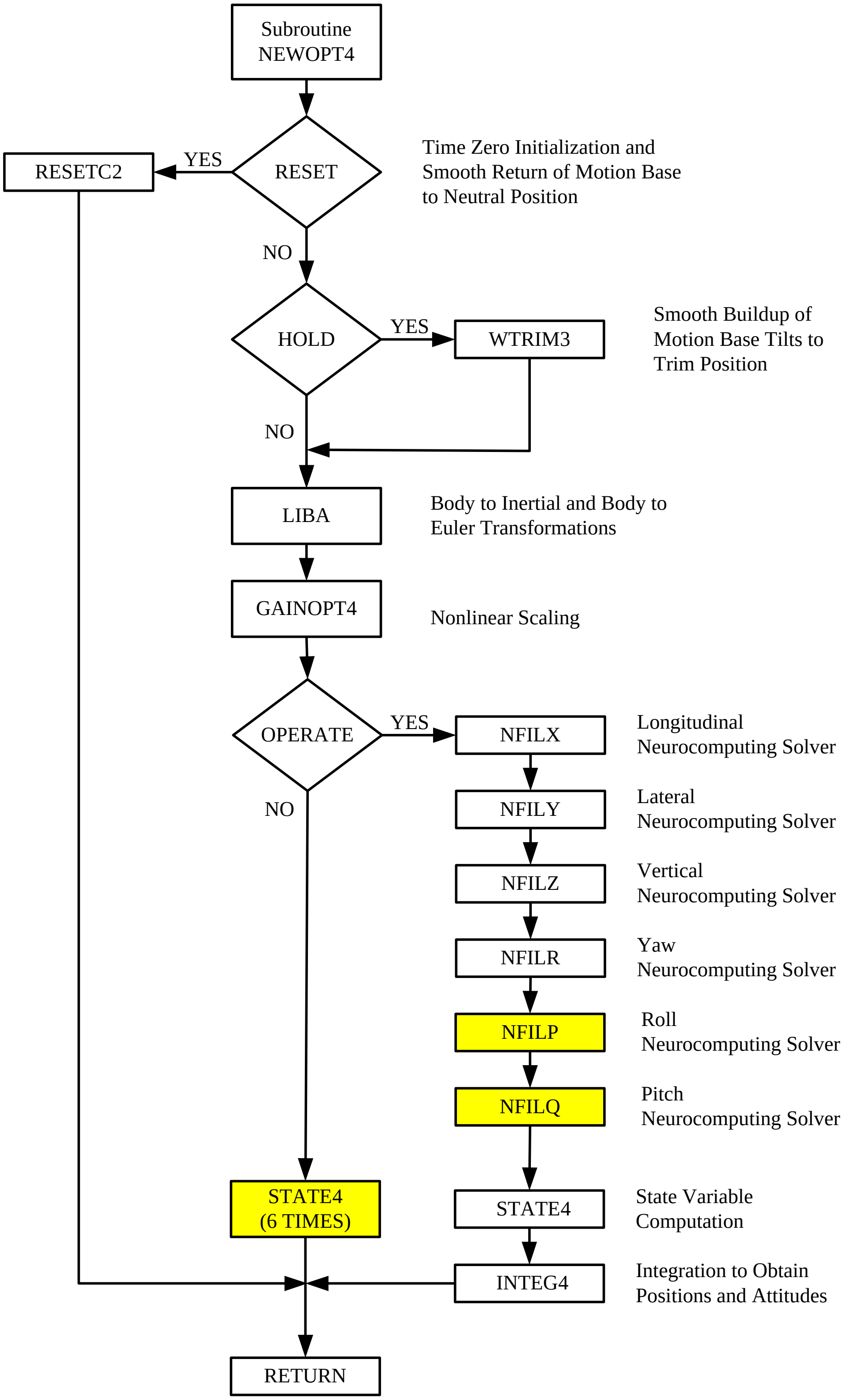

Subroutine NEWOPT4
RESET
YES
RESETC2
Time Zero Initialization and Smooth Return of Motion Base to Neutral Position
NO
HOLD
YES
WTRIM3
Smooth Buildup of Motion Base Tilts to Trim Position
NO
LIBA
Body to Inertial and Body to Euler Transformations
GAINOPT4
Nonlinear Scaling
OPERATE
YES
NFILX
Longitudinal Neurocomputing Solver
NO
NFILY
Lateral Neurocomputing Solver
NFILZ
Vertical Neurocomputing Solver
NFILR
Yaw Neurocomputing Solver
NFILP
Roll Neurocomputing Solver
NFILQ
Pitch Neurocomputing Solver
STATE4 (6 TIMES)
STATE4
State Variable Computation
INTEG4
Integration to Obtain Positions and Attitudes
RETURN

Figure 4.2. Flowchart of the augmented nonlinear washout algorithm. NFILP and NFILQ are the Riccati equation solvers for the roll and pitch channels respectively

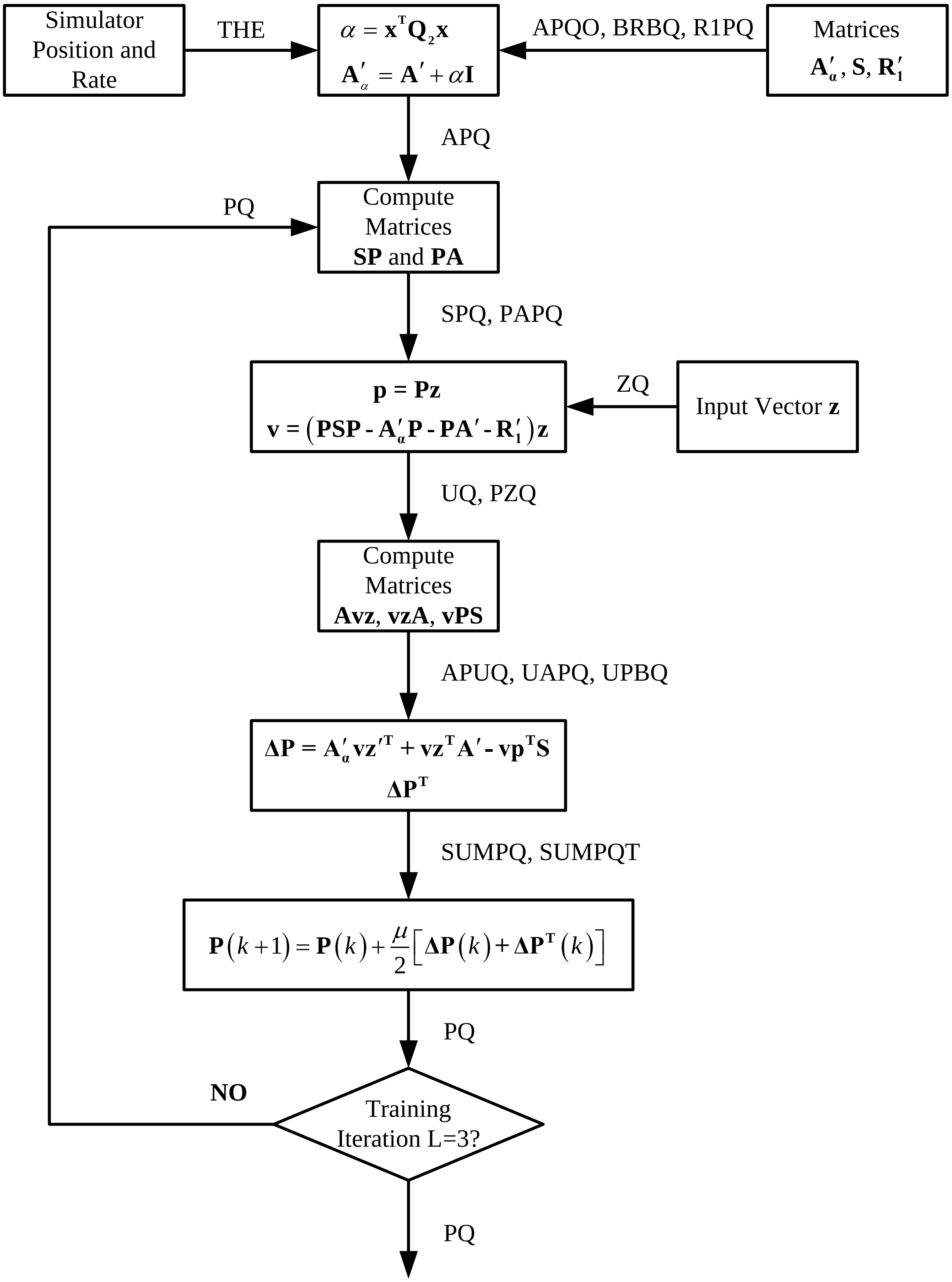

Simulator Position and Rate
THE
$\alpha = \mathbf{x}^{\mathrm{T}}\mathbf{Q}_2\mathbf{x}$
$\mathbf{A}'_{\alpha} = \mathbf{A}' + \alpha\mathbf{I}$
APQO, BRBQ, R1PQ
Matrices
$\mathbf{A}'_{\alpha}, \mathbf{S}, \mathbf{R}'_1$
APQ
PQ
Compute Matrices
SP and **PA**
SPQ, PAPQ
$\mathbf{p = Pz}$
$\mathbf{v} = \left(\mathbf{PSP} - \mathbf{A}'_{\alpha}\mathbf{P} - \mathbf{PA}' - \mathbf{R}'_1\right)\mathbf{z}$
ZQ
Input Vector **z**
UQ, PZQ
Compute Matrices
Avz, **vzA**, **vPS**
APUQ, UAPQ, UPBQ
$\Delta\mathbf{P} = \mathbf{A}'_{\alpha}\mathbf{vz}'^{\mathrm{T}} + \mathbf{vz}^{\mathrm{T}}\mathbf{A}' - \mathbf{vp}^{\mathrm{T}}\mathbf{S}$
$\Delta\mathbf{P}^{\mathrm{T}}$
SUMPQ, SUMPQT
$\mathbf{P}(k+1) = \mathbf{P}(k) + \frac{\mu}{2}\left[\Delta\mathbf{P}(k) + \Delta\mathbf{P}^{\mathrm{T}}(k)\right]$
PQ
NO
Training Iteration L=3?
PQ

Figure 4.3. NFILQ subroutine flowchart

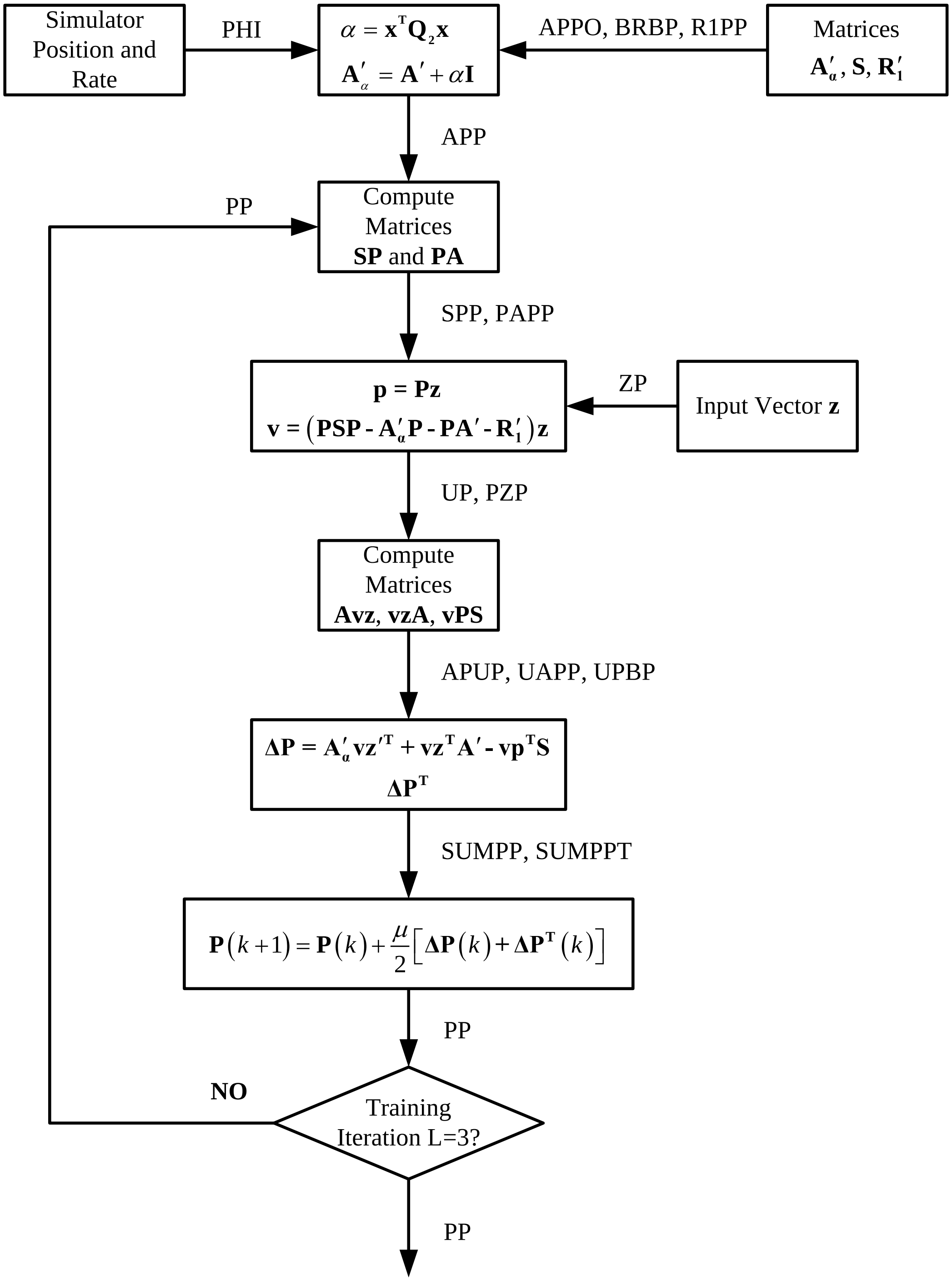

Simulator Position and Rate
PHI
$\alpha = \mathbf{x}^T \mathbf{Q}_2 \mathbf{x}$
$\mathbf{A}'_\alpha = \mathbf{A}' + \alpha \mathbf{I}$
APPO, BRBP, R1PP
Matrices
$\mathbf{A}'_\alpha, \mathbf{S}, \mathbf{R}'_1$
APP
PP
Compute Matrices **SP** and **PA**
SPP, PAPP
$\mathbf{p} = \mathbf{Pz}$
$\mathbf{v} = \left(\mathbf{PSP} - \mathbf{A}'_\alpha \mathbf{P} - \mathbf{PA}' - \mathbf{R}'_1\right)\mathbf{z}$
ZP
Input Vector **z**
UP, PZP
Compute Matrices **Avz**, **vzA**, **vPS**
APUP, UAPP, UPBP
$\Delta\mathbf{P} = \mathbf{A}'_\alpha \mathbf{v}\mathbf{z}'^{\mathbf{T}} + \mathbf{v}\mathbf{z}^{\mathbf{T}}\mathbf{A}' - \mathbf{v}\mathbf{p}^{\mathbf{T}}\mathbf{S}$
$\Delta\mathbf{P}^{\mathbf{T}}$
SUMPP, SUMPPT
$\mathbf{P}(k+1) = \mathbf{P}(k) + \frac{\mu}{2}\left[\Delta\mathbf{P}(k) + \Delta\mathbf{P}^{\mathbf{T}}(k)\right]$
PP
NO
Training Iteration L=3?
PP

Figure 4.4. NFILP subroutine flowchart

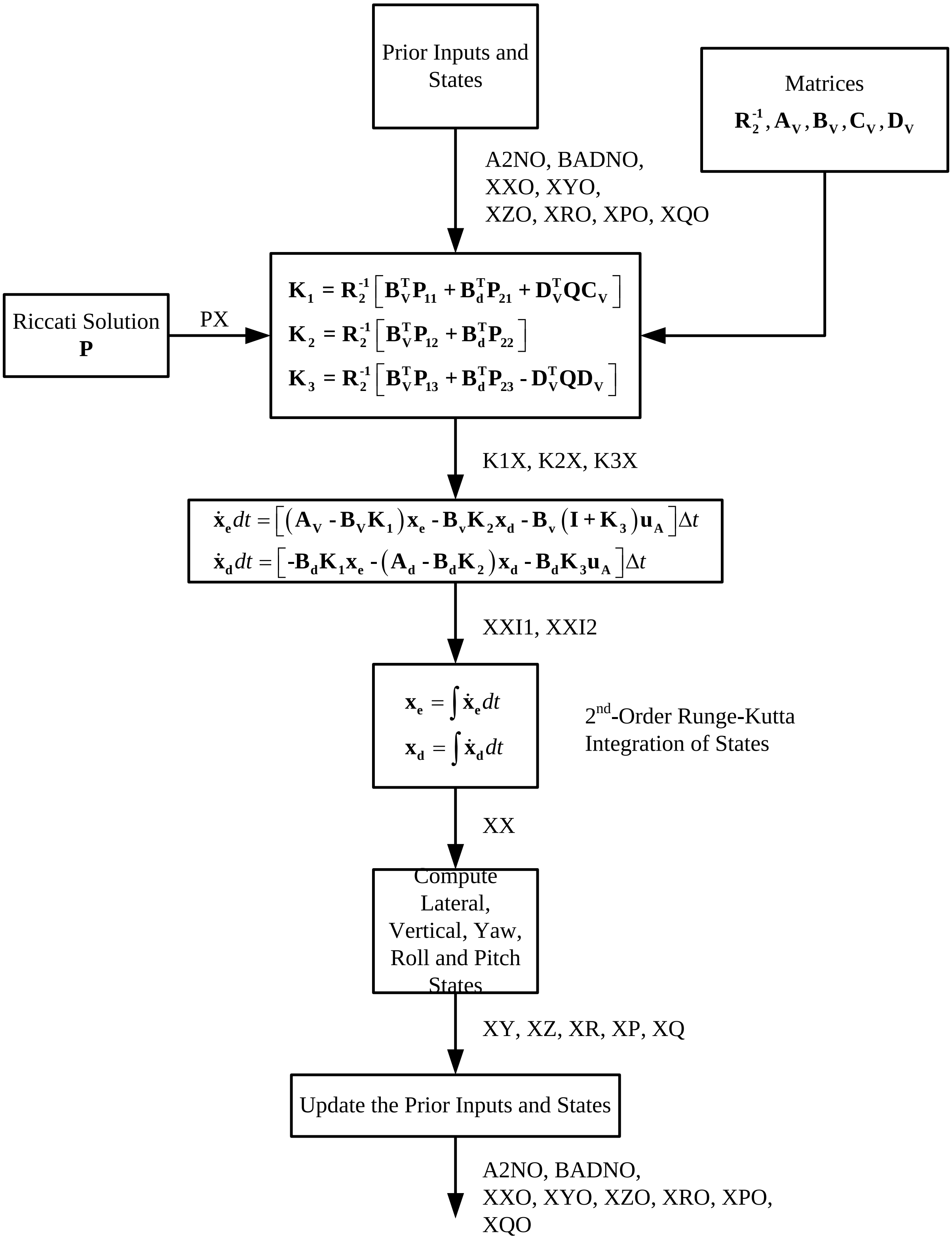

Prior Inputs and States
Matrices
$\mathbf{R}_2^{-1}, \mathbf{A}_V, \mathbf{B}_V, \mathbf{C}_V, \mathbf{D}_V$
A2NO, BADNO, XXO, XYO, XZO, XRO, XPO, XQO
Riccati Solution
$\mathbf{P}$
PX
$\mathbf{K}_1 = \mathbf{R}_2^{-1}\left[\mathbf{B}_V^T\mathbf{P}_{11} + \mathbf{B}_d^T\mathbf{P}_{21} + \mathbf{D}_V^T\mathbf{Q}\mathbf{C}_V\right]$
$\mathbf{K}_2 = \mathbf{R}_2^{-1}\left[\mathbf{B}_V^T\mathbf{P}_{12} + \mathbf{B}_d^T\mathbf{P}_{22}\right]$
$\mathbf{K}_3 = \mathbf{R}_2^{-1}\left[\mathbf{B}_V^T\mathbf{P}_{13} + \mathbf{B}_d^T\mathbf{P}_{23} - \mathbf{D}_V^T\mathbf{Q}\mathbf{D}_V\right]$
K1X, K2X, K3X
$\dot{\mathbf{x}}_e dt = \left[\left(\mathbf{A}_V - \mathbf{B}_V\mathbf{K}_1\right)\mathbf{x}_e - \mathbf{B}_v\mathbf{K}_2\mathbf{x}_d - \mathbf{B}_v\left(\mathbf{I} + \mathbf{K}_3\right)\mathbf{u}_A\right]\Delta t$
$\dot{\mathbf{x}}_d dt = \left[-\mathbf{B}_d\mathbf{K}_1\mathbf{x}_e - \left(\mathbf{A}_d - \mathbf{B}_d\mathbf{K}_2\right)\mathbf{x}_d - \mathbf{B}_d\mathbf{K}_3\mathbf{u}_A\right]\Delta t$
XXI1, XXI2
$\mathbf{x}_e = \int \dot{\mathbf{x}}_e dt$
$\mathbf{x}_d = \int \dot{\mathbf{x}}_d dt$
2nd-Order Runge-Kutta Integration of States
XX
Compute Lateral, Vertical, Yaw, Roll and Pitch States
XY, XZ, XR, XP, XQ
Update the Prior Inputs and States
A2NO, BADNO, XXO, XYO, XZO, XRO, XPO, XQO

Figure 4.5. STATE4 subroutine flowchart

4.4. Algorithm tuning

Figure 4.6 contains comparison graphs of augmented filtering algorithms versus original washout filters for the *pitch channel.* Sensed angular rate and specific forces at the PS are of particular interest here.

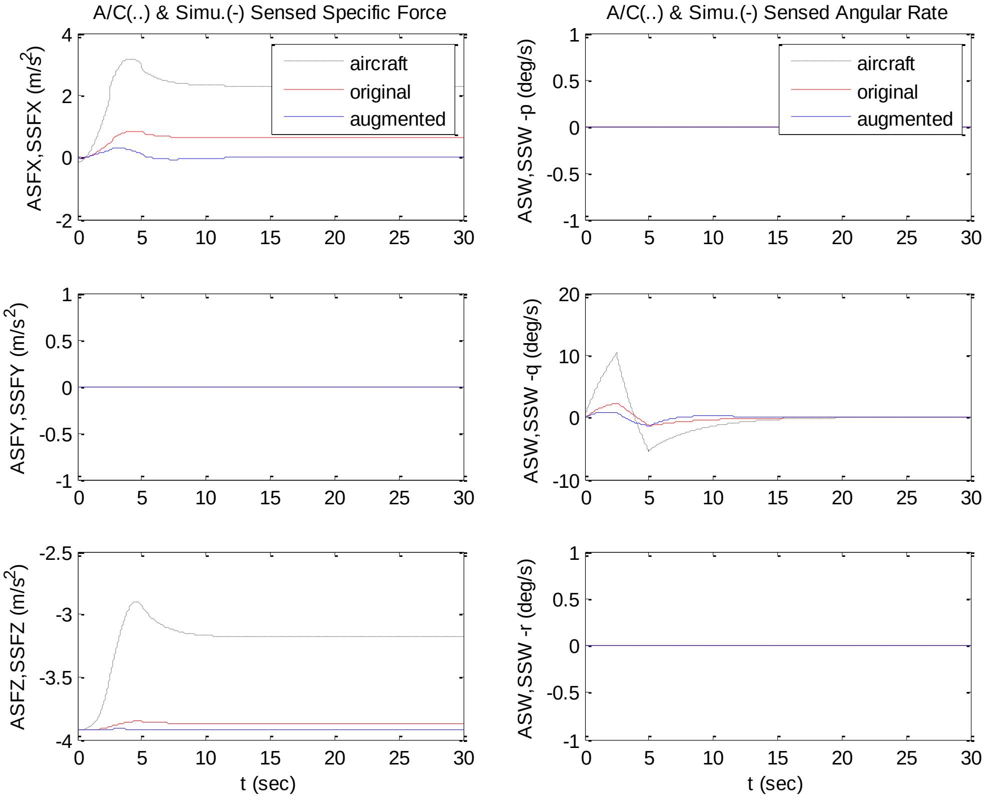


Figure 4.6. Sensed specific force and angular rates for the pitch channel, with the tuned version of the nonlinear washout filter

It can be seen that augmented filters respond in an "under-gained" manner. For example, sensed specific force at the PS appears to be less then with the original non-linear washout filters. Such a tendency can be observed in the roll channel as well. In order to increase the performance of the augmented filters an auxiliary gain was introduced for the pitch and roll channels. Subroutine "integ4.f" (Telban and Cardullo [3]) was modified in the following manner to accommodate such a gain. Desired pitch and roll angles are "boosted" before being combined with the tilt signal (due to gravity align). The modified code is highlighted with yellow color.

```
      SUBROUTINE INTEG4

      INCLUDE 'optint3.com'

      INCLUDE 'comint2.com'

      INCLUDE 'wcom2.com'

      INCLUDE 'matrix1c.com'

      INCLUDE 'nopt4.com'
C
C     SURGE FILTER OUTPUT ASI(1) & BSDT(2)
C
      ASI(1)=-K1X(2,1)*XX(1)-K1X(2,2)*XX(2)-K1X(2,3)*XX(3)
     x       -K1X(2,4)*XX(4)-K1X(2,5)*XX(5)-K1X(2,6)*XX(6)
     x       -K2X(2,1)*XX(7)-K2X(2,2)*XX(8)-K2X(2,3)*XX(9)
     x       -K3X(2)*A2N(1)

      BSDT(2)=-K1X(1,1)*XX(1)-K1X(1,2)*XX(2)-K1X(1,3)*XX(3)
     x        -K1X(1,4)*XX(4)-K1X(1,5)*XX(5)-K1X(1,6)*XX(6)
     x              -K2X(1,1)*XX(7)-K2X(1,2)*XX(8)-K2X(1,3)*XX(9)
     x              -K3X(1)*A2N(1)
C
C     SWAY FILTER OUTPUT ASI(2) & BSDT(1)
C
      ASI(2)=-K1Y(2,1)*XY(1)-K1Y(2,2)*XY(2)-K1Y(2,3)*XY(3)
     x       -K1Y(2,4)*XY(4)-K1Y(2,5)*XY(5)-K1Y(2,6)*XY(6)
     x       -K2Y(2,1)*XY(7)-K2Y(2,2)*XY(8)-K2Y(2,3)*XY(9)
     x       -K3Y(2)*A2N(2)

      BSDT(1)=-K1Y(1,1)*XY(1)-K1Y(1,2)*XY(2)-K1Y(1,3)*XY(3)
     x        -K1Y(1,4)*XY(4)-K1Y(1,5)*XY(5)-K1Y(1,6)*XY(6)
     x              -K2Y(1,1)*XY(7)-K2Y(1,2)*XY(8)-K2Y(1,3)*XY(9)
     x              -K3Y(1)*A2N(2)
C
C     HEAVE FILTER OUTPUT ASI(3)
C
  ASI(3)=(-K1Z(1)*XZ(1)-K1Z(2)*XZ(2)-K2Z(1)*XZ(3)
     x       -K2Z(2)*XZ(4)-K2Z(3)*XZ(5)-K3Z*A2N(3))
C
C     YAW FILTER OUTPUT BSDR(3)
C
  BSDR(3)=-K1R(1)*XR(1)-K1R(2)*XR(2)-K1R(3)*XR(3)
     X        -K2R*XR(4)-K3R*BADN(3)
C
```

```
C       PITCH FILTER OUTPUT BSDR(2)
C
    BSDR(2)=-K1P(1)*XP(1)-K1P(2)*XP(2)-K1P(3)*XP(3)
   X       -K2P*XP(4)-K3P*BADN(2)
C
C       ROLL FILTER OUTPUT BSDR(1)
C
    BSDR(1)=-K1Q(1)*XQ(1)-K1Q(2)*XQ(2)-K1Q(3)*XQ(3)
   X       -K2Q*XQ(4)-K3Q*BADN(1)


C
C       LIMIT THE ANGULAR RATE IN THE CROSS-OVER TILT CHANNEL.
C       THE REAL TILT POSITION WILL BE DETERMINED BY BOTH THE
DESIRED
C       POSITION AND THE DIFFERENCE BETWEEN THE DESIRED AND REAL
C       TILT POSITION.
C
        DO K=1,2
                BETASR(K)=BETASRO(K)+DT*BSDRO(K)
                BETAST(K)=BETASTO(K)+DT*BSDTO(K)
                DIF(K)=0.005*(BETAST(K)-BETASTLO(K))+(BETAST(K)-
BETASTO(K))
                BETASTL(K)=BETASTLO(K)+MAX(-
BDLIM*DT,MIN(BDLIM*DT,DIF(K)))
C
C       COMPUTE THE TILT ANGULAR VELOCITY
C
                BSDTL(K)=(BETASTL(K)-BETASTLO(K))/DT

                BSDRO(K) = BSDR(K)
                BETASRO(K)=BETASR(K)
                BETASTO(K)=BETAST(K)
                BETASTLO(K)=BETASTL(K)
           BSDTO(K)=BSDT(K)
        END DO
C
C       COMBINE THE TILT AND ROTATIONAL CHANNELS TO OBTAIN
C       THE DESIRED ANGULAR POSITION

        G1=3
C
        BETAS1(1)=BETASTL(1)+G1*BETASR(1)
        BETAS1(2)=BETASTL(2)+G1*BETASR(2)
        BETAS1(3)=XR(4)
C
```

```
C    USE DIFFERENCE BETWEEN DESIRED BETAST AND REAL BETAST
C    TO GENERATE ADDITIONAL LINEAR RESPONSE AND ACHIEVE
C    COORDINATION BETWEEN THE LINEAR AND TILT CHANNELS
C
    SSI1(1)=XX(8)+RRS(3)*(BETAST(2)-BETASTL(2))
    SSI1(2)=XY(8)-RRS(3)*(BETAST(1)-BETASTL(1))
C
C        FOR ON-GROUND MOTION, ADD RUNWAY ROUGHNESS EFFECT
C        AMPLITUDE IS FAIRED UPON TOUCHDOWN OR TAKEOFF
C
    SSI1(3)=XZ(4)+XKA*SIN((WB+XKG*VGSPD)*T)
C
C        Swap Variables To Match Modified Algorithm
C        For Input to JACKDRVR
C

C
        XDD = ASI(1)
        YDD = ASI(2)
        ZDD = ASI(3)
        XD = XX(9)
        YD = XY(9)
        ZD = XZ(5)
        X = SSI1(1)
        Y = SSI1(2)
        Z = SSI1(3)
        PHI = BETAS1(1)
        THE =BETAS1(2)
        PSI = BETAS1(3)
        PHID = BSDTL(1)+BSDR(1)
        THED = BSDTL(2)+BSDR(2)
        PSID = BSDR(3)

        RETURN
        END
```

Trial and error method yields a value of G1 = 3, which provides best tuning of the algorithm. Figure 4.7 contains comparison graphs of the modified augmented filtering algorithms against the original washout filters. It can be seen that modified augmented filters result in better (at least the same order of magnitude) cueing at the PS.

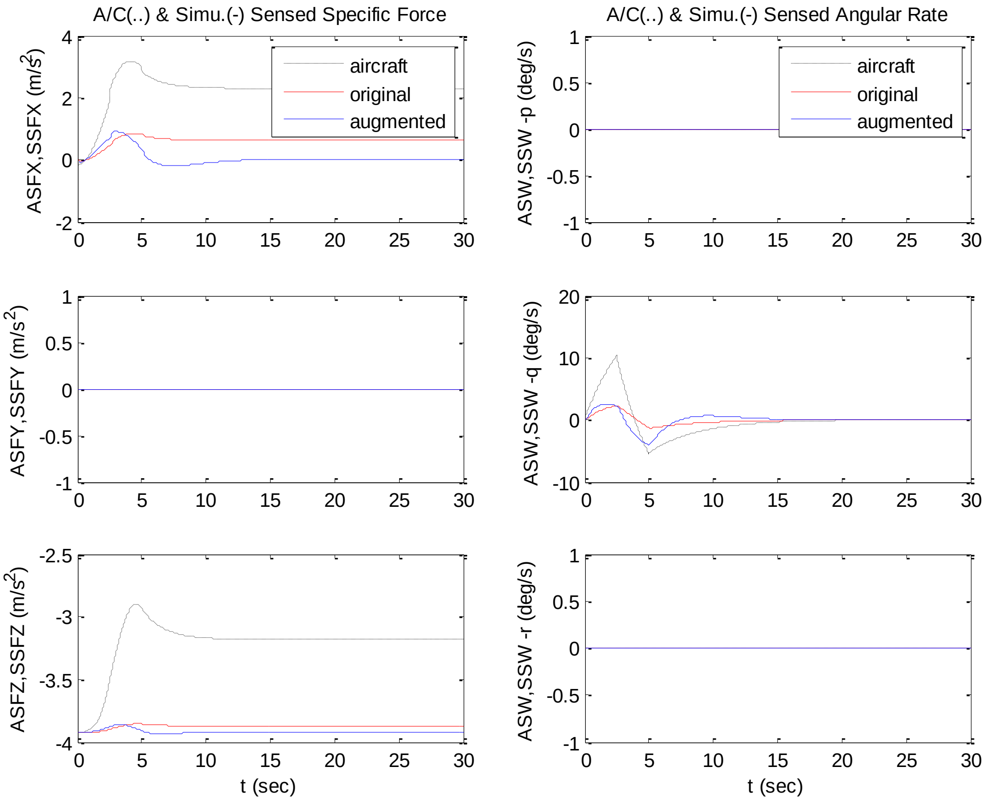


Figure 4.7. Sensed specific force and angular rates for the pitch channel, with the tuned version of the nonlinear washout filter

4.5. Discussion

A discussion of the benefits of applying the nonlinear filters to all degrees of freedom (augmented filtering), is presented using the pitch channel as an example. Appendix C contains a comprehensive set of graphs, which compares the augmented filtering with the original set of non-linear optimal filters.

As can be seen, augmented filtering algorithms provide at least as much cueing as original filters. Figures C.1.5 and C.1.7 in Appendix C also clearly illustrate how nonlinear filters washout the simulator platform attitude, as opposed to the original filter design, which result in sustained cues.

Recall that for the pitch channel, the reference signal was the pulse doublet. Figure C.1.1 clearly illustrates how nonlinear filters provide cue onset with the following washout. The same observation holds true for the roll channel as well (Appendix C).

It can also be seen that introduction of non-linear washout filters to the pitch and roll channels had no effect on other degrees of freedom.

It is useful to compare the augmented filtering algorithms against the original nonlinear filters applied at the PS. The latter were developed in Sections 3 of the current report. Such comparison makes sense since both filtering algorithms clearly have certain advantages over the original nonlinear filters. Appendix D contains a complete set of comparison graphs.

Using the pitch channel as an example it is possible to draw a few conclusions, which hold true for other degrees of freedom. It can be seen (Figure D.1.1) that original nonlinear filters applied at the PS as opposed to the augmented filters produce a noticeable accelerations at the MB centroid, which is undesirable. Moreover, as it has been noted previously, augmented filters provide cue washout (Figure D.1.2). Figure D.1.3 demonstrates, that if expressed in terms of the platform angular rate, both approaches yielded comparable results. Specific forces at the pilot’s head location (Figure D.1.4) are of almost the same magnitude. The augmented filters, however, produced the desired washout. Moreover, the augmented filters resulted in smaller displacements of the platform, which can be seen in Figure D.1.7.

Appendix A. Programming updates

1. Common variable listing

Followed is the common variables listing, which was enhanced due to introduction of the pitch and roll nonlinear filters. The listing contents had been preserved intact from the original work by Telban and Cardullo [3], save for some additions, which are marked in yellow.

1.1. comint2.com

Variable	Description
X, Y, Z	Desired Platform Displacements (m)
XD, YD, ZD	Desired Platform Velocities (m/s)
XDD, YDD, ZDD	Desired Platform Accelerations (m/s/s)
PHI, THE, PSI	Desired Platform Attitudes (rad)
PHID, THED, PSID	Desired Platform Angular Velocities (rad/s)

1.2. optint3.com

Variable	Description
DT	Time Step (Sec)
XX1(8), X1O(8)	Filter State Variable 1 (Current and Prior Time)
X2(8), X2O(8)	Filter State Variable 2 (Current and Prior Time)
X3(8), X3O(8)	Filter State Variable 3 (Current and Prior Time)
X4(8), X4O(8)	Filter State Variable 4 (Current and Prior Time)
X5(6), X5O(6)	Filter State Variable 5 (Current and Prior Time)
X6(6), X6O(6)	Filter State Variable 6 (Current and Prior Time)
ACA(3), ACAO(3)	Aircraft Body Acceleration Vector (m/s/s)
BETAA(3)	Aircraft Euler Angle Vector (rad)
BETAAD(3)	Aircraft Euler Rate Vector (rad/sec)
A2(3)	Aircraft Inertial Acceleration Vector (m/s/s)
A2N(3), A2NO(3)	Scaled Aircraft Inertial Acceleration Vector (m/s/s)
BADN(3), BADNO(3)	Scaled Aircraft Euler Rate Vector (rad/s)
ASI(3), ASIO(3)	Desired Platform Acceleration Cue (m/s/s)
VSI(3), VSIO(3)	Desired Platform Velocity (m/s)
SSIU(3), SSI1(3), SSIO(3)	Desired Platform Displacement (m)
WAA(3)	Aircraft Body Velocity Vector (rad/sec)
BSDT(2), BSDTO(2), BSDTL(2)	Platform Tilt Cue (Current, Prior, and Limited) (rad/sec)
BETAS1(3)	Desired Platform Angular Position (rad)
BDLIM	Platform Tilt Cue Limit (rad/sec)
BSDR(3), BSDRO(3)	Platform Rotational Cue (Current and Prior) (rad/sec)
BETASR(3), BETASRO(3)	Platform Rotational Angle (Current and Prior) (rad/sec)

BETAST(2), BETASTO(2)	Platform Tilt Angle (Current and Prior) (rad)
BETASTL(2), BETASTLO(2)	Platform Tilt Angle with Limit (Current and Prior) (rad)
DIF(2)	Difference between Current and Limited Tilt Angles
XH(2), XHO(2)	Trim Filter State Variables
T1N1, T1DO, T2N1, T2DO	Trim Filter Coefficients
XT, XTO, XT2, XT2O	Augmented Turbulence Filter State Variables
ACZT	Augmented Turbulence Acceleration
WGUST, WGUSTO	Z-Axis Gust Velocity (m/sec)
G1D0, G1D1	Augumented Turbulence Filter Coefficients (Denominator)
G1N0, G1N1, G1N2	Augumented Turbulence Filter Coefficients (Numerator)

1.3. matrix1c.com

Variable	Description
AAIS(3,6)	Motion Base Actuator Coordinates (m)
BBII(3,6)	Fixed Base Actuator Coordinates (m)
RRS(3)	Vector from Motion Base Centroid to Pilot Head (m)
LENEUT	Actuator Neutral Length (m)
LI(6)	Desired Actuator Extensions (m)
RLI(6), RLIO(6)	Actual Actuator Extensions (m)
LEGC(6)	Actual Actuator Extensions (in)
SSI(3)	Actual Simulator Displacements (m)
BETAS(3)	Actual Simulator Attitudes (rad)
BRAKE(6)	Actuator Braking Region Value
RATIO(6)	Actuator Braking Ratio
LAVAIL	Actuator Available Length (m)
RLID(6), RLIDO(6)	Actuator Velocity (m/s)
RLIDD(6)	Actuator Acceleration (m/s/s)
FLAG(6)	Braking Region Flag (0 or 1)
FLAG2	Braking Region Flag (0 or 1)
IT2, NC2	Braking Recovery Indices
SUMFLAG	Sum of FLAG(6) Values

1.4. nopt4.com

Variable	Description
Longitudinal Mode	
ALPX, ALPXMAX	Prescribed Nonlinearity α
APX(11,11), APXO(11)	State Space System Matrix $\mathbf{A}'$
BRBX(11,11), R1PX(11,11), R2IX(2)	System Weighting Matrix $\mathbf{S}, \mathbf{R}_1', \mathbf{R}_2$
AVX(6,6), BVX(6,2), DQCX(6)	Vestibular State Space Matrices $\mathbf{A}_V, \mathbf{B}_V, \mathbf{D}_V\mathbf{Q}\mathbf{C}_V$
K1X(2,6), K2X(2,3), K3X(2)	Feedback Matrices $\mathbf{K}_1, \mathbf{K}_2, \mathbf{K}_3$
ZX(11,11)	Neurocomputing Solver Bi-Polar Vectors $\mathbf{Z}$
PX(11,11), PXVEC(66)	Riccati Equation Solution $\mathbf{P}$
XX(9), XXO(9)	State Vector $\mathbf{x}$
Lateral Mode	
ALPY, ALPYMAX	Prescribed Nonlinearity α
APY(11,11), APYO(11)	State Space System Matrix $\mathbf{A}'$
BRBY(11,11), R1PX(11,11), R2IY(2)	System Weighting Matrix $\mathbf{S}, \mathbf{R}_1', \mathbf{R}_2$

AVY(6,6), BVY(6,2), DQCY(6)	Vestibular State Space Matrices $\mathbf{A_V, B_V, D_VQC_V}$
K1Y(2,6), K2Y(2,3), K3Y(2)	Feedback Matrices $\mathbf{K_1, K_2, K_3}$
ZY(11,11)	Neurocomputing Solver Bi-Polar Vectors $\mathbf{Z}$
PY(11,11), PYVEC(66)	Riccati Equation Solution $\mathbf{P}$
XY(9), XYO(9)	State Vector $\mathbf{x}$
Yaw Mode	
ALPR, ALPRMAX	Prescribed Nonlinearity α
APR(5,5), APRO(5)	State Space System Matrix $\mathbf{A'}$
BRBR(5,5), R1PR(5,5), R2IR	System Weighting Matrix $\mathbf{S, R_1', R_2}$
AVR(3,3), BVR(3), DQCR(3), DQDR	Vestibular State Space Matrices $\mathbf{A_V, B_V, D_VQC_V, D_VQD_V}$
K1R(3), K2R, K3R	Feedback Matrices $\mathbf{K_1, K_2, K_3}$
ZR(5,5)	Neurocomputing Solver Bi-Polar Vectors $\mathbf{Z}$
PR(5,5), PRVEC(15)	Riccati Equation Solution $\mathbf{P}$
XR(4), XRO(4)	State Vector $\mathbf{x}$
Roll Mode	
ALPP, ALPPMAX	Prescribed Nonlinearity α
APP(5,5), APPO(5)	State Space System Matrix $\mathbf{A'}$
BRBP(5,5), R1PP(5,5), R2IP	System Weighting Matrix $\mathbf{S, R_1', R_2}$
AVP(3,3), BVP(3), DQCP(3), DQDP	Vestibular State Space Matrices $\mathbf{A_V, B_V, D_VQC_V, D_VQD_V}$
K1P(3), K2P, K3P	Feedback Matrices $\mathbf{K_1, K_2, K_3}$
ZP(5,5)	Neurocomputing Solver Bi-Polar Vectors $\mathbf{Z}$
PP(5,5), PPVEC(15)	Riccati Equation Solution $\mathbf{P}$
XP(4), XPO(4)	State Vector $\mathbf{x}$
Pitch Mode	
ALPQ, ALPQMAX	Prescribed Nonlinearity α
APQ(5,5), APQO(5)	State Space System Matrix $\mathbf{A'}$
BRBQ(5,5), R1PQ(5,5), R2IQ	System Weighting Matrix $\mathbf{S, R_1', R_2}$
AVQ(3,3), BVQ(3), DQCQ(3), DQDQ	Vestibular State Space Matrices $\mathbf{A_V, B_V, D_VQC_V, D_VQD_V}$
K1Q(3), K2Q, K3Q	Feedback Matrices $\mathbf{K_1, K_2, K_3}$
ZQ(5,5)	Neurocomputing Solver Bi-Polar Vectors $\mathbf{Z}$
PQ(5,5), PQVEC(15)	Riccati Equation Solution $\mathbf{P}$
XQ(4), XQO(4)	State Vector $\mathbf{x}$
Heave Mode	
ALPZ, ALPZMAX	Prescribed Nonlinearity α
APZ(6,6), APZO(6)	State Space System Matrix $\mathbf{A'}$
BRBZ(6,6), R1PZ(6,6)	System Weighting Matrix $\mathbf{S, R_1'}$
AVZ(2,2), BVZ(2)	Vestibular State Space Matrices $\mathbf{A_V, B_V}$
K1Z(2), K2Z(2), K3Z	Feedback Matrices $\mathbf{K_1, K_2, K_3}$
ZZ(6,6)	Neurocomputing Solver Bi-Polar Vectors $\mathbf{Z}$
PZ(6,6), PZVEC(21)	Riccati Equation Solution $\mathbf{P}$
XZ(5), XZO(5)	State Vector $\mathbf{x}$
Nonlinear Gains and Turbulence	
GX4,GY4,GZ4,GP4,GQ4,GR4	In-Flight Polynomial Scaling Coefficients
AMX4,BMX4	In-Flight Translational and Rotational Limits
GZ40,GZ4S,AMX40,AMX4S	On-Ground Scaling Coefficients and Limits
GT4	Augmented Turbulence Acceleration Gain
G2D0, G2D1	Augumented Turbulence Filter Coefficients (Denominator)

G2N0, G2N1, G2N2	Augumented Turbulence Filter Coefficients (Numerator)

2. Program Listing

Followed is the program listing of the on-line implementation of the augmented nonlinear washout algorithm.

2.1. gainopt4.f

```
C*************************************************************
C  NONLINEAR ALGORITHM NONLINEAR GAIN SUBROUTINE.
C  THE INPUT IS FIRST LIMITED AND THEN SCALED BY A POLYNOMIAL.
C*************************************************************
C
      SUBROUTINE GAINOPT4

      INCLUDE 'optint3.com'

      INCLUDE 'nopt4.com'

      REAL AA4(3),BA4(3)
C
C  Take Absolute Value of Input
C
      AA4(1)=ABS(A2(1))
      AA4(2)=ABS(A2(2))
      AA4(3)=ABS(A2(3))
      BA4(1)=ABS(BETAAD(1))
      BA4(2)=ABS(BETAAD(2))
      BA4(3)=ABS(BETAAD(3))
C
C  Limit Translational and Rotational Inputs
C
      AAM=MAX(AA4(1),AA4(2),AA4(3))
      BAM=MAX(BA4(1),BA4(2),BA4(3))
      IF(AAM.GT.AMX4) THEN
         RATIO=AMX4/AAM
         AA4(1)=AA4(1)*RATIO
         AA4(2)=AA4(2)*RATIO
         AA4(3)=AA4(3)*RATIO
      END IF
      IF(BAM.GT.BMX4) THEN
         RATIO=BMX4/BAM
         BA4(1)=BA4(1)*RATIO
         BA4(2)=BA4(2)*RATIO
         BA4(3)=BA4(3)*RATIO
      END IF
C
C     Perform Nonlinear Scaling of Inputs
C
      A2N(1)=(GX4(1)*AA4(1)+GX4(2)*AA4(1)**2.+GX4(3)*AA4(1)**3.)
     +*SIGN(1.,A2(1))
      A2N(2)=(GY4(1)*AA4(2)+GY4(2)*AA4(2)**2.+GY4(3)*AA4(2)**3.)
     +*SIGN(1.,A2(2))
      A2N(3)=(GZ4(1)*AA4(3)+GZ4(2)*AA4(3)**2.+GZ4(3)*AA4(3)**3.)
     +*SIGN(1.,A2(3))
```

```
      BADN(1)=(GP4(1)*BA4(1)+GP4(2)*BA4(1)**2.+GP4(3)*BA4(1)**3.)
     +*SIGN(1.,BETAAD(1))
      BADN(2)=(GQ4(1)*BA4(2)+GQ4(2)*BA4(2)**2.+GQ4(3)*BA4(2)**3.)
     +*SIGN(1.,BETAAD(2))
      BADN(3)=(GR4(1)*BA4(3)+GR4(2)*BA4(3)**2.+GR4(3)*BA4(3)**3.)
     +*SIGN(1.,BETAAD(3))

   RETURN
   END
C
```

2.2. integ4.f

```
         SUBROUTINE INTEG4

      INCLUDE 'optint3.com'

      INCLUDE 'comint2.com'

      INCLUDE 'wcom2.com'

      INCLUDE 'matrix1c.com'

      INCLUDE 'nopt4.com'
C
C     SURGE FILTER OUTPUT ASI(1) & BSDT(2)
C
      ASI(1)=-K1X(2,1)*XX(1)-K1X(2,2)*XX(2)-K1X(2,3)*XX(3)
     x      -K1X(2,4)*XX(4)-K1X(2,5)*XX(5)-K1X(2,6)*XX(6)
     x      -K2X(2,1)*XX(7)-K2X(2,2)*XX(8)-K2X(2,3)*XX(9)
     x      -K3X(2)*A2N(1)

      BSDT(2)=-K1X(1,1)*XX(1)-K1X(1,2)*XX(2)-K1X(1,3)*XX(3)
     x       -K1X(1,4)*XX(4)-K1X(1,5)*XX(5)-K1X(1,6)*XX(6)
     x      -K2X(1,1)*XX(7)-K2X(1,2)*XX(8)-K2X(1,3)*XX(9)
     x      -K3X(1)*A2N(1)
C
C     SWAY FILTER OUTPUT ASI(2) & BSDT(1)
C
      ASI(2)=-K1Y(2,1)*XY(1)-K1Y(2,2)*XY(2)-K1Y(2,3)*XY(3)
     x      -K1Y(2,4)*XY(4)-K1Y(2,5)*XY(5)-K1Y(2,6)*XY(6)
     x      -K2Y(2,1)*XY(7)-K2Y(2,2)*XY(8)-K2Y(2,3)*XY(9)
     x      -K3Y(2)*A2N(2)

      BSDT(1)=-K1Y(1,1)*XY(1)-K1Y(1,2)*XY(2)-K1Y(1,3)*XY(3)
     x       -K1Y(1,4)*XY(4)-K1Y(1,5)*XY(5)-K1Y(1,6)*XY(6)
     x      -K2Y(1,1)*XY(7)-K2Y(1,2)*XY(8)-K2Y(1,3)*XY(9)
     x      -K3Y(1)*A2N(2)
C
C     HEAVE FILTER OUTPUT ASI(3)
C
      ASI(3)=(-K1Z(1)*XZ(1)-K1Z(2)*XZ(2)-K2Z(1)*XZ(3)
     x        -K2Z(2)*XZ(4)-K2Z(3)*XZ(5)-K3Z*A2N(3))
C
C     YAW FILTER OUTPUT BSDR(3)
C
      BSDR(3)=-K1R(1)*XR(1)-K1R(2)*XR(2)-K1R(3)*XR(3)
     X       -K2R*XR(4)-K3R*BADN(3)
C
C     PITCH FILTER OUTPUT BSDR(2)
C
      BSDR(2)=-K1P(1)*XP(1)-K1P(2)*XP(2)-K1P(3)*XP(3)
     X       -K2P*XP(4)-K3P*BADN(2)
C
C     ROLL FILTER OUTPUT BSDR(1)
C
      BSDR(1)=-K1Q(1)*XQ(1)-K1Q(2)*XQ(2)-K1Q(3)*XQ(3)
     X        -K2Q*XQ(4)-K3Q*BADN(1)

C
C      LIMIT THE ANGULAR RATE IN THE CROSS-OVER TILT CHANNEL.
C      THE REAL TILT POSITION WILL BE DETERMINED BY BOTH THE DESIRED
C      POSITION AND THE DIFFERENCE BETWEEN THE DESIRED AND REAL
C      TILT POSITION.
C
       DO K=1,2
          BETASR(K)=BETASRO(K)+DT*BSDRO(K)
          BETAST(K)=BETASTO(K)+DT*BSDTO(K)
          DIF(K)=0.005*(BETAST(K)-BETASTLO(K))+(BETAST(K)-BETASTO(K))
          BETASTL(K)=BETASTLO(K)+MAX(-BDLIM*DT,MIN(BDLIM*DT,DIF(K)))
C
C      COMPUTE THE TILT ANGULAR VELOCITY
C
          BSDTL(K)=(BETASTL(K)-BETASTLO(K))/DT

          BSDRO(K)  = BSDR(K)
          BETASRO(K)=BETASR(K)
          BETASTO(K)=BETAST(K)
          BETASTLO(K)=BETASTL(K)
           BSDTO(K)=BSDT(K)
       END DO
C
C      COMBINE THE TILT AND ROTATIONAL CHANNELS TO OBTAIN
C      THE DESIRED ANGULAR POSITION
C
       BETAS1(1)=BETASTL(1)+BETASR(1)
       BETAS1(2)=BETASTL(2)+BETASR(2)
       BETAS1(3)=XR(4)
C
C      USE DIFFERENCE BETWEEN DESIRED BETAST AND REAL BETAST
C      TO GENERATE ADDITIONAL LINEAR RESPONSE AND ACHIEVE
C      COORDINATION BETWEEN THE LINEAR AND TILT CHANNELS
C
       SSI1(1)=XX(8)+RRS(3)*(BETAST(2)-BETASTL(2))
       SSI1(2)=XY(8)-RRS(3)*(BETAST(1)-BETASTL(1))
C
C      FOR ON-GROUND MOTION, ADD RUNWAY ROUGHNESS EFFECT
C      AMPLITUDE IS FAIRED UPON TOUCHDOWN OR TAKEOFF
C
       SSI1(3)=XZ(4)+XKA*SIN((WB+XKG*VGSPD)*T)
C
C      Swap Variables To Match Modified Algorithm
C      For Input to JACKDRVR
C
       XDD = ASI(1)
       YDD = ASI(2)
       ZDD = ASI(3)
       XD = XX(9)
       YD = XY(9)
       ZD = XZ(5)
       X = SSI1(1)
       Y = SSI1(2)
       Z = SSI1(3)
```

```
PHI = BETAS1(1)
THE = BETAS1(2)
PSI = BETAS1(3)
PHID = BSDTL(1)+BSDR(1)
THED = BSDTL(2)+BSDR(2)
PSID = BSDR(3)

RETURN
END
```

2.3. invplf.f

```
C  THIS SUBROUTINE WILL UNDERTAKE AN INVERSE TRANSFORMATION DEVELOPED
C  BY THE NEWTON-RAPHSON TECHNIQUE. LEG EXTENSIONS WILL BE TRANSFORMED
C  TO THE DEGREES OF FREEDOM.  THIS INVERSE TRANSFORMATION IS PERFORMED
C  BY AN ITERATIVE METHOD DENOTED AS NEWTON-RAPHSON TECHNIQUE.
C  ITERATIONS ARE TERMINATED WHEN THE DIFFERENCE BETWEEN TWO SUBSEQUENT
C  ITERATIONS IS LESS THAN SOME ERROR CRITERION.

C  RLI IS THE LEG EXTENSIONS.
C  SSI IS THE TRANSLATIONAL DISPLACEMENT OF THE PLATFORM.
C  BETAS IS THE ANGULAR DISPLACEMENT OF THE PLATFORM.
C  XS,YS,ZS: COORDINATES OF THE FIXED ENDS OF THE LEGS.
C  XM,YM,ZM: COORDINATES OF THE MOVING ENDS OF THE LEGS.
C  AAIS,BBII: GEOMETRY OF THE MOTION SYSTEM.
C  SSIIN: INITIAL TRANSLATIONAL DISPLACEMENT.
C  RRS: VECTOR NOT USED BY THIS SUBROUTINE.
C  LENEUT: LENGTH OF LEGS IN NEUTRAL POSITION.
C
SUBROUTINE INVPLF
      REAL RAML(6),XS(6),YS(6),ZS(6),XM(6),YM(6),ZM(6)
      REAL F(6),PFX(6),PFY(6),PFZ(6),PFS(6),PFT(6),PFP(6),
     + A(3,3),ZEBRA(36),P

      INCLUDE 'matrix1c.com'

      DATA IFLAG/0/
C*********************************************
C INITIALIZE SIMULATOR POSITION.
      DATA X/0./,Y/0./,Z/0./,P/0./,T/0./,S/0./
C*********************************************
C
      SAVE

      IF(IFLAG.EQ.0) THEN
          DO JACK=1,6
              XM(JACK)=AAIS(1,JACK)
              YM(JACK)=AAIS(2,JACK)
              ZM(JACK)=AAIS(3,JACK)
              XS(JACK)=BBII(1,JACK)
              YS(JACK)=BBII(2,JACK)
              ZS(JACK)=BBII(3,JACK)
          END DO
          IFLAG=1
      END IF
C***********************
C      X=SSI(1)+SSIIN(1)
C      Y=SSI(2)+SSIIN(2)
C      Z=SSI(3)+SSIIN(3)
C      P=BETAS(1)
C      T=BETAS(2)
C      S=BETAS(3)
C***********************
      DO JACK=1,6
          RAML(JACK)=RLI(JACK)+LENEUT
      END DO
      IT=0
 9    CONTINUE
      A(1,1)=COS(S)*COS(T)
      A(1,2)=SIN(S)*COS(T)
      A(1,3)=-SIN(T)
      A(2,1)=COS(S)*SIN(T)*SIN(P)-SIN(S)*COS(P)
      A(2,2)=SIN(S)*SIN(T)*SIN(P)+COS(S)*COS(P)
      A(2,3)=COS(T)*SIN(P)
      A(3,1)=COS(S)*SIN(T)*COS(P)+SIN(S)*SIN(P)
      A(3,2)=SIN(S)*SIN(T)*COS(P)-COS(S)*SIN(P)
      A(3,3)=COS(T)*COS(P)
      DO 17 I=1,6
        F(I)=XM(I)**2.+YM(I)**2.+ZM(I)**2.+XS(I)**2.+YS(I)**2.+
     +    ZS(I)**2.+X**2.+Y**2.+Z**2.-RAML(I)**2.
     +    +2.*(X-XS(I))*(XM(I)*A(1,1)+YM(I)*A(2,1)+ZM(I)*A(3,1))
     +    +2.*(Y-YS(I))*(XM(I)*A(1,2)+YM(I)*A(2,2)+ZM(I)*A(3,2))
     +    +2.*(Z-ZS(I))*(XM(I)*A(1,3)+YM(I)*A(2,3)+ZM(I)*A(3,3))
     +    -2.*(X*XS(I)+Y*YS(I)+Z*ZS(I))
        PFX(I)=2.*(X+XM(I)*A(1,1)+YM(I)*A(2,1)+ZM(I)*A(3,1)-XS(I))
        PFY(I)=2.*(Y+XM(I)*A(1,2)+YM(I)*A(2,2)+ZM(I)*A(3,2)-YS(I))
        PFZ(I)=2.*(Z+XM(I)*A(1,3)+YM(I)*A(2,3)+ZM(I)*A(3,3)-ZS(I))
        PFS(I)=-2.*(X-XS(I))*(XM(I)*A(1,2)+YM(I)*A(2,2)+ZM(I)*A(3,2))
     +         +2.*(Y-YS(I))*(XM(I)*A(1,1)+YM(I)*A(2,1)+ZM(I)*A(3,1))
        PFT(I)= 2.*(X-XS(I))*(-XM(I)*SIN(T)*COS(S)+YM(I)*SIN(P)*COS(T)*
     +    COS(S)+ZM(I)*COS(P)*COS(T)*COS(S))+2.*(Y-YS(I))*(-XM(I)*
     +    SIN(T)*SIN(S)+YM(I)*SIN(P)*COS(T)*SIN(S)+ZM(I)*COS(P)*COS(T)
     +    *SIN(S))-2.*(Z-ZS(I))*(XM(I)*COS(T)+YM(I)*SIN(P)*SIN(T)
     +    +ZM(I)*COS(P)* SIN(T))
        PFP(I)=2.*(X-XS(I))*(YM(I)*A(3,1)-ZM(I)*A(2,1))
     +        +2.*(Y-YS(I))*(YM(I)*A(3,2)-ZM(I)*A(2,2))
     +        +2.*(Z-ZS(I))*(YM(I)*A(3,3)-ZM(I)*A(2,3))
 17   CONTINUE
      DO 1 N=1,6
          ZEBRA(N)   =PFX(N)
          ZEBRA(N+6) =PFY(N)
          ZEBRA(N+12)=PFZ(N)
          ZEBRA(N+18)=PFS(N)
          ZEBRA(N+24)=PFT(N)
          ZEBRA(N+30)=PFP(N)
 1    CONTINUE
      N=6
      CALL SIMQ(ZEBRA,F,N,KS)
      IF(KS.EQ.1) THEN
          WRITE(*,*) ' 1 MATRIX IS SINGULAR'
          GOTO 22
      END IF
      IT=IT+1
      IF(IT.EQ.51) GO TO 22
      X=X-F(1)
      Y=Y-F(2)
      Z=Z-F(3)
      S=S-F(4)
      T=T-F(5)
      P=P-F(6)
      ZLIM1=0.01
      ZLIM2=0.1/57.296
      IF(MAX(ABS(F(1)),ABS(F(2)),ABS(F(3))).GT.ZLIM1) GO TO 9
```

```
      IF(MAX(ABS(F(4)),ABS(F(5)),ABS(F(6))).GT.ZLIM2) GO TO 9
 22   SSI(1)=X
      SSI(2)=Y
      SSI(3)=Z
      BETAS(1)=P
      BETAS(2)=T
      BETAS(3)=S
      RETURN
      END
C
```

2.4. *jackdrvr.f*

```
C  COMPUTE THE ACTUATOR EXTENSION COMMANDS BASED ON POSITION
C  IN INERTIAL FRAME.
C
      SUBROUTINE JACKDRVR

      INCLUDE 'matrix1c.com'

      INCLUDE 'comint2.com'

      INCLUDE 'optint3.com'

      REAL DUMMY31A(3,1),LLIS(3,3),L1(6),L2(6),L3(6),LENGTHTOT(6)

      REAL LLIMH,LLIML

C
C********** Langley VMS motion system geometry **********
      DATA LENEUT/3.2649/
      DATA RRS/0.0254,-0.635,-2.1946/
      DATA AAIS/2.1117179,   0.0762, 0.0,
     x           2.1117179,  -0.0762, 0.0,
     x          -0.98986594, -1.8669, 0.0,
     x          -1.12184942, -1.7907, 0.0,
     x          -1.12184942,  1.7907, 0.0,
     x          -0.98986594,  1.8669, 0.0/
      DATA BBII/  1.5021179,   1.9812,     2.58064,
     x             1.5021179,  -1.9812,     2.58064,
     x             0.96471232, -2.29147116, 2.58064,
     x            -2.46682768, -0.31027116, 2.58064,
     x            -2.46682768,  0.31027116, 2.58064,
     x             0.96471232,  2.29147116, 2.58064/
      DATA RLI/6*0./, SSI/3*0.0/, BETAS/3*0.0/
C********************************************************
C
C     McFadden Actuator Stroke Limit
C     (When Used Replace LLIMH/LLIML with LLIM)
C      DATA LLIM/0.92075/
C
C     Langley VMS Actuator Stroke Limits
      DATA LLIMH/0.7864/,LLIML/0.6487/
C
      DATA ACMAX/0.7/
      DATA FLAG/6*0/,FLAG2/0/,IT2/400/,NC2/400/,SUMFLAG/0/
      DATA RLID/6*0./,RLIDD/6*0./,RLIO/6*0./,RLIDO/6*0./

C
C     EXACT ANGLE COMPUTATIONS
C
      SINPHI = SIN(PHI)
      SINTH  = SIN(THE)
      SINPSI = SIN(PSI)
      COSPHI = COS(PHI)
      COSTH  = COS(THE)
      COSPSI = COS(PSI)
```

```
C
C     FORM LLIS TRANSFORMATION MATRIX
C
      LLIS(1,1) = COSPSI*COSTH
      LLIS(2,1) = SINPSI*COSTH
      LLIS(3,1) = -SINTH
      LLIS(1,2) = COSPSI*SINTH*SINPHI - SINPSI*COSPHI
      LLIS(2,2) = SINPSI*SINTH*SINPHI + COSPSI*COSPHI
      LLIS(3,2) = COSTH*SINPHI
      LLIS(1,3) = COSPSI*SINTH*COSPHI + SINPSI*SINPHI
      LLIS(2,3) = SINPSI*SINTH*COSPHI - COSPSI*SINPHI
      LLIS(3,3) = COSTH*COSPHI
C
C     Compute Leg Extensions
C
      DO JACK = 1,6
         CALL VMULT(LLIS,AAIS(1,JACK),DUMMY31A,3,3,1)
         L1(JACK) = DUMMY31A(1,1) + X - BBII(1,JACK)
         L2(JACK) = DUMMY31A(2,1) + Y - BBII(2,JACK)

         L3(JACK) = DUMMY31A(3,1) + Z - BBII(3,JACK)
         LENGTHTOT(JACK) = SQRT(L1(JACK)**2+L2(JACK)**2+L3(JACK)**2)
         LI(JACK)=LENGTHTOT(JACK) - LENEUT
      END DO

C
C***************** JACK EXTENSION LIMITING **********************
      DO JACK=1,6
         IF(FLAG(JACK).EQ.1) GOTO 5
C
C     Avail. Length for Same +/- Extension Limits
C         LAVAIL=LLIM-RLI(JACK)*SIGN(1.,RLID(JACK))
C
C     Avail. Length for Different +/- Extension Limits
C
          IF (RLI(JACK).GT.0.) THEN
              LAVAIL=LLIMH-RLI(JACK)*SIGN(1.,RLID(JACK))
          ELSE
              LAVAIL=LLIML-RLI(JACK)*SIGN(1.,RLID(JACK))
          END IF
C
          BRAKE(JACK)=ABS(RLID(JACK))**2-1.98*ACMAX*LAVAIL
          IF(BRAKE(JACK).LT.0.) GOTO 5
          FLAG(JACK)=1
          VLEAD=RLID(JACK)
          FLAG2=1
          DO JK=1,6
             IF(FLAG(JK).EQ.0) THEN
                 RATIO(JK)=ABS(RLID(JK)/VLEAD)
             ELSE
                 RATIO(JK)=1.
             END IF
          END DO
5     END DO
      SUMFLAG=FLAG(1)+FLAG(2)+FLAG(3)+FLAG(4)+FLAG(5)+FLAG(6)
C
C
```

```
C     When brake is set, determine if brake should be released
C
      DXX=ABS(X)-ABS(SSI(1))
      DYY=ABS(Y)-ABS(SSI(2))
      DZZ=ABS(Z)-ABS(SSI(3))
      DPHI=ABS(PHI)-ABS(BETAS(1))
      DTHE=ABS(THE)-ABS(BETAS(2))
      DPSI=ABS(PSI)-ABS(BETAS(3))
      DMAX=MAX(DXX,DYY,DZZ,DPHI,DTHE,DPSI)
      DMIN=MIN(DXX,DYY,DZZ,DPHI,DTHE,DPSI)
      IF((DMAX.LE.1.E-5).AND.(DMIN.LE.-0.01)) THEN
         ID=0
      ELSE
         ID=1
      END IF

      DO JACK=1,6
          IF(FLAG(JACK).EQ.0) GOTO 20
          RLIDD(JACK)=-ACMAX*SIGN(1.,RLID(JACK))
          RLID(JACK) = RLID(JACK)+RLIDD(JACK)*H
          GOTO 30
20        IF(SUMFLAG.EQ.0) GOTO 50
          IF(ABS(RLID(JACK)).GT.0.001) THEN
              RLIDD(JACK)=-ACMAX*SIGN(1.,RLID(JACK))*RATIO(JACK)
              RLID(JACK) = RLID(JACK)+RLIDD(JACK)*H
          END IF
30        IF(ABS(RLID(JACK)).GT.(ACMAX*H)) THEN
              RLI(JACK)=RLI(JACK)+RLID(JACK)*H
          ELSE
              RLID(JACK)=0.
              FLAG(JACK)=0
          END IF
          GOTO 70
50        IF(FLAG2.EQ.0) GOTO 60
          IF(ID.NE.0) GOTO 70
          FLAG2=0
          IT2=0
60        RLI(JACK)  =RLI(JACK) +
     +      (1.-COS(3.1416/2.*IT2/NC2))*(LI(JACK)-RLI(JACK))
          IF((JACK.EQ.6).AND.(IT2.LT.NC2)) IT2=IT2+1
C
70    END DO
C
      DO JACK=1,6
C
C     Same +/- Extension limits
C         RLI(JACK)=MIN(0.999*LLIM,MAX(-0.999*LLIM,RLI(JACK)))
C
C     Different +/- Extension Limits
          RLI(JACK)=MIN(0.999*LLIMH,MAX(-0.999*LLIML,RLI(JACK)))
C
          RLID(JACK)=(RLI(JACK)-RLIO(JACK))/H
          RLIDD(JACK)=(RLID(JACK)-RLIDO(JACK))/H
C
          RLIO(JACK)=RLI(JACK)
          RLIDO(JACK)=RLID(JACK)
      END DO
      RETURN
      END
```

2.5. liba.f

```
C
C
C  COMPUTE THE TRANSFORMATION MATRICES LIA AND TS
C
      SUBROUTINE LIBA

      INCLUDE 'optint3.com'

      REAL LIA(3,3), TA(3,3)

      DATA TA/1.,3*0.0,1.,3*0.0,1./

C
C     EXACT ANGLE COMPUTATIONS
C
      SINPHI = SIN(BETAA(1))
      SINTH  = SIN(BETAA(2))
      SINPSI = SIN(BETAA(3))
      COSPHI = COS(BETAA(1))
      COSTH  = COS(BETAA(2))
      COSPSI = COS(BETAA(3))
      TANTH  = SINTH/COSTH
C
C     FORM LIA TRANSFORMATION MATRIX
C
      LIA(1,1) = COSPSI*COSTH
      LIA(2,1) = SINPSI*COSTH
      LIA(3,1) = -SINTH
      LIA(1,2) = COSPSI*SINTH*SINPHI - SINPSI*COSPHI
      LIA(2,2) = SINPSI*SINTH*SINPHI + COSPSI*COSPHI
      LIA(3,2) = COSTH*SINPHI
      LIA(1,3) = COSPSI*SINTH*COSPHI + SINPSI*SINPHI
      LIA(2,3) = SINPSI*SINTH*COSPHI - COSPSI*SINPHI
      LIA(3,3) = COSTH*COSPHI
C
C     FORM TA TRANSFORMATION MATRIX
C
      TA(1,2)=SINPHI*TANTH
      TA(1,3)=COSPHI*TANTH
      TA(2,2)=COSPHI
      TA(2,3)=-SINPHI
      TA(3,2)=SINPHI/COSTH
      TA(3,3)=COSPHI/COSTH
C
C     Compute Inertial Accleration A2
C
      CALL VMULT(LIA,ACA,A2,3,3,1)
C
C     Compute euler Rates BETAAD
C
      CALL VMULT(TA,WAA,BETAAD,3,3,1)

      RETURN
      END
```

2.6. newopt4.f

```
C***** SUBROUTINE NEWOPT4.F ******
C
C     NONLINEAR WASHOUT ALGORITHM: ANG. VELOCITY DEVELOPMENT.
C     GIVEN  A/C ACCELS ACA AND EULER RATES BETAAD,
C     COMPUTE SIMULATOR INERTIAL DISPLACEMENT AND EULER ANGLES.
C
      SUBROUTINE NEWOPT4(MODE)

      INCLUDE 'comint2.com'

      INCLUDE 'wcom2.com'

      INCLUDE 'optint3.com'

      INCLUDE 'nopt4.com'

      INCLUDE 'matrix1c.com'

C     DATA IRESET/0/,IHOLD/0/

C
C     Compute Fairing Parameters
C
      SQWASH=SQWASHP*EA+SQWASHI*(1.0-EA)
      DELSQ=MAX(MIN(SQWASH-SQWASHP,1.0),-1.0)
      SQWASHP=SQWASH+DELSQ

      A=1.0-SQWASHP
      AA=1.0-SQWASHI
C
C     Fairing of Heave Nonlinear Gain and Limit
C
      GZ4(1)=AA*GZ40(1)+SQWASHI*GZ4S(1)
      GZ4(2)=AA*GZ40(2)+SQWASHI*GZ4S(2)
      GZ4(3)=AA*GZ40(3)+SQWASHI*GZ4S(3)
      AMX4=AA*AMX40+SQWASHI*AMX4S
C
C     Fairing of Runway Roughness Amplitude
C
      XKA=A*XKA0+SQWASHP*XKAS

      IF(MODE.EQ.1) THEN
         H = DT
C
C     Set "old" variables for future use in HOLD and OPERATE modes
C
         DO I=1,3
            A2NO(I)=0.
            BADNO(I)=0.
         END DO

         DO I=1,9
            XXO(I)=0.
            XYO(I)=0.
         END DO

         DO J=1,11
            DO I=1,11
               IF (I.GE.J) THEN
                  PX(I,J)=PXVEC((J-1)*11-J*(J-1)/2+I)
                  PX(J,I)=PX(I,J)
                  PY(I,J)=PYVEC((J-1)*11-J*(J-1)/2+I)
                  PY(J,I)=PY(I,J)
               END IF
            END DO
         END DO

         DO I=1,4
            XRO(I)=0.
              XPO(I)=0.
              XQO(I)=0.
         END DO

         DO J=1,5
            DO I=1,5
               IF (I.GE.J) THEN
                  PR(I,J)=PRVEC((J-1)*5-J*(J-1)/2+I)
                  PR(J,I)=PR(I,J)
                  PP(I,J)=PPVEC((J-1)*5-J*(J-1)/2+I)
                  PP(J,I)=PP(I,J)
                  PQ(I,J)=PQVEC((J-1)*5-J*(J-1)/2+I)
                  PQ(J,I)=PQ(I,J)
               END IF
            END DO
         END DO


         DO I=1,5
            XZO(I)=0.
         END DO

         DO J=1,6
            DO I=1,6
               IF (I.GE.J) THEN
                  PZ(I,J)=PZVEC((J-1)*6-J*(J-1)/2+I)
                  PZ(J,I)=PZ(I,J)
               END IF
            END DO
         END DO

         CALL RESETC2
C
C     Set "old" variables for future use in HOLD and OPERATE modes
C
         BETASRO(1)=PHI
         BETASRO(2)=THE
         BSDRO(1)=PHID
          BSDRO(2)=THED

         DO I=1,2
            XHO(I)=0.
            ACAO(I)=0.
            BSDTO(I)=0.
            BETASTO(I)=0.
            BETASTLO(I)=0.
            XTO=0.
            XT2O=0.
            WGUSTO=0.
            ACZT=0.
         END DO

          GO TO 1
      END IF

      IF(MODE.EQ.2) THEN
         CALL WTRIM3
      END IF
C
C     Compute Augmented Acceleration from W-Gust
C
      IF(MODE.EQ.3) THEN
         WGAV=0.5*(WGUST+WGUSTO)
         XT=XTO+DT*(-G2D1*XTO+XT2O+(G2N1-G2D1*G2N2)*WGAV)
         XTAV=0.5*(XT+XTO)
         XT2=XT2O+DT*(-G2D0*XTAV+(G2N0-G2D0*G2N2)*WGAV)
         ACZT=XT+G2N2*WGUST
         XTO=XT
         XT2O=XT2
         WGUSTO=WGUST
C
C     (first-order turbulence model no longer used)
C
C        XT=XTO+DT*(-G1D0*XTO+(G1N0-G1D0*G1N1)*WGUSTO)
C        XTO=XT
C        WGUSTO=WGUST
C        ACZT=XT+G1N1*WGUST
      END IF

      CALL LIBA
      CALL GAINOPT4
         A2N(3)=A2N(3)+GT4*ACZT

      IF(MODE.EQ.3) THEN
         CALL NFILX
         CALL NFILY
         CALL NFILZ
         CALL NFILR
         CALL NFILP
         CALL NFILQ
         CALL STATE4
         ELSE IF(MODE.EQ.2) THEN
            CALL STATE4
            CALL STATE4
            CALL STATE4
            CALL STATE4
            CALL STATE4
            CALL STATE4
      END IF
      IF(MODE.EQ.3) CALL INTEG4


    1 RETURN
      END
C
```

2.7. *nfilr.f*

```
C
C     Yaw Filter Neurocomputing Solver for the Riccati Equation
C
      SUBROUTINE NFILR

      INCLUDE 'comint2.com'

      INCLUDE 'nopt4.com'

      REAL SPR(5,5),SUMER,SUMPR,SUMPRT
      REAL PAPR(5,5),UPBR(5,5),UAPR(5,5),APUR(5,5)
      REAL EUR(5,5),UR(5),PZR(5)
C
C     Compute Prescribed Nonlinearity Alpha
C
      ALPR=PSI*Q2R*PSI
      IF(ALPR.GE.ALPRMAX) ALPR=ALPRMAX
      DO I=1,5
         APR(I,I)=APRO(I)+ALPR
      END DO
C
C     Start Training Iterations & Initialize Variables
C
      DO L=1,3

         DO I=1,5
            DO J=1,5
               SPR(I,J)=0.
               UPBR(I,J)=0.
               PAPR(I,J)=0.
               UAPR(I,J)=0.
               APUR(I,J)=0.
            END DO
         END DO
C
C     Compute Matrix Products SP and PA
C
         DO I=1,5
            DO J=1,5
               DO K=1,5
                  SPR(I,J)=SPR(I,J)+BRBR(I,K)*PR(K,J)
               END DO
            END DO
            DO K=1,5
               PAPR(I,1)=PAPR(I,1)+PR(I,K)*APR(K,1)
               PAPR(I,3)=PAPR(I,3)+PR(I,K)*APR(K,3)
               PAPR(I,5)=PAPR(I,5)+PR(I,K)*APR(K,5)
            END DO
            PAPR(I,2)=PR(I,1)*APR(1,2)+PR(I,2)*APR(2,2)
            PAPR(I,4)=PR(I,4)*APR(4,4)
         END DO
C
C     Compute Error Signal v, Vector p and Matrix Product pz
C     Note: Matrix Product A'P is transpose of PA by symmetry of P
```

```
C
         DO I=1,5
            UR(I)=0.
            PZR(I)=0.
            DO J=1,5
               IF(I.LE.J) THEN
                  SUMER=0.
                  DO K=1,5
                     SUMER=SUMER+PR(I,K)*SPR(K,J)
                  END DO
                  EUR(I,J)=SUMER-PAPR(I,J)-PAPR(J,I)-R1PR(I,J)
                  EUR(J,I)=EUR(I,J)
               END IF
               UR(I)=UR(I)+EUR(I,J)*ZR(L,J)
               PZR(I)=PZR(I)+PR(I,J)*ZR(L,J)
            END DO
         END DO
C
C     Compute Matrix Product Avz
C
         DO I=1,2
            DO J=1,5
               DO K=1,3
                  APUR(I,J)=APUR(I,J)+APR(I,K)*UR(K)*ZR(L,J)
               END DO
                  APUR(I,J)=APUR(I,J)+APR(I,5)*UR(5)*ZR(L,J)
            END DO
         END DO
         DO I=3,4
            DO J=1,5
                  APUR(I,J)=APUR(I,J)+APR(I,1)*UR(1)*ZR(L,J)
               DO K=3,5
                  APUR(I,J)=APUR(I,J)+APR(I,K)*UR(K)*ZR(L,J)
               END DO
            END DO
         END DO
            DO J=1,5
               APUR(5,J)=APR(5,5)*UR(5)*ZR(L,J)
            END DO
C
C     Compute Matrix Product vzA
C
         DO I=1,5
            DO K=1,5
               UAPR(I,1)=UAPR(I,1)+UR(I)*ZR(L,K)*APR(K,1)
               UAPR(I,3)=UAPR(I,3)+UR(I)*ZR(L,K)*APR(K,3)
               UAPR(I,5)=UAPR(I,5)+UR(I)*ZR(L,K)*APR(K,5)
            END DO
            UAPR(I,2)=UR(I)*ZR(L,1)*APR(1,2)
     x         +UR(I)*ZR(L,2)*APR(2,2)
            UAPR(I,4)=UR(I)*ZR(L,4)*APR(4,4)
         END DO
C
C     Compute Matrix Product vp'S
C
         DO I=1,5
            DO J=1,4
```

```
               DO K=1,4
                  UPBR(I,J)=UPBR(I,J)+UR(I)*PZR(K)*BRBR(K,J)
               END DO
            END DO
         END DO
C
C     Sum Avz + vzA + vp'S and integrate to update Riccati Solution P
C
         DO I=1,5
            DO J=1,5
               IF(I.LE.J) THEN
                  SUMPR=APUR(I,J)+UAPR(I,J)-UPBR(I,J)
                  IF(I.NE.J) THEN
                     SUMPRT=APUR(J,I)+UAPR(J,I)-UPBR(J,I)
                  ELSE
                     SUMPRT=SUMPR
                  END IF
                  PR(I,J)=PR(I,J)+MUR*(SUMPR+SUMPRT)
                  PR(J,I)=PR(I,J)
               END IF
            END DO
         END DO

      END DO

      RETURN
      END
```

2.8. nfilp.f

```
C
C     Roll Filter Neurocomputing Solver for the Riccati Equation
C
      SUBROUTINE NFILP

      INCLUDE 'comint2.com'

      INCLUDE 'nopt4.com'

      REAL SPP(5,5),SUMEP,SUMPP,SUMPPT
      REAL PAPP(5,5),UPBP(5,5),UAPP(5,5),APUP(5,5)
      REAL EUP(5,5),UP(5),PZP(5)
C
C     Compute Prescribed Nonlinearity Alpha
C
      ALPP=PHI*Q2P*PHI
      IF(ALPP.GE.ALPPMAX) ALPP=ALPPMAX
      DO I=1,5
         APP(I,I)=APPO(I)+ALPP
      END DO
C
C     Start Training Iterations & Initialize Variables
C
      DO L=1,3

         DO I=1,5
            DO J=1,5
               SPP(I,J)=0.
               UPBP(I,J)=0.
               PAPP(I,J)=0.
               UAPP(I,J)=0.
               APUP(I,J)=0.
            END DO
         END DO
C
C     Compute Matrix Products SP and PA
C
         DO I=1,5
            DO J=1,5
               DO K=1,5
                  SPP(I,J)=SPP(I,J)+BRBP(I,K)*PP(K,J)
               END DO
            END DO
            DO K=1,5
               PAPP(I,1)=PAPP(I,1)+PP(I,K)*APP(K,1)
               PAPP(I,3)=PAPP(I,3)+PP(I,K)*APP(K,3)
               PAPP(I,5)=PAPP(I,5)+PP(I,K)*APP(K,5)
            END DO
            PAPP(I,2)=PP(I,1)*APP(1,2)+PP(I,2)*APP(2,2)
            PAPP(I,4)=PP(I,4)*APP(4,4)
         END DO
C
C     Compute Error Signal v, Vector p and Matrix Product pz
C     Note: Matrix Product A'P is transpose of PA by symmetry of P
```

```
C
         DO I=1,5
            UP(I)=0.
            PZP(I)=0.
            DO J=1,5
               IF(I.LE.J) THEN
                  SUMEP=0.
                  DO K=1,5
                     SUMEP=SUMEP+PP(I,K)*SPP(K,J)
                  END DO
                  EUP(I,J)=SUMEP-PAPP(I,J)-PAPP(J,I)-R1PP(I,J)
                  EUP(J,I)=EUP(I,J)
               END IF
               UP(I)=UP(I)+EUP(I,J)*ZP(L,J)
               PZP(I)=PZP(I)+PP(I,J)*ZP(L,J)
            END DO
         END DO
C
C     Compute Matrix Product Avz
C
         DO I=1,2
            DO J=1,5
               DO K=1,3
                  APUP(I,J)=APUP(I,J)+APP(I,K)*UP(K)*ZP(L,J)
               END DO
                  APUP(I,J)=APUP(I,J)+APP(I,5)*UP(5)*ZP(L,J)
            END DO
         END DO
         DO I=3,4
            DO J=1,5
                  APUP(I,J)=APUP(I,J)+APP(I,1)*UP(1)*ZP(L,J)
               DO K=3,5
                  APUP(I,J)=APUP(I,J)+APP(I,K)*UP(K)*ZP(L,J)
               END DO
            END DO
         END DO
            DO J=1,5
               APUP(5,J)=APP(5,5)*UP(5)*ZP(L,J)
            END DO
C
C     Compute Matrix Product vzA
C
         DO I=1,5
            DO K=1,5
               UAPP(I,1)=UAPP(I,1)+UP(I)*ZP(L,K)*APP(K,1)
               UAPP(I,3)=UAPP(I,3)+UP(I)*ZP(L,K)*APP(K,3)
               UAPP(I,5)=UAPP(I,5)+UP(I)*ZP(L,K)*APP(K,5)
            END DO
            UAPP(I,2)=UP(I)*ZP(L,1)*APP(1,2)
     x         +UP(I)*ZP(L,2)*APP(2,2)
            UAPP(I,4)=UP(I)*ZP(L,4)*APP(4,4)
         END DO
C
C     Compute Matrix Product vp'S
C
         DO I=1,5
            DO J=1,4
```

```
               DO K=1,4
                  UPBP(I,J)=UPBP(I,J)+UP(I)*PZP(K)*BRBP(K,J)
               END DO
            END DO
         END DO
C
C     Sum Avz + vzA + vp'S and integrate to update Riccati Solution P
C
         DO I=1,5
            DO J=1,5
               IF(I.LE.J) THEN
                  SUMPP=APUP(I,J)+UAPP(I,J)-UPBP(I,J)
                  IF(I.NE.J) THEN
                     SUMPPT=APUP(J,I)+UAPP(J,I)-UPBP(J,I)
                  ELSE
                     SUMPPT=SUMPP
                  END IF
                  PP(I,J)=PP(I,J)+MUP*(SUMPP+SUMPPT)
                  PP(J,I)=PP(I,J)
               END IF
            END DO
         END DO

      END DO

      RETURN
      END
```

2.9. nfilq.f

```
C
C     Pitch Filter Neurocomputing Solver for the Riccati Equation
C
      SUBROUTINE NFILQ

      INCLUDE 'comint2.com'

      INCLUDE 'nopt4.com'

      REAL SPQ(5,5),SUMEQ,SUMPQ,SUMPQT
      REAL PAPQ(5,5),UPBQ(5,5),UAPQ(5,5),APUQ(5,5)
      REAL EUQ(5,5),UQ(5),PZQ(5)
C
C     Compute Prescribed Nonlinearity Alpha
C
      ALPQ=THE*Q2Q*THE
      IF(ALPQ.GE.ALPQMAX) ALPQ=ALPQMAX
      DO I=1,5
         APQ(I,I)=APQO(I)+ALPQ
      END DO
C
C     Start Training Iterations & Initialize Variables
C
      DO L=1,3

         DO I=1,5
            DO J=1,5
               SPQ(I,J)=0.
               UPBQ(I,J)=0.
               PAPQ(I,J)=0.
               UAPQ(I,J)=0.
               APUQ(I,J)=0.
            END DO
         END DO
C
C     Compute Matrix Products SP and PA
C
         DO I=1,5
            DO J=1,5
               DO K=1,5
                  SPQ(I,J)=SPQ(I,J)+BRBQ(I,K)*PQ(K,J)
               END DO
            END DO
            DO K=1,5
               PAPQ(I,1)=PAPQ(I,1)+PQ(I,K)*APQ(K,1)
               PAPQ(I,3)=PAPQ(I,3)+PQ(I,K)*APQ(K,3)
               PAPQ(I,5)=PAPQ(I,5)+PQ(I,K)*APQ(K,5)
            END DO
            PAPQ(I,2)=PQ(I,1)*APQ(1,2)+PQ(I,2)*APQ(2,2)
            PAPQ(I,4)=PQ(I,4)*APQ(4,4)
         END DO
C
C     Compute Error Signal v, Vector p and Matrix Product pz
```

```
C     Note: Matrix Product A'P is transpose of PA by symmetry of P
C
         DO I=1,5
            UQ(I)=0.
            PZQ(I)=0.
            DO J=1,5
               IF(I.LE.J) THEN
                  SUMEQ=0.
                  DO K=1,5
                     SUMEQ=SUMEQ+PQ(I,K)*SPQ(K,J)
                  END DO
                  EUQ(I,J)=SUMEQ-PAPQ(I,J)-PAPQ(J,I)-R1PQ(I,J)
                  EUQ(J,I)=EUQ(I,J)
               END IF
               UQ(I)=UQ(I)+EUQ(I,J)*ZQ(L,J)
               PZQ(I)=PZQ(I)+PQ(I,J)*ZQ(L,J)
            END DO
         END DO
C
C     Compute Matrix Product Avz
C
         DO I=1,2
            DO J=1,5
               DO K=1,3
                  APUQ(I,J)=APUQ(I,J)+APQ(I,K)*UQ(K)*ZQ(L,J)
               END DO
                  APUQ(I,J)=APUQ(I,J)+APQ(I,5)*UQ(5)*ZQ(L,J)
            END DO
         END DO
         DO I=3,4
            DO J=1,5
                  APUQ(I,J)=APUQ(I,J)+APQ(I,1)*UQ(1)*ZQ(L,J)
               DO K=3,5
                  APUQ(I,J)=APUQ(I,J)+APQ(I,K)*UQ(K)*ZQ(L,J)
               END DO
            END DO
         END DO
            DO J=1,5
               APUQ(5,J)=APQ(5,5)*UQ(5)*ZQ(L,J)
            END DO
C
C     Compute Matrix Product vzA
C
         DO I=1,5
            DO K=1,5
               UAPQ(I,1)=UAPQ(I,1)+UQ(I)*ZQ(L,K)*APQ(K,1)
               UAPQ(I,3)=UAPQ(I,3)+UQ(I)*ZQ(L,K)*APQ(K,3)
               UAPQ(I,5)=UAPQ(I,5)+UQ(I)*ZQ(L,K)*APQ(K,5)
            END DO
            UAPQ(I,2)=UQ(I)*ZQ(L,1)*APQ(1,2)
     x         +UQ(I)*ZQ(L,2)*APQ(2,2)
            UAPQ(I,4)=UQ(I)*ZQ(L,4)*APQ(4,4)
         END DO
C
C     Compute Matrix Product vp'S
C
         DO I=1,5
```

```
            DO J=1,4
               DO K=1,4
                  UPBQ(I,J)=UPBQ(I,J)+UQ(I)*PZQ(K)*BRBQ(K,J)
               END DO
            END DO
         END DO
C
C     Sum Avz + vzA + vp'S and integrate to update Riccati Solution P
C
         DO I=1,5
            DO J=1,5
               IF(I.LE.J) THEN
                  SUMPQ=APUQ(I,J)+UAPQ(I,J)-UPBQ(I,J)
                  IF(I.NE.J) THEN
                     SUMPQT=APUQ(J,I)+UAPQ(J,I)-UPBQ(J,I)
                  ELSE
                     SUMPQT=SUMPQ
                  END IF
                  PQ(I,J)=PQ(I,J)+MUQ*(SUMPQ+SUMPQT)
                  PQ(J,I)=PQ(I,J)
               END IF
            END DO
         END DO

      END DO

      RETURN
      END
```

2.10. nfilx.f

```
C
C     Surge Filter Neurocomputing Solver for the Riccati Equation
C
      SUBROUTINE NFILX

      INCLUDE 'comint2.com'

      INCLUDE 'nopt4.com'

      REAL SPX(11,11),SUMEX,SUMPX,SUMPXT
      REAL PAPX(11,11),UPBX(11,11),UAPX(11,11),APUX(11,11)
      REAL EUX(11,11),UX(11),PZX(11)

C
C     Compute Prescribed Nonlinearity Alpha
C
      ALPX=X*Q2X(1)*X+XD*Q2X(2)*XD
      IF(ALPX.GT.ALPXMAX) ALPX=ALPXMAX
      DO I=1,11
         APX(I,I)=APXO(I)+ALPX
      END DO
C
C     Start Training Iterations & Initialize Variables
C
      DO L=1,3

         DO I=1,11
            DO J=1,11
               SPX(I,J)=0.0
               PAPX(I,J)=0.0
               UPBX(I,J)=0.0
               UAPX(I,J)=0.0
               APUX(I,J)=0.0
            END DO
         END DO
C
C     Compute Matrix Product SP
C
         DO I=1,6
            DO J=1,11
               DO K=1,6
                  SPX(I,J)=SPX(I,J)+BRBX(I,K)*PX(K,J)
               END DO
                  SPX(I,J)=SPX(I,J)+BRBX(I,9)*PX(9,J)
            END DO
         END DO
            DO J=1,11
               DO K=1,6
                  SPX(9,J)=SPX(9,J)+BRBX(9,K)*PX(K,J)
               END DO
                  SPX(9,J)=SPX(9,J)+BRBX(9,9)*PX(9,J)
            END DO
C
C     Compute Matrix Product PA
```

```
C
         DO I=1,11
            DO J=1,6
               DO K=1,6
                  PAPX(I,J)=PAPX(I,J)+PX(I,K)*APX(K,J)
               END DO
            END DO
            PAPX(I,7)=PX(I,7)*APX(7,7)
            PAPX(I,8)=PX(I,7)*APX(7,8)+PX(I,8)*APX(8,8)
            PAPX(I,9)=PX(I,8)*APX(8,9)+PX(I,9)*APX(9,9)
               DO K=1,6
                  PAPX(I,10)=PAPX(I,10)+PX(I,K)*APX(K,10)
               END DO
                  PAPX(I,10)=PAPX(I,10)+PX(I,10)*APX(10,10)
               DO K=1,6
                  PAPX(I,11)=PAPX(I,11)+PX(I,K)*APX(K,11)
               END DO
                  PAPX(I,11)=PAPX(I,11)+PX(I,11)*APX(11,11)
         END DO
C
C     Compute Error Signal v, Vector p and Matrix Product vz
C     Note: Matrix Product A'P is transpose of PA by symmetry of P
C
         DO I=1,11
            UX(I)=0.
            PZX(I)=0.
            DO J=1,11
               IF(I.LE.J) THEN
                  SUMEX=0.
                  DO K=1,11
                     SUMEX=SUMEX+PX(I,K)*SPX(K,J)
                  END DO
                  EUX(I,J)=SUMEX-PAPX(J,I)-PAPX(I,J)-R1PX(I,J)
                  EUX(J,I)=EUX(I,J)
               END IF
               UX(I)=UX(I)+EUX(I,J)*ZX(L,J)
               PZX(I)=PZX(I)+PX(I,J)*ZX(L,J)
            END DO
         END DO
C
C     Compute Matrix Product Avz
C
         DO I=1,6
            DO J=1,11
               DO K=1,6
                  APUX(I,J)=APUX(I,J)+APX(I,K)*UX(K)*ZX(L,J)
               END DO
                  APUX(I,J)=APUX(I,J)+APX(I,10)*UX(10)*ZX(L,J)
     x            +APX(I,11)*UX(11)*ZX(L,J)
            END DO
         END DO
            DO J=1,11
               APUX(7,J)=APX(7,7)*UX(7)*ZX(L,J)
     x         +APX(7,8)*UX(8)*ZX(L,J)
               APUX(8,J)=APX(8,8)*UX(8)*ZX(L,J)
     x         +APX(8,9)*UX(9)*ZX(L,J)
               APUX(9,J)=APX(9,9)*UX(9)*ZX(L,J)
               APUX(10,J)=APX(10,10)*UX(10)*ZX(L,J)
               APUX(11,J)=APX(11,11)*UX(11)*ZX(L,J)
            END DO
C
C     Compute Matrix Product vzA
C
         DO I=1,11
            DO J=1,6
               DO K=1,6
                  UAPX(I,J)=UAPX(I,J)+UX(I)*ZX(L,K)*APX(K,J)
               END DO
            END DO
            UAPX(I,7)=UX(I)*ZX(L,7)*APX(7,7)
            UAPX(I,8)=UX(I)*ZX(L,7)*APX(7,8)
     x            +UX(I)*ZX(L,8)*APX(8,8)
            UAPX(I,9)=UX(I)*ZX(L,8)*APX(8,9)
     x            +UX(I)*ZX(L,9)*APX(9,9)
            DO K=1,6
                UAPX(I,10)=UAPX(I,10)+UX(I)*ZX(L,K)*APX(K,10)
            END DO
                UAPX(I,10)=UAPX(I,10)+UX(I)*ZX(L,10)*APX(10,10)
            DO K=1,6
                UAPX(I,11)=UAPX(I,11)+UX(I)*ZX(L,K)*APX(K,11)
            END DO
                UAPX(I,11)=UAPX(I,11)+UX(I)*ZX(L,11)*APX(11,11)
         END DO
C
C     Compute Matrix Product vp'S
C
         DO I=1,11
            DO J=1,6
               DO K=1,6
                   UPBX(I,J)=UPBX(I,J)+UX(I)*PZX(K)*BRBX(K,J)
               END DO
                   UPBX(I,J)=UPBX(I,J)+UX(I)*PZX(9)*BRBX(9,J)
            END DO
               DO K=1,6
                   UPBX(I,9)=UPBX(I,9)+UX(I)*PZX(K)*BRBX(K,9)
               END DO
                   UPBX(I,9)=UPBX(I,9)+UX(I)*PZX(9)*BRBX(9,9)
         END DO
C
C     Sum Avz + vzA + vp'S and integrate to update Riccati Solution P
C
         DO I=1,11
            DO J=1,11
                IF(I.LE.J) THEN
                  SUMPX=APUX(I,J)+UAPX(I,J)-UPBX(I,J)
                  IF(I.NE.J) THEN
                  SUMPXT=APUX(J,I)+UAPX(J,I)-UPBX(J,I)
                  ELSE
                  SUMPXT=SUMPX
                  END IF
                  PX(I,J)=PX(I,J)+MUX*(SUMPX+SUMPXT)
                  PX(J,I)=PX(I,J)
                END IF
            END DO
```

```
   END DO
END DO

RETURN
END
```

2.11. nfily.f

```
C
C     Sway Filter Neurocomputing Solver for the Riccati Equation
C
      SUBROUTINE NFILY

      INCLUDE 'comint2.com'

      INCLUDE 'nopt4.com'

      REAL SPY(11,11),SUMEY,SUMPY,SUMPYT
      REAL PAPY(11,11),UPBY(11,11),UAPY(11,11),APUY(11,11)
      REAL EUY(11,11),UY(11),PZY(11)

C
C     Compute Prescribed Nonlinearity Alpha
C
      ALPY=Y*Q2Y(1)*Y+YD*Q2Y(2)*YD
      IF(ALPY.GT.ALPYMAX) ALPY=ALPYMAX
      DO I=1,11
         APY(I,I)=APYO(I)+ALPY
      END DO
C
C     Start Training Iterations & Initialize Variables
C
      DO L=1,3

         DO I=1,11
            DO J=1,11
               SPY(I,J)=0.0
               PAPY(I,J)=0.0
               UPBY(I,J)=0.0
               UAPY(I,J)=0.0
               APUY(I,J)=0.0
            END DO
         END DO
C
C     Compute Matrix Product SP
C
         DO I=1,6
            DO J=1,11
               DO K=1,6
                  SPY(I,J)=SPY(I,J)+BRBY(I,K)*PY(K,J)
               END DO
                  SPY(I,J)=SPY(I,J)+BRBY(I,9)*PY(9,J)
            END DO
         END DO
            DO J=1,11
               DO K=1,6
                  SPY(9,J)=SPY(9,J)+BRBY(9,K)*PY(K,J)
               END DO
                  SPY(9,J)=SPY(9,J)+BRBY(9,9)*PY(9,J)
            END DO
C
C     Compute Matrix Product PA
```

```
C
         DO I=1,11
            DO J=1,6
               DO K=1,6
                  PAPY(I,J)=PAPY(I,J)+PY(I,K)*APY(K,J)
               END DO
            END DO
            PAPY(I,7)=PY(I,7)*APY(7,7)
            PAPY(I,8)=PY(I,7)*APY(7,8)+PY(I,8)*APY(8,8)
            PAPY(I,9)=PY(I,8)*APY(8,9)+PY(I,9)*APY(9,9)
               DO K=1,6
                  PAPY(I,10)=PAPY(I,10)+PY(I,K)*APY(K,10)
               END DO
                  PAPY(I,10)=PAPY(I,10)+PY(I,10)*APY(10,10)
               DO K=1,6
                  PAPY(I,11)=PAPY(I,11)+PY(I,K)*APY(K,11)
               END DO
                  PAPY(I,11)=PAPY(I,11)+PY(I,11)*APY(11,11)
         END DO
C
C     Compute Error Signal v, Vector p and Matrix Product vz
C     Note: Matrix Product A'P is transpose of PA by symmetry of P
C
         DO I=1,11
            UY(I)=0.
            PZY(I)=0.
            DO J=1,11
               IF(I.LE.J) THEN
                  SUMEY=0.
                  DO K=1,11
                     SUMEY=SUMEY+PY(I,K)*SPY(K,J)
                  END DO
                  EUY(I,J)=SUMEY-PAPY(J,I)-PAPY(I,J)-R1PY(I,J)
                  EUY(J,I)=EUY(I,J)
               END IF
               UY(I)=UY(I)+EUY(I,J)*ZY(L,J)
               PZY(I)=PZY(I)+PY(I,J)*ZY(L,J)
            END DO
         END DO

C
C     Compute Matrix Product Avz
C
         DO I=1,6
            DO J=1,11
               DO K=1,6
                  APUY(I,J)=APUY(I,J)+APY(I,K)*UY(K)*ZY(L,J)
               END DO
                  APUY(I,J)=APUY(I,J)+APY(I,10)*UY(10)*ZY(L,J)
     x                +APY(I,11)*UY(11)*ZY(L,J)
            END DO
         END DO
            DO J=1,11
               APUY(7,J)=APY(7,7)*UY(7)*ZY(L,J)
     x         +APY(7,8)*UY(8)*ZY(L,J)
               APUY(8,J)=APY(8,8)*UY(8)*ZY(L,J)
     x         +APY(8,9)*UY(9)*ZY(L,J)
```

```
               APUY(9,J)=APY(9,9)*UY(9)*ZY(L,J)
               APUY(10,J)=APUY(10,J)+APY(10,10)*UY(10)*ZY(L,J)
               APUY(11,J)=APUY(11,J)+APY(11,11)*UY(11)*ZY(L,J)
            END DO
C
C     Compute Matrix Product vzA
C
         DO I=1,11
            DO J=1,6
               DO K=1,6
                  UAPY(I,J)=UAPY(I,J)+UY(I)*ZY(L,K)*APY(K,J)
               END DO
            END DO
            UAPY(I,7)=UY(I)*ZY(L,7)*APY(7,7)
            UAPY(I,8)=UY(I)*ZY(L,7)*APY(7,8)
      x             +UY(I)*ZY(L,8)*APY(8,8)
            UAPY(I,9)=UY(I)*ZY(L,8)*APY(8,9)
      x             +UY(I)*ZY(L,9)*APY(9,9)
            DO K=1,6
                UAPY(I,10)=UAPY(I,10)+UY(I)*ZY(L,K)*APY(K,10)
            END DO
                UAPY(I,10)=UAPY(I,10)+UY(I)*ZY(L,10)*APY(10,10)
               DO K=1,6
                  UAPY(I,11)=UAPY(I,11)+UY(I)*ZY(L,K)*APY(K,11)
               END DO
                  UAPY(I,11)=UAPY(I,11)+UY(I)*ZY(L,11)*APY(11,11)
         END DO
C
C     Compute Matrix Product vp'S
C
         DO I=1,11
            DO J=1,6
               DO K=1,6
                  UPBY(I,J)=UPBY(I,J)+UY(I)*PZY(K)*BRBY(K,J)
               END DO
                  UPBY(I,J)=UPBY(I,J)+UY(I)*PZY(9)*BRBY(9,J)
            END DO
               DO K=1,6
                  UPBY(I,9)=UPBY(I,9)+UY(I)*PZY(K)*BRBY(K,9)
               END DO
                  UPBY(I,9)=UPBY(I,9)+UY(I)*PZY(9)*BRBY(9,9)
         END DO
C
C     Sum Avz + vzA + vp'S and integrate to update Riccati Solution P
C
         DO I=1,11
            DO J=1,11
               IF(I.LE.J) THEN
                  SUMPY=APUY(I,J)+UAPY(I,J)-UPBY(I,J)
                  IF(I.NE.J) THEN
                     SUMPYT=APUY(J,I)+UAPY(J,I)-UPBY(J,I)
                  ELSE
                     SUMPYT=SUMPY
                  END IF
                  PY(I,J)=PY(I,J)+MUY*(SUMPY+SUMPYT)
                  PY(J,I)=PY(I,J)
               END IF
            END DO
         END DO

      END DO

      RETURN
      END
```

2.12. *nfilz.f*

```
C
C     Heave Filter Neurocomputing Solver for the Riccati Equation
C
      SUBROUTINE NFILZ

      INCLUDE 'comint2.com'

      INCLUDE 'nopt4.com'

      REAL SPZ(6,6),SUMEZ,SUMPZ,SUMPZT
      REAL PAPZ(6,6),UPBZ(6,6),UAPZ(6,6),APUZ(6,6)
      REAL EUZ(6,6),UZ(6),PZZ(6)

C
C     Compute Prescribed Nonlinearity Alpha
C
      ALPZ=Z*Q2Z(1)*Z+ZD*Q2Z(2)*ZD
      IF(ALPZ.GT.ALPZMAX) ALPZ=ALPZMAX
      DO I=1,6
         APZ(I,I)=APZO(I)+ALPZ
      END DO
C
C     Start Training Iterations & Initialize Variables
C
      DO L=1,3

         DO I=1,6
            DO J=1,6
               SPZ(I,J)=0.
               PAPZ(I,J)=0.
               UPBZ(I,J)=0.
               UAPZ(I,J)=0.
               APUZ(I,J)=0.
            END DO
         END DO
C
C     Compute Matrix Product SP
C
         DO I=1,2
            DO J=1,6
               SPZ(I,J)=BRBZ(I,1)*PZ(1,J)
     x                 +BRBZ(I,2)*PZ(2,J)+BRBZ(I,5)*PZ(5,J)
            END DO
         END DO
            DO J=1,6
               SPZ(5,J)=BRBZ(5,1)*PZ(1,J)
     x                 +BRBZ(5,2)*PZ(2,J)+BRBZ(5,5)*PZ(5,J)
            END DO
C
C     Compute Matrix Product PA
C

         DO I=1,6
            PAPZ(I,1)=PZ(I,1)*APZ(1,1)+PZ(I,2)*APZ(2,1)
            PAPZ(I,2)=PZ(I,1)*APZ(1,2)+PZ(I,2)*APZ(2,2)
            PAPZ(I,3)=PZ(I,3)*APZ(3,3)
            PAPZ(I,4)=PZ(I,3)*APZ(3,4)+PZ(I,4)*APZ(4,4)
            PAPZ(I,5)=PZ(I,4)*APZ(4,5)+PZ(I,5)*APZ(5,5)
            PAPZ(I,6)=PZ(I,1)*APZ(1,6)+PZ(I,2)*APZ(2,6)
      x              +PZ(I,6)*APZ(6,6)
         END DO
C
C     Compute Error Signal v, Vector p and Matrix Product vz
C     Note: Matrix Product A'P is transpose of PA by symmetry of P
C
         DO I=1,6
            UZ(I)=0.
            PZZ(I)=0.
            DO J=1,6
               IF(I.LE.J) THEN

                  SUMEZ=0.
                  DO K=1,6
                     SUMEZ=SUMEZ+PZ(I,K)*SPZ(K,J)
                  END DO
                  EUZ(I,J)=SUMEZ-PAPZ(J,I)-PAPZ(I,J)-R1PZ(I,J)
                  EUZ(J,I)=EUZ(I,J)
               END IF
               UZ(I)=UZ(I)+EUZ(I,J)*ZZ(L,J)
               PZZ(I)=PZZ(I)+PZ(I,J)*ZZ(L,J)
            END DO
         END DO
C
C     Compute Matrix Product Avz
C
         DO I=1,2
            DO J=1,6
               APUZ(I,J)=APZ(I,1)*UZ(1)*ZZ(L,J)
     x             +APZ(I,2)*UZ(2)*ZZ(L,J)+APZ(I,6)*UZ(6)*ZZ(L,J)
            END DO
         END DO
            DO J=1,6
               APUZ(3,J)=APZ(3,3)*UZ(3)*ZZ(L,J)
     x             +APZ(3,4)*UZ(4)*ZZ(L,J)
               APUZ(4,J)=APZ(4,4)*UZ(4)*ZZ(L,J)
     x             +APZ(4,5)*UZ(5)*ZZ(L,J)
               APUZ(5,J)=APZ(5,5)*UZ(5)*ZZ(L,J)
               APUZ(6,J)=APZ(6,6)*UZ(6)*ZZ(L,J)
            END DO
C
C     Compute Matrix Product vzA
C
         DO I=1,6
            UAPZ(I,1)=UZ(I)*ZZ(L,1)*APZ(1,1)+UZ(I)*ZZ(L,2)*APZ(2,1)
            UAPZ(I,2)=UZ(I)*ZZ(L,1)*APZ(1,2)+UZ(I)*ZZ(L,2)*APZ(2,2)
            UAPZ(I,3)=UZ(I)*ZZ(L,3)*APZ(3,3)
            UAPZ(I,4)=UZ(I)*ZZ(L,3)*APZ(3,4)+UZ(I)*ZZ(L,4)*APZ(4,4)
            UAPZ(I,5)=UZ(I)*ZZ(L,4)*APZ(4,5)+UZ(I)*ZZ(L,5)*APZ(5,5)
            UAPZ(I,6)=UZ(I)*ZZ(L,1)*APZ(1,6)
     x              +UZ(I)*ZZ(L,2)*APZ(2,6)+UZ(I)*ZZ(L,6)*APZ(6,6)
```

```
         END DO
C
C     Compute Matrix Product vp'S
C
         DO I=1,6
            DO J=1,2
               UPBZ(I,J)=UZ(I)*PZZ(1)*BRBZ(1,J)
     x             +UZ(I)*PZZ(2)*BRBZ(2,J)+UZ(I)*PZZ(5)*BRBZ(5,J)
            END DO
               UPBZ(I,5)=UZ(I)*PZZ(1)*BRBZ(1,5)
     x             +UZ(I)*PZZ(2)*BRBZ(2,5)+UZ(I)*PZZ(5)*BRBZ(5,5)

         END DO
C
C     Sum Avz + vzA + vp'S and integrate to update Riccati Solution P
C
         DO I=1,6
            DO J=1,6
               IF(I.LE.J) THEN
                  SUMPZ=APUZ(I,J)+UAPZ(I,J)-UPBZ(I,J)
                  IF(I.NE.J) THEN
                     SUMPZT=APUZ(J,I)+UAPZ(J,I)-UPBZ(J,I)
                  ELSE
                     SUMPZT=SUMPZ
                  END IF
                  PZ(I,J)=PZ(I,J)+MUZ*(SUMPZ+SUMPZT)
                  PZ(J,I)=PZ(I,J)
               END IF
            END DO
         END DO

      END DO

      RETURN
      END
```

2.13. resetc2.f

```
      SUBROUTINE RESETC2
C
C     THIS ROUTINE:
C
C    (1) DOES T=0 INITIALIZATION OF MOTION VARIABLES
C
C    (2) USES A SECOND ORDER SCHEME TO DRIVE TO THE NEUTRAL
C        POSITION. (OVERDAMPED OSCILLATOR; ZETA = 1.5, OMEGAN = 1.0 )
C
      INCLUDE 'comint2.com'

      INCLUDE 'wcom2.com'

      INCLUDE 'matrix1c.com'

C**********************************************************************
C
C      GAINS, ACCELERATION AND VELOCITY LIMITS FOR SECOND ORDER.
C
C      VALUES FOR ACCELERATION AND VELOCITY ARE METERS/SEC**2
C      AND METERS/SEC.  ROTATIONS AND ROTATIONAL VELOCITIES
C      ARE IN RADIANS AND RADIANS/SECOND.
C
C**********************************************************************
C
C      .03492 RADIANS/SEC**2 == 2.0  DEG/SEC**2
C      .294   METERS/SEC**2  ==  .03 G
C
      PARAMETER (A_ACCLIM = .03491)
      PARAMETER (T_ACCLIM = .294  )
C
C      THESE PARAMETERS ARE SET TO THE PERFORMANCE LIMIT OF THE BASE
C
C      .2617 RAD/SEC == 15 DEG/SEC
C      .610  METERS/SEC
C
      PARAMETER (A_VELLIM = .2617 )
      PARAMETER (T_VELLIM = .610  )
C
C      VALUES FOR X FILTER
C
      DATA XDDLIM /  T_ACCLIM /
      DATA XDLIM  /  T_VELLIM /
C
C     VALUES FOR Y FILTER
C
      DATA YDDLIM /  T_ACCLIM /
      DATA YDLIM  /  T_VELLIM /
C
C     VALUES FOR Z FILTER
C
      DATA ZDDLIM /  T_ACCLIM /
      DATA ZDLIM  /  T_VELLIM /
```

```
C
C        VALUES FOR PSI FILTER
C
       DATA PSIDDLIM /  A_ACCLIM  /
       DATA PSIDLIM  /  A_VELLIM  /
C
C        VALUES FOR THETA FILTER
C
       DATA THEDDLIM /  A_ACCLIM  /
       DATA THEDLIM  /  A_VELLIM  /
C
C       VALUES FOR PHI FILTER
C
       DATA PHIDDLIM /  A_ACCLIM  /
       DATA PHIDLIM  /  A_VELLIM  /
       DATA TWOZOMGN/ 3.0 /
C
C       local functions
       CLIMIT(X,XMIN,XMAX) = MIN( MAX( X, XMIN ), XMAX )
C
C       If last operate run ended braked, reset braking algorithm
C       to unbraked state
C
       IF (FLAG2.EQ.1) THEN
          X = SSI(1)
          Y = SSI(2)
          Z = SSI(3)
          PHI = BETAS(1)
          THE = BETAS(2)
          PSI = BETAS(3)
          DO IJ=1,6
             RLID(IJ)=0.
             RLIDO(IJ)=0.
          END DO
           IT2=0
           FLAG2=0
       END IF

C
C       T = 0 INITIALIZATION;
C
       T       = 0.
       INT     = 0
       DXDLX   = 0.
       DXDLXD  = 0.
       DXDDX   = 0.
       DXDDXD  = 0.
       DTHDDX  = 0.
       LAMX    = LAMX0
       DELX    = DELX0
       DYDLY   = 0.
       DYDLYD  = 0.
       DYDDY   = 0.
       DYDDYD  = 0.
       DPHDDY  = 0.
       LAMY    = LAMY0
       DELY    = DELY0
```

```
      DZDEZ   = 0.
      DZDEZD  = 0.
      ETAZ    = ETAZ0
      DPSDE   = 0.
      ETAPS   = ETAPS0

C
C       FADE TO THE NEUTRAL POSITION USING SECOND ORDER FILTER TO ROVIDE
C       VELOCITY AND ACCELERATION CONTROL.
C
C
C       DRIVE X TO NEUTRAL POSITION (X = 0)
C
      XDDF  = -X - TWOZOMGN*XD
      XDD   = CLIMIT(XDDF,-XDDLIM,XDDLIM)
      XDF   = XD + XDD*H
      XD    = CLIMIT(XDF,-XDLIM,XDLIM)
      X     = X + XD*H
C
C       DRIVE Y TO NEUTRAL POSITION (Y = 0)
C
      YDDF  = -Y - TWOZOMGN*YD
      YDD   = CLIMIT(YDDF,-YDDLIM,YDDLIM)
      YDF   = YD + YDD*H
      YD    = CLIMIT(YDF,-YDLIM,YDLIM)
      Y     = Y + YD*H
C
C         DRIVE Z TO NEUTRAL POSITION (Z = 0)
C
      ZDDF  = -Z - TWOZOMGN*ZD
      ZDD   = CLIMIT(ZDDF,-ZDDLIM,ZDDLIM)
      ZDF   = ZD + ZDD*H
      ZD    = CLIMIT(ZDF,-ZDLIM,ZDLIM)
      Z     = Z + ZD*H
C
C         DRIVE PSI TO NEUTRAL POSITION (PSI = 0)
C
      PSIDDF  = -PSI - TWOZOMGN*PSID
      PSIDDFL = CLIMIT(PSIDDF,-PSIDDLIM,PSIDDLIM)
      PSIDF   = PSID + PSIDDFL*H
      PSID    = CLIMIT(PSIDF,-PSIDLIM,PSIDLIM)
      PSI     = PSI + PSID*H
C
C         DRIVE THETA TO NEUTRAL POSITION (THETA = 0)
C
      THEDDF  = -THE - TWOZOMGN*THED
      THEDDFL = CLIMIT(THEDDF,-THEDDLIM,THEDDLIM)
      THEDF   = THED + THEDDFL*H
      THED    = CLIMIT(THEDF,-THEDLIM,THEDLIM)
      THE     = THE + THED*H
C
C         DRIVE PHI TO NEUTRAL POSITION (PHI = 0)
C
      PHIDDF  = -PHI - TWOZOMGN*PHID
      PHIDDFL = CLIMIT(PHIDDF,-PHIDDLIM,PHIDDLIM)
      PHIDF   = PHID + PHIDDFL*H
      PHID    = CLIMIT(PHIDF,-PHIDLIM,PHIDLIM)
      PHI     = PHI + PHID*H
C
C     DUMMY INTEGRATIONS
C
      XD1     = XD
      DXDLXD1 = DXDLXD
      DXDDXD1 = DXDDXD
      YD1     = YD
      DYDLYD1 = DYDLYD
      DYDDYD1 = DYDDYD
      ZD1     = ZD
      DZDEZD1 = DZDEZD
      RETURN
      END
```

2.14. *simq.f*

```
      SUBROUTINE SIMQ(A,B,N,KS)
      DIMENSION A(36),B(6)
      TOL=0.
      KS=0
      JJ=-N
      DO 65 J=1,N
          JY=J+1
          JJ=JJ+N+1
          BIGA=0.
          IT=JJ-J
          DO 30 I=J,N
              IJ=IT+I
              IF(ABS(BIGA)-ABS(A(IJ))) 20,30,30
 20           BIGA=A(IJ)
              IMAX=I
 30       CONTINUE
          IF(ABS(BIGA)-TOL) 35,35,40
 35       KS=1
          RETURN
 40       I1=J+N*(J-2)
          IT=IMAX-J
          DO 50 K=J,N
              I1=I1+N
              I2=I1+IT
              SAVE1=A(I1)
              A(I1)=A(I2)
              A(I2)=SAVE1
 50       A(I1)=A(I1)/BIGA
          SAVE1=B(IMAX)
          B(IMAX)=B(J)
          B(J)=SAVE1/BIGA
          IF(J-N) 55,70,55
 55       IQS=N*(J-1)
          DO 65 IX=JY,N
              IXJ=IQS+IX
              IT=J-IX
              DO 60 JX=JY,N
                  IXJX=N*(JX-1)+IX
                  JJX=IXJX+IT
 60           A(IXJX)=A(IXJX)-(A(IXJ)*A(JJX))
 65   B(IX)=B(IX)-(B(J)*A(IXJ))
 70   NY=N-1
      IT=N*N
      DO 80 J=1,NY
          IA=IT-J
          IB=N-J
          IC=N
          DO 80 K=1,J
              B(IB)=B(IB)-A(IA)*B(IC)
              IA=IA-N
 80   IC=IC-1
      RETURN
      END
C
```

2.15. *state4.f*

```
C
C     NONLINEAR STATE SPACE FILTERS (ALL IN INERTIAL FRAME):
C
      SUBROUTINE STATE4

      INCLUDE 'optint3.com'

      INCLUDE 'nopt4.com'

      REAL ABK1X(6,6),BK2X(6,3),BK3X(6),XXI1(9),XXI2(9)
      REAL ABK1Y(6,6),BK2Y(6,3),BK3Y(6),XYI1(9),XYI2(9)
      REAL XZI1(5),XZI2(5),XRI1(4),XRI2(4)
      REAL XPI1(4),XPI2(4),XQI1(4),XQI2(4)
C
C     ROLL AND PITCH UNITY GAIN FILTERS
C
C     BSDR(1)=BADNO(1)
C     BSDR(2)=BADNO(2)
C
C     9TH ORDER SURGE/PITCH STATE SPACE FILTER
C
      DO I=1,6
         DO J=1,6
            K1X(1,J)=R2IX(1)*
     x      (BVX(1,1)*PX(1,J)+BVX(2,1)*PX(2,J)+BVX(3,1)*PX(3,J)
     x      +BVX(4,1)*PX(4,J)+BVX(5,1)*PX(5,J)+BVX(6,1)*PX(6,J)
     x      +DQCX(J))

            K1X(2,J)=R2IX(2)*
     x      (BVX(1,2)*PX(1,J)+BVX(2,2)*PX(2,J)+BVX(3,2)*PX(3,J)
     x      +BVX(4,2)*PX(4,J)+BVX(5,2)*PX(5,J)+BVX(6,2)*PX(6,J)
     x      +PX(9,J))

            ABK1X(I,J)=
     x      AVX(I,J)-BVX(I,1)*K1X(1,J)-BVX(I,2)*K1X(2,J)
         END DO
      END DO

      DO I=1,6
         DO J=1,3
            K2X(1,J)=R2IX(1)*
     x      (BVX(1,1)*PX(1,J+6)+BVX(2,1)*PX(2,J+6)+BVX(3,1)*PX(3,J+6)
     x      +BVX(4,1)*PX(4,J+6)+BVX(5,1)*PX(5,J+6)+BVX(6,1)*PX(6,J+6))

            K2X(2,J)=R2IX(2)*
     x      (BVX(1,2)*PX(1,J+6)+BVX(2,2)*PX(2,J+6)+BVX(3,2)*PX(3,J+6)
     x      +BVX(4,2)*PX(4,J+6)+BVX(5,2)*PX(5,J+6)+BVX(6,2)*PX(6,J+6)
     x      +PX(9,J+6))

            BK2X(I,J)=BVX(I,1)*K2X(1,J)+BVX(I,2)*K2X(2,J)
         END DO
      END DO

         K3X(1)=R2IX(1)*
     x   (BVX(1,1)*PX(1,11)+BVX(2,1)*PX(2,11)+BVX(3,1)*PX(3,11)
     x   +BVX(4,1)*PX(4,11)+BVX(5,1)*PX(5,11)+BVX(6,1)*PX(6,11))

         K3X(2)=R2IX(2)*
     x   (BVX(1,2)*PX(1,11)+BVX(2,2)*PX(2,11)+BVX(3,2)*PX(3,11)
     x   +BVX(4,2)*PX(4,11)+BVX(5,2)*PX(5,11)+BVX(6,2)*PX(6,11)
     x   +PX(9,11))

      DO I=1,6
         BK3X(I)=BVX(I,1)*K3X(1)+BVX(I,2)*(1.0+K3X(2))
      END DO

      DO I=1,6
         XXI1(I)=DT*
     x   (ABK1X(I,1)*XXO(1)+ABK1X(I,2)*XXO(2)+ABK1X(I,3)*XXO(3)
     x    +ABK1X(I,4)*XXO(4)+ABK1X(I,5)*XXO(5)+ABK1X(I,6)*XXO(6)
     x    -BK2X(I,1)*XXO(7)-BK2X(I,2)*XXO(8)-BK2X(I,3)*XXO(9)
     x    -BK3X(I)*A2NO(1))
      END DO
      XXI1(7)=DT*XXO(8)
      XXI1(8)=DT*XXO(9)
      XXI1(9)=DT*
     x   (-K1X(2,1)*XXO(1)-K1X(2,2)*XXO(2)-K1X(2,3)*XXO(3)
     x     -K1X(2,4)*XXO(4)-K1X(2,5)*XXO(5)-K1X(2,6)*XXO(6)
     x    -K2X(2,1)*XXO(7)-K2X(2,2)*XXO(8)-K2X(2,3)*XXO(9)
     x    -K3X(2)*A2NO(1))

      DO I=1,6
         XXI2(I)=DT*
     x   (ABK1X(I,1)*(XXO(1)+XXI1(1))+ABK1X(I,2)*(XXO(2)+XXI1(2))
     x   +ABK1X(I,3)*(XXO(3)+XXI1(3))+ABK1X(I,4)*(XXO(4)+XXI1(4))
     x   +ABK1X(I,5)*(XXO(5)+XXI1(5))+ABK1X(I,6)*(XXO(6)+XXI1(6))
     x    -BK2X(I,1)*(XXO(7)+XXI1(7))-BK2X(I,2)*(XXO(8)+XXI1(8))
     x   -BK2X(I,3)*(XXO(9)+XXI1(9))-BK3X(I)*A2N(1))
      END DO
      XXI2(7)=DT*(XXO(8)+XXI1(8))
      XXI2(8)=DT*(XXO(9)+XXI1(9))
      XXI2(9)=DT*(-K1X(2,1)*(XXO(1)+XXI1(1))
     x   -K1X(2,2)*(XXO(2)+XXI1(2))-K1X(2,3)*(XXO(3)+XXI1(3))
     x    -K1X(2,4)*(XXO(4)+XXI1(4))-K1X(2,5)*(XXO(5)+XXI1(5))
     x   -K1X(2,6)*(XXO(6)+XXI1(6))-K2X(2,1)*(XXO(7)+XXI1(7))
     x   -K2X(2,2)*(XXO(8)+XXI1(8))-K2X(2,3)*(XXO(9)+XXI1(9))
     x   -K3X(2)*A2N(1))

      DO I=1,9
         XX(I)=XXO(I)+0.5*(XXI1(I)+XXI2(I))
      END DO
C
C     9TH ORDER SWAY/ROLL STATE SPACE FILTER
C
      DO I=1,6
         DO J=1,6
            K1Y(1,J)=R2IY(1)*
     x      (BVY(1,1)*PY(1,J)+BVY(2,1)*PY(2,J)+BVY(3,1)*PY(3,J)
     x      +BVY(4,1)*PY(4,J)+BVY(5,1)*PY(5,J)+BVY(6,1)*PY(6,J)
     x      +DQCY(J))
```

```
       K1Y(2,J)=R2IY(2)*
x      (BVY(1,2)*PY(1,J)+BVY(2,2)*PY(2,J)+BVY(3,2)*PY(3,J)
x      +BVY(4,2)*PY(4,J)+BVY(5,2)*PY(5,J)+BVY(6,2)*PY(6,J)
x      +PY(9,J))

       ABK1Y(I,J)=
x      AVY(I,J)-BVY(I,1)*K1Y(1,J)-BVY(I,2)*K1Y(2,J)
    END DO
 END DO

 DO I=1,6
    DO J=1,3
       K2Y(1,J)=R2IY(1)*
x      (BVY(1,1)*PY(1,J+6)+BVY(2,1)*PY(2,J+6)+BVY(3,1)*PY(3,J+6)
x      +BVY(4,1)*PY(4,J+6)+BVY(5,1)*PY(5,J+6)+BVY(6,1)*PY(6,J+6))

       K2Y(2,J)=R2IY(2)*
x      (BVY(1,2)*PY(1,J+6)+BVY(2,2)*PY(2,J+6)+BVY(3,2)*PY(3,J+6)
x      +BVY(4,2)*PY(4,J+6)+BVY(5,2)*PY(5,J+6)+BVY(6,2)*PY(6,J+6)
x      +PY(9,J+6))

       BK2Y(I,J)=BVY(I,1)*K2Y(1,J)+BVY(I,2)*K2Y(2,J)
    END DO
 END DO

    K3Y(1)=R2IY(1)*
x   (BVY(1,1)*PY(1,11)+BVY(2,1)*PY(2,11)+BVY(3,1)*PY(3,11)
x   +BVY(4,1)*PY(4,11)+BVY(5,1)*PY(5,11)+BVY(6,1)*PY(6,11))

    K3Y(2)=R2IY(2)*
x   (BVY(1,2)*PY(1,11)+BVY(2,2)*PY(2,11)+BVY(3,2)*PY(3,11)
x   +BVY(4,2)*PY(4,11)+BVY(5,2)*PY(5,11)+BVY(6,2)*PY(6,11)
x   +PY(9,11))

 DO I=1,6
    BK3Y(I)=BVY(I,1)*K3Y(1)+BVY(I,2)*(1.0+K3Y(2))
 END DO

 DO I=1,6
    XYI1(I)=DT*
x   (ABK1Y(I,1)*XYO(1)+ABK1Y(I,2)*XYO(2)+ABK1Y(I,3)*XYO(3)
x    +ABK1Y(I,4)*XYO(4)+ABK1Y(I,5)*XYO(5)+ABK1Y(I,6)*XYO(6)
x    -BK2Y(I,1)*XYO(7)-BK2Y(I,2)*XYO(8)-BK2Y(I,3)*XYO(9)
x    -BK3Y(I)*A2NO(2))
 END DO
 XYI1(7)=DT*XYO(8)
 XYI1(8)=DT*XYO(9)
 XYI1(9)=DT*
x   (-K1Y(2,1)*XYO(1)-K1Y(2,2)*XYO(2)-K1Y(2,3)*XYO(3)
x     -K1Y(2,4)*XYO(4)-K1Y(2,5)*XYO(5)-K1Y(2,6)*XYO(6)
x    -K2Y(2,1)*XYO(7)-K2Y(2,2)*XYO(8)-K2Y(2,3)*XYO(9)
x    -K3Y(2)*A2NO(2))

 DO I=1,6
    XYI2(I)=DT*
x   (ABK1Y(I,1)*(XYO(1)+XYI1(1))+ABK1Y(I,2)*(XYO(2)+XYI1(2))
x   +ABK1Y(I,3)*(XYO(3)+XYI1(3))+ABK1Y(I,4)*(XYO(4)+XYI1(4))
```

```
     x   +ABK1Y(I,5)*(XYO(5)+XYI1(5))+ABK1Y(I,6)*(XYO(6)+XYI1(6))
     x    -BK2Y(I,1)*(XYO(7)+XYI1(7))-BK2Y(I,2)*(XYO(8)+XYI1(8))
     x   -BK2Y(I,3)*(XYO(9)+XYI1(9))-BK3Y(I)*A2N(2))
      END DO
      XYI2(7)=DT*(XYO(8)+XYI1(8))
      XYI2(8)=DT*(XYO(9)+XYI1(9))
      XYI2(9)=DT*(-K1Y(2,1)*(XYO(1)+XYI1(1))
     x   -K1Y(2,2)*(XYO(2)+XYI1(2))-K1Y(2,3)*(XYO(3)+XYI1(3))
     x    -K1Y(2,4)*(XYO(4)+XYI1(4))-K1Y(2,5)*(XYO(5)+XYI1(5))
     x   -K1Y(2,6)*(XYO(6)+XYI1(6))-K2Y(2,1)*(XYO(7)+XYI1(7))
     x   -K2Y(2,2)*(XYO(8)+XYI1(8))-K2Y(2,3)*(XYO(9)+XYI1(9))
     x   -K3Y(2)*A2N(2))

      DO I=1,9
         XY(I)=XYO(I)+0.5*(XYI1(I)+XYI2(I))
      END DO
C
C     5TH ORDER HEAVE STATE SPACE FILTER
C
      K1Z(1)=BVZ(1)*PZ(1,1)+BVZ(2)*PZ(2,1)+PZ(5,1)
      K1Z(2)=BVZ(1)*PZ(1,2)+BVZ(2)*PZ(2,2)+PZ(5,2)
      K2Z(1)=BVZ(1)*PZ(1,3)+BVZ(2)*PZ(2,3)+PZ(5,3)
      K2Z(2)=BVZ(1)*PZ(1,4)+BVZ(2)*PZ(2,4)+PZ(5,4)
      K2Z(3)=BVZ(1)*PZ(1,5)+BVZ(2)*PZ(2,5)+PZ(5,5)
         K3Z=BVZ(1)*PZ(1,6)+BVZ(2)*PZ(2,6)+PZ(5,6)

      DO I=1,2
      XZI1(I)=DT*
     x   ((AVZ(I,1)-BVZ(I)*K1Z(1))*XZO(1)
     x   +(AVZ(I,2)-BVZ(I)*K1Z(2))*XZO(2)
     x   -BVZ(I)*(K2Z(1)*XZO(3)+K2Z(2)*XZO(4)+K2Z(3)*XZO(5))
     x   -BVZ(I)*(1+K3Z)*A2NO(3))
      END DO
      XZI1(3)=DT*XZO(4)
      XZI1(4)=DT*XZO(5)
      XZI1(5)=DT*(-K1Z(1)*XZO(1)-K1Z(2)*XZO(2)-K2Z(1)*XZO(3)
     x        -K2Z(2)*XZO(4)-K2Z(3)*XZO(5)-K3Z*A2NO(3))

      DO I=1,2
      XZI2(I)=DT*
     x   ((AVZ(I,1)-BVZ(I)*K1Z(1))*(XZO(1)+XZI1(1))
     x   +(AVZ(I,2)-BVZ(I)*K1Z(2))*(XZO(2)+XZI1(2))
     x   -BVZ(I)*(K2Z(1)*(XZO(3)+XZI1(3))+K2Z(2)*(XZO(4)+XZI1(4))
     x         +K2Z(3)*(XZO(5)+XZI1(5)))
     x   -BVZ(I)*(1+K3Z)*A2N(3))
      END DO
      XZI2(3)=DT*(XZO(4)+XZI1(4))
      XZI2(4)=DT*(XZO(5)+XZI1(5))
      XZI2(5)=DT*(-K1Z(1)*(XZO(1)+XZI1(1))
     x      -K1Z(2)*(XZO(2)+XZI1(2))
     x        -K2Z(1)*(XZO(3)+XZI1(3))
     x        -K2Z(2)*(XZO(4)+XZI1(4))
     x        -K2Z(3)*(XZO(5)+XZI1(5))-K3Z*A2N(3))

      DO I=1,5
         XZ(I)=XZO(I)+0.5*(XZI1(I)+XZI2(I))
      END DO
```

```
C
C     4TH ORDER YAW STATE SPACE FILTER
C
      DO I=1,3
         K1R(I)=R2IR*
     x   (BVR(1)*PR(1,I)+BVR(2)*PR(2,I)+BVR(3)*PR(3,I)+PR(4,I)+DQCR(I))

      END DO
      K2R=R2IR*
     x   (BVR(1)*PR(1,4)+BVR(2)*PR(2,4)+BVR(3)*PR(3,4)+PR(4,4))
      K3R=R2IR*
     x    (BVR(1)*PR(1,5)+BVR(2)*PR(2,5)+BVR(3)*PR(3,5)+PR(4,5)-DQDR)

      DO I=1,3
         XRI1(I)=DT*
     x   ((AVR(I,1)-BVR(I)*K1R(1))*XRO(1)
     x    +(AVR(I,2)-BVR(I)*K1R(2))*XRO(2)
     x    +(AVR(I,3)-BVR(I)*K1R(3))*XRO(3)
     x    -BVR(I)*K2R*XRO(4)
     x    -BVR(I)*(1+K3R)*BADNO(3))
      END DO
      XRI1(4)=DT*(-K1R(1)*XRO(1)-K1R(2)*XRO(2)
     x        -K1R(3)*XRO(3)-K2R*XRO(4)-K3R*BADNO(3))

      DO I=1,3
         XRI2(I)=DT*
     x   ((AVR(I,1)-BVR(I)*K1R(1))*(XRO(1)+XRI1(1))
     x    +(AVR(I,2)-BVR(I)*K1R(2))*(XRO(2)+XRI1(2))
     x    +(AVR(I,3)-BVR(I)*K1R(3))*(XRO(3)+XRI1(3))
     x    -BVR(I)*K2R*(XRO(4)+XRI1(4))
     x    -BVR(I)*(1+K3R)*BADN(3))
      END DO
      XRI2(4)=DT*(-K1R(1)*(XRO(1)+XRI1(1))
     x         -K1R(2)*(XRO(2)+XRI1(2))
     x         -K1R(3)*(XRO(3)+XRI1(3))
     x         -K2R*(XRO(4)+XRI1(4))-K3R*BADN(3))

      DO I=1,4
         XR(I)=XRO(I)+0.5*(XRI1(I)+XRI2(I))
      END DO

C
C     4TH ORDER PITCH STATE SPACE FILTER
C
      DO I=1,3
         K1P(I)=R2IP*
     x   (BVP(1)*PP(1,I)+BVP(2)*PP(2,I)+BVP(3)*PP(3,I)+PP(4,I)+DQCP(I))

      END DO
      K2P=R2IP*
     x   (BVP(1)*PP(1,4)+BVP(2)*PP(2,4)+BVP(3)*PP(3,4)+PP(4,4))
      K3P=R2IP*
     x    (BVP(1)*PP(1,5)+BVP(2)*PP(2,5)+BVP(3)*PP(3,5)+PP(4,5)-DQDP)

      DO I=1,3
         XPI1(I)=DT*
     x   ((AVP(I,1)-BVP(I)*K1P(1))*XPO(1)
     x    +(AVP(I,2)-BVP(I)*K1P(2))*XPO(2)
     x    +(AVP(I,3)-BVP(I)*K1P(3))*XPO(3)
     x    -BVP(I)*K2P*XPO(4)
     x    -BVP(I)*(1+K3P)*BADNO(2))
      END DO
      XPI1(4)=DT*(-K1P(1)*XPO(1)-K1P(2)*XPO(2)
     x        -K1P(3)*XPO(3)-K2P*XPO(4)-K3P*BADNO(2))

      DO I=1,3
         XPI2(I)=DT*
     x   ((AVP(I,1)-BVP(I)*K1P(1))*(XPO(1)+XPI1(1))
     x    +(AVP(I,2)-BVP(I)*K1P(2))*(XPO(2)+XPI1(2))
     x    +(AVP(I,3)-BVP(I)*K1P(3))*(XPO(3)+XPI1(3))
     x    -BVP(I)*K2P*(XPO(4)+XPI1(4))
     x    -BVP(I)*(1+K3P)*BADN(2))
      END DO
      XPI2(4)=DT*(-K1P(1)*(XPO(1)+XPI1(1))
     x         -K1P(2)*(XPO(2)+XPI1(2))
     x         -K1P(3)*(XPO(3)+XPI1(3))
     x         -K2P*(XPO(4)+XPI1(4))-K3P*BADN(2))

      DO I=1,4
         XP(I)=XPO(I)+0.5*(XPI1(I)+XPI2(I))
      END DO
C
C     4TH ORDER ROLL STATE SPACE FILTER
C
      DO I=1,3
         K1Q(I)=R2IQ*
     x   (BVQ(1)*PQ(1,I)+BVQ(2)*PQ(2,I)+BVQ(3)*PQ(3,I)+PQ(4,I)+DQCQ(I))

      END DO
      K2Q=R2IQ*
     x   (BVQ(1)*PQ(1,4)+BVQ(2)*PQ(2,4)+BVQ(3)*PQ(3,4)+PQ(4,4))
      K3Q=R2IQ*
     x    (BVQ(1)*PQ(1,5)+BVQ(2)*PQ(2,5)+BVQ(3)*PQ(3,5)+PQ(4,5)-DQDQ)

      DO I=1,3
         XQI1(I)=DT*
     x   ((AVQ(I,1)-BVQ(I)*K1Q(1))*XQO(1)
     x    +(AVQ(I,2)-BVQ(I)*K1Q(2))*XQO(2)
     x    +(AVQ(I,3)-BVQ(I)*K1Q(3))*XQO(3)
     x    -BVQ(I)*K2Q*XQO(4)
     x    -BVQ(I)*(1+K3Q)*BADNO(1))
      END DO
      XQI1(4)=DT*(-K1Q(1)*XQO(1)-K1Q(2)*XQO(2)
     x        -K1Q(3)*XQO(3)-K2Q*XQO(4)-K3Q*BADNO(1))

      DO I=1,3
         XQI2(I)=DT*
     x   ((AVQ(I,1)-BVQ(I)*K1Q(1))*(XQO(1)+XQI1(1))
     x    +(AVQ(I,2)-BVQ(I)*K1Q(2))*(XQO(2)+XQI1(2))
     x    +(AVQ(I,3)-BVQ(I)*K1Q(3))*(XQO(3)+XQI1(3))
     x    -BVQ(I)*K2Q*(XQO(4)+XQI1(4))
     x    -BVQ(I)*(1+K3Q)*BADN(1))
      END DO
      XQI2(4)=DT*(-K1Q(1)*(XQO(1)+XQI1(1))
     x          -K1Q(2)*(XQO(2)+XQI1(2))
     x          -K1Q(3)*(XQO(3)+XQI1(3))
     x          -K2Q*(XQO(4)+XQI1(4))-K3Q*BADN(1))

      DO I=1,4
         XQ(I)=XQO(I)+0.5*(XQI1(I)+XQI2(I))
      END DO
C
C************* UPDATE ALL THE DUMMY VARIABLES: ********************
C
      DO I=1,9
          XXO(I)=XX(I)
         XYO(I)=XY(I)
      END DO
C
      DO I=1,5
         XZO(I)=XZ(I)
      END DO

      DO I=1,4
          XRO(I)=XR(I)
          XPO(I)=XP(I)
          XQO(I)=XQ(I)
      END DO

      A2NO(1) = A2N(1)
      A2NO(2) = A2N(2)
      A2NO(3) = A2N(3)
      BADNO(1) = BADN(1)
      BADNO(2) = BADN(2)
      BADNO(3) = BADN(3)

      RETURN
      END
```

2.16. *vmult.f*

```
C
C**********************************************************************
C       Subroutine VMULT : MATRIX MULTIPLICATION.
C**********************************************************************
C
      SUBROUTINE VMULT(A,B,C,K,L,M)
      DIMENSION A(K,L),B(K,L),C(K,M)
      DO 20 KK = 1,K
          DO 20 MM = 1,M
              C(KK,MM) = 0.0
              DO 20 LL = 1,L
                  C(KK,MM) = C(KK,MM) + A(KK,LL)*B(LL,MM)
  20  CONTINUE
      RETURN
      END
```

2.17. *winit4.f*

```
            SUBROUTINE WINIT4
C
C     THIS ROUTINE LOADS THE INITIAL VALUES INTO THE WASHOUT
C     PARAMETER ARRAYS.
C

      INCLUDE 'nopt4.com'

      REAL BRBXVEC(66),R1PXVEC(66),ZXVEC(66)
      REAL BRBYVEC(66),R1PYVEC(66),ZYVEC(66)
      REAL BRBRVEC(15),R1PRVEC(15),ZRVEC(15)
      REAL BRBPVEC(15),R1PPVEC(15),ZPVEC(15)
      REAL BRBQVEC(15),R1PQVEC(15),ZQVEC(15)
      REAL BRBZVEC(21),R1PZVEC(21),ZZVEC(21)

C
C     Initialization of Nonlinear Algorithm Inputs
C
      DATA XXO/9*0./XYO/9*0./,XRO/4*0./,XPO/4*0./,XQO/4*0./,XZO/5*0./

C
C  Parameters for nonlinear roll/sway channel filters.
C
      DATA ALPY /0.0/, ALPYMAX /1.0/, Q2Y /0.0,0.8/, MUY /4.0E-6 /

      DATA APY /
     + -0.48601433,  1.50095561,  0.43295640, -2.00166583,  2.30852675,
     +  0.93783312,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     + -0.22785440,  1.23627334,  0.43548518, -2.00719798,  2.32816934,
     +  0.92719057,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.00000000,  0.00000000,  0.00000000, -0.50000000,  0.50000000,
     + -0.00000000,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.17852148, -0.42864297,  0.00091112, -0.01882892,  0.19024153,
     +  0.74839400,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.84518815,  0.23802370,  0.00091112,  0.18117108, -0.00975847,
     +  0.08172733,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.47047268, -2.17119788, -0.42654860,  1.84882203, -2.39757925,
     + -1.63405743,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.00000000,  0.00000000,  0.00000000,  0.00000000,  0.00000000,
     +  0.00000000,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.00000000,  0.00000000,  0.00000000,  0.00000000,  0.00000000,
     +  0.00000000,  1.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.00000000,  0.00000000,  0.00000000,  0.00000000,  0.00000000,
     +  0.00000000,  0.0000,  1.0000,  0.0000,  0.0000,  0.0000,
     + -0.00007038,  0.00070080,  0.00016391, -0.00074143,  0.00089035,
     +  0.00036336,  0.0000,  0.0000,  0.0000, -1.000000,  0.0000,
     + -1.33333333, -1.33333333,  0.00000000, -0.20000000,  0.20000000,
     +  1.33333333,  0.0000,  0.0000,  0.0000,  0.0000, -3.14159265/
      DATA BRBYVEC /
     +  1.77789635,  1.77659704, -0.00027616,  0.26791584, -0.26816675,
     + -1.77838998,  0.0000,  0.0000,  1.33333333,  0.0000,  0.0000,
     +  1.78953524,  0.00274996,  0.25422767, -0.25172914,
     + -1.77168162,  0.0000,  0.0000,  1.33333333,  0.0000,  0.0000,
     +  0.00064319, -0.00290936,  0.00349374,
     +  0.00142583,  0.0000,  0.0000, -0.00000000,  0.0000,  0.0000,
     +  0.05316003, -0.05580338,
     + -0.27311620,  0.0000,  0.0000,  0.20000000,  0.0000,  0.0000,
     +  0.05897769,
     +  0.27441166,  0.0000,  0.0000, -0.20000000,  0.0000,  0.0000,
     +  1.78093859,  0.0000,  0.0000, -1.33333333,  0.0000,  0.0000,
     +  0.0000,  0.0000,  0.00000000,  0.0000,  0.0000,
     +  0.0000,  0.00000000,  0.0000,  0.0000,
     +  1.00000000,  0.0000,  0.0000,
     +  0.0000,  0.0000,
     +  0.0000/
      DATA R1PYVEC /
     +  8.63477261,  7.08082902,  0.00000000, -0.55988506, -0.55988506,
     +-12.57237449,  0.0000,  0.0000,  0.0000, -0.11033547,  0.0000,
     +  5.80695939,  0.00000000, -0.45897456, -0.45897456,
     +-10.30873990,  0.0000,  0.0000,  0.0000, -0.11097991,  0.0000,
     +  0.00000000, -0.00000000, -0.00000000,
     + -0.00000000,  0.0000,  0.0000,  0.0000,  0.00000000,  0.0000,
     +  0.03635800,  0.03635800,
     +  0.81558635,  0.0000,  0.0000,  0.0000, -0.00023219,  0.0000,
     +  0.03635800,
     +  0.81558635,  0.0000,  0.0000,  0.0000, -0.00023219,  0.0000,
     + 18.30829171,  0.0000,  0.0000,  0.0000,  0.10870250,  0.0000,
     +  8.00000000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  4.00000000,  0.0000,  0.0000,  0.0000,
     +  1.00000000,  0.0000,  0.0000,
     +  1.0000,  0.00000000,
     +  0.0000/
      DATA R2IY /4.17714546E-005,  1.00000000/
      DATA AVY /
     + -0.3001182, -0.3501544, -0.0, -0.0432552, -0.0432552, -
0.0219541,
     + -0.0408725, -0.6256486, -0.0, -0.0373488, -0.0373488, -
0.0382025,
     +  0.0000000,  0.0000000,  0.0, -0.5000000,  0.5000000, -
0.0000000,
     +  0.1789127, -0.4325385,  0.0, -0.0147076,  0.1852924,
0.7463742,
     +  0.8455793,  0.2341282, -0.0,  0.1852924, -0.0147076,
0.0797075,
     +  0.2873278, -0.3474845,  0.0, -0.0806039, -0.0806039, -
0.6884752/
      DATA BVY /
     +  1.684826,-16.777107, -3.924000, 17.749601,-21.314831, -
8.698809,
     +  1.333333,  1.333333, -0.000000,  0.200000, -0.200000, -
1.333333/
      DATA DQCY /
     +   2641.408443,   2656.836237,     -0.000000,
     +      5.558626,      5.558626,  -2602.315320/
      DATA ZYVEC /
     +       1.0,      -1.0,      -1.0,      -1.0,      -1.0,
     +      -1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,      -1.0,      -1.0,      -1.0,
     +      -1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,      -1.0,      -1.0,
     +      -1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,      -1.0,
     +      -1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,
     +      -1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,      -1.0,      -1.0,      -1.0,      -1.0,
     +       1.0,      -1.0,      -1.0,      -1.0,
     +       1.0,      -1.0,      -1.0,
     +       1.0,      -1.0,
     +       1.0/
      DATA PYVEC /
     +  8.78919914,
     +  8.64675152,  2.04454782, -5.18310331,  3.53876667, -7.88399752,
     + -8.38739821,-21.02141997,-25.10394095,  0.01775090, -6.40258907,
     +  9.07316301,  2.21477279, -4.18934594,  4.64570745, -7.69883299,
     + -8.39486263,-21.05959150,-25.21567898,  0.01774509, -6.43447599,
     +  0.71635788, -1.20003026,  0.98991751, -1.32889642,
     + -1.74100084, -4.45442250, -5.59861393,  0.02613645, -1.44219625,
     +  5.44431336,  0.18951117,  3.77151434,
     +  4.13378917, 10.88195613, 13.90068610, -0.02161095,  3.56872382,
     +  4.49770413, -3.84403097,
     + -4.01767838,-10.33185268,-12.56415459,  0.02169120, -3.19600160,
     +  8.54553179,
     +  8.27250466, 20.46798345, 23.69772741, -0.01783242,  6.00808010,
     + 23.81195147, 33.64457162, 29.33323432, -0.00748064,  6.63816656,
     + 71.85128707, 71.56090170, -0.03103290, 16.77905545,
     + 82.30634518, -0.06573714, 19.98961531,
     +  0.49999450, -0.01797396,
     +  5.06794969/

      DO J=1,11
         APYO(J)=APY(J,J)
         DO I=1,11
            IF(I.GE.J) THEN
```

```
               BRBY(I,J)=BRBYVEC((J-1)*11-J*(J-1)/2+I)
               BRBY(J,I)=BRBY(I,J)
               R1PY(I,J)=R1PYVEC((J-1)*11-J*(J-1)/2+I)
               R1PY(J,I)=R1PY(I,J)
               PY(I,J)=PYVEC((J-1)*11-J*(J-1)/2+I)
               PY(J,I)=PY(I,J)
               ZY(I,J)=ZYVEC((J-1)*11-J*(J-1)/2+I)
               ZY(J,I)=ZY(I,J)
            END IF
         END DO
      END DO
c
c  Parameters for nonlinear pitch/surge channel filters.
c
      DATA ALPX /0.0/, ALPXMAX /1.0/, Q2X /0.0,0.6/, MUX /4.0E-6/

      DATA APX /
     +  0.35214308, -1.72273247,  0.43037039, -2.38099014,  1.90345806,
     + -1.44348410,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.60755620, -1.99016155,  0.42784160, -2.36134755,  1.89792591,
     + -1.45137984,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.00000000,  0.00000000,  0.00000000, -0.50000000,  0.50000000,
     + -0.00000000,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.17753181, -0.42963264, -0.00091112, -0.00975847,  0.18117108,
     +  0.74938368,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.84419847,  0.23703402, -0.00091112,  0.19024153, -0.01882892,
     +  0.08271701,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     + -0.37464499,  1.04552994, -0.43677819,  2.29193764, -2.05630186,
     +  0.75422005,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.00000000,  0.00000000,  0.00000000,  0.00000000,  0.00000000,
     +  0.00000000,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.00000000,  0.00000000,  0.00000000,  0.00000000,  0.00000000,
     +  0.00000000,  1.0000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  0.00000000,  0.00000000,  0.00000000,  0.00000000,  0.00000000,
     +  0.00000000,  0.0000,  1.0000,  0.0000,  0.0000,  0.0000,
     + -0.00024842,  0.00052276, -0.00016391,  0.00089035, -0.00074143,
     +  0.00054140,  0.0000,  0.0000,  0.0000, -1.000000,  0.0000,
     + -1.33333333, -1.33333333,  0.00000000, -0.20000000,  0.20000000,
     +  1.33333333,  0.0000,  0.0000,  0.0000,  0.0000, -3.14159265/
      DATA BRBXVEC /
     +  1.77925517,  1.77466884,  0.00097480,  0.26137162, -0.26225730,
     + -1.78099759,  0.0000,  0.0000,  1.33333333,  0.0000,  0.0000,
     +  1.78432002, -0.00205131,  0.27780923, -0.27594547,
     + -1.77100221,  0.0000,  0.0000,  1.33333333,  0.0000,  0.0000,
     +  0.00064319, -0.00349374,  0.00290936,
     + -0.00212447,  0.0000,  0.0000, -0.00000000,  0.0000,  0.0000,
     +  0.05897769, -0.05580338,
     + -0.25512671,  0.0000,  0.0000,  0.20000000,  0.0000,  0.0000,
     +  0.05316003,
     +  0.25705694,  0.0000,  0.0000, -0.20000000,  0.0000,  0.0000,
     +  1.78479499,  0.0000,  0.0000, -1.33333333,  0.0000,  0.0000,
     +  0.0000,  0.0000,  0.00000000,  0.0000,  0.0000,
     +  0.0000,  0.00000000,  0.0000,  0.0000,
     +  1.00000000,  0.0000,  0.0000,
     +  0.0000,  0.0000,
     +  0.0000/
      DATA R1PXVEC /
     + 12.10587580, 13.94623075, -0.00000000,  0.66307892,  0.66307892,
     + -7.44252436,  0.0000,  0.0000,  0.0000,  0.10967645,  0.0000,
     + 16.06665966, -0.00000000,  0.76398942,  0.76398942,
     + -8.57318831,  0.0000,  0.0000,  0.0000,  0.10903201,  0.0000,
     +  0.00000000, -0.00000000, -0.00000000,
     +  0.00000000,  0.0000,  0.0000,  0.0000,  0.00000000,  0.0000,
     +  0.03635800,  0.03635800,
     + -0.40737763,  0.0000,  0.0000,  0.0000, -0.00023219,  0.0000,
     +  0.03635800,
     + -0.40737763,  0.0000,  0.0000,  0.0000, -0.00023219,  0.0000,
     +  4.57748825,  0.0000,  0.0000,  0.0000, -0.11130943,  0.0000,
     +  8.00000000,  0.0000,  0.0000,  0.0000,  0.0000,
     +  4.00000000,  0.0000,  0.0000,  0.0000,
     +  1.00000000,  0.0000,  0.0000,
     +  1.0000,  0.00000000,
     +  0.0000/
      DATA R2IX /4.17714546E-005,  1.00000000/
      DATA AVX /
     + -0.3001182, -0.3501544, -0.0, -0.0432552, -0.0432552, -
0.0219541,
     + -0.0408725, -0.6256486, -0.0, -0.0373488, -0.0373488, -
0.0382025,
     +  0.0000000,  0.0000000,  0.0, -0.5000000,  0.5000000, -
0.0000000,
     +  0.1789127, -0.4325385,  0.0, -0.0147076,  0.1852924,
0.7463742,
     +  0.8455793,  0.2341282, -0.0,  0.1852924, -0.0147076,
0.0797075,
     +  0.2873278, -0.3474845,  0.0, -0.0806039, -0.0806039, -
0.6884752/
      DATA BVX /
     +  5.947141,-12.514793,  3.924000,-21.314831, 17.749601,-
12.961123,
     +  1.333333,  1.333333, -0.000000,  0.200000, -0.200000, -
1.333333/
      DATA DQCX /
     +  -2625.631557,  -2610.203763,     -0.000000,
     +      5.558626,      5.558626,   2664.724680/
      DATA ZXVEC /
     +       1.0,      -1.0,      -1.0,      -1.0,      -1.0,
     +      -1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,      -1.0,      -1.0,      -1.0,
     +      -1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,      -1.0,      -1.0,
     +      -1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,      -1.0,
     +      -1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,
     +      -1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,      -1.0,      -1.0,      -1.0,      -1.0,      -
1.0,
     +       1.0,      -1.0,      -1.0,      -1.0,      -1.0,
     +       1.0,      -1.0,      -1.0,      -1.0,
     +       1.0,      -1.0,      -1.0,
     +       1.0,      -1.0,
     +       1.0/
      DATA PXVEC /
     +  8.30351624,
     +  8.09520238,  1.68093020, -4.48023672,  3.57953908, -8.19270520,
     + -8.31577879,-20.67790997,-24.24095727, -0.01780137, -6.16084104,
     +  8.45574766,  1.51070523, -3.37329594,  4.57329645, -7.94167444,
     + -8.30831437,-20.63973845,-24.12921925, -0.01780718, -6.12895412,
     +  0.71635788, -0.98991751,  1.20003026, -2.39658160,
     + -1.74100084, -4.45442250, -5.59861393, -0.02613645, -1.44219625,
     +  4.49770413,  0.18951117,  4.17497242,
     +  4.01767838, 10.33185268, 12.56415459,  0.02169120,  3.19600160,
     +  5.44431336, -4.99112805,
     + -4.13378917,-10.88195613,-13.90068610, -0.02161095, -3.56872382,
     +  9.64863006,
     +  8.43067234, 21.23134650, 25.64717081,  0.01771985,  6.55535001,
     + 23.81195147, 33.64457162, 29.33323432,  0.00748064,  6.63816656,
     + 71.85128707, 71.56090170,  0.03103290, 16.77905545,
     + 82.30634518,  0.06573714, 19.98961531,
     +  0.49999450,  0.01797396,
     +  5.06794969/

      DO J=1,11
         APXO(J)=APX(J,J)
         DO I=1,11
            IF(I.GE.J) THEN
               BRBX(I,J)=BRBXVEC((J-1)*11-J*(J-1)/2+I)
               BRBX(J,I)=BRBX(I,J)
               R1PX(I,J)=R1PXVEC((J-1)*11-J*(J-1)/2+I)
               R1PX(J,I)=R1PX(I,J)
               PX(I,J)=PXVEC((J-1)*11-J*(J-1)/2+I)
               PX(J,I)=PX(I,J)
               ZX(I,J)=ZXVEC((J-1)*11-J*(J-1)/2+I)
               ZX(J,I)=ZX(I,J)
            END IF
         END DO
      END DO
c
c  Parameters for nonlinear yaw channel filters.
c
      DATA ALPR /0.0/, ALPRMAX /1.0/, Q2R /120.0/, MUR /2.0E-6 /

      DATA APR /
     +-1.45728460E-004,-1.69985373E-006,-4.89593935E-004,
     +-2.79035083E-002,   0.0,
     +   1.0,   0.0,   0.0,   0.0,   0.0,
     +1.86874341E-001,2.17980102E-003,-4.89593935E-004,
     +-2.79035083E-002,0.00000000E+000,
     +   0.0,   0.0,   0.0,   0.0,   0.0,
     +5.21851607E-003,6.08715277E-005,1.75322913E-002,
     +9.99220787E-001,  -1.0/
      DATA BRBRVEC /
     +3.49492524E-002,4.07666539E-004,1.17416612E-001,-5.21851607E-003,
     +   0.0,
     +4.75523782E-006,1.36960937E-003,-6.08715277E-005,   0.0,
     +3.94476555E-001,-1.75322913E-002,   0.0,
     +7.79212948E-004,   0.0,
     +   0.0/
      DATA R1PRVEC /
     +7.79212948E-004,   0.0,7.79212948E-004,   0.0,-2.79035083E-002,
     +0.00000000E+000,   0.0,0.00000000E+000,   0.0,
     +7.79212948E-004,   0.0,-2.79035083E-002,
     +2.00000000E+002,   0.0,
     +9.99220787E-001/
      DATA R2IR /7.79212948E-004/
      DATA AVR /
     +-1.87020070E-001,-2.18150087E-003,-6.28318531E-001,
     +1.00000000E+000,0.00000000E+000,0.00000000E+000,
     +0.00000000E+000,0.00000000E+000,-6.28318531E-001/
      DATA BVR /-6.69716293E+000,-7.81192456E-002,-2.25000000E+001/
      DATA DQCR / 35.80986220,  0.00000000, 35.80986220/
      DATA DQDR /1.28234623E+003/
      DATA ZRVEC /
     +   1.0,  -1.0,  -1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,
     +   1.0/
      DATA PRVEC /
     +  0.52254103,  0.13331932,  0.53598671, -7.30258353, -6.33348013,
     +  5.01432503,  1.07135777,  6.89175648,  5.57001008,
     +  0.73962239, -5.97893648, -5.25519323,
     + 323.73106725, 186.47187109,
     + 139.87165376/

      DO J=1,5
         APRO(J)=APR(J,J)
         DO I=1,5
            IF(I.GE.J) THEN
               BRBR(I,J)=BRBRVEC((J-1)*5-J*(J-1)/2+I)
               BRBR(J,I)=BRBR(I,J)
               R1PR(I,J)=R1PRVEC((J-1)*5-J*(J-1)/2+I)
               R1PR(J,I)=R1PR(I,J)
               PR(I,J)=PRVEC((J-1)*5-J*(J-1)/2+I)
               PR(J,I)=PR(I,J)
               ZR(I,J)=ZRVEC((J-1)*5-J*(J-1)/2+I)
               ZR(J,I)=ZR(I,J)
            END IF
         END DO
      END DO


c
c  Parameters for nonlinear pitch channel filters.


      DATA ALPQ /0.0/, ALPQMAX /1.0/, Q2Q /200.0/, MUQ /2.0E-6 /

      DATA APQ/
     +0.0,0.0,0.0,
     +0.0,   0.0,
     +   1.0,   0.0,   0.0,   0.0,   0.0,
     +5.86874341E-001,7.17980102E-003,-2.89593935E-004,
     +-2.79035083E-002,0.00000000E+000,
     +   0.0,   0.0,   0.0,   0.0,   0.0,
     +5.21851607E-003,6.08715277E-005,1.75322913E-002,
     +9.99220787E-001,  -1.0/
      DATA BRBQVEC /
     +3.49492524E-002,4.07666539E-004,1.17416612E-001,-5.21851607E-003,
     +   0.0,
     +4.75523782E-006,1.36960937E-003,-6.08715277E-005,   0.0,
     +3.94476555E-001,-1.75322913E-002,   0.0,
     +7.79212948E-004,   0.0,
     +   0.0/
      DATA R1PQVEC /
     +7.79212948E-004,   0.0,7.79212948E-004,   0.0,-2.79035083E-002,
     +0.00000000E+000,   0.0,0.00000000E+000,   0.0,
     +7.79212948E-004,   0.0,-2.79035083E-002,
     +2.00000000E+002,   0.0,
     +9.99220787E-001/
      DATA R2IQ /7.79212948E-004/
      DATA AVQ /
     +-1.87020070E-001,-2.18150087E-003,-6.28318531E-001,
     +1.00000000E+000,0.00000000E+000,0.00000000E+000,
     +0.00000000E+000,0.00000000E+000,-6.28318531E-001/
      DATA BVQ /-6.69716293E+000,-7.81192456E-002,-2.25000000E+001/
      DATA DQCQ / 35.80986220,  0.00000000, 35.80986220/
      DATA DQDQ /1.28234623E+003/
      DATA ZQVEC /
     +   1.0,  -1.0,  -1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,
     +   1.0/
      DATA PQVEC /
     +  0.52254103,  0.13331932,  0.53598671, -7.30258353, -6.33348013,
     +  5.01432503,  1.07135777,  6.89175648,  5.57001008,
     +  0.73962239, -5.97893648, -5.25519323,
     + 323.73106725, 186.47187109,
     + 139.87165376/

      DO J=1,5
         APQO(J)=APQ(J,J)
         DO I=1,5
            IF(I.GE.J) THEN
               BRBQ(I,J)=BRBQVEC((J-1)*5-J*(J-1)/2+I)
               BRBQ(J,I)=BRBQ(I,J)
               R1PQ(I,J)=R1PQVEC((J-1)*5-J*(J-1)/2+I)
               R1PQ(J,I)=R1PQ(I,J)
               PQ(I,J)=PQVEC((J-1)*5-J*(J-1)/2+I)
               PQ(J,I)=PQ(I,J)
               ZQ(I,J)=ZQVEC((J-1)*5-J*(J-1)/2+I)
               ZQ(J,I)=ZQ(I,J)
            END IF
         END DO
      END DO
c
c   Parameters for nonlinear roll channel filters.
```

```
c
      DATA ALPP /0.0/, ALPPMAX /1.0/, Q2P /120.0/, MUP /2.0E-6 /

      DATA APP /
     +-1.45728460E-004,-1.69985373E-006,-4.89593935E-004,
     +-2.79035083E-002,   0.0,
     +   1.0,   0.0,   0.0,   0.0,   0.0,
     +1.86874341E-001,2.17980102E-003,-4.89593935E-004,
     +-2.79035083E-002,0.00000000E+000,
     +   0.0,   0.0,   0.0,   0.0,   0.0,
     +5.21851607E-003,6.08715277E-005,1.75322913E-002,
     +9.99220787E-001,  -1.0/
      DATA BRBPVEC /
     +3.49492524E-002,4.07666539E-004,1.17416612E-001,-5.21851607E-003,
     +   0.0,
     +4.75523782E-006,1.36960937E-003,-6.08715277E-005,   0.0,
     +3.94476555E-001,-1.75322913E-002,   0.0,
     +7.79212948E-004,   0.0,
     +   0.0/
      DATA R1PPVEC /
     +7.79212948E-004,   0.0,7.79212948E-004,   0.0,-2.79035083E-002,
     +0.00000000E+000,   0.0,0.00000000E+000,   0.0,
     +7.79212948E-004,   0.0,-2.79035083E-002,
     +2.00000000E+002,   0.0,
     +9.99220787E-001/
      DATA R2IP /7.79212948E-004/
      DATA AVP /
     +-1.87020070E-001,-2.18150087E-003,-6.28318531E-001,
     +1.00000000E+000,0.00000000E+000,0.00000000E+000,
     +0.00000000E+000,0.00000000E+000,-6.28318531E-001/
      DATA BVP /-6.69716293E+000,-7.81192456E-002,-2.25000000E+001/
      DATA DQCP / 35.80986220,  0.00000000, 35.80986220/
      DATA DQDP /1.28234623E+003/
      DATA ZPVEC /
     +   1.0,  -1.0,  -1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,
     +   1.0/
      DATA PPVEC /
     +  0.52254103,  0.13331932,  0.53598671, -7.30258353, -6.33348013,
     +  5.01432503,  1.07135777,  6.89175648,  5.57001008,
     +  0.73962239, -5.97893648, -5.25519323,
     + 323.73106725, 186.47187109,
     + 139.87165376/

      DO J=1,5
         APPO(J)=APP(J,J)
         DO I=1,5
            IF(I.GE.J) THEN
               BRBP(I,J)=BRBPVEC((J-1)*5-J*(J-1)/2+I)
               BRBP(J,I)=BRBP(I,J)
               R1PP(I,J)=R1PPVEC((J-1)*5-J*(J-1)/2+I)
               R1PP(J,I)=R1PP(I,J)
               PP(I,J)=PPVEC((J-1)*5-J*(J-1)/2+I)
               PP(J,I)=PP(I,J)
               ZP(I,J)=ZPVEC((J-1)*5-J*(J-1)/2+I)
               ZP(J,I)=ZP(I,J)
            END IF
         END DO
      END DO



c
c  Parameters for nonlinear heave channel filters.
c
      DATA ALPZ /0.0/, ALPZMAX /0.2/, Q2Z /1.0,2.0/, MUZ /1.0E-7 /

      DATA APZ /
     +   -0.060606,    0.139394,  0.0000,  0.0000,  0.0000,
0.000000,
     +   -0.567713,   -0.767713,  0.0000,  0.0000,  0.0000,
0.000000,
     +    0.000000,    0.000000,  0.0000,  0.0000,  0.0000,
0.000000,
     +    0.000000,    0.000000,  1.0000,  0.0000,  0.0000,
0.000000,
     +    0.000000,    0.000000,  0.0000,  1.0000,  0.0000,
0.000000,
     +   -1.717157,   -2.282843,  0.0000,  0.0000,  0.0000,  -
62.831853/
      DATA BRBZVEC /
     +    2.948629,    3.920000,  0.0000,  0.0000,    1.717157,
0.0000,
     +    5.211371,  0.0000,  0.0000,    2.282843,  0.0000,
     +    0.000000,  0.0000,  0.0000,  0.0000,
     +    0.000000,  0.0000,  0.0000,
     +    1.000000,  0.0000,
     +    0.000000/
      DATA R1PZVEC /
     +  200.0000,  200.0000,    0.0000,    0.0000,    0.0000,
0.0000,
     +  200.0000,    0.0000,    0.0000,    0.0000,    0.0000,
     +   40.0000,    0.0000,    0.0000,    0.0000,
     +  400.0000,    0.0000,    0.0000,
     +   40.0000,    0.0000,
     +    0.0000/
      DATA AVZ /   -0.060606,    0.139394,   -0.567713,   -0.767713/
      DATA BVZ /    1.717157,    2.282843/
      DATA ZZVEC /
     +   1.0,  -1.0,  -1.0,  -1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,  -1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,  -1.0,
     +   1.0,  -1.0,
     +   1.0/
      DATA PZVEC /
     +  910.190970, -315.435226,   -1.160668,  -79.558688, -844.169063,
     +  -13.404542,  327.670260,  -60.259856, -315.797740, -198.948877,
     +   -3.146942,  193.813146,  269.544193,  145.881379,    2.202307,
     + 1160.148818,  888.175899,   13.591950, 1946.358732,   30.388540,
     +    0.480397/
```

```
      DO J=1,6
         APZO(J)=APZ(J,J)
         DO I=1,6
            IF(I.GE.J) THEN
               BRBZ(I,J)=BRBZVEC((J-1)*6-J*(J-1)/2+I)
               BRBZ(J,I)=BRBZ(I,J)
               R1PZ(I,J)=R1PZVEC((J-1)*6-J*(J-1)/2+I)
               R1PZ(J,I)=R1PZ(I,J)
               PZ(I,J)=PZVEC((J-1)*6-J*(J-1)/2+I)
               PZ(J,I)=PZ(I,J)
               ZZ(I,J)=ZZVEC((J-1)*6-J*(J-1)/2+I)
               ZZ(J,I)=ZZ(I,J)
            END IF
         END DO
      END DO
c
c     Nonlinear Scaling Coefficients
c
      DATA GX4/0.5,-0.05,0.002/
      DATA GY4/0.4,-0.035,0.001/
      DATA GZ40/0.6,-0.082,0.0038/
      DATA GZ4S/2.0,-0.05, 0.0/
      DATA GP4/0.3,-0.3,0.1/
      DATA GQ4/0.3,-0.3,0.1/
      DATA GR4/1.1,-1.46,0.64/
c
c     Translational and Rotational Limits
c
      DATA AMX40/10./,BMX4/1./,AMX4S/20./
c
c     Augmented Turbulence Parameters
c
      DATA G2D0,G2D1,G2N0,G2N1,G2N2
     +   /25.0,12.5,2.5,12.0,14.4/
      DATA GT4/1.2/

      RETURN
      END
```

Appendix B. Non-linear optimal algorithm: filtering at platform centroid (original) vs. filtering at PS (modified)

Nonlinear optimal algorithm when filtered at the centroid of the motion platform (original) versus filtering at the pilot station (modified).

General note: if only one or two curves are visible on the plot, assume that the remaining curves are underneath the visible ones.

1. Pitch

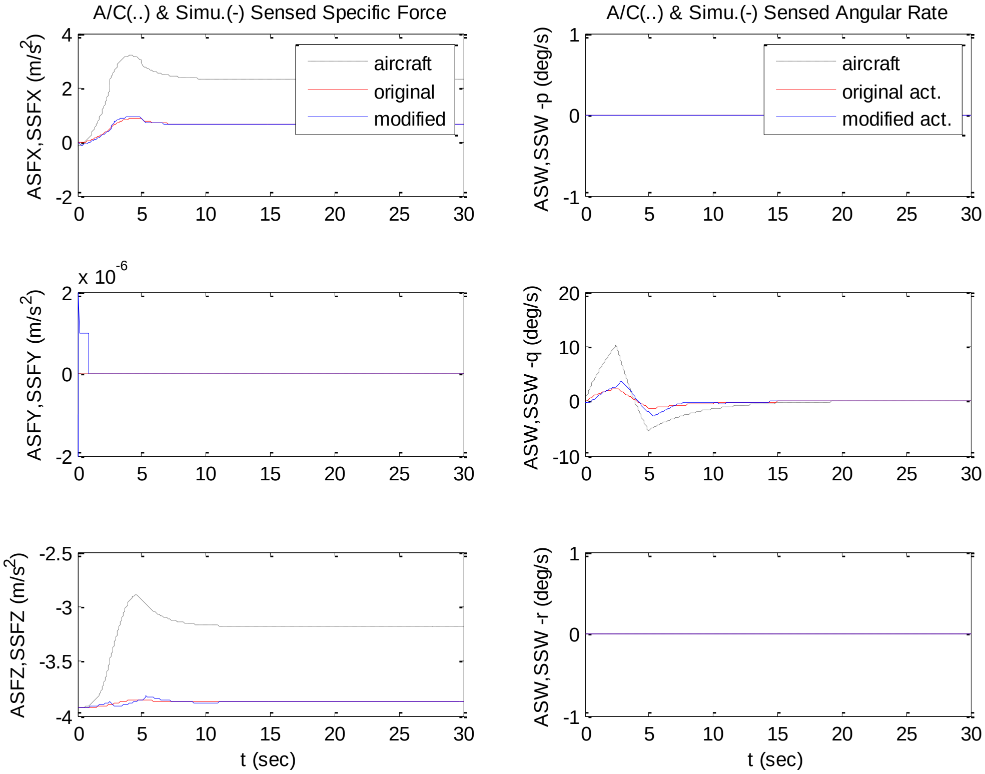


Figure B.1. 1.

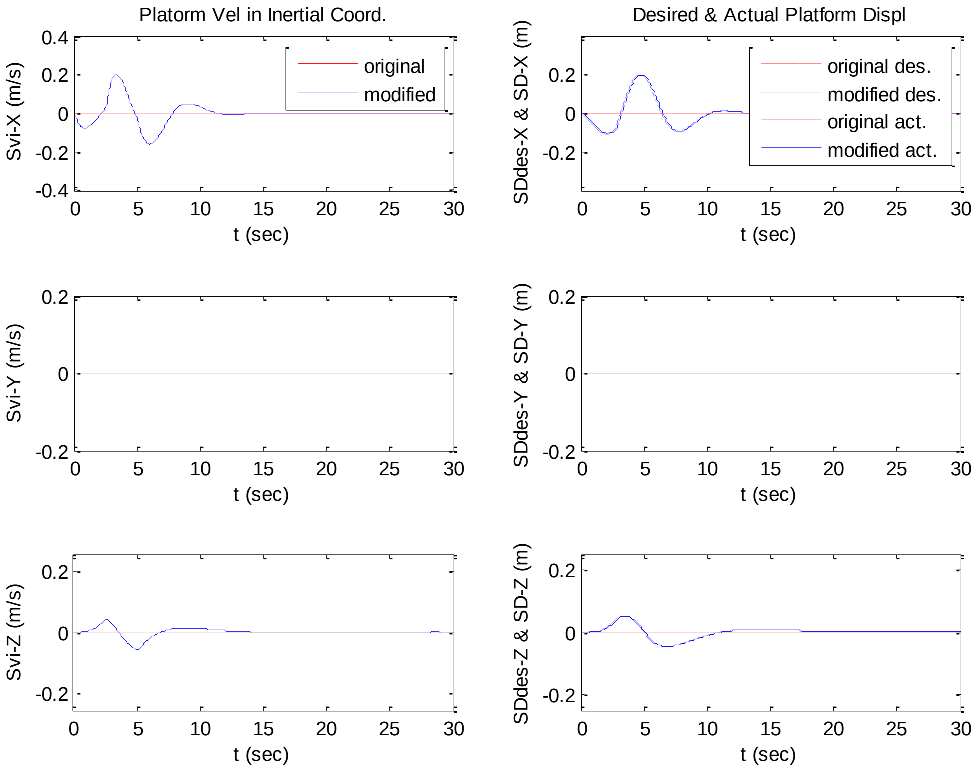

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
Svi-X (m/s)
Svi-Y (m/s)
Svi-Z (m/s)
SDdes-X & SD-X (m)
SDdes-Y & SD-Y (m)
SDdes-Z & SD-Z (m)
original
modified
original des.
modified des.
original act.
modified act.
0.4
0.2
0
-0.2
-0.4
t (sec)
0
5
10
15
20
25
30

Figure B.1. 2.

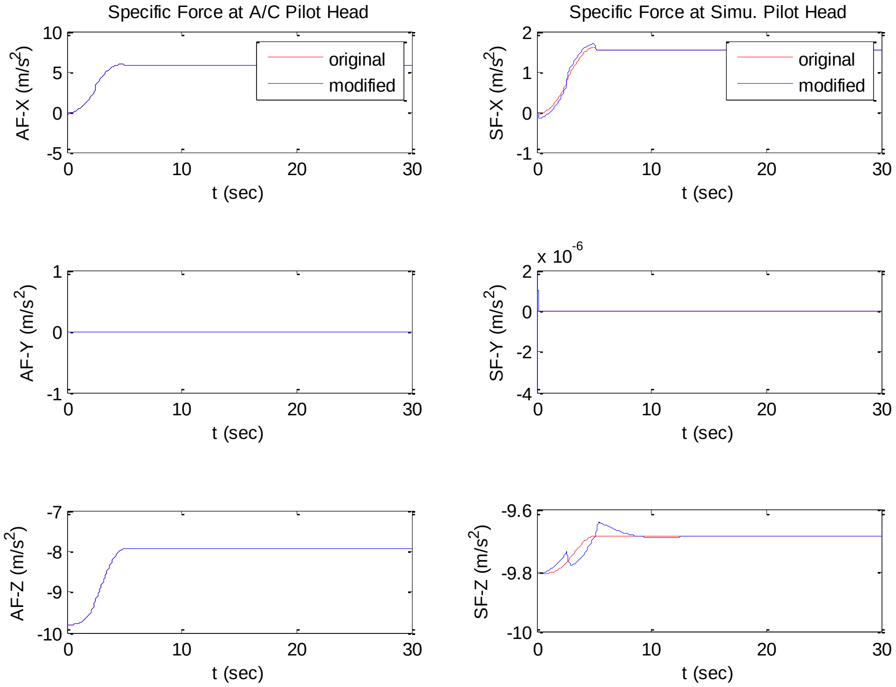

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
original
modified
AF-X (m/s^2)
SF-X (m/s^2)
AF-Y (m/s^2)
SF-Y (m/s^2)
AF-Z (m/s^2)
SF-Z (m/s^2)
x 10^{-6}
10
5
0
-5
2
1
0
-1
1
0
-1
2
0
-2
-4
-7
-8
-9
-10
-9.6
-9.8
-10
0
10
20
30
t (sec)

Figure B.1. 3.

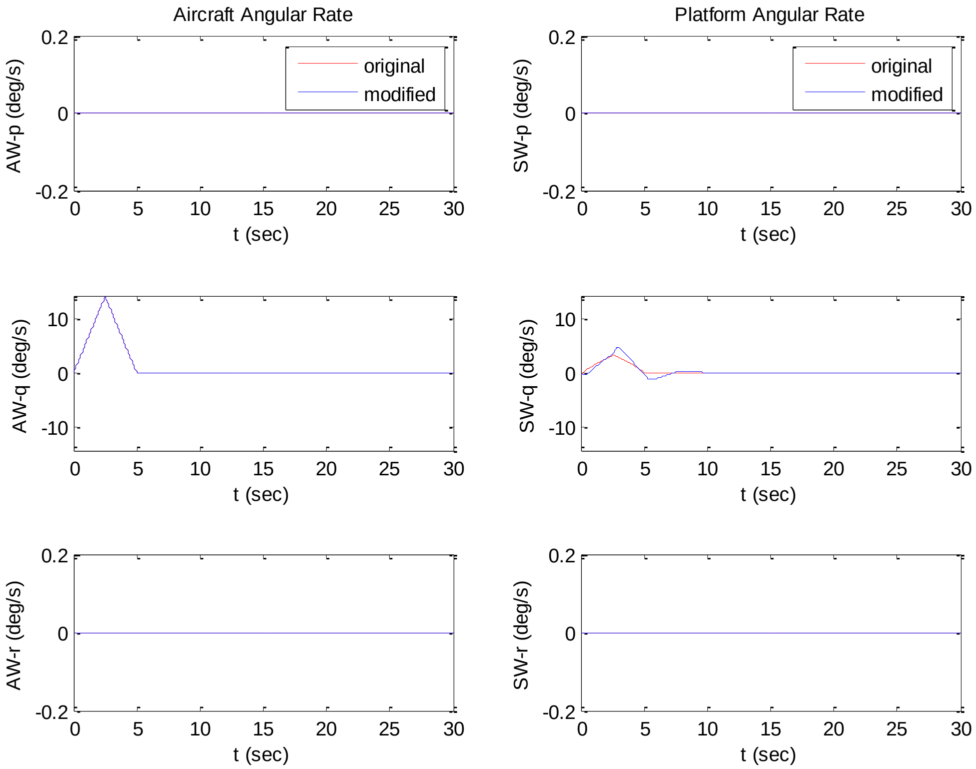

Aircraft Angular Rate
Platform Angular Rate
original
modified
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
0.2
0
-0.2
10
0
-10
0
5
10
15
20
25
30
t (sec)

Figure B.1. 4.

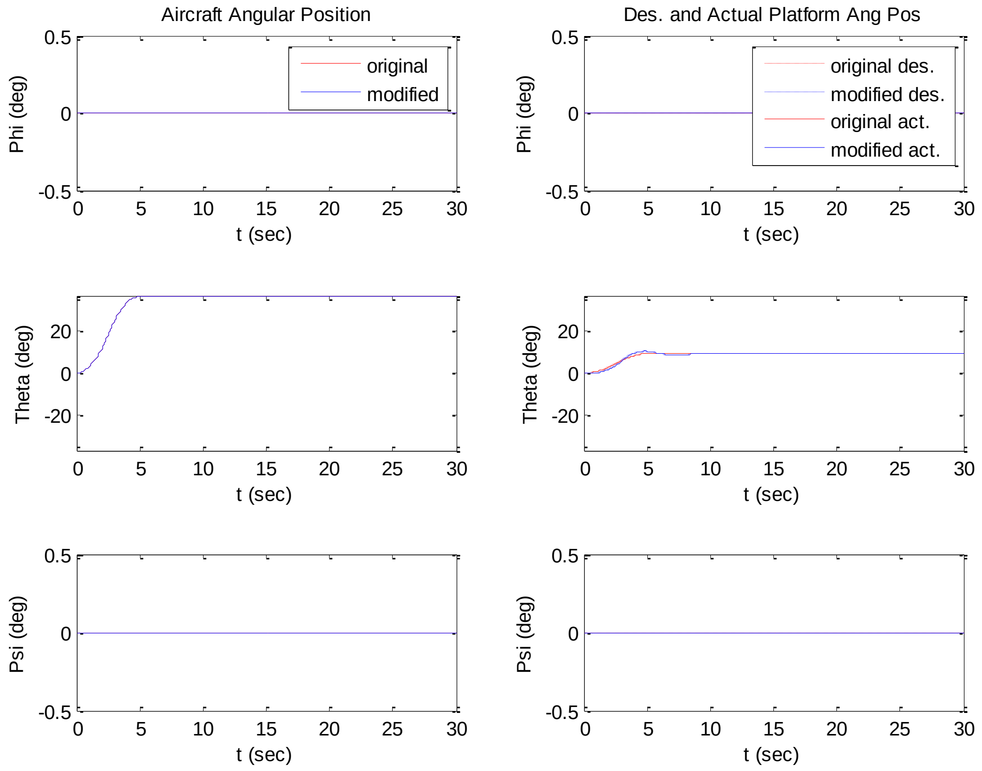

Aircraft Angular Position
Des. and Actual Platform Ang Pos
Phi (deg)
Theta (deg)
Psi (deg)
t (sec)
0.5
0
-0.5
20
-20
0
5
10
15
20
25
30
original
modified
original des.
modified des.
original act.
modified act.

Figure B.1. 5.

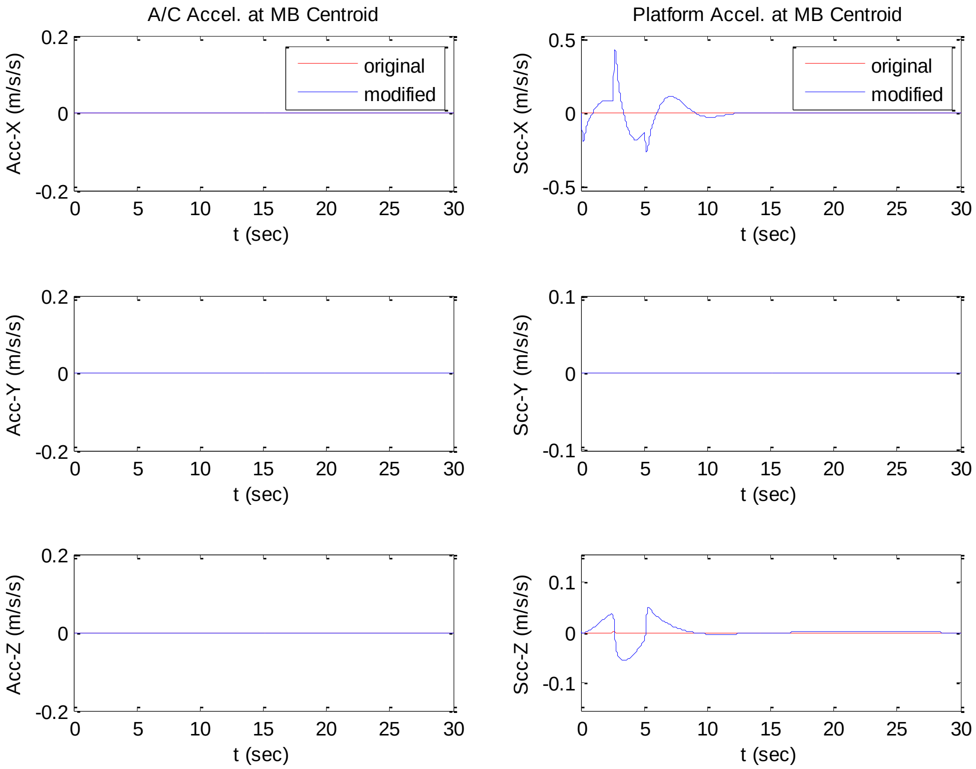

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
modified
original
modified
Acc-X (m/s/s)
Scc-X (m/s/s)
Acc-Y (m/s/s)
Scc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.5
0
-0.5
0.1
0
-0.1
0
5
10
15
20
25
30
t (sec)

Figure B.1. 6.

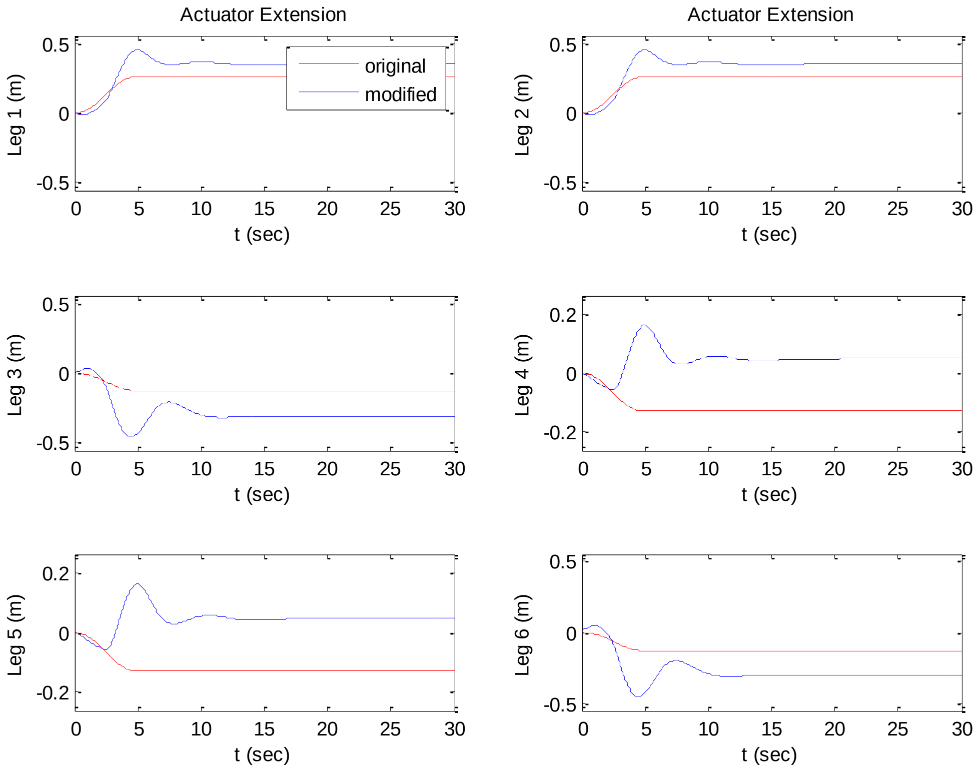

Actuator Extension
Actuator Extension
original
modified
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.5
0
-0.5
0.2
-0.2
0
5
10
15
20
25
30
t (sec)

Figure B.1. 7.

2. Roll

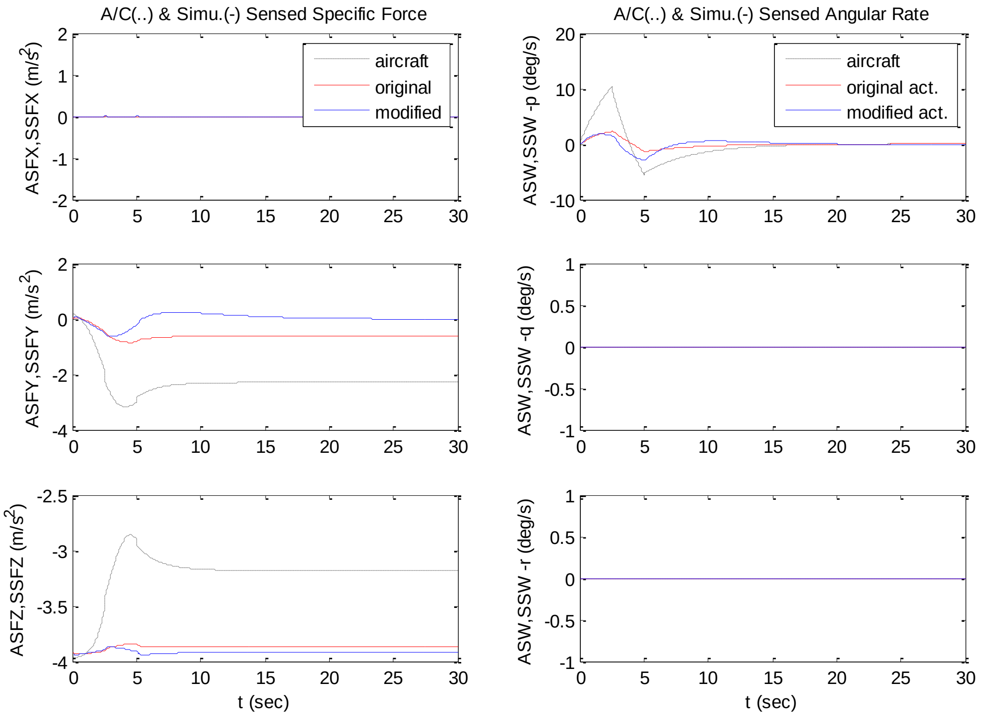


Figure B.2. 1.

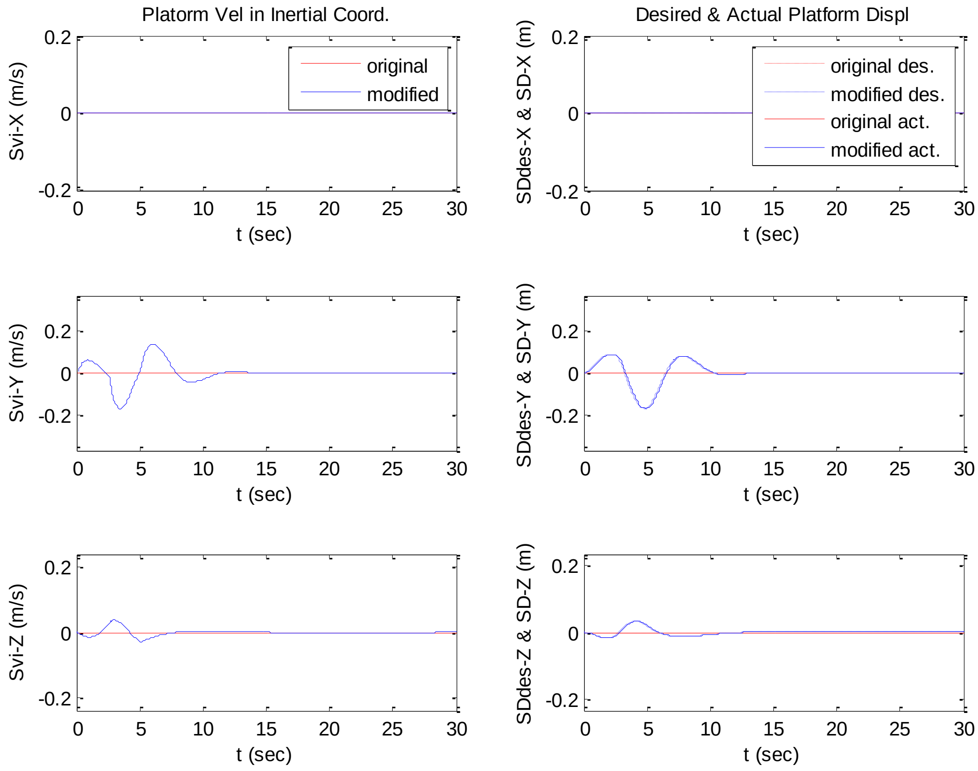

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
Svi-X (m/s)
Svi-Y (m/s)
Svi-Z (m/s)
SDdes-X & SD-X (m)
SDdes-Y & SD-Y (m)
SDdes-Z & SD-Z (m)
original
modified
original des.
modified des.
original act.
modified act.
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure B.2. 2.

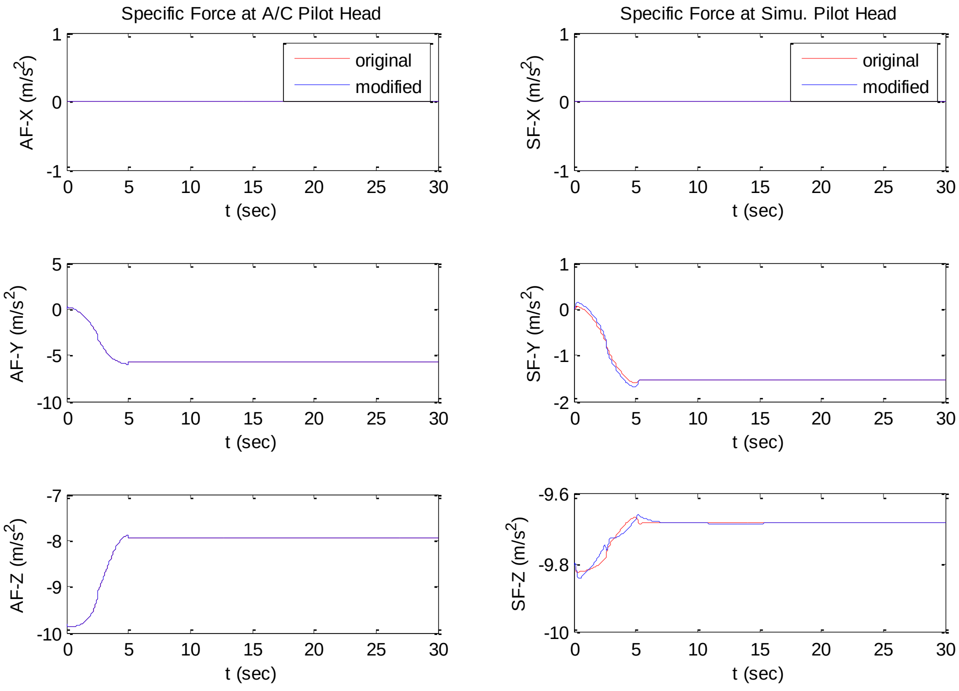

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
AF-X (m/s^2)
AF-Y (m/s^2)
AF-Z (m/s^2)
SF-X (m/s^2)
SF-Y (m/s^2)
SF-Z (m/s^2)
original
modified
1
0
-1
5
-5
-10
-7
-8
-9
-2
-9.6
-9.8
0
5
10
15
20
25
30
t (sec)

Figure B.2. 3.

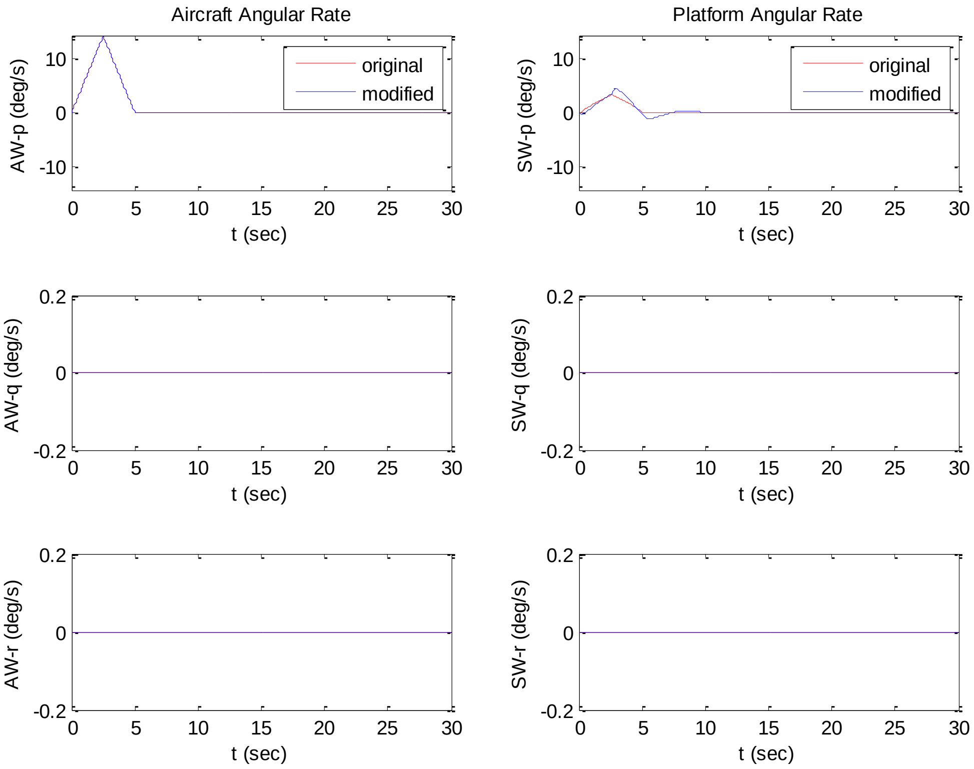


Figure B.2. 4.

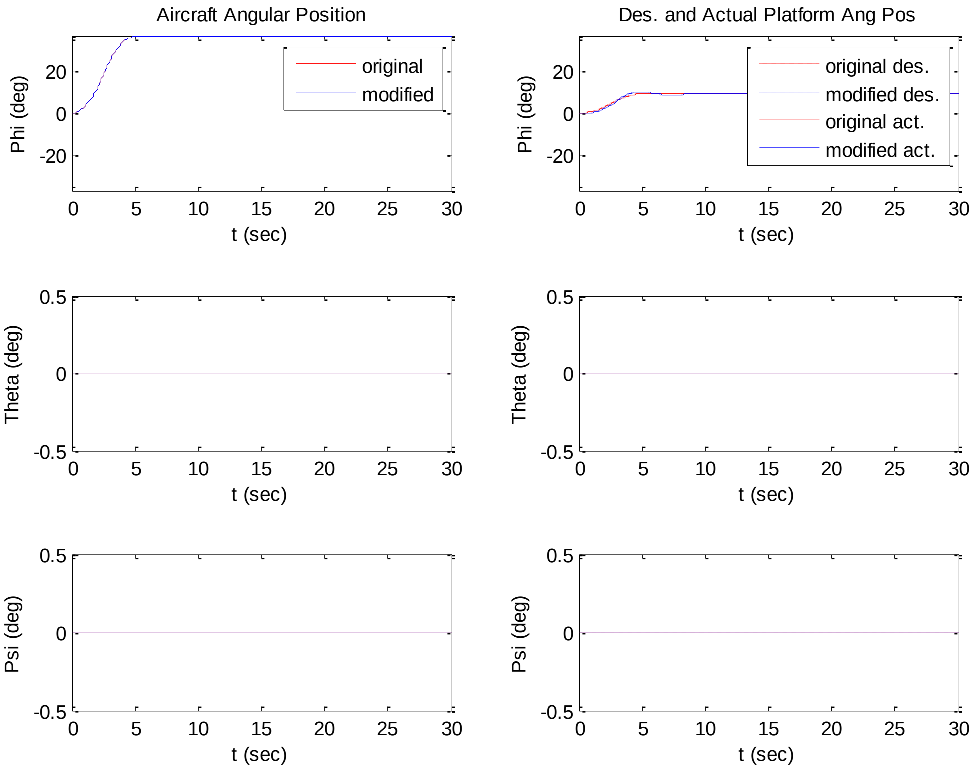

Aircraft Angular Position
Des. and Actual Platform Ang Pos
Phi (deg)
Theta (deg)
Psi (deg)
t (sec)
original
modified
original des.
modified des.
original act.
modified act.
20
0
-20
0.5
-0.5
0
5
10
15
20
25
30

Figure B.2. 5.

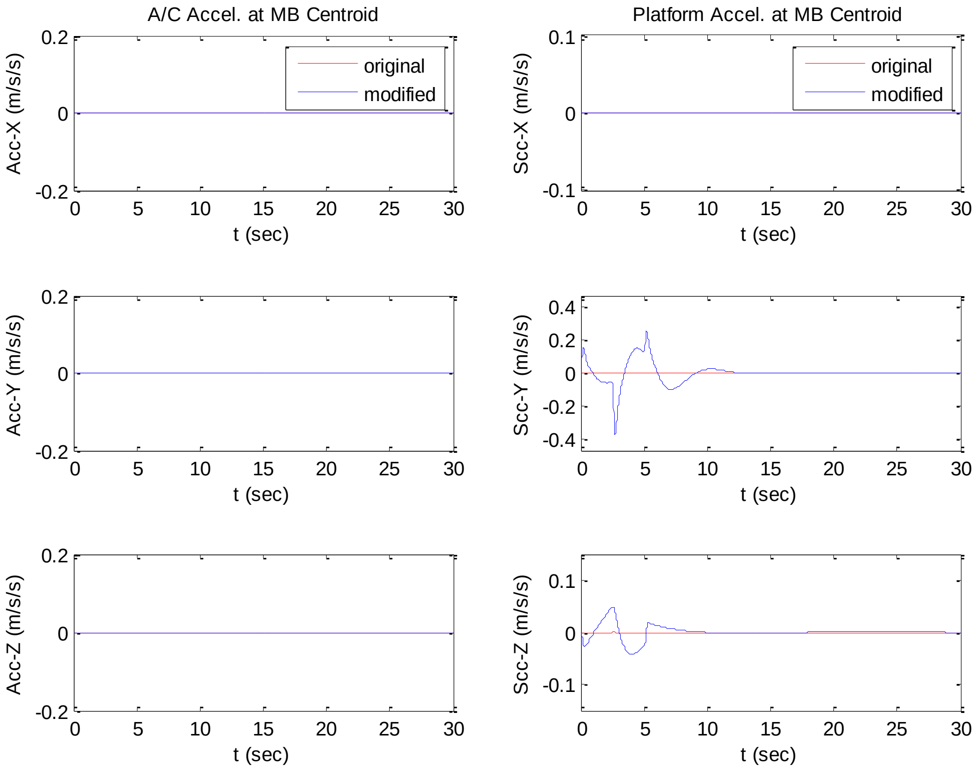

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
modified
original
modified
Acc-X (m/s/s)
Acc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-X (m/s/s)
Scc-Y (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.1
0
-0.1
0.4
0.2
0
-0.2
-0.4
0.1
0
-0.1
0
5
10
15
20
25
30
t (sec)

Figure B.2. 6.

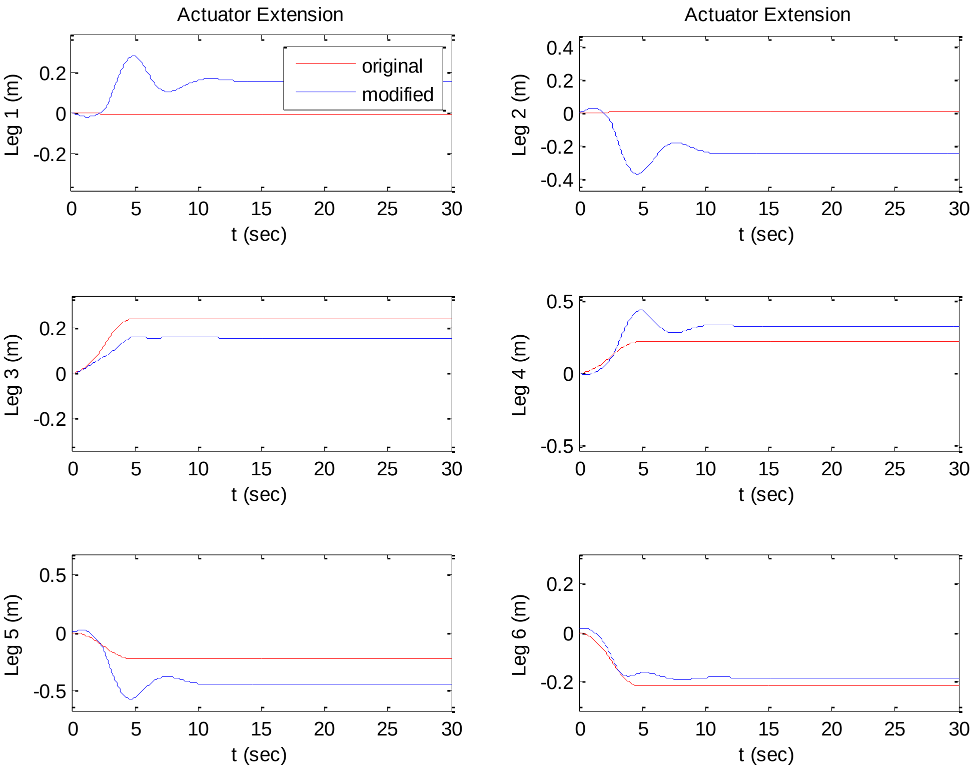

Actuator Extension
Actuator Extension
original
modified
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.4
0.2
0
-0.2
-0.4
0.5
-0.5
0
5
10
15
20
25
30
t (sec)

Figure B.2. 7.

3. Yaw

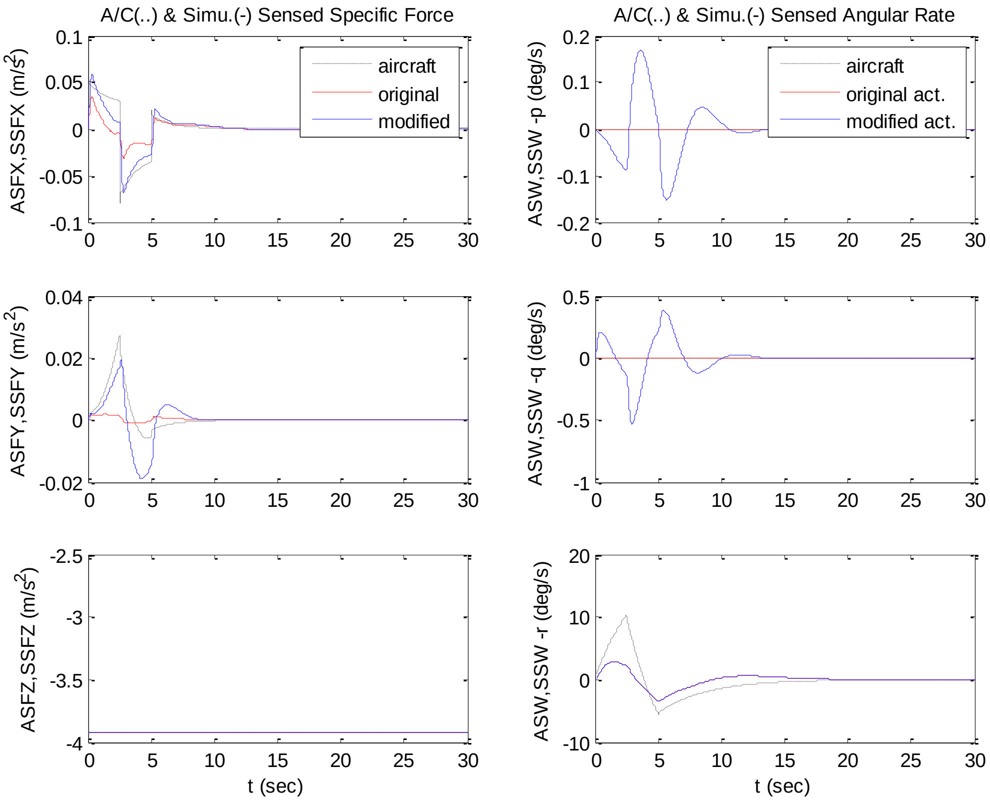


Figure B.3. 1.

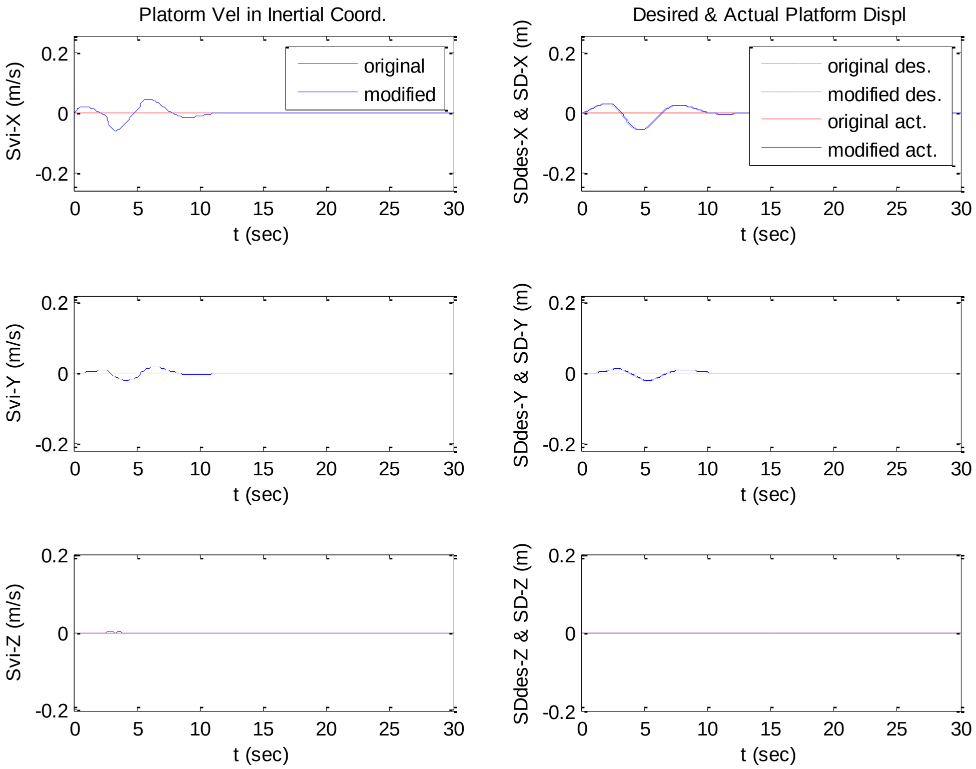

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
original
modified
original des.
modified des.
original act.
modified act.
Svi-X (m/s)
Svi-Y (m/s)
Svi-Z (m/s)
SDdes-X & SD-X (m)
SDdes-Y & SD-Y (m)
SDdes-Z & SD-Z (m)
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure B.3. 2.

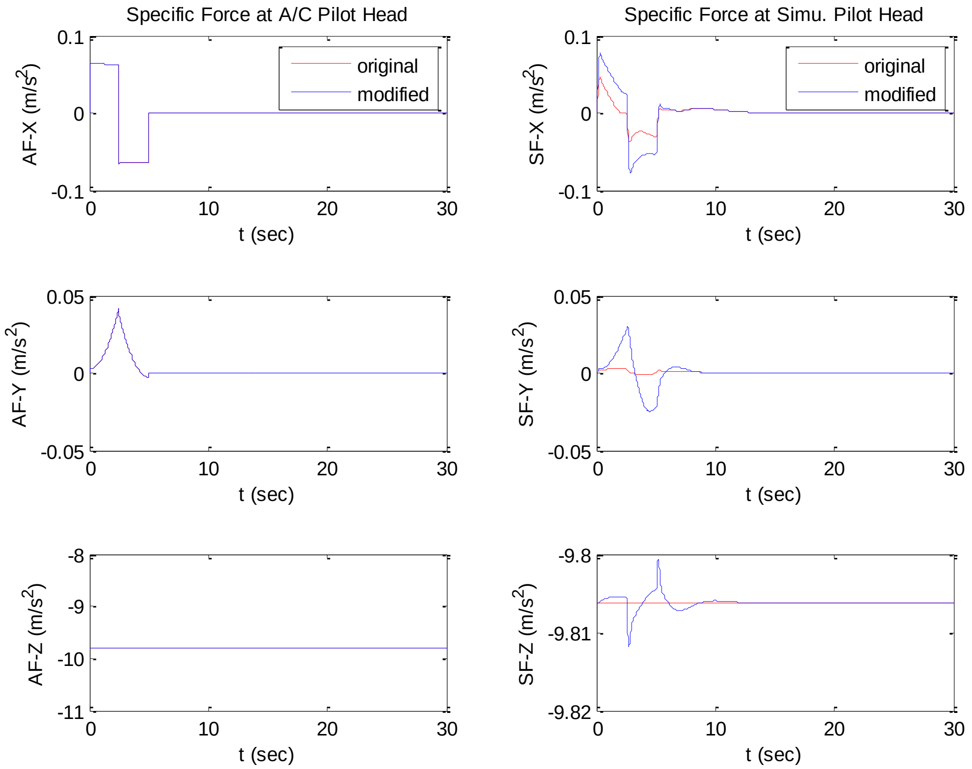

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
original
modified
AF-X (m/s^2)
SF-X (m/s^2)
AF-Y (m/s^2)
SF-Y (m/s^2)
AF-Z (m/s^2)
SF-Z (m/s^2)
0.1
0
-0.1
0.05
-0.05
-8
-9
-10
-11
-9.8
-9.81
-9.82
0
10
20
30
t (sec)

Figure B.3. 3.

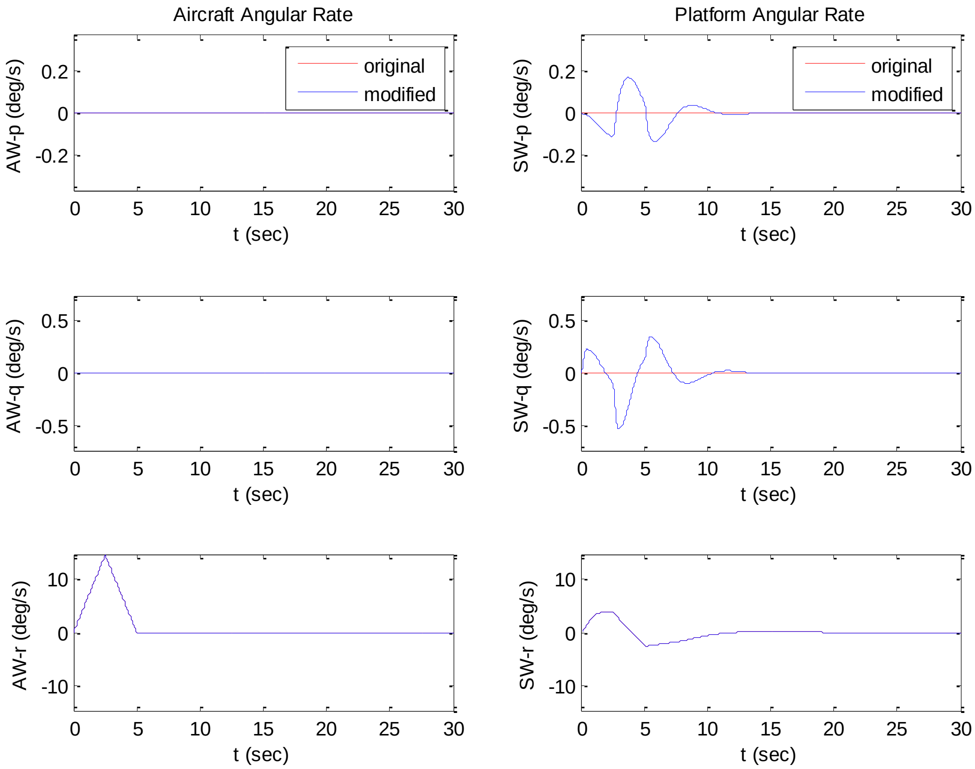

Aircraft Angular Rate
Platform Angular Rate
original
modified
original
modified
AW-p (deg/s)
SW-p (deg/s)
0.2
0
-0.2
AW-q (deg/s)
SW-q (deg/s)
0.5
0
-0.5
AW-r (deg/s)
SW-r (deg/s)
10
0
-10
0
5
10
15
20
25
30
t (sec)

Figure B.3. 4.

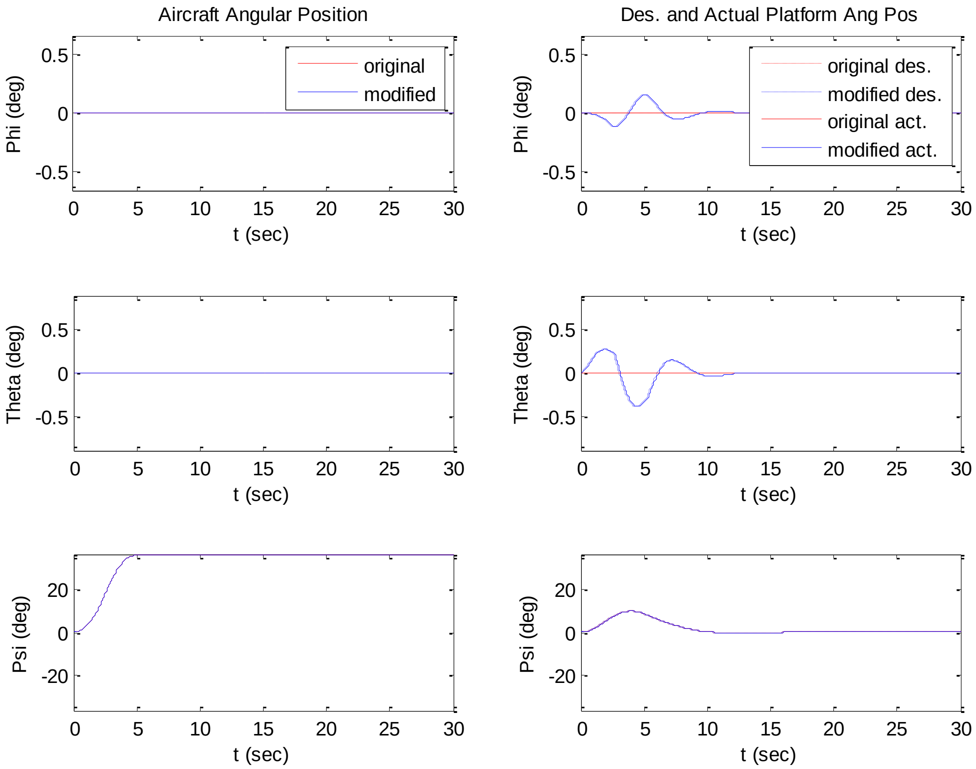

Aircraft Angular Position
Des. and Actual Platform Ang Pos
Phi (deg)
0.5
0
-0.5
original
modified
original des.
modified des.
original act.
modified act.
Theta (deg)
Psi (deg)
20
-20
0
5
10
15
20
25
30
t (sec)

Figure B.3. 5.

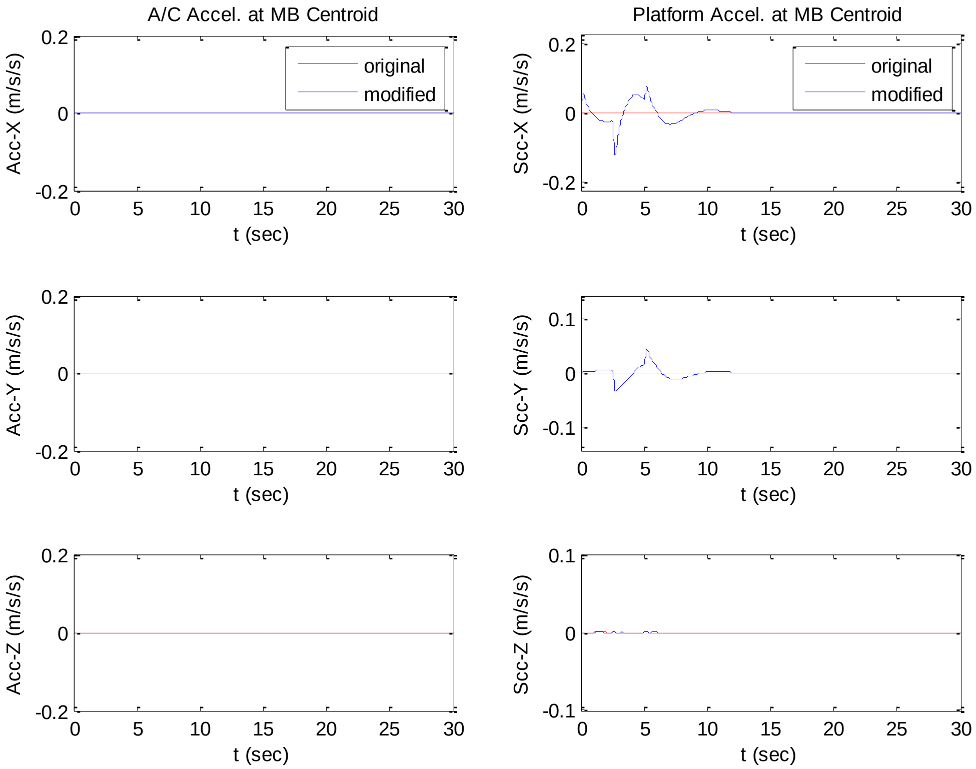
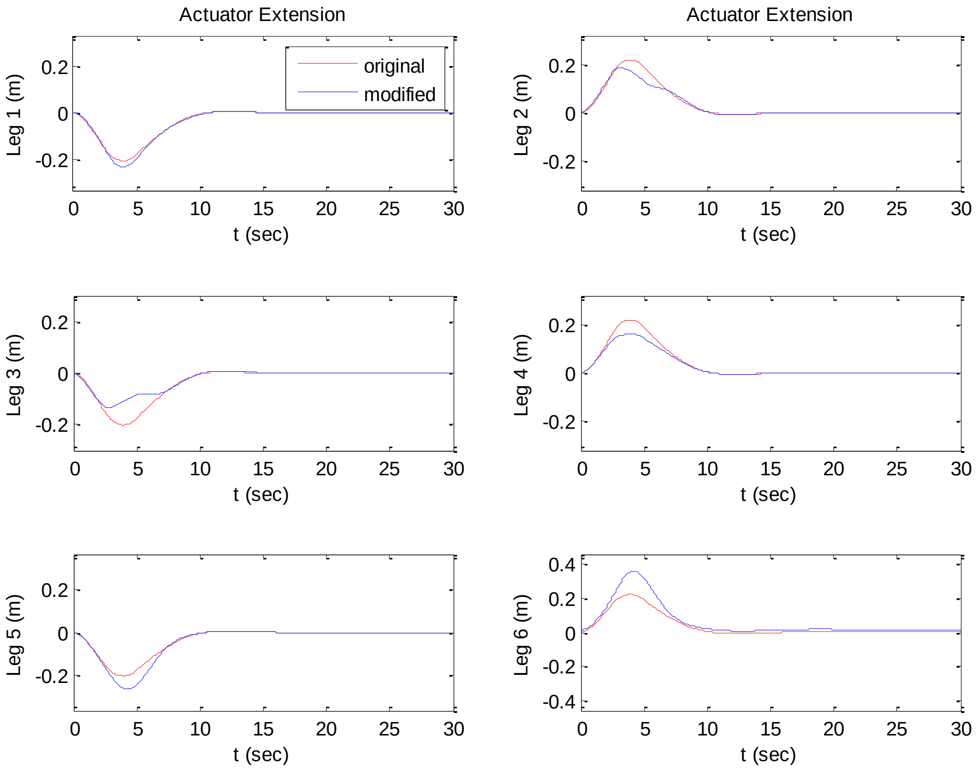

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
modified
original
modified
Acc-X (m/s/s)
Acc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-X (m/s/s)
Scc-Y (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.1
-0.1
0
5
10
15
20
25
30
t (sec)

Figure B.3. 6.



Actuator Extension
Actuator Extension
original
modified
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.2
0
-0.2
0.4
-0.4
0
5
10
15
20
25
30
t (sec)

Figure B.3. 7.

4. Surge

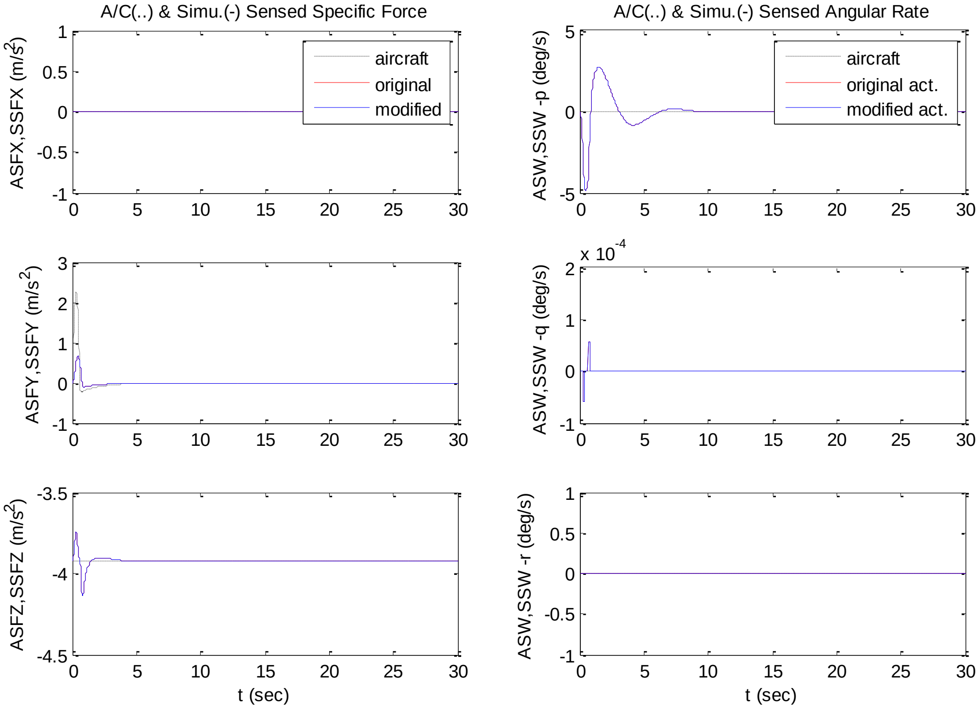


Figure B.4. 1.

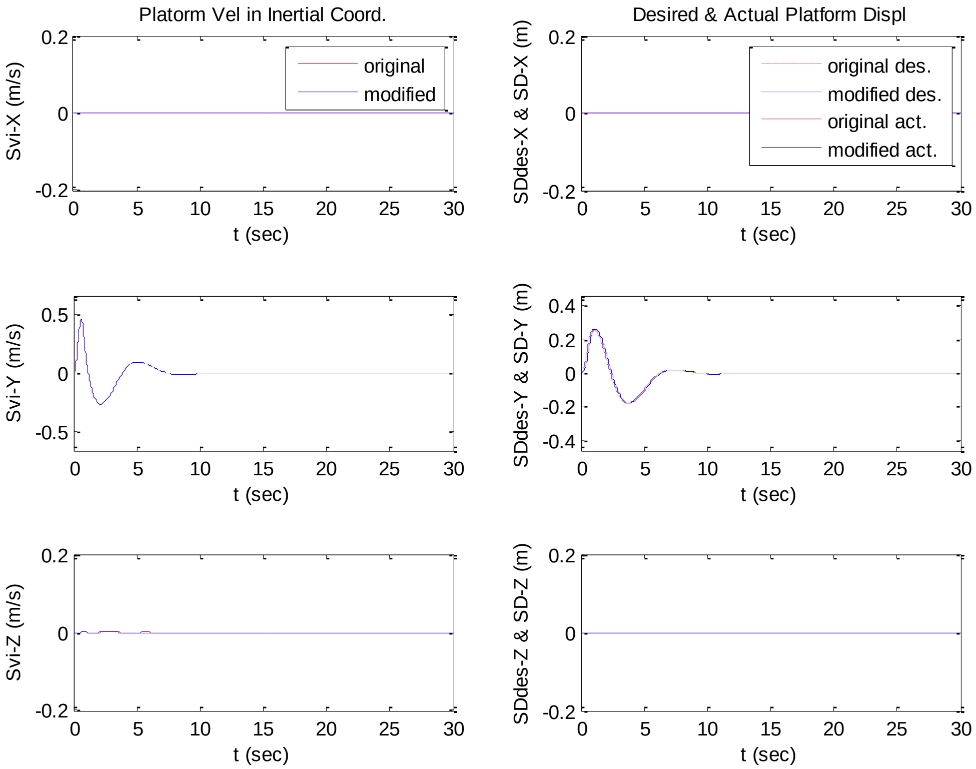

Platorm Vel in Inertial Coord.
Svi-X (m/s)
0.2
0
-0.2
original
modified
Desired & Actual Platform Displ
SDdes-X & SD-X (m)
original des.
modified des.
original act.
modified act.
Svi-Y (m/s)
0.5
0
-0.5
SDdes-Y & SD-Y (m)
0.4
0.2
0
-0.2
-0.4
Svi-Z (m/s)
SDdes-Z & SD-Z (m)
0 5 10 15 20 25 30
t (sec)

Figure B.4. 2.

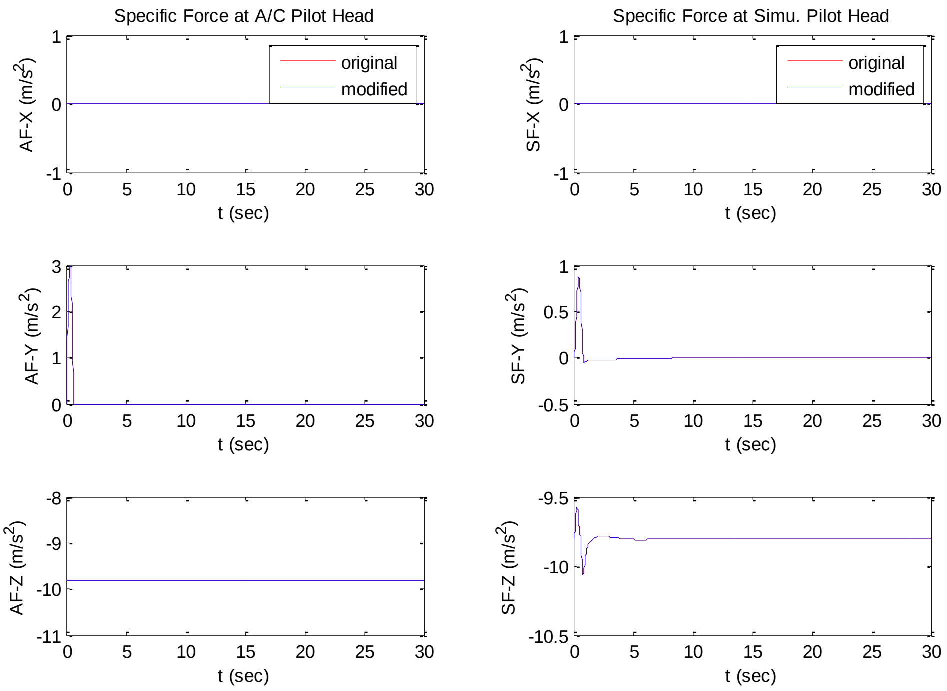

Specific Force at A/C Pilot Head
AF-X (m/s^2)
1
0
-1
original
modified
Specific Force at Simu. Pilot Head
SF-X (m/s^2)
AF-Y (m/s^2)
3
2
1
0
SF-Y (m/s^2)
1
0.5
0
-0.5
AF-Z (m/s^2)
-8
-9
-10
-11
SF-Z (m/s^2)
-9.5
-10
-10.5
0 5 10 15 20 25 30
t (sec)

Figure B.4. 3.

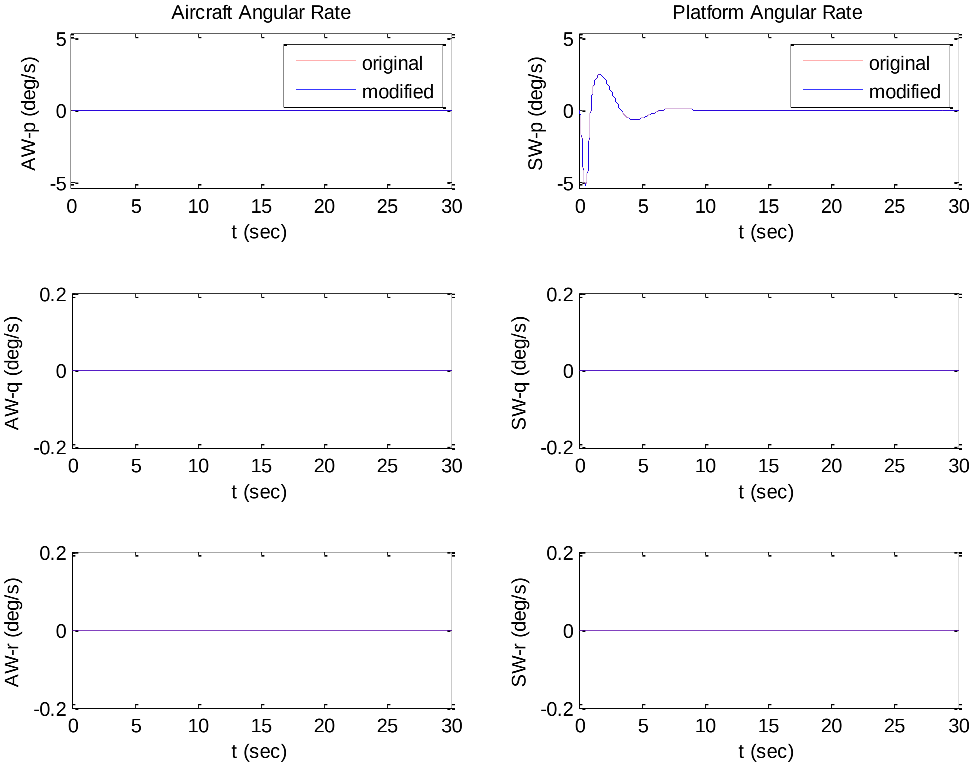


Figure B.4. 4.

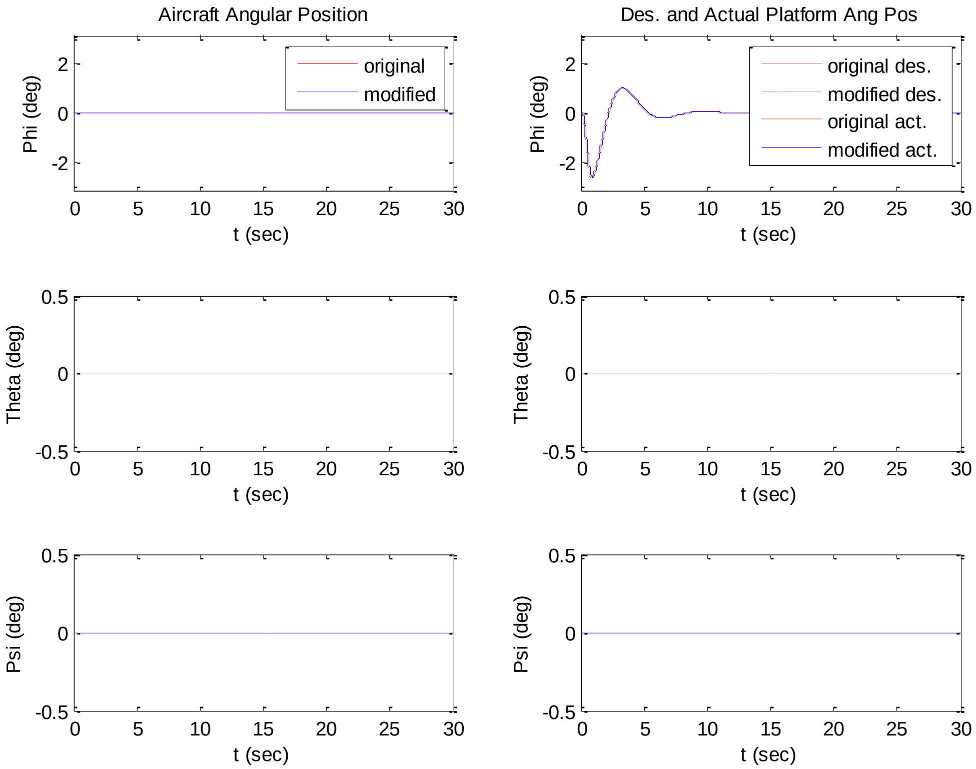

Aircraft Angular Position
Des. and Actual Platform Ang Pos
original
modified
original des.
modified des.
original act.
modified act.
Phi (deg)
Theta (deg)
Psi (deg)
t (sec)
2
0
-2
0.5
-0.5
0
5
10
15
20
25
30

Figure B.4. 5.

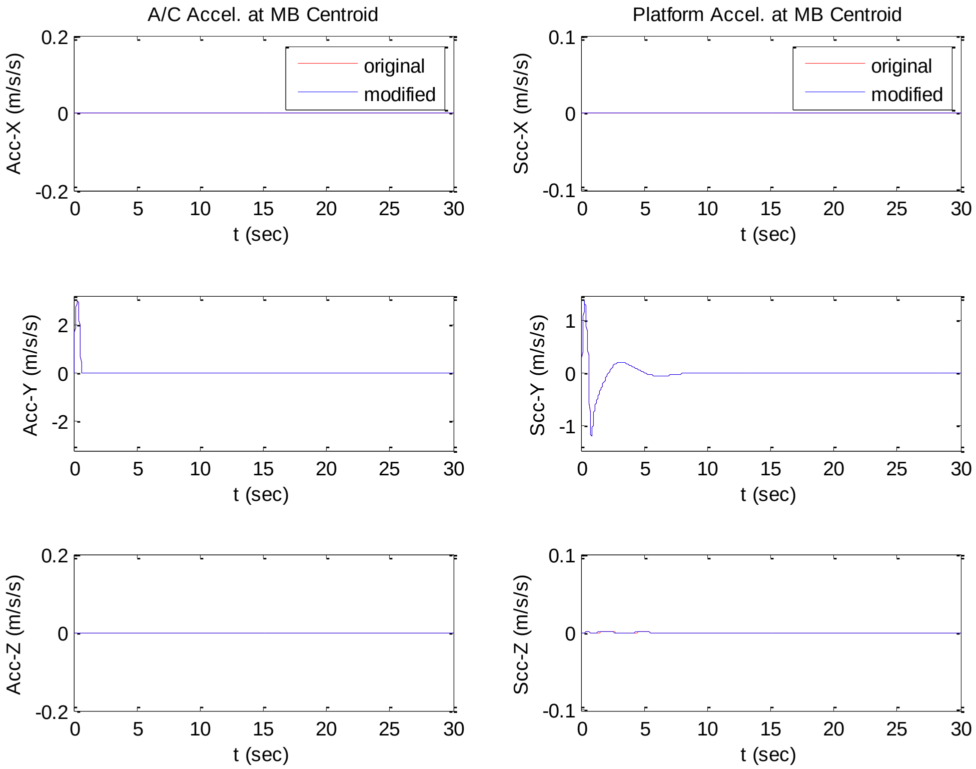

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
modified
original
modified
Acc-X (m/s/s)
Scc-X (m/s/s)
Acc-Y (m/s/s)
Scc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.1
0
-0.1
2
0
-2
1
0
-1
0.2
0
-0.2
0.1
0
-0.1
0 5 10 15 20 25 30
t (sec)

Figure B.4. 6.

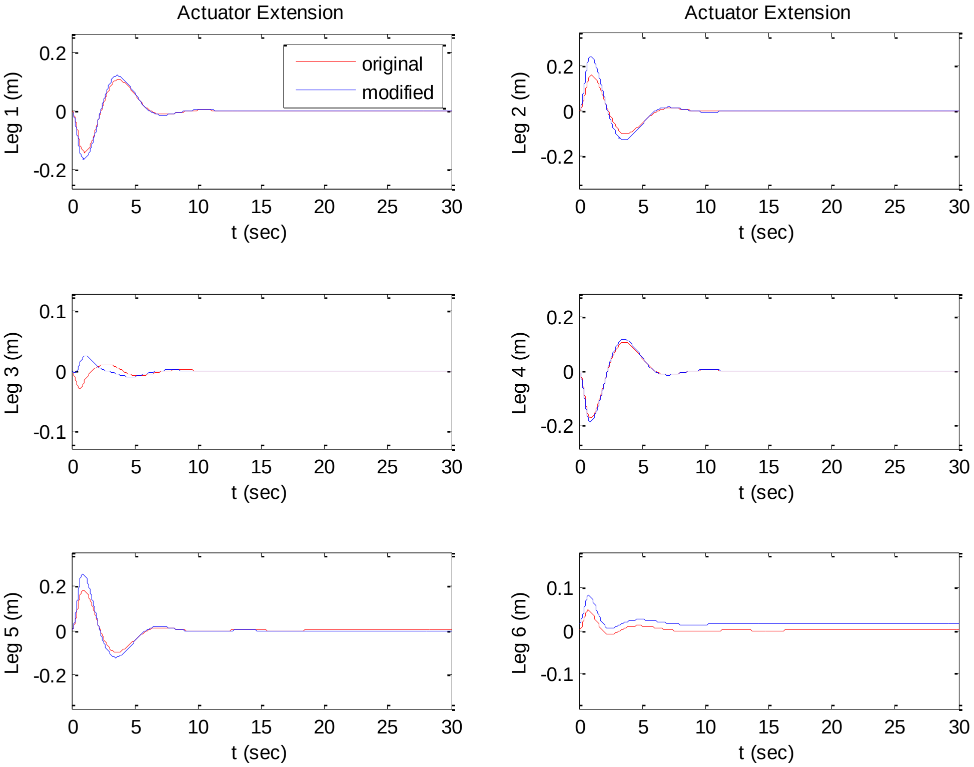

Actuator Extension
Actuator Extension
original
modified
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.2
0
-0.2
0.1
-0.1
0
5
10
15
20
25
30
t (sec)

Figure B.4. 7.

5. Sway

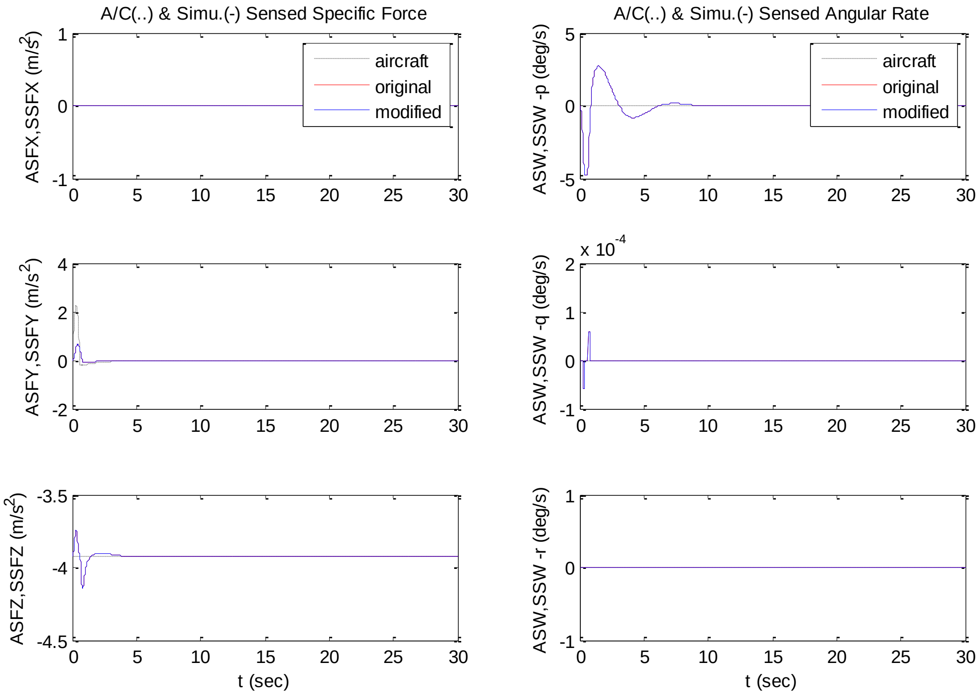


Figure B.5. 1.

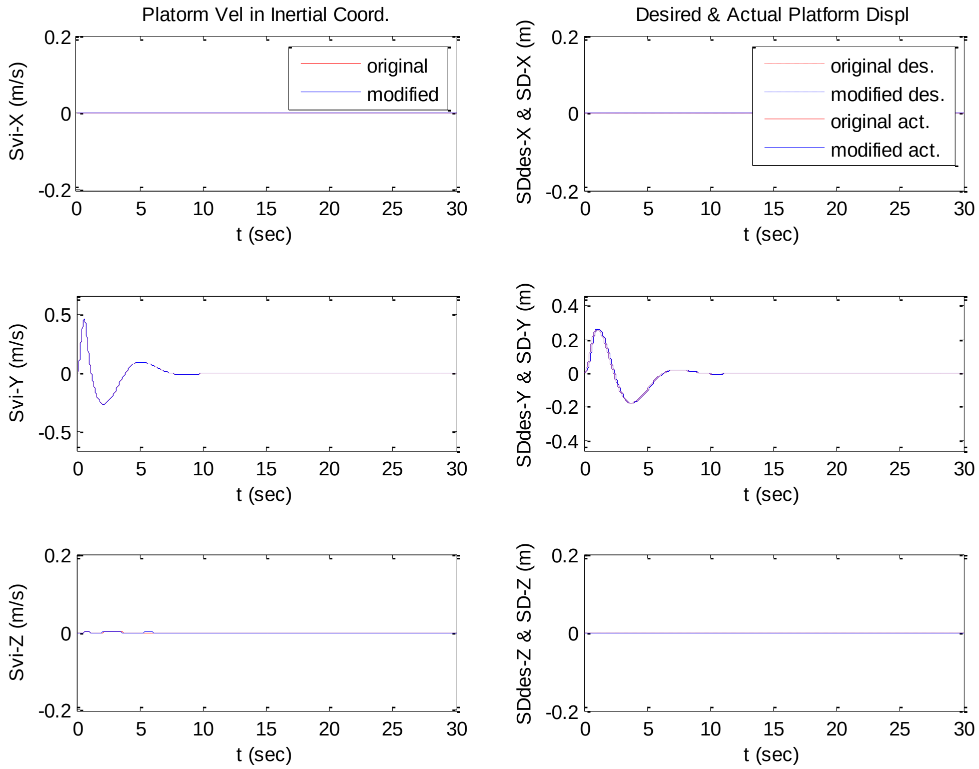

Platorm Vel in Inertial Coord.
Svi-X (m/s)
original
modified
Desired & Actual Platform Displ
SDdes-X & SD-X (m)
original des.
modified des.
original act.
modified act.
Svi-Y (m/s)
SDdes-Y & SD-Y (m)
Svi-Z (m/s)
SDdes-Z & SD-Z (m)
0.2
0
-0.2
0.5
-0.5
0.4
0.2
-0.4
0
5
10
15
20
25
30
t (sec)

Figure B.5. 2.

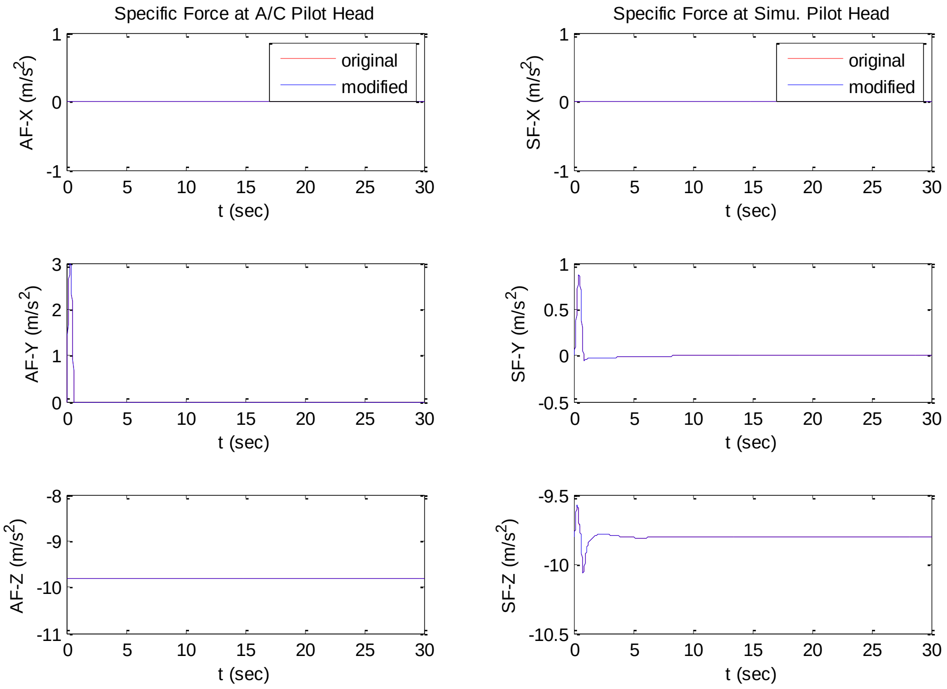

Specific Force at A/C Pilot Head
AF-X (m/s^2)
original
modified
Specific Force at Simu. Pilot Head
SF-X (m/s^2)
AF-Y (m/s^2)
SF-Y (m/s^2)
AF-Z (m/s^2)
SF-Z (m/s^2)
1
0
-1
3
2
0.5
-0.5
-8
-9
-10
-11
-9.5
-10.5
0
5
10
15
20
25
30
t (sec)

Figure B.5. 3.

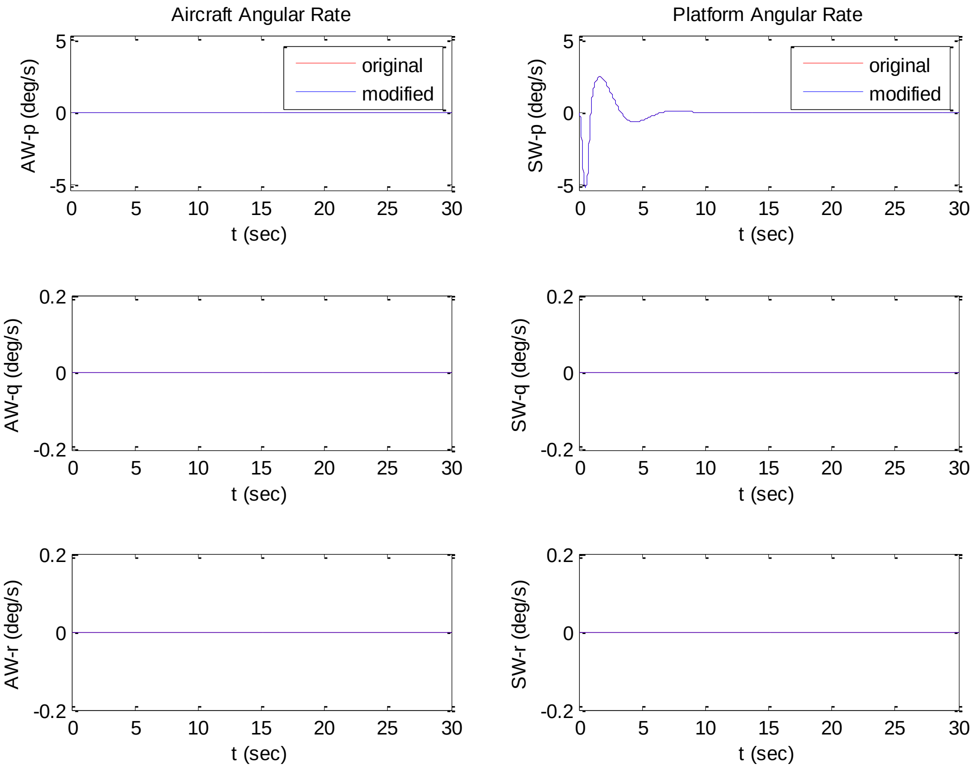


Figure B.5. 4.

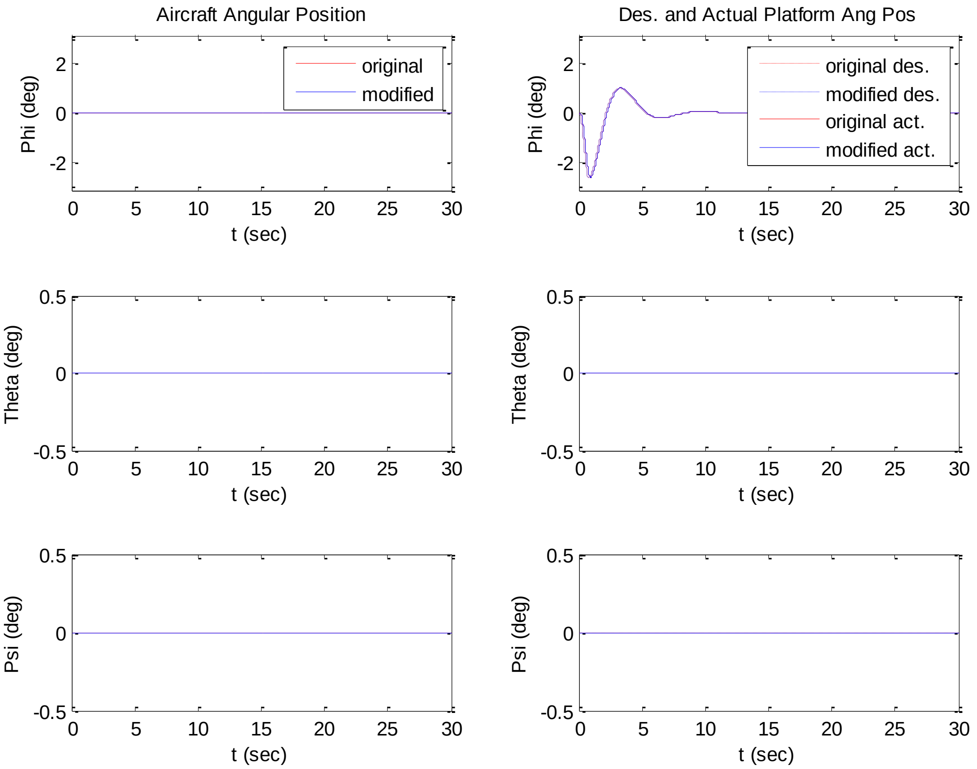

Aircraft Angular Position
Des. and Actual Platform Ang Pos
Phi (deg)
2
0
-2
original
modified
original des.
modified des.
original act.
modified act.
Theta (deg)
0.5
0
-0.5
Psi (deg)
0.5
0
-0.5
0
5
10
15
20
25
30
t (sec)

Figure B.5. 5.

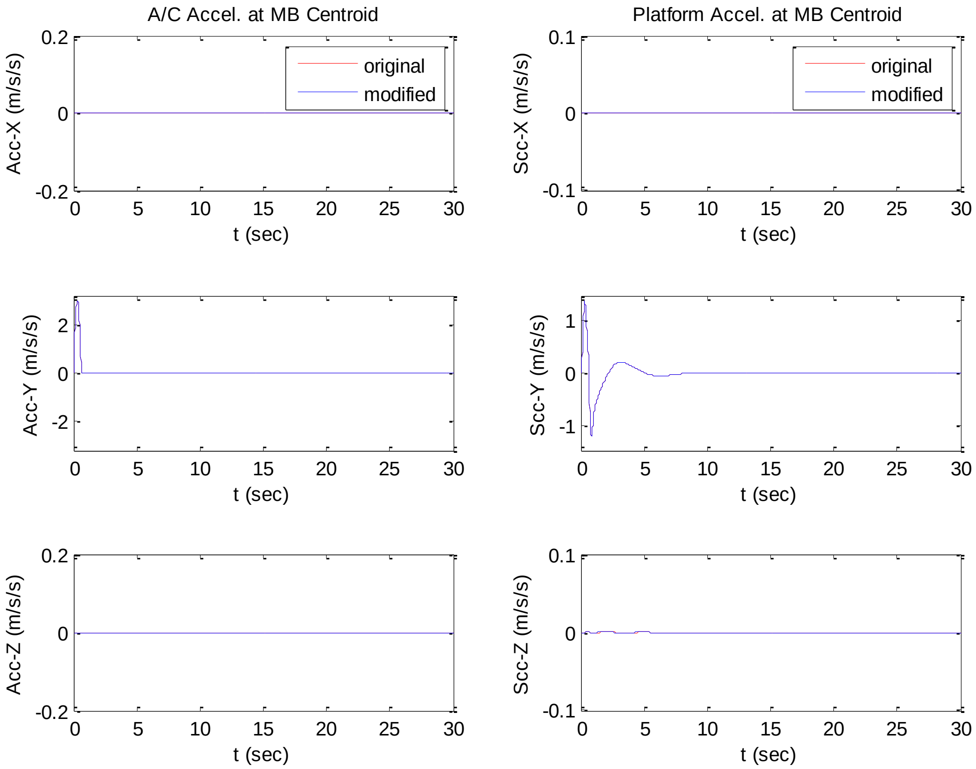

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
modified
Acc-X (m/s/s)
Scc-X (m/s/s)
Acc-Y (m/s/s)
Scc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.1
0
-0.1
2
0
-2
1
0
-1
0
5
10
15
20
25
30
t (sec)

Figure B.5. 6.

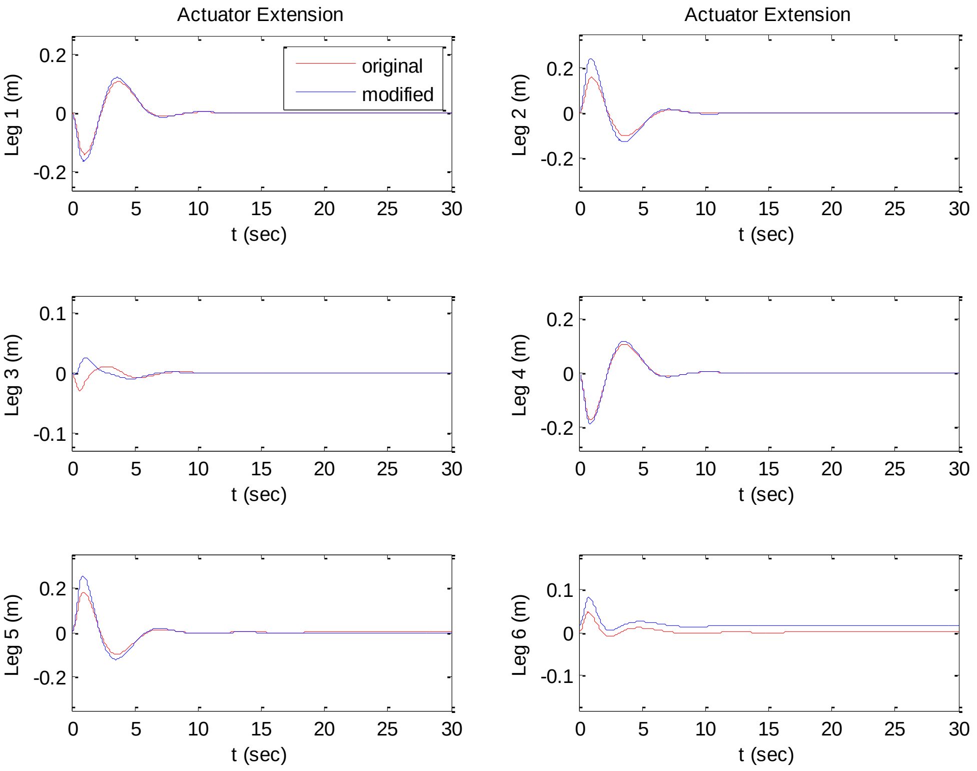

Actuator Extension
Actuator Extension
original
modified
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.2
0
-0.2
0.1
-0.1
0
5
10
15
20
25
30
t (sec)

Figure B.5. 7.

6. Heave

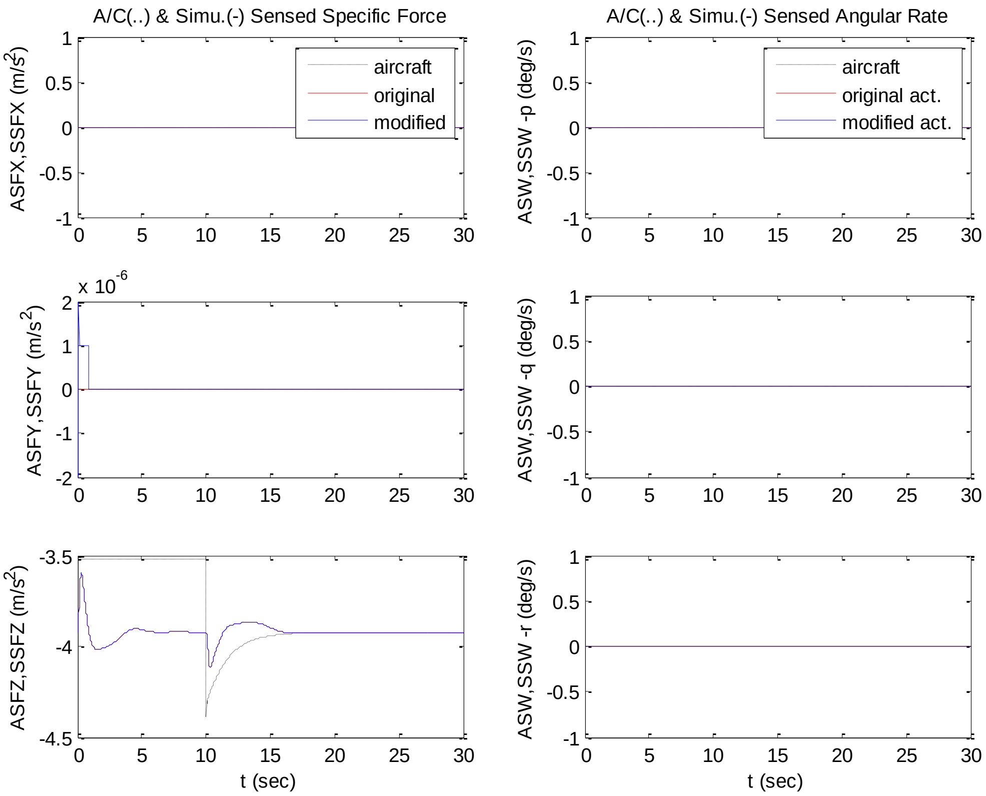


Figure B.6. 1.

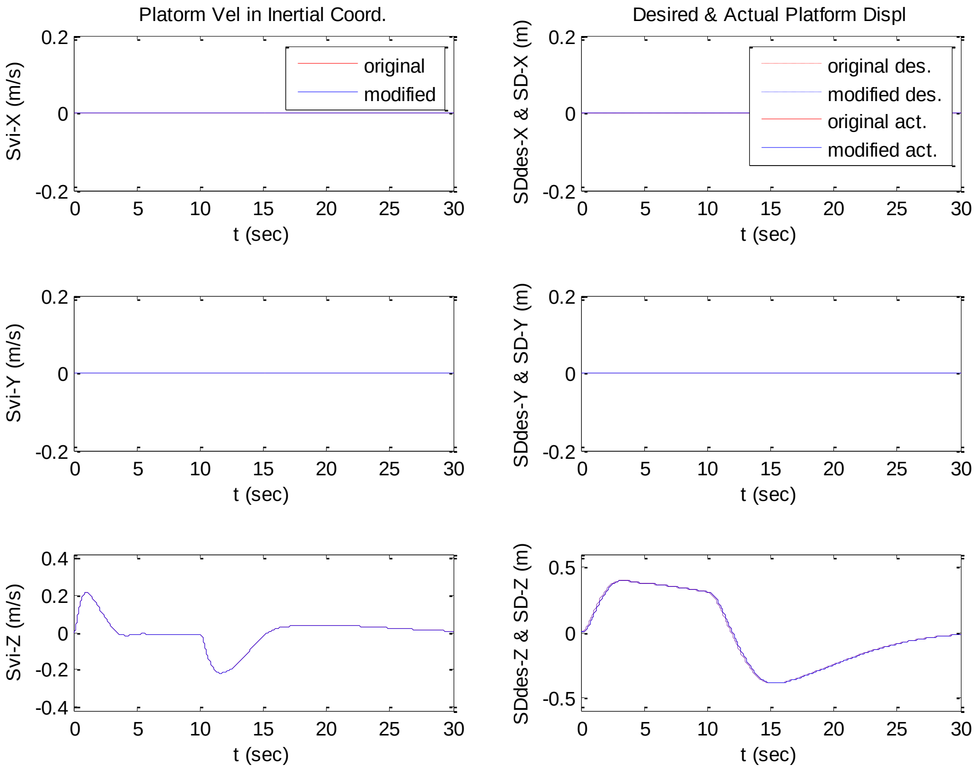

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
original
modified
original des.
modified des.
original act.
modified act.
Svi-X (m/s)
SDdes-X & SD-X (m)
Svi-Y (m/s)
SDdes-Y & SD-Y (m)
Svi-Z (m/s)
SDdes-Z & SD-Z (m)
0.2
0
-0.2
0.4
-0.4
0.5
-0.5
0
5
10
15
20
25
30
t (sec)

Figure B.6. 2.

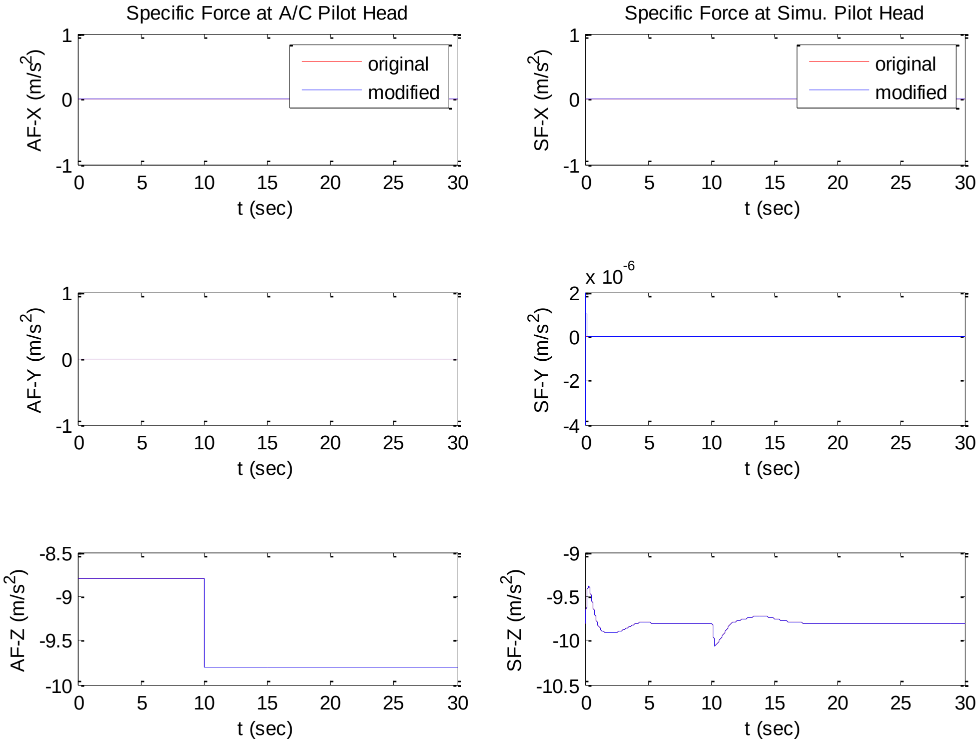

Specific Force at A/C Pilot Head
AF-X (m/s^2)
1
0
-1
original
modified
0
5
10
15
20
25
30
t (sec)
Specific Force at Simu. Pilot Head
SF-X (m/s^2)
1
0
-1
original
modified
t (sec)
AF-Y (m/s^2)
t (sec)
x 10^{-6}
2
0
-2
-4
SF-Y (m/s^2)
t (sec)
AF-Z (m/s^2)
-8.5
-9
-9.5
-10
t (sec)
SF-Z (m/s^2)
-9
-9.5
-10
-10.5
t (sec)

Figure B.6. 3.

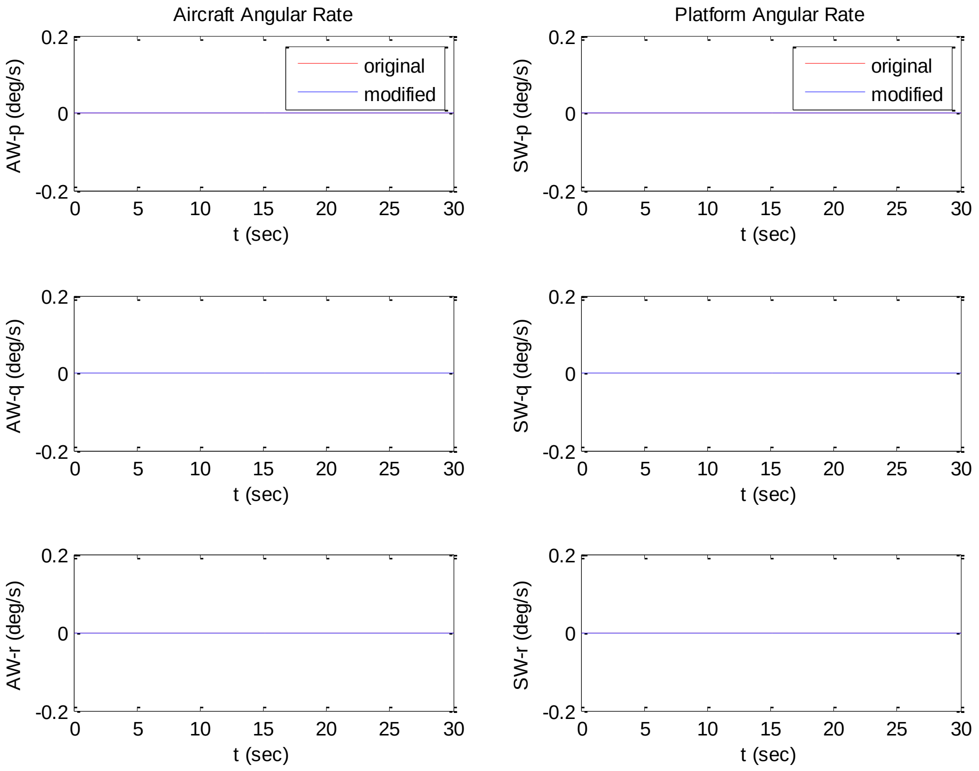

Aircraft Angular Rate
Platform Angular Rate
original
modified
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure B.6. 4.

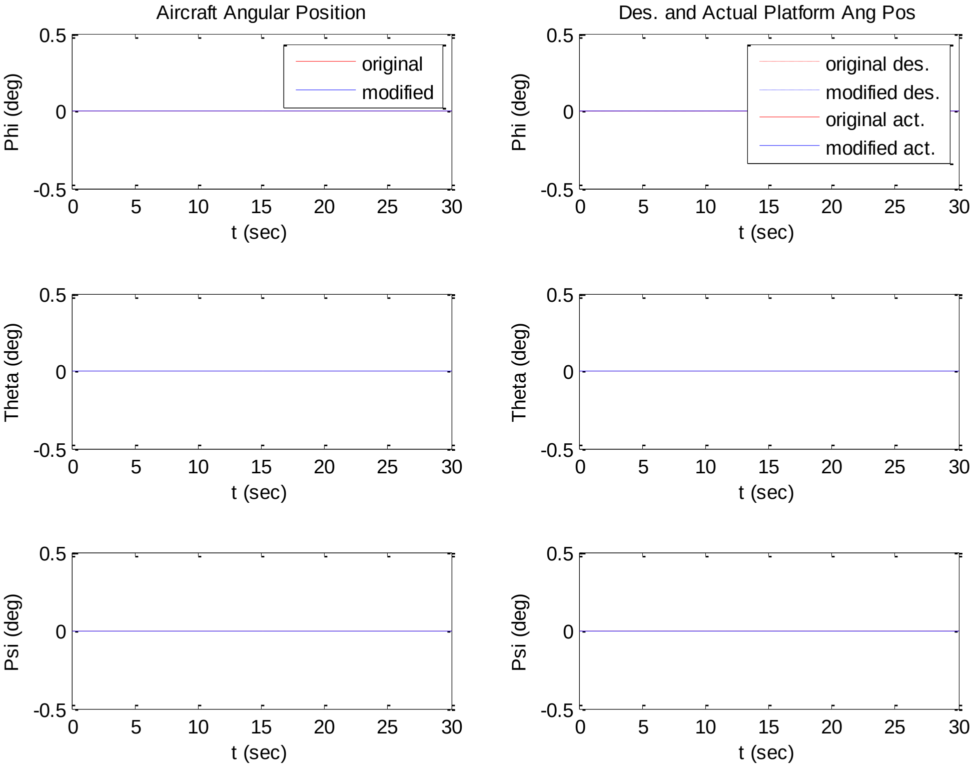

Aircraft Angular Position
Des. and Actual Platform Ang Pos
original
modified
original des.
modified des.
original act.
modified act.
Phi (deg)
Theta (deg)
Psi (deg)
0.5
0
-0.5
0
5
10
15
20
25
30
t (sec)

Figure B.6. 5.

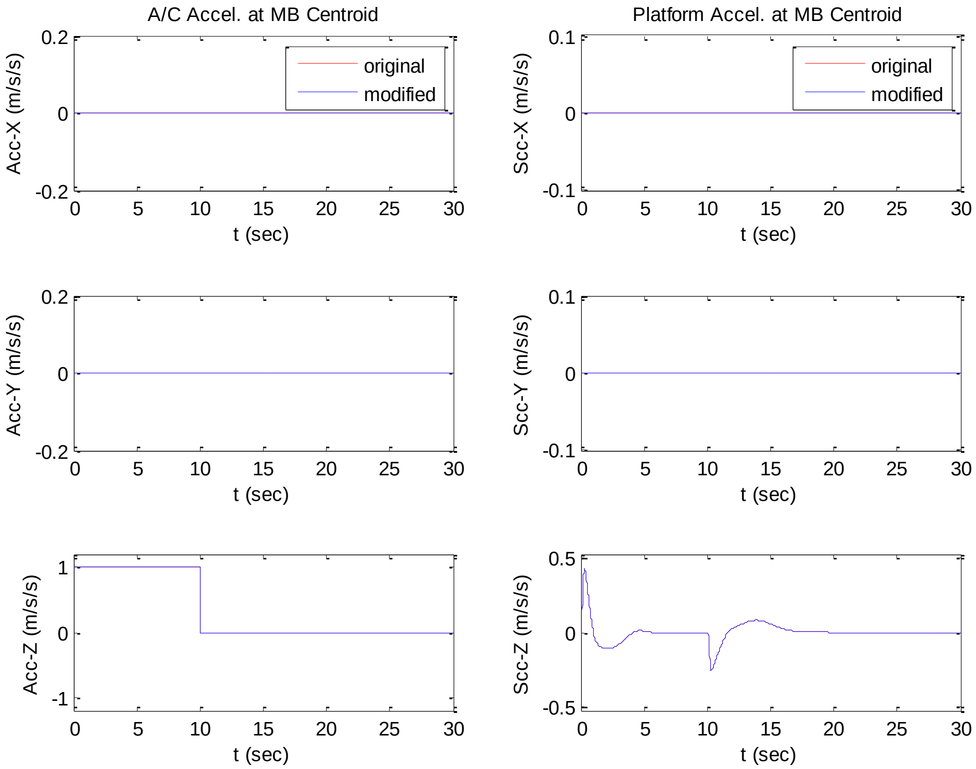

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
modified
original
modified
Acc-X (m/s/s)
Scc-X (m/s/s)
Acc-Y (m/s/s)
Scc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.1
0
-0.1
1
0
-1
0.5
0
-0.5
0
5
10
15
20
25
30
t (sec)

Figure B.6. 6.

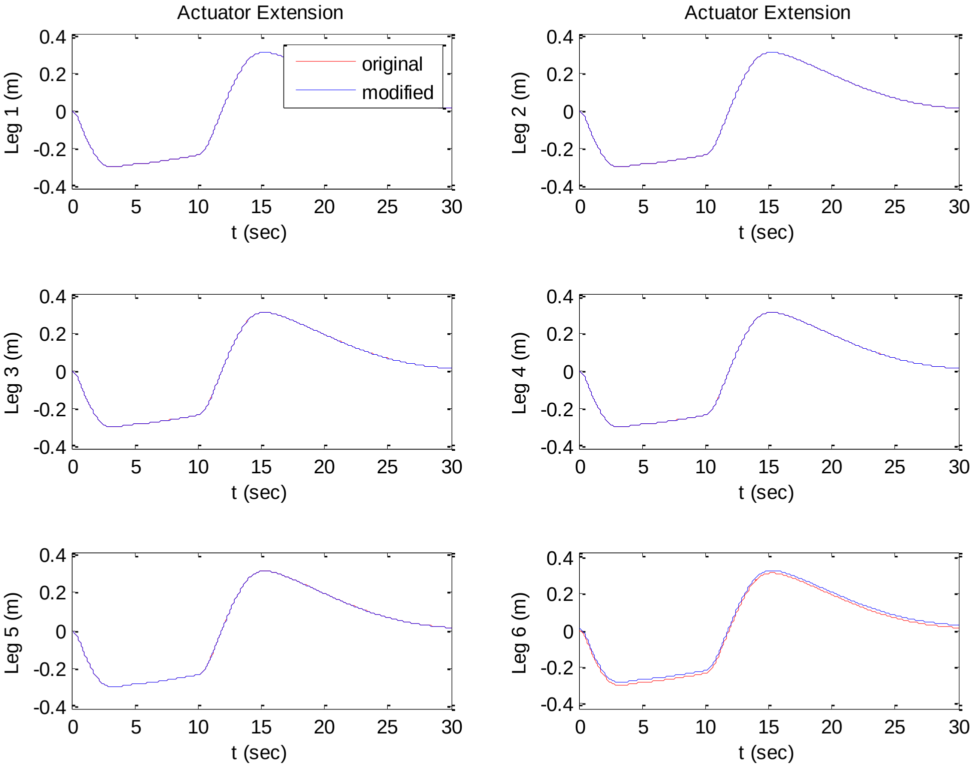

Actuator Extension
Actuator Extension
original
modified
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
30
t (sec)

Figure B.6. 7.

Appendix C. Non-linear optimal algorithm: original vs. augmented

General note: if only one or two curves are visible on the plot, assume that the remaining curves are underneath the visible ones.

1. Pitch

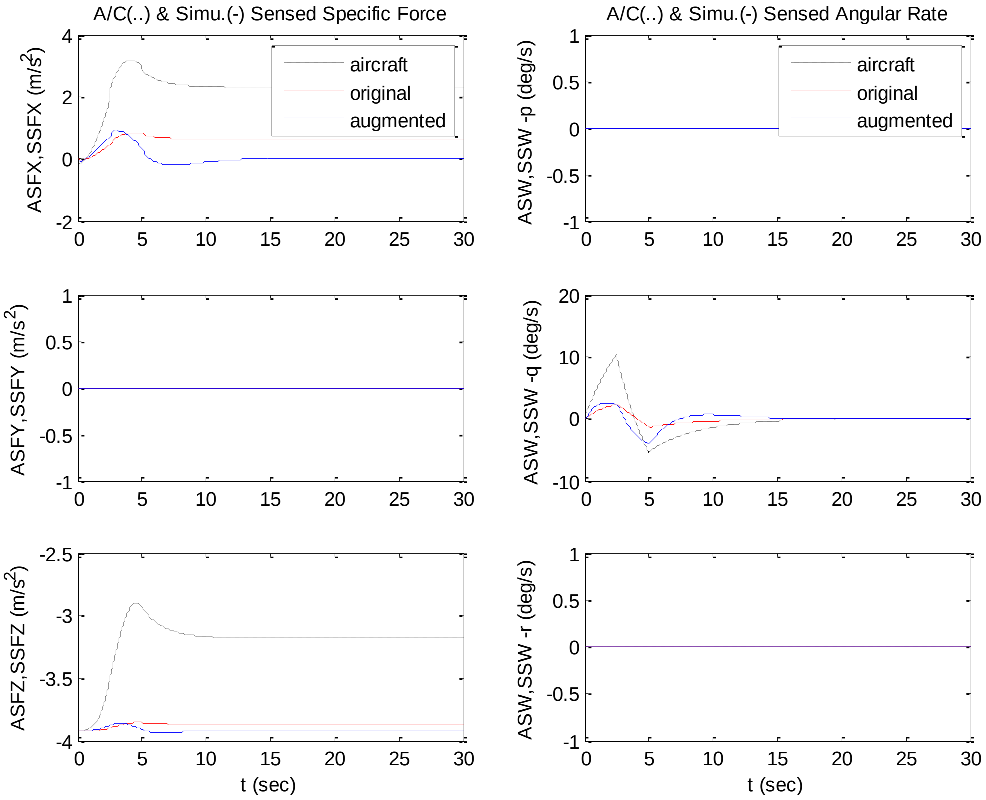


Figure C.1. 1.

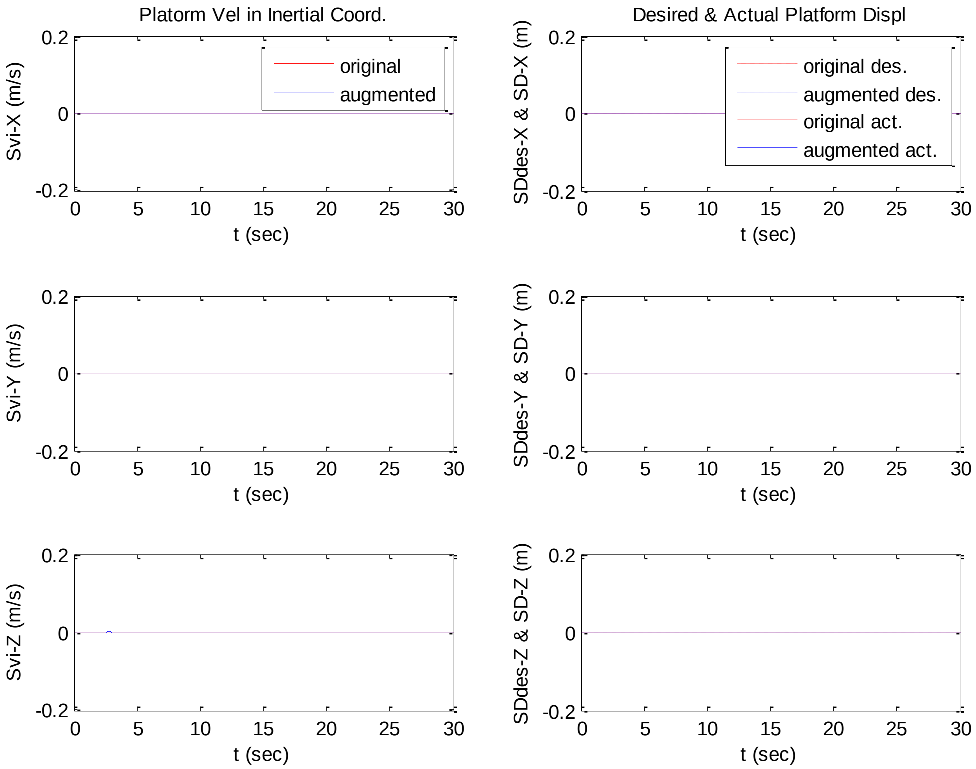

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
Svi-X (m/s)
SDdes-X & SD-X (m)
Svi-Y (m/s)
SDdes-Y & SD-Y (m)
Svi-Z (m/s)
SDdes-Z & SD-Z (m)
original
augmented
original des.
augmented des.
original act.
augmented act.
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure C.1. 2.

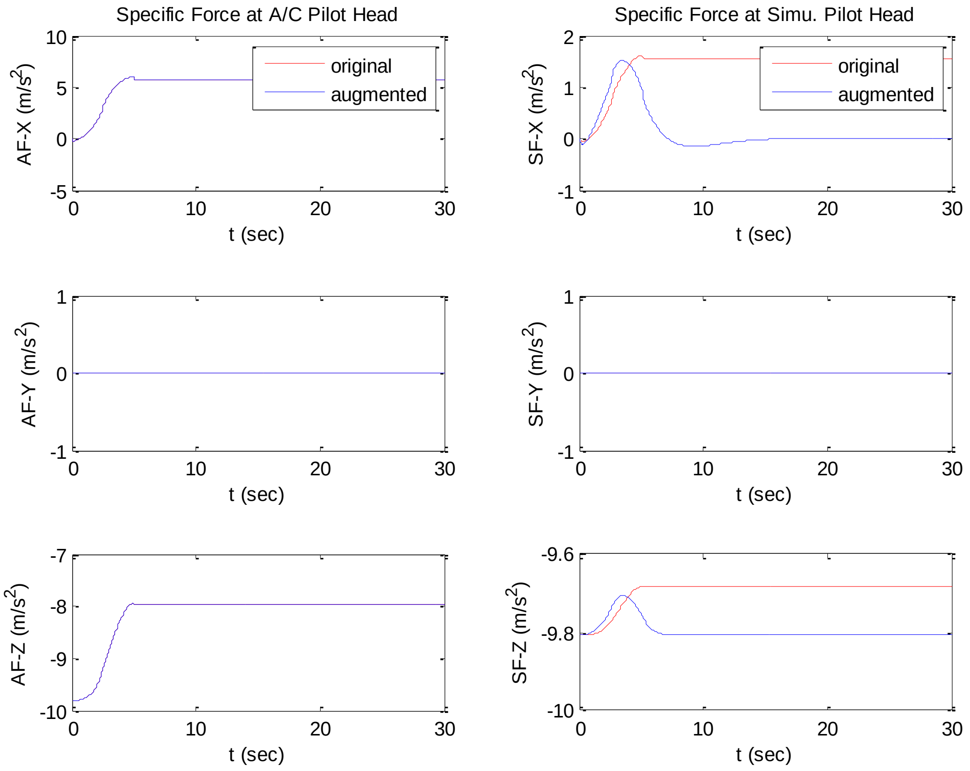

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
original
augmented
original
augmented
AF-X (m/s^2)
SF-X (m/s^2)
AF-Y (m/s^2)
SF-Y (m/s^2)
AF-Z (m/s^2)
SF-Z (m/s^2)
t (sec)
10
5
0
-5
2
1
-1
-7
-8
-9
-10
-9.6
-9.8
20
30

Figure C.1. 3.

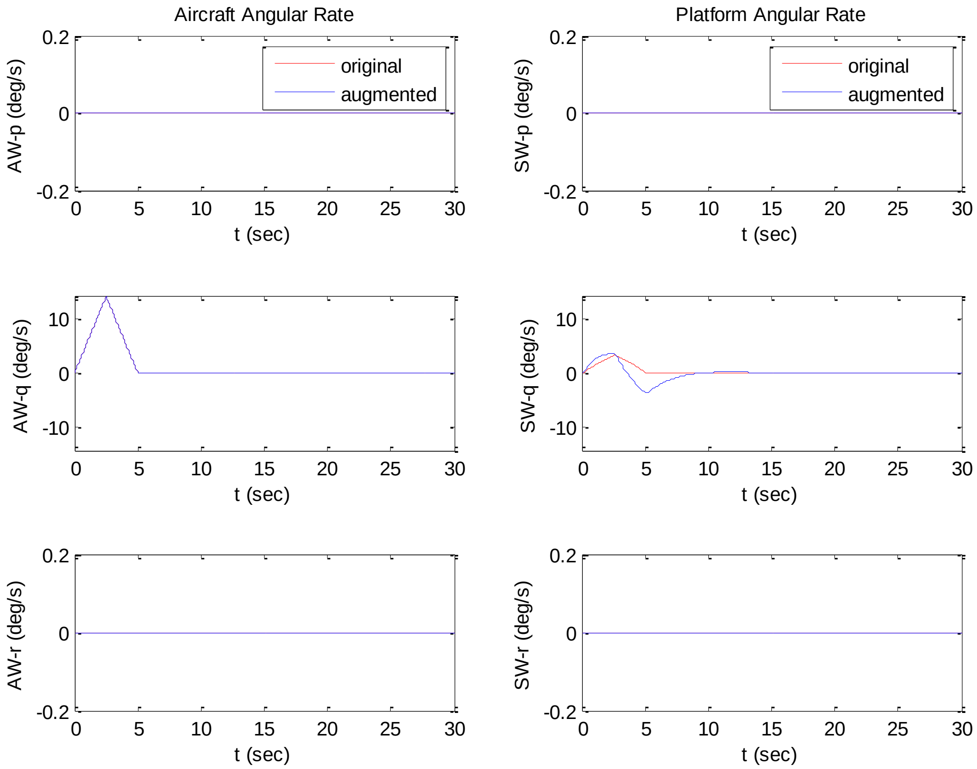

Aircraft Angular Rate
Platform Angular Rate
original
augmented
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
0.2
0
-0.2
10
0
-10
0
5
10
15
20
25
30
t (sec)

Figure C.1. 4.

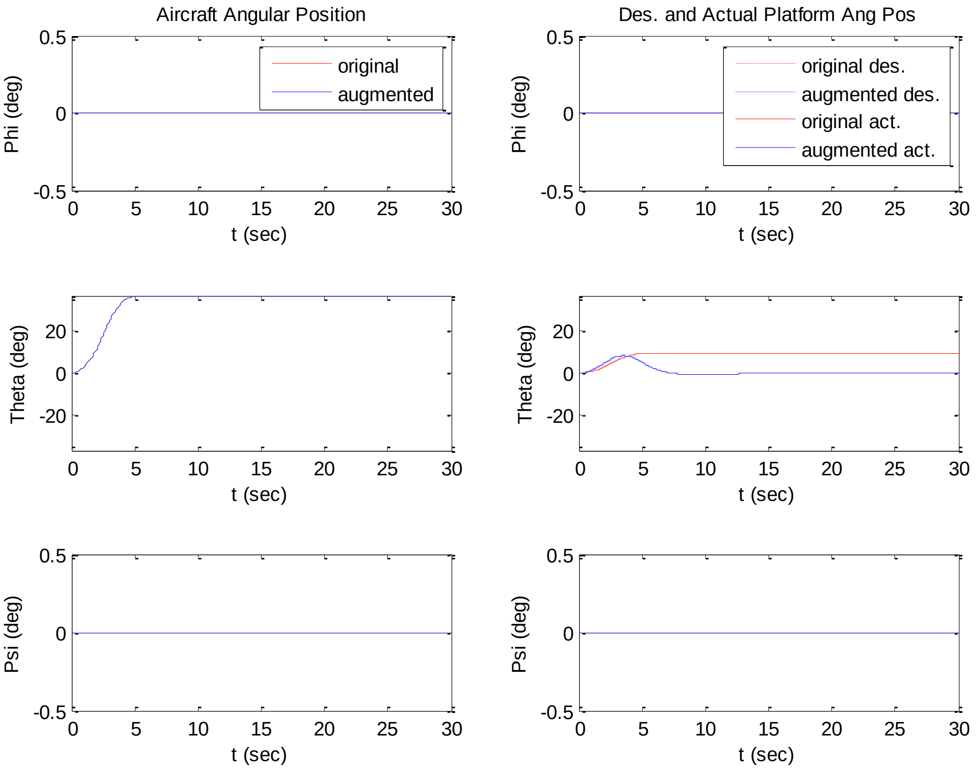

Aircraft Angular Position
Des. and Actual Platform Ang Pos
original
augmented
original des.
augmented des.
original act.
augmented act.
Phi (deg)
Theta (deg)
Psi (deg)
0.5
0
-0.5
20
0
-20
0
5
10
15
20
25
30
t (sec)

Figure C.1. 5.

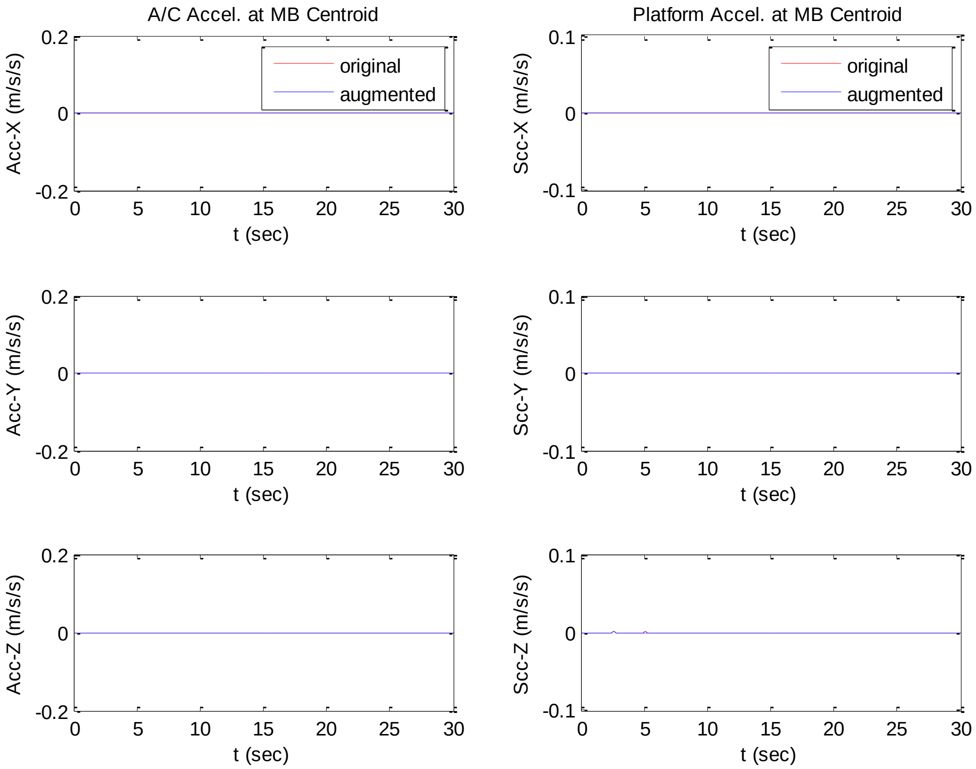

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
augmented
Acc-X (m/s/s)
Acc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-X (m/s/s)
Scc-Y (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.1
0
-0.1
0
5
10
15
20
25
30
t (sec)

Figure C.1. 6.

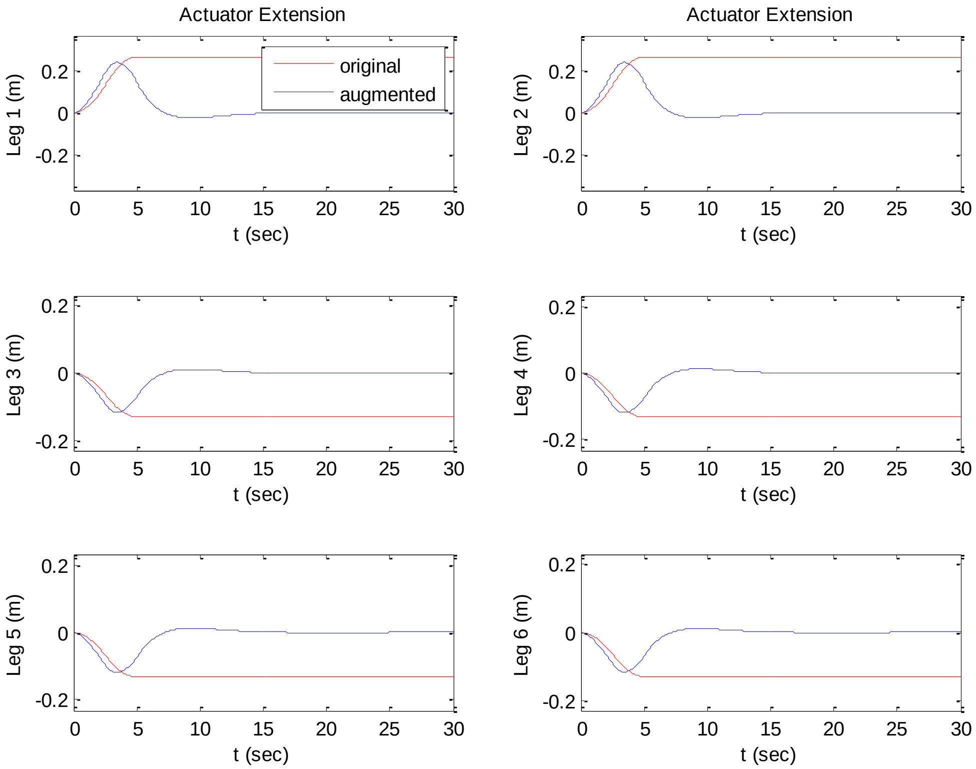

Actuator Extension
Actuator Extension
original
augmented
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure C.1. 7.

2. Roll

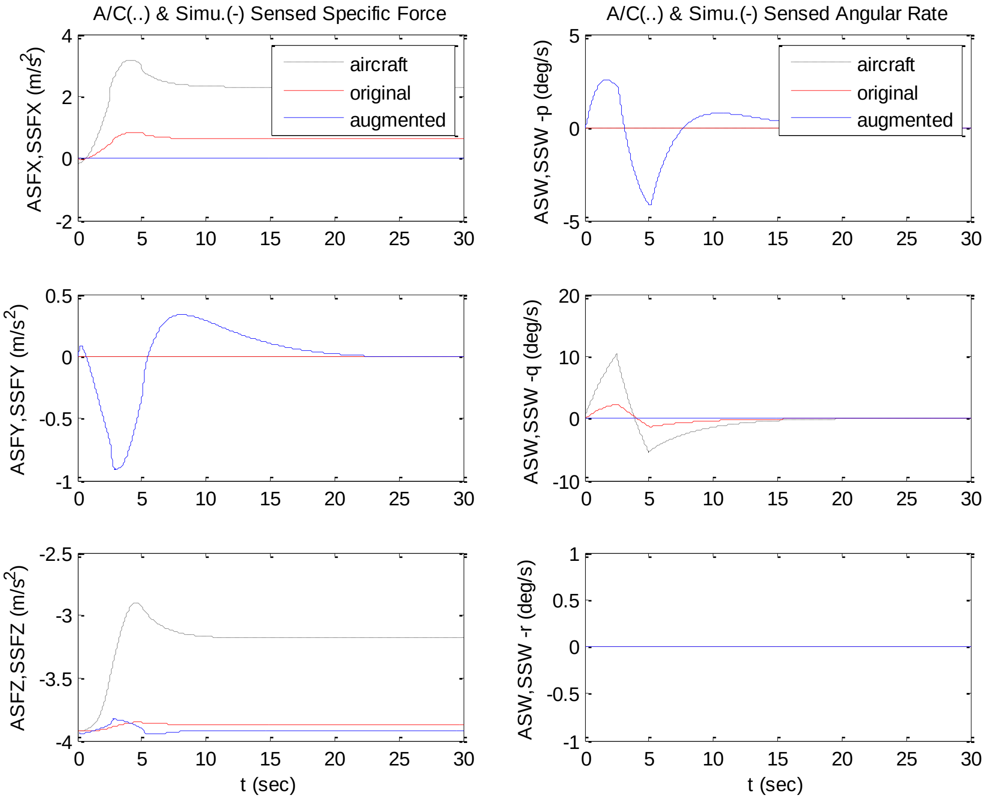


Figure C.2. 1.

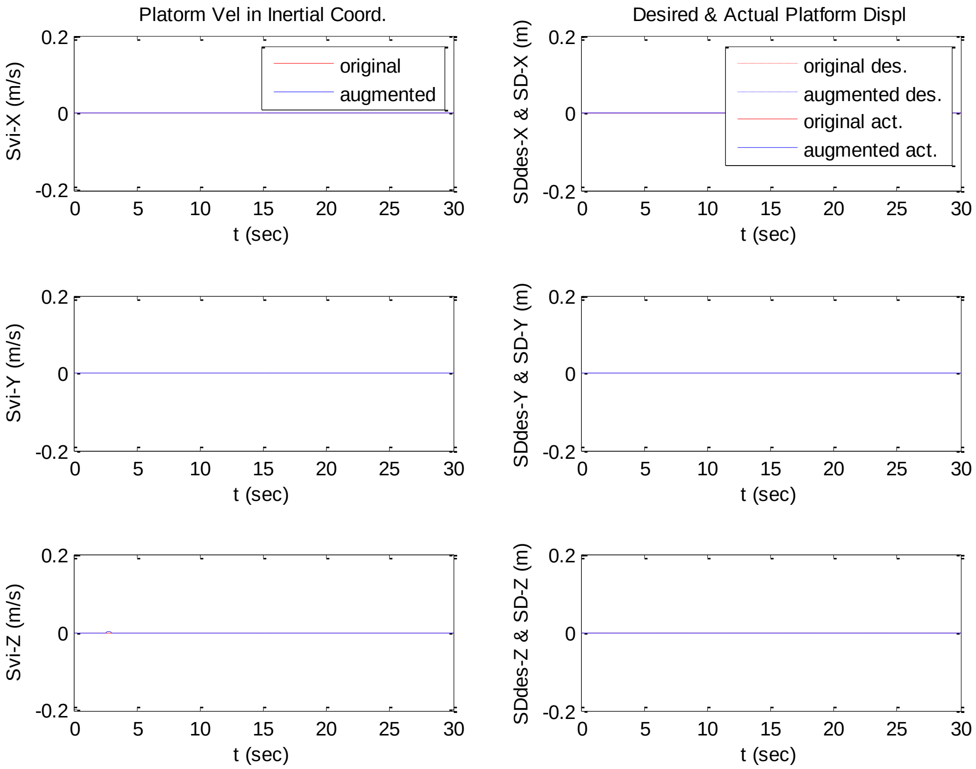

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
original
augmented
original des.
augmented des.
original act.
augmented act.
Svi-X (m/s)
Svi-Y (m/s)
Svi-Z (m/s)
SDdes-X & SD-X (m)
SDdes-Y & SD-Y (m)
SDdes-Z & SD-Z (m)
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure C.2. 2.

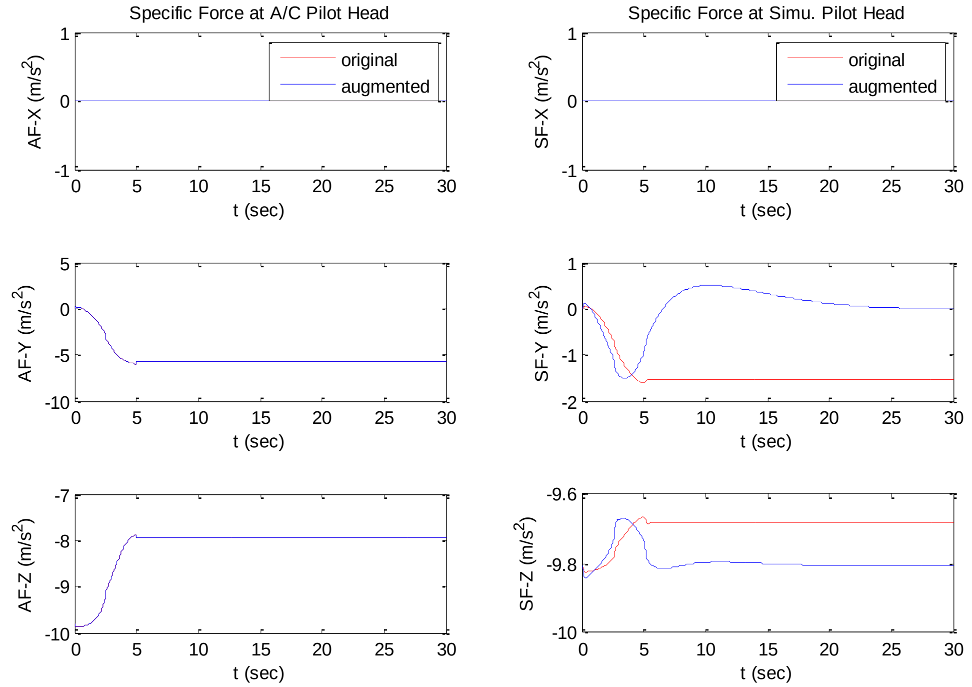

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
original
augmented
AF-X (m/s^2)
AF-Y (m/s^2)
AF-Z (m/s^2)
SF-X (m/s^2)
SF-Y (m/s^2)
SF-Z (m/s^2)
1
0
-1
5
-5
-10
-2
-7
-8
-9
-9.6
-9.8
0
5
10
15
20
25
30
t (sec)

Figure C.2. 3.

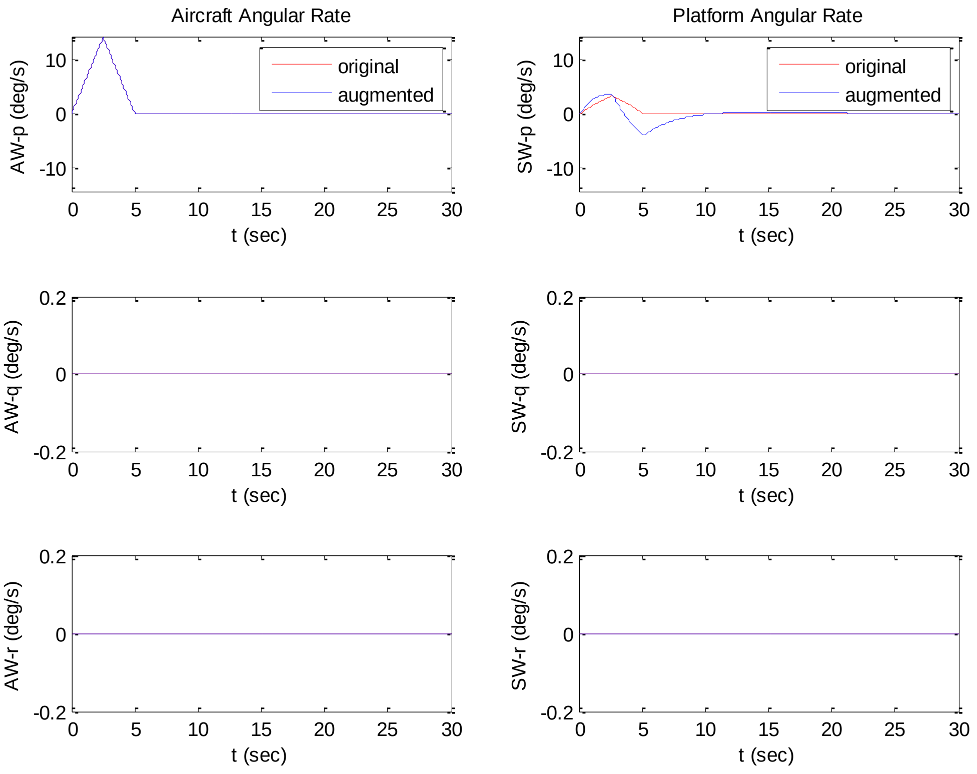

Aircraft Angular Rate
Platform Angular Rate
original
augmented
AW-p (deg/s)
AW-q (deg/s)
AW-r (deg/s)
SW-p (deg/s)
SW-q (deg/s)
SW-r (deg/s)
10
0
-10
0.2
-0.2
0
5
10
15
20
25
30
t (sec)

Figure C.2. 4.

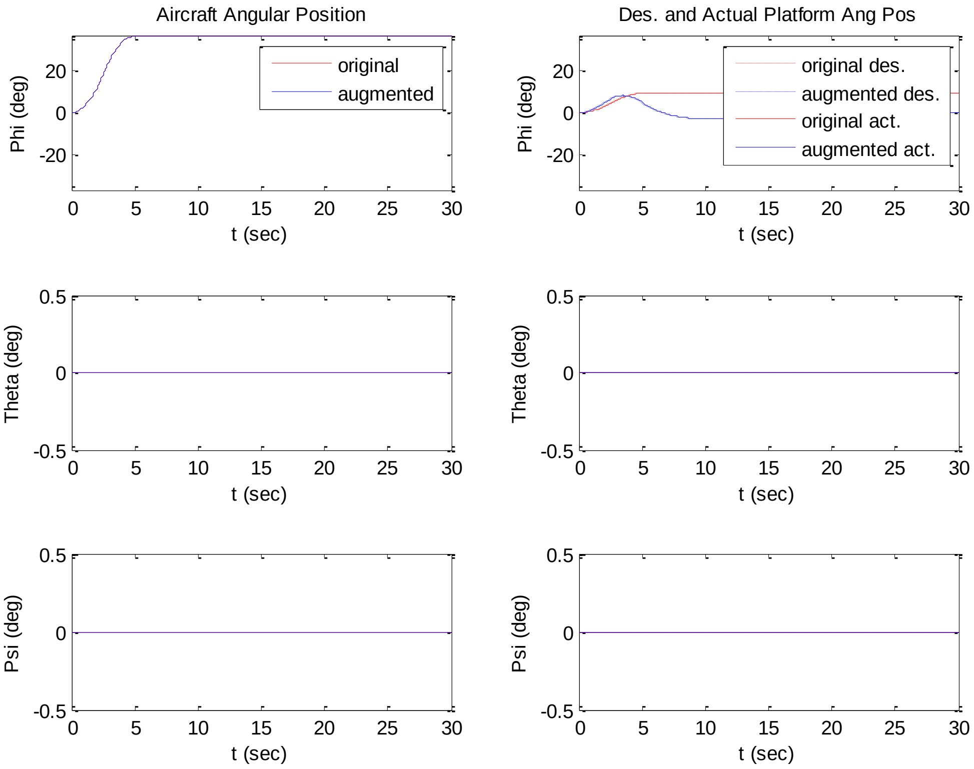


Figure C.2. 5.

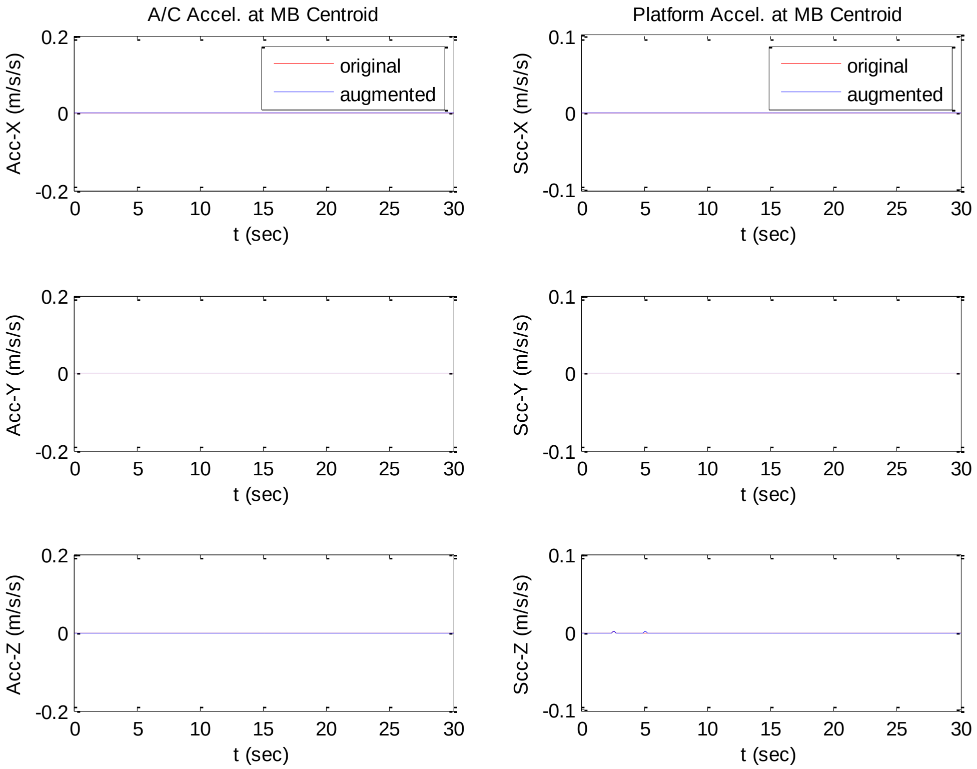

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
augmented
Acc-X (m/s/s)
Acc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-X (m/s/s)
Scc-Y (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.1
0
-0.1
0
5
10
15
20
25
30
t (sec)

Figure C.2. 6.

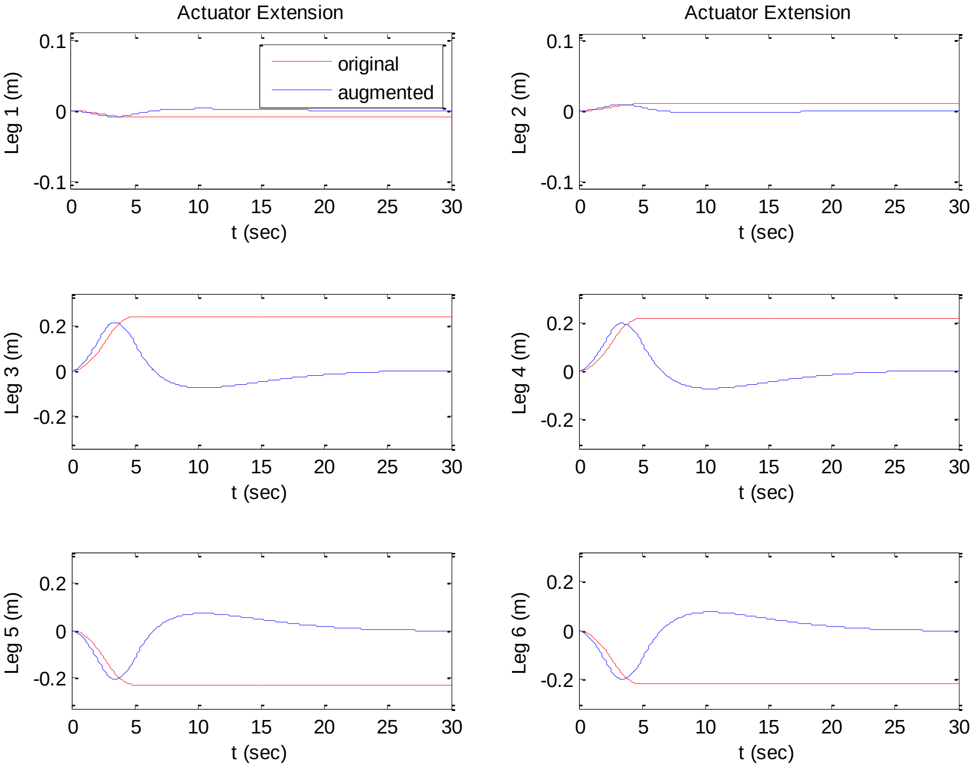

Actuator Extension
Actuator Extension
original
augmented
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.1
0
-0.1
0.2
-0.2
0
5
10
15
20
25
30
t (sec)

Figure C.2. 7.

3. Yaw

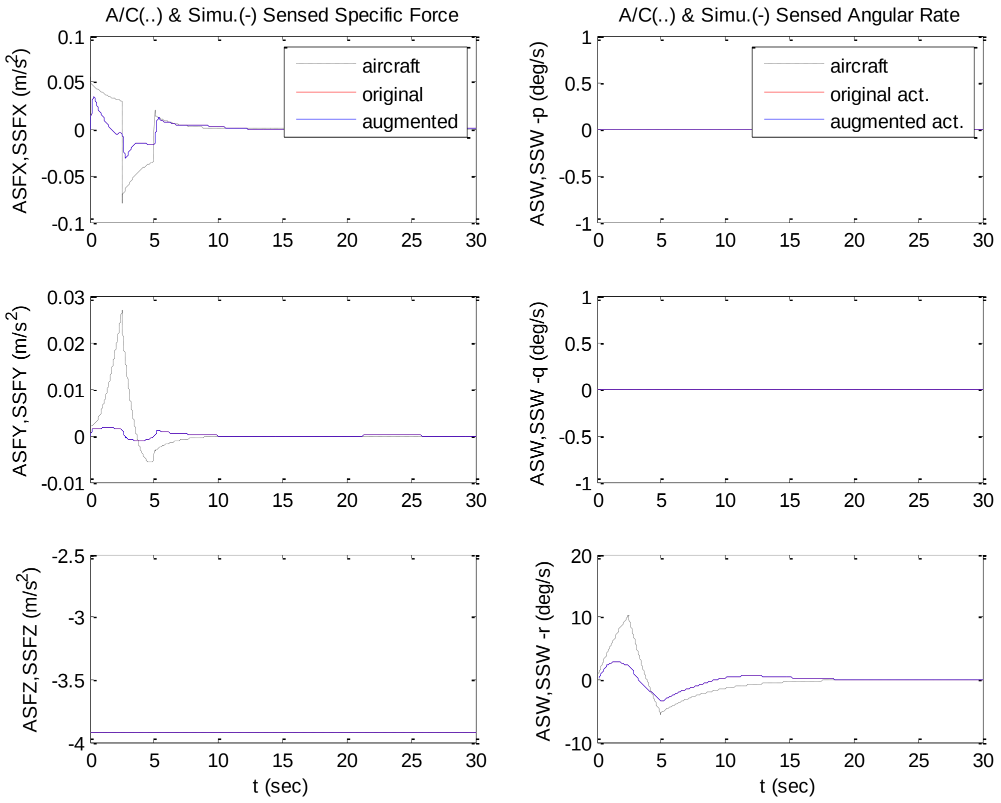


Figure C.3. 1.

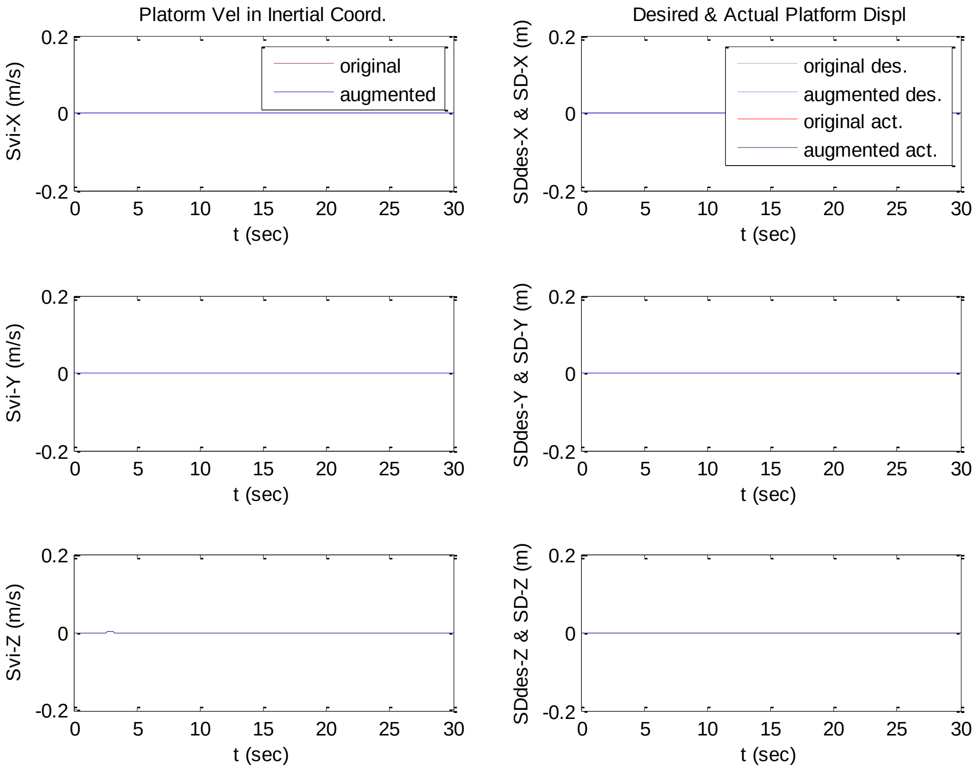

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
Svi-X (m/s)
Svi-Y (m/s)
Svi-Z (m/s)
SDdes-X & SD-X (m)
SDdes-Y & SD-Y (m)
SDdes-Z & SD-Z (m)
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)
original
augmented
original des.
augmented des.
original act.
augmented act.

Figure C.3. 2.

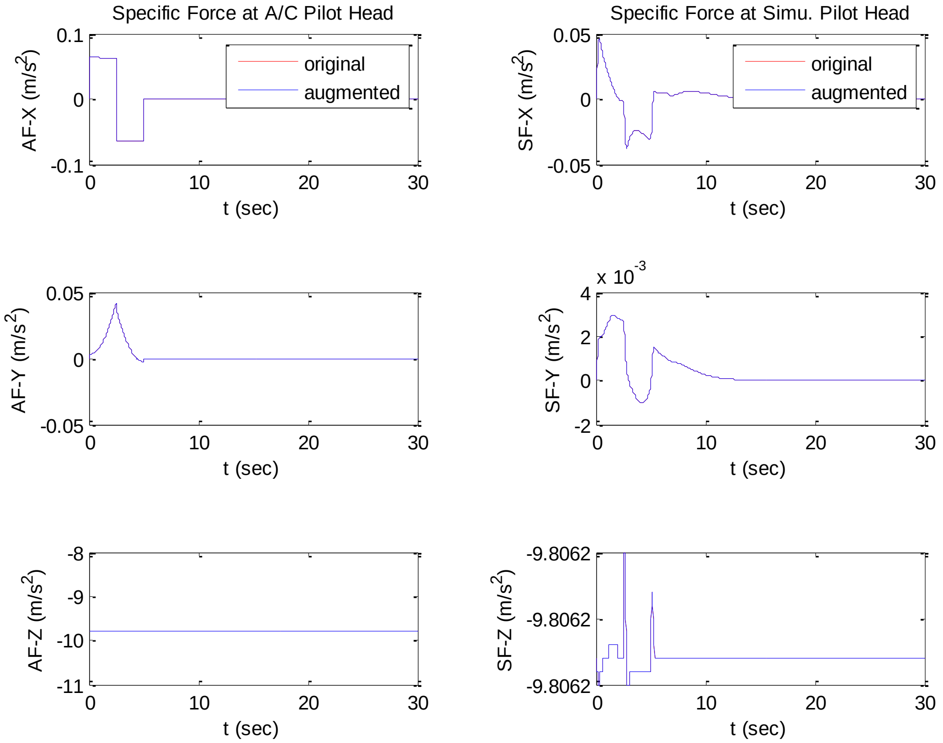

Specific Force at A/C Pilot Head
AF-X (m/s^2)
0.1
0
-0.1
original
augmented
Specific Force at Simu. Pilot Head
SF-X (m/s^2)
0.05
0
-0.05
original
augmented
AF-Y (m/s^2)
0.05
0
-0.05
x 10^{-3}
SF-Y (m/s^2)
4
2
0
-2
AF-Z (m/s^2)
-8
-9
-10
-11
SF-Z (m/s^2)
-9.8062
-9.8062
-9.8062
0
10
20
30
t (sec)

Figure C.3. 3.

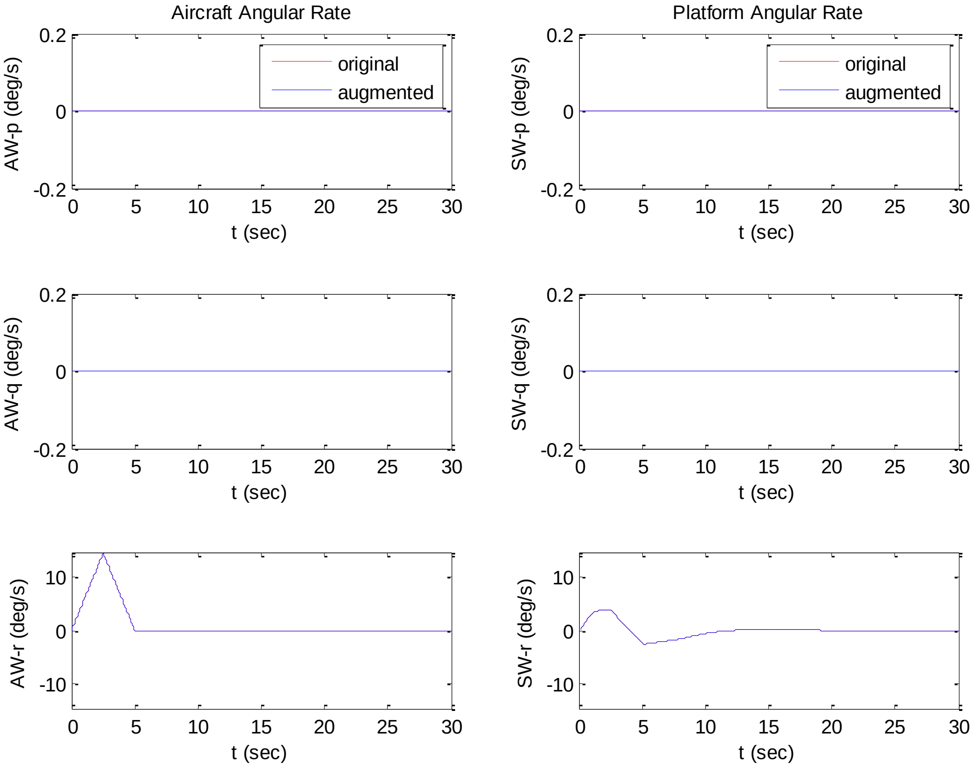

Aircraft Angular Rate
Platform Angular Rate
original
augmented
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
0.2
0
-0.2
10
-10
0
5
10
15
20
25
30
t (sec)

Figure C.3. 4.

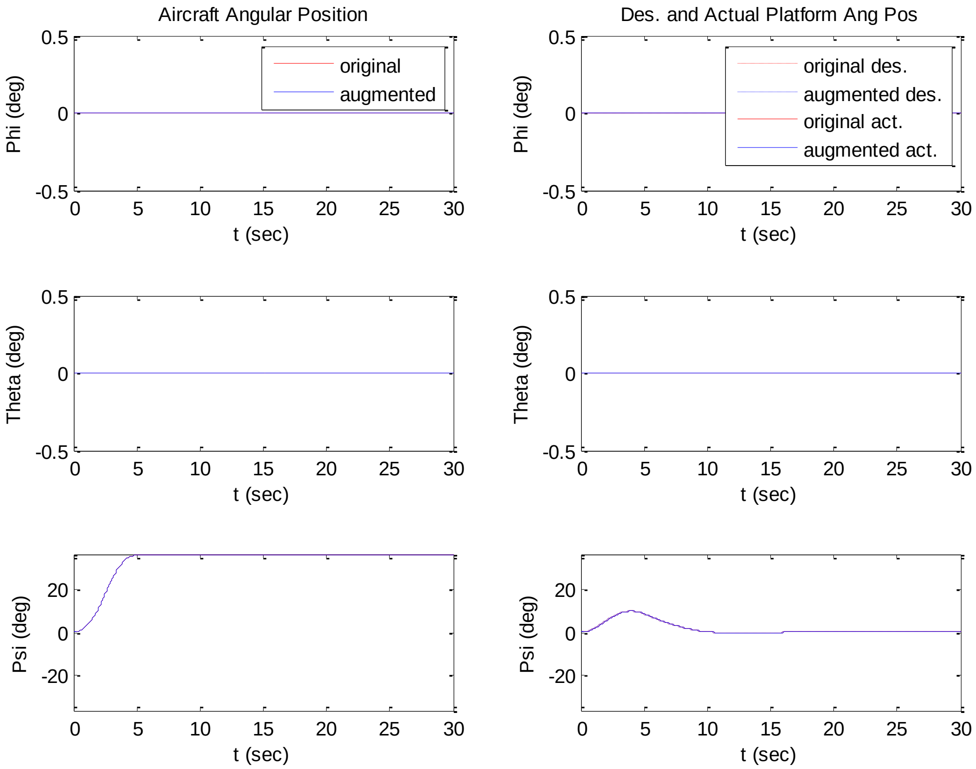

Aircraft Angular Position
Des. and Actual Platform Ang Pos
original
augmented
original des.
augmented des.
original act.
augmented act.
Phi (deg)
Theta (deg)
Psi (deg)
t (sec)
0.5
0
-0.5
20
-20
0
5
10
15
20
25
30

Figure C.3. 5.

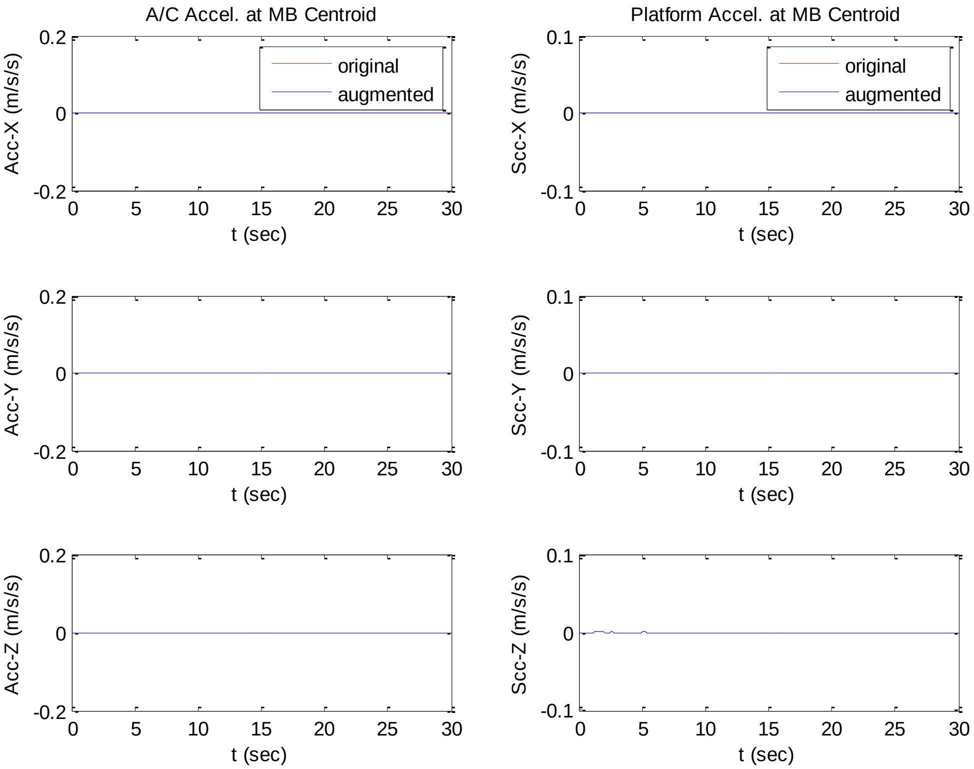

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
augmented
original
augmented
Acc-X (m/s/s)
Acc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-X (m/s/s)
Scc-Y (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.1
0
-0.1
0
5
10
15
20
25
30
t (sec)

Figure C.3. 6.

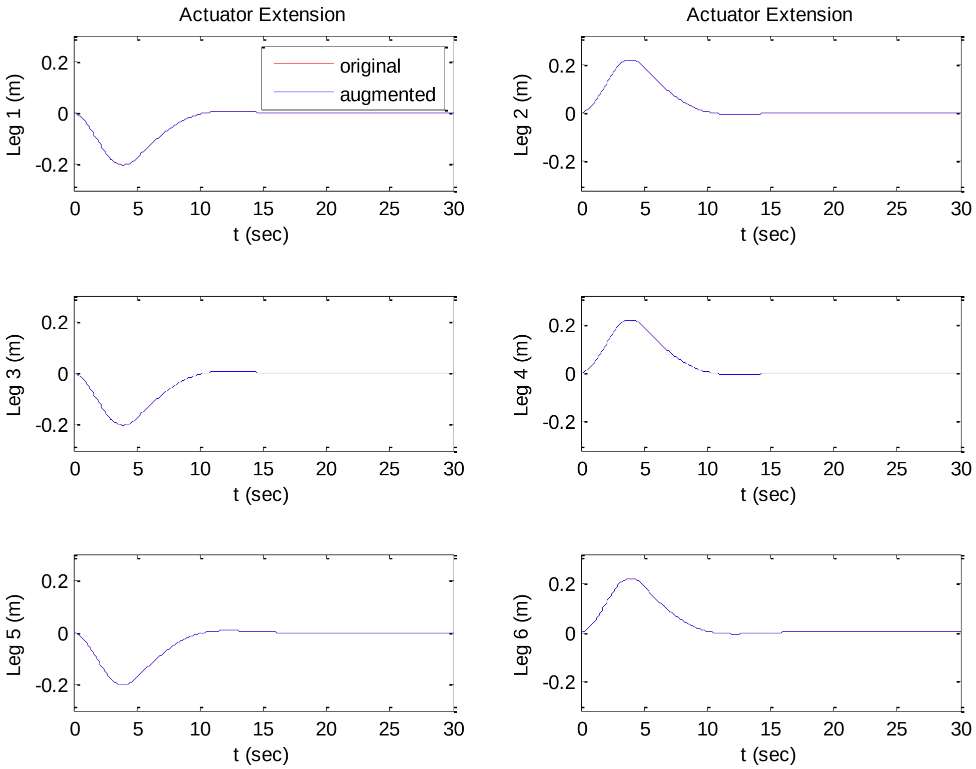

Actuator Extension
Actuator Extension
original
augmented
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure C.3. 7.

4. Surge

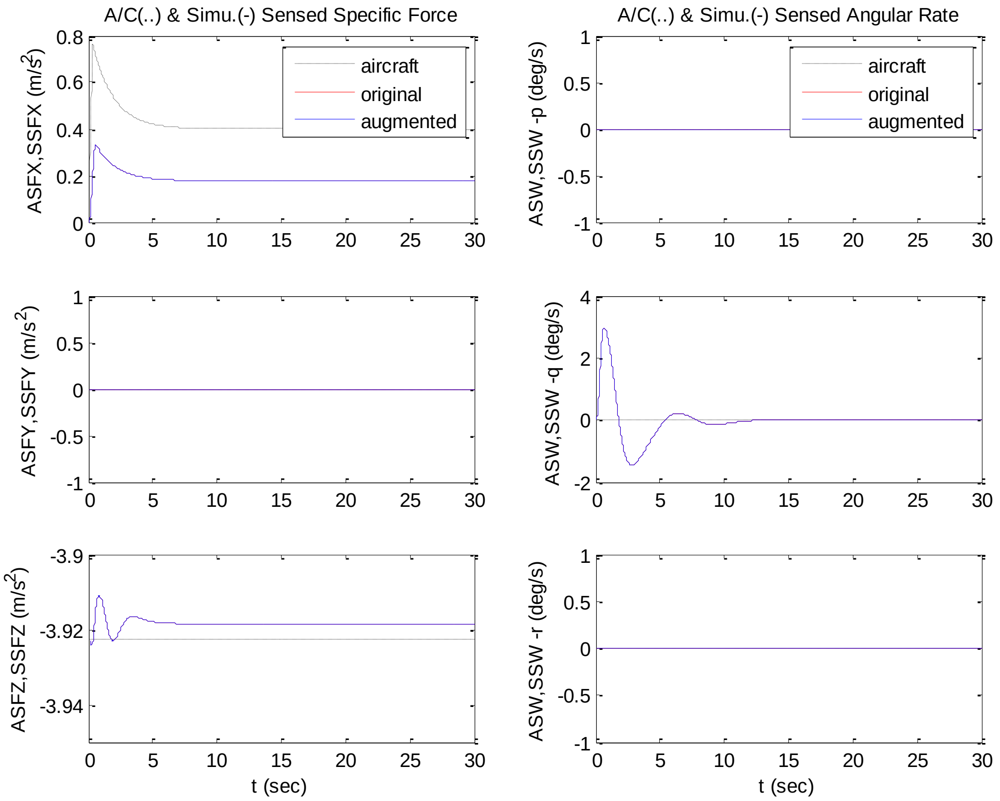


Figure C.4. 1.

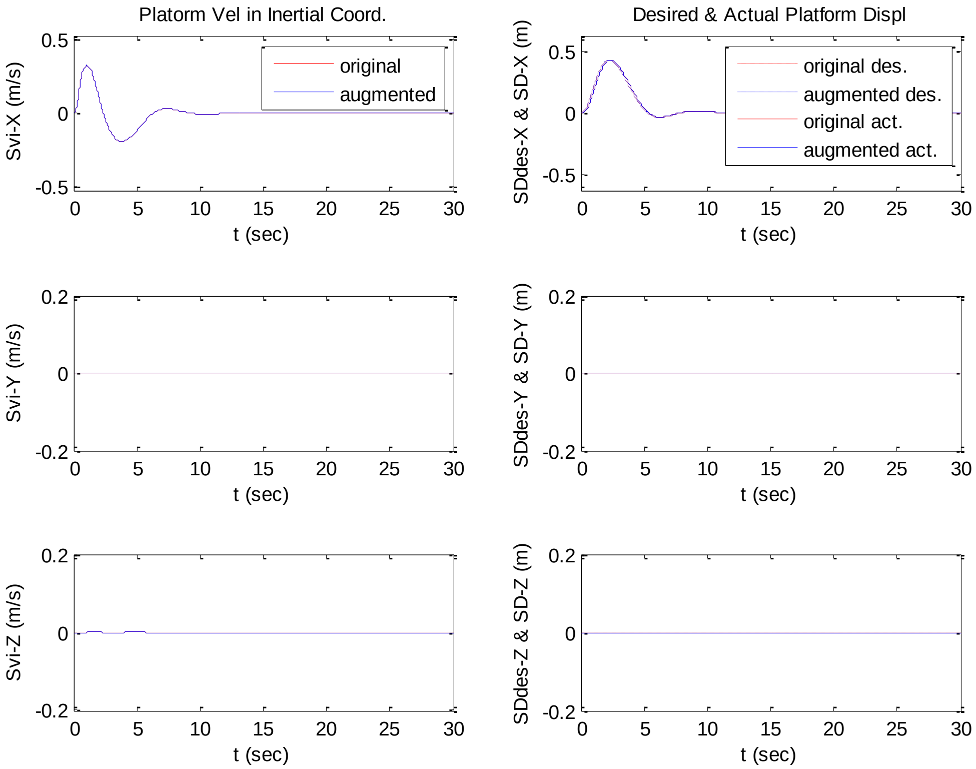

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
Svi-X (m/s)
0.5
0
-0.5
original
augmented
SDdes-X & SD-X (m)
original des.
augmented des.
original act.
augmented act.
Svi-Y (m/s)
SDdes-Y & SD-Y (m)
Svi-Z (m/s)
SDdes-Z & SD-Z (m)
0.2
-0.2
0
5
10
15
20
25
30
t (sec)

Figure C.4. 2.

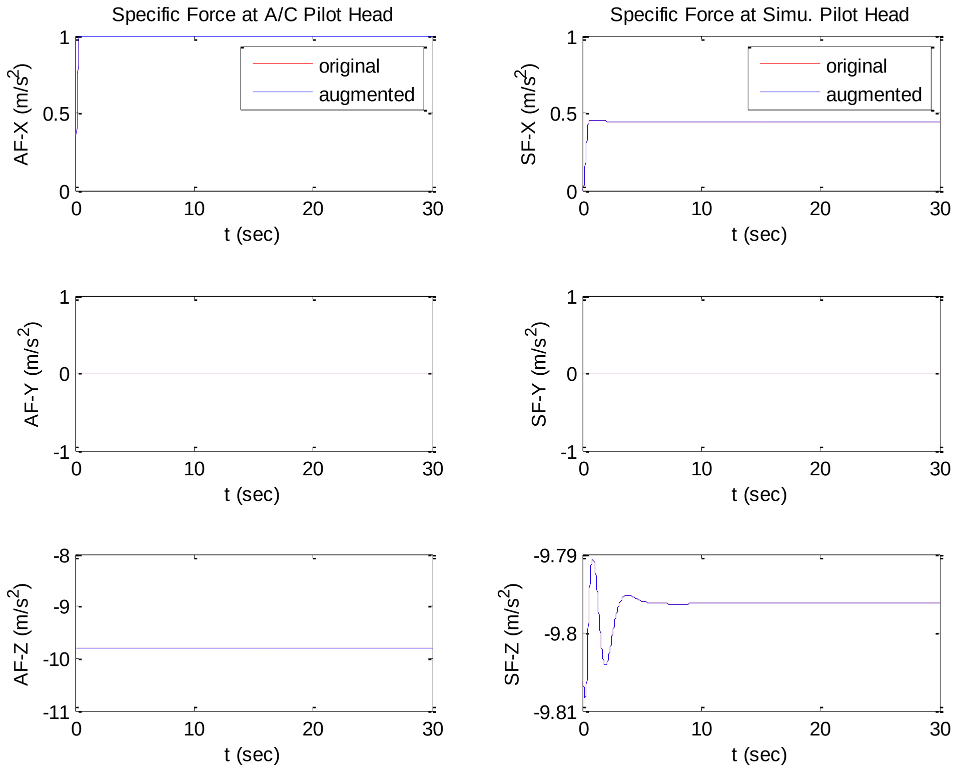

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
original
augmented
AF-X (m/s^2)
SF-X (m/s^2)
AF-Y (m/s^2)
SF-Y (m/s^2)
AF-Z (m/s^2)
SF-Z (m/s^2)
1
0.5
0
-1
-8
-9
-10
-11
-9.79
-9.8
-9.81
10
20
30
t (sec)

Figure C.4. 3.

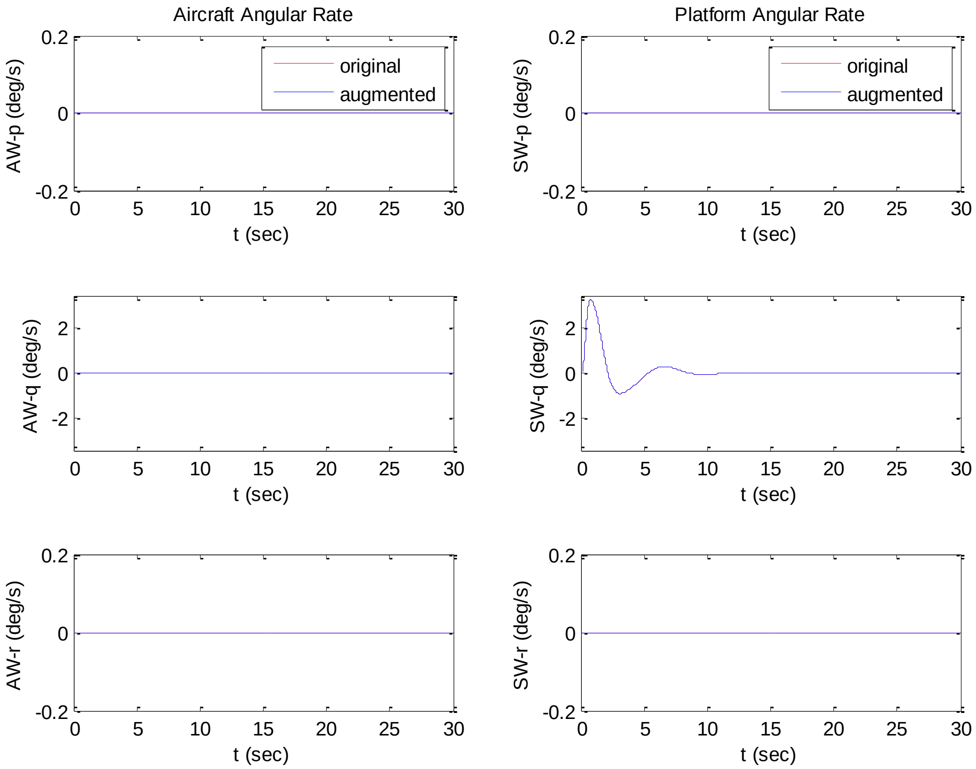

Aircraft Angular Rate
Platform Angular Rate
original
augmented
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
0.2
0
-0.2
2
0
-2
0
5
10
15
20
25
30
t (sec)

Figure C.4. 4.

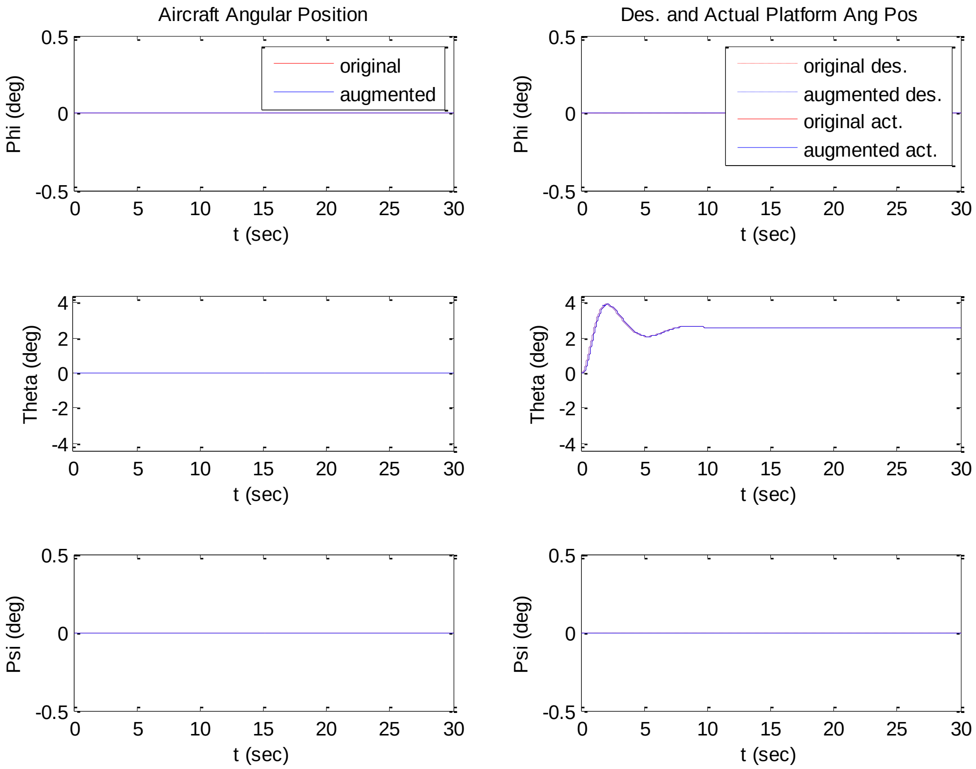

Aircraft Angular Position
Des. and Actual Platform Ang Pos
original
augmented
original des.
augmented des.
original act.
augmented act.
Phi (deg)
Theta (deg)
Psi (deg)
0.5
0
-0.5
4
2
0
-2
-4
0
5
10
15
20
25
30
t (sec)

Figure C.4. 5.

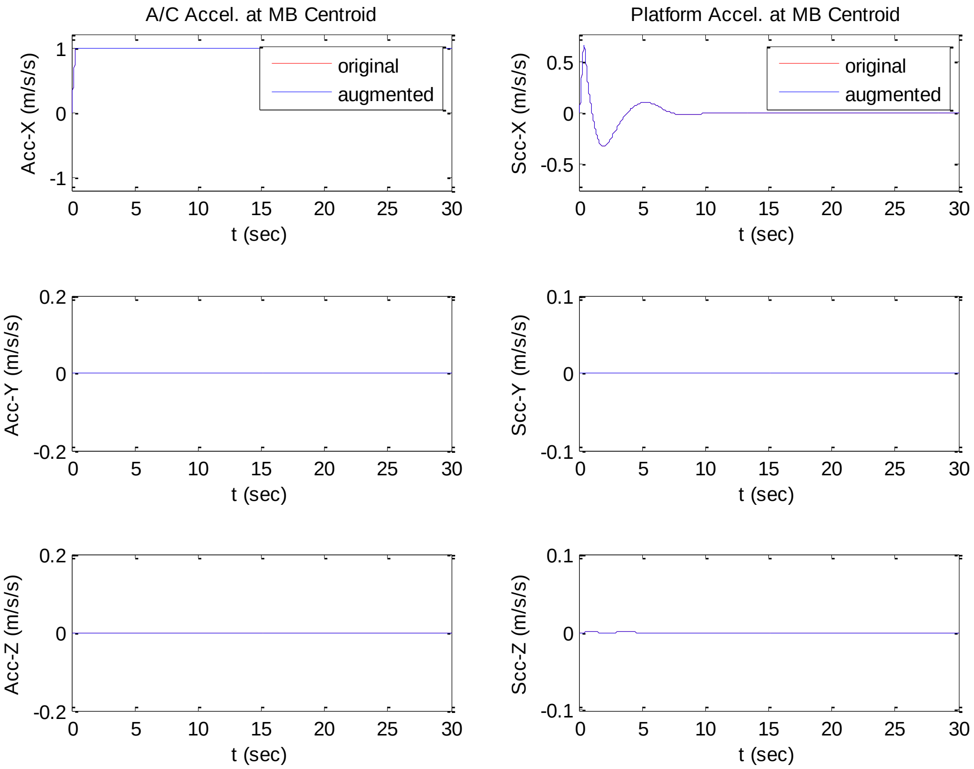

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
augmented
original
augmented
Acc-X (m/s/s)
Scc-X (m/s/s)
Acc-Y (m/s/s)
Scc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-Z (m/s/s)
1
0
-1
0.5
0
-0.5
0.2
0
-0.2
0.1
0
-0.1
0.2
0
-0.2
0.1
0
-0.1
0
5
10
15
20
25
30
t (sec)

Figure C.4. 6.

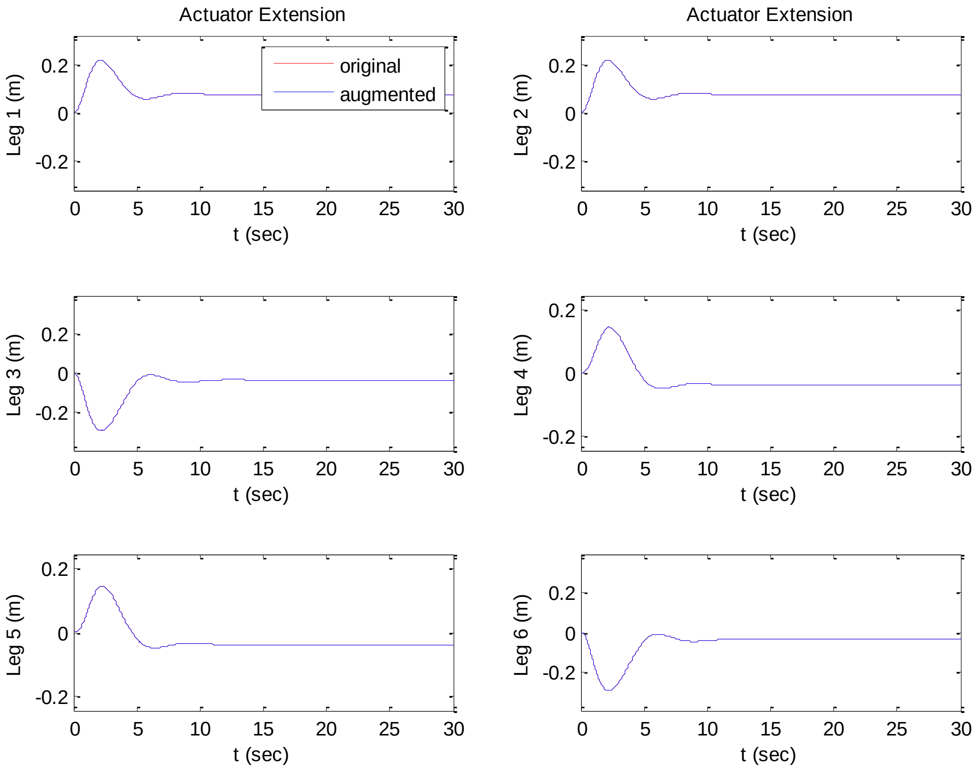

Actuator Extension
Actuator Extension
original
augmented
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure C.4. 7.

5. Sway

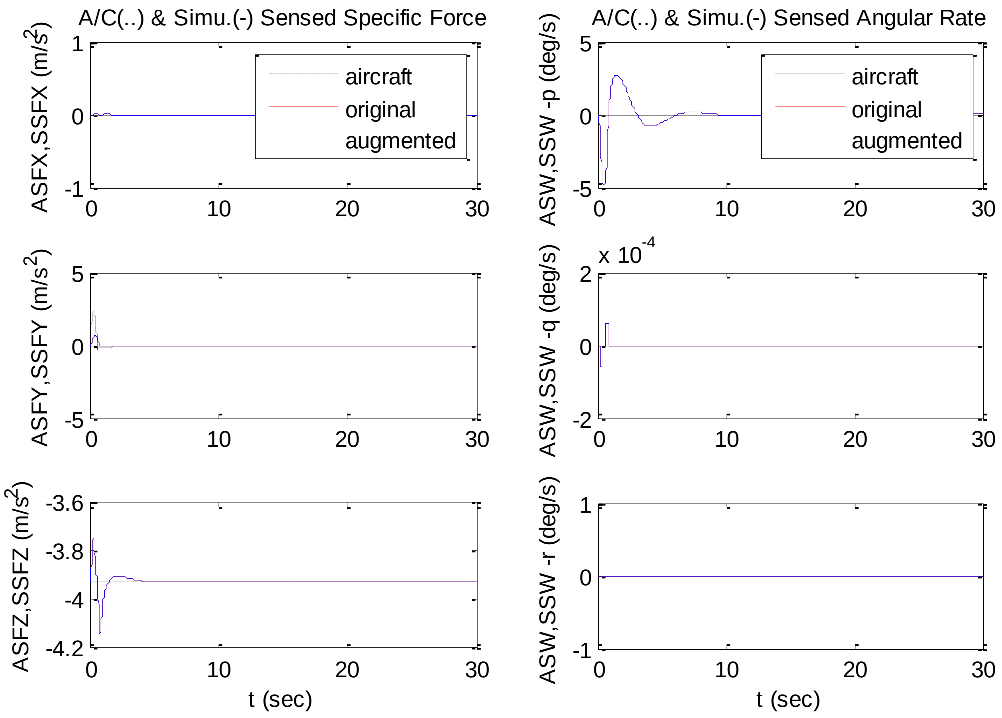


Figure C.5. 1.

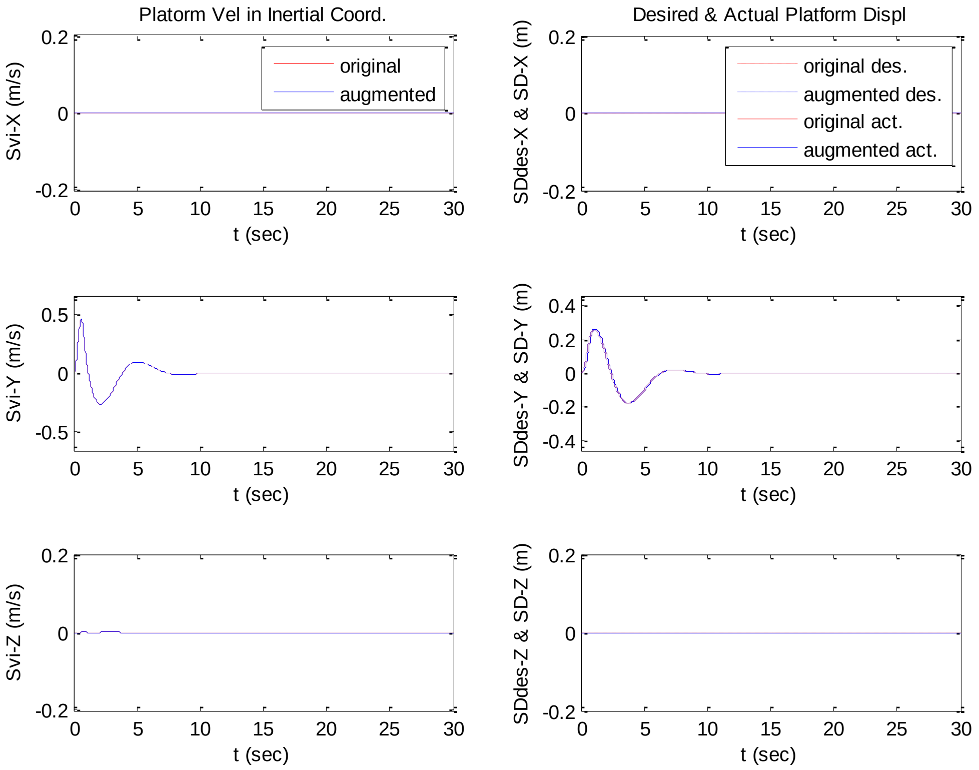

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
Svi-X (m/s)
original
augmented
SDdes-X & SD-X (m)
original des.
augmented des.
original act.
augmented act.
Svi-Y (m/s)
SDdes-Y & SD-Y (m)
Svi-Z (m/s)
SDdes-Z & SD-Z (m)
0.2
0
-0.2
0.5
-0.5
0.4
-0.4
0
5
10
15
20
25
30
t (sec)

Figure C.5. 2.

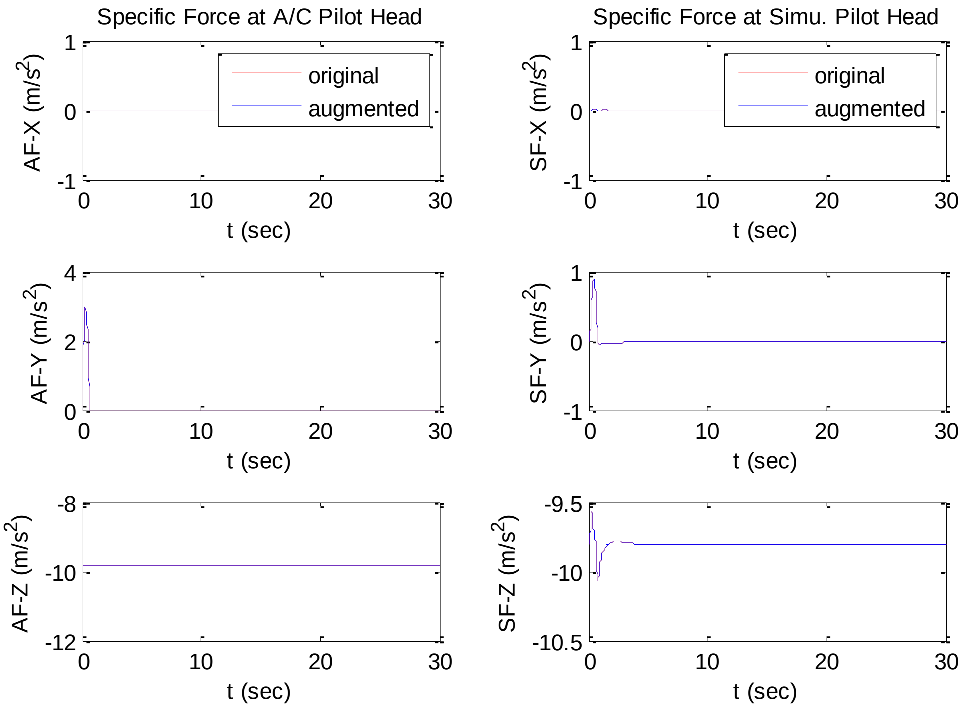

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
original
augmented
AF-X (m/s^2)
SF-X (m/s^2)
AF-Y (m/s^2)
SF-Y (m/s^2)
AF-Z (m/s^2)
SF-Z (m/s^2)
1
0
-1
4
2
0
-8
-10
-12
-9.5
-10.5
10
20
30
t (sec)

Figure C.5. 3.

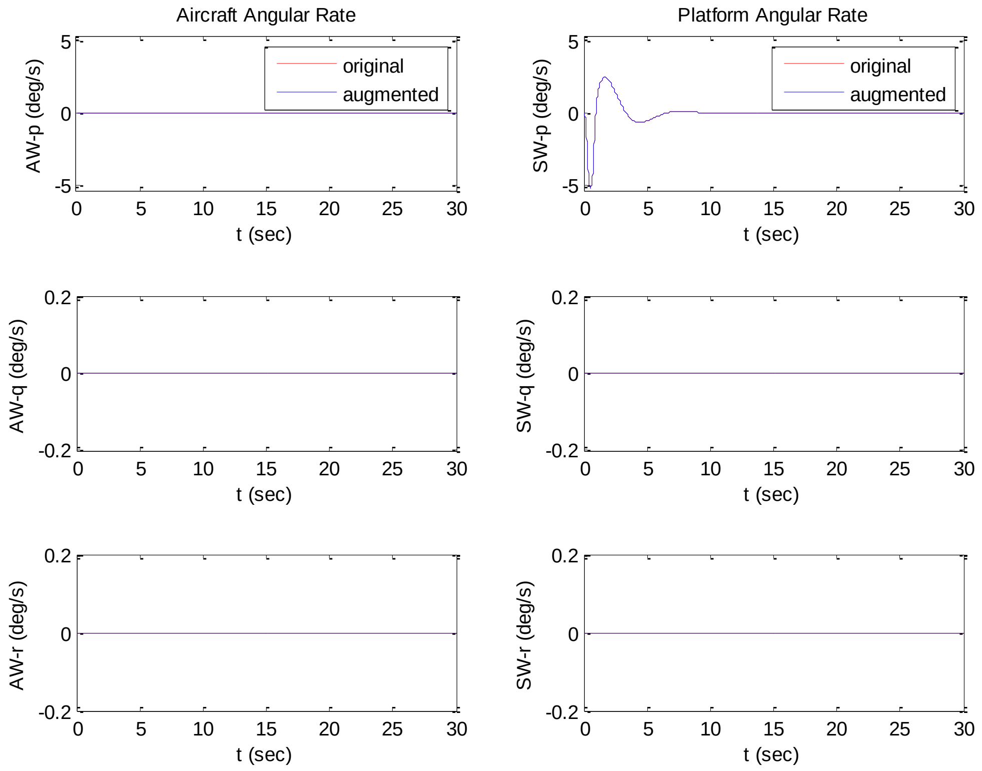

Aircraft Angular Rate
Platform Angular Rate
original
augmented
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
5
0
-5
0.2
-0.2
10
15
20
25
30
t (sec)

Figure C.5. 4.

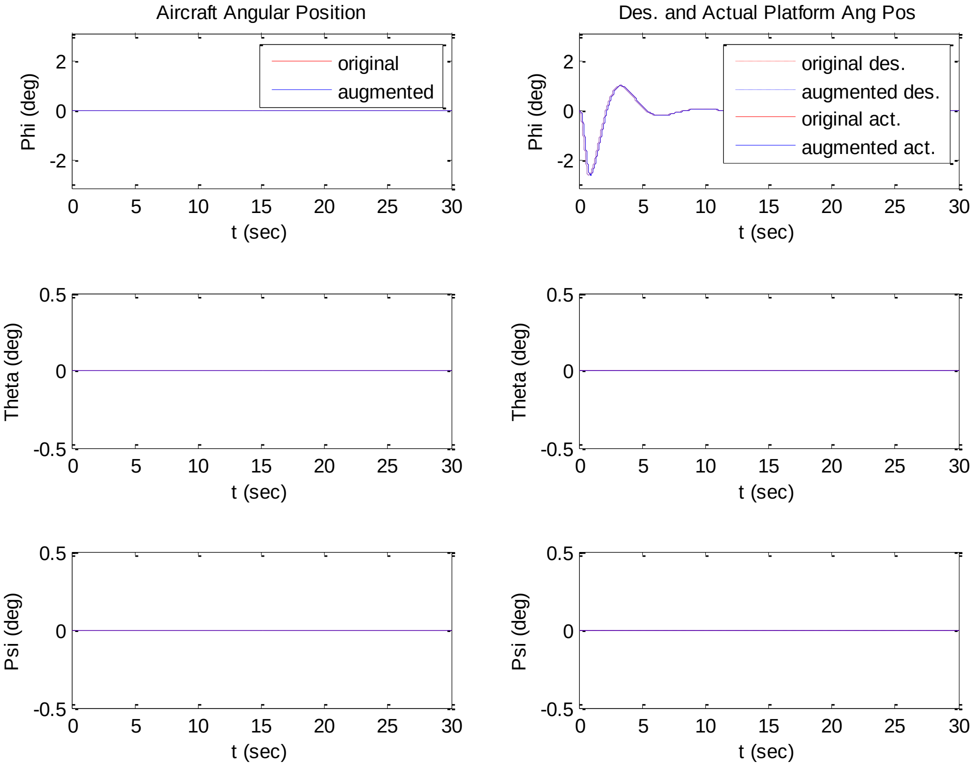


Figure C.5. 5.

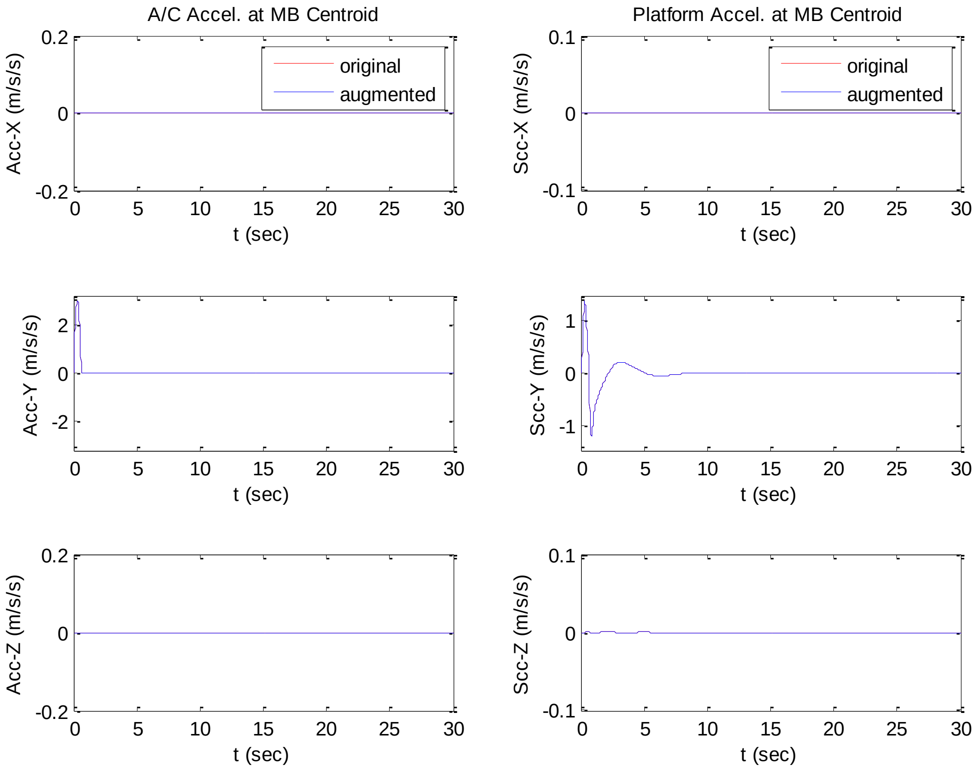

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
augmented
original
augmented
Acc-X (m/s/s)
Scc-X (m/s/s)
Acc-Y (m/s/s)
Scc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.1
0
-0.1
2
0
-2
1
0
-1
0.2
0
-0.2
0.1
0
-0.1
0
5
10
15
20
25
30
t (sec)

Figure C.5. 6.

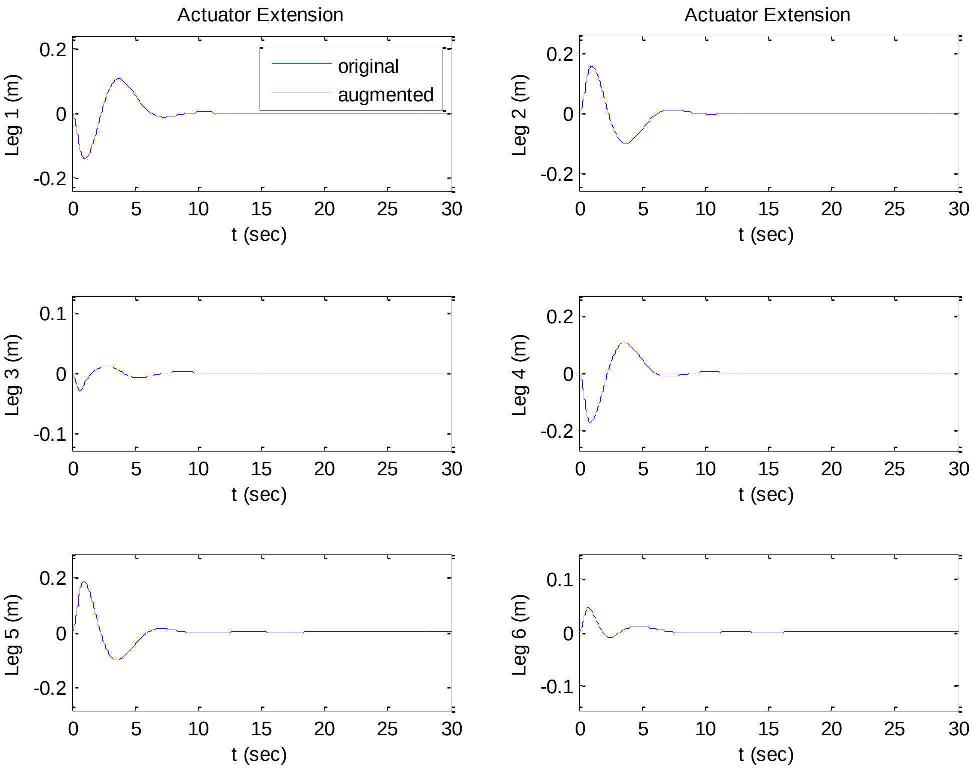

Actuator Extension
Actuator Extension
original
augmented
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.2
0
-0.2
0.1
-0.1
0
5
10
15
20
25
30
t (sec)

Figure C.5. 7.

6. Heave

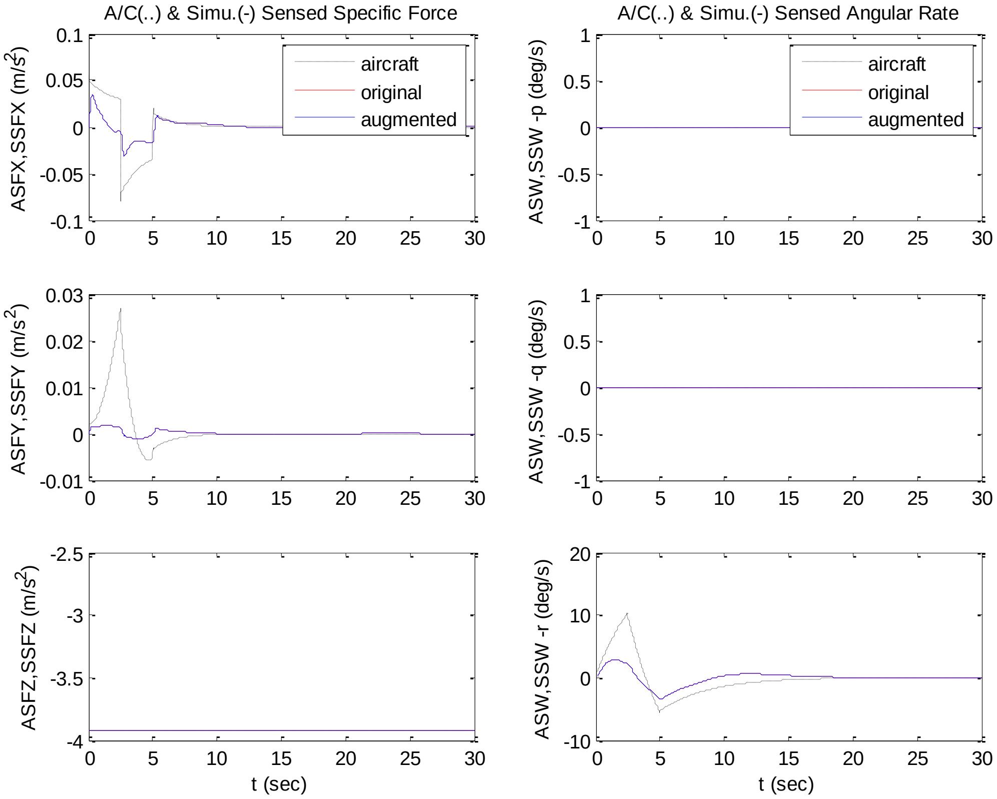


Figure C.6. 1.

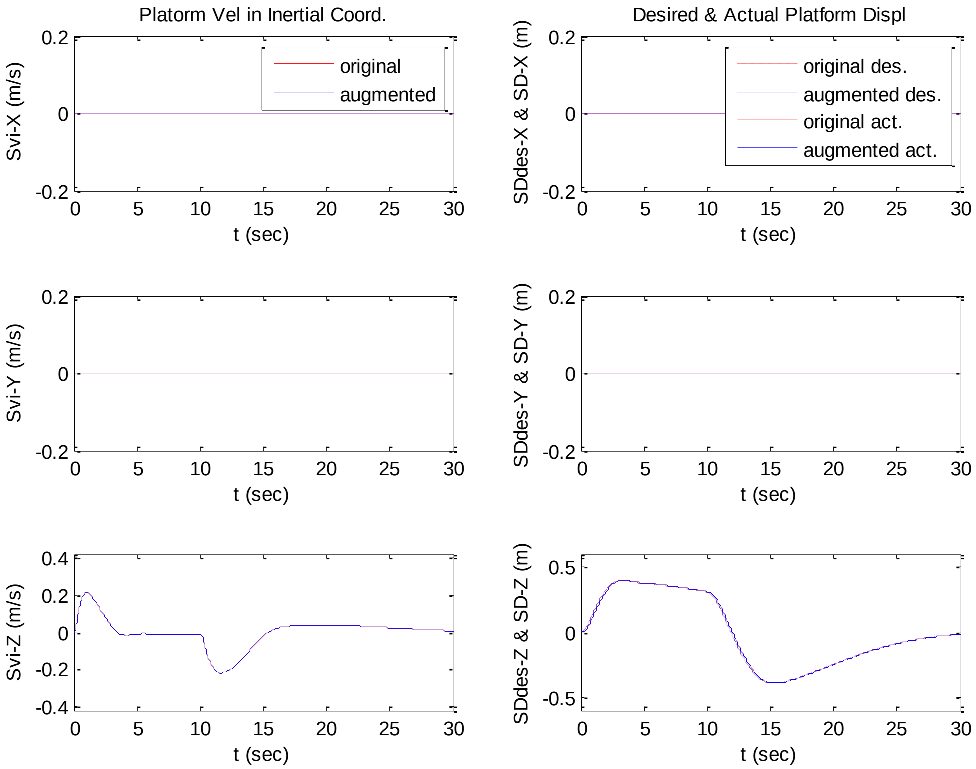

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
Svi-X (m/s)
SDdes-X & SD-X (m)
original
augmented
original des.
augmented des.
original act.
augmented act.
Svi-Y (m/s)
SDdes-Y & SD-Y (m)
Svi-Z (m/s)
SDdes-Z & SD-Z (m)
0.2
0
-0.2
0.4
-0.4
0.5
-0.5
0
5
10
15
20
25
30
t (sec)

Figure C.6. 2.

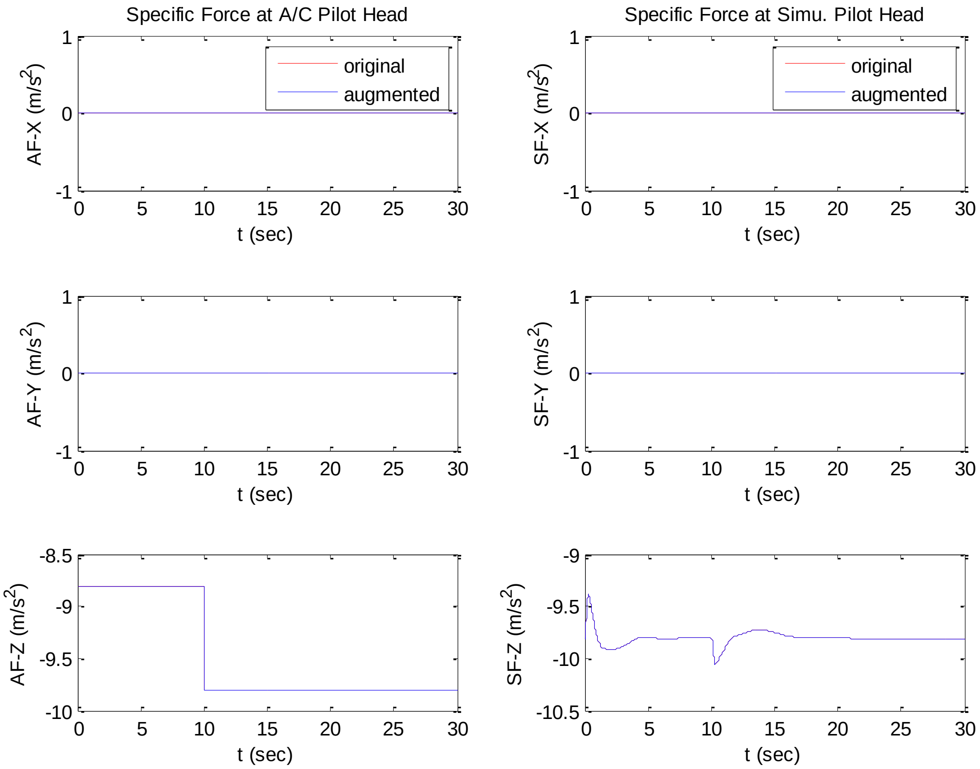

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
original
augmented
AF-X (m/s^2)
SF-X (m/s^2)
AF-Y (m/s^2)
SF-Y (m/s^2)
AF-Z (m/s^2)
SF-Z (m/s^2)
1
0
-1
-8.5
-9
-9.5
-10
-10.5
0
5
10
15
20
25
30
t (sec)

Figure C.6. 3.

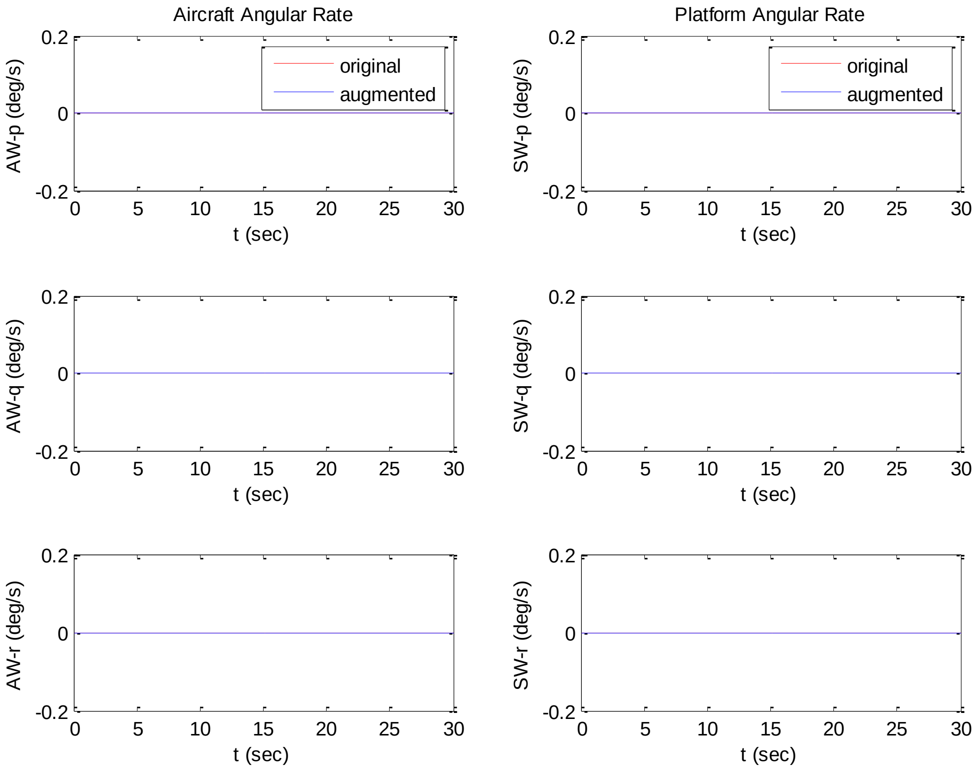

Aircraft Angular Rate
Platform Angular Rate
original
augmented
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure C.6. 4.

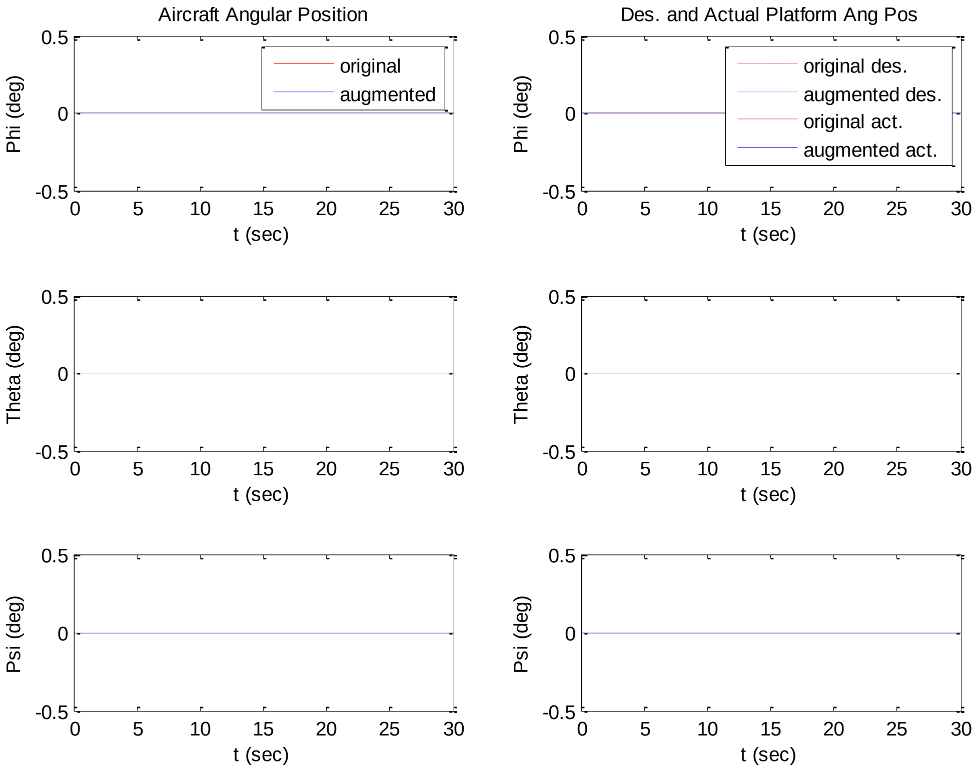

Aircraft Angular Position
Des. and Actual Platform Ang Pos
original
augmented
original des.
augmented des.
original act.
augmented act.
Phi (deg)
Theta (deg)
Psi (deg)
0.5
0
-0.5
0
5
10
15
20
25
30
t (sec)

Figure C.6. 5.

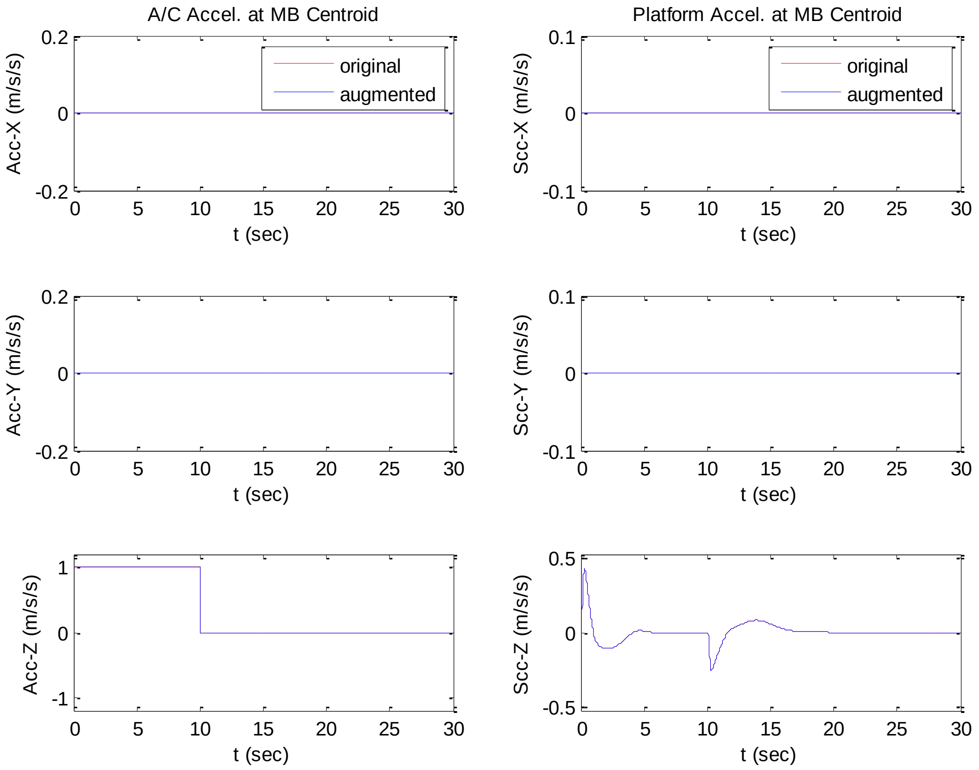

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
original
augmented
Acc-X (m/s/s)
Scc-X (m/s/s)
Acc-Y (m/s/s)
Scc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.1
-0.1
1
-1
0.5
-0.5
0
5
10
15
20
25
30
t (sec)

Figure C.6. 6.

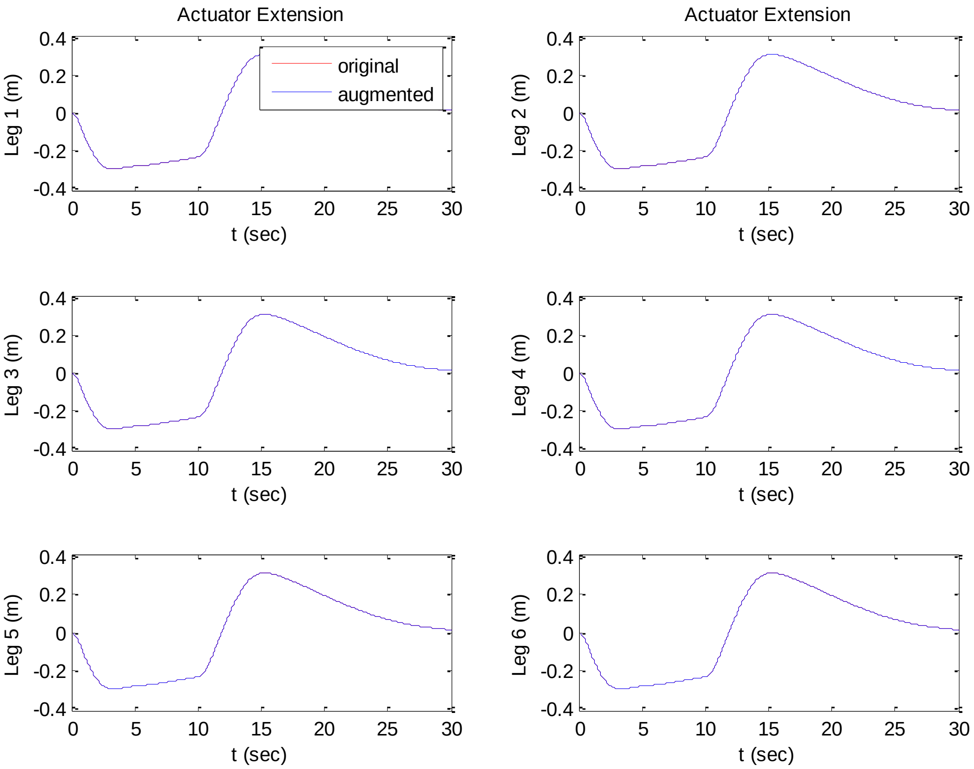

Actuator Extension
Actuator Extension
original
augmented
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
30
t (sec)

Figure C.6. 7.

Appendix D. Non-linear optimal algorithm: original applied at PS (filt. @ PS Original) vs. augmented (Augmented)

General note: if only one or two curves are visible on the plot, assume that the remaining curves are underneath the visible ones.

1. Pitch

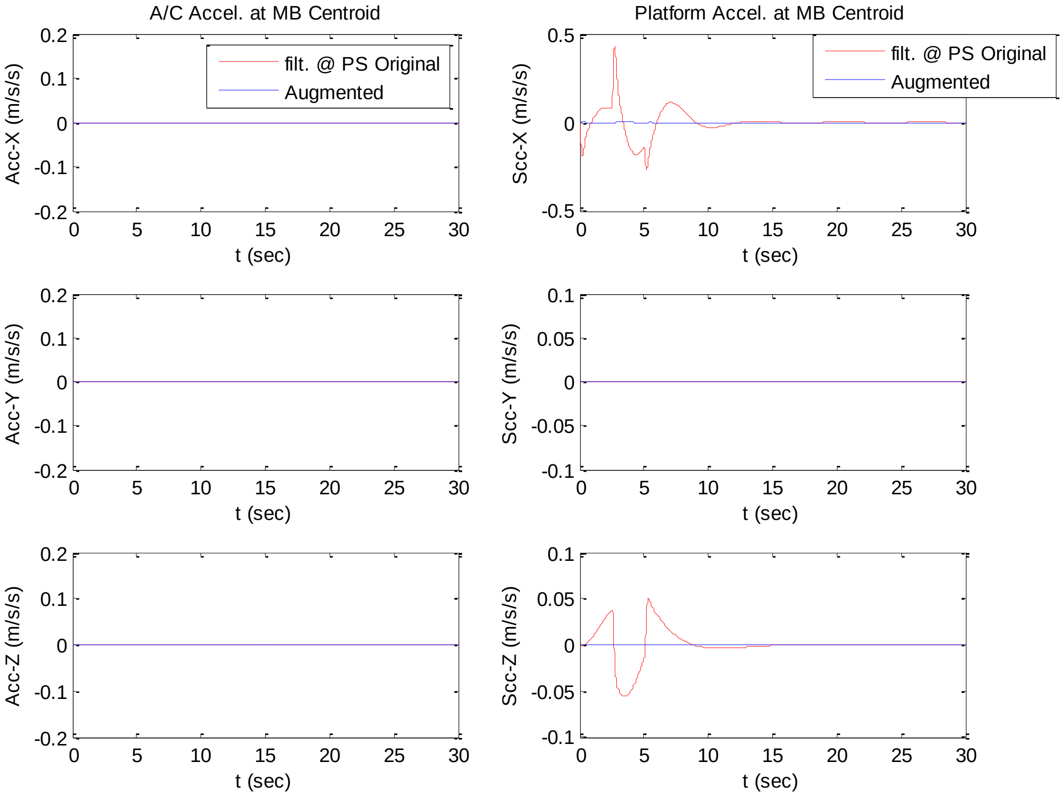


Figure D.1. 1.

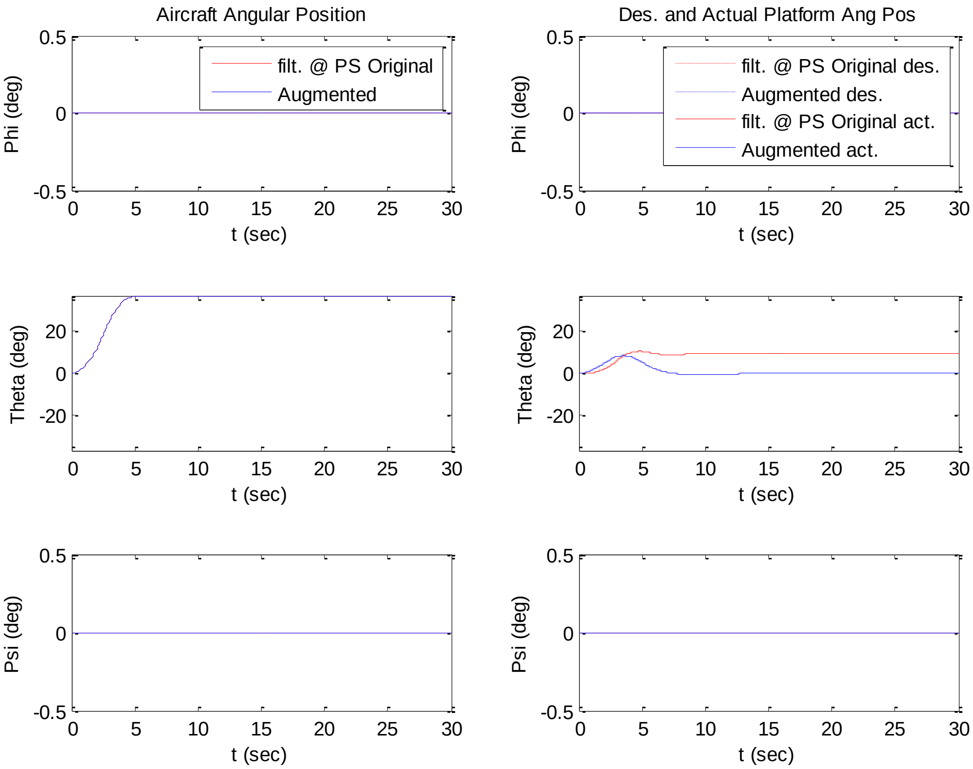
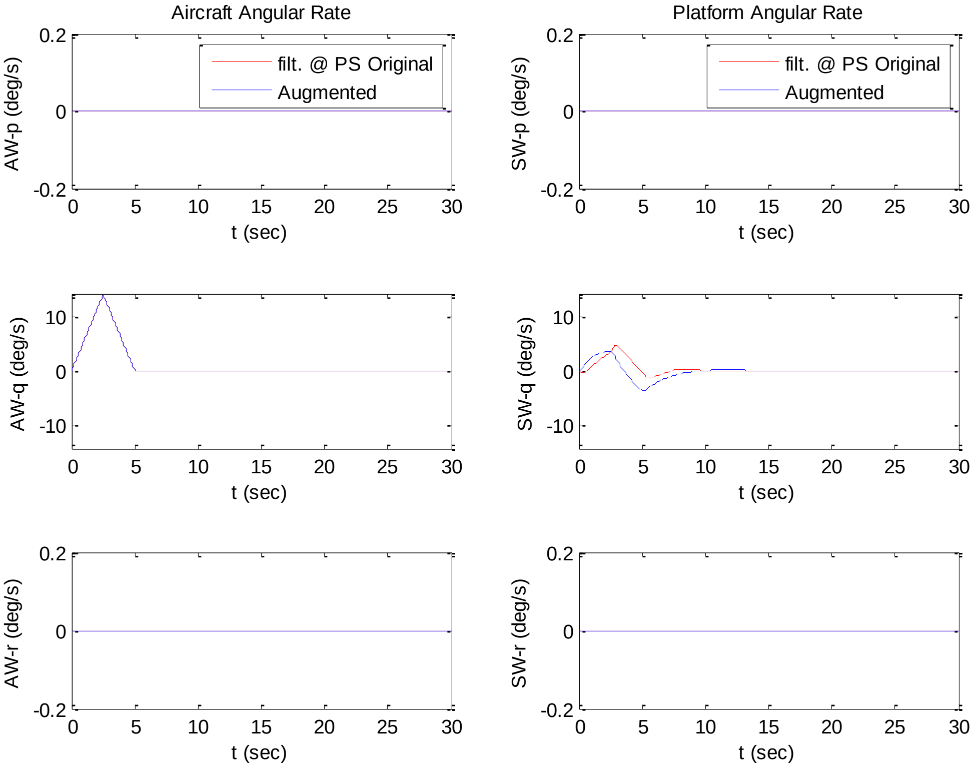

Aircraft Angular Position
Des. and Actual Platform Ang Pos
filt. @ PS Original
Augmented
filt. @ PS Original des.
Augmented des.
filt. @ PS Original act.
Augmented act.
Phi (deg)
Theta (deg)
Psi (deg)
0.5
0
-0.5
20
0
-20
0
5
10
15
20
25
30
t (sec)

Figure D.1. 2.



Aircraft Angular Rate
Platform Angular Rate
filt. @ PS Original
Augmented
filt. @ PS Original
Augmented
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
0.2
0
-0.2
10
0
-10
0
5
10
15
20
25
30
t (sec)

Figure D.1. 3.

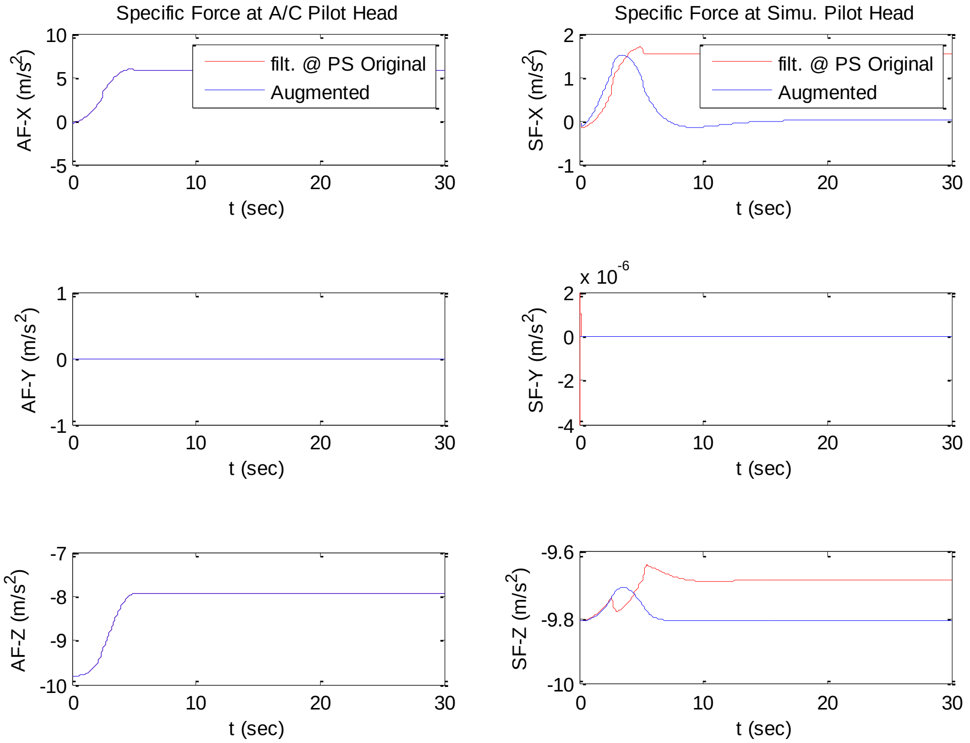

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
filt. @ PS Original
Augmented
AF-X (m/s^2)
SF-X (m/s^2)
AF-Y (m/s^2)
SF-Y (m/s^2)
AF-Z (m/s^2)
SF-Z (m/s^2)
x 10^{-6}
t (sec)
10
5
0
-5
2
1
-1
-2
-4
-7
-8
-9
-10
-9.6
-9.8
20
30

Figure D.1. 4.

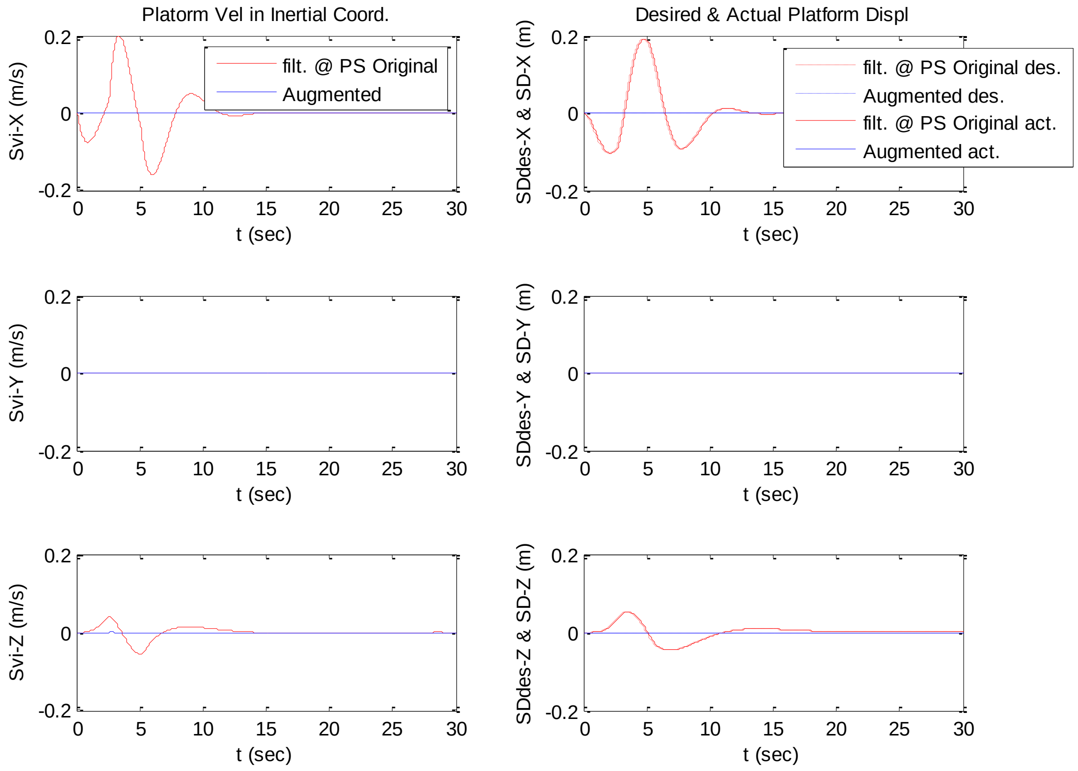
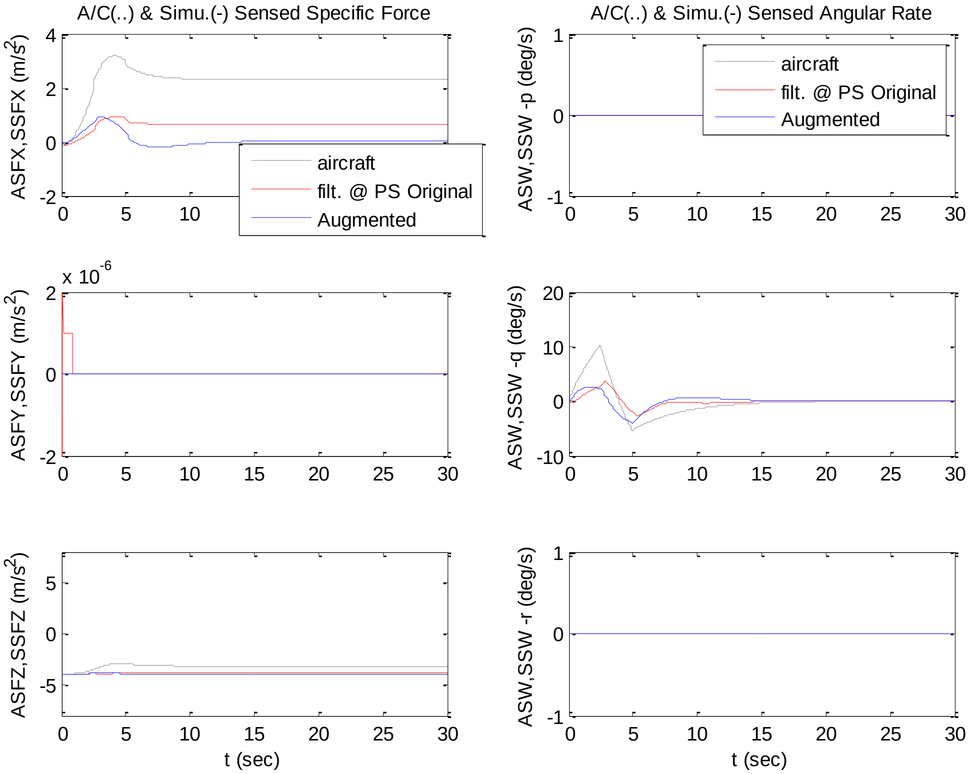

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
Svi-X (m/s)
Svi-Y (m/s)
Svi-Z (m/s)
SDdes-X & SD-X (m)
SDdes-Y & SD-Y (m)
SDdes-Z & SD-Z (m)
filt. @ PS Original
Augmented
filt. @ PS Original des.
Augmented des.
filt. @ PS Original act.
Augmented act.
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure D.1. 5.



A/C(..) & Simu.(-) Sensed Specific Force
A/C(..) & Simu.(-) Sensed Angular Rate
ASFX,SSFX (m/s^2)
ASW,SSW -p (deg/s)
ASFY,SSFY (m/s^2)
x 10^{-6}
ASW,SSW -q (deg/s)
ASFZ,SSFZ (m/s^2)
ASW,SSW -r (deg/s)
aircraft
filt. @ PS Original
Augmented
t (sec)
t (sec)
4
2
0
-2
1
0
-1
20
10
0
-10
5
0
-5
0
5
10
15
20
25
30

Figure D.1. 6.

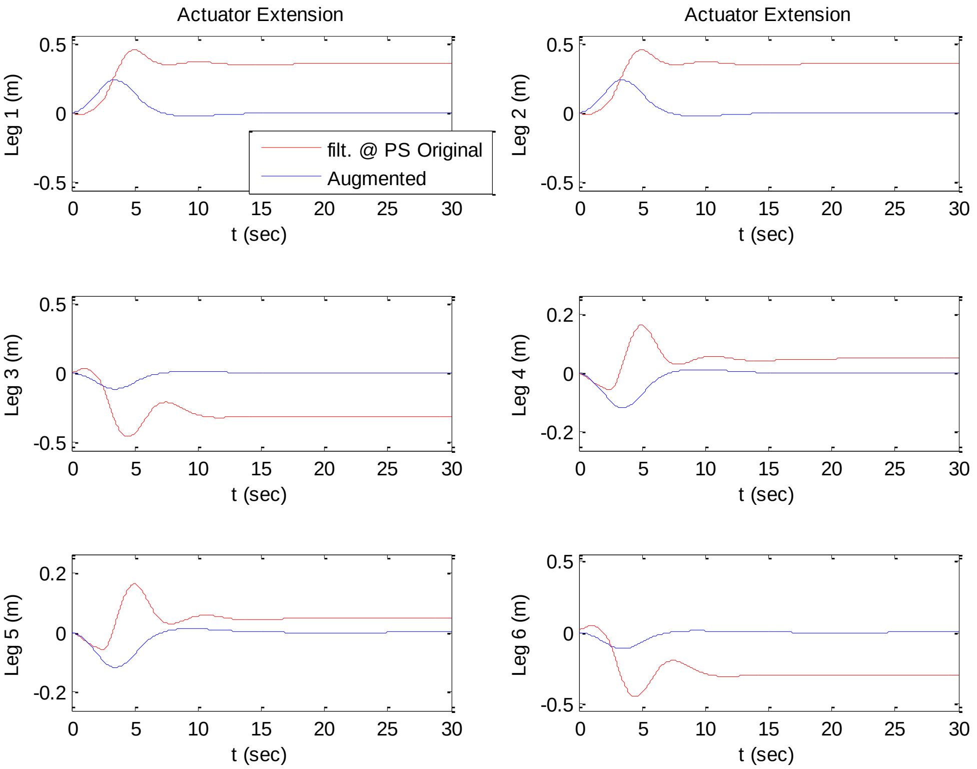

Actuator Extension
Actuator Extension
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
t (sec)
0
5
10
15
20
25
30
0.5
0
-0.5
0.2
-0.2
filt. @ PS Original
Augmented

Figure D.1. 7.

2. Roll

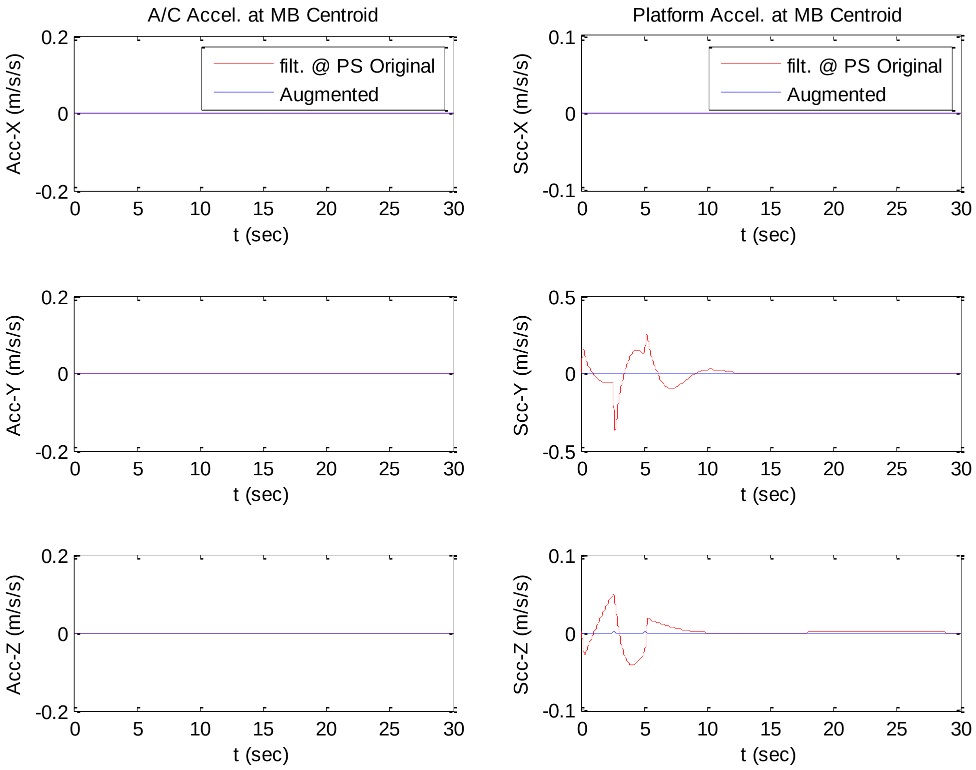


Figure D.2. 1.

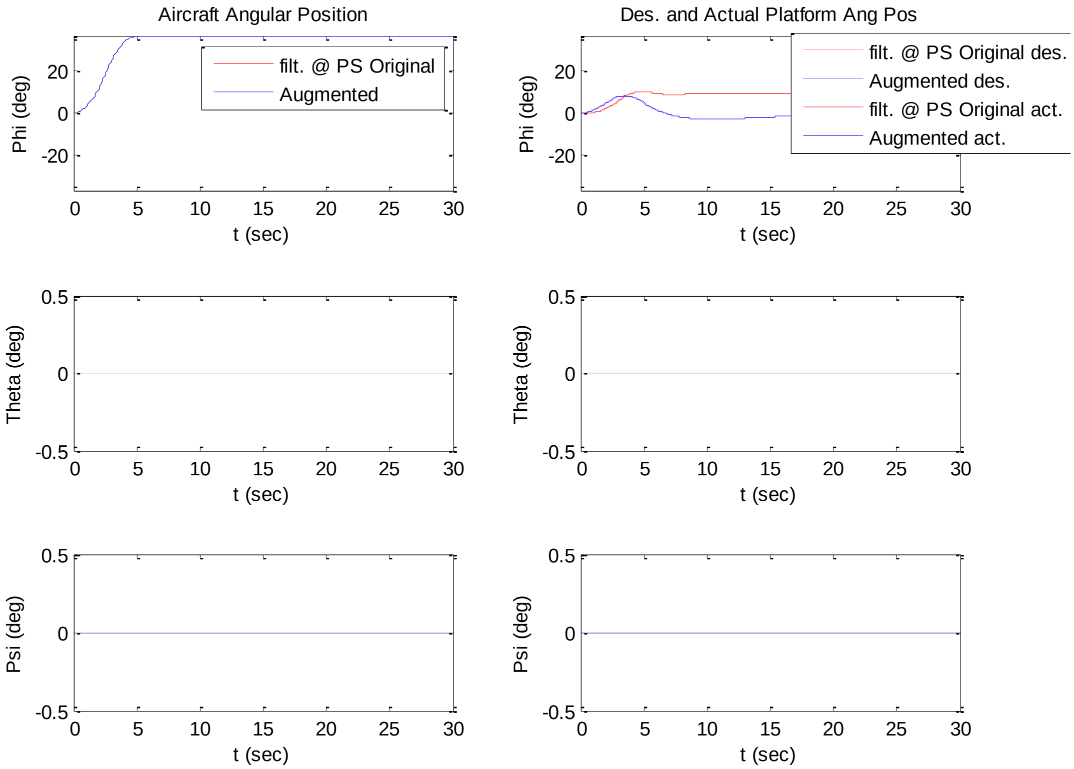

Aircraft Angular Position
Des. and Actual Platform Ang Pos
filt. @ PS Original
Augmented
filt. @ PS Original des.
Augmented des.
filt. @ PS Original act.
Augmented act.
Phi (deg)
Theta (deg)
Psi (deg)
20
0
-20
0.5
0
-0.5
0
5
10
15
20
25
30
t (sec)

Figure D.2. 2.

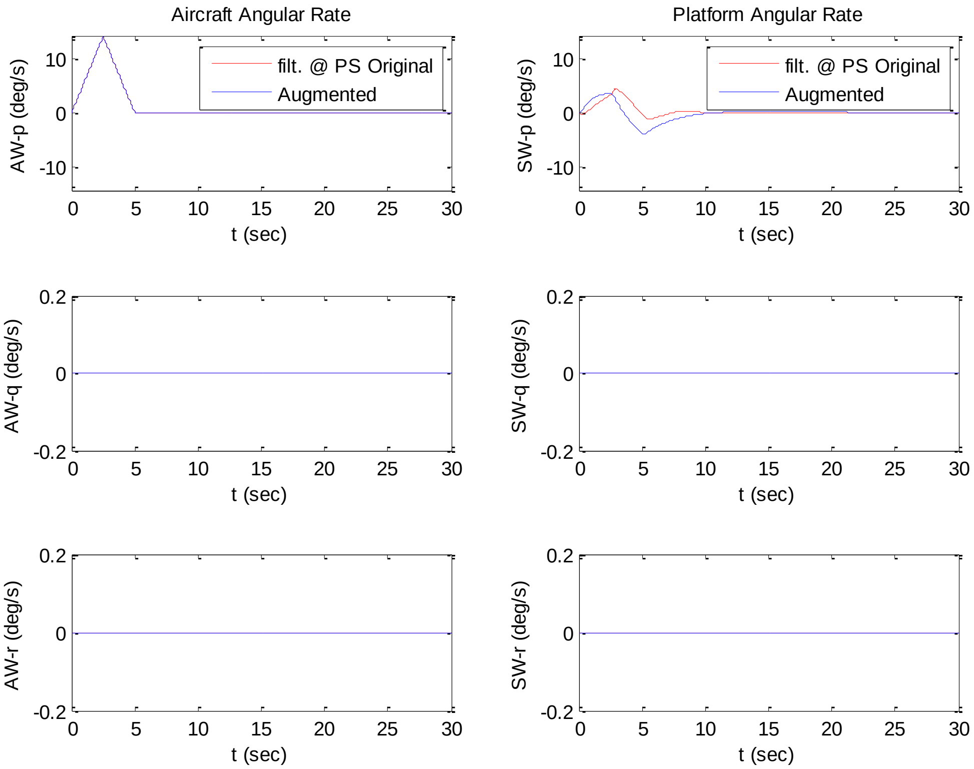

Aircraft Angular Rate
Platform Angular Rate
filt. @ PS Original
Augmented
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
10
0
-10
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure D.2. 3.

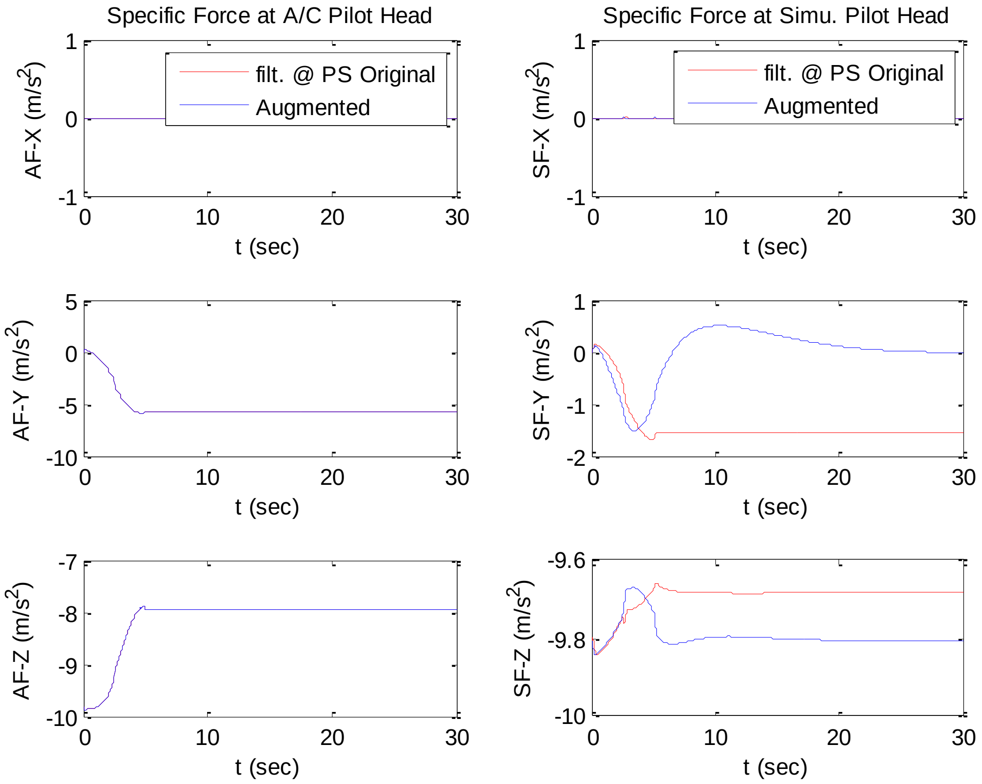

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
filt. @ PS Original
Augmented
AF-X (m/s^2)
AF-Y (m/s^2)
AF-Z (m/s^2)
SF-X (m/s^2)
SF-Y (m/s^2)
SF-Z (m/s^2)
t (sec)
0
10
20
30
1
0
-1
5
-5
-10
-2
-7
-8
-9
-9.6
-9.8

Figure D.2. 4.

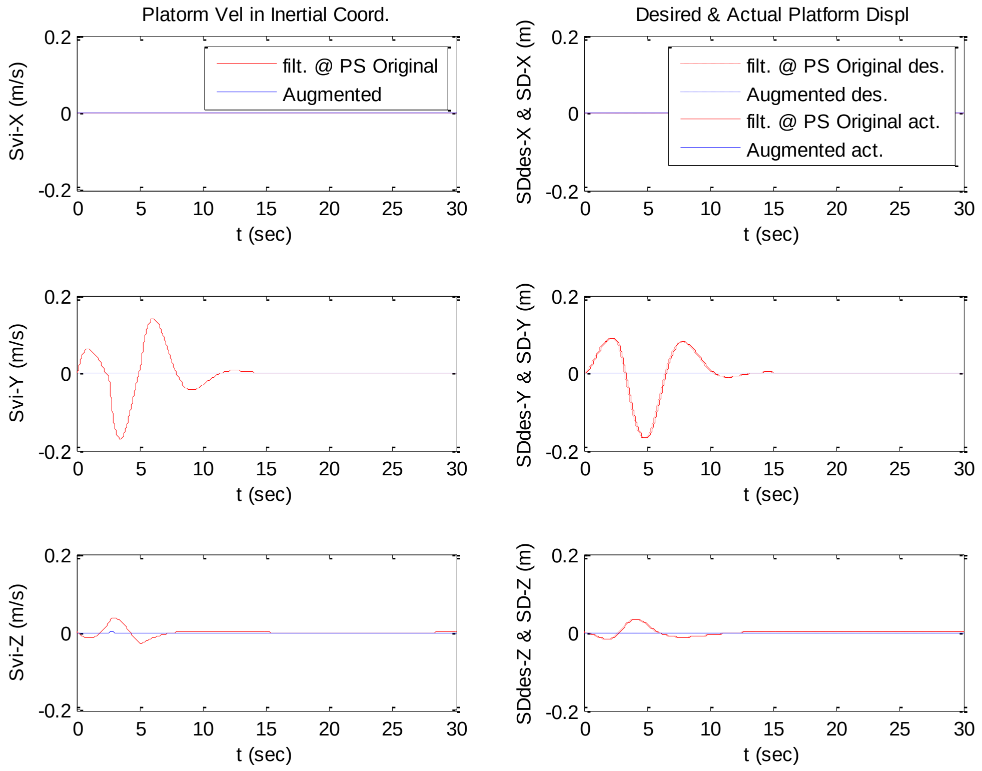

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
Svi-X (m/s)
Svi-Y (m/s)
Svi-Z (m/s)
SDdes-X & SD-X (m)
SDdes-Y & SD-Y (m)
SDdes-Z & SD-Z (m)
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)
filt. @ PS Original
Augmented
filt. @ PS Original des.
Augmented des.
filt. @ PS Original act.
Augmented act.

Figure D.2. 5.

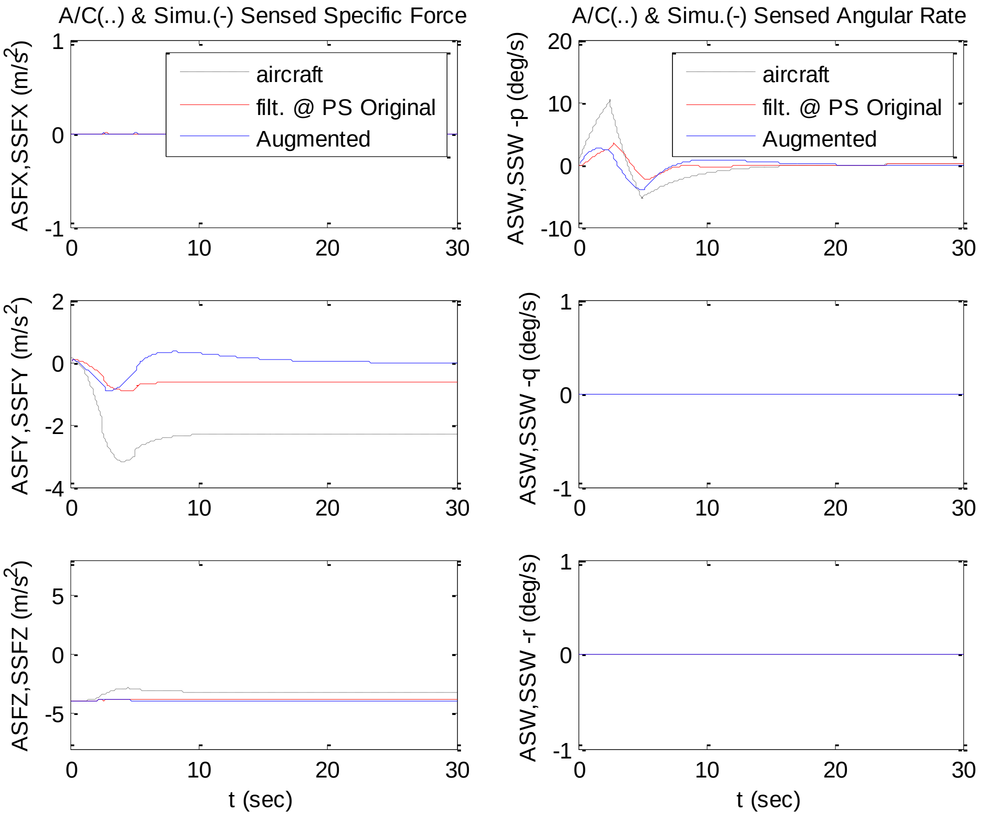

A/C(..) & Simu.(-) Sensed Specific Force
A/C(..) & Simu.(-) Sensed Angular Rate
aircraft
filt. @ PS Original
Augmented
ASFX,SSFX (m/s^2)
ASFY,SSFY (m/s^2)
ASFZ,SSFZ (m/s^2)
ASW,SSW -p (deg/s)
ASW,SSW -q (deg/s)
ASW,SSW -r (deg/s)
1
0
-1
2
-2
-4
5
-5
20
10
-10
0
10
20
30
t (sec)
t (sec)

Figure D.2. 6.

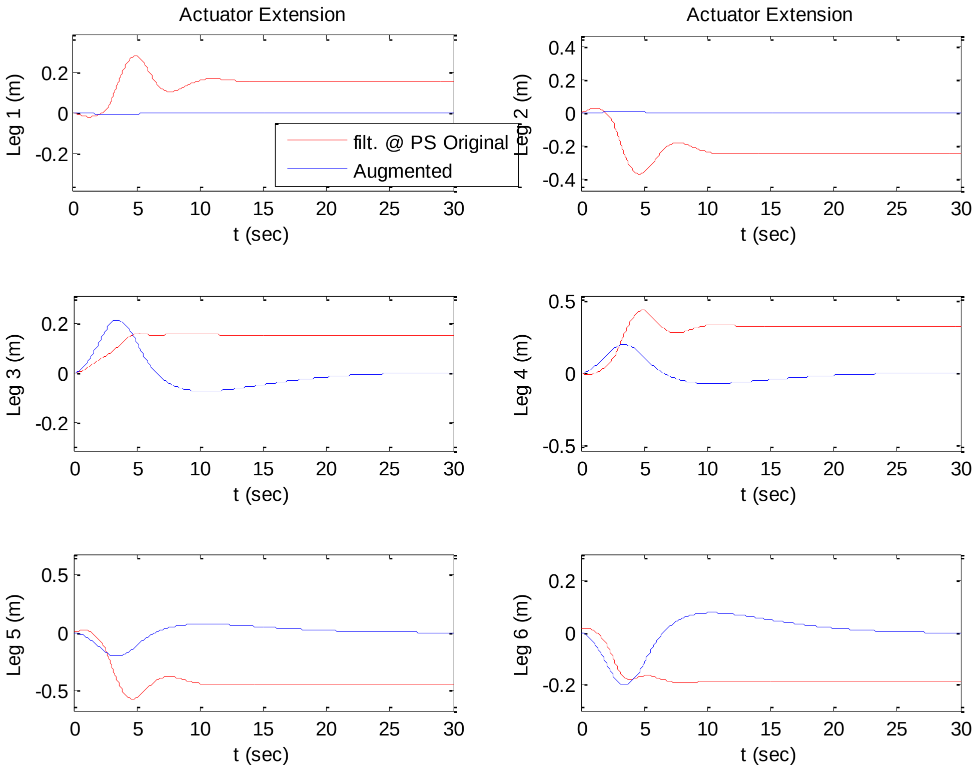

Actuator Extension
Leg 1 (m)
0.2
0
-0.2
filt. @ PS Original
Augmented
0
5
10
15
20
25
30
t (sec)
Actuator Extension
Leg 2 (m)
0.4
0.2
0
-0.2
-0.4
t (sec)
Leg 3 (m)
0.2
0
-0.2
t (sec)
Leg 4 (m)
0.5
0
-0.5
t (sec)
Leg 5 (m)
0.5
0
-0.5
t (sec)
Leg 6 (m)
0.2
0
-0.2
t (sec)

Figure D.2. 7.

3. Yaw

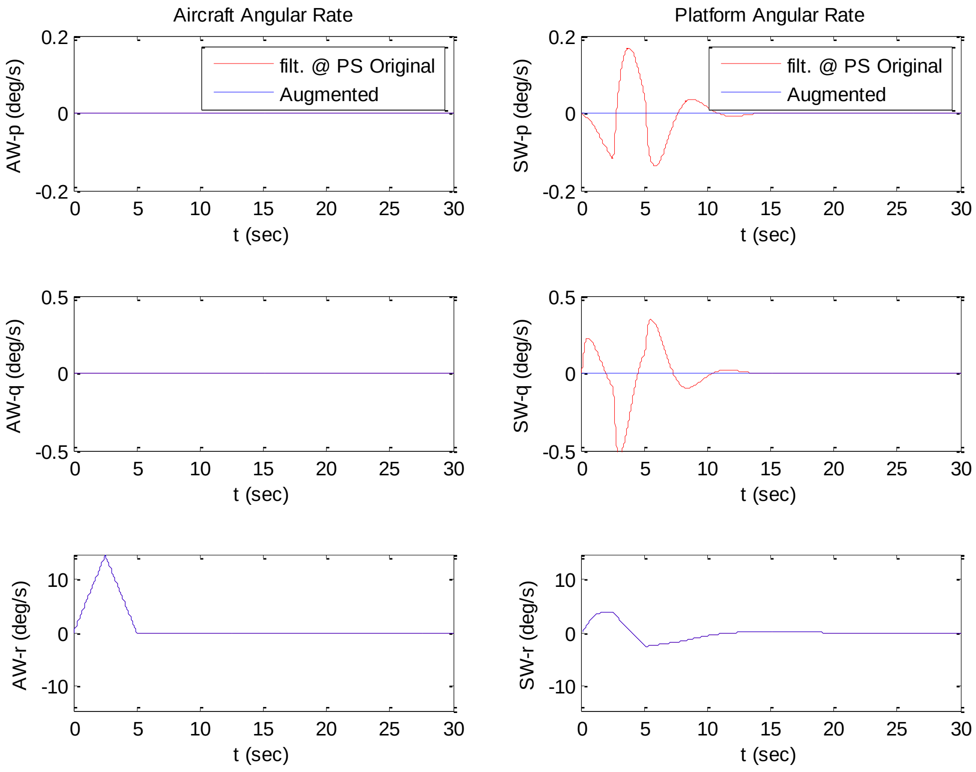


Figure D.3. 1.

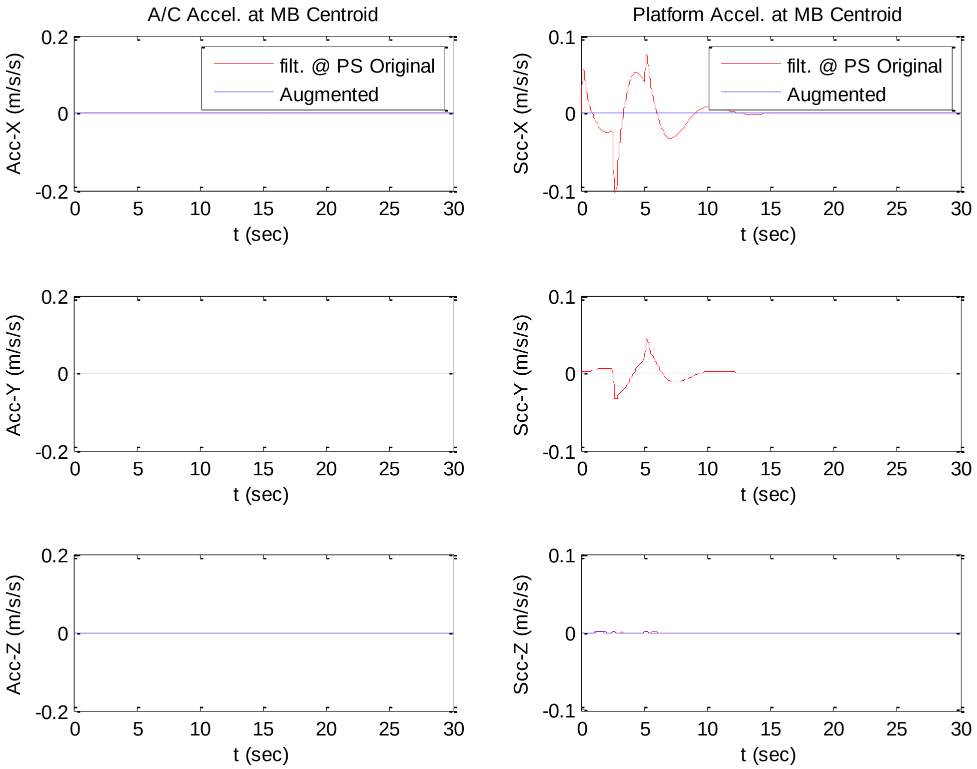
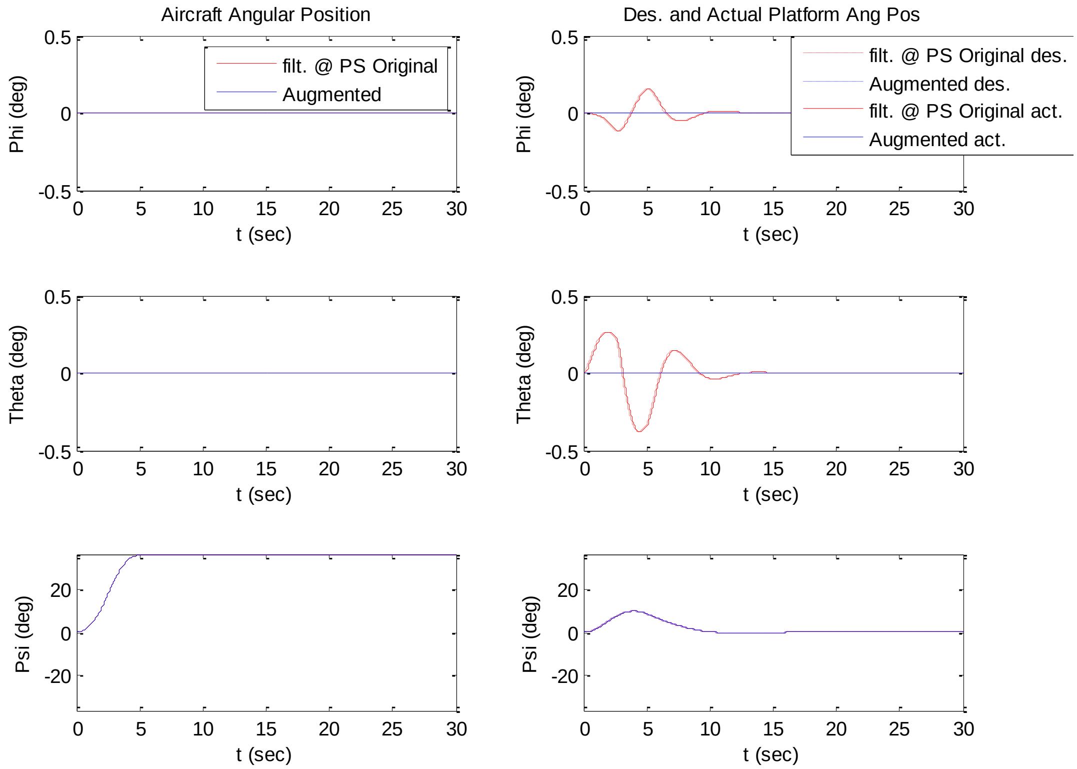

A/C Accel. at MB Centroid
Platform Accel. at MB Centroid
filt. @ PS Original
Augmented
Acc-X (m/s/s)
Acc-Y (m/s/s)
Acc-Z (m/s/s)
Scc-X (m/s/s)
Scc-Y (m/s/s)
Scc-Z (m/s/s)
0.2
0
-0.2
0.1
-0.1
0
5
10
15
20
25
30
t (sec)

Figure D.3. 2.



Aircraft Angular Position
Des. and Actual Platform Ang Pos
filt. @ PS Original
Augmented
filt. @ PS Original des.
Augmented des.
filt. @ PS Original act.
Augmented act.
Phi (deg)
Theta (deg)
Psi (deg)
0.5
0
-0.5
20
0
-20
0
5
10
15
20
25
30
t (sec)

Figure D.3. 3.

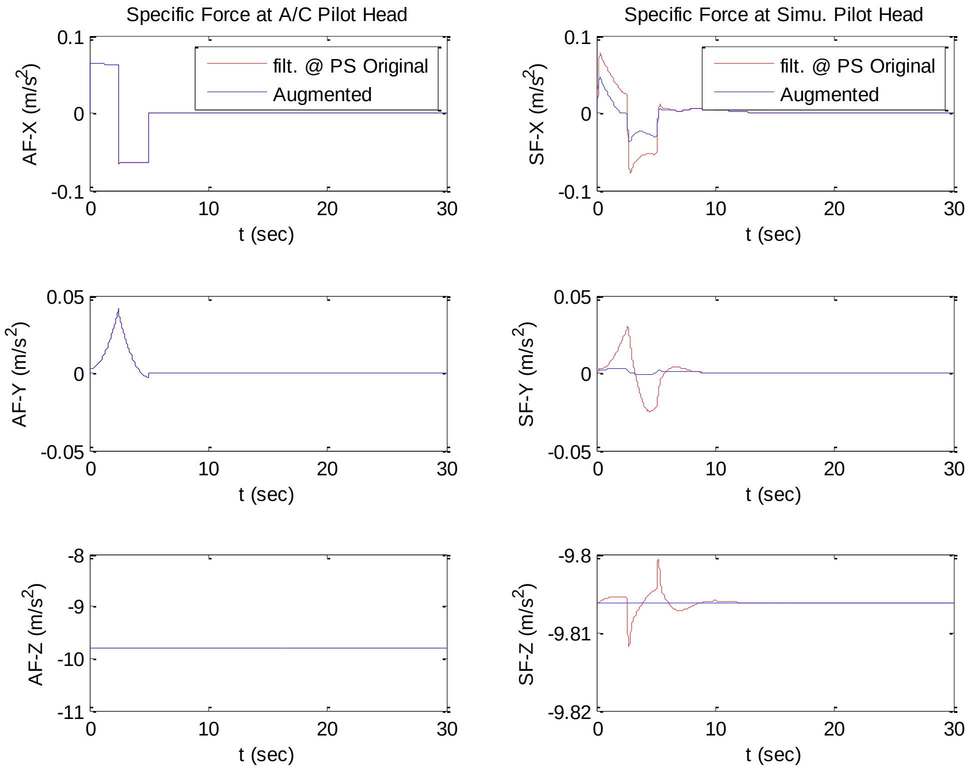

Specific Force at A/C Pilot Head
AF-X (m/s^2)
0.1
0
-0.1
0
10
20
30
t (sec)
filt. @ PS Original
Augmented
Specific Force at Simu. Pilot Head
SF-X (m/s^2)
0.1
0
-0.1
0
10
20
30
t (sec)
filt. @ PS Original
Augmented
AF-Y (m/s^2)
0.05
0
-0.05
0
10
20
30
t (sec)
SF-Y (m/s^2)
0.05
0
-0.05
0
10
20
30
t (sec)
AF-Z (m/s^2)
-8
-9
-10
-11
0
10
20
30
t (sec)
SF-Z (m/s^2)
-9.8
-9.81
-9.82
0
10
20
30
t (sec)

Figure D.3. 4.

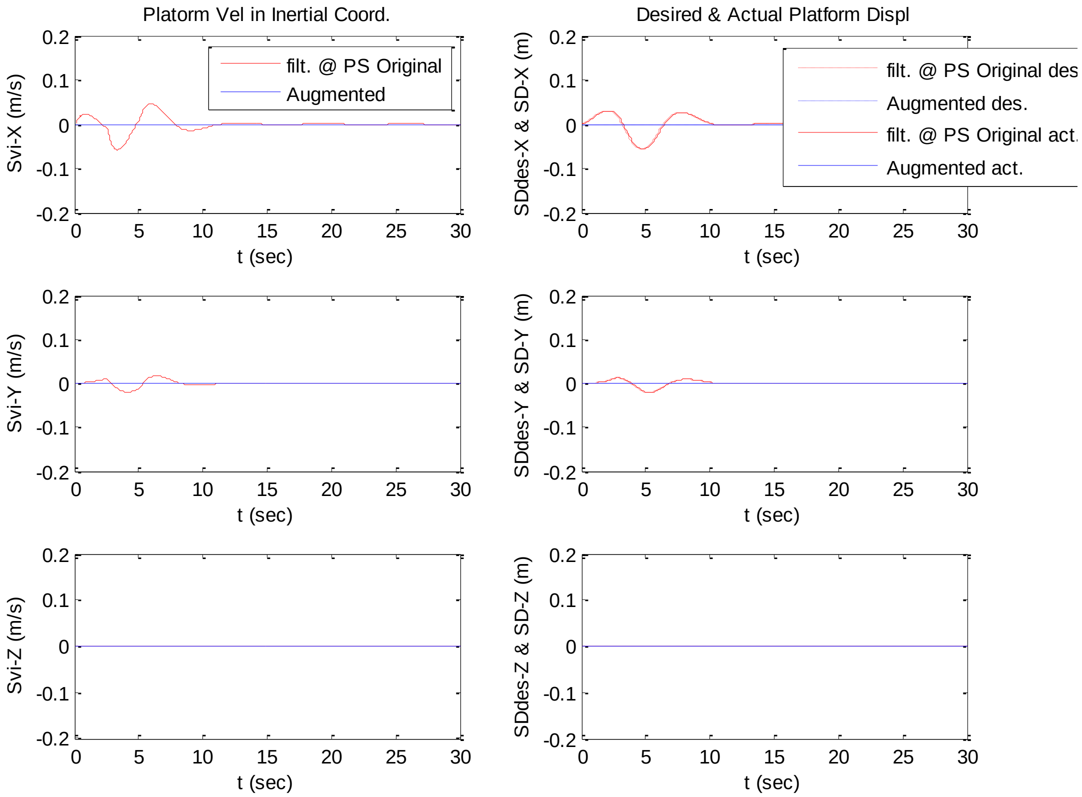

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
filt. @ PS Original
Augmented
filt. @ PS Original des
Augmented des.
filt. @ PS Original act.
Augmented act.
Svi-X (m/s)
SDdes-X & SD-X (m)
Svi-Y (m/s)
SDdes-Y & SD-Y (m)
Svi-Z (m/s)
SDdes-Z & SD-Z (m)
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20
25
30
t (sec)

Figure D.3. 5.

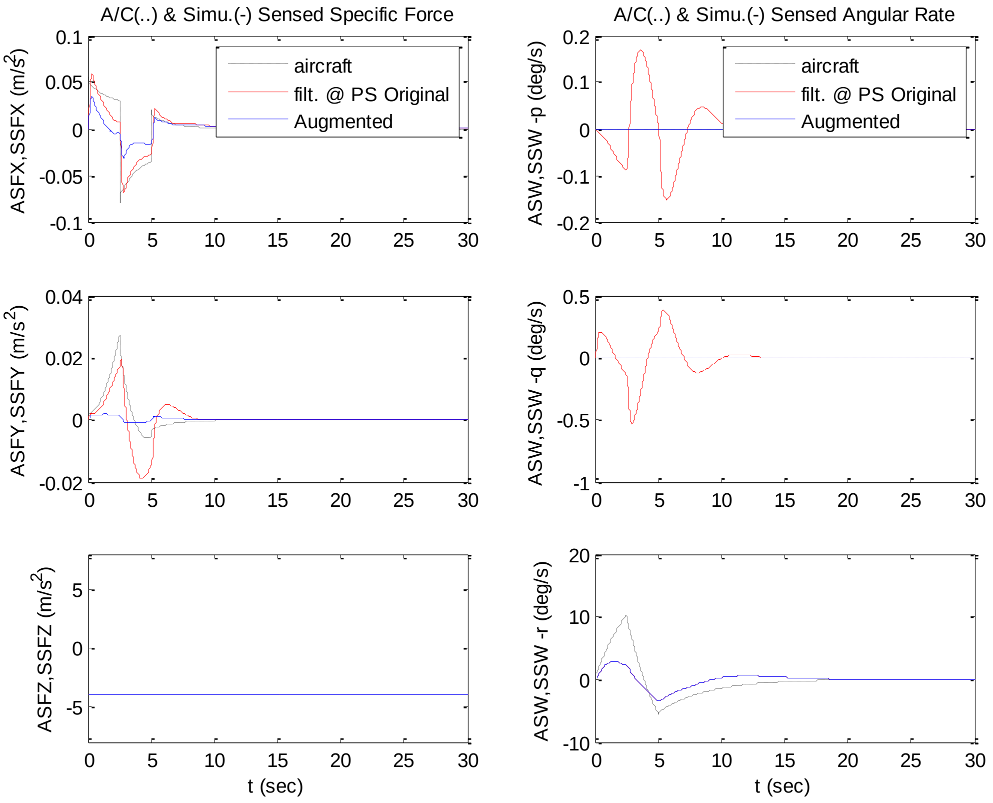

A/C(..) & Simu.(-) Sensed Specific Force
A/C(..) & Simu.(-) Sensed Angular Rate
aircraft
filt. @ PS Original
Augmented
ASFX,SSFX (m/s^2)
ASFY,SSFY (m/s^2)
ASFZ,SSFZ (m/s^2)
ASW,SSW -p (deg/s)
ASW,SSW -q (deg/s)
ASW,SSW -r (deg/s)
t (sec)
t (sec)
0.1
0.05
0
-0.05
-0.1
0.04
0.02
0
-0.02
5
0
-5
0.2
0.1
0
-0.1
-0.2
0.5
0
-0.5
-1
20
10
0
-10
0
5
10
15
20
25
30

Figure D.3. 6.

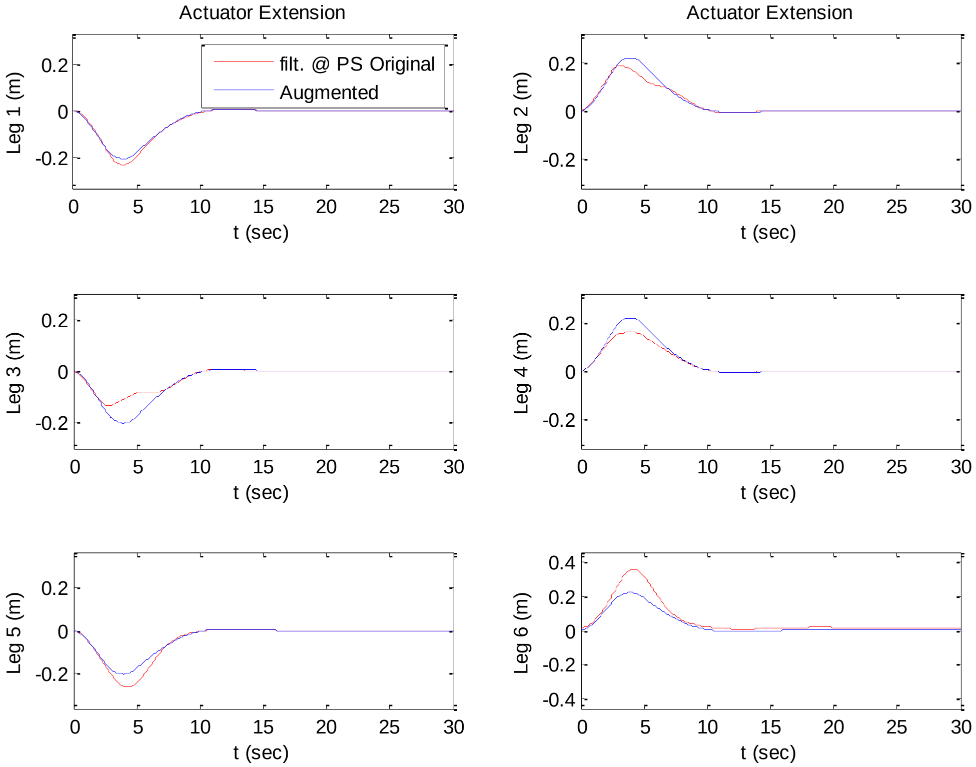

Actuator Extension
Actuator Extension
filt. @ PS Original
Augmented
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
30
t (sec)

Figure D.3. 7.

4. Surge

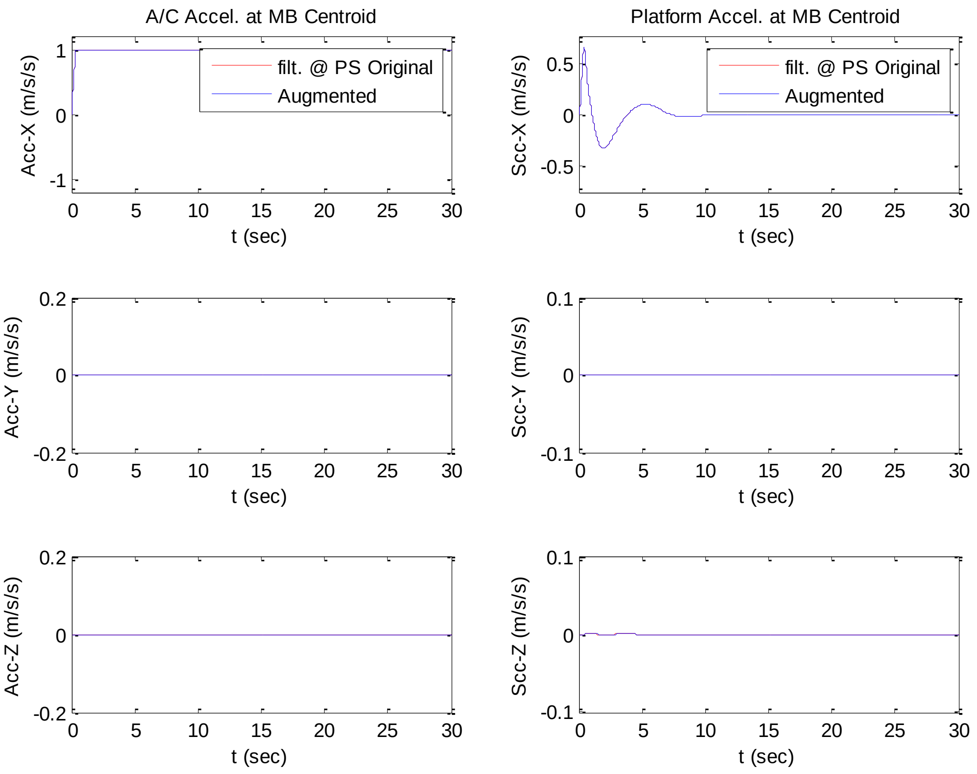


Figure D.4. 1.

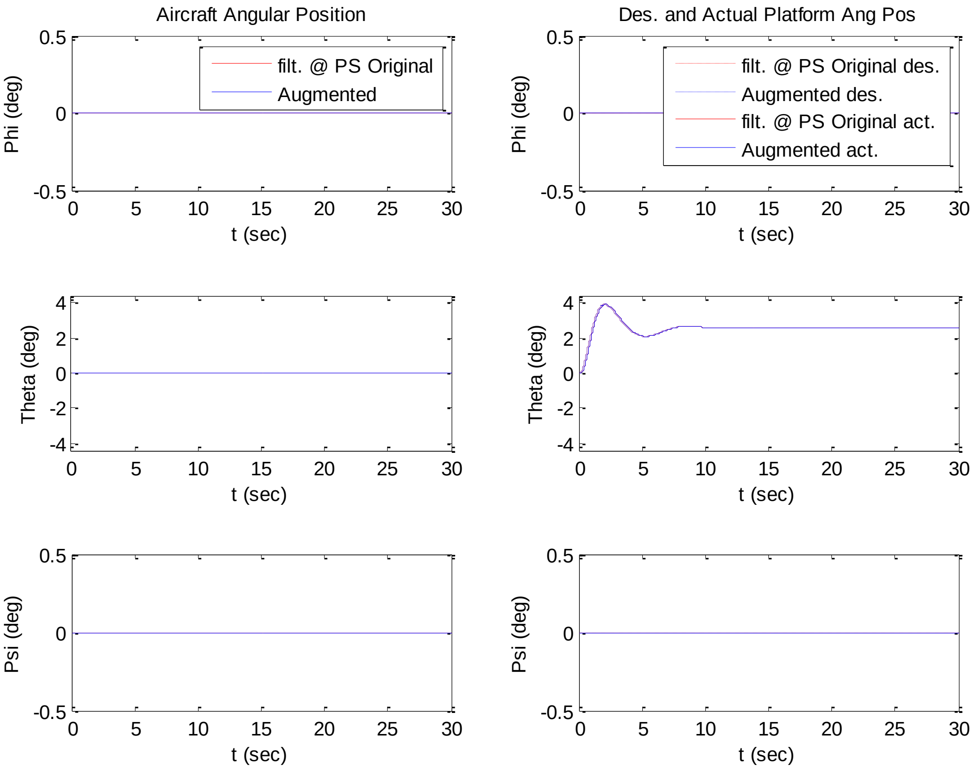

Aircraft Angular Position
Des. and Actual Platform Ang Pos
filt. @ PS Original
Augmented
filt. @ PS Original des.
Augmented des.
filt. @ PS Original act.
Augmented act.
Phi (deg)
Theta (deg)
Psi (deg)
t (sec)
0.5
0
-0.5
4
2
0
-2
-4
0
5
10
15
20
25
30

Figure D.4. 2.

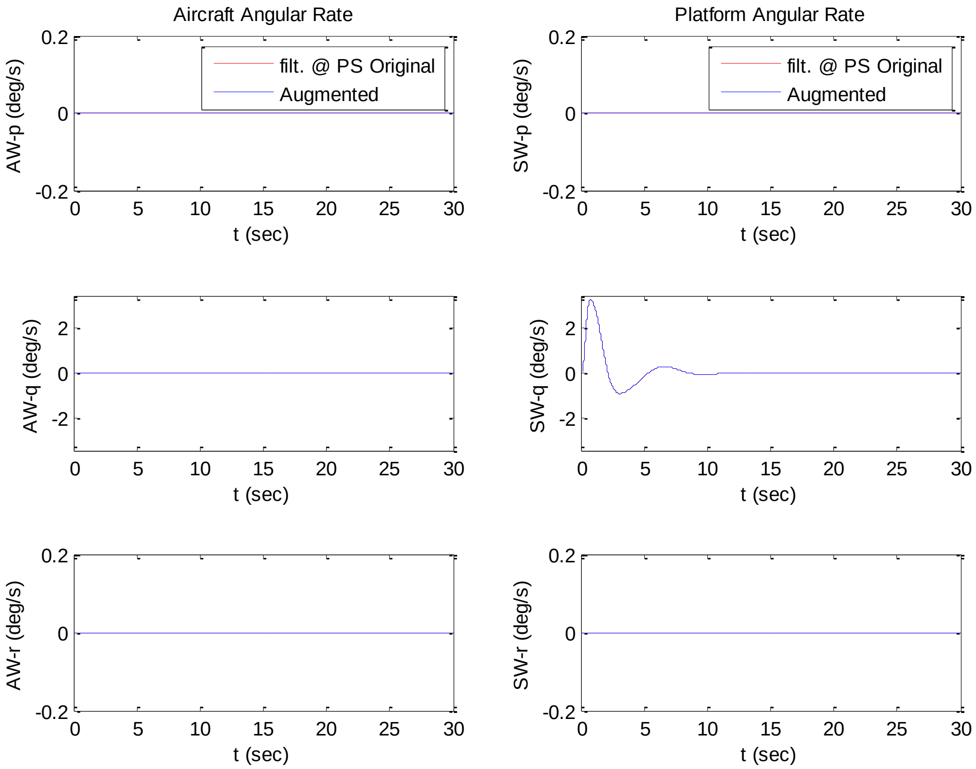

Aircraft Angular Rate
Platform Angular Rate
filt. @ PS Original
Augmented
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
0.2
0
-0.2
2
0
-2
0
5
10
15
20
25
30
t (sec)

Figure D.4. 3.

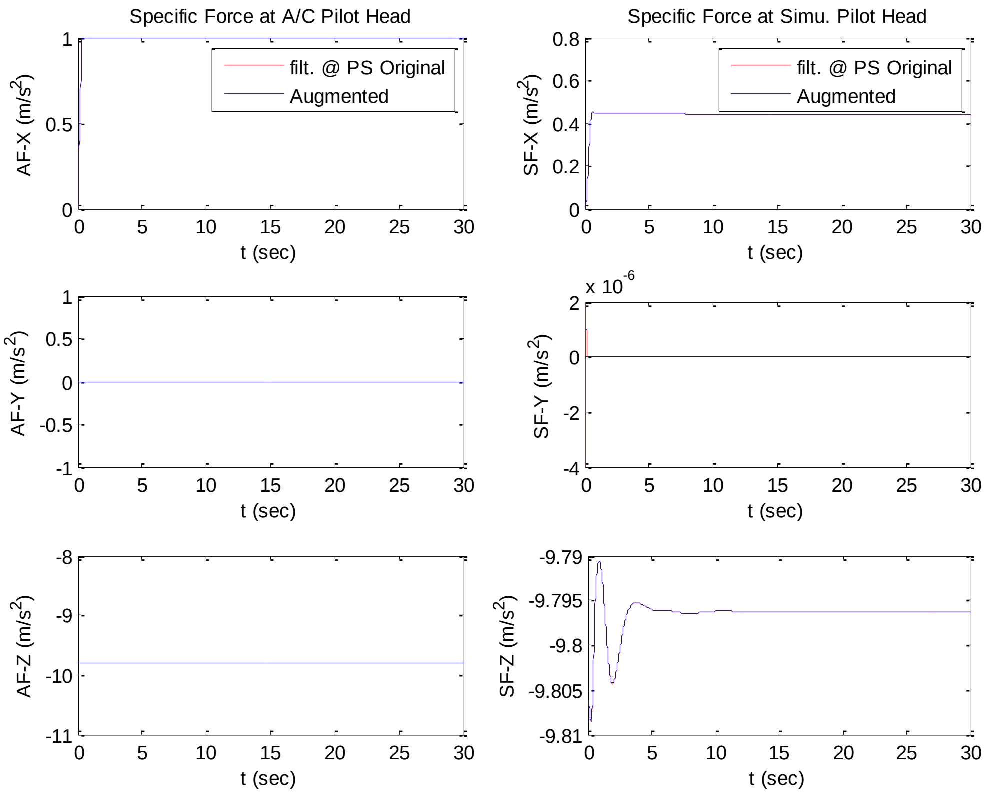

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
filt. @ PS Original
Augmented
AF-X (m/s^2)
SF-X (m/s^2)
AF-Y (m/s^2)
SF-Y (m/s^2)
AF-Z (m/s^2)
SF-Z (m/s^2)
x 10^{-6}
t (sec)
0
5
10
15
20
25
30
1
0.5
0
0.8
0.6
0.4
0.2
-0.5
-1
2
-2
-4
-8
-9
-10
-11
-9.79
-9.795
-9.8
-9.805
-9.81

Figure D.4. 4.

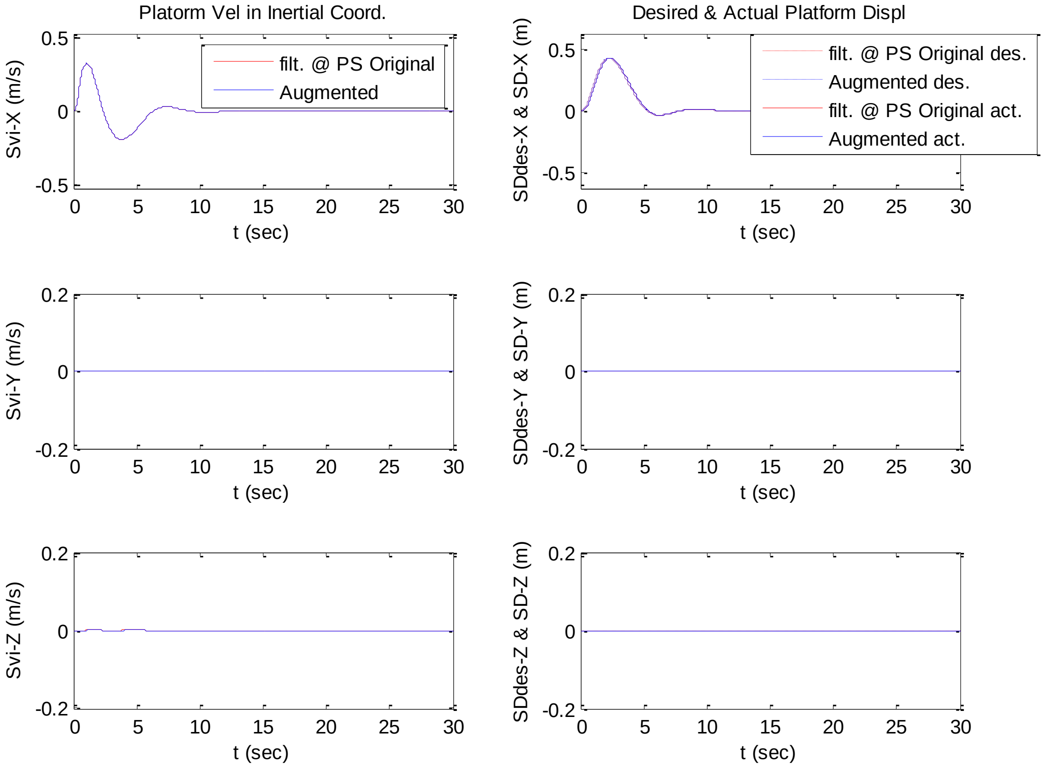

Platorm Vel in Inertial Coord.
Svi-X (m/s)
0.5
0
-0.5
filt. @ PS Original
Augmented
t (sec)
0 5 10 15 20 25 30
Desired & Actual Platform Displ
SDdes-X & SD-X (m)
0.5
0
-0.5
filt. @ PS Original des.
Augmented des.
filt. @ PS Original act.
Augmented act.
Svi-Y (m/s)
0.2
0
-0.2
SDdes-Y & SD-Y (m)
Svi-Z (m/s)
SDdes-Z & SD-Z (m)

Figure D.4. 5.

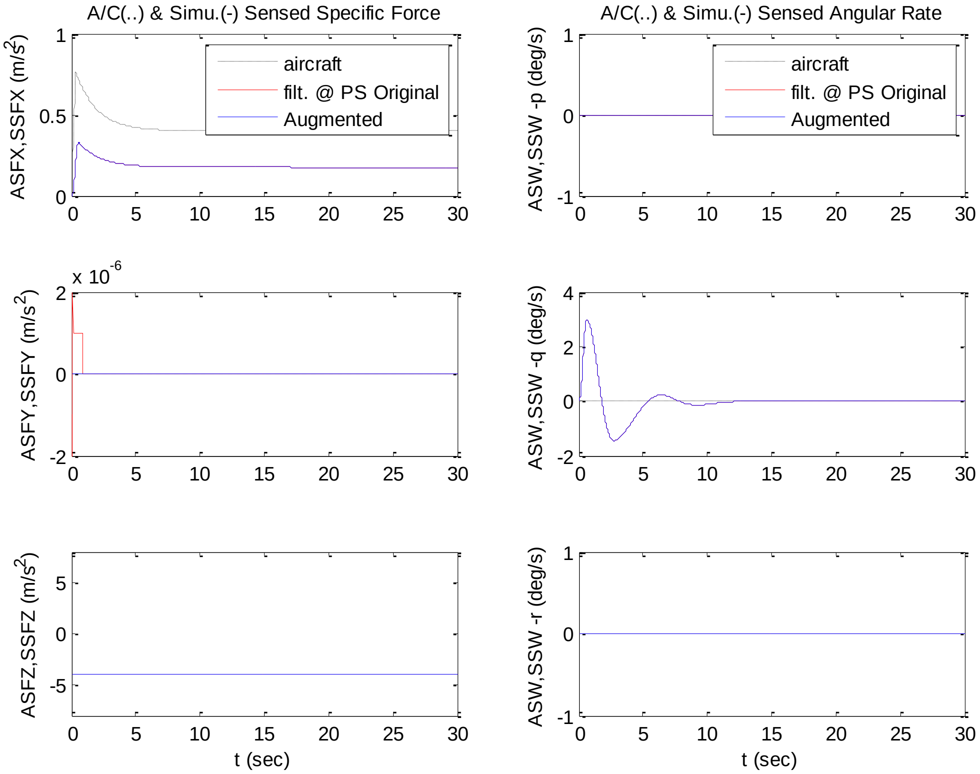

A/C(..) & Simu.(-) Sensed Specific Force
A/C(..) & Simu.(-) Sensed Angular Rate
aircraft
filt. @ PS Original
Augmented
ASFX,SSFX (m/s2)
ASFY,SSFY (m/s2)
ASFZ,SSFZ (m/s2)
ASW,SSW -p (deg/s)
ASW,SSW -q (deg/s)
ASW,SSW -r (deg/s)
x 10-6
1
0.5
0
2
-2
5
-5
4
-1
0
5
10
15
20
25
30
t (sec)

Figure D.4. 6.

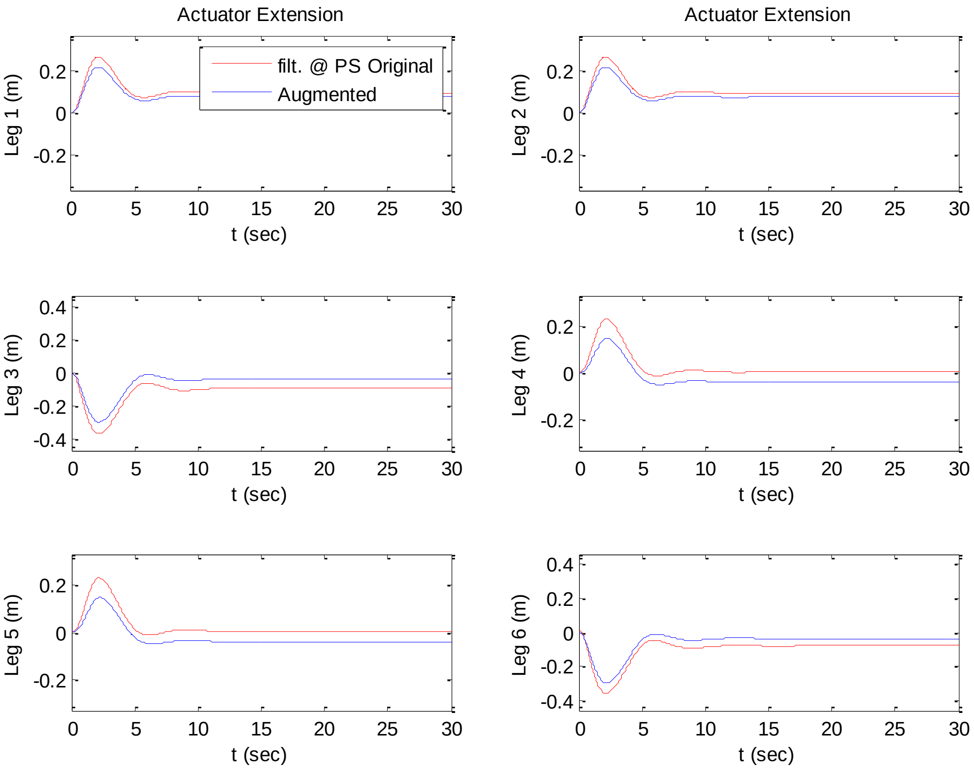

Actuator Extension
Actuator Extension
filt. @ PS Original
Augmented
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
30
t (sec)

Figure D.4. 7.

5. Sway

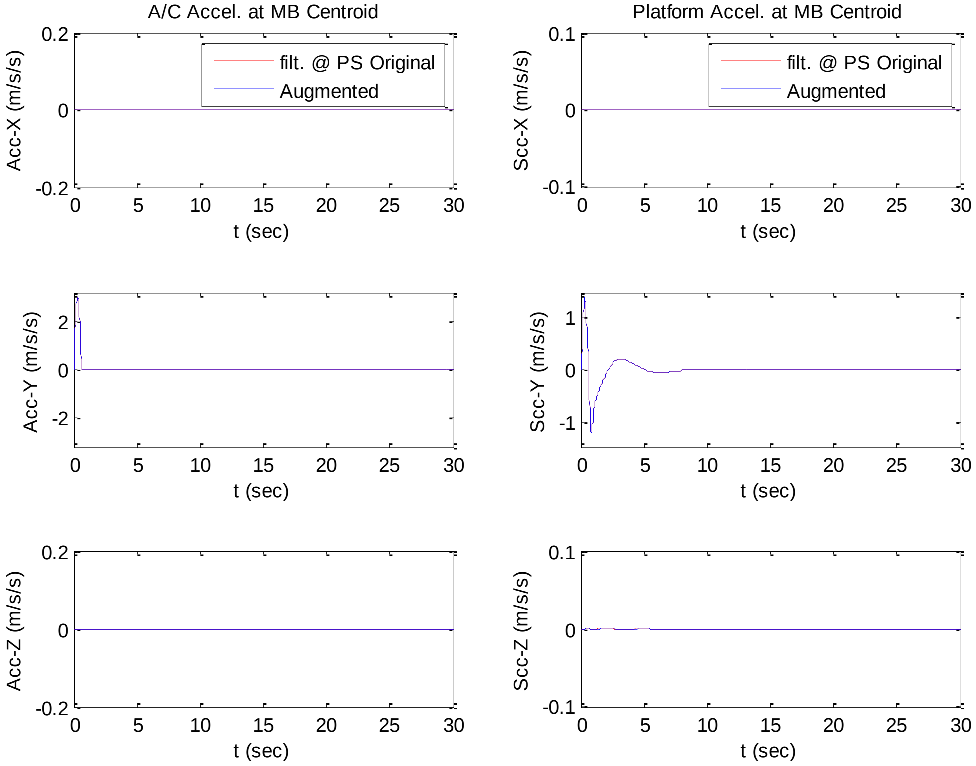


Figure D.5. 1.

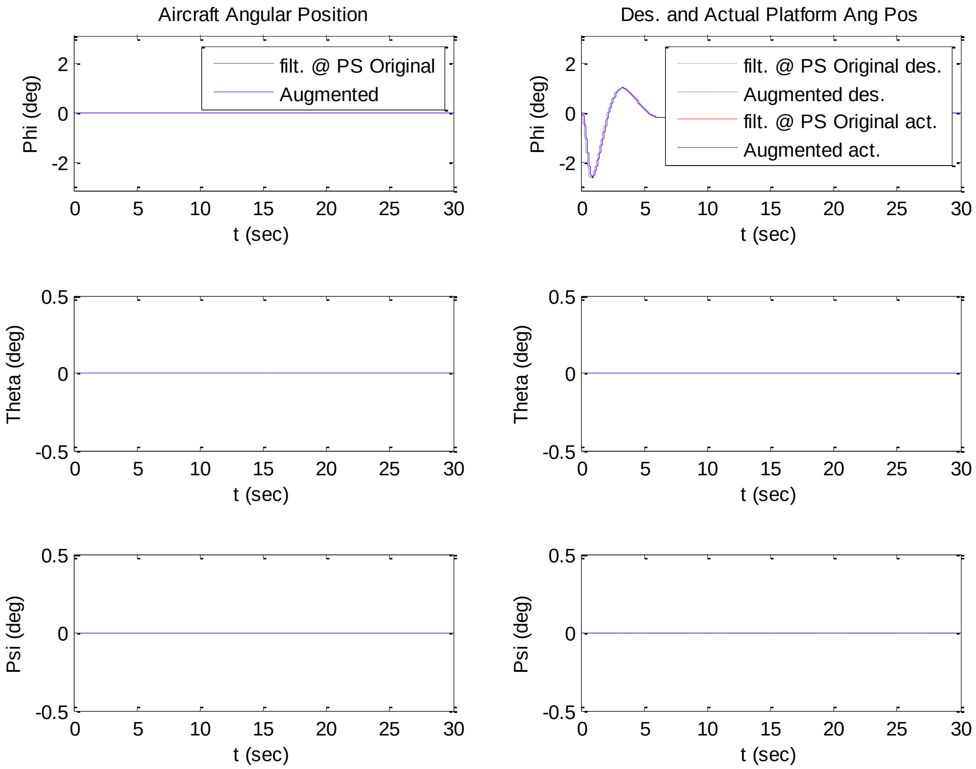

Aircraft Angular Position
Des. and Actual Platform Ang Pos
filt. @ PS Original
Augmented
filt. @ PS Original des.
Augmented des.
filt. @ PS Original act.
Augmented act.
Phi (deg)
Theta (deg)
Psi (deg)
2
0
-2
0.5
0
-0.5
0
5
10
15
20
25
30
t (sec)

Figure D.5. 2.

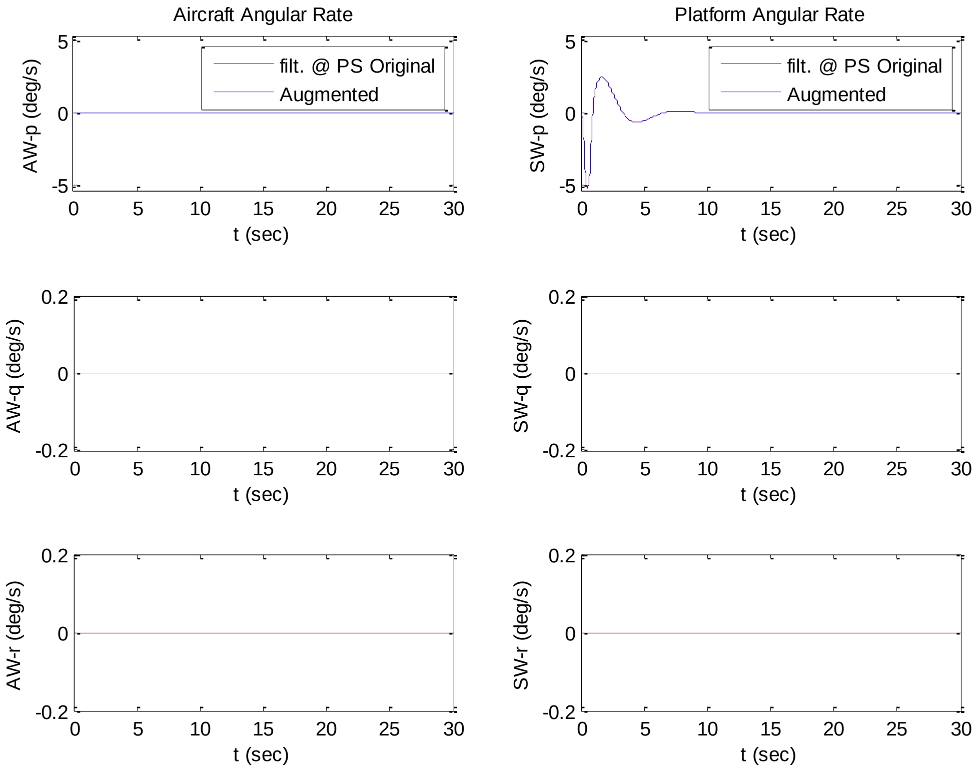

Aircraft Angular Rate
Platform Angular Rate
filt. @ PS Original
Augmented
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
5
0
-5
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure D.5. 3.

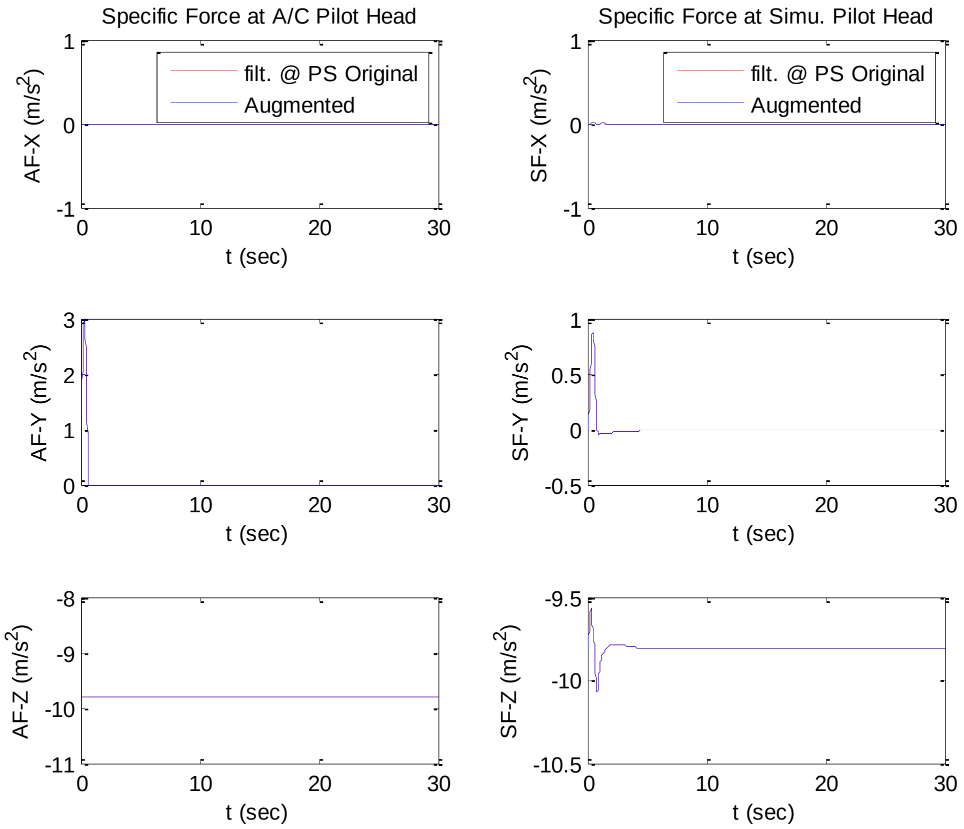

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
filt. @ PS Original
Augmented
AF-X (m/s^2)
SF-X (m/s^2)
AF-Y (m/s^2)
SF-Y (m/s^2)
AF-Z (m/s^2)
SF-Z (m/s^2)
t (sec)
0
10
20
30
1
0
-1
3
2
0.5
-0.5
-8
-9
-10
-11
-9.5
-10.5

Figure D.5. 4.

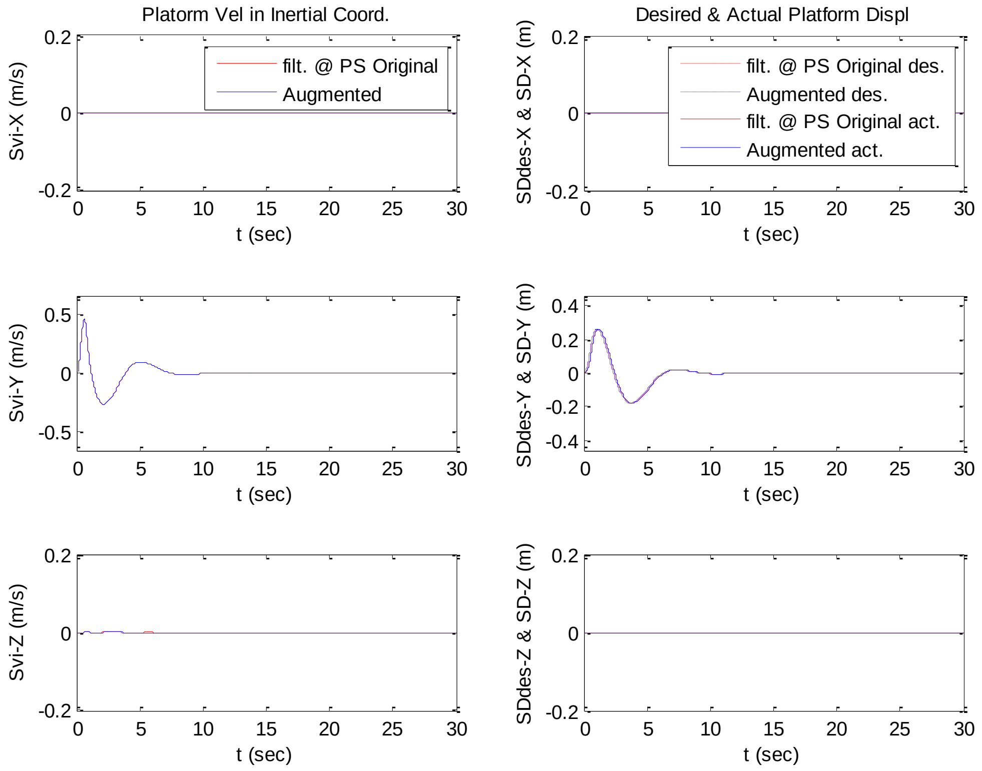

Platorm Vel in Inertial Coord.
Svi-X (m/s)
0.2
0
-0.2
filt. @ PS Original
Augmented
Desired & Actual Platform Displ
SDdes-X & SD-X (m)
filt. @ PS Original des.
Augmented des.
filt. @ PS Original act.
Augmented act.
Svi-Y (m/s)
0.5
-0.5
SDdes-Y & SD-Y (m)
0.4
-0.4
Svi-Z (m/s)
SDdes-Z & SD-Z (m)
0
5
10
15
20
25
30
t (sec)

Figure D.5. 5.

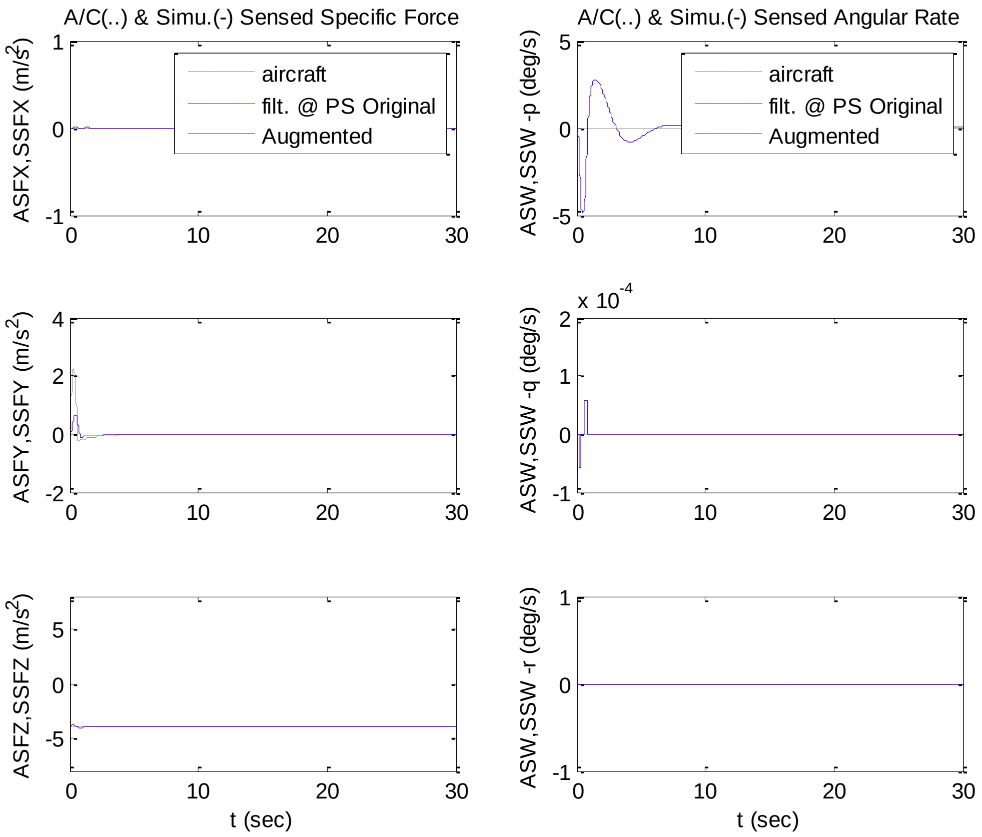

A/C(..) & Simu.(-) Sensed Specific Force
A/C(..) & Simu.(-) Sensed Angular Rate
ASFX,SSFX (m/s^2)
ASW,SSW -p (deg/s)
aircraft
filt. @ PS Original
Augmented
1
0
-1
5
0
-5
0
10
20
30
ASFY,SSFY (m/s^2)
ASW,SSW -q (deg/s)
x 10^{-4}
4
2
0
-2
1
-1
ASFZ,SSFZ (m/s^2)
ASW,SSW -r (deg/s)
t (sec)

Figure D.5. 6.

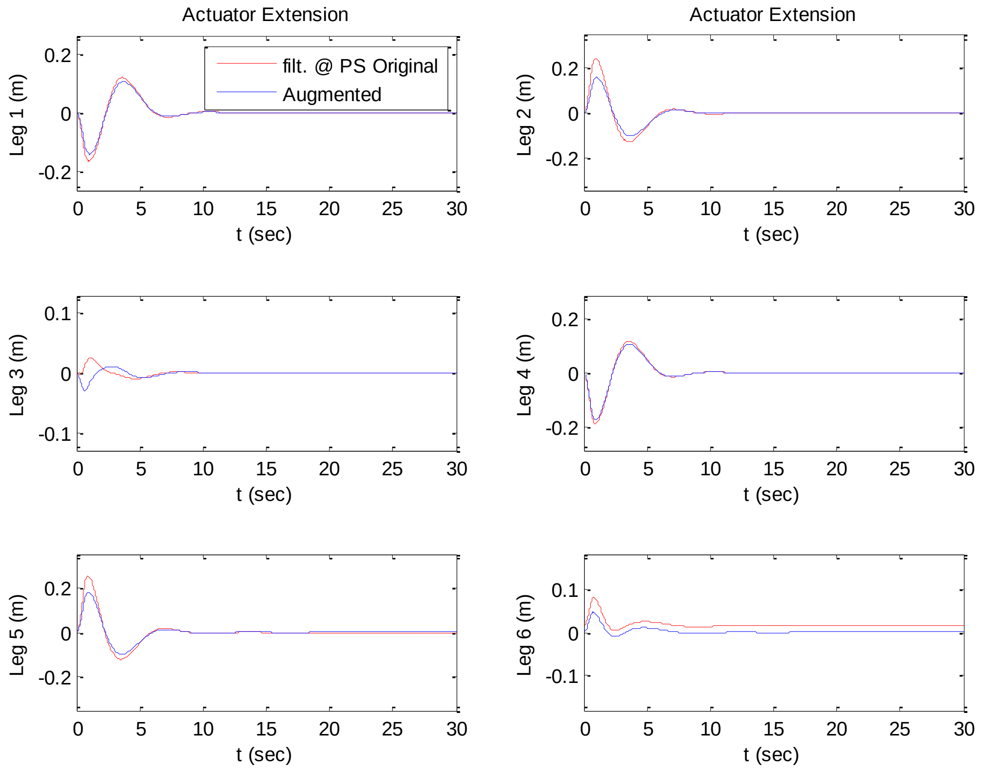

Actuator Extension
Actuator Extension
filt. @ PS Original
Augmented
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.2
0
-0.2
0.1
-0.1
0
5
10
15
20
25
30
t (sec)

Figure D.5. 7.

6. Heave

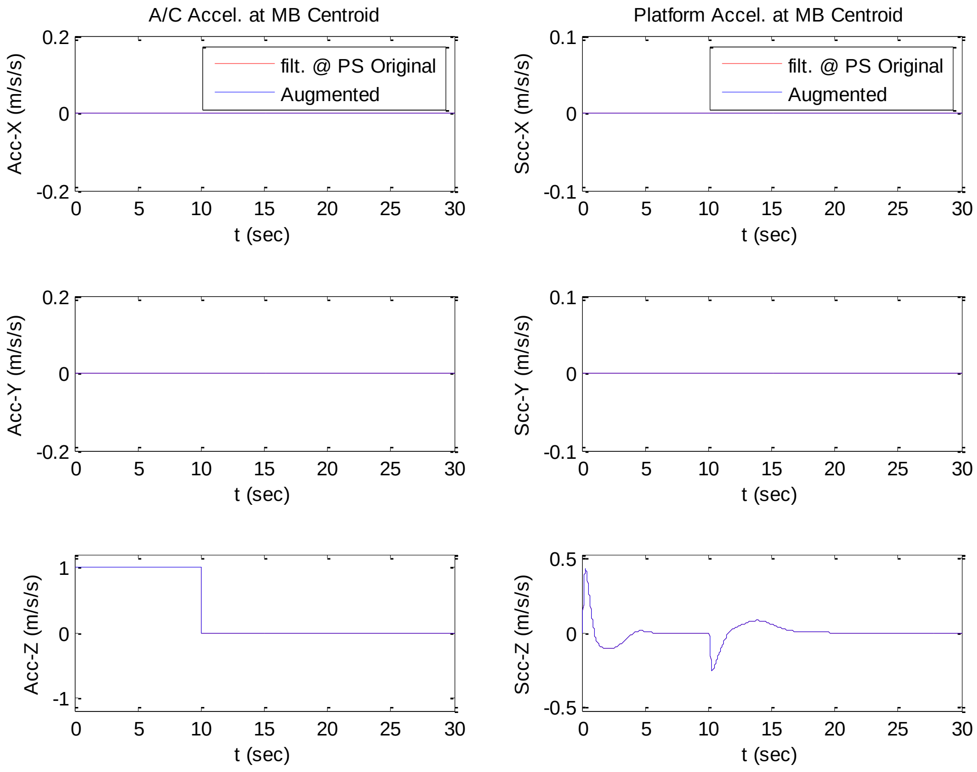


Figure D.6. 1.

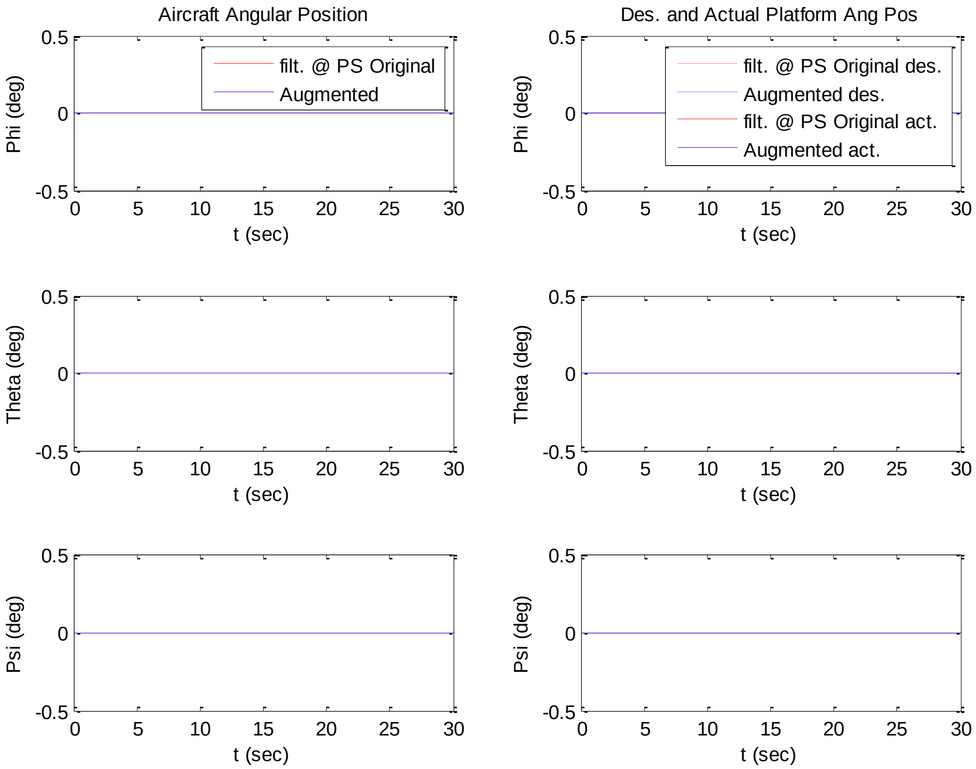

Aircraft Angular Position
Des. and Actual Platform Ang Pos
filt. @ PS Original
Augmented
filt. @ PS Original des.
Augmented des.
filt. @ PS Original act.
Augmented act.
Phi (deg)
Theta (deg)
Psi (deg)
0.5
0
-0.5
0
5
10
15
20
25
30
t (sec)

Figure D.6. 2.

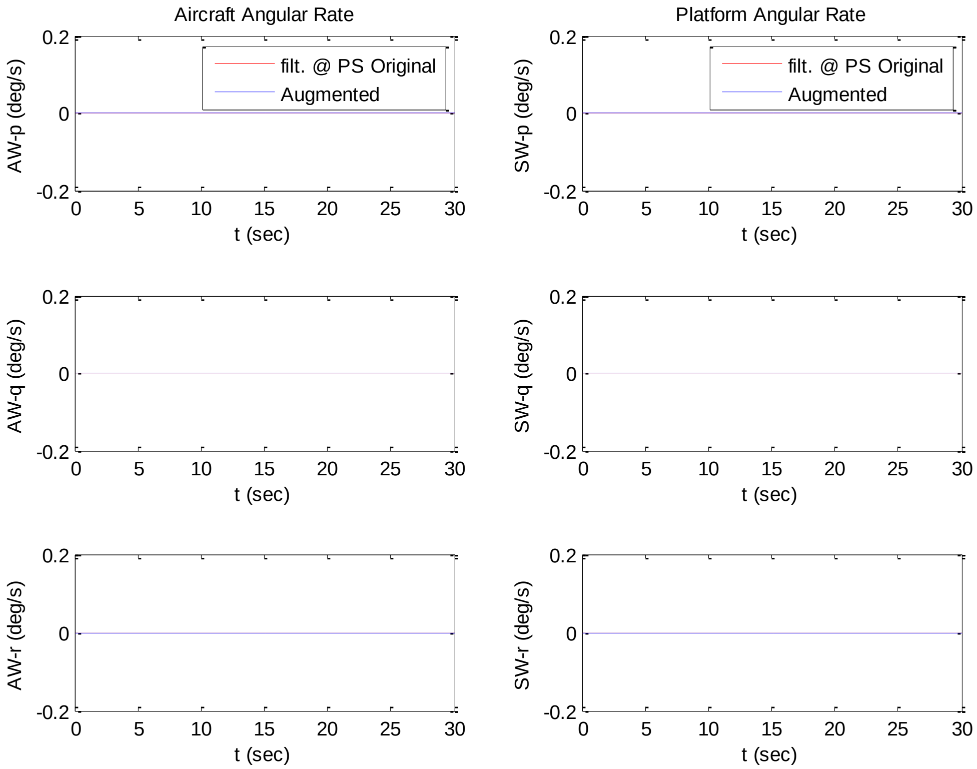

Aircraft Angular Rate
Platform Angular Rate
filt. @ PS Original
Augmented
AW-p (deg/s)
SW-p (deg/s)
AW-q (deg/s)
SW-q (deg/s)
AW-r (deg/s)
SW-r (deg/s)
0.2
0
-0.2
0
5
10
15
20
25
30
t (sec)

Figure D.6. 3.

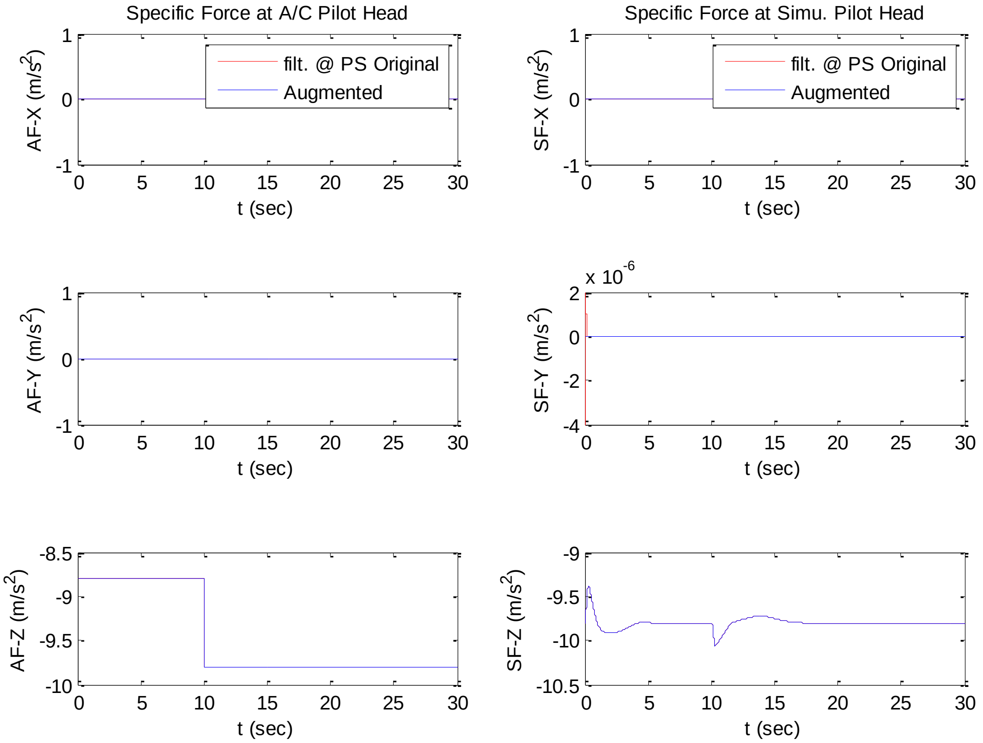

Specific Force at A/C Pilot Head
Specific Force at Simu. Pilot Head
filt. @ PS Original
Augmented
AF-X (m/s^2)
SF-X (m/s^2)
AF-Y (m/s^2)
SF-Y (m/s^2)
AF-Z (m/s^2)
SF-Z (m/s^2)
x 10^{-6}
1
0
-1
2
-2
-4
-8.5
-9
-9.5
-10
-10.5
0
5
10
15
20
25
30
t (sec)

Figure D.6. 4.

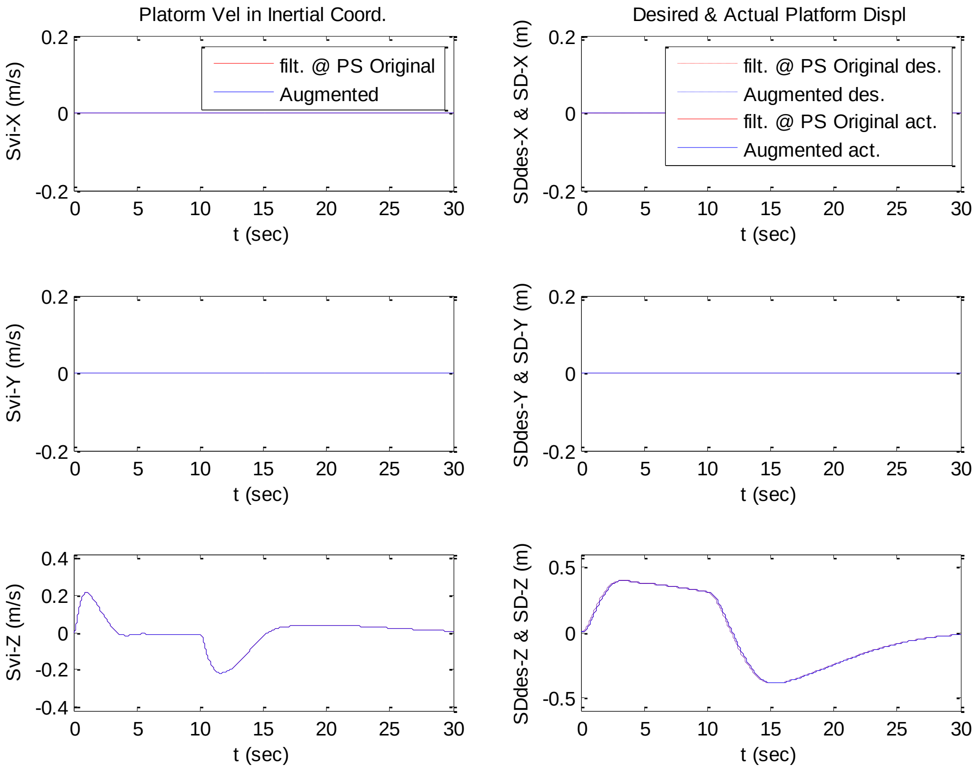

Platorm Vel in Inertial Coord.
Desired & Actual Platform Displ
filt. @ PS Original
Augmented
filt. @ PS Original des.
Augmented des.
filt. @ PS Original act.
Augmented act.
Svi-X (m/s)
Svi-Y (m/s)
Svi-Z (m/s)
SDdes-X & SD-X (m)
SDdes-Y & SD-Y (m)
SDdes-Z & SD-Z (m)
0.4
0.2
0
-0.2
-0.4
0.5
-0.5
0
5
10
15
20
25
30
t (sec)

Figure D.6. 5.

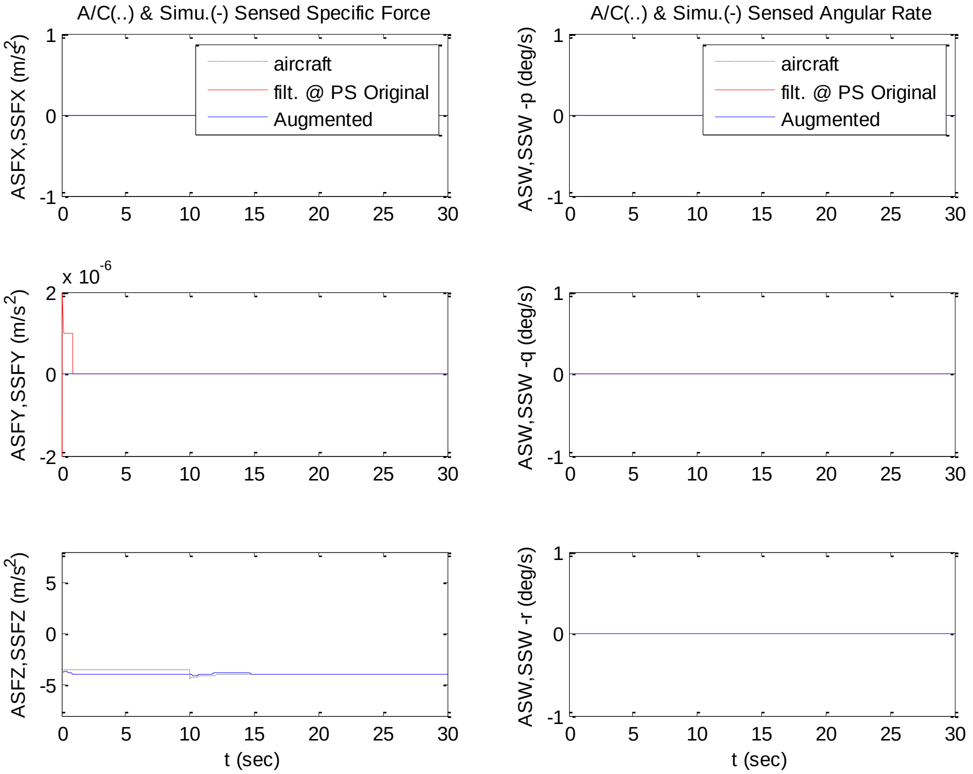

A/C(..) & Simu.(-) Sensed Specific Force
A/C(..) & Simu.(-) Sensed Angular Rate
aircraft
filt. @ PS Original
Augmented
ASFX,SSFX (m/s2)
ASW,SSW -p (deg/s)
ASFY,SSFY (m/s2)
x 10-6
ASW,SSW -q (deg/s)
ASFZ,SSFZ (m/s2)
ASW,SSW -r (deg/s)
t (sec)
0
5
10
15
20
25
30

Figure D.6. 6.

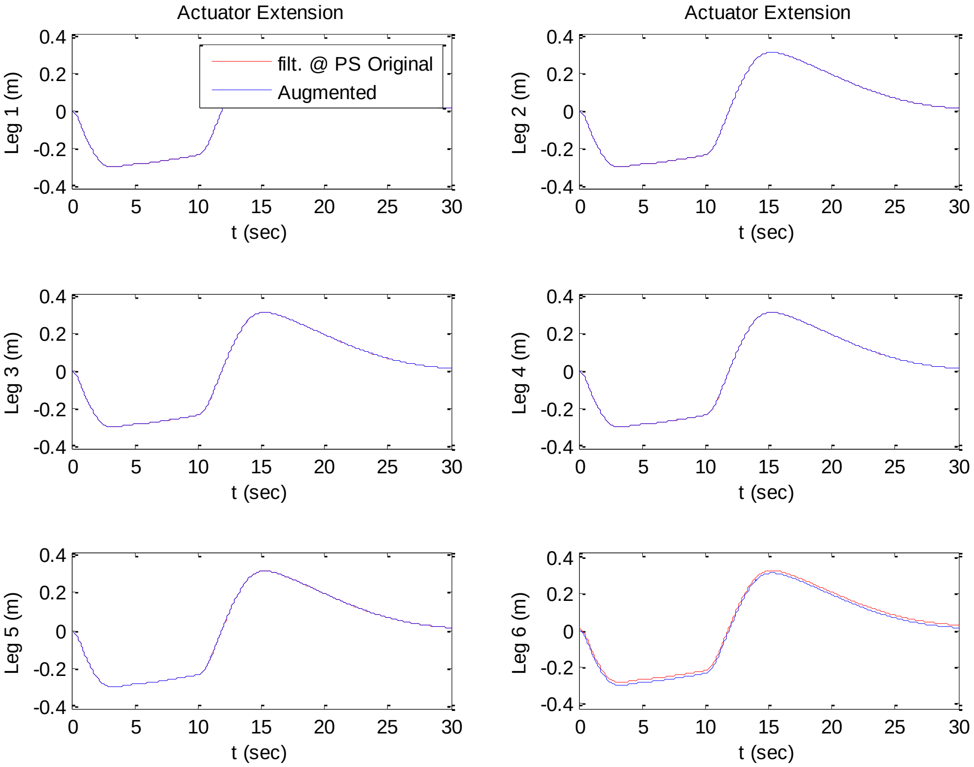

Actuator Extension
Actuator Extension
filt. @ PS Original
Augmented
Leg 1 (m)
Leg 2 (m)
Leg 3 (m)
Leg 4 (m)
Leg 5 (m)
Leg 6 (m)
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
30
t (sec)

Figure D.6. 7.

References

[1] Telban, R. J., Cardullo, F. M.: "*Motion Cueing Algorithm Development: Human-Centered Linear and Nonlinear Approaches*", NASA Langley Research Center, NASA/CR-2005-213747, 2005.

[2] Anderson, B. D., Moore, J. B.: *Linear Optimal Control*. Englewood Cliffs, NJ: Prentice-Hall, 1971

[3] Telban, R. J., Cardullo, F. M.: "*Motion Cueing Algorithm Development: Human-Centered Linear and Nonlinear Approaches*", NASA Langley Research Center, NASA/CR-2005-2137476 2005.

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Langley Technical Monitor: Jacob A. Houck

14. ABSTRACT

Telban and Cardullo have developed and successfully implemented the non-linear optimal motion cueing algorithm at the Visual Motion Simulator (VMS) at the NASA Langley Research Center in 2005. The latest version of the non-linear algorithm performed filtering of motion cues in all degrees-of-freedom except for pitch and roll. This manuscript describes the development and implementation of the non-linear optimal motion cueing algorithm for the pitch and roll degrees of freedom. Presented results indicate improved cues in the specified channels as compared to the original design. To further advance motion cueing in general, this manuscript describes modifications to the existing algorithm, which allow for filtering at the location of the pilot's head as opposed to the centroid of the motion platform. The rational for such modification to the cueing algorithms is that the location of the pilot's vestibular system must be taken into account as opposed to the off-set of the centroid of the cockpit relative to the center of rotation alone. Results provided in this report suggest improved performance of the motion cueing algorithm.

15. SUBJECT TERMS
Cueing Algorithms; Flight Simulator; Motion Systems

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