Motion Cueing Algorithm Development: New Motion Cueing Program Implementation and Tuning

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Acknowledgments

Jacob Houck of the Flight Simulation and Software Branch at the NASA Langley Research Center assisted in the preparation of this report.
Abstract

A computer program has been developed for the purpose of driving the NASA Langley Research Center Visual Motion Simulator (VMS). This program includes two new motion cueing algorithms, the optimal algorithm and the nonlinear algorithm. A general description of the program is given along with a description and flowcharts for each cueing algorithm, and also descriptions and flowcharts for subroutines used with the algorithms. Common block variable listings and a program listing are also provided.

The new cueing algorithms have a nonlinear gain algorithm implemented that scales each aircraft degree-of-freedom input with a third-order polynomial. A description of the nonlinear gain algorithm is given along with past tuning experience and procedures for tuning the gain coefficient sets for each degree-of-freedom to produce the desired piloted performance. This algorithm tuning will be needed when the nonlinear motion cueing algorithm is implemented on a new motion system in the Cockpit Motion Facility (CMF) at the NASA Langley Research Center.
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# Table of Contents

Abstract .............................................................................................................................. iii
Table of Contents................................................................................................................ v
Nomenclature.................................................................................................................... vii
1. Introduction................................................................................................................ .1
2. Background Information............................................................................................. 5
  2.1. NASA Langley Visual Motion Simulator (VMS) .............................................. 5
  2.2. Reference Frames.............................................................................................. 7
      2.2.1. Aircraft Center of Gravity........................................................................... 7
      2.2.2. Simulator..................................................................................................... 7
      2.2.3. Aircraft........................................................................................................ 7
      2.2.4. Inertial ......................................................................................................... 8
      2.2.5. Reference Frame Locations ........................................................................ 8
  2.3. Coordinate Transformations ............................................................................... 9
  2.4. Nonlinear Input Scaling .................................................................................... 10
  2.5. Actuator Geometry............................................................................................ 13
  2.6. Augmented Turbulence Cue ............................................................................. 16
  2.7. Trim Algorithm................................................................................................. 17
3. Optimal Motion Cueing Algorithm .......................................................................... 19
  3.1. Algorithm Description ...................................................................................... 19
  3.2. Program Implementation .................................................................................. 21
4. Nonlinear Motion Cueing Algorithm........................................................................ 27
  4.1. Algorithm Description ...................................................................................... 27
  4.2. Program Implementation .................................................................................. 30
5. Nonlinear Algorithm Tuning .................................................................................... 41
  5.1. Prior Tuning Experience................................................................................... 41
  5.2. Tuning Procedure.............................................................................................. 44
6. Suggested Future Implementation ............................................................................ 49
7. Common Block Variable Listings ............................................................................ 53
  7.1. comint2.com (Variables Used in Optimal and Nonlinear Algorithms) .......... 53
  7.2. optint3.com ....................................................................................................... 53
  7.3. wopt3.com ......................................................................................................... 54
  7.4. matrix1c.com .................................................................................................... 54
  7.5. nopt4.com ......................................................................................................... 55
8. Program Listing ........................................................................................................ 57
  8.1. gainopt3.f .......................................................................................................... 57
  8.2. gainopt4.f .......................................................................................................... 59
  8.3. integ3.f .............................................................................................................. 61
  8.4. integ4.f .............................................................................................................. 63
  8.5. invplf.f ............................................................................................................... 65
  8.6. jackdrvr.f .......................................................................................................... 68
  8.7. liba.f .................................................................................................................. 72
  8.8. newopt4.f .......................................................................................................... 73
  8.9. nfilr.f ................................................................................................................. 76
  8.10. nfilx.f ................................................................................................................ 79
Nomenclature

a: acceleration $\mathbf{a} = [a_x, a_y, a_z]^T$

A, B, C, D, H: matrices of the state-space model of a control system

A': system matrix of the standard form optimal control system

c_0, c_1, c_2, c_3: coefficients of the nonlinear scaling polynomial

f: specific force

Fr: reference frame


g: acceleration due to gravity

H_g: augmented turbulence transfer function

J: system cost function

K: state feedback gain matrix

l_j: displacement of the j-th motion platform actuator

P: solution of the algebraic Riccati equation

Q, R, R_d: weighting matrices in a cost function (tracking form)

Q_2: weighting matrix for nonlinear algorithm control law

R_1, R_2, R_{12}: weighting matrices in a cost function (standard form)

R: radius vector

S: simulator centroid displacement

s: Laplace variable

s_0, s_1: slopes of the nonlinear gain polynomial

T_s: transformation matrix from angular velocity to Euler angle rates
\[ u \] input to a control system

\[ v \] error output of neurocomputing solver

\[ W(s) \] optimal algorithm transfer function matrix

\[ x \] system state vector

\[ y \] desired state space system output

\[ z \] excitatory input signal for neurocomputing system

\[ \alpha \] prescribed degree of nonlinearity for nonlinear algorithm

\[ \beta \] Euler angles \( \beta = [\phi \ \theta \ \psi]^T \)

\[ \delta \] pilot control input vector

\[ \mu \] learning parameter for neurocomputing solver

\[ \omega \] angular velocity about the body frame \( \omega = [p \ q \ r]^T \)

**Subscripts**

Subscripts indicate to what the main symbol is related

\( (.)_A \) aircraft

\( (.)_d \) simulator states included in the cost function

\( (.)_I \) inertial reference frame

\( (.)_j \) j-th actuator of the motion platform

\( (.)_S \) simulator

\( (.)_{SR} \) simulator rotation

\( (.)_{ST} \) simulator tilt coordination channel

\( (.)_{STL} \) simulator tilt coordination channel with limit

\( (.)_{x,y,z} \) 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
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1. Introduction

The flowchart for the new Langley Research Center Visual Motion Simulator (VMS) drive software is shown in Figure 2.1. Originally, three motion cueing algorithms were available: a modified version of the standard NASA adaptive algorithm (WCNTRL2), the optimal algorithm (WASHOPT3) and the nonlinear algorithm (NEWOPT4) discussed by Telban and Cardullo [1]. The modified adaptive algorithm is not operational. A one-time initialization of the cueing algorithm parameters and initial states is accomplished with a FORTRAN call to the subroutines WINIT2 and WINIT4. WINIT2 initializes variables exclusive to the adaptive and optimal algorithms, and variables common to both the optimal and nonlinear algorithms. WINIT4 initializes variables exclusive to the nonlinear algorithm, with symmetric matrices generated from initial vectors that contain the upper triangular elements.

The real time program sends a flag to the motion cueing algorithm that indicates the current “mode” of the simulation, i.e. “RESET”, “HOLD”, or “OPERATE”. When the simulation is in the RESET mode, the motion base is driven slowly (in about 15 seconds) to its neutral position. During the HOLD mode, the motion base is driven slowly from the neutral position to the required trim orientation. In the OPERATE mode, the motion cueing algorithm uses the aircraft states to drive the motion base in real time.

The motion cueing algorithm produces the desired simulator displacement and attitude commands. These commands serve as input to the subroutine JACKDRV, which performs a kinematic transformation to compute six actuator extensions and also activates a braking algorithm in the event any of the actuators reaches its extension limit.
The subroutine INVPLF performs an inverse kinematic transformation [2] to obtain the platform positions and attitudes from the computed leg extensions.

The executive cueing algorithm subroutines WASHOPT3 and NEWOPT4 also incorporate special cueing effects. The augmented turbulence cue for the vertical mode developed by Telban and Cardullo [1] is implemented in each subroutine. In order to increase the sensation of the touchdown and ground effects, an approach proposed by Parrish and Martin [3] was implemented in each subroutine. This approach uses increased nonlinear gains for the vertical mode that are instantaneously activated upon touchdown, and runway roughness amplitude that is gradually added to the simulator z-axis displacement after touchdown.

Table 1.1 provides a list of all the FORTRAN subroutines and common blocks used in the new software. The subroutines and common blocks used exclusively with the optimal algorithm are noted with an asterisk. All of the files have the extension .f unless otherwise noted. Listings of the variables for each common block used in the programs are given in Section 7.

Table 1.1. FORTRAN Files for New Drive Software.

<table>
<thead>
<tr>
<th>gainopt3*</th>
<th>liba</th>
<th>ofil3*</th>
<th>winit2*</th>
<th>comint2.com</th>
</tr>
</thead>
<tbody>
<tr>
<td>gainopt4</td>
<td>newopt4</td>
<td>resectc2</td>
<td>winit4</td>
<td>matrix1c.com</td>
</tr>
<tr>
<td>integ3*</td>
<td>nfilr</td>
<td>simq</td>
<td>wtrim3</td>
<td>nopt4.com</td>
</tr>
<tr>
<td>integ4</td>
<td>nfilx</td>
<td>state4</td>
<td></td>
<td>optint3.com*</td>
</tr>
<tr>
<td>invplf</td>
<td>nfily</td>
<td>vmult</td>
<td></td>
<td>wopt3.com</td>
</tr>
<tr>
<td>jackdrvr</td>
<td>nfilz</td>
<td></td>
<td>washopt3*</td>
<td></td>
</tr>
</tbody>
</table>
Table 1.2 provides a list of the aircraft model inputs required for the motion cueing algorithms. Given are the cueing algorithm FORTRAN variables.

**Table 1.2. Motion Cueing Algorithm Inputs.**

<table>
<thead>
<tr>
<th></th>
<th>Optimal (IWASH=2)</th>
<th>Nonlinear (IWASH=3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Accel. at Motion Base Centroid</td>
<td>ACA(3)</td>
<td>ACA(3)</td>
</tr>
<tr>
<td>Aircraft Angular Velocity</td>
<td>WAA(3)</td>
<td>WAA(3)</td>
</tr>
<tr>
<td>Aircraft Euler Angles</td>
<td>BETAA(3)</td>
<td>BETAA(3)</td>
</tr>
<tr>
<td>Time Step Size</td>
<td>DT</td>
<td>DT</td>
</tr>
<tr>
<td>In-Air/On-Ground Flag</td>
<td>SQWASHI</td>
<td>SQWASHI</td>
</tr>
<tr>
<td>Aircraft Ground Speed</td>
<td>VGSPD</td>
<td>VGSPD</td>
</tr>
<tr>
<td>Vertical Gust</td>
<td>WGUST</td>
<td>WGUST</td>
</tr>
</tbody>
</table>
One Time Initialization of Cueing Algorithm Constants

Simulated Aircraft Dynamics

Simulated Aircraft Math Model Dynamics

Adaptive

Cueing Algorithm

Optimal

Motion Cueing Algorithm Produces the Desired Platform Displacements and Attitudes

Kinematic Transformation to Compute Leg Extensions and Activate Braking Algorithm if Extension Limits are Reached

Inverse Kinematic Transformation to Obtain the Platform Positions and Attitudes from the Computed Leg Extensions

Figure 1.1. Langley Visual Motion Simulator (VMS) Drive Software Flow Chart.
2. Background Information

2.1. NASA Langley Visual Motion Simulator (VMS)

The NASA Langley Visual Motion Simulator (VMS), shown in Figure 2.1, is a general-purpose flight simulator consisting of a two-crewmember cockpit mounted on a 60-inch stroke six-degree-of-freedom synergistic motion base [4], [5].

![NASA Langley Visual Motion Simulator (VMS)](image)

Figure 2.1. NASA Langley Visual Motion Simulator (VMS). NASA Langley Research Center, Hampton, Virginia.

Motion cues are provided in the simulator by the extension or retraction of the six hydraulic actuators of the motion base relative to the simulator neutral position. The NASA adaptive algorithm and the new optimal and nonlinear algorithms were used to drive the motion base during the tuning of the new algorithms and the piloted test evaluation.

The cockpit of the VMS, shown in Figure 2.2, is designed to accommodate a generic transport aircraft configuration on the left side and a generic fighter or rotorcraft configuration on the right side. Both sides of the cockpit are outfitted with three heads-down CRT displays (primary flight display, navigation/map display, and engine display), a number of small standard electromechanical circular instruments and a landing gear handle mounted in the instrument panel. The left side contains a two-axis side stick
control loader, and the right side contains a control loaded two-axis center stick. Both sides contain control loaded rudder systems. The center aisle stand is outfitted with a control display unit, a four-lever throttle quadrant, a flap handle, a speed brake handle, and a slats handle. The cockpit is outfitted with four collimated window display systems to provide an out-the-window visual scene. During the piloted evaluations, the test subject flew from the left seat of the cockpit, while an observer/test conductor rode in the right seat.

Figure 2.2. Visual Motion Simulator Cockpit. NASA Langley Research Center, Hampton, Virginia.

The simulator includes a high fidelity, highly nonlinear mathematical model of a Boeing 757-200 aircraft, complete with landing gear dynamics, gust and wind models, flight management systems, and flight control computer systems. For this study, the test subjects flew the simulated aircraft in the manual control mode (without the autopilot), and with manual throttle control (without the autothrottle).

The out-the-window visual scene is driven by an Evans and Sutherland ESIG 3000/GT computer generated image system. The visual database represented the Dallas/Fort Worth airport and its surrounding terrain. The study utilized runways 18L and 18R for approach maneuvers and runway 18R for takeoff maneuvers. The runways
were equipped with approach lights, precision approach path indicator lights, runway markings, and signage. The database included all runways and taxiways, and all airport structures and buildings. All tests were conducted in a daylight environment with full visibility.

2.2. Reference Frames

A series of reference frames are used in the definition of the motion cueing algorithms. These reference frames are defined below and are shown in Figure 2.3.

2.2.1. Aircraft Center of Gravity

The aircraft center of gravity reference frame Fr\(_{CG}\) has its origin at the center of gravity of the aircraft. Frame Fr\(_{CG}\) has an orientation for X\(_{CG}\), Y\(_{CG}\), and Z\(_{CG}\) that is parallel to reference frames Fr\(_S\) and Fr\(_A\).

2.2.2. Simulator

The simulator reference frame Fr\(_S\) has its origin at the centroid of the simulator payload platform, i.e. the centroid of the upper bearing attachment points. The origin is fixed with respect to the simulator payload platform. X\(_S\) points forward and Z\(_S\) points downward with respect to the simulator cockpit, and Y\(_S\) points toward the pilot's right hand side. The x-y plane is parallel to the floor of the cockpit.

2.2.3. Aircraft

The aircraft reference frame Fr\(_A\) has its origin at the same relative cockpit location as the simulator reference frame Fr\(_S\). Fr\(_A\) has the same orientation for X\(_A\), Y\(_A\), and Z\(_A\) with respect to the cockpit as the simulator frame Fr\(_S\).
2.2.4. Inertial

The inertial reference frame $F_{rI}$ is earth-fixed with $Z_i$ aligned with the gravity vector $g$. Its origin is located at the center of the fixed platform motion base. $X_i$ points forward and $Y_i$ points to the right hand side with respect to the simulator pilot.

2.2.5. Reference Frame Locations

In Figure 2.3 are four vectors that define the relative location of the reference frames. $R_i$ defines the location of $F_{rS}$ with respect to $F_{rI}$. $R_s$ defines the location of $F_{rPS}$ with respect to $F_{rS}$. Similarly, $R_A$ defines the location of $F_{rPA}$ with respect to $F_{rA}$, where $R_A = R_S$. $R_{CG}$ defines the location of $F_{rA}$ with respect to $F_{rCG}$.

Figure 2.3. Reference Frame Locations. Adapted from Wu [6].
2.3. Coordinate Transformations

The orientation between the body-fixed simulator reference frame Frs and the inertial reference frame FrI can be specified by three Euler angles: \( \mathbf{\beta} = [\phi \ \theta \ \psi]^T \) that define a sequence of rotations that carry Frs into FrI. A vector \( \mathbf{V} \) expressed in the two frames can be related by the transformation matrix \( \mathbf{L}_{IS} \) (FrI to Frs) or \( \mathbf{L}_{SI} \) (FrS to FrI), with

\[
\mathbf{V}^S = \mathbf{L}_{IS} \mathbf{V}^I \quad \text{and} \quad \mathbf{V}^I = \mathbf{L}_{SI} \mathbf{V}^S,
\]

where \( \mathbf{L}_{IS} = \mathbf{L}_{SI}^T \), and

\[
\mathbf{L}_{SI} = \begin{bmatrix}
\cos \theta \cos \psi & \sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi & \cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi \\
\cos \theta \sin \psi & \sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi & \cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi \\
-\sin \theta & \sin \phi \cos \theta & \cos \phi \cos \theta
\end{bmatrix}.
\] (2.1)

The angular velocity of Frs with respect to FrI can be related to the Euler angle rates \( \dot{\mathbf{\beta}} \) by the following expression. Let \( \mathbf{\omega}_A^\Lambda \) represent the components of this angular velocity in frame Frs, then \( \dot{\mathbf{\beta}} = \mathbf{T}_s \mathbf{\omega}_A^\Lambda \), where

\[
\mathbf{T}_s = \begin{bmatrix}
1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\
0 & \cos \phi & -\sin \phi \\
0 & \sin \phi \sec \theta & \cos \phi \sec \theta
\end{bmatrix}.
\] (2.2)

Note that in this example, the body-fixed aircraft reference frame FrA can replace the body-fixed simulator reference frame Frs.

The subroutine LIBA computes the coordinate transformations of Eqs. (2.1) and (2.2) as shown in the flowchart given in Figure 2.4.
2.4. Nonlinear Input Scaling

Limiting and scaling are applied to both aircraft translational input signals $\mathbf{a}_A^A$ and rotational input signals $\mathbf{\omega}_A^A$. Limiting and scaling modify the amplitude of the input uniformly across all frequencies. Limiting is a nonlinear process that clips the signal so that it is limited to be less than a given magnitude. Limiting and scaling can be used to reduce the motion response of a flight simulator. A third-order polynomial scaling was developed [6] and has been implemented in the new simulator motion cueing algorithms.

When the magnitude of the input to the simulator motion system is small, the gain is desired to be relatively high, or the output will be below the pilot’s perception threshold. When the magnitude of input is high, the gain is desired to be relatively low or
the simulator may attempt to go beyond the hardware limits. Let us define the input as \( x \) and the output as \( y \). Now define \( x_{\text{max}} \) as the expected maximum input and \( y_{\text{max}} \) as the maximum output, and \( s_0 \) and \( s_1 \) as the slopes at \( x = 0 \) and \( x = x_{\text{max}} \) respectively. Four desired characteristics for the nonlinear scaling are expressed as:

\[
\begin{align*}
(1) & \quad x = 0 \Rightarrow y = 0, \\
(2) & \quad x = x_{\text{max}} \Rightarrow y = y_{\text{max}}, \\
(3) & \quad y'_{x=0} = s_0, \\
(4) & \quad y'_{x=x_{\text{max}}} = s_1,
\end{align*}
\]

A third-order polynomial is then employed to provide functions with all the desired characteristics. This polynomial will be of the form

\[
y = c_3 x^3 + c_2 x^2 + c_1 x + c_0
\]

where

\[
\begin{align*}
c_0 &= 0, \\
c_1 &= s_0, \\
c_2 &= x_{\text{max}}^{-2} \left( 3 y_{\text{max}} - 2 s_0 x_{\text{max}} - s_1 x_{\text{max}} \right), \\
c_3 &= x_{\text{max}}^{-3} \left( s_0 x_{\text{max}}^2 - 2 y_{\text{max}} + s_1 x_{\text{max}} \right).
\end{align*}
\]

One example of this polynomial gain is shown in Figure 2.5, with parameters set as \( x_{\text{max}} = 10, \ y_{\text{max}} = 6, \ s_0 = 1.0, \ s_1 = 0.1 \).

The subroutine GAINOPT3 is used to compute the polynomial scaling coefficients for each aircraft degree-of-freedom input for the optimal algorithm. The flowchart for GAINOPT3 is given in Figure 2.6. The subroutine GAINOPT4 computes the coefficients for the nonlinear algorithm, and follows the same variable flow as shown in Figure 2.6. Each subroutine contains scaling coefficients specific to either the optimal algorithm (GAINOPT3) or the nonlinear algorithm (GAINOPT4).
Figure 2.5. Nonlinear Input Scaling.

Figure 2.6. GAINOPT3/GAINOPT4 Subroutine Flowchart.
2.5. Actuator Geometry

The geometry of a six-degree-of-freedom synergistic motion system is given in Figure 2.7. The relevant vectors relating the locations of the upper and lower bearings of the j-th actuator are shown below in Figure 2.8.

![Figure 2.7. Geometry of a Six-Degree-of-Freedom Motion System. Adapted from Wu (1997).](image-url)
In Figure 2.8, $O_S$ and $O_I$ are the centroids of the motion platform and fixed platform respectively, and are also respectively the origins for $Fr_S$ and $Fr_I$. It can be seen that the relation among those vectors is

$$R_I + A_I^j = R_j = B_I^j + l_j. \tag{2.4}$$

The actuator length vector can then be found from

$$l_j = A_I^j + R_I - B_I^j. \tag{2.5}$$

The expression of $l_j$ in the inertial reference frame $Fr_I$ is desired:

$$l_I^j = A_I^j + R_I - B_I^j = L_{RS} A_S^j + R_I - B_I^j, \tag{2.6}$$

where $A_S^j$ are the coordinates of the upper bearing attachment point of the j-th actuator in $Fr_S$ and $B_I^j$ are the coordinates of the lower bearing attachment point of the j-th actuator in $Fr_I$. The actuator extension is computed from a neutral platform position, where $R_I = 0$, therefore

$$\Delta l_I^j = L_{RS} A_S^j + \Delta R_I. \tag{2.7}$$
The subroutine JACKDRVR is used to compute the actuator extension lengths that are derived from the motion platform displacements and attitudes in Eq. (2.7). The flowchart for JACKDRVR is given in Figure 2.9. The variable inputs and outputs for the subroutine INVPLF are also shown in Figure 2.9. The actuator extension limiting performed within JACKDRVR is discussed in Section 6 and Appendix A.

![Flowchart](image)

**Figure 2.9.** JACKDRVR/INVPLF Subroutine Flowchart.
2.6. Augmented Turbulence Cue

Reid and Robinson [7] first addressed the problem of producing acceptable motion cues to turbulence inputs. They noted that heave is the most critical cue in representing turbulence, but is also the most restricted cue when constraining motion within the platform geometry. To overcome this limitation, they developed an approach in which a second set of aircraft equations of motion driven only by the turbulence inputs is employed. The output from this augmented channel is then added to the output from the primary equations of motion, being driven by both turbulence and the pilot control inputs, before serving as input to the motion system. A similar approach to that developed by Reid and Robinson [7] has been implemented and is shown in Figure 2.10.

![Figure 2.10. Optimal Algorithm Vertical Mode with Augmented Turbulence Channel.](image)

The input to the augmented channel is the z-axis component $w_G$ of the turbulence vector $G$. Reid and Robinson showed that $w_G$ is the dominant turbulence component needed in producing vertical acceleration due to turbulence. The secondary flight equations can then be represented by a transfer function $H_G(s)$. The secondary acceleration $a^I_G$ is then scaled with a constant gain $K_G$. Both the primary and secondary signals are then combined before input to the vertical motion cueing filter $W_{22}$.
From a simulated Being 757-200 aircraft test run, a system identification of aircraft vertical accelerations in response to turbulence was performed. The transfer function $H_d(s)$ was then created not only to represent the acceleration, but also incorporate some desired motion cueing characteristics, i.e., attenuated low-frequency content and increased high-frequency content. The following second-order transfer function was obtained for $H_d(s)$:

$$
H_G(s) = 0.1 \frac{(2.4s + 1)(2.4s + 1)}{(0.4s + 1)(0.1s + 1)}.
$$

For the optimal algorithm, a gain of $K_G$ equal to 0.8 was chosen to maximize the desired sensation of turbulence while sustaining the actuator extensions within the motion limits. A similar implementation to that shown in Figure 2.10 was applied for the nonlinear algorithm. In this approach, the linear cueing filter $W_{22}$ was replaced with the nonlinear heave filter, with the gain $K_G$ set equal to 1.2.

The transfer function given in Eq. (2.8) was implemented in state space form for the optimal and nonlinear algorithms in the subroutines WASHOPT3 and NEWOPT4 respectively. The transfer function coefficients and gain terms for each algorithm are initialized in the subroutines WINIT2 and WINIT4 respectively.

### 2.7. Trim Algorithm

Martin [8] reported that before going from the RESET mode to the OPERATE mode, several seconds are needed in the HOLD mode to produce pitch and roll angles that balance out any steady state longitudinal or lateral accelerations that may occur at time zero. In the subroutine WTRIM3 shown in Figure 2.11, a first-order washout filter is used to allow a smooth transition from the platform neutral state to the desired pitch angle:
\[ \frac{\dot{\theta}(s)}{a_1(s)} = \frac{b_1 s}{s + a_0}. \]  

(2.9)

Both \( b_1 \) and \( a_0 \) are chosen to produce the desired transition rate and attitude. As noted in Figure 2.11, Eq. (2.9) is integrated to produce the pitch attitude. Similar computations are performed to obtain the roll velocity \( \dot{\phi} \), which is then integrated to produce the desired roll angle.

![Figure 2.11. WTRIM3 Subroutine Flowchart.](image-url)
3. Optimal Motion Cueing Algorithm

3.1. Algorithm Description

The theory and development of the optimal algorithm is well discussed by Telban and Cardullo [1]. The problem is to determine a transfer function matrix $W(s)$ that relates the desired simulator motion input to the aircraft input such that a cost function constraining the pilot sensation error (between simulator and aircraft) is minimized. A mathematical model of the human vestibular system [1] is used in the filter development. The optimal algorithm uses an off-line program [1] to generate the desired transfer functions $W(s)$ which are then implemented on-line. $W(s)$ will relate the simulator commands to the aircraft states by $u_s = W(s) \times u_A$. The block diagram for the on-line algorithm implementation is shown in Figure 3.1. Similar to the NASA adaptive algorithm [8], there are separate filtering channels for the translational and rotational degrees of freedom with the cross-feed path providing the tilt coordination cues.
The aircraft acceleration input vector is first transformed from the simulator body frame $F_{rS}$ to the inertial frame $F_{rI}$ as shown in Eq. (2.1). Nonlinear scaling in combination with limiting as described in Section 2.4 is then applied to the aircraft inputs. The scaled inertial acceleration $a^I_A$ is then filtered through the translational filter $W_{22}$ to produce a simulator translational acceleration command $\dot{S}_1$. This acceleration is integrated twice to produce the simulator translational position command $S_1$.

The aircraft angular velocity input $\omega^A_A$ is transformed to the Euler angular rate vector $\dot{\beta}_A$ as shown in Eq. (2.2), and is limited and scaled similar to the translational channel. This input is then passed through the rotational filter $W_{11}$ to produce the vector $\dot{\beta}_{sr}$. The tilt coordination rate $\dot{\beta}_{st}$ is formed from the acceleration $a^I_A$ being passed through the tilt coordination filter $W_{12}$. The summation of $\dot{\beta}_{st}$ and $\dot{\beta}_{sr}$ yields $\dot{\beta}_S$, which is then integrated to generate $\beta_S$, the simulator angular position command.

The simulator translational position $S^I$ and the angular position $\beta_S$ are then used to transform the simulator motion from degree-of-freedom space to actuator space as given in Eq. (2.7), generating the actuator commands required to achieve the desired platform motion.

The motion cueing filter $W(s)$ is represented by a Laplace transform transfer function:

$$W(s) = \frac{b_n s^n + b_{n-1} s^{n-1} + \cdots + b_1 s + b_0}{s^n + a_{n-1} s^{n-1} + \cdots + a_1 s + a_0}.$$ (3.1)

For numerical computation, Eq. (3.1) is realized in state space by the observable canonical form [9]:

---

20
\[ \dot{x}(t) = Ax(t) + Bu(t), \]  

(3.2)

where the matrices \( A \) and \( B \) are

\[
A = \begin{bmatrix}
-a_{n-1} & 1 & 0 & \cdots & 0 \\
-a_{n-2} & 0 & 1 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
-a_i & 0 & 0 & \cdots & 1 \\
-a_0 & 0 & 0 & \cdots & 0
\end{bmatrix}, \quad B = \begin{bmatrix}
b_{n-1} - a_{n-1} b_n \\
b_{n-2} - a_{n-2} b_n \\
\vdots \\
b_1 - a_1 b_n \\
b_0 - a_0 b_n
\end{bmatrix},
\]

and \( y(t) = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \end{bmatrix} x(t) + b_n u(t). \)

The state equations of Eq. (3.2) are integrated with a 2nd-order Runge-Kutta method [10]. This ensures stable responses for sample rates of at least 32 Hz.

3.2. Program Implementation

The flowchart for the optimal algorithm subroutine WASHOPT3 is shown in Figure 3.2. The subroutine RESETC2 is similar to that described by Martin [8], providing a smooth return of the motion base to the neutral position in the reset mode. The subroutine WTRIM3 uses a set of first-order filters as shown in Section 2.7 to produce a smooth buildup of the motion platform pitch and roll tilt angles to the trim position based upon the aircraft trim states. The subroutine LIBA transforms the aircraft translational accelerations from the body to the inertial reference frame, and the aircraft angular velocities from the body to the Euler reference frame as discussed in Section 2.3 and shown in Figure 2.4. These transformed aircraft states then undergo a nonlinear scaling with the subroutine GAINOPT3 described in Section 2.4 and shown in Figure 2.6. The subroutine OFIL3 computes the responses to the linear filters for each mode. The subroutine INTEG4 then computes the desired simulator displacements and attitudes, taking the tilt coordination into account.
The flowchart for OFIL3 is given in Figure 3.3. Each filter is formulated in state space as shown in Eq. (3.2), and is integrated using the 2nd-order Runge-Kutta method. The outputs of OFIL3 are the desired motion cues that drive the simulator, i.e., three translational accelerations, three rotational angular velocities, and two tilt angular velocities that represent the tilt coordination cues.

The flowchart for INTEG3 is given in Figure 3.4. The simulator translational accelerations and angular velocities are first integrated to obtain the translational displacements and angular positions. The commanded pitch tilt position $\theta_{STL}$ is determined from both the “desired” tilt position $\theta_{ST}$ and the difference between the desired and commanded tilt positions:

$$
\Delta \theta_{STL} = 0.005 \left( \theta^{(i)}_{ST} - \theta^{(i-1)}_{STL} \right) + \left( \theta^{(i)}_{ST} - \theta^{(i-1)}_{ST} \right), \quad (3.3)
$$

Where the superscripts (i) and (i-1) refer to the current and prior time steps. The commanded tilt position $\theta_{STL}$ is then computed, taking into account the tilt velocity limit $\dot{\theta}_{\text{lim}} = 5 \text{ deg/sec}$ and the time step $\Delta t$:

$$
\theta^{(i)}_{STL} = \theta^{(i)}_{ST} + \max \left[ -\dot{\theta}_{\text{lim}} \Delta t, \min \left( \dot{\theta}_{\text{lim}} \Delta t, \Delta \theta_{STL} \right) \right], \quad (3.4)
$$

The difference between the desired and commanded tilt angles is then used to generate additional translational response and achieve coordination between the translational and tilt channels:

$$
x_{\text{com}} = x_{\text{der}} - R_{Sc} \left( \theta_{ST} - \theta_{STL} \right), \quad (3.5)
$$

where $R_{Sc}$ is the radius from the motion platform centroid to the pilot’s head. Similar computations are performed to obtain the commanded roll tilt position $\phi_{STL}^{(i)}$ and the commanded displacement $y_{\text{com}}$. 

22
Program Initialization and Smooth Return of Motion Base to Neutral Position

Smooth Transition to Trim Angles

Body to Inertial and Body to Euler Transformations

Nonlinear Scaling of Linear Acceleration and Angular Velocity Inputs

Optimal Motion Cueing Filters: Longitudinal, Lateral, Vertical, Yaw

Integration to Obtain Positions and Attitudes

Figure 3.2. Optimal Algorithm Flowchart.
Prior Inputs and States → Lateral Filter $W_{11}$ → Lateral Filter $W_{12}$ → Lateral Filter $W_{22}$ → Longitudinal Filter $W_{11}$ → Longitudinal Filter $W_{12}$ → Longitudinal Filter $W_{22}$ → Yaw Filter $W_{11}$ → Vertical Filter $W_{22}$ → Obtain the Simulator Translational Accelerations, Tilt and Rotational Velocities → BSDT, BSDR, ASI → Update the Prior Inputs and States → A2NO, BADNO, XX1O, X2O, X3O, X4O, X5O, X6O

Figure 3.3. OFIL3 Subroutine Flowchart.
Figure 3.4. INTEG3 Subroutine Flowchart.
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4. Nonlinear Motion Cueing Algorithm

4.1. Algorithm Description

The theory and development of the nonlinear algorithm is well discussed by Telban and Cardullo [1]. The algorithm is formulated as a linear optimal control problem similar to the optimal algorithm, but is also updated in real time with a nonlinear control law. Furthermore, it incorporates models of the human vestibular sensation system along with an integrated visual-vestibular perception model [1]. The block diagram for the online implementation is shown in Figure 4.1. Similar to the optimal algorithm, there are separate filtering channels for the translational and rotational degrees of freedom with the cross-feed path providing the tilt coordination cues. Telban and Cardullo [1] reported that for the pitch and roll rotational channels, no benefit resulted from updating the Riccati equation in real time; thus the nonlinear filters are replaced with unity-gain filters.

![Nonlinear Algorithm Implementation with Unity-Gain Pitch Filter.](image)

Figure 4.1. Nonlinear Algorithm Implementation with Unity-Gain Pitch Filter.

A nonlinear control law is implemented to generate a scalar coefficient $\alpha$ that is a function of the simulator motion system states:
\[ \alpha = x_d^T Q_2 x_d, \quad \text{(4.1)} \]

where \( Q_2 \) is a weighting matrix that is at least positive semi-definite. As the computed system states increase in magnitude, i.e., with large commanded platform displacements and velocities, then \( \alpha \) increases, resulting in faster control action to quickly wash out the platform to its neutral state. For small commands there will be limited control action, resulting in motion cues sustained for longer durations.

The solution of the algebraic Riccati equation is given as [1]

\[ (A' + \alpha I)^T P(\alpha) + P(\alpha)(A' + \alpha I) - P(\alpha)BR_2^TBR_1P(\alpha) + R'_1 = 0, \quad \text{(4.2)} \]

where \( A' \) and \( B \) are system matrices and \( R'_1 \) and \( R_2 \) are the standard optimal control weighting matrices defined by Telban and Cardullo [1] in the algorithm development. The system matrix \( A' \) is augmented with \( \alpha \) times the identity matrix \( I \). The solution of Eq. (4.2) from the linear optimal algorithm that was computed off-line in MATLAB is used as the initial solution for the first time step. The Riccati equation of Eq. (4.2) is then updated in real time with a structured neural network developed by Ham and Collins [11] that is shown in Figure 4.2.
Figure 4.2. Structured Neural Network for Solving the Riccati Equation.

The error signal $v(t)$ in Figure 4.2 is given as

$$v(t) = \left[ P(t)SP(t) - A'^T(t)P(t) - P(t)A' - R' \right] z(t),$$

where $A' = A + \alpha I$ and $S = B^T R_2 B$. The external excitatory vector input signals $z(t)$ are a set of linearly independent bi-polar vectors given as

$$z^{(1)} = [1 \ -1 \ \cdots \ -1], \ z^{(2)} = [-1 \ 1 \ \cdots \ -1], \ z^{(n)} = [-1 \ -1 \ \cdots \ 1],$$

where each vector $z^{(k)}$ is presented once to the neural network in an iteration, i.e., for one iteration there are a total of $n$ presentations of the training step given in Eq. (4.4), with the solution $P(k)$ updated with each training step. The update term $\Delta P(k)$ is given as

$$\Delta P(k) = \left[ A'_a(k) v(k) z(k) + v(k) z^T(k) A'_a(k) - v(k) p^T(k) S \right],$$

where $p(t) = P(t) z(t)$ as shown in Figure 4.2. The updated Riccati equation solution $P(k+1)$ is then computed:

$$P(k+1) = P(k) + \mu \Delta P(k),$$

where $\mu > 0$ is the learning rate parameter.
The feedback matrix $K(\alpha)$ is partitioned corresponding to the partition of the state vector $x$ [1]:

$$u_x = -\begin{bmatrix} K_1(\alpha) & K_2(\alpha) \end{bmatrix} \begin{bmatrix} x_e \\ x_d \end{bmatrix} - K_3(\alpha) u_A,$$  \hspace{1cm} (4.7)

and the Riccati equation solution $P(\alpha)$ can be partitioned as

$$P(\alpha) = \begin{bmatrix} P_{11}(\alpha) & P_{12}(\alpha) & P_{13}(\alpha) \\ P_{21}(\alpha) & P_{22}(\alpha) & P_{23}(\alpha) \\ P_{31}(\alpha) & P_{32}(\alpha) & P_{33}(\alpha) \end{bmatrix},$$  \hspace{1cm} (4.8)

where the partitions correspond to the partitions of the system matrix $A$.

The partitioned feedback matrix is then given as

$$K_1(\alpha) = R_2^d \left[ B^T_v P_{11} + B^T_d P_{21} + D^T_v QC_v \right]$$
$$K_2(\alpha) = R_2^d \left[ B^T_v P_{12} + B^T_d P_{22} \right]$$
$$K_3(\alpha) = R_2^d \left[ B^T_v P_{13} + B^T_d P_{23} - D^T_v QC_v \right],$$  \hspace{1cm} (4.9)

where the matrices $B_v$, $B_d$, and $D_v QC_v$ are defined by Telban and Cardullo [1], and by symmetry, $P_{12} = P_{21}^T$. The resulting state equations are then computed in real time:

$$\begin{bmatrix} \dot{x}_e \\ \dot{x}_d \end{bmatrix} = \begin{bmatrix} A_v - B_v K_1(\alpha) & -B_v K_2(\alpha) \\ -B_d K_1(\alpha) & A_d - B_d K_2(\alpha) \end{bmatrix} \begin{bmatrix} x_e \\ x_d \end{bmatrix} + \begin{bmatrix} -B_v (I + K_3(\alpha)) \\ -B_d K_3(\alpha) \end{bmatrix} u_A,$$  \hspace{1cm} (4.10)

with the matrices $A_v$ and $A_d$ defined by Telban and Cardullo [1]. These state equations are then integrated with a 2nd-order Runge-Kutta method [10].

4.2. Program Implementation

The nonlinear algorithm was developed to achieve the desired motion cues at an update rate of 60 Hz. Since the computer image generator, which provides the out-the-window visual imagery to the simulator pilot, also runs at 60 Hz, the motion cues would
be synchronous with the visual cues. However, because of the computer operating system, the real time operating system and the I/O system on the Langley real time computing system, the minimum interval must be an integer multiple of 125 \( \mu \text{sec} \) and a power of 2. Therefore, a time step of 16 msec or an update rate of 62.5 Hz was selected for the real time implementation and the pilot tests.

The flowchart for the nonlinear algorithm subroutine NEWOPT4 is shown in Figure 4.3. The RESET/HOLD modes and transformation subroutines are identical to the optimal algorithm discussed in the preceding section. The transformed aircraft states then undergo a nonlinear scaling with the subroutine GAINOPT4.

The subroutine NFILX accomplishes the task of solving the Riccati equation in real time for the longitudinal mode. Similarly, NFILY, NFILZ, and NFILR compute the Riccati equation solutions for the lateral, vertical, and yaw mode respectively. The feedback matrices and updated motion states for each mode are then computed in the subroutine STATE4. The subroutine INTEG4 computes the desired simulator displacements and attitudes, taking into account the tilt coordination limits. Note that STATE4 is computed four times when in the HOLD mode; this was done to produce faster convergence to the neutral state while eliminating discontinuities when transitioning from the HOLD to the OPERATE mode.

The flowchart for NFILX is given in Figure 4.4. The coefficient \( \alpha \) is computed from the simulator motion states given in Eq. (4.1). For each training step, the corresponding input vector \( z \) given in Eq. (4.4) is referenced. The update term \( \Delta P \) given in Eq. (4.5) and its matrix transpose \( \Delta P^T \) are then computed and used to update the Riccati equation solution \( P(k+1) \) given in Eq. (4.6). The flowcharts for NFILY,
NFILZ, and NFILR are given in Figure 4.5, Figure 4.6, and Figure 4.7 respectively. The variable flow for each subroutine is identical to that shown for NFILX in Figure 4.4. Note that each subroutine uses the motion states specific to its mode for computing the coefficient \( \alpha \), with the system variables defined for each mode ending with the same letter as the subroutine name.

During implementation on the NASA Langley real time system, it was discovered that for a time step of 16 msec, the real time requirement for the nonlinear algorithm was not being met. The baseline software for the nonlinear algorithm, with all presentations of the excitatory vector \( \mathbf{z}(t) \) given for each mode given in Eq. (4.4), i.e., \( n \) presentations for an \( n^{th} \) order system, resulted in an average CPU time of 34 msec. This CPU time also includes the contributions of the aircraft model and control loader. In the subroutines NFILX, NFILY, NFILZ, and NFILR, matrix operations were optimized by taking advantage of the matrices \( \mathbf{A}' \) and \( \mathbf{S} \) being sparse, i.e., eliminating computations involving matrix elements of zero. In addition, the symmetry of the Riccati solution \( \mathbf{P} \) and other matrices computed in the subroutines were also exploited to reduce computation. Optimizing matrix operations resulted in an average CPU time of 24 msec. Reducing the number of presentations of the vector \( \mathbf{z}(t) \) for each mode to the first three vectors produced a CPU time of 12 msec, which meets the real time requirement. Telban and Cardullo [1] reported that this change resulted in imperceptible degradation of the motion cues.

The flowchart for STATE4 is given in Figure 4.8. The variable flow for computing the longitudinal mode simulator states is shown in detail. The partitions of the feedback matrix are computed as given in Eq. (4.9). The state equations are then updated
as given in Eq. (4.10) and integrated with a 2\textsuperscript{nd}-order Runge-Kutta method, resulting in the updated simulator motion states. The computation of the lateral, vertical, and yaw states follows the same variable flow as the longitudinal states, with the system variable names corresponding to the respective mode.

The flowchart for INTEG4 is given in Figure 4.9. The simulator translational accelerations, rotational angular velocities, and tilt angular velocities are computed as given in Eq. (4.7). The remaining computations are identical to those performed in the subroutine INTEG3 for the optimal algorithm as shown in Figure 3.4, and discussed in Section 3.2.
Figure 4.3. Nonlinear Algorithm Flowchart.
\[ \alpha = x^T Q x \]
\[ A' = A' + \alpha I \]

\[ \Delta P = A' v z^T + v z^T A' - v p^T S \]
\[ \Delta P^T \]

\[ P(k+1) = P(k) + \frac{\mu}{2} \left[ \Delta P(k) + \Delta P^T(k) \right] \]

**Figure 4.4. NFILX Subroutine Flowchart.**
Compute Matrices \( \alpha = x^TQx \)
\[
A'' = A' + \alpha I
\]

APY, BRBY, R1PY

Matrices \( A''', S, R' \)

Compute Matrices \( SP \) and \( PA \)

\( p = Pz \)
\[
v = (PSP - A'P - PA' - R')z
\]

SPY, PAPY

Input Vector \( z \)

UY, PZY

Compute Matrices \( Avz, vzA, vPS \)

APY, UAPY, UPBY

\[
\Delta P = A''vz^\tau + vz^\tau A' - vz^\tau S
\]

\( \Delta P^\tau \)

SUMPY, SUMPYT

\[
P(k+1) = P(k) + \mu \left[ \Delta P(k) + \Delta P^\tau(k) \right]
\]

NO

Training Iteration L=3?

Figure 4.5. NFILY Subroutine Flowchart.
Input Vector $z$

Compute Matrices $SP$ and $PA$

$$p = P_z$$
$$v = (PSP - A'_1 P - PA' - R'_1)z$$

Compute Matrices $A_vz, vzA, vPS$

$$\Delta P = A'_v vz^T + vz^T A' - vz^T S$$

$$\Delta P^T$$

$$P(k+1) = P(k) + \mu \left[ \Delta P(k) + \Delta P^T(k) \right]$$

Training Iteration $L = 3$?

Figure 4.6. NFILZ Subroutine Flowchart.
\[ \alpha = x^T Q x \]
\[ A'_\alpha = A' + \alpha I \]

\[ p = P z \]
\[ v = (PSP - A'_\alpha P - PA' - R'_r)z \]

\[ \Delta P = A'_\alpha vz^T + vz^T A' - vp^T S \]
\[ \Delta P^T \]

\[ P(k+1) = P(k) + \frac{\mu}{2} [\Delta P(k) + \Delta P^T(k)] \]

**Figure 4.7.** NFILR Subroutine Flowchart.
Figure 4.8. STATE4 Subroutine Flowchart.
Figure 4.9. INTEG4 Subroutine Flowchart.
5. Nonlinear Algorithm Tuning

This section covers the procedures needed for tuning the nonlinear algorithm in order to produce the desired pilot performance. It is expected that the algorithm will require tuning with either a change of aircraft dynamics (the initial pilot tuning was done with the Boeing 757-200 aircraft model) or implementation on a new motion system such as the Cockpit Motion Facility (CMF).

The “off-line” development of the nonlinear algorithm mentioned in Section 4.1 and discussed in greater detail by Telban and Cardullo [1], resulted in a set of filters consisting of system matrices and an initial Riccati equation solution implemented for each mode. Each filter was optimized with single degree-of-freedom responses for synergistic six-degree-of-freedom motion systems similar to Figure 2.7. Except for special circumstances driven by suggested future research [1], these filters do not need to be re-synthesized. Only the nonlinear scaling coefficients for each degree-of-freedom, given in Eq. (2.3), will need to be adjusted to accommodate changes in aircraft dynamics or motion platform geometry.

It is expected that the optimal algorithm discussed in Section 3 will be used infrequently. However, in the event that future work with the optimal algorithm is desired, the same procedures described in this section for tuning the nonlinear algorithm gains can be applied.

5.1. Prior Tuning Experience

In order to determine the nonlinear scaling (gain) coefficients for each degree-of-freedom that resulted in the most desired pilot performance, a trained simulator pilot executed a series of pilot controlled maneuvers with the optimal algorithm on the Visual
Motion Simulator (VMS). A series of maneuvers were first executed with the coefficients determined prior to testing. Coefficients for each degree-of-freedom were then adjusted until the simulator pilot subjectively felt the desired perception and performance were reached, while ensuring that the simulator motion platform limits were not exceeded. The following maneuvers were executed for both algorithms:

- Straight Approach and Landing (with varying wind from head to tail)
- Offset Approach and Landing (with and without turbulence)
- Pitch, Roll, and Yaw Doublets
- Throttle Increase and Decrease
- Coordinated Turn
- Ground Maneuvers (taxiing, effect of aircraft brakes)
- Takeoff from Full Stop.

The optimal algorithm resulted in motion cues with which the simulator pilot commented he had more control and confidence in comparison to the NASA adaptive algorithm. For both pitch and roll doublets, a fast response was observed when changing directions. On takeoffs, the optimal algorithm was found to be easier to pitch up to the desired attitude and control the aircraft. A noticeably large side force was observed with the coordinated turn maneuver. By reducing the gains for the roll degree-of-freedom, this side force was reduced to a minimal sensation. The pitch gains were decreased to reduce the likelihood of entering the braking region or exceeding the actuator limits. Reducing the gains for both roll and pitch degrees-of-freedom still yielded acceptable motion cues.

The severe turbulence effects that were included with the offset approach and landing maneuver were hardly noticeable. An increase of the vertical gain coefficients resulted in increased cues, but still less than satisfactory. This increase in the vertical gains (coupled with an increase of the surge gains) resulted in forward surge cues that are more coordinated with the pitch cues, and a larger aft surge cue (initially, the aft cue was
noticeably smaller than the forward cue). The unsatisfactory turbulence cues resulted in the inclusion of the augmented motion cue driven by the vertical gust.

A second pilot tuning evaluation was later performed on the VMS with both the optimal and nonlinear algorithms, with augmented turbulence cues implemented for both algorithms. A series of maneuvers were first executed with the polynomial gain coefficients determined prior to testing. Coefficients for each degree-of-freedom were then adjusted until the simulator pilot subjectively felt the desired perception and performance were reached, while ensuring that the simulator motion platform limits were not exceeded. The following maneuvers were executed for both algorithms:

- Straight Approach and Landing (with varying wind from head to tail)
- Offset Approach and Landing (with and without turbulence)
- Takeoff from Full Stop (with and without engine failure)
- Ground Maneuvers (taxiing, effect of aircraft brakes).

No additional tuning was needed for either the straight-in or offset approach maneuvers. However, both algorithms showed a tendency to exceed the actuator limits of the motion system with the takeoff maneuver. Reducing the surge gains for the optimal algorithm and both the surge and pitch gains for the nonlinear algorithm resulted in platform motion within the actuator limits during the takeoff maneuvers. The augmented turbulence gain terms for the optimal and nonlinear algorithms discussed in Section 2.6 were adjusted to produce the desired turbulence cues.

Table 5.1 lists the resulting nonlinear gains by degree-of-freedom implemented for each algorithm. From Eq. (2.3), the coefficients $c_1$, $c_2$, and $c_3$ are given for each degree-of-freedom.
Table 5.1. Nonlinear Gain Coefficients for the Cueing Algorithms.

<table>
<thead>
<tr>
<th>Degree-of-Freedom</th>
<th>Optimal Algorithm</th>
<th>Nonlinear Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1</td>
<td>C2</td>
</tr>
<tr>
<td>Surge (X)</td>
<td>0.6</td>
<td>-0.055</td>
</tr>
<tr>
<td>Sway (Y)</td>
<td>0.5</td>
<td>-0.055</td>
</tr>
<tr>
<td>In-Air (Z)</td>
<td>0.6</td>
<td>-0.082</td>
</tr>
<tr>
<td>On-Ground (Z)</td>
<td>1.3</td>
<td>-0.0375</td>
</tr>
<tr>
<td>Roll (p)</td>
<td>0.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>Pitch (q)</td>
<td>0.4</td>
<td>-0.54</td>
</tr>
<tr>
<td>Yaw (r)</td>
<td>1.1</td>
<td>-1.46</td>
</tr>
</tbody>
</table>

5.2. Tuning Procedure

Nonlinear gain coefficients can be computed from Eq. (2.3) for each degree-of-freedom with the use of an Excel™ spreadsheet. Using this approach, a set of coefficients for each degree-of-freedom can be tested with piloted simulations, resulting in the desired nonlinear gains for the cueing algorithm. Table 5.2 provides five sets of coefficients computed for each in-air degree-of-freedom (excluding yaw) for the nonlinear algorithm, with an additional set of coefficients for the on-ground heave gain. The yaw coefficients are omitted since these gains remained unchanged with initial tuning of both algorithms.

Each degree-of-freedom consists of five sets of gain coefficients, which are labeled to identify both the degree-of-freedom and the coefficient set, e.g., the roll degree-of-freedom coefficient sets are labeled from NP1 to NP5. The nonlinear gain coefficients for the nonlinear algorithm are initialized in data statements in the subroutine WINIT4. These data statements can be edited as individual degree-of-freedom coefficient sets are updated during the tuning process.
Table 5.2. Nonlinear Gain Coefficient Pilot Test Spreadsheet.

<table>
<thead>
<tr>
<th>ROLL</th>
<th>S0</th>
<th>S1</th>
<th>XMAX</th>
<th>YMAX</th>
<th>GP4(1)</th>
<th>GP4(2)</th>
<th>GP4(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP1</td>
<td>0.26</td>
<td>0</td>
<td>1</td>
<td>0.1</td>
<td>0.26</td>
<td>-0.22</td>
<td>0.06</td>
</tr>
<tr>
<td>NP2</td>
<td>0.28</td>
<td>0</td>
<td>1</td>
<td>0.1</td>
<td>0.28</td>
<td>-0.26</td>
<td>0.08</td>
</tr>
<tr>
<td>NP3</td>
<td>0.3</td>
<td>0</td>
<td>1</td>
<td>0.1</td>
<td>0.3</td>
<td>-0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>NP4</td>
<td>0.32</td>
<td>0</td>
<td>1</td>
<td>0.1</td>
<td>0.32</td>
<td>-0.34</td>
<td>0.12</td>
</tr>
<tr>
<td>NP5</td>
<td>0.34</td>
<td>0</td>
<td>1</td>
<td>0.1</td>
<td>0.34</td>
<td>-0.38</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PITCH</th>
<th>S0</th>
<th>S1</th>
<th>XMAX</th>
<th>YMAX</th>
<th>GQ4(1)</th>
<th>GQ4(2)</th>
<th>GQ4(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NQ1</td>
<td>0.3</td>
<td>0.1</td>
<td>1</td>
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<th>GX4(2)</th>
<th>GX4(3)</th>
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<td>0</td>
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<th>XMAX</th>
<th>YMAX</th>
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<table>
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<th>XMAX</th>
<th>YMAX</th>
<th>GZ4S(1)</th>
<th>GZ4S(2)</th>
<th>GZ4S(3)</th>
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<td>20</td>
<td>1.6</td>
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<td>-0.0010</td>
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<tr>
<td>NL2</td>
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<td>20</td>
<td>1.8</td>
<td>-0.030</td>
<td>-0.0005</td>
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<tr>
<td>NL3</td>
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<td>20</td>
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<td>2</td>
<td>-0.050</td>
<td>0.0000</td>
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<tr>
<td>NL4</td>
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<td>2.2</td>
<td>-0.070</td>
<td>0.0005</td>
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<tr>
<td>NL5</td>
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<td>20</td>
<td>20</td>
<td>2.4</td>
<td>-0.090</td>
<td>0.0010</td>
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</table>
Prior to adjustment of individual degree-of-freedom gain coefficient sets, it is suggested that an experienced simulator pilot execute a series of maneuvers to determine the baseline pilot performance for the current gain set, noting deficiencies for each degree-of-freedom that may arise from specific maneuvers. From prior piloted tuning tests, the following maneuvers are recommended for large transport aircraft:

- Pitch Stick, Roll Stick, and Rudder Pedal Doublets
- Throttle Increase and Decrease
- Takeoff from Full Stop
- Straight Approach and Landing (with and without turbulence)
- Coordinated Turn
- Offset Approach and Landing
- Ground Maneuvers (taxiing, effect of aircraft brakes).

Table 5.3 lists the maneuvers, the degrees of freedom that require tuning for the maneuver, and the desired outcomes that result from the tuning. The maneuvers should be executed in the order listed in Table 5.3. Adjustment of gains for individual degrees of freedom should be done repeatedly for each maneuver. In general, individual degree-of-freedom gain coefficient sets should be adjusted until the desired motion cues and pilot performance result for each maneuver, while ensuring that the platform does not exceed the actuator extension limits. Following execution of the maneuvers with tuning of the degree-of-freedom nonlinear gain sets, the simulator pilot should repeat execution of all maneuvers, noting any final deficiencies in the motion cues and piloted performance that may persist. If necessary, additional fine tuning of any degree-of-freedom can then be performed.

The augmented turbulence gain $K_G$ given in Figure 2.10 can be increased or decreased to produce the desired turbulence cues within the capabilities of the motion platform. An adjustment of $K_G$ may also be sufficient with a change of the aircraft
dynamics; a large transport aircraft similar to a Boeing 757-200 should produce similar turbulence cues. The transfer function time constants given in Eq. (2.8) can also be adjusted to produce the desired motion cues for greater changes in aircraft dynamics. The lead time constants in the numerator can be increased to increase the magnitude of the low-frequency cues. Decreasing the time constants in the denominator will increase the magnitude of the high-frequency cues, but these terms should be large enough so that the transfer function can be integrated within the simulation time step.

Table 5.3. Maneuvers with Degree-of-Freedom Gains.

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Degree-of-Freedom</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>Pitch Stick Doublet</td>
<td>Pitch</td>
<td>Adjust gains to obtain desired cues</td>
</tr>
<tr>
<td>Roll Stick Doublet</td>
<td>Roll/Yaw</td>
<td>Adjust gains to obtain desired cues</td>
</tr>
<tr>
<td>Rudder Pedal Doublet</td>
<td>Roll/Yaw</td>
<td>Adjust gains to obtain desired cues</td>
</tr>
<tr>
<td>Throttle Increase/Decrease</td>
<td>Surge/Heave</td>
<td>Adjust gains to obtain desired cues</td>
</tr>
<tr>
<td>Takeoff</td>
<td>Pitch/Surge/Heave</td>
<td>Ease in control of takeoff to desired pitch attitude, forward surge cues should be coordinated with pitch cues, vertical cues noticeable, ensure pitch and heave gains do not exceed platform limits</td>
</tr>
<tr>
<td>Straight-In Approach</td>
<td>Pitch/Surge/Heave</td>
<td>Ease in control of approach, forward surge cues should be coordinated with pitch cues, vertical cues noticeable</td>
</tr>
<tr>
<td>Coordinated Turn</td>
<td>Roll/Sway/Yaw</td>
<td>Minimize side force by reducing roll and/or increasing sway cues, ensure roll and sway gains do not exceed platform limits</td>
</tr>
<tr>
<td>Offset Approach</td>
<td>Roll/Sway/Yaw</td>
<td>Ease in control of approach, forward surge cues should be coordinated with pitch cues, minimal side forces</td>
</tr>
<tr>
<td>Turbulence</td>
<td>Heave</td>
<td>Adjust augmented turbulence gains to obtain desired turbulence sensation</td>
</tr>
<tr>
<td>Landing Touchdown</td>
<td>On-Ground Heave</td>
<td>Increase on-ground heave gain to obtain desired touchdown sensation, ensure motion platform limits are not exceeded</td>
</tr>
<tr>
<td>Ground Maneuvers</td>
<td>On-Ground Heave</td>
<td>Increase on-ground heave gain to obtain desired ground motion sensation, ensure motion platform limits are not exceeded</td>
</tr>
</tbody>
</table>
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6. Suggested Future Implementation

Reducing the nonlinear gains for the optimal algorithm (surge) and the nonlinear algorithm (surge and pitch) was necessary so that the takeoff maneuver could be flown within the 60-inch actuator extension limits and low bandwidth (2-Hz) of the Langley Visual Motion Simulator (VMS). However, gain reductions contributed to degradation in pilot performance that was observed most frequently with the straight-in approach. These results were observed during piloted performance tests conducted with the optimal and nonlinear motion cueing algorithms [12]. Implementation of the optimal and nonlinear algorithms on a platform with increased actuator extensions would allow for increased gains, thus resulting in improved pilot performance. One such motion platform is located in the Cockpit Motion Facility (CMF) [13], shown in Figure 6.1, presently being erected at the NASA Langley Research Center.

Figure 6.1. NASA Langley Cockpit Motion Facility (CMF).
The Cockpit Motion Facility is made up of one motion system site and four fixed-base sites. The motion system site contains a six-degree-of-freedom state-of-the-art synergistic motion base with 76-inch actuator extensions. The four fixed-base sites allow the simulator cockpits to be used in fixed-base mode when they are not resident on the motion system. Each cockpit has its own visual display system and all cockpits share Evans and Sutherland ESIG 3000 image generators.

Pilot tests with the optimal algorithm [12] revealed a number of cases in which the braking algorithm arrested the motion, but with the braking algorithm being unable to recover the motion. In one case, an experienced military aircraft pilot exceeded the motion system actuator limits on several test runs due to aggressive liftoff rotations that resulted in a very high rate of climb and large heave displacement. Similar tests revealed that the nonlinear algorithm was less likely to enter the braking region, due to the fact that the algorithm progressively reduces the platform displacements for large inputs; thus resulting in a larger motion envelope than the optimal algorithm. However, similar problems persisted with the braking algorithm when simulator motion was restrained, with the braking algorithm failing to recover to normal motion. Based upon these results, the braking algorithm is not performing its desired function and future improvements need to be investigated. An improved algorithm that is effective in both restraining large excursions and resuming regular simulator motion would allow increased nonlinear gains and improve motion cueing performance. One suggested approach is the algorithm developed by McFarland [14] for NASA Ames.

The nonlinear algorithm will ultimately be implemented on the CMF. Pilot tuning of the nonlinear gains, similar to that previously done for the new algorithms on
the VMS as discussed in Section 5.1, will be performed. The tuning procedure given in
Section 5.2 can be followed. The gain coefficient sets given in Table 5.2 were set up for
tuning the CMF with increased actuator extensions in comparison to the VMS. It is
expected that the CMF will accommodate increased gains for the pitch, surge, and
possibly the heave degrees of freedom. Due to the algorithm producing faster washout
with large motion cues, the necessity for a braking algorithm to address large excursions
may be minimal. It is suggested that the nonlinear algorithm be first implemented and
tuned without a braking algorithm, with a new braking algorithm to be developed if
needed based on that performance.
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7. Common Block Variable Listings

7.1. comint2.com (Variables Used in Optimal and Nonlinear Algorithms)

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</tr>
<tr>
<td>XD, YD, ZD</td>
<td>Desired Platform Velocities (m/s)</td>
</tr>
<tr>
<td>XDD, YDD, ZDD</td>
<td>Desired Platform Accelerations (m/s/s)</td>
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<tr>
<td>PHI, THI, PSI</td>
<td>Desired Platform Attitudes (rad)</td>
</tr>
<tr>
<td>PHID, THID, PSID</td>
<td>Desired Platform Angular Velocities (rad/s)</td>
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</table>

7.2. optint3.com

<table>
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<td>Aircraft Euler Rate Vector (rad/sec)</td>
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<td>Platform Tilt Cue Limit (rad/sec)</td>
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### 7.3. wopt3.com

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<td>Augmented Turbulence Acceleration Gain</td>
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### 7.4. matrix1c.com

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<tr>
<td>BBII(3,6)</td>
<td>Fixed Base Actuator Coordinates (m)</td>
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<td>Vector from Motion Base Centroid to Pilot Head (m)</td>
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<td>Actuator Neutral Length (m)</td>
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<td>RATIO(6)</td>
<td>Actuator Braking Ratio</td>
</tr>
<tr>
<td>LAVAIL</td>
<td>Actuator Available Length (m)</td>
</tr>
<tr>
<td>RLID(6), RLIDO(6)</td>
<td>Actuator Velocity (m/s)</td>
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<tr>
<td>RLIDD(6)</td>
<td>Actuator Acceleration (m/s/s)</td>
</tr>
<tr>
<td>FLAG(6)</td>
<td>Braking Region Flag (0 or 1)</td>
</tr>
<tr>
<td>FLAG2</td>
<td>Braking Region Flag (0 or 1)</td>
</tr>
<tr>
<td>IT2, NC2</td>
<td>Braking Recovery Indices</td>
</tr>
<tr>
<td>SUMFLAG</td>
<td>Sum of FLAG(6) Values</td>
</tr>
</tbody>
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### 7.5. nopt4.com

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal Mode</strong></td>
<td></td>
</tr>
<tr>
<td>ALPX, ALPXMAMAX</td>
<td>Prescribed Nonlinearity $\alpha$</td>
</tr>
<tr>
<td>APX(11,11), APXO(11)</td>
<td>State Space System Matrix $A'$</td>
</tr>
<tr>
<td>BRBX(11,11), R1PX(11,11), R2IX(2)</td>
<td>System Weighting Matrix $S$, $R_1'$, $R_2$</td>
</tr>
<tr>
<td>AVX(6,6), BVX(6,2), DQCX(6)</td>
<td>Vestibular State Space Matrices $A_V$, $B_V$, $D_QC_V$</td>
</tr>
<tr>
<td>K1X(2,6), K2X(2,3), K3X(2)</td>
<td>Feedback Matrices $K_1$, $K_2$, $K_3$</td>
</tr>
<tr>
<td>ZX(11,11)</td>
<td>Neurocomputing Solver Bi-Polar Vectors $Z$</td>
</tr>
<tr>
<td>PX(11,11), PXVEC(66)</td>
<td>Riccati Equation Solution $P$</td>
</tr>
<tr>
<td>XX(9), XXO(9)</td>
<td>State Vector $x$</td>
</tr>
<tr>
<td><strong>Lateral Mode</strong></td>
<td></td>
</tr>
<tr>
<td>ALPY, ALPYMAX</td>
<td>Prescribed Nonlinearity $\alpha$</td>
</tr>
<tr>
<td>APY(11,11), APYO(11)</td>
<td>State Space System Matrix $A'$</td>
</tr>
<tr>
<td>BRBY(11,11), R1PX(11,11), R2IY(2)</td>
<td>System Weighting Matrix $S$, $R_1'$, $R_2$</td>
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<tr>
<td>AVY(6,6), BVY(6,2), DQCY(6)</td>
<td>Vestibular State Space Matrices $A_V$, $B_V$, $D_QC_Y$</td>
</tr>
<tr>
<td>K1Y(2,6), K2Y(2,3), K3Y(2)</td>
<td>Feedback Matrices $K_1$, $K_2$, $K_3$</td>
</tr>
<tr>
<td>ZY(11,11)</td>
<td>Neurocomputing Solver Bi-Polar Vectors $Z$</td>
</tr>
<tr>
<td>PY(11,11), PYVEC(66)</td>
<td>Riccati Equation Solution $P$</td>
</tr>
<tr>
<td>XY(9), XYO(9)</td>
<td>State Vector $x$</td>
</tr>
<tr>
<td><strong>Yaw Mode</strong></td>
<td></td>
</tr>
<tr>
<td>ALPR, ALPRMAX</td>
<td>Prescribed Nonlinearity $\alpha$</td>
</tr>
<tr>
<td>APR(5,5), APRO(5)</td>
<td>State Space System Matrix $A'$</td>
</tr>
<tr>
<td>BRBR(5,5), R1PR(5,5), R2IR</td>
<td>System Weighting Matrix $S$, $R_1'$, $R_2$</td>
</tr>
<tr>
<td>AVY(3,3), BVR(3), DQCR(3), DQDR</td>
<td>Vestibular State Space Matrices $A_V$, $B_V$, $D_QC_V$, $D_QD_V$</td>
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<tr>
<td>K1R(3), K2R, K3R</td>
<td>Feedback Matrices $K_1$, $K_2$, $K_3$</td>
</tr>
<tr>
<td>ZR(5,5)</td>
<td>Neurocomputing Solver Bi-Polar Vectors $Z$</td>
</tr>
<tr>
<td>PR(5,5), PRVEC(15)</td>
<td>Riccati Equation Solution $P$</td>
</tr>
<tr>
<td>XR(4), XRO(4)</td>
<td>State Vector $x$</td>
</tr>
<tr>
<td><strong>Heave Mode</strong></td>
<td></td>
</tr>
<tr>
<td>ALPZ, ALPZMAX</td>
<td>Prescribed Nonlinearity $\alpha$</td>
</tr>
<tr>
<td>APZ(6,6), APZO(6)</td>
<td>State Space System Matrix $A'$</td>
</tr>
<tr>
<td>BRBZ(6,6), R1PZ(6,6)</td>
<td>System Weighting Matrix $S$, $R_1'$</td>
</tr>
<tr>
<td>AVZ(2,2), BVZ(2)</td>
<td>Vestibular State Space Matrices $A_V$, $B_V$</td>
</tr>
<tr>
<td>K1Z(2), K2Z(2), K3Z</td>
<td>Feedback Matrices $K_1$, $K_2$, $K_3$</td>
</tr>
<tr>
<td>ZZ(6,6)</td>
<td>Neurocomputing Solver Bi-Polar Vectors $Z$</td>
</tr>
<tr>
<td>PZ(6,6), PZVEC(21)</td>
<td>Riccati Equation Solution $P$</td>
</tr>
<tr>
<td>XZ(5), XZO(5)</td>
<td>State Vector $x$</td>
</tr>
<tr>
<td><strong>Nonlinear Gains and Turbulence</strong></td>
<td></td>
</tr>
<tr>
<td>GX4, GY4, GZ4, GP4, GQ4, GR4</td>
<td>In-Flight Polynomial Scaling Coefficients</td>
</tr>
<tr>
<td>AMX4, BMX4</td>
<td>In-Flight Translational and Rotational Limits</td>
</tr>
<tr>
<td>GZ40, GZ4S, AMX40, AMX4S</td>
<td>On-Ground Scaling Coefficients and Limits</td>
</tr>
<tr>
<td>GT4</td>
<td>Augmented Turbulence Acceleration Gain</td>
</tr>
<tr>
<td>G2D0, G2D1</td>
<td>Augmented Turbulence Filter Coefficients (Denominator)</td>
</tr>
<tr>
<td>G2N0, G2N1, G2N2</td>
<td>Augmented Turbulence Filter Coefficients (Numerator)</td>
</tr>
</tbody>
</table>
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8. Program Listing

8.1. gainopt3.f

C*******************************************************
C  OPTIMAL ALGORITHM NONLINEAR GAIN SUBROUTINE.
C  THE INPUT IS FIRST LIMITED AND THEN SCALED BY A POLYNOMIAL.
C*******************************************************
C
SUBROUTINE GAINOPT3

INCLUDE 'optint3.com'
INCLUDE 'wopt3.com'

REAL AA(3),BA(3)

C     Take Absolute Value of Input

AA(1)=ABS(A2(1))
AA(2)=ABS(A2(2))
AA(3)=ABS(A2(3))
BA(1)=ABS(BETAAD(1))
BA(2)=ABS(BETAAD(2))
BA(3)=ABS(BETAAD(3))

C     Limit Translational and Rotational Inputs

AAM=MAX(AA(1),AA(2),AA(3))
BAM=MAX(BA(1),BA(2),BA(3))
IF(AAM.GT.AMX3) THEN
  RATIO=AMX3/AAM
  AA(1)=AA(1)*RATIO
  AA(2)=AA(2)*RATIO
  AA(3)=AA(3)*RATIO
END IF
IF(BAM.GT.BMX3) THEN
  RATIO=BMX3/BAM
  BA(1)=BA(1)*RATIO
  BA(2)=BA(2)*RATIO
  BA(3)=BA(3)*RATIO
END IF

C     Perform Nonlinear Scaling of Inputs

A2N(1)=(GX3(1)*AA(1)+GX3(2)*AA(1)**2.+GX3(3)*AA(1)**3.)
  +SIGN(1.,A2(1))
A2N(2)=(GY3(1)*AA(2)+GY3(2)*AA(2)**2.+GY3(3)*AA(2)**3.)
  +SIGN(1.,A2(2))
A2N(3)=(GZ3(1)*AA(3)+GZ3(2)*AA(3)**2.+GZ3(3)*AA(3)**3.)
  +SIGN(1.,A2(3))
BADN(1)=(GP3(1)*BA(1)+GP3(2)*BA(1)**2.+GP3(3)*BA(1)**3.)
  +SIGN(1.,BETAAD(1))
BADN(2)=(GQ3(1)*BA(2)+GQ3(2)*BA(2)**2.+GQ3(3)*BA(2)**3.)
  +SIGN(1.,BETAAD(2))
BADN(3)=(GR3(1)*BA(3)+GR3(2)*BA(3)**2.+GR3(3)*BA(3)**3.)
+SIGN(1.,BETAAD(3))

RETURN
END
8.2. 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))

59
RETURN
END
C
8.3. integ3.f

SUBROUTINE INTEG3

INCLUDE 'optint3.com'

INCLUDE 'comint2.com'

INCLUDE 'wcom2.com'

INCLUDE 'matrix1c.com'

C INTEGRATE:
C SIMULATOR LINEAR ACCEL TO LINEAR DISPL
C SIMULATOR ANGULAR VEL TO ANGULAR DISPL
C
DO K=1,3
  VSI(K)=VSIO(K)+DT*0.5*(ASI(K)+ASIO(K))
  SSIU(K)=SSIO(K)+DT*0.5*(VSI(K)+VSIO(K))
  BETASR(K)=BETASRO(K)+DT*0.5*(BSDR(K)+BSDRO(K))
  ASIO(K)=ASI(K)
  VSIO(K)=VSI(K)
  SSIU(K)=SSIO(K)
  BSDRO(K)=BSDR(K)
  BETASRO(K)=BETASR(K)
END DO
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
  BETAST(K)=BETASTO(K)+DT*0.5*(BSDT(K)+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 COMPUTE THE TILT ANGULAR VELOCITY
C
  BSDTL(K)=(BETASTL(K)-BETASTLO(K))/DT

  BETASTO(K)=BETAST(K)
  BETASTL(K)=BETASTL(K)
  BSDTO(K)=BSDT(K)
END DO
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)=BETASR(3)
C USE DIFFERENCE BETWEEN DESIRED BETAST AND REAL BETAST
TO GENERATE ADDITIONAL LINEAR RESPONSE AND ACHIEVE
COORDINATION BETWEEN THE LINEAR AND TILT CHANNELS

SSI1(1) = SSIU(1) + RRS(3) * (BETAST(2) - BETASTL(2))
SSI1(2) = SSIU(2) - RRS(3) * (BETAST(1) - BETASTL(1))

FOR ON-GROUND MOTION, ADD RUNWAY ROUGHNESS EFFECT
AMPLITUDE IS FAIRED UPON TOUCHDOWN OR TAKEOFF

SSI1(3) = SSIU(3) + XKA * SIN((WB + XKG * VGSPD) * T)

Swap Variables To Match Modified Algorithm
For Input to JACKDRV

XDD = ASI(1)
YDD = ASI(2)
ZDD = ASI(3)
XD = VSI(1)
YD = VSI(2)
ZD = VSI(3)
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
8.4. integ4.f

SUBROUTINE INTEG4

INCLUDE 'optint3.com'

INCLUDE 'comint2.com'

INCLUDE 'wcom2.com'

INCLUDE 'matrix1c.com'

INCLUDE 'nopt4.com'

SURGE FILTER OUTPUT ASI(1) & BSDT(2)

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)

SWAY FILTER OUTPUT ASI(2) & BSDT(1)

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)

HEAVE FILTER OUTPUT ASI(3)

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))

YAW FILTER OUTPUT BSDR(3)

BSDR(3)=-K1R(1)*XR(1)-K1R(2)*XR(2)-K1R(3)*XR(3)
  x -K2R*XR(4)-K3R*BAND(3)

LIMIT THE ANGULAR RATE IN THE CROSS-OVER TILT CHANNEL.

THE REAL TILT POSITION WILL BE DETERMINED BY BOTH THE DESIRED
POSITION AND THE DIFFERENCE BETWEEN THE DESIRED AND REAL
TILT POSITION.

DO K=1,2
  BETASR(K)=BETASRO(K)+DT*BSDRO(K)
  BETAST(K)=BETASTO(K)+DT*BSTD(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)))

COMPUTE THE TILT ANGULAR VELOCITY

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

COMBINE THE TILT AND ROTATIONAL CHANNELS TO OBTAIN THE DESIRED ANGULAR POSITION

BETAS1(1) = BETASTL(1) + BETASR(1)
BETAS1(2) = BETASTL(2) + BETASR(2)
BETAS1(3) = XR(4)

USE DIFFERENCE BETWEEN DESIRED BETAST AND REAL BETAST TO GENERATE ADDITIONAL LINEAR RESPONSE AND ACHIEVE COORDINATION BETWEEN THE LINEAR AND TILT CHANNELS

SSI1(1) = XX(8) + RRS(3) * (BETAST(2) - BETASTL(2))
SSI1(2) = XY(8) - RRS(3) * (BETAST(1) - BETASTL(1))

FOR ON-GROUND MOTION, ADD RUNWAY ROUGHNESS EFFECT AMPLITUDE IS FAIRED UPON TOUCHDOWN OR TAKEOFF

SSI1(3) = XZ(4) + XKA * SIN((WB + XKG*VGSPD) * T)

Swap Variables To Match Modified Algorithm For Input to JACKDRVR

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
8.5. 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 SSIN: 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
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
+ 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+YM(I)) * A(1, 2) + YM(I) * A(2, 2) + ZM(I) * A(3, 2) - YS(I))
PFZ(I) = 2.* (Z+ZM(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, 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))
PFT(I) = 2.*(X- XS(I)) * (-XM(I) * SIN(T) * COS(S) + YM(I) * SIN(P) * COS(T) *
+ CO S(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) * COS(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
8.6. 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*0.0/, 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*0.0/,FLAG2/0.,IT2/400.,NC2/400.,SUMFLAG/0/
DATA RLID/6*0.0/.,RLIDD/6*0.0/.,RLIO/6*0.0/.,RLIDO/6*0.0/
C
C     EXACT ANGLE COMPUTATIONS
C
SINPHI = SIN(PHI)
SINTH  = SIN(THE)
SINPSI = SIN(PSI)
COSPHI = COS(PHI)
COSTH  = COS(THE)
COSPSI = COS(PSI)
FORM LLIS TRANSFORMATION MATRIX

\[
\begin{align*}
\text{LLIS}(1,1) &= \cos \psi \cos \theta \\
\text{LLIS}(2,1) &= \sin \psi \cos \theta \\
\text{LLIS}(3,1) &= -\sin \theta \\
\text{LLIS}(1,2) &= \cos \psi \sin \theta \sin \phi - \sin \psi \cos \phi \\
\text{LLIS}(2,2) &= \sin \psi \sin \theta \sin \phi + \cos \psi \cos \phi \\
\text{LLIS}(3,2) &= \cos \theta \sin \phi \\
\text{LLIS}(1,3) &= \cos \psi \sin \theta \cos \phi + \sin \psi \sin \phi \\
\text{LLIS}(2,3) &= \sin \psi \sin \theta \cos \phi - \cos \psi \sin \phi \\
\text{LLIS}(3,3) &= \cos \theta \cos \phi \\
\end{align*}
\]

Compute Leg Extensions

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)
LENHTHTOT(JACK) = SQRT(L1(JACK)**2+L2(JACK)**2+L3(JACK)**2)
LI(JACK)=LENHTHTOT(JACK) - LENEUT
END DO

C****************** JACK EXTENSION LIMITING ***********************
DO JACK=1,6
IF(FLAG(JACK).EQ.1) GOTO 5
C
Avail. Length for Same +/- Extension Limits
LAVAIL=LLIM-RLI(JACK)*SIGN(1.,RLID(JACK))
C
Avail. Length for Different +/- Extension Limits
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)
When brake is set, determine if brake should be released

\[
\begin{align*}
DXX &= |X| - |SSI(1)| \\
DYY &= |Y| - |SSI(2)| \\
DZZ &= |Z| - |SSI(3)| \\
DPHI &= |PHI| - |BETAS(1)| \\
DTHE &= |THE| - |BETAS(2)| \\
DPSI &= |PSI| - |BETAS(3)| \\
DMAX &= \max(DXX, DYY, DZZ, DPHI, DTHE, DPSI) \\
DMIN &= \min(DXX, DYY, DZZ, DPHI, DTHE, DPSI) \\
\end{align*}
\]

If \((\text{DMAX} \leq 1. \times 10^{-5}). \text{AND.} (\text{DMIN} \leq -0.01)) \text{ THEN}
\[
\begin{align*}
ID &= 0 \\
\text{ELSE} \\
ID &= 1 \\
\end{align*}
\]
\text{END IF}

\[
\begin{align*}
\text{DO } \text{JACK}=1,6 \\
\text{IF (FLAG(JACK).EQ.0) GOTO 20} \\
\text{RLIDD(JACK)} &= -\text{ACMAX} \times \text{SIGN}(1., \text{RLID(JACK)}) \\
\text{RLID(JACK)} &= \text{RLID(JACK)} + \text{RLIDD(JACK)} \times H \\
\text{GOTO 30} \\
\text{DO } \text{JACK}=1,6 \\
\text{IF (SUMFLAG.EQ.0) GOTO 50} \\
\text{IF (ABS(RLID(JACK)).GT.0.001) THEN} \\
\text{RLIDD(JACK)} &= -\text{ACMAX} \times \text{SIGN}(1., \text{RLID(JACK)}) \times \text{RATIO(JACK)} \\
\text{RLID(JACK)} &= \text{RLID(JACK)} + \text{RLIDD(JACK)} \times H \\
\text{END IF} \\
\text{IF (ABS(RLID(JACK)).GT.(ACMAX*H)) THEN} \\
\text{RLI(JACK)} &= \text{RLID(JACK)} + \text{RLIDD(JACK)} \times H \\
\text{ELSE} \\
\text{RLID(JACK)} &= 0. \\
\text{FLAG(JACK)} &= 0 \\
\text{END IF} \\
\text{END IF} \\
\text{END IF} \\
\text{GOTO 70} \\
\text{IF (FLAG2.EQ.0) GOTO 60} \\
\text{IF (ID.NE.0) GOTO 70} \\
\text{FLAG2} &= 0 \\
\text{IT2} &= 0 \\
\text{RLI(JACK)} &= \text{RLI(JACK)} + \\
&\quad (1. - \cos(3.1416/2. \times IT2/NC2)) \times (\text{LI(JACK)} - \text{RLI(JACK)}) \\
\text{IF ((JACK.EQ.6).AND. (IT2.LT.NC2)) IT2 = IT2 + 1} \\
\end{align*}
\]

\text{DO } \text{END DO} \\
\text{DO } \text{JACK}=1,6 \\
\text{Same +/- Extension limits} \\
\text{RLI(JACK)} &= \min(0.999 \times \text{LLIM}, \max(-0.999 \times \text{LLIM}, \text{RLI(JACK)})) \\
\text{Different +/- Extension Limits} \\
\text{RLI(JACK)} &= \min(0.999 \times \text{LLIML}, \max(-0.999 \times \text{LLIML}, \text{RLI(JACK)})) \\
\text{RLID(JACK)} &= (\text{RLI(JACK)} - \text{RLIO(JACK)}) / H \\
\text{RLIDD(JACK)} &= (\text{RLID(JACK)} - \text{RLIDO(JACK)}) / H \\
\text{RLIO(JACK)} &= \text{RLI(JACK)} \\
\text{RLIDO(JACK)} &= \text{RLID(JACK)} \\
\text{END DO}
RETURN
END
SUBROUTINE LIBA

INCLUDE 'optint3.com'

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

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

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

FORM LIA TRANSFORMATION MATRIX

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

FORM TA TRANSFORMATION MATRIX

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

Compute Inertial Accleration A2

CALL VMULT(LIA,ACA,A2,3,3,1)

Compute euler Rates BETAAD

CALL VMULT(TA,WAA,BETAAD,3,3,1)

RETURN
END
8.8. 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'
  DATA IRESET/0/,IHOLD/0/
  Compute Fairing Parameters
  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
  Fairing of Heave Nonlinear Gain and Limit
  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
  Fairing of Runway Roughness Amplitude
  XKA=A*XKA0+SQWASHP*XKAS
  IF(MODE.EQ.1) THEN
    H = DT
  Set "old" variables for future use in HOLD and OPERATE modes
  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.
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)
    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 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
ENDIF

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
ENDIF

C C (first-order turbulence model no longer used)
C
   XT=XTO+DT*(-G1D0*XTO+(G1N0-G1D0*G1N1)*WGUSTO)
   XTO=XT
   WGUSTO=WGUST
   ACZT=XT+G1N1*WGUST

ENDIF

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

IF(MODE.EQ.3) THEN
   CALL NFILX
   CALL NFILY
   CALL NFILZ
   CALL NFILR
   CALL STATE4
ELSE IF(MODE.EQ.2) THEN
   CALL STATE4
   CALL STATE4
   CALL STATE4
   CALL STATE4
ENDIF

IF(MODE.EQ.3) CALL INTEG4

1 RETURN
END
8.9. nfilr.f

YW Filter Neurocomputing Solver for the Riccati Equation

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 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
         SPR(I,J)=SPR(I,J)+BRBR(I,K)*PR(K,J)
      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 $P$
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
    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,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
8.10. nfilx.f

SUBROUTINE NFILX

INCLUDE 'comint2.com'
INCLUDE 'nopt4.com'

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

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 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
         UBX(I,J)=0.0
         UAPX(I,J)=0.0
         APUX(I,J)=0.0
      END DO
   END DO

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
   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=1,11
DO K=1,11
  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
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
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)
    APUX(I,J)=APUX(I,J)+APX(I,11)*UX(11)*ZX(L,J)
  END DO
  APUX(I,J)=APUX(I,J)+APX(I,10)*UX(10)*ZX(L,J)
END DO
END DO

DO J=1,11
  APUX(7, J)=APX(7, 7)*UX(7)*ZX(L, J)
  APUX(8, J)=APX(8, 8)*UX(8)*ZX(L, J)
  APUX(9, J)=APX(9, 9)*UX(9)*ZX(L, J)
END DO

80
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
    UAPX(I, 7) = UX(I) * ZX(L, 7) * APX(7, 7)
    UAPX(I, 8) = UX(I) * ZX(L, 8) * APX(8, 8)
    UAPX(I, 9) = 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, 11) = UAPX(I, 11) + UX(I) * ZX(L, 11) * APX(11, 11)
  END DO
  UAPX(I, 7) = UX(I) * ZX(L, 7) * APX(7, 7)
  UAPX(I, 8) = UX(I) * ZX(L, 8) * APX(8, 8)
  UAPX(I, 9) = 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, 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, 9) = UX(I) * PZX(9) * BRBX(9, 9)
    UPBX(I, 9) = UPBX(I, 9) + UX(I) * PZX(K) * BRBX(K, 9)
    DO K=1, 6
      UPBX(I, 9) = UPBX(I, 9) + UX(I) * PZX(K) * BRBX(K, 9)
    END DO
  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)
    END IF
    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 DO
END DO
8.11. nfily.f

C Sway Filter Neurocomputing Solver for the Riccati Equation
C
SUBROUTINE NFILY
C
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.ALPMAX) ALPY=ALPMAX
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
   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=1,11
    DO K=1,11
      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=1,11
    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=1,11
    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

Compute Error Signal v, Vector p and Matrix Product vz

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

Compute Matrix Product Avz

DO I=1,11
  DO J=1,11
    DO K=1,11
      APUY(I,J) = APUY(I,J) + APY(I,K) * UY(K) * ZY(L,J)
    END DO
  END DO
  APUY(I,7) = APY(7,7) * UY(7) * ZY(L,J)
  APUY(I,8) = APY(7,8) * UY(7) * ZY(L,J)
  APUY(I,9) = APY(8,8) * UY(8) * ZY(L,J)
  END DO
END DO

DO I=1,11
  DO J=1,11
    APUY(7,J) = APY(7,7) * UY(7) * ZY(L,J)
    + APY(7,8) * UY(8) * ZY(L,J)
    APUY(8,J) = APY(7,8) * UY(7) * ZY(L,J)
    + APY(8,8) * UY(8) * ZY(L,J)
    APUY(8,9) = APY(8,8) * UY(8) * ZY(L,J)
    + APY(8,9) * UY(9) * ZY(L,J)
  END DO
END DO
APUY(9,J) = APY(9,9) * UY(9) * ZY(L,J)
APUY(10,J) = APUY(10,9) + APY(10,10) * UY(10) * ZY(L,J)
APUY(11,J) = APUY(11,9) + APY(11,11) * UY(11) * ZY(L,J)

END DO

C
Compute Matrix Product vzA

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,8) * APY(7,8)
  UAPY(I,9) = UY(I) * ZY(L,8) * APY(8,9)
  UAPY(I,10) = UY(I) * ZY(L,10) * APY(10,10)
  UAPY(I,11) = UY(I) * ZY(L,11) * APY(11,11)
END DO

C
Compute Matrix Product vp'S

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
Sum Avz + vzA + vp'S and integrate to update Riccati Solution P

DO I=1,11
  DO J=1,11
    IF (I.LE.J) THEN
      SUMPY = APUY(I,J) + UAPY(I,J) - UPBY(I,J)
    ELSE
      SUMPY = APUY(J,I) + UAPY(J,I) - UPBY(J,I)
    END IF
    IF (I.EQ.J) THEN
      SUMPYT = SUMPY
      ELSE
        SUMPYT = SUMPY + SUMPY
      END IF
      PY(I,J) = PY(I,J) + MUY * (SUMPY + SUMPYT)
    END IF
  END DO
END DO
END DO
END DO

END DO

RETURN

END
8.12. nfilz.f

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 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 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
    DO J=1,6
        SPZ(5,J)=BRBZ(5,1)*PZ(1,J)
        +BRBZ(5,2)*PZ(2,J)+BRBZ(5,5)*PZ(5,J)
    END DO

C Compute Matrix Product SP
C
 DO I=1,2
    DO J=1,6
        SPZ(I,J)=BRBZ(I,1)*PZ(1,J)
    END DO

END DO

END DO

DO J=1,6
    SPZ(5,J)=BRBZ(5,1)*PZ(1,J)
    +BRBZ(5,2)*PZ(2,J)+BRBZ(5,5)*PZ(5,J)
END DO

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)

87
\[
PAPZ(I,2) = PZ(I,1) \cdot APZ(1,2) + PZ(I,2) \cdot APZ(2,2)
\]
\[
PAPZ(I,3) = PZ(I,1) \cdot APZ(3,3)
\]
\[
PAPZ(I,4) = PZ(I,3) \cdot APZ(3,4) + PZ(I,4) \cdot APZ(4,4)
\]
\[
PAPZ(I,5) = PZ(I,4) \cdot APZ(4,5) + PZ(I,5) \cdot APZ(5,5)
\]
\[
PAPZ(I,6) = PZ(I,1) \cdot APZ(1,6) + PZ(I,2) \cdot APZ(2,6) + PZ(I,6) \cdot APZ(6,6)
\]

END DO

C Compute Error Signal \(v\), Vector \(p\) and Matrix Product \(vz\)
C Note: Matrix Product \(A'P\) is transpose of \(PA\) by symmetry of \(P\)

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) \cdot 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) \cdot ZZ(L,J)
PZZ(I) = PZZ(I) + PZ(I,J) \cdot ZZ(L,J)
END DO
END DO

C Compute Matrix Product \(Avz\)

DO I=1,2
DO J=1,6
APUZ(I,J) = APZ(I,1) \cdot UZ(1) \cdot ZZ(L,J) + APZ(I,2) \cdot UZ(2) \cdot ZZ(L,J) + APZ(I,6) \cdot UZ(6) \cdot ZZ(L,J)
END DO
END DO

DO J=1,6
APUZ(3,J) = APZ(3,3) \cdot UZ(3) \cdot ZZ(L,J) + APZ(3,4) \cdot UZ(4) \cdot ZZ(L,J)
APUZ(4,J) = APZ(4,4) \cdot UZ(4) \cdot ZZ(L,J) + APZ(4,5) \cdot UZ(5) \cdot ZZ(L,J)
APUZ(5,J) = APZ(5,5) \cdot UZ(5) \cdot ZZ(L,J)
APUZ(6,J) = APZ(6,6) \cdot UZ(6) \cdot ZZ(L,J)
END DO

C Compute Matrix Product \(vzA\)

DO I=1,6
UAPZ(I,1) = UZ(I) \cdot ZZ(L,1) \cdot APZ(1,1) + UZ(I) \cdot ZZ(L,2) \cdot APZ(2,1)
UAPZ(I,2) = UZ(I) \cdot ZZ(L,1) \cdot APZ(1,2) + UZ(I) \cdot ZZ(L,2) \cdot APZ(2,2)
UAPZ(I,3) = UZ(I) \cdot ZZ(L,3) \cdot APZ(3,3)
UAPZ(I,4) = UZ(I) \cdot ZZ(L,3) \cdot APZ(3,4) + UZ(I) \cdot ZZ(L,4) \cdot APZ(4,4)
UAPZ(I,5) = UZ(I) \cdot ZZ(L,4) \cdot APZ(4,5) + UZ(I) \cdot ZZ(L,5) \cdot APZ(5,5)
UAPZ(I,6) = UZ(I) \cdot ZZ(L,1) \cdot APZ(1,6)
END DO

END

88
END DO

C Compute Matrix Product \( vp'S \)

DO I=1,6
    DO J=1,2
        UPBZ(I,J)=UZ(I)*PZZ(1)*BRBZ(1,J)
        +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)
    +UZ(I)*PZZ(2)*BRBZ(2,5)+UZ(I)*PZZ(5)*BRBZ(5,5)
END DO

C Sum \( Avz + vzA + vp'S \) and integrate to update Riccati Solution \( P \)

DO I=1,6
    DO J=1,6
        IF(I.LE.J) THEN
            SUMPZ=APUZ(I,J)+UAPZ(I,J)-UPBZ(I,J)
        ELSE 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

RETURN
END
8.13. ofil3.f

C OPTIMAL FILTERS (ALL IN INERTIAL FRAME):
C
C 6TH ORDER PHIAD TO PHISD
C 6TH ORDER A2(2) TO PHISD
C 6TH ORDER A2(2) TO AYSI
C 6TH ORDER THETAAD TO THETASD
C 6TH ORDER A2(1) TO THETASD
C 6TH ORDER A2(1) TO AXSI
C 4TH ORDER PSIA TO PSIS
C 4TH ORDER A2(3) TO AZSI
C

SUBROUTINE OFIL3

REAL B1(8),C1(8),D1(8),E1(8),F1(6),G1(6)
REAL B2(8),C2(8),D2(8),E2(8),F2(6),G2(6)

INCLUDE 'matrix1c.com'

INCLUDE 'optint3.com'

INCLUDE 'wopt3.com'

C************************* BLOCK NO. C1 *************************
C FILTER FROM PHIAD TO PHISD:
C
B1(1)=DT*(-R1D5*X1O(1)+X2O(1)+(R1N5-R1D5*R1N6)*BADNO(1))
C1(1)=DT*(-R1D4*X1O(1)+X3O(1)+(R1N4-R1D4*R1N6)*BADNO(1))
D1(1)=DT*(-R1D3*X1O(1)+X4O(1)+(R1N3-R1D3*R1N6)*BADNO(1))
E1(1)=DT*(-R1D2*X1O(1)+X5O(1)+(R1N2-R1D2*R1N6)*BADNO(1))
F1(1)=DT*(-R1D1*X1O(1)+X6O(1)+(R1N1-R1D1*R1N6)*BADNO(1))
G1(1)=DT*(-R1D0*X1O(1)+(R1N0-R1D0*R1N6)*BADNO(1))

B2(1)=DT*
  (-R1D5*(X1O(1)+B1(1))+X2O(1)+C1(1)+(R1N5-R1D5*R1N6)*BADN(1))
C2(1)=DT*
  (-R1D4*(X1O(1)+B1(1))+X3O(1)+D1(1)+(R1N4-R1D4*R1N6)*BADN(1))
D2(1)=DT*
  (-R1D3*(X1O(1)+B1(1))+X4O(1)+E1(1)+(R1N3-R1D3*R1N6)*BADN(1))
E2(1)=DT*
  (-R1D2*(X1O(1)+B1(1))+X5O(1)+F1(1)+(R1N2-R1D2*R1N6)*BADN(1))
F2(1)=DT*
  (-R1D1*(X1O(1)+B1(1))+X6O(1)+G1(1)+(R1N1-R1D1*R1N6)*BADN(1))
G2(1)=DT*
  (-R1D0*(X1O(1)+B1(1))+(R1N0-R1D0*R1N6)*BADN(1))

XX1(1)=X1O(1)+0.5*(B1(1)+B2(1))
X2(1)=X2O(1)+0.5*(C1(1)+C2(1))
X3(1)=X3O(1)+0.5*(D1(1)+D2(1))
X4(1)=X4O(1)+0.5*(E1(1)+E2(1))
X5(1)=X5O(1)+0.5*(F1(1)+F2(1))
X6(1)=X6O(1)+0.5*(G1(1)+G2(1))

C
C************************ BLOCK NO. C2 ****************************
C   FILTER FROM A2(2) TO PHISD:
C
B1(2) = DT* (-R1D5*X1O(2)+X2O(2)+C1(2)+(R2N5-R1D5*R2N6)*A2NO(2))
C1(2) = DT* (-R1D4*X1O(2)+X3O(2)+(R2N4-R1D4*R2N6)*A2NO(2))
D1(2) = DT* (-R1D3*X1O(2)+X4O(2)+(R2N3-R1D3*R2N6)*A2NO(2))
E1(2) = DT* (-R1D2*X1O(2)+X5O(2)+(R2N2-R1D2*R2N6)*A2NO(2))
F1(2) = DT* (-R1D1*X1O(2)+X6O(2)+(R2N1-R1D1*R2N6)*A2NO(2))
G1(2) = DT* (-R1D0*X1O(2)+X7O(2)+(R2N0-R1D0*R2N6)*A2NO(2))

B2(2) = DT*
  X (-R1D5*(X1O(2)+B1(2))+X2O(2)+C1(2)+(R2N5-R1D5*R2N6)*A2N(2))
C2(2) = DT*
  X (-R1D4*(X1O(2)+B1(2))+X3O(2)+D1(2)+(R2N4-R1D4*R2N6)*A2N(2))
D2(2) = DT*
  X (-R1D3*(X1O(2)+B1(2))+X4O(2)+E1(2)+(R2N3-R1D3*R2N6)*A2N(2))
E2(2) = DT*
  X (-R1D2*(X1O(2)+B1(2))+X5O(2)+F1(2)+(R2N2-R1D2*R2N6)*A2N(2))
F2(2) = DT*
  X (-R1D1*(X1O(2)+B1(2))+X6O(2)+G1(2)+(R2N1-R1D1*R2N6)*A2N(2))
G2(2) = DT*
  X (-R1D0*(X1O(2)+B1(2))+X7O(2)+(R2N0-R1D0*R2N6)*A2N(2))

XX1(2) = X1O(2) + 0.5*(B1(2)+B2(2))
X2(2) = X2O(2) + 0.5*(C1(2)+C2(2))
X3(2) = X3O(2) + 0.5*(D1(2)+D2(2))
X4(2) = X4O(2) + 0.5*(E1(2)+E2(2))
X5(2) = X5O(2) + 0.5*(F1(2)+F2(2))
X6(2) = X6O(2) + 0.5*(G1(2)+G2(2))

C************************ BLOCK NO. C3 ****************************
C   FILTER FROM A2(2) TO AYSI:
C
B1(3) = DT* (-R1D5*X1O(3)+X2O(3)+C1(3)+(R4N5-R1D5*R4N6)*A2NO(2))
C1(3) = DT* (-R1D4*X1O(3)+X3O(3)+(R4N4-R1D4*R4N6)*A2NO(2))
D1(3) = DT* (-R1D3*X1O(3)+X4O(3)+(R4N3-R1D3*R4N6)*A2NO(2))
E1(3) = DT* (-R1D2*X1O(3)+X5O(3)+(R4N2-R1D2*R4N6)*A2NO(2))
F1(3) = DT* (-R1D1*X1O(3)+X6O(3)+(R4N1-R1D1*R4N6)*A2NO(2))
G1(3) = DT* (-R1D0*X1O(3)+X7O(3)+(R4N0-R1D0*R4N6)*A2NO(2))

B2(3) = DT*
  X (-R1D5*(X1O(3)+B1(3))+X2O(3)+C1(3)+(R4N5-R1D5*R4N6)*A2N(2))
C2(3) = DT*
  X (-R1D4*(X1O(3)+B1(3))+X3O(3)+D1(3)+(R4N4-R1D4*R4N6)*A2N(2))
D2(3) = DT*
  X (-R1D3*(X1O(3)+B1(3))+X4O(3)+E1(3)+(R4N3-R1D3*R4N6)*A2N(2))
E2(3) = DT*
  X (-R1D2*(X1O(3)+B1(3))+X5O(3)+F1(3)+(R4N2-R1D2*R4N6)*A2N(2))
F2(3) = DT*
  X (-R1D1*(X1O(3)+B1(3))+X6O(3)+G1(3)+(R4N1-R1D1*R4N6)*A2N(2))
G2(3) = DT*
  X (-R1D0*(X1O(3)+B1(3))+X7O(3)+(R4N0-R1D0*R4N6)*A2N(2))

XX1(3) = X1O(3) + 0.5*(B1(3)+B2(3))
X2(3) = X2O(3) + 0.5*(C1(3)+C2(3))
X3(3) = X3O(3) + 0.5*(D1(3)+D2(3))
X4(3) = X4O(3) + 0.5*(E1(3)+E2(3))
\[ X5(3) = X5O(3) + 0.5 \times (F1(3) + F2(3)) \]

\[ X6(3) = X6O(3) + 0.5 \times (G1(3) + G2(3)) \]

********** BLOCK NO. C4 **********

FILTER FROM THETAAD TO THETASD:

\[ B1(4) = DT \times (-P1D5 \times X1O(4) + X2O(4) + (P1N5 - P1D5 \times P1N6) \times BADNO(2)) \]
\[ C1(4) = DT \times (-P1D4 \times X1O(4) + X3O(4) + (P1N4 - P1D4 \times P1N6) \times BADNO(2)) \]
\[ D1(4) = DT \times (-P1D3 \times X1O(4) + X4O(4) + (P1N3 - P1D3 \times P1N6) \times BADNO(2)) \]
\[ E1(4) = DT \times (-P1D2 \times X1O(4) + X5O(4) + (P1N2 - P1D2 \times P1N6) \times BADNO(2)) \]
\[ F1(4) = DT \times (-P1D1 \times X1O(4) + X6O(4) + (P1N1 - P1D1 \times P1N6) \times BADNO(2)) \]
\[ G1(4) = DT \times (-P1D0 \times X1O(4) + (P1N0 - P1D0 \times P1N6) \times BADNO(2)) \]

\[ B2(4) = DT \times (-P1D5 \times X1O(4) + B1(4)) + X2O(4) + C1(4) + (P1N5 - P1D5 \times P1N6) \times BADN(2) \]
\[ C2(4) = DT \times (-P1D4 \times X1O(4) + B1(4)) + X3O(4) + D1(4) + (P1N4 - P1D4 \times P1N6) \times BADN(2) \]
\[ D2(4) = DT \times (-P1D3 \times X1O(4) + B1(4)) + X4O(4) + E1(4) + (P1N3 - P1D3 \times P1N6) \times BADN(2) \]
\[ E2(4) = DT \times (-P1D2 \times X1O(4) + B1(4)) + X5O(4) + F1(4) + (P1N2 - P1D2 \times P1N6) \times BADN(2) \]
\[ F2(4) = DT \times (-P1D1 \times X1O(4) + B1(4)) + X6O(4) + G1(4) + (P1N1 - P1D1 \times P1N6) \times BADN(2) \]
\[ G2(4) = DT \times (-P1D0 \times X1O(4) + B1(4)) + (P1N0 - P1D0 \times P1N6) \times BADN(2) \]

\[ XX1(4) = X1O(4) + 0.5 \times (B1(4) + B2(4)) \]
\[ XX2(4) = X2O(4) + 0.5 \times (C1(4) + C2(4)) \]
\[ XX3(4) = X3O(4) + 0.5 \times (D1(4) + D2(4)) \]
\[ XX4(4) = X4O(4) + 0.5 \times (E1(4) + E2(4)) \]
\[ XX5(4) = X5O(4) + 0.5 \times (F1(4) + F2(4)) \]
\[ XX6(4) = X6O(4) + 0.5 \times (G1(4) + G2(4)) \]

********** BLOCK NO. C5 **********

FILTER FROM A2(1) TO THETASD:

\[ B1(5) = DT \times (-P1D5 \times X1O(5) + X2O(5) + (P2N5 - P1D5 \times P2N6) \times A2N0(1)) \]
\[ C1(5) = DT \times (-P1D4 \times X1O(5) + X3O(5) + (P2N4 - P1D4 \times P2N6) \times A2N0(1)) \]
\[ D1(5) = DT \times (-P1D3 \times X1O(5) + X4O(5) + (P2N3 - P1D3 \times P2N6) \times A2N0(1)) \]
\[ E1(5) = DT \times (-P1D2 \times X1O(5) + X5O(5) + (P2N2 - P1D2 \times P2N6) \times A2N0(1)) \]
\[ F1(5) = DT \times (-P1D1 \times X1O(5) + X6O(5) + (P2N1 - P1D1 \times P2N6) \times A2N0(1)) \]
\[ G1(5) = DT \times (-P1D0 \times X1O(5) + (P2N0 - P1D0 \times P2N6) \times A2N0(1)) \]

\[ B2(5) = DT \times (-P1D5 \times X1O(5) + B1(5)) + X2O(5) + C1(5) + (P2N5 - P1D5 \times P2N6) \times A2N(1) \]
\[ C2(5) = DT \times (-P1D4 \times X1O(5) + B1(5)) + X3O(5) + D1(5) + (P2N4 - P1D4 \times P2N6) \times A2N(1) \]
\[ D2(5) = DT \times (-P1D3 \times X1O(5) + B1(5)) + X4O(5) + E1(5) + (P2N3 - P1D3 \times P2N6) \times A2N(1) \]
\[ E2(5) = DT \times (-P1D2 \times X1O(5) + B1(5)) + X5O(5) + F1(5) + (P2N2 - P1D2 \times P2N6) \times A2N(1) \]
\[ F2(5) = DT \times (-P1D1 \times X1O(5) + B1(5)) + X6O(5) + G1(5) + (P2N1 - P1D1 \times P2N6) \times A2N(1) \]
\[ G2(5) = DT \times (-P1D0 \times X1O(5) + B1(5)) + (P2N0 - P1D0 \times P2N6) \times A2N(1) \]

\[ XX1(5) = X1O(5) + 0.5 \times (B1(5) + B2(5)) \]

92
\[ X_2(5) = X_2(5) + 0.5 \cdot (C_1(5) + C_2(5)) \]
\[ X_3(5) = X_3(5) + 0.5 \cdot (D_1(5) + D_2(5)) \]
\[ X_4(5) = X_4(5) + 0.5 \cdot (E_1(5) + E_2(5)) \]
\[ X_5(5) = X_5(5) + 0.5 \cdot (F_1(5) + F_2(5)) \]
\[ X_6(5) = X_6(5) + 0.5 \cdot (G_1(5) + G_2(5)) \]

**C**

**C************************ BLOCK NO. C6 ****************************

**C** FILTER FROM A2(1) TO AXSI:

\[ B_1(6) = DT \cdot (-P_1D_5 \cdot X_1(6) + X_2(6) + (P_4N_5 - P_1D_5 \cdot P_4N_6) \cdot A2NO(1)) \]
\[ C_1(6) = DT \cdot (-P_1D_4 \cdot X_1(6) + X_3(6) + (P_4N_4 - P_1D_4 \cdot P_4N_6) \cdot A2NO(1)) \]
\[ D_1(6) = DT \cdot (-P_1D_3 \cdot X_1(6) + X_4(6) + (P_4N_3 - P_1D_3 \cdot P_4N_6) \cdot A2NO(1)) \]
\[ E_1(6) = DT \cdot (-P_1D_2 \cdot X_1(6) + X_5(6) + (P_4N_2 - P_1D_2 \cdot P_4N_6) \cdot A2NO(1)) \]
\[ F_1(6) = DT \cdot (-P_1D_1 \cdot X_1(6) + X_6(6) + (P_4N_1 - P_1D_1 \cdot P_4N_6) \cdot A2NO(1)) \]
\[ G_1(6) = DT \cdot (-P_1D_0 \cdot X_1(6) + (P_4N_0 - P_1D_0 \cdot P_4N_6) \cdot A2NO(1)) \]

\[ B_2(6) = DT \cdot (-P_1D_5 \cdot (X_1(6) + B_1(6)) + X_2(6) + C_1(6) + (P_4N_5 - P_1D_5 \cdot P_4N_6) \cdot A2(1)) \]
\[ C_2(6) = DT \cdot (-P_1D_4 \cdot (X_1(6) + B_1(6)) + X_3(6) + D_1(6) + (P_4N_4 - P_1D_4 \cdot P_4N_6) \cdot A2(1)) \]
\[ D_2(6) = DT \cdot (-P_1D_3 \cdot (X_1(6) + B_1(6)) + X_4(6) + E_1(6) + (P_4N_3 - P_1D_3 \cdot P_4N_6) \cdot A2(1)) \]
\[ E_2(6) = DT \cdot (-P_1D_2 \cdot (X_1(6) + B_1(6)) + X_5(6) + F_1(6) + (P_4N_2 - P_1D_2 \cdot P_4N_6) \cdot A2(1)) \]
\[ F_2(6) = DT \cdot (-P_1D_1 \cdot (X_1(6) + B_1(6)) + X_6(6) + G_1(6) + (P_4N_1 - P_1D_1 \cdot P_4N_6) \cdot A2(1)) \]
\[ G_2(6) = DT \cdot (-P_1D_0 \cdot (X_1(6) + B_1(6)) + (P_4N_0 - P_1D_0 \cdot P_4N_6) \cdot A2(1)) \]

XX1(6) = X_1(6) + 0.5 \cdot (B_1(6) + B_2(6))

XX1(6) = X_1(6) + 0.5 \cdot (B_1(6) + B_2(6))

**C************************ BLOCK NO. C7 ****************************

**C** FILTER FROM PSIAD2 TO PSISD2:

\[ B_1(7) = DT \cdot (-Y_1D_3 \cdot X_1(7) + X_2(7) + (Y_1N_3 - Y_1D_3 \cdot Y_1N_4) \cdot BADNO(3)) \]
\[ C_1(7) = DT \cdot (-Y_1D_2 \cdot X_1(7) + X_3(7) + (Y_1N_2 - Y_1D_2 \cdot Y_1N_4) \cdot BADNO(3)) \]
\[ D_1(7) = DT \cdot (-Y_1D_1 \cdot X_1(7) + X_4(7) + (Y_1N_1 - Y_1D_1 \cdot Y_1N_4) \cdot BADNO(3)) \]
\[ E_1(7) = DT \cdot (-Y_1D_0 \cdot X_1(7) + (Y_1N_0 - Y_1D_0 \cdot Y_1N_4) \cdot BADNO(3)) \]

\[ B_2(7) = DT \cdot (-Y_1D_3 \cdot (X_1(7) + B_1(7)) + X_2(7) + C_1(7) + (Y_1N_3 - Y_1D_3 \cdot Y_1N_4) \cdot BAD(3)) \]
\[ C_2(7) = DT \cdot (-Y_1D_2 \cdot (X_1(7) + B_1(7)) + X_3(7) + D_1(7) + (Y_1N_2 - Y_1D_2 \cdot Y_1N_4) \cdot BAD(3)) \]
\[ D_2(7) = DT \cdot (-Y_1D_1 \cdot (X_1(7) + B_1(7)) + X_4(7) + E_1(7) + (Y_1N_1 - Y_1D_1 \cdot Y_1N_4) \cdot BAD(3)) \]
\[ E_2(7) = DT \cdot (-Y_1D_0 \cdot (X_1(7) + B_1(7)) + (Y_1N_0 - Y_1D_0 \cdot Y_1N_4) \cdot BAD(3)) \]

XX1(7) = X_1(7) + 0.5 \cdot (B_1(7) + B_2(7))

XX1(7) = X_1(7) + 0.5 \cdot (B_1(7) + B_2(7))

**C**

**C**********************************************************
FILTER FROM A2(3) TO AZSI:

\[
B1(8) = DT \cdot (-H1D3 \cdot X1(8) + X2(8) + (H1N3 - H1D3 \cdot H1N4) \cdot A2N(3))
\]

\[
C1(8) = DT \cdot (-H1D2 \cdot X1(8) + X3(8) + (H1N2 - H1D2 \cdot H1N4) \cdot A2N(3))
\]

\[
D1(8) = DT \cdot (-H1D1 \cdot X1(8) + X4(8) + (H1N1 - H1D1 \cdot H1N4) \cdot A2N(3))
\]

\[
E1(8) = DT \cdot (-H1D0 \cdot X1(8) + (H1N0 - H1D0 \cdot H1N4) \cdot A2N(3))
\]

\[
B2(8) = DT \cdot (-H1D3 \cdot (X1(8) + B1(8)) + X2(8) + C1(8) + (H1N3 - H1D3 \cdot H1N4) \cdot A2N(3))
\]

\[
C2(8) = DT \cdot (-H1D2 \cdot (X1(8) + B1(8)) + X3(8) + D1(8) + (H1N2 - H1D2 \cdot H1N4) \cdot A2N(3))
\]

\[
D2(8) = DT \cdot (-H1D1 \cdot (X1(8) + B1(8)) + X4(8) + E1(8) + (H1N1 - H1D1 \cdot H1N4) \cdot A2N(3))
\]

\[
E2(8) = DT \cdot (-H1D0 \cdot (X1(8) + B1(8)) + (H1N0 - H1D0 \cdot H1N4) \cdot A2N(3))
\]

\[
XX1(8) = X1(8) + 0.5 \cdot (B1(8) + B2(8))
\]

\[
X2(8) = X2(8) + 0.5 \cdot (C1(8) + C2(8))
\]

\[
X3(8) = X3(8) + 0.5 \cdot (D1(8) + D2(8))
\]

\[
X4(8) = X4(8) + 0.5 \cdot (E1(8) + E2(8))
\]

COMPUTE STATE VARIABLES TO OBTAIN:

SIMULATOR TRANS ACCEL

SIMULATOR ANGULAR VEL (TILT AND PURE)

\[
BSDT(1) = XX1(2) + R2N6 \cdot A2N(2)
\]

\[
BSDT(2) = XX1(5) + P2N6 \cdot A2N(1)
\]

\[
BSDR(1) = XX1(1) + R1N6 \cdot BADN(1)
\]

\[
BSDR(2) = XX1(4) + P1N6 \cdot BADN(2)
\]

\[
BSDR(3) = XX1(7) + Y1N4 \cdot BADN(3)
\]

\[
AS1(1) = XX1(6) + P4N6 \cdot A2N(1)
\]

\[
AS1(2) = XX1(3) + R4N6 \cdot A2N(2)
\]

\[
AS1(3) = XX1(8) + H1N4 \cdot A2N(3)
\]

UPDATE ALL THE DUMMY VARIABLES:

DO I=1,8
    X1O(I) = XX1(I)
    X2O(I) = X2(I)
    X3O(I) = X3(I)
    X4O(I) = X4(I)
END DO

DO I=1,6
    X5O(I) = X5(I)
    X6O(I) = X6(I)
END DO

DO IJ=1,3
    A2NO(IJ) = A2N(IJ)
    BADNO(IJ) = BADN(IJ)
END DO
RETURN
END
8.14. resetc2.f

SUBROUTINE RESETC2

C
C     THIS ROUTINE:
C
(1) DOES T=0 INITIALIZATION OF MOTION VARIABLES
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
VALUES FOR X FILTER
DATA XDDLIM /  T_ACCLIM /
DATA XDLIM  /  T_VELLIM /

VALUES FOR Y FILTER
DATA YDDLIM /  T_ACCLIM /
DATA YDLIM  /  T_VELLIM /

VALUES FOR Z FILTER
DATA ZDDLIM /  T_ACCLIM /
DATA ZDLIM  /  T_VELLIM /
VALUES FOR PSI FILTER

DATA PSIDDLM / A_ACCLIM /
DATA PSIDLIM / A_VELLIM /

VALUES FOR THETA FILTER

DATA THEDDLM / A_ACCLIM /
DATA THEDLIM / A_VELLIM /

VALUES FOR PHI FILTER

DATA PHIDDLM / A_ACCLIM /
DATA PHIDLIM / A_VELLIM /
DATA TWOZOMGN/ 3.0 /

local functions

CLIMIT(X,XMIN,XMAX) = MIN( MAX( X, XMIN ), XMAX )

If last operate run ended braked, reset braking algorithm
to unbraked state

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

T = 0 INITIALIZATION;

T    = 0.
INT  = 0
DXDLX = 0.
DXDLXD = 0.
DXDDX = 0.
DXDDXD = 0.
DTHDDX = 0.
LAMX  = LAMX0
DELTX = DELX0
DYDLY = 0.
DYDLYD = 0.
DYDDY = 0.
DYDDYD = 0.
DPHDDY = 0.
LAMY  = LAMY0
DELEY = DELY0
DZDEZ = 0.
DZDEZD = 0.
ETAZ = ETAZ0
DPSDE = 0.
ETAPS = ETAPS0

FADE TO THE NEUTRAL POSITION USING SECOND ORDER FILTER TO PROVIDE VELOCITY AND ACCELERATION CONTROL.

DRIVE X TO NEUTRAL POSITION (X = 0)

XDDF = -X - TWOZOMGN*XD
XDD = CLIMIT(XDDF,-XDDLIM,XDDLIM)
XDF = XD + XDD*H
XD = CLIMIT(XDF,-XDLIM,XDLIM)
X  = X + XD*H

DRIVE Y TO NEUTRAL POSITION (Y = 0)

YDDF = -Y - TWOZOMGN*YD
YDD = CLIMIT(YDDF,-YDDLIM,YDDLIM)
YDF = YD + YDD*H
YD = CLIMIT(YDF,-YDLIM,YDLIM)
Y  = Y + YD*H

DRIVE Z TO NEUTRAL POSITION (Z = 0)

ZDDF = -Z - TWOZOMGN*ZD
ZDD = CLIMIT(ZDDF,-ZDDLIM,ZDDLIM)
ZDF = ZD + ZDD*H
ZD = CLIMIT(ZDF,-ZDLIM,ZDLIM)
Z  = Z + ZD*H

DRIVE PSI TO NEUTRAL POSITION (PSI = 0)

PSIDDF = -PSI - TWOZOMGN*PSID
PSIDDFL = CLIMIT(PSIDDF,-PSIDDLIM,PSIDDLIM)
PSIDF = PSID + PSIDDFL*H
PSID = CLIMIT(PSIDF,-PSIDLIM,PSIDLIM)
PSI  = PSI + PSID*H

DRIVE THETA TO NEUTRAL POSITION (THETA = 0)

THEDDF = -THE - TWOZOMGN*THED
THEDDFL = CLIMIT(THEDDF,-THEDDLIM,THEDDLIM)
THEDF = THED + THEDDFL*H
THED = CLIMIT(THEDF,-THEDLIM,THEDLIM)
THE  = THE + THED*H

DRIVE PHI TO NEUTRAL POSITION (PHI = 0)

PHIDDF = -PHI - TWOZOMGN*PHID
PHIDDFL = CLIMIT(PHIDDF,-PHIDLIM,PHIDLIM)
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
8.15. 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
      BIGA=A(IJ)
      IMAX=I
   20   CONTINUE
   IF(ABS(BIGA)-TOL) 35,35,40
   35   KS=1
   RETURN
  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
         A(IXJX)=A(IXJX)-(A(IXJ)*A(JJX))
  60   B(IX)=B(IX)-(B(J)*A(IXJ))
  65  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
8.16. state4.f

NONLINEAR STATE SPACE FILTERS (ALL IN INERTIAL FRAME):

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)

ROLL AND PITCH UNITY GAIN FILTERS

BSDR(1)=BADNO(1)
BSDR(2)=BADNO(2)

9TH ORDER SURGE/PITCH STATE SPACE FILTER

DO I=1,6
  DO J=1,6
    K1X(I,J)=R2IX(I)*((BVX(1,1)*PX(1,J)+BVX(2,1)*PX(2,J)+BVX(3,1)*PX(3,J)+BVX(4,1)*PX(4,J)+BVX(5,1)*PX(5,J)+BVX(6,1)*PX(6,J)+DQCX(J))
    ABK1X(I,J)=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(I,J)=R2IX(I)*((BVX(1,1)*PX(1,J+6)+BVX(2,1)*PX(2,J)+BVX(3,1)*PX(3,J)+BVX(4,1)*PX(4,J)+BVX(5,1)*PX(5,J)+BVX(6,1)*PX(6,J)+DQCX(J))
    BK2X(I,J)=BVX(I,1)*K2X(1,J)+BVX(I,2)*K2X(2,J)
  END DO
END DO

K3X(1)=R2IX(1)*((BVX(1,1)*PX(1,11)+BVX(2,1)*PX(2,11)+BVX(3,1)*PX(3,11)+BVX(4,1)*PX(4,11)+BVX(5,1)*PX(5,11)+BVX(6,1)*PX(6,11))
K3X(2) = R2IX(2) *
K3X(2) = (BVX(1, 2) * PX(1, 11) + BVX(2, 2) * PX(2, 11) + BVX(3, 2) * PX(3, 11)
+ BVX(4, 2) * PX(4, 11) + BVX(5, 2) * PX(5, 11) + BVX(6, 2) * PX(6, 11)
+ 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 * (ABK1X(I, 1) * XXO(1) + ABK1X(I, 2) * XXO(2) + ABK1X(I, 3) * XXO(3)
+ ABK1X(I, 4) * XXO(4) + ABK1X(I, 5) * XXO(5) + ABK1X(I, 6) * XXO(6)
- BK2X(I, 1) * XXO(7) - BK2X(I, 2) * XXO(8) - BK2X(I, 3) * XXO(9)
- BK3X(I) * A2NO(1))
END DO

XXI1(7) = DT * XXO(8)
XXI1(8) = DT * XXO(9)

DO I = 1, 6
    XX12(I) = DT *
(ABK1X(I, 1) * (XXO(1) + XXI1(1)) + ABK1X(I, 2) * (XXO(2) + XXI1(2))
+ ABK1X(I, 3) * (XXO(3) + XXI1(3)) + ABK1X(I, 4) * (XXO(4) + XXI1(4))
+ ABK1X(I, 5) * (XXO(5) + XXI1(5)) + ABK1X(I, 6) * (XXO(6) + XXI1(6))
- BK2X(I, 1) * XXO(7) - BK2X(I, 2) * XXO(8) - BK2X(I, 3) * XXO(9)
- BK3X(I) * A2NO(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))
- K1X(2, 2) * (XXO(2) + XXI1(2)) - K1X(2, 3) * (XXO(3) + XXI1(3))
- K1X(2, 4) * (XXO(4) + XXI1(4)) - K1X(2, 5) * (XXO(5) + XXI1(5))
- K1X(2, 6) * (XXO(6) + XXI1(6)) - K2X(2, 1) * (XXO(7) + XXI1(7))
- K2X(2, 2) * (XXO(8) + XXI1(8)) - K2X(2, 3) * (XXO(9) + XXI1(9))
- K3X(2) * A2NO(1))

DO I = 1, 9
    XX(I) = XXO(I) + 0.5 * (XXI1(I) + XXI2(I))
END DO

C

9TH ORDER SWAY/ROLL STATE SPACE FILTER
C

DO I = 1, 6
    DO J = 1, 6
        K1Y(I, J) = R2IY(I) *
(BVY(1, 1) * PY(1, J) + BVY(2, 1) * PY(2, J) + BVY(3, 1) * PY(3, J)
+ BVY(4, 1) * PY(4, J) + BVY(5, 1) * PY(5, J) + BVY(6, 1) * PY(6, J)
+ DQCY(J))
K1Y(2, J) = R2IY(2) *
(BVY(1,2) * PY(1, J) + BVY(2, 2) * PY(2, J) + BVY(3, 2) * PY(3, J)
+ BVY(4, 2) * PY(4, J) + BVY(5, 2) * PY(5, J) + BVY(6, 2) * PY(6, J)
+ PY(9, J))

ABK1Y(I, J) = 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) * (BVY(1, 1) * PY(1, J+6) + BVY(2, 1) * PY(2, J+6) + BVY(3, 1) * PY(3, J+6)
    + 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) * (BVY(1, 2) * PY(1, J+6) + BVY(2, 2) * PY(2, J+6) + BVY(3, 2) * PY(3, J+6)
    + BVY(4, 2) * PY(4, J+6) + BVY(5, 2) * PY(5, J+6) + BVY(6, 2) * PY(6, J+6)
    + 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) * (BVY(1, 1) * PY(1, 11) + BVY(2, 1) * PY(2, 11) + BVY(3, 1) * PY(3, 11)
    + BVY(4, 1) * PY(4, 11) + BVY(5, 1) * PY(5, 11) + BVY(6, 1) * PY(6, 11))

K3Y(2) = R2IY(2) * (BVY(1, 2) * PY(1, 11) + BVY(2, 2) * PY(2, 11) + BVY(3, 2) * PY(3, 11)
    + BVY(4, 2) * PY(4, 11) + BVY(5, 2) * PY(5, 11) + BVY(6, 2) * PY(6, 11)
    + 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 * (ABK1Y(I, 1) * XYO(1) + ABK1Y(I, 2) * XYO(2) + ABK1Y(I, 3) * XYO(3)
    + ABK1Y(I, 4) * XYO(4) + ABK1Y(I, 5) * XYO(5) + ABK1Y(I, 6) * XYO(6)
    - BK2Y(I, 1) * XYO(7) - BK2Y(I, 2) * XYO(8) - BK2Y(I, 3) * XYO(9)
    - BK3Y(I) * A2NO(2))
END DO

XYI1(7) = DT * XYO(8)
XYI1(8) = DT * XYO(9)
XYI1(9) = DT *

  (- K1Y(2, 1) * XYO(1) - K1Y(2, 2) * XYO(2) - K1Y(2, 3) * XYO(3)
  - K1Y(2, 4) * XYO(4) - K1Y(2, 5) * XYO(5) - K1Y(2, 6) * XYO(6)
  - K2Y(2, 1) * XYO(7) - K2Y(2, 2) * XYO(8) - K2Y(2, 3) * XYO(9)
  - K3Y(2) * A2NO(2))

DO I=1, 6
  XYI2(I) = DT * (ABK1Y(I, 1) * (XYO(1) + XYI1(1)) + ABK1Y(I, 2) * (XYO(2) + XYI1(2))
    + ABK1Y(I, 3) * (XYO(3) + XYI1(3)) + ABK1Y(I, 4) * (XYO(4) + XYI1(4))
    + ABK1Y(I, 5) * (XYO(5) + XYI1(5)) + ABK1Y(I, 6) * (XYO(6) + XYI1(6)))

103
\[
\begin{align*}
\text{x} & \quad -BK2Y(I,1)*(XYO(7)+XYI1(7)) - BK2Y(I,2)*(XYO(8)+XYI1(8)) \\
\text{x} & \quad -BK2Y(I,3)*(XYO(9)+XYI1(9)) - BK3Y(I)*A2N(2)) \\
\end{align*}
\]

END DO

\[
\begin{align*}
XYI2(7) &= DT*(XYO(8)+XYI1(8)) \\
XYI2(8) &= DT*(XYO(9)+XYI1(9)) \\
XYI2(9) &= DT*(-K1Y(2,1)*(XYO(1)+XYI1(1))) \\
\text{x} & \quad -K1Y(2,2)*(XYO(2)+XYI1(2)) - K1Y(2,3)*(XYO(3)+XYI1(3)) \\
\text{x} & \quad -K1Y(2,4)*(XYO(4)+XYI1(4)) - K1Y(2,5)*(XYO(5)+XYI1(5)) \\
\text{x} & \quad -K1Y(2,6)*(XYO(6)+XYI1(6)) - K2Y(2,1)*(XYO(7)+XYI1(7)) \\
\text{x} & \quad -K2Y(2,2)*(XYO(8)+XYI1(8)) - K2Y(2,3)*(XYO(9)+XYI1(9)) \\
\text{x} & \quad -K3Y(2)*A2N(2)) \\
\end{align*}
\]

DO I=1,9

\[
\begin{align*}
XY(I) &= XYO(I) + 0.5*(XYI1(I)+XYI2(I)) \\
\end{align*}
\]

END DO

\[
\begin{align*}
5^\text{TH ORDER HEAVE STATE SPACE FILTER} \\
\text{C} \\
\text{C} \\
K1Z(1) &= BVZ(1)*PZ(1,1) + BVZ(2)*PZ(2,1) + PZ(5,1) \\
K1Z(2) &= BVZ(1)*PZ(1,2) + BVZ(2)*PZ(2,2) + PZ(5,2) \\
K2Z(1) &= BVZ(1)*PZ(1,3) + BVZ(2)*PZ(2,3) + PZ(5,3) \\
K2Z(2) &= BVZ(1)*PZ(1,4) + BVZ(2)*PZ(2,4) + PZ(5,4) \\
K2Z(3) &= BVZ(1)*PZ(1,5) + BVZ(2)*PZ(2,5) + PZ(5,5) \\
K3Z &= BVZ(1)*PZ(1,6) + BVZ(2)*PZ(2,6) + PZ(5,6) \\
\end{align*}
\]

DO I=1,2

\[
\begin{align*}
XZI1(I) &= DT* \left( (AVZ(I,1) - BVZ(I)*K1Z(1))*XZO(I) + (AVZ(I,2) - BVZ(I)*K1Z(2))*XZO(2) \\
\text{x} & \quad -BVZ(I)*(K2Z(1)*XZO(3) + K2Z(2)*XZO(4) + K2Z(3)*XZO(5)) \\
\text{x} & \quad -BVZ(I)*(1+K3Z)*A2NO(3) \right) \\
\end{align*}
\]

END DO

\[
\begin{align*}
XZI1(3) &= DT*XZO(4) \\
XZI1(4) &= DT*XZO(5) \\
XZI1(5) &= DT*(-K1Z(1)*XZO(1) - K1Z(2)*XZO(2) - K2Z(1)*XZO(3) - K2Z(2)*XZO(4) - K2Z(3)*XZO(5) - K3Z*A2NO(3)) \\
\end{align*}
\]

DO I=1,2

\[
\begin{align*}
XZI2(I) &= DT* \left( (AVZ(I,1) - BVZ(I)*K1Z(1))*XZO(1) + XZI1(I) \right) + (AVZ(I,2) - BVZ(I)*K1Z(2))*XZO(2) + XZI1(2) \\
\text{x} & \quad -BVZ(I)*(K2Z(1)*(XZO(3)+XZI1(3)) + K2Z(2)*(XZO(4)+XZI1(4)) + K2Z(3)*(XZO(5)+XZI1(5))) \\
\text{x} & \quad -BVZ(I)*(1+K3Z)*A2N(3) \right) \\
\end{align*}
\]

END DO

\[
\begin{align*}
XZI2(3) &= DT*(XZO(4)+XZI1(4)) \\
XZI2(4) &= DT*(XZO(5)+XZI1(5)) \\
XZI2(5) &= DT*(-K1Z(1)*(XZO(1)+XZI1(1)) - K1Z(2)*(XZO(2)+XZI1(2)) - K2Z(1)*(XZO(3)+XZI1(3)) - K2Z(2)*(XZO(4)+XZI1(4)) - K2Z(3)*(XZO(5)+XZI1(5)) - K3Z*A2N(3)) \\
\end{align*}
\]

DO I=1,5

\[
\begin{align*}
XZ(I) &= XZO(I) + 0.5*(XZI1(I)+XZI2(I)) \\
\end{align*}
\]

END DO

\[
\begin{align*}
\text{C} \\
\end{align*}
\]
4TH ORDER YAW STATE SPACE FILTER

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

*************** UPDATE ALL THE DUMMY VARIABLES: ***********************

DO I=1,9
  XXO(I)=XX(I)
  XYO(I)=XY(I)
END DO

DO I=1,5
  XZO(I)=XZ(I)
END DO

DO I=1,4
  XRO(I)=XR(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
8.17. vmult.f

```
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
```
**8.18. washopt3.f**

```
C***** SUBROUTINE WASHOPT3.FOR *****

OPTIMAL WASHOUT ALGORITHM: ANG. VELOCITY DEVELOPMENT.
GIVEN A/C ACCELS ACA AND EULER RATES BETAAD,
COMPUTE SIMULATOR INERTIAL DISPLACEMENT AND EULER ANGLES.

SUBROUTINE WASHOPT3(MODE)

INCLUDE 'comint2.com'
INCLUDE 'wcom2.com'
INCLUDE 'optint3.com'
INCLUDE 'wopt3.com'
INCLUDE 'matrix1c.com'

C Compute Fairing Parameters

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 Fairing of Heave Nonlinear Gain and Limit

GZ3(1)=AA*GZ30(1)+SQWASHI*GZ3S(1)
GZ3(2)=AA*GZ30(2)+SQWASHI*GZ3S(2)
GZ3(3)=AA*GZ30(3)+SQWASHI*GZ3S(3)
AMX3=AA*AMX30+SQWASHI*AMX3S

C Fairing of Runway Roughness Amplitude

XKA=A*XKA0+SQWASHP*XKAS

IF(MODE.EQ.1) THEN
  H = DT
ENDIF

C Set "old" variables for future use in OFIL3

DO I=1,3
  A2NO(I)=0.
  BADNO(I)=0.
END DO

DO I=1,8
  X1O(I)=0.
  X2O(I)=0.
  X3O(I)=0.
  X4O(I)=0.
```

108
END DO

DO I=1,6
   X50(I)=0.
   X60(I)=0.
END DO

CALL RESETC2

C Set "old" variables for future use in HOLD and OPERATE modes
C
ASIO(1)=XDD
ASIO(2)=YDD
ASIO(3)=ZDD
VSIO(1)=XD
VSIO(2)=YD
VSIO(3)=ZD
SSIO(1)=X
SSIO(2)=Y
SSIO(3)=Z
BETASRO(1)=PHI
BETASRO(2)=THE
BETASRO(3)=PSI
BSDRO(1)=PHID
BSDRO(2)=THED
BSDRO(3)=PSID

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) CALL WTRIM3

C Compute Augmented Acceleration from W-Gust
C
IF(MODE.EQ.3) THEN
   WGAV=0.5*(WGUST+WGUSTO)
   XT=XTO+DT*(-G1D1*XTO+XT2O+(G1N1-G1D1*G1N2)*WGAV)
   XTAV=0.5*(XT+XTO)
   XT2=XT2O+DT*(-G1D0*XTAV+(G1N0-G1D0*G1N2)*WGAV)
   ACZT=XT+G1N2*WGUST
   XTO=XT
   XT2O=XT2
   WGUSTO=WGUST
C (first-order turbulence model no longer used)
C
C  XT=XT0+DT*(-G1D0*XT0+(G1N0-G1D0*G1N1)*WGUST0)
C  ACZT=XT+G1N1*WGUST0
C  XTO=XT
C  WGUSTO=WGUST
END IF

CALL LIBA
CALL GAINOPT3
  A2N(3)=A2N(3)+GT2*ACZT

CALL OFIL3

IF (MODE.EQ.3) CALL INTEG3

1 RETURN
END
8.19. winit2.f

SUBROUTINE WINIT2
C
C THIS ROUTINE LOADS THE INITIAL VALUES INTO THE WASHOUT
C PARAMETER ARRAYS.

INCLUDE 'comint2.com'
INCLUDE 'wcom2.com'
INCLUDE 'optint3.com'
INCLUDE 'wopt3.com'
INCLUDE 'matrix1c.com'
REAL DERIV(64)
C
EQUIVALENCE (DERIV (1), THESDD )
C
C initialization of adaptive algorithm derivatives
C
DO 10 I = 1,64
   DERIV(I) = 0.
10 CONTINUE
C
C***************************** WU **********************************
C NOTE: RX,RY,RZ HAVE DIFFERENT MEANING FROM THOSE IN UTIAS REPORT.
C R IS THE VECTOR FROM C.G. TO CENTROID OF A/C.
C RX = SSIN(1)
C RY = SSIN(2)
C RZ = SSIN(3)
DATA RX/0./, RY/0./, RZ/0./
*************************************************************
C
C FOR 737 MOTION BASE RX,RY,RZ = 12.192,0.2286,1.7399
C
C INTEGRATION CONSTANTS
C
C**********changed by wu**********
DATA T /0./
DATA INT /0/
DATA NEQ /30/
C********** Changed by wu **********
C** GAINS ARE CHANGED FOR CONVENIENCE OF COMPARISON
C** BETWEEN NASA & ADAPTIVE ALGORITHMS.
C DATA X1 /3.6576/
C DATA SX0 /0.500/
C DATA Y1 /2.4384/
C DATA SY0 /0.50/
C DATA Z1 /1.2192/
C DATA SZ0 /0.50/
DATA X1 /3.6576/
DATA SX0     /1.0/
DATA Y1      /2.4384/
DATA SY0     /1.0/
DATA Z1      /1.2192/
DATA SZ0     /1.0/
C*****************************************************
DATA P1      /.18/
DATA SP0     /1.0/
DATA Q1      /.5/
DATA SQ0     /1.0/
DATA R1      /.15/
DATA SR0     /1.0/
C
C   LONGITUDINAL PARAMETERS
C
DATA WX      /0.00929/
DATA BX      /0.01/
DATA CX      /.2/
DATA DX      /.707/
DATA EX      /.25/
DATA GAMX    /.1640419948/
DATA KLX     /.3229173125/
DATA KDX     /.0107639104/
DATA KILX    /.02/
DATA KIDX    /.5/
DATA LAMXL   /-.1/
DATA LAMXU   /1./
DATA DELXL   /0./
DATA DELXU   /1./
DATA LAMXDL  /-.06/
DATA DELXDL  /-1000./
DATA LAMX0   /1.0/
DATA DELX0   /0.5/
C
C     LATERAL PARAMETERS
C
DATA WY      /0.00929/
DATA BY      /0.1/
DATA CY      /2.0/
DATA DY      /1.2727/
DATA EY      /0.81/
C************** CHANGE BY WU **************
C DATA GAMY    /0.0328084/
DATA GAMY    /.1640419948/
C************************************
DATA KLY     /0.516668/
DATA KDY     /0.269098/
DATA KILY    /.05/
DATA KIDY    /1.5/
DATA LAMYL   /-.1/
DATA LAMYU   /.8/
DATA DELYL   /0./
DATA DELYU   /.3/
DATA LAMYDL  /-.06/
DATA DELYDL  /-.2/
DATA LAMY0   /0.8/
DATA DELY0   /0.3/
C
C    DATA WY      /1500./
C    DATA BY      /400.0/
C    DATA CY      /100.0/
C    DATA DY      /12.80/
C    DATA EY      /10.24/
C    DATA GAMY    /0.05/
C    DATA KLY     /0.085/
C    DATA KDY     /0.15/
C    DATA KILY    /.05/
C    DATA KIDY    /1.5/
C    DATA LAMYL   /-.1/
C    DATA LAMYU   /.2/
C    DATA DELYL   /0./
C    DATA DELYU   /.3/
C    DATA LAMYDL  /-.06/
C    DATA DELYDL  /-.04/
C    DATA LAMY0   /0.2/
C    DATA DELY0   /0.3/
C
C VERTICAL PARAMETERS
C
DATA BZ      /.1/
DATA CZ      /0.1/
DATA DZ      /1.2727/
DATA EZ      /.81/
DATA KEZ     /.516669/
DATA KIEZ    /.05/
DATA ETAZL   /0./
DATA ETAZU   /.25/
DATA ETAZDL  /-.06/
DATA ETAZ0   /.25/
C
C YAW PARAMETERS
C
DATA BPS     /1.0/
DATA EPS     /0.3/
DATA KEPS   /100.0/
DATA KIEPS  /0.1/
DATA ETAPSU /1.0/
DATA ETAPSL /0.0/
DATA ETAPSDL /-.4/
DATA ETAPS0  /1.0/

TOUCHDOWN PARAMETERS

DATA KLXS    /3.229173125/
DATA KILXS   /.1/
DATA LAMXDSL /-.1/
DATA LAMX0S  /1.0/
DATA WYS     /.009290304/
DATA BYS     /.01/
DATA CYS     /.2/
DATA DYS     /.707/
DATA EYS     /.25/
DATA GAMYS   /.1640419948/
DATA KLYS    /3.229173125/
DATA KILYS   /-.1/
DATA LAMYSL  /-.1/
DATA LAMYUS  /1.0/
DATA LAMYDLS /-.1/
DATA LAMY0S  /1.0/
DATA ETAZUS  /0.5/
DATA ETAZ0S  /0.5/

FLIGHT PARAMETERS

KLX0    = KLX
KILX0   = KILX
LAMXDL0 = LAMXDL
LAMX00  = LAMX0
WY0     = WY
BY0     = BY
CY0     = CY
DY0     = DY
EY0     = EY
GAMY0   = GAMY
KLY0    = KLY
KILY0   = KILY
LAMYL0  = LAMYL
LAMYU0  = LAMYU
LAMYDL0 = LAMYDL
LAMY00  = LAMY0
ETAZU0  = ETAZU
ETAZ00  = ETAZ0

Runway Roughness Parameters

DATA XKA0/0.0/,XKAS/0.00027/,WB/30.0/,XKG/0.1/

Fairing Parameters
DATA SQWASHI/0.0/, EA/0.939413/, SQWASHP/0.0/

COMPENSATION TERMS

DATA CCXA / .0069/
DATA CCYA / .0069/
DATA CCZA / .0069/
DATA CCXV / .15/
DATA CCYV / .15/
DATA CCZV / .133/
DATA CCPS / .12/
DATA CCTH / .12/
DATA CCPH / .12/

GRAVITATIONAL CONSTANT

DATA G / 9.806178/

Initialization of Optimal Algorithm Inputs

DATA SSI1/3*0.0/, VSI/3*0.0/, BETAS1/3*0.0/

Initialization of Dummy Variables

DATA A2NO/3*0./, BADNO/3*0./
DATA X1O/8*0./, X2O/8*0./, X3O/8*0./, X4O/8*0./
DATA X5O/6*0./, X6O/6*0./
DATA SSIO/3*0.0/, VSIO/3*0.0/, ASIO/3*0./
DATA BSDTO/2*0.0/, BSDRO/3*0.0/
DATA BETASRO/3*0.0/, BETASTO/2*0.0/, BETASTLO/2*0.0/
DATA XHO/2*0.0/, ACAO/2*0.0/
DATA T1N1,T1D0,T2N1,T2D0/-0.019,0.333333,0.019,0.333333/

Tilt Coordination Limit

DATA BDLIM/0.0873/

Nonlinear Scaling Coefficients

DATA GX/0.6,-0.046,0.0014/
DATA GY/0.6,-0.064,0.0026/
DATA GZ0/0.6,-0.082,0.0038/
DATA GZS/0.6,-0.01,0.0/
DATA GP/1.0,-1.35,0.6/
DATA GQ/1.0,-0.5,0.0/
DATA GR/1.1,-1.46,0.64/

Translational and Rotational Limits

DATA AMX0/10./, BMX/1./, AMXS/50./

Parameters for optimal roll/sway channel filters.

DATA R1N6,R1N5,R1N4,
   + R1N3,R1N2,R1N1,R1N0,
   + R2N6,R2N5,R2N4,
   + R2N3,R2N2,R2N1,R2N0,
+ R4N6,R4N5,R4N4,
+ R4N3,R4N2,R4N1,R4N0,
+ R1D5,R1D4,
+ R1D3,R1D2,R1D1,R1D0/
+ 1.0006, 15.9733, 42.0572,
+ 56.8102, 43.5211, 16.2283, 1.2344,
+ -0.0008, -1.1663, -4.7183,
+ -3.5599, -1.2765, -0.0785, 0.0000,
+ 3.4188, 24.4014, 29.7868,
+ -0.0048, 0.0000, 0.0000, 0.0000,
+ 16.3952, 43.7546,
+ 58.6718, 44.7900, 16.7041, 1.2927/

C Parameters for optimal pitch/surge channel filters.

DATA P1N6,P1N5,P1N4,
+ P1N3,P1N2,P1N1,P1N0,
+ P2N6,P2N5,P2N4,
+ P2N3,P2N2,P2N1,P2N0,
+ P4N6,P4N5,P4N4,
+ P4N3,P4N2,P4N1,P4N0,
+ P1D5,P1D4,
+ P1D3,P1D2,P1D1,P1D0/
+ 1.0006, 15.9733, 42.0572,
+ 56.8102, 43.5210, 16.2282, 1.2344,
+ 0.0008, 1.1663, 4.7183,
+ 3.5599, 1.2765, 0.0785, -0.0000,
+ 3.4188, 24.4014, 29.7868,
+ -0.0048, 0.0000, 0.0000, 0.0000,
+ 16.3952, 43.7546,
+ 58.6718, 44.7900, 16.7041, 1.2927/

C Parameters for optimal yaw channel filters.

DATA Y1N4,Y1N3,Y1N2,Y1N1,Y1N0,
+ Y1D3,Y1D2,Y1D1,Y1D0/
+ 0.9734, 11.7588, 1.6345, 0.0000, 0.0000,
+ 17.1168, 10.1205, 1.4510, 0.0232/

C Parameters for optimal heave channel filters.

DATA H1N4,H1N3,H1N2,H1N1,H1N0,
+ H1D3,H1D2,H1D1,H1D0/
+ 0.2779, 0.0540, 0.0000, 0.0000, 0.0000,
+ 1.5321, 1.1124, 0.2736, 0.0209/

C Nonlinear Scaling Coefficients

DATA GX3/0.6,-0.055,0.002/
DATA GY3/0.5,-0.055,0.002/
DATA GZ30/0.6,-0.082,0.0038/
DATA GZ3S/1.3,-0.0375,0.0003/
DATA GP3/0.3,-0.3,0.1/
DATA GQ3/0.4,-0.54,0.26/
DATA GR3/1.1,-1.46,0.64/

Translational and Rotational Limits
DATA AMX30/10.,BMX3/1.,AMX3S/20./

Augmented Turbulence Parameters
DATA G1D0,G1D1,G1N0,G1N1,G1N2
+ /25.0,12.5,2.5,12.0,14.4/
DATA XTO,XT20/2*0.0/,WGUSTO/0.0/,ACZT/0.0/
DATA GT2/0.8/

RETURN
END
8.20. winit4.f

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

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 BRBZVEC(21),R1PZVEC(21),ZZVEC(21)
C
C Initialization of Nonlinear Algorithm Inputs
C
DATA XXO/9*0.,XYO/9*0.,XRO/4*0.,XZO/5*0./
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,  0.4358518,  -2.00719798,  2.3016934,
+   0.92719057,  0.0000,  0.0000,  0.0000,  0.0000,  0.0000,
+   0.00000000,  0.00000000,  0.00000000,  -0.50000000,  0.50000000,
+  -0.00000000,  0.00000000,  0.00000000,  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, -0.0975847,
+   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,  0.00000000,  0.00000000,  0.00000000,  0.00000000,
+   0.00000000,  0.00000000,  0.00000000,  0.00000000,  0.00000000,
+   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, -1.0000000,  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, -0.0027616,  0.26791584, -0.2681675,
+  -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,
+   0.0012583,  0.0000,  0.0000,  -0.0000000,  0.0000,  0.0000,
+   0.0516003, -0.0580338,
+  -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,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 1.00000000, 0.0000, 0.0000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 0.0000, 0.0000, 0.00000000, 0.0000, 0.0000, 0.0000,
+ 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, 23.81195147, 33.64457162, 29.33323432, -0.00748064,
+ 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)
END DO
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
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, -2.38099104,  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,
  +  0.00000000,  0.00000000,  0.00000000,  0.00000000,  0.00000000,
  +  0.00000000,  0.00000000,  0.00000000,  0.00000000,  0.00000000,
  +  0.00000000,  0.00000000,  0.00000000,  0.00000000,  0.00000000,
  +  0.00000000,  1.0000,  0.0000,  0.0000,  0.0000,  0.0000,
  +  0.00000000,  0.0000,  1.0000,  0.0000,  0.0000,  0.0000,
<table>
<thead>
<tr>
<th>DATA PXVEC /</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 8.30351624,</td>
</tr>
<tr>
<td>+ 8.09520238, 1.68093020, -4.48023672, 3.57953908, -8.19270520,</td>
</tr>
<tr>
<td>+ -8.31577879, -20.67790997, -24.24095727, -0.01780137, -6.16084104,</td>
</tr>
<tr>
<td>+ 8.45574766, 1.51070523, -3.37329594, 4.57329645, -7.94167444,</td>
</tr>
<tr>
<td>+ -8.30831437, -20.63973845, -24.12921925, -0.01780718, -6.12895412,</td>
</tr>
<tr>
<td>+ 0.71635788, -0.98991751, 1.20003026, -2.39658160,</td>
</tr>
<tr>
<td>+ -1.74100084, -4.45442250, -5.9861393, -0.02613645, -1.44219625,</td>
</tr>
<tr>
<td>+ 4.49770413, 0.18951117, 4.17497242,</td>
</tr>
<tr>
<td>+ 4.01767838, 10.33185268, 12.56415459, 0.02169120, 3.19600160,</td>
</tr>
<tr>
<td>+ 5.44431336, -4.99112805,</td>
</tr>
<tr>
<td>+ -4.13378917, -10.88195613, -13.90068610, -0.02161095, -3.56872382,</td>
</tr>
<tr>
<td>+ 9.64863006,</td>
</tr>
<tr>
<td>+ 8.43067234, 21.23134650, 25.64717081, 0.01771985, 6.55535001,</td>
</tr>
<tr>
<td>+ 23.81195147, 33.64457162, 29.3323432, 0.00748064, 6.63816656,</td>
</tr>
<tr>
<td>+ 71.85128707, 71.5609170, 0.03103290, 16.77905545,</td>
</tr>
<tr>
<td>+ 82.30634518, 0.06573714, 19.98961531,</td>
</tr>
<tr>
<td>+ 0.49999450, 0.01797396,</td>
</tr>
<tr>
<td>+ 5.06794969/</td>
</tr>
</tbody>
</table>

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 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, 
+ 7.99212948E-004, 0.0, 
+ 0.0/
DATA R1PRVEC /
+ 7.99212948E-004, 0.0, 7.99212948E-004, 0.0, -2.79035083E-002, 
+ 0.00000000E+000, 0.0, 0.00000000E+000, 0.0, 
+ 7.99212948E-004, 0.0, -2.79035083E-002, 
+ 2.00000000E+002, 0.0, 
+ 9.99220787E-001/
DATA R2IR /7.99212948E-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 /-6.9716293E+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, 1.57135777, 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
  BRRBR(I,J)=BRBRVEC((J-1)*5-J*(J-1)/2+I)
  BRRBR(J,I)=BRRBR(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

Parameters for nonlinear heave channel filters.

123
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, 0.000000,

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,
  + 1.000000/

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, 0.0000,
  + 1.0, -1.0, -1.0, -1.0, -1.0, 0.0000,
  + 1.0, -1.0, -1.0, -1.0, 0.0000,
  + 1.0, -1.0, 0.0000,
  + 1.0, 0.0000,
  + 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)
END DO

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

c Nonlinear Scaling Coefficients
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/

Translational and Rotational Limits

DATA AMX40/10./,BMX4/1./,AMX4S/20./

Augmented Turbulence Parameters

DATA G2D0,G2D1,G2N0,G2N1,G2N2 +/25.0,12.5,2.5,12.0,14.4/
DATA GT4/1.2/

RETURN
END
SUBROUTINE WTRIM3

C     THIS ROUTINE USES TILT ANGLES TO TRIM OUT ANY INITIAL
C     STEADY-STATE LONGITUDINAL OR LATERAL ACCELERATIONS
C
INCLUDE 'optint3.com'

INCLUDE 'comint2.com'

C First-Order Washout Filters to Obtain Angular Rates
C
XH(1)=XHO(1)+DT*(-T1D0*(XHO(1)+T1N1*ACAO(2)))
BSDT(1)=XH(1)+T1N1*ACA(2)
XH(2)=XHO(2)+DT*(-T2D0*(XHO(2)+T2N1*ACAO(1)))
BSDT(2)=XH(2)+T2N1*ACA(1)

C Integrate Rates to Obtain Angular Displacements
C
DO K=1,2
   BETAST(K)=BETASTO(K)+DT*0.5*(BSDT(K)+BSDTO(K))
   BSDTO(K)=BSDT(K)
   BETASTO(K)=BETAST(K)
   BETASTLO(K)=BETASTO(K)
   XHO(K)=XH(K)
   ACAO(K)=ACA(K)
END DO

C Assign Variable Names To Match Modified Algorithm
C For Input to JACKDRVR
C
PHI = BETAST(1)
THE = BETAST(2)
PHID = BSDT(1)
THED = BSDT(2)

RETURN
END
Appendix A. Actuator Extension Limiting

There exists the possibility that, without restriction, the output of the cueing algorithm may drive the motion platform beyond its hardware limits. This raises the requirement that the simulation software should be able to handle the situation that the motion platform may need to be arrested before encountering the hardware limits. A braking algorithm was developed [6] to perform this task. When approaching the hardware limits, the braking algorithm takes over the control of the motion platform from the motion cueing algorithm. It is also necessary that the braking algorithm return control to the cueing algorithm when the cueing algorithm begins to drive the platform toward smaller excursions. In other words, the braking algorithm should release the motion platform to gradually resume normal function.

The logic of the braking algorithm is shown in Figure A.1. The algorithm makes a series of decisions to determine when to arrest, or “brake” the platform and while “braked”, to determine when to release the brake. The first decision is based on an evaluation of the expression $2b_0a_bl_{avail} - \dot{l}^2$ for each actuator at each simulation cycle, where $\dot{l}$ is the velocity of the actuator, $l_{avail}$ is the available actuator length, i.e. the difference between the maximum and computed actuator extensions, $a_b$ is the deceleration by which the braking algorithm will slow down (and stop) the actuator, and $b_0$ is a coefficient set less than or equal to 1 that is described below. When one actuator reaches the braking region defined by

$$2b_0a_bl_{avail} - \dot{l}^2 \leq 0,$$  \hspace{1cm} (A.1)

it will be decelerated by $a_b$. At the same time, all the other actuators will be decelerated proportionally to their respective velocities.
Figure A.1. Braking Algorithm in the JACKDRVR Subroutine.
The braking deceleration $a_b$, noted by the variable ACMAX in Figure A.1, should be set much smaller than the maximum actuator acceleration so that the perceptual effect of entering the braking region and stopping the motion platform is minimal. The braking algorithm sets a software limit position that is slightly before the simulator hardware limit position. When $b_0 = 1$, the actuator will be stopped exactly at the software limit position; when $b_0 < 1$, the actuator will be stopped before the software limit position.

From Eq. A.1, the available length $l_{avail}$ can be found as a function of the actuator velocity $\dot{n}$. Figure A.2 shows the available length for various combinations of the coefficient $b_0$ and deceleration $a_b$. Note that a reduction in the deceleration results in an increase in the available actuator length when entering the braking region. For smaller values of deceleration, larger values of $b_0$ are used to reduce the available length.

![Figure A.2. Available Actuator Length upon Entering the Braking Region.](image)

In order to “release” the brake, a decision is based on a comparison between the actual motion platform states and the cueing algorithm output. This comparison begins
when the platform has been completely stopped by the braking algorithm. When the

cueing algorithm output states become smaller than the corresponding actual platform
states, the braking algorithm will “release” the brake.

When the brake is released, the cueing algorithm output may have large velocities
while the simulator has small velocities at that instant. To avoid the normal cueing
algorithm output being resumed with any excessively large acceleration, an algorithm
that allows the simulator to gradually follow the washout algorithm output was
developed. The algorithm expresses the actuator extension command to the motion
platform as

\[
    l_{\text{com}} = l_{\text{act}} + f(t)(l_{\text{des}} - l_{\text{act}}),
\]

(A.2)

where \( l_{\text{com}} \) is the commanded actuator extension that drives the motion platform, \( l_{\text{act}} \) is the
actual extension of the actuator (limited by the braking algorithm), \( l_{\text{des}} \) is the desired
actuator extension generated by the cueing algorithm, and \( f(t) \) is a function of time.

During normal operation \( f(t) \) is set equal to one. After the brake is released \( f(t) \) is set
to zero and is gradually increased to one.
References


**4. TITLE AND SUBTITLE**

Motion Cueing Algorithm Development: New Motion Cueing Program Implementation and Tuning

**6. AUTHOR(S)**

Telban, Robert J.; Cardullo, Frank M.; and Kelly, Lon C.

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Unclassified - Unlimited

**13. SUPPLEMENTARY NOTES**


**14. ABSTRACT**

A computer program has been developed for the purpose of driving the NASA Langley Research Center Visual Motion Simulator (VMS). This program includes two new motion cueing algorithms, the optimal algorithm and the nonlinear algorithm. A general description of the program is given along with a description and flowcharts for each cueing algorithm, and also descriptions and flowcharts for subroutines used with the algorithms. Common block variable listings and a program listing are also provided. The new cueing algorithms have a nonlinear gain algorithm implemented that scales each aircraft degree-of-freedom input with a third-order polynomial. A description of the nonlinear gain algorithm is given along with past tuning experience and procedures for tuning the gain coefficient sets for each degree-of-freedom to produce the desired piloted performance. This algorithm tuning will be needed when the nonlinear motion cueing algorithm is implemented on a new motion system in the Cockpit Motion Facility (CMF) at the NASA Langley Research Center.

**15. SUBJECT TERMS**

Flight Simulation, Simulators, Motion Systems, Cueing Algorithms, Motion Perception