Chapter 1

Introduction

1.1 Flight Simulation

Flight simulation has developed during the 20th Century into a tool that has far reaching uses in Flight Training, research and crash investigation to name a few fields. This section provides a background to the development of the flight simulator. For more in depth material [31] and [1] are excellent sources.

1.1.1The Flight Simulator - Early Days

Since man first took to the air, the importance of simulation has been realised. By its very nature taking to the air in a machine is a costly venture. Aircraft cost money, fuel costs money, lives are irreplaceable. Flight simulation has developed over the last century as a means of reducing the cost of aviation, both in terms of the lives of pilots and passengers, as well as reducing hull losses and time spent airborne in expensive machines for the purposes of training.

Early simulators were designed to give novice pilots a feel for the air. Whilst today a student can study various subjects such as Aerodynamics and Flight Mechanics so as to prepare him for flight, early flight instruction was not so scientific. The basics of these subjects were of course known, but the best way to learn in the first decade of the last century seems to have been via trial and error, a dangerous way to learn. As aircraft performance increased and pilots were placed in greater danger every time they took to the skies, it was realised that some sort of ground based training aid was required. An article in Flight magazine sums up the problem:

> *"The invention therefore, of a device which will enable the novice to obtain a clear conception of the workings of the control of an aeroplane, and of the conditions existent in the air, without any risk personally or otherwise, is to be welcomed without a doubt." [1]*

One of the first such aids was the Sanders Teacher. Taken from gliding, it involved an aircraft mounted on a universal joint. The action of the prevailing wind allowed the Teacher to 'fly' in a limited sense in that the aircraft would respond to control inputs. Obviously, this relied heavily upon the wind at the time and as such was not a success.

A better move was a French device utilising two barrel halves mounted so as to allow rotation about both the pitch and roll axes. The inputs were made by the 'instructor', moving the system about these axes. It was the student pilot's job to keep an attached reference bar parallel to the horizon. In this way, the device replicated the pilot task of keeping the aircraft's wings level in response to atmospheric disturbances.

Such devices were also utilised during World War I for pilot selection. Again, as the instructor or in this case the testing officer inputted disturbances to the system, it was the job of the pilot to correct for these disturbances, returning the 'aircraft' to a stable attitude. The addition of an electrical recording device allowed records to be kept, an early version of a Flight Data Recorder perhaps. In a training exercise, this recording of data from a training session allows feedback to the pilot as to his or her performance. Whether or not useful training from these devices could be obtained is doubtful.

A development known as the Ruggles Orientator consisted of the pupil seated within a three degree of freedom[1] gimbal system. The device was also able to move in the Z axis, giving 4 degrees of freedom, or 4 DOF. In this device, all motions are produced by electrical motors in response to both Instructor and Student inputs. It was claimed that the device was useful for:

> *"Developing and training the functions of the semi-circular canals..."* [1]

as well as:

> *"so that the sense of direction may be sensitised without the assistance of the visual senses"* [1]

In effect saying that the problems of flying aircraft in reduced visibility or at night without reference to a visible horizon could be mastered by training in such a device. Today, it is known that such a claim is unsupportable, that flying in such conditions must in no way be predicated upon the feeling from the seat of one's pants.

All of the machines described so far in some way involved the student's interaction with the aircraft's dynamics through inputs from an instructor. In other words, the instructor is responsible for reacting to the student's control inputs as shown in Figure 1.

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[1] **A degree of freedom in this instance refers to the machine's ability to move around one axis. If it can rotate in Pitch, it has a degree of freedom about the lateral axis. A three degree of freedom machine as mentioned here can rotate in Pitch, Roll and Yaw. There are also three degrees of freedom in Translation. Heave, or movement in the Z axis (up and down) is a degree of freedom, as is Surge (X axis) and Sway (Y axis). Together they give us 6 degrees of freedom, or 6 DOF**

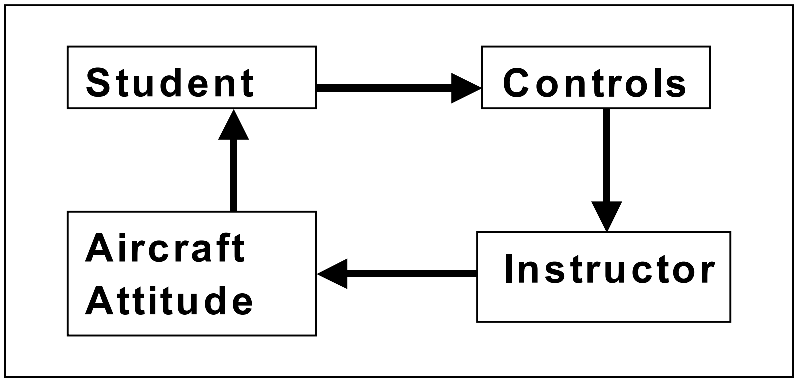

Figure 1 Open Loop Simulation

Obviously this is not the ideal way to operate as it relies on the instructor to replicate the dynamics of the aircraft after interpreting the student’s inputs.

Devices that removed the human operator from the aircraft dynamics loop began appearing in 1917, designed by Lender and Heidelberg [1]. Other devices followed with the best example being that constructed by Edwin Link between 1927 and 1929. Pneumatic bellows driving the device in Pitch, Roll and Yaw were driven by signals from control inputs. Another motor was used to provide disturbances for the student to practice with. This crude set-up provided a basic simulation of aircraft dynamics, as shown in Figure 2.

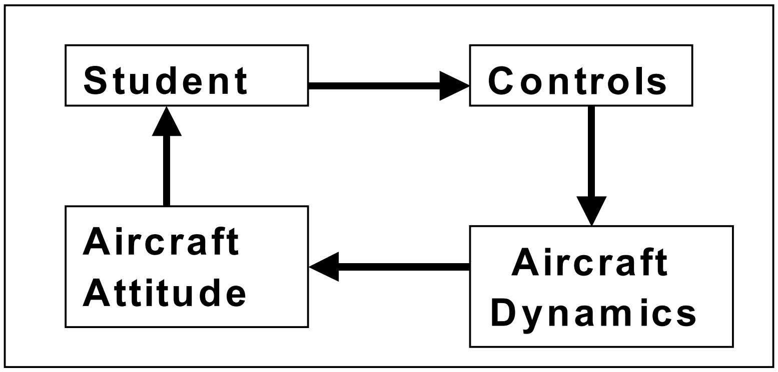

Figure 2 Closed Loop Simulation

In such a system there is no interaction between control axes and the system could not provide a realistic simulation of aircraft behaviour.

1.1.2 Instrument Flight Instruction

At the end of the 1920's, a new application for simulation appeared. Already alluded to were claims by early flight training devices that using them (without flight instruments) could train the human vestibular system so as to be able to fly in reduced visibility without becoming disorientated. The vestibular system is that part of our body which senses accelerations and rotations, much as an accelerometer in an aircraft would. In fact the system can be modelled as such. The system itself is quite physiologically complex. For a good layman's description, Human Factors texts used for pilot training are an excellent source.

On the ground, the vestibular system in orientation. In the two dimensions that one moves about in day to day, it provides the brain with information on how we the body is moving, how it is rotating and which way is up and down. In a sense it provides similar information to that provided by an aircraft's inertial reference system. The system is by no means perfect, with rapid rotations, humans become dizzy as the system is overloaded.

When motion is added in the third dimension, there are several problems that can occur. These are known well to instrument rated pilots and include:

The "Leans", whereby the pilot senses a turn/roll rate that does not exist. The feeling is very unsettling. Even though the flight instruments tell the pilot that the aircraft is flying straight and level, the feeling received from the 'senses' is that the aircraft is in a steep turn. Attempts to correct such a false turn exacerbate the problem and can easily lead to a loss of control.

Like an aircraft navigation system, our brain requires updates from other senses to accurately determine our orientation. Because our vestibular system cannot detect motion below certain thresholds, low frequency information is not processed. If blindfolded, and one is turned around on a smoothly rotating surface , it is almost impossible to gauge the final direction, because we cannot detect such small accelerations and motions.

"Acceleration Error" is another hazard that can occur when flying without reference to a visual horizon. As a basic explanation, our body is not capable of differentiating between the nose of the aircraft pitching up and a rapid acceleration. For example, on takeoff at night, the large acceleration along the runway and after takeoff can be sensed as a rapid nose pitch up. If the pilot miss-interprets this, he may push the nose of the aircraft down to avoid a nose high attitude. This causes both a speed increase, as the aircraft accelerates even faster, which in turn causes the pilot to sense even more of a nose up pitch. This cycle can and has led to pilots crashing aircraft soon after takeoff.

The leans and acceleration error are but two of many effects that pilots can experience when operating in three dimensions. Initial training devices claimed that they could train the senses to overcome such problems.

It was the realization in the 1920's however, that visual cues are more important to orientation than vestibular cues, that convinced pilot's and instructors alike to develop Instrument Flying. Simulation for instrument instruction involved moving simulators fitted with instruments as well as non-moving or fixed based simulators designed for instrument training.

Again, the initial instrument indications were altered by the instructor in response to student inputs. It would take development in simulator systems to again remove the instructor from the loop. Such trainers with their limited or non-existent motion platforms allowed student to learn to de-couple the information received from the eyes from the often incorrect data received from the vestibular system.

1.1.3 The Crew Trainer

The next development in simulation came about during the Second World War with the use of multi crew combat aircraft. The operation of these aircraft in war conditions as well as bad weather with large numbers of crew required training devices to reduce losses in battle. One such device was commissioned by the Royal Air Force (RAF) as a Celestial Navigation Trainer. Such a device allowed crews to train in the use of celestial navigation 24 hours a day, i.e. without having to wait for darkness. They also could be used to simulate night bombing raids using the same techniques.

The idea of the crew trainer involves more than just a simulation of the aircraft’s flying characteristics and in some cases these may even be considered irrelevant to the training being undertaken. Such devices allow the crew members to train with an accurate simulation of the aircraft systems they will operate in real flight.

As aircraft have become more complicated, systems and procedures training takes up more and more time in an aircraft training programme. Today flight simulators are used for almost all flight training on large aircraft with often the first time a pilot actually operates the real aircraft being with a full load of passengers.

1.1.4 The Full Flight Simulator Today

The full flight simulator today is primarily used for training. Not just pilot training, though this may be its main objective, it is also used for cabin crew and ground crew training. Such a device can also be used as a research tool, as will be described in the next section. These devices are accredited by various countries regulatory bodies to accomplish almost all of a crew members flight training in a flight simulator. A more in-depth analysis follows in Chapter 2. Training carried out in such a device includes

- Take off and landing training
- Instrument flying
- Instrument approaches
- Normal, non-normal and emergency procedures
- Crew co-ordination

A full flight simulator differs from lower end synthetic trainers in the following ways that make them suitable for such training:

- Exact replication of the flight deck environment
- Wide angle, collimated visual display
- Motion cues including ground effects and buffet
- Flight control loading
- Full aircraft flight model including ground effect

1.1.5 The Engineering Simulator

"The Author is a true believer that the simulator is the next best thing to being there, especially if it is out in deep space"

Bill Chen [7]

To the general public, the term 'flight simulator' refers either to programmes run on home computers, or to training simulators found in flying training organisations. Another use for the flight simulator is that of the engineering flight simulator, whether as a dedicated system, or a training device employed periodically in this capacity. With the ever increasing fidelity of flight simulators to their target aircraft, the relevance of flight experienced in such a device increases. So much so that today, not only training, but accident investigation, performance investigation and engineering development is possible in these machines. In short, it has been shown that results obtained in the flight simulator can be expected to hold for the aircraft if the simulator models have been built with sufficient attention to detail.

Training flight simulators have been used for many years to investigate aircraft performance[5]. The introduction of jet aircraft with a T-Tail configuration led to instances of Deep Stalls, an almost irrecoverable situation. Investigation into this phenomena was carried out in a simulator, resulting in the addition of a fully powered elevator to the BAC 111 as well as a stick pusher. The problem of jet upsets, borne out of jet aircraft flying through Clear Air Turbulence (CAT) in the vicinity of Jet Streams, was also investigated in the flight simulator. It was determined through such work that the best way to fly in CAT is not to chase airspeed, rather to fly an appropriate attitude and thrust setting and to accept deviations in altitude and speed, a technique still practised today [48].

Development of the Concorde was significantly aided through use of a flight simulator through design, development and certification [5]. The risks inherent in the creation of such a complex and costly project dictated the need for such a device. Topics of interest were stability and control, systems, failures and crew workload. Although much of the information gathered was confirmed in-flight, it can be safely said that much of the hard work was done first in the flight simulator.

The simulator is also a good start to the examination of possibly dangerous situations. The Greek air force used simulation of the F-16 to investigate high angle of attack flight and recovery [8]. Subsequently, changes have been made to the aircraft's flight control system to increase controllability in the post-stall environment. The Grumman X29 relied extensively on a development flight simulator [9]. The composite winged aircraft with forward swept wings employed a sophisticated fly by wire flight control system that required extensive simulator validation before first flight. During this process several significant errors were uncovered and fixed. The operation of the V22 Osprey Tilt-Rotor aircraft aboard ships was also extensively simulated to investigate such a hazardous operation [6].

The Boeing 777, the largest twin engined jet transport extensively utilised engineering simulation. Two were built for the project, the first ready 50 months ahead of completion of the first airframe. The simulator was used as part of the 'design/build' process and evolved as the aircraft design evolved. Used in the 'Systems Integration Laboratory' and the 'Flight Controls Test Rig', the simulators provided the ability for Human Factors Experiments, Training Manual Development, initial pilot training and test flying. Such use of a simulator allowed Boeing to 'get it right the first time'.

The engineering flight simulator has proven itself over many years of use. Whether built as a dedicated research tool, or a high fidelity training device employed for research, much time, effort and cost has been saved through the use of a simulator in place of an aeroplane. With running costs particularly of large transport aircraft running to tens of thousands of dollars an hour, as well as the high utilisation rates, the benefits are easy to see.

1.1.6 The Variable Stability Flight Simulator

The Variable Stability Flight Simulator this project intended to create is a combination of the two main types of simulator in use today. The initial stages of the project focussed on creating a generic flight simulator with loaded flight controls and a 3 degree of freedom motion system. At the end of this stage the device resembles a full flight simulator used for the training of pilots, however, it will not replicate a specific aircraft type as required of such a device. As the project develops and the Variable Stability module is included, the system will constitute an engineering simulator useful for teaching, research and investigation.

The Variable stability module will allow on-line and real time modification of aerodynamic stability and control stability parameters, inertias and propulsive characteristics. When in use for teaching, several students will be present in the flight deck to experience the effect of changing these values whilst flying the aircraft. It is hoped that this will enhance the understanding of concepts related to aircraft stability, controllability, handling qualities and control system design.

1.2 Background and Initial Studies

It has been the intent of this project to create a Flight Simulator that could assist in teaching of Flight Mechanics concepts. It was decided that such a teaching tool would require both a motion base and flight controls with some sort of force feedback to the pilot. The initial part of the work focussed on simulator design concepts that could satisfy this requirement. Previously in the department undergraduate thesis work had been done in implementing a low cost control loading system using electric stepper motors. This system has not been in use for over three years and its potential was limited. However, as mentioned [24], the system design was sound and additional work could have been carried out to fully exploit the system

A more advanced concept involved the creation of a motion base surrounded by three linear electric actuators donated to the department by the Defence Science Technology Organisation (DSTO). It was thought that these actuator could be used to construct a moving platform with at least two degrees of freedom (in pitch and roll). The power and stroke of these actuators would have limited the system to a small platform with one pilot occupant, flight controls, CRT display of instruments and a visual display.

Early in the development of the system , the opportunity arose to procure a Military surplus flight simulator from the Royal Australian Air force. This system simulated a Boeing 707 aircraft and consisted of a flight deck with seating for two pilots, a flight engineer, an observer and an instructor, a two channel visual system, sound system as well as hydraulically loaded flight controls and a three degree of freedom motion base. The motion available was pitch, roll and heave (vertical translation). Such a system, if interfaced with a suitable motion flight simulator program would provide a much greater simulation capability to the department, but would involve a much greater effort in interfacing to legacy systems with new PC based software and control hardware.

1.2.1 An Early Control Loading System Concept

Initial work in the Department on a force feedback to the simulator pilot began with an undergraduate thesis project [24] carried out by Megan Whitlock in 1996 under the Supervision of Dr Dan Newman. The system was designed to be used as part of the Undergraduate teaching programme in Flight Mechanics to provide a simulator environment whereby the pilot could experience realistic forces experienced through the flight controls of the aircraft being simulated.

The system comprised the pilot sitting in a chair with a monitor representing flight controls and a three axis control system comprising a Control Stick for elevator and aileron control and rudder pedals for rudder control. The mechanical design for the elevator is shown in Figure 3 and is similar in concept for the aileron and rudder.

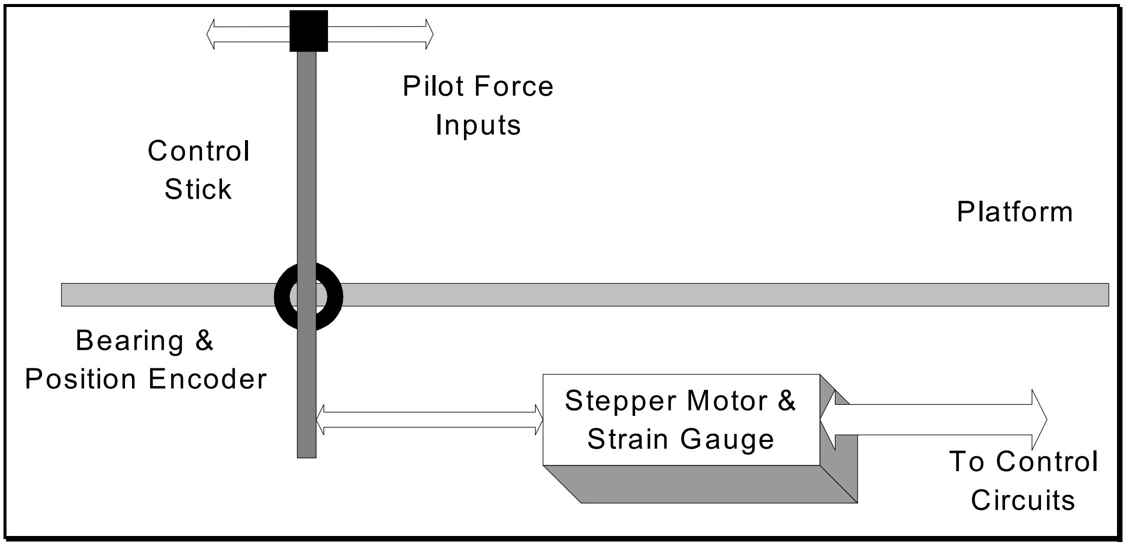

Figure 3 An Early Control Loading Concept

A direct connection via metal rod is attached between the control and the stepper motor/force transducer. The basic operational cycle is as below:

1. Measure the force the pilot is placing on the control

2. Determine the appropriate control position based on this force (in the 'Control Circuits')
3. Position the control at this position
4. Repeat

This cycle forms the basis upon which all flight control loading systems operate. It is not actually the pilot who physically moves the control axis, it is the driving motor[2] that moves it in response to an output calculated by the loading system based upon the pilot's force input.

This system was investigated for use in the original system plan. However, the system was in some state of disrepair having not been used for several years and was not well documented. In addition to this, although the specifications for the stepper motors gave a maximum linear velocity of approximately 130mm per second, demonstrated velocity was more of the order of 50mm/s with no load. Under load this could be expected to decrease, the resultant control speed being insufficient for the system's needs.

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[2] **In this case an electric stepper motor**

1.2.2 An Early Motion System Concept

Initial work on a motion base for the system was orientated towards the use of three large electric screw actuators[3] donated to the Department by the DSTO. These are similar in operation to the smaller electric stepper motors outlined in the previous section in that the motor drives a rotary actuator which in turn creates a linear motion of the actuator. The basic conceptual set-up is shown in Figure 4

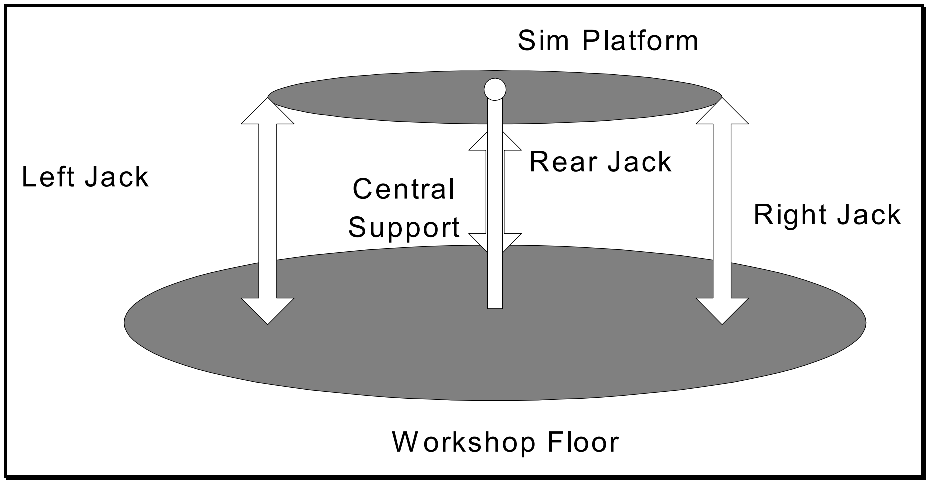

Figure 4 Early Motion Concept – shown from rear

The simulator platform is attached via a central support to the workshop floor. The three motion actuators are attached around the circumference of the motion platform at approximately 120 degree separations. Such a platform would be capable of producing roll and pitch and heave cues for the pilot. As the actuators in the Figure 4 are all mounted so as to allow motion in the vertical frame only they can only produce these cues. As four actuators were available, it would also have been possible to use the fourth actuator to produce some measure of yaw motion.

It was planned to install a single control station in the center of the platform with flight controls and a visual display. This would in effect be similar to the original simulation

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[3] **From here on known as motion actuators**

developed by Newman and Whitlocke with the addition of the motion base capability. Investigations into this system were not extensive, as soon after project commencement a system with much greater capability became available to us that presented much greater capability potential. The introduction of this system, a 1960's 707 simulator, meant that it was no longer necessary to utilise either the Whitlocke system or the DSTO actuators to produce control loading and motion.

1.2.3 Link 707 Simulator Acquisition

In early 1999 the opportunity arose to acquire a full flight simulator that had become surplus to requirements as determined by the Royal Australian Air Force (RAAF). At that time the device was situated at the QANTAS Airways ltd. Flight Training facility at Sydney Airport. The simulator was representative of a Boeing 707-338 series aircraft powered by Pratt and Whitney engines configured as RAAF 707 A20-627[4]. This aircraft had in turn been acquired from QANTAS as VH-EAG.

The simulator was installed at QANTAS in 1969 to support aircrew training on the type. It was sold to Aer Lingus of Ireland in 1979, then came back to Australia and QANTAS in 1986 when the RAAF purchased it to support its 707 operations. Maintenance and development of the device was provided by QANTAS Flight Simulator Maintenance.

The simulator was built by Singer Link and utilized a single channel McDonnell Douglas computer generated image (CGI) system known as the Vital IV system. The digital computer used to operate the system is a Link Miles GP4 computer. It held a CASA level 3 certification and provided over 3000 hours of training time annually[5]. It weighs approximately six tonnes, has a 2.5g heave performance with roll and pitch capability. More specific data will follow as each system is examined.

The simulator is shown in Figure 5 from the QANTAS computer room. Half of the device's total area is taken up by the simulator itself, the other half by associated computers, power supplies , cables and interface equipment.

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[4] The A20 is the RAAF's designation for aircraft type 20. Each type operated by the RAAF has such a designated code. The 627 is the particular airframe in each series.

[5] Information from Info poster provided with Sim.

Figure 5 707 Simulator in situ at QANTAS

Figure 5 shows the device in the initial stages of its disassembly prior to relocation the University of Sydney. Perhaps the most apparent items are the hundreds of black cables protruding from the bottom of the main cab. These cables provide channels for Input/Output (I/O) between the simulator and the analogue peripheral equipment. All data travels through these cables. Figure 6 shows a view in the other direction, back into the computer room. Several items are clearly visible, the most prevalent being the mass of black cables that come from the system's numerous cabinets. These cabinets provided electrical power, air-conditioning, instrument displays and computer power and storage. The cables are routed around the facility underneath a false floor and interface at the Junction Box. Also visible at far left is an emergency stop button. This can instantly stop all power to the device should a dangerous situation arise. There were several of these around the device to allow timely shutdown.

Shown in Figure 6 is cabinet three, otherwise known as the 'Junction Box'. It is here that cables from the simulator and from the computer room are interfaced. Seen here is the front plane where the cables' 50 pin connectors are attached to the relevant receptacle.

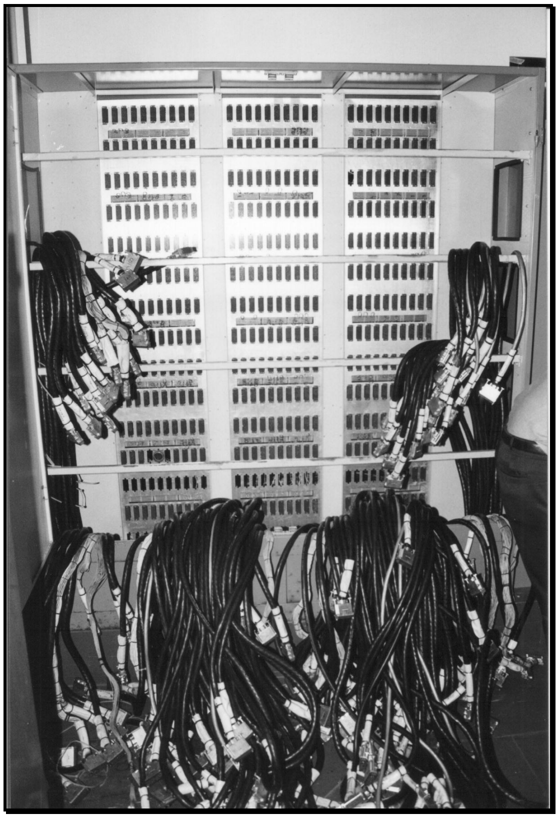

Figure 6 Junction Box – Pre Delivery

One of the major problems that occurred during the development of our own facility is already apparent in this photo. There are 420 cable receptacles. On the end of each cable is a short white collar held in place with small ties. These collars are annotated with the cables identification, most importantly which junction connectors they come from and go to. Over the years this information has become faded and on many of the cables unintelligible. During disassembly some of the cables were labelled to indicate which receptacle they were pulled from, this would allow us to re attach them if necessary. However, most were either not labelled or were labelled with a non-permanent marker pen that quickly disappeared from view.

This complicated the process of determining which cable was connected to which piece of hardware. Determining which cables we would need would require manually tracing each cable from its associated piece of hardware to find the connector. This was a time consuming and sometimes difficult procedure, particularly when a cable entered an inaccessible space in the simulator amongst other identical cables.

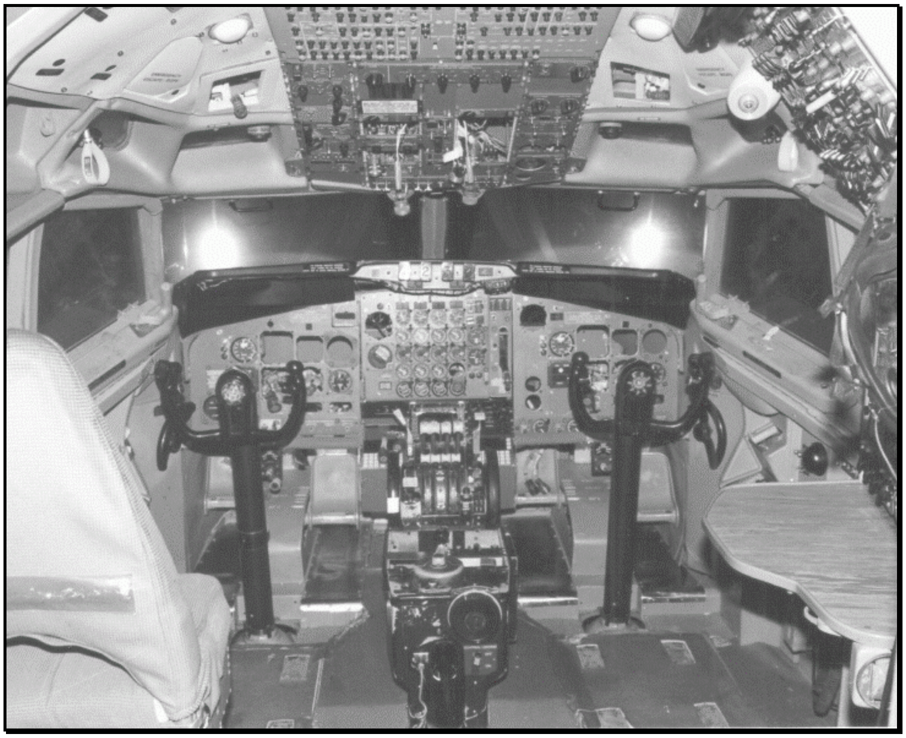

Figure 7 707 Flightdeck – Pre Delivery

Figure 7 shows a view of the flight deck of the simulator. There are several holes in the flight instruments visible. When the simulator was decommissioned by the RAAF, a new machine was built for their training purposes. To save money, usable instruments were 'scavenged' from the device to be re-used.

The main areas of interest in the above photograph are

1. Flight controls – These form the main interface between the pilot and the simulation. Each control axis is hydraulically loaded to provide for realistic flight control forces. They form a major part of the new device.
2. Control Console – Also important as it provides realistic thrust levers for as many as four engines as well as engine start switches, speed brake, flaps and trim inputs.

3. Forward windows – The glare visible through the forward windows is actually a reflection from each of the mirror's in the visual pathway of the collimated visual system.
4. Lack of main seats – The two main seats in the flight deck were removed as part of the aforementioned 'scavenging' process. They were replaced with automotive seats of similar operation.
5. The engineer's panel shown in Figure 8 The 707 is a first generation transport jet and as such required the use of a flight engineer. With the demise of the Boeing 747 'Classic'[6] series, almost all transport aircraft utilize two crew members only, both pilots. It is therefore superfluous and has been removed.
6. Numerous dials and switches - Once again, as a 'classic' aircraft, the 707 flight deck contained many switches and analogue displays. Modern aircraft rely heavily upon computer displays and computerized switching to reduce workload, accordingly, many of these switches and panels are redundant.

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[6] 'Classic' refers to 747 aircraft with Flight Engineers, i.e. the 100, 200 and 300 series aircraft. 'Classic' is also becoming a more common term to differentiate the older series of aircraft from new series that utilize glass cockpits, i.e. with CRT or LCD displays.

Figure 8 707 Flight Engineer's Panel

A detailed overview of the cockpit conversion is given in Chapter Three.

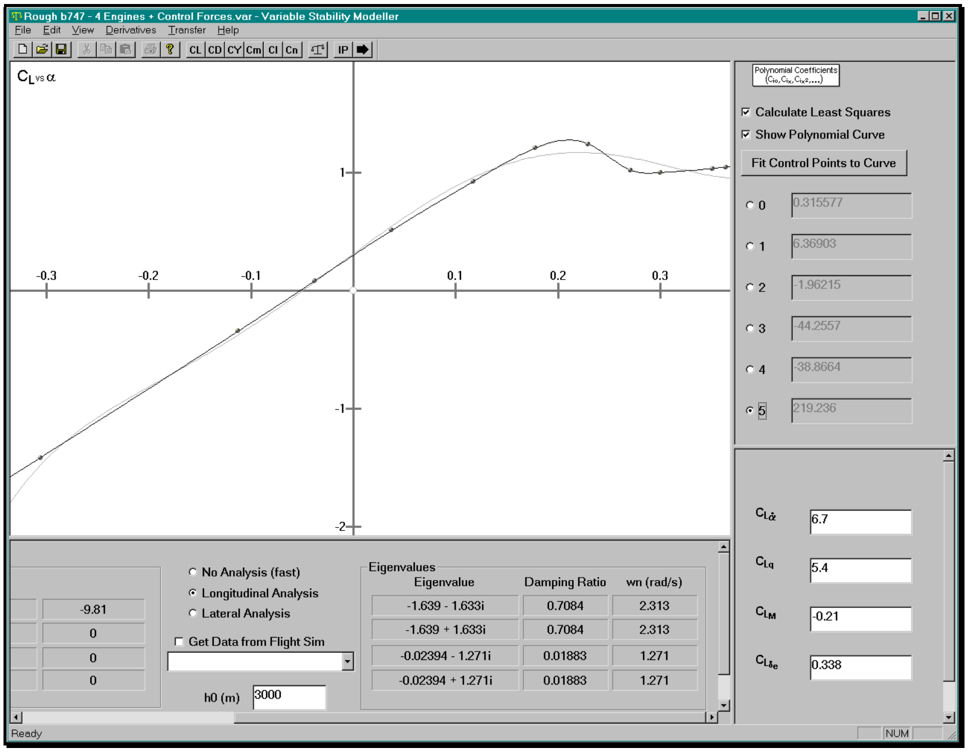
1.3 Variable Stability Simulation

One of the main goals of this project is to produce a teaching tool for undergraduate teaching in the areas of aircraft stability, handling qualities control systems and design. Each of these could be enhanced by the use of the PC based flight simulator. The addition of the 707 flight deck, control loading and motion base enhance the realism and teaching capability of the device by providing a normal training or engineering flight simulator environment. The addition of a variable stability module will allow for even more in-depth engineering instruction as it allows on-line interaction with the flight simulation models.

The Variable Stability Module (VSM) is being developed by Simon Nailor, a Postgraduate student in the Department. It will allow online changes to the following types of parameters in the flight model of the simulator:

1. Aerodynamic and Control Derivatives and Coefficients
2. Inertial Characteristics
3. Center of Gravity Location
4. Propulsive Characteristics

The Variable Stability interface displays these properties in multi-dimensional polynomial / spline form. These can be modified graphically by moving control points on a curve for strongly state dependent parameters, or by numerical specification for constant parameters, then downloaded into the flight model for instant inclusion into the simulation. The interface also analyses the instantaneous stability and handling characteristics of the aircraft. A typical interface is shown in Figure 9, illustrating the lift coefficient’s relationship to angle of attack.



☑ Calculate Least Squares
☑ Show Polynomial Curve

○ 0 0.315577
○ 1 6.36903
○ 2 -1.96215
○ 3 -44.2557
○ 4 -38.8664
● 5 219.236

$C_{L_{\dot{\alpha}}}$ 6.7
C_{L_q} 5.4
C_{L_M} -0.21
$C_{L_{\delta_e}}$ 0.338

-9.81
0
0
0

○ No Analysis (fast)
● Longitudinal Analysis
○ Lateral Analysis
☐ Get Data from Flight Sim
h0 (m) 3000

Eigenvalues

Eigenvalue	Damping Ratio	wn (rad/s)
-1.639 - 1.633i	0.7084	2.313
-1.639 + 1.633i	0.7084	2.313
-0.02394 - 1.271i	0.01883	1.271
-0.02394 + 1.271i	0.01883	1.271

Figure 9 Typical VSM Interface

1. Alteration of Aerodynamic Derivatives / Coefficients

The main purpose of variable stability simulation is to investigate the affects of aerodynamic characteristics on aircraft stability, controllability and handling qualities. For example, the first stability topic a student studies in flight mechanics is that of longitudinal stability. This refers to an aircraft's tendency in pitch to return to an equilibrium angle of attack if a disturbance is introduced, a gust for example. If a gust affects an aircraft so as to increase its angle of attack, the pitching moment coefficient (Cm) produced determines the system's static stability, or its tendency to return to the equilibrium position.

This is determined by the following derivative $\delta_{Cm} / \delta_{\alpha}$ which relates the change in pitching moment coefficient about the center of gravity to the change in angle of attack experienced. If a positive angle of attack disturbance creates a pitching moment that reduces the angle attack and vice versa, the system is statically stable. If the tendency is to further increase the angle of attack, the system is statically unstable.

A typical first order representation of this situation is

$$C_m = C_{m0} + C_{m\alpha}\alpha$$

and is shown in Figure 10

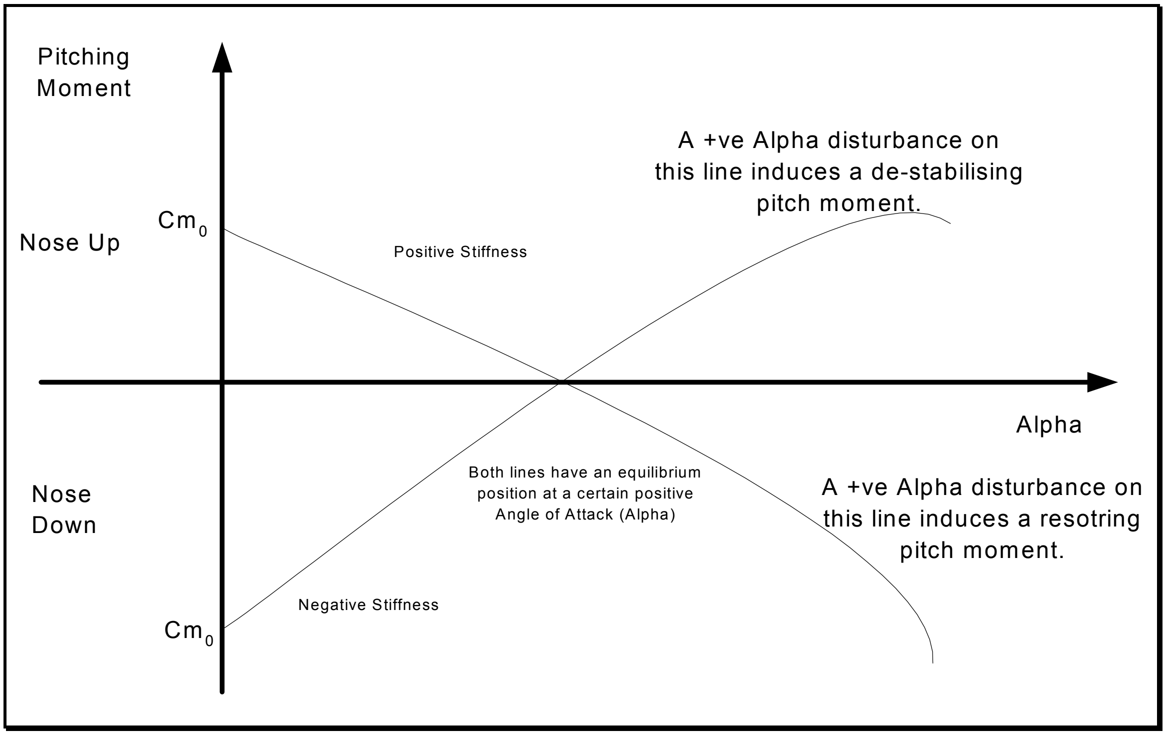


Figure 10 Pitch Stiffness

In this case, the slope of the curve, known as the “pitch stiffness” $C_{m\alpha}$ has a critical effect on the longitudinal flight stability while the offset C_{m0} determines the equilibrium point. A suitable interface will allow students to quickly alter these characteristics so that their effects on stability and handling qualities can be assessed.

2. Changes in Moments of Inertia

Alteration of Moments of Inertia effect rotational accelerations from applied forces. affecting the response speed of the aircraft to control inputs and atmospheric disturbances.

3. Changes to Center of Gravity (CofG) Location

The location of the Center of Gravity of an aircraft is critical to its longitudinal stability. It must be restricted between designated forward and aft limits for the aircraft to remain controllable.

As the CofG approaches the aft limit a reduction in stability occurs until at the aft limit the aircraft is unstable. This has been evident involving aircraft crashed following the shift of large amounts of freight to the aft section of an aircraft's cargo hold.

As the CofG approaches the forward limit, stability increases to the extent that the flight control system lacks sufficient control authority to change the aircraft in pitch. This can become particularly evident when attempting to flare the aircraft in the landing manoeuvre. At the reduced airspeed associated with landing, a forward CofG restricts control authority to the extent that full up elevator will not be enough to raise the nose, resulting in an excessive vertical speed at touchdown.

Changing the location of the center of gravity changes all of the aerodynamic derivatives and produces an overall stability change rather than the effect of changes to single derivatives.

All of these situations have important impacts not only on the teaching of flight mechanics, but also in control system design and crash reconstruction.

1.4 System Integration Steps

The basis of the new simulation system is a PC based flight simulation developed by Professor David Allerton of the Cranfield College of Aeronautics in the UK. This system will be detailed in Chapter 3. The system in its basic form operates with three PC systems linked via Ethernet to create a real time flight simulation of several aircraft. It comprises a three channel visual system, an Instructor / Engineering display with provision for 32 analogue and digital inputs.

The first stage in development is shown in Figure 11 and involved the addition of the new simulator flightdeck. This was a major task that also included the development of the external laboratory environment with the addition of an air-conditioning system, a computer cabinet, electrical power supply, Hydraulic Power Unit (HPU), a false floor, safety lights and an enclosure of the simulator facility.

Substantial internal modifications were undertaken as detailed in Chapter 3. These included the removal of much of the original flight deck environment including the entire engineer's station, the installation of four new seats and new visual hardware.

Before the control loading and motion systems could be implemented, it was necessary to develop a Supervisory Control and Data Acquisition System (SCADA) that would provide a software / hardware environment in which to run the control loading and motion software as detailed in Chapters 3 & 4.

Each of the three primary flight control axes is loaded with an identical but separate hydraulic actuator. In turn each of these comprises an analogue control loop receiving position commands from software through a digital to analogue converter. It was necessary to reengineer the system as the original system made extensive use of obsolete hardware and software.

The final stage of the current project was the re-commissioning of the motion system. The control circuits driving the motion actuators are identical to those driving the control loading system.

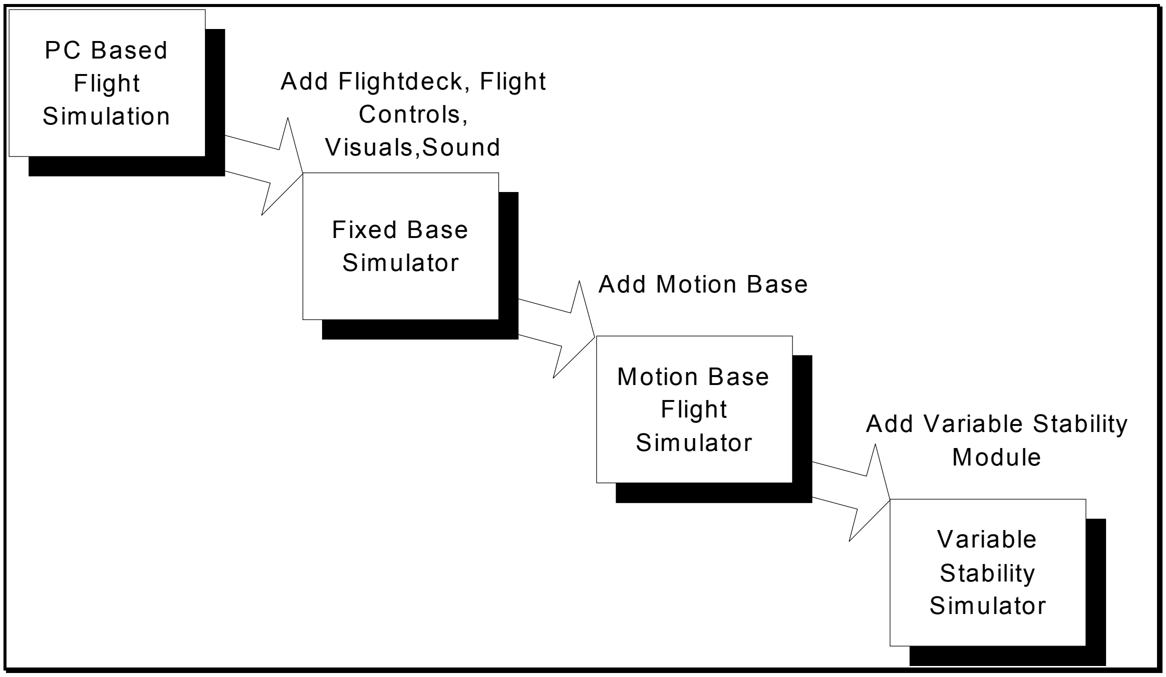


Figure 11 System Integration Steps

1.5 Thesis Outline

1.5.1 Objectives & Scope

The objectives of the project were to re-engineer the 707 simulator to provide a system suitable for both research and teaching in flight mechanics, propulsion, aircraft handling qualities and human factors. Much of the original hardware was not viably supportable with the motion and flight control loading systems requiring an inordinate amount of resources and uneconomical work. Therefore these systems would need to be implemented with new hardware and software embedded in a supervisory control system with extensive interfacing to the core simulation.

There was also a need to re-engineer the visual system to be compatible with new visual software. The cockpit was originally designed and operated as a 707 flightdeck with provision for two pilots and a flight engineer. The flightdeck has been remodelled to provide seating for two pilots as well as two observers and an instructor station has been implemented at the rear to provide control of the simulation session. A summary of the steps involved is:

1. Re-engineer the systems to provide hydraulically loaded flight controls
2. Re-engineer the systems to provide a 3 Degree of Freedom motion base
3. Create a collimated, daylight colour visual scene
4. Install a “Glass Cockpit” to replace custom 707 analogue displays
5. Provide seating for multiple occupants – including two observers
6. Create a “Safe” system with full supervisory control

The aim of this project has been to create a safe, easily maintainable, re-configurable flight simulator from a large, complex, legacy system. All of this work must be accomplished before the variable stability module can be implemented to form a true Variable Stability Flight Simulator.

Section 2.1 begins by detailing aspects of flight simulator fidelity with regards to current regulations. It is not the intention to create a training simulator as outlined in these documents, rather to create a realistic environment in which to explore many areas of flight. As such, an understanding of some of the requirements placed upon a training simulator is of benefit.

Section 2.2 outlines a very brief introduction to the physiology of flight simulator fidelity. This information will be used in Chapter 6 to help determine the form of the filters in the motion system and to assess its effectiveness.

Section 2.3 includes a justification for our decision to implement a motion system

Chapter 3 details the infrastructure required by the facility. Section 3.1 involves initial design decisions regarding much of the original hardware. Section 3.2 moves further into the modifications made to the simulator interior while Section 3.3 details further external support systems. Section 3.4 details the Cranfield Flight Simulation System, followed by a description in Section 3.5 of the new structure of the simulator. Section 3.6 is a detailed description of the integration of several systems of the simulator into the SCADA system.

Chapter 4 deals with safety aspects of the facility as well as a detailed description of the Supervisory system that in essence runs the simulator.

Chapter 5 describes the Flight Controls, including the software that produces the digital position commands used by the hydraulic system

Chapter 6 details the development of the Motion system. Section 6.1 analyses the theoretical performance available from the motion system. Section 6.2 describes the software that drives the motion hardware. Section 6.3 presents the results of motion performance tests. Section 6.4 presents the theory behind the use of high pass filters for motion base commands and attempts to provide initial values for the filters in our system. Section 6.5 details some objective tests of the roll channel of the motion system. This section uses models developed in Chapter 2 to attempt to objectively assess the motion produced by the system.

It is not the intention of this work to prove the correctness of our system using purely objective means. In any simulation system it is the subjective feedback provided by a pilot that is of most importance.

Chapter 2

Flight Simulator Fidelity

2.1 Flight Simulator Fidelity

Training Flight Simulators are accredited at various levels according to their intended use. The accreditation level a simulator achieves is of great importance to the user of the device as it dictates what training can be completed in a simulator. The level of compliance required is dependent on the intended functions and purpose of the simulator. As the intent of compliance with these regulations is to produce a device that creates a good simulation of an aircraft in flight, it is relevant at this stage to analyse several sections of the regulations, not with the intent of compliance, but as a benchmark against which we can compare the simulation. This is particularly relevant to the motion system that has been created because such a system, if improperly implemented, can produce cues to the pilot that degrade the quality of the simulation.

This discussion will examine the relevant Australian regulations which are similar in content and intent to worldwide standards in use. The regulations for Simulator Fidelity in Australia are found in a document known as FSD-1 [12]. This document will be used to provide an overview of the standards required of a simulator to be accredited as a training device.

Flight simulators produce two types of cues for the occupant pilot. These are

- Equipment cues
- Environment cues.

Equipment cues are produced by a realistic re-production of the aircraft flight deck environment. Internally, a flight simulator, particularly one designed to replicate a specific aircraft type will represent that aircraft exactly. In most if not all high fidelity training simulators this is a regulatory requirement and it is usually achieved by the extensive use of aircraft parts, these being supplied to the simulator manufacturer by the aircraft manufacturer.

Reference [45], “Chapter 5 – Flight Simulator Functional Requirements” is the Australian Civil Aviation Safety Authority’s ‘ (CASA’s) document which outlines what a flight simulator must have installed to operate as an approved aircraft flight simulator. Some sections are reproduced in Table 1:

This means that for approved training, the flight deck must be a perfect replica of the aircraft. We are not interested in replicating a specific aircraft, however, the intent of the regulations is to provide a flightdeck environment which provides the pilot occupant with a realistic situation in which to operate. Although not being used for training crew as such, the system is trying to provide students and researchers with the sensation that they are operating a real aircraft.

Section	***Function***	***Proper Indications and Functions to be demonstrated***
5.1.2	General	Proper functioning of all switches, indicators and systems including flight management, autothrottle and communication equipment at all flight crew stations applicable to the credits[7] being sought. Proper functioning of all switches and controls located at the flight simulator instructor stations.....

Table 1 Environment Cues from FSD-1

Fidelity in terms of equipment cues can therefore be described as how well the simulator replicates the equipment that the pilot interacts with, in terms of location, size, colour, working characteristics etc.

Environment Cues are concerned with replicating the sensory environment in which the aircraft operates. This includes cues such as

- Motion
- Visual cues
- Aural cues

2.1 1 Motion System Requirements

[45] defines acceptable performance for these areas for use in a training simulator:

5.1.11

The motion systems shall meet the general specifications listed in Part 11 and additional specifications applicable to the various Levels listed in Part 13.

5.1.12

---

[7] 'Credits being sought' refers to what flying sequences can be considered as being completed in the simulator, i.e completing a series of engine out takeoffs to a satisfactory standard. The more complex the manoeuvre, the more sophisticated the flight simulator must be to obtain 'credit'

Proper indications and functions in the following effects where appropriate:

a. Buffet due to speedbrake and flap extension.
b. Buffet during approach to stall.
c. Runway rumble and oleo deflection related to speed and runway surface.
d. Buffet due to ground spoiler and reverse thrust during ground roll.
e. Impulses resulting from nose and main landing gear extension and retraction.
f. Impulses resulting from spoiler extension and retraction.
g. Landing gear ground contact impulses.
h. Nose wheel scuffing and breakaway.
i. Pitch effect resulting from brake and thrust application.
j. Roll effect.

Part 11 (as referenced above) says:

11.3.1
The system provided shall be automatic in operation and shall reasonably portray in at least three degrees of freedom of movement the various accelerations appropriate to the aircraft in all simulated manoeuvres.

Part 13 contains more specific data for each level of training. Level 5 is the highest level (as at December 2001) to which an Australian simulator can be qualified. It is analogous to the highest levels of JAA[8] *and FAA*[9] *certifications. A level 5 simulator can be used to train in all endorsement sequences including an endorsement examination. They are used for training and checking in all sequences of aircraft operation. It has the following requirements for its motion systems*

---

[8] JAA – Joint Aviation Authority
[9] FAA – Federal Aviation Administration, USA's Civil Aviation Authority.

13.4.4 Motion System

13.4.4.1 The system shall provide motion cues representative of all aircraft manoeuvres and systems operations. The quality of the cues developed must be equal to or better than those developed by a synergistic low friction motion system possessing six degrees of freedom of movement.

13.4.4.2 To demonstrate quietness, the motion system shall remain within 0.025% of full leg extension while the input signal is held static (e.g. within 15/1000" for a 60" system).

13.4.4.3 The system shall possess a linear frequency response to a sine wave input with a tolerance of +1 dB amplitude performance up to a corner frequency of 3 Hz where it may be no more than 3 dB down.

13.4.4.4 The system shall be capable of producing an acceleration of 1 g (+0.5 to - 0.5 g amplitude change) up to 10 Hz and better than .02 g (+0.01 to -0.01 g amplitude change) at 30 Hz. The acceleration performance, once established, will not be required to be demonstrated on a repetitive basis because of the possibility of damage at the higher frequencies.

Whilst we only have a 3 degree of freedom motion base, the other parameters mentioned above provide direct measures that we can make of our motion as a benchmark of its performance.

2.1.2 Visual System Requirements

For the Visual System, the requirements are as follows:

5.1.13 The visual system shall meet the general specifications listed in Part 11 and additional specifications applicable to the various Levels listed in Part 13.

5.1.14 Visibility shall be assessed with the flight deck instrument lighting set at an appropriate level for normal operations.

From Part 11:

Visual System

11.3.2 Aspects to be Included

11.3.2.1 The visual system shall reasonably portray individual scenes normally viewed from each pilot station of the aircraft and shall include the aerodrome surrounding areas, runways and taxiways. Buildings, aprons and other outstanding features shall be suitably detailed and the overall visual scene shall be realistic

.

11.3.2.2 Realistic approach, runway and taxiway lighting where appropriate shall be provided.

11.3.2.3 Approach lighting, runway lighting and VASI intensities shall be independently variable.

11.3.2.4 Visual systems approved for instrument take-off and instrument approach shall provide a realistic simulation of the appropriate weather conditions.

11.3.2.5 A means shall be provided at the flight simulator instructor station to permit control of cloud base, runway visual range and visibility.

11.3.3 Stability of Scene

11.3.3.1 The visual scene displayed shall be reasonably stable in static and dynamic states, both on the ground and in the air. In a multi-channel system the visual scene shall have no obvious mismatch between channels.

11.3.4 Latency

11.3.4.1 Visual scene changes from steady state disturbance shall not occur before the resultant motion onset, but be within the system dynamic response tolerance.

And from Part 13 (once again for a Level 5 simulator)

13.3.6 Visual System

13.3.6.1 The visual system shall be fully compatible with the aerodynamic program of the flight simulator.

13.3.6.2 The visual cues provided shall be such as to permit the assessment of sink rate and depth perception during landings.

13.3.6.3 The visual scene when compared to flight instrument readouts shall show no perceptible lag.

13.3.6.4 The effect of the aircraft landing and taxi lights shall be adequately portrayed and shall be selectable.

Parts 13.3.6.1 through 13.6.3 show the importance of having a ‘correct’ visual scene. What this means is that the visuals are a very important part of the simulation experience and do not exist just for the sake of having something to look at outside the windows. The importance of a proper visual scene will be examined later.

2.1.3 Sound System Requirements

Further from [45];

11.4.1 A sound system, automatic in operation, shall be provided to reasonably simulate the various engine, system and aerodynamic sounds at the various noise levels associated with flight deck operation of the appropriate aircraft.

11.4.2 The flight simulator instructor station shall be fitted with a sound control switch.[10]

11.4.3 External sounds which are not recognised as being associated with the aircraft in a particular mode of operation shall not be noticeable within the crew compartment of the flight simulator.

It is very important that the crew be isolated from external, non-aircraft cues. Such cues destroy the simulated environment and detract from the learning environment. In particular the hydraulic power supply creates a large amount of noise, somewhat muffled by its placement in an external room. It may be necessary to provide extra sound insulation for this room.

In summary, although we are not attempting to build a training flight simulator, the intent is to create a generic simulator with a motion base, visual and aural system that are as convincing as those found in a training simulator. Specific aircraft data is not available to compare our device to but the proceeding discussion does outline relevant performance indicators.

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[10] **It is sometimes preferable to a be able to turn the sounds volume down easily from the Instructor's station when talking to the crew, or when moving the simulator around the simulated world.**

2.2 Physiological Aspects of Motion Fidelity

Ideally, an aircraft flight simulator would be capable of exactly reproducing the “flight” experience for its operator. This means that it is capable of faithfully creating the same environment as perceived by the pilot in the aircraft. Here the flight environment is defined as :

- Proprioceptive & Tactile Cues
- Vestibular Cues
- Visual Cues

The three areas are all important in correct motion cue generation and will be examined separately.

In terms of dynamic response, the three are ordered as follows;

1. Proprioceptive & Tactile cues (section 2.2.1) provide almost instant information pertaining to a rapid onset of motion.

2. Vestibular cues (section 2.2.2) detect linear acceleration and angular acceleration. They are produced by platform motion and are useful over time periods from approximately 0.1ms to 10 secs.

3. Visual Cues (section 2.2.3) provide excellent rate information at time periods greater than 10 seconds. Visual cues are generated by computer systems and due to their nature are readily analysed for correctness. They are available both in motion and fixed base simulation and are not limited by the restricted nature of the flight simulator motion envelope. It is quite possible for a fixed base simulation to provide the pilot with visuals showing the aircraft in inverted flight when in fact the device is firmly bolted to the floor. In fact, it is this unlimited

range of ‘motion’ that the visual system can present that can be used to advantage when presenting cues to the pilot.

When two sensors provide conflicting information, the higher frequency system will usually prevail. It is essential that a well produced visual cue, previously preceded by a vestibular cue, is not then destroyed by a clumsy washout of that vestibular cue in an opposing direction.

Because of the aforementioned obstacles to full motion reproduction, it is necessary to determine how a pilot senses aircraft motion, what the pilot can detect, and how he/she interprets it in operating the aircraft. Such analysis is very in depth and it is not the intention of this thesis to examine this question. Much work has been done on the subject by many authors and the outcomes will be examined.

2.2.1 Proprioceptive & Tactile Cues

Proprioceptive information is used by the brain to determine the relative position of parts of the body. There are three main types of such measurements [42] which determine the following information

- Muscle length
- Muscle Tension
- Joint Orientation

This information, along with pressure information from tactile cues can be used to provide information of body orientation and the forces experienced by the body on a very short time scale. This type of cue is also referred to as the seat of one’s pants.

2.2.2 Vestibular Cues

The Vestibular system is that part of the inner ear that is used to determine information on a bodies motion in both linear and rotational senses. It is composed of two basic components, the Otolith and the Semicircular Canals, which measure linear accelerations and angular accelerations respectively. They are analogous to linear accelerometers and rotational accelerometers found in an aircraft inertial reference system.

2.2.2.1 Specific Force

At this stage it is appropriate to introduce the concept of Specific Force. Specific Force is that acceleration measured by an accelerometer and is the acceleration measured by the Otolith organ to be discussed. It is defined [43] as the vector difference between translational inertial acceleration and acceleration due to gravity:

$$\vec{f} = \vec{a} - \vec{g}$$

2.2.2.2 The Otolith System

The mechanics of otolith operation are complicated and the reader is referred to reference [43] for a more technical discussion. The basic idea of the otolith is that it is comprised of a dense supporting base (the macula) which contains sensory hair cells and a dense overlying membrane (the otoconia). The whole system is surrounded by endolymph (a fluid) with specific gravity of 1.003, much lower than the value of 2.71 for the denser otoconia.

The dense membrane acts as the inertial mass, when a force parallel to the macula is experienced, it causes a shearing of the otoconia relative to the supporting base, this is detected by the embedded hair cells as they bend. The bending of the hair cells causes different firing rates of the neurons responsible for information passage.

The otolith can be modelled as an overdamped mass-spring-dashpot accelerometer represented by the following differential equation:

$$m\ddot{x}_0 + c\dot{x}_0 + k\dot{x}_0{}^2 = \ddot{x}_h$$

where

m = otolith mass
c = viscous damping coefficient
k = spring stiffness
x_0 = displacement of the otoconia relative to the macula
x_h = displacement of the head.

The transfer function of this (basic) system was first developed by Steinhausen for the Otolith and is shown below:

$$H(s) = \frac{K}{(1 + \mathrm{T}_1 s)(1 + \mathrm{T}_2 s)}$$

This has a low pass frequency response with time constants T1 and T2 in the vicinity of 5.3 and 0.67 seconds. It has been determined that the time constant T2 is well outside the bandwidth of normal head movements and the transfer function can be effectively reduced to a first order low pass filter with the following transfer function:

$$H(s) = \frac{K}{(1 + \mathrm{T}_1 s)}$$

With K given a value of 1, the frequency response is shown in the Bode Plot below. Reference [43] develops the theory for several experimental results.

2.2.2.3 Frequency Response of the Otolith System

The frequency response of this system (with K=1) is shown in Figure 12.

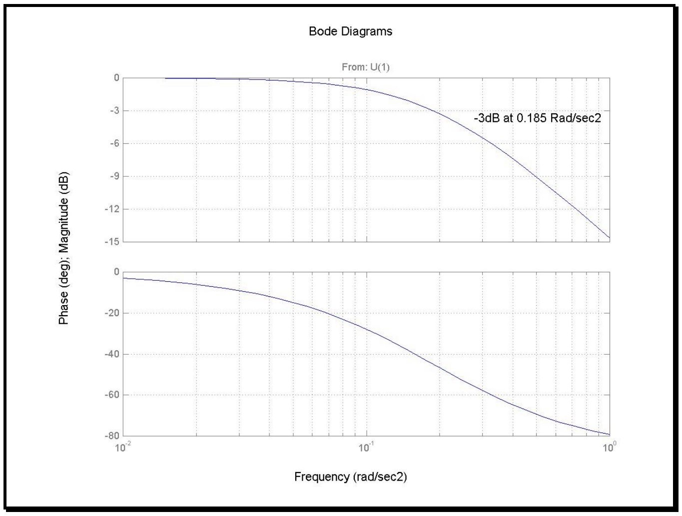

Figure 12 Otolith Frequency Response

The system shows a low pass response with a 3dB cut-off of just over 0.173 rad/s^2.

2.2.2.4 Upper and Lower Amplitude Detection Thresholds for Specific Force

Reference [43] investigates acceleration perception thresholds using a 3 DOF simulator not unlike our own. It determines values for an upper and a lower threshold of input acceleration. The upper threshold determines when a pilot can first detect motion when the input acceleration frequency is increasing. The lower threshold is the lowest frequency a pilot can detect with a decreasing input acceleration amplitude (from a high value). The results are listed in Table 2

Input Stimulus	***Upper Threshold***	***Lower Threshold***
Vertical Acceleration	0.085 ms^{-2}	0.040 ms^{-2}

Table 2 Upper and Lower Thresholds of Vertical Acceleration Detection

It is interesting to note that the upper threshold is at least 200% that of the lower threshold. This is explained by the 'Information Processor Model' of the system. Basically it says that the Central Nervous System (CNS) determines when it senses the accelerations or not depending on the level of input signal. There is a certain amount of background noise present in the sensory system and the CNS will only register a signal when the input is above the appropriate threshold. In the case of the lower threshold, it is lower because the input is decreasing towards the noise barrier, allowing the subject to track it to a lower frequency until it is not differentiable from the noise.

2.2.2.5 The Semicircular Canals

The semicircular canal can be modelled as a circular tube with a 'flapper valve' installed in the fluid pathway as shown in Figure 13:

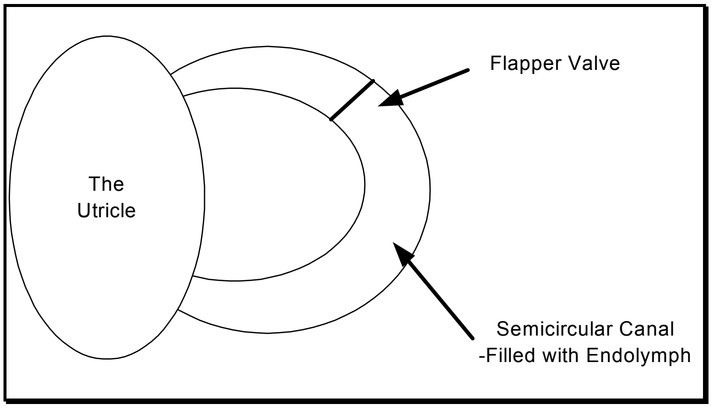

Figure 13 The Semicircular Canals

When the canal is affected by an angular acceleration around an axis perpendicular to the canals axis (in this case an axis into or out of the page), the inertia of the endolymph fluid causes it to flow around the canal, deflecting the valve (or cupula) by a value proportional to the acceleration. The system does not respond to specific forces as the otolith does as both the endolymph and the cupula (valve) have the same densities.

The first dynamic model for the semicircular canals was proposed by Steinhausen in 1931 and developed further by Van Egmond Et Al in 1949 as an overdamped torsion pendulum with the following differential equation:

$$\theta\ddot{\xi}_e + \pi\dot{\xi}_e + \Delta\xi_e = \theta\xi_h(t)$$

where

ξ_e = angular displacement of the endolymph
ξ_h = head angular acceleration
θ = the effective moment of inertia of the endolymph
π = the viscous damping coefficient of the endolymph in the canal
Δ = torsion spring stiffness due to cupula elasticity

As in the case of the otolith system, this basic model also has a low pass transfer frequency characteristic. It has been developed by many authors to take account of various aspects including different types of sensory hair cells and adaptation (causes phase lead and gain attenuation at low frequencies) .

The final transfer function is given as:

$$H(s) = \frac{T_a s}{1 + T_a s} \bullet \frac{1 + T_L s}{(1 + T_1 s)(1 + T_2 s)}$$

where

T_a = adaptation time constant (in the order of 80s)
T_L = time constant relating to Type 1 hair cells (vs. type 2) (in the order of 0.1s)
T_1,T_2 = time constants of pendulum model (in the order of 5 to 20 seconds for T_1 and 0.005 seconds for T_2)

The normal frequency range of pilot head motion as well as aircraft motion is in the range of 0.1 to 10 rad/s, therefore , the adaptation term with a time constant of ~80 seconds can be neglected with no appreciable affect on the model. Also, low frequency motion detection by the pilot increasingly becomes a visual phenomena.

We can now reduce the transfer function of the canals to the following (with parameters included):

$$H(s) = \frac{1 + 0.1097s}{(1 + 5.924s)(1 + 0.005s)} \qquad [43]$$

2.2.2.6 Frequency Response of the Semi-Circular Canals

Its frequency response is plotted in Figure 14.

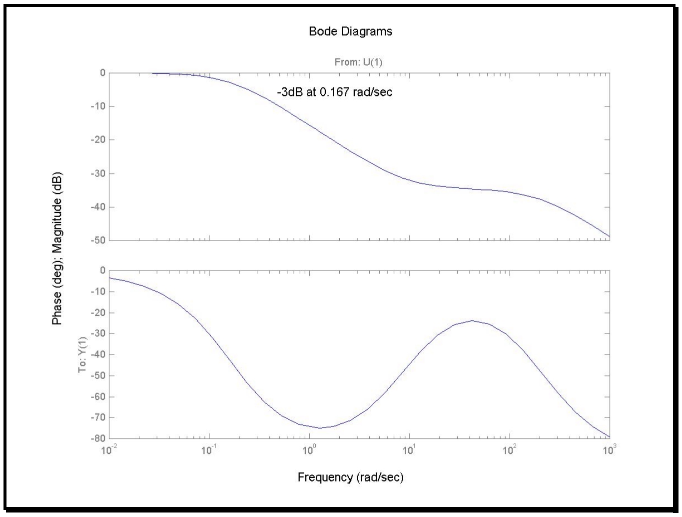

Figure 14 Frequency Response of the Semi-Circular Canals

From the frequency response we can see that the semi-circular canal system is only a good transducer of angular acceleration below the –3dB frequency of approximately 0.16rad/s^2.

2.2.2.7 Thresholds of Angular Acceleration Detection

The results from [43] listed in Table 3

Input Stimulus	***Upper Threshold***	***Lower Threshold***
Roll	0.055 rad/s^2	0.022 rad/s^2
Pitch	0.072 rad/s^2	0.035 rad/s^2

Table 3 Thresholds of Angular Acceleration Detection

2.2.2.8 Summary of Vestibular Motion Cue Detection

The otolith is that part of the vestibular system responsible for measurement of linear acceleration. We have seen that it is effective up to a frequency of around 0.185 rad/s^2 with a lower threshold of between 0.085ms^{-2} to 0.04ms^{-2}.

For the semicircular canal system which determines angular accelerations, there is a corresponding cut-off frequency of 0.167 rad/s^2 with minimum detection thresholds of 0.055 rad/s^2 to 0.022 rad/s^2 in roll and 0.072 rad/s^2 to 0.035 rad/s^2 in pitch.

In these regions, we can assume that the vestibular system will detect accelerations as required.

One hazard with using only vestibular cues is that they can be very wrong. Instrument pilots are all too aware of ‘the leans’, a sensation of the aircraft experiencing a high rate of turn whist flying straight and level. Also, a pilot is often not able to differentiate between a rapid acceleration and a rapid pitch-up in areas of reduced visual cues. While this is not good for the instrument pilot, this ability to ‘fool’ the vestibular system is what allows us to reproduce many motion cues in a simulator. In an inverse use of the above phenomena, with appropriate motion cues, we can convince a pilot that he is accelerating down a runway by tilting the simulator cab backwards. Also, we can use visual cues to maintain a rotation sensation even though the physical rotational signal has long since been removed.

2.2.3 Visual Cues

Visually induced motion is very effective in inducing a sensation of low frequency angular velocity and somewhat effective in inducing a sensation of linear velocity. The main problem with utilisation of visual cues for motion generation involves rapid changes in visual field imagery that is not accompanied by appropriate platform motion cues. Such contradictory motion inhibits the development of motion sensations. From this it can be seen that visual cues alone, while useful in the absence of motion are greatly enhanced by the coordinated addition of motion cues.

Visual cues can be used to produce motion sensations in both a linear and a rotational sense. Such sensations are known as linearvection (LV) and circularvection (CV) respectively. In general, CV is more predominant and has been studied the most.

Visual cues can also be responsible for inducing motion sickness, particularly when visual cues do not align themselves with vestibular cues as presented to the pilot. Studies of ‘vection’ have shown the following sequence in motion sensation from visual fields [44]. Initially, there is a sensation that the field is moving with the subject remaining stationary. After a latency period, the differential velocity is reversed with the subject assessing the field to be stationary with the subject moving in an opposite direction to that of the initial field movement, i.e. in the correct direction.

2.2.3.1 Yaw Circularvection

CV in Yaw has received the greatest concentration of work. This is for several reasons. Helicopter flight relies heavily on correct assessment of yaw rates, particularly in the low level environment. Flight simulator motion systems are often heavily restricted in Yaw motion and so a visual system capable of creating good circularvection is essential. Also, for a simulator such as ours that has absolutely no physical yaw capability, the only way to induce yaw motion is to do so by CV.

Some basic data regarding Yaw CV follows[11]. The most important aspect of the visual stimulus required to produce CV is the location of the stimulus. For yaw this requires the stimulus to be located in the peripheral field of view. In modern simulators this is not a problem with many having fields of view in excess of 150 degrees horizontally.

1. CV latencies in Yaw are in the order of 1 to 5 seconds.
2. CV rise times, being the time taken to fully detect the signal after the latency period has lapsed are in the order of ten seconds.
3. In the absence of other cues, steady state yaw motion induced by CV is very hard to separate from actual motion.

As the motion system has no capability of producing yaw motion, the only way it can produce such cues for the pilot will be via the visual system.

2.2.3.2 Roll Circularvection

If the visual field rotates around the pilot's longitudinal axis, roll CV is produced, but in a different way to that of yaw CV.

1. Peripheral cues important again
2. Latencies of the order of several seconds
3. Perceived motion in the correct direction followed by
4. Perceived motion in the opposite direction which leaves the subject with a sensation of a steady state angular offset or tilt.

The motion system can produce roll cues to the pilot, however due to the restrictive nature of the motion platform, the visual cues are needed to continue the physical cues. The above information indicates this will be possible after several seconds.

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[11] **[44] pp25-26**

2.2.3.3 Pitch Circularvection

Pitch is different again to both roll and yaw CV in that it is asymmetric. A pitch down sensation produced by CV is stronger than a pitch up sensation produced by a similar visual field change.

Again, as the motion base reaches its limits in pitch, visual cues will be required to continue the motion experience for the pilot.

2.2.3.4 Linearvection

Linearvection is the sensation of linear motion induced by a visual field. Important facts about LV are

1. Latencies of around 1 second
2. Adaptation over a longer time period requires an increase in visual stimulus to maintain the same linear sensation.

Linear acceleration can be maintained over longer time periods in the simulator through the use of cabin tilt to induce the sensation of linear acceleration and as such these cues are not as necessary from the visual system.

2.2.3.5 Summary of Visual Cues

As the most interest is in the generation of rotational cues in the simulation, the properties of CV can be used. This is particularly important in the yaw case as there are no physical means of creating yaw motions with the motion base. Also, with the limited range of motions in roll and pitch, CV in these axes will only help the simulation fidelity.

2.2.4 Summary

In summary then, flight simulator motion cues are produced in three stages in terms of dynamic response.

1. Tactile cues are the fastest, providing motion data instantly to the pilot.
2. Vestibular cues are next and provide important acceleration data for linear and angular motion to the pilot.
3. Visual cues provide long term rate information, particularly in the rotational axes.

Of particular interest then is how these three seemingly disparate cues can be combined by the central nervous system to produce a ‘state vector’[12] of head motion. It was proposed by Young [1970 MIT] that the body processes the cues in parallel, then compares the states they produce. If they are in agreement, they can be used, if they are not, the body must asses the two states and use a weighted mix of the two. This is the same principle employed in a Kalman filter to produce an optimal state estimate for aerospace motion.

We will use the information from this section to evaluate the motion system response in Chapter 6.

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[12] **A ‘state vector’ is an aerospace term that refers to a time dependent set of numbers that record a vehicle’s states. States include position, velocity, acceleration in general but can also detail mass, fuel load etc. etc.**

2.3 Motivation for a Motion Base

Motion base simulation is now and has been for some time the accepted method of equipping flight simulators with the correct cues for training and testing of pilots. The addition of a properly installed visual system augments this to produce as realistic a re-creation as is possible of the flight environment. This capability alone provides the Department with a research tool for flight simulation itself. The architecture of the system and the way the software controlling the motion base is rapidly reconfigurable provides a significant tool for flight dynamics and handling qualities assessment in an engineering context.

The system also provides a significant tool for research and teaching in control theory especially as it relates to the control of complex dynamic systems including flight control feedback, control of a three degree of freedom platform with significant mass and inertia and for autopilot development and assessment.

A motion base, if properly implemented will enhance the learning experience of students in understanding such concepts as static and dynamic stability and the effects on an aircraft in flight of changing aerodynamic derivatives, aircraft inertias, center of gravity locations and atmospheric conditions. The visual system alone can produce powerful motion cues but as the lag in such a system is significant, the motion base is designed to provide the appropriate short term cues until the visual system can take over.

Teaching and research into handling qualities is also enhanced by the addition of a motion base. This is because the pilot forms an integral part of the closed loop control system and because assessment of handling qualities is inherently based on subjective analysis of the total flight experience, including both motion and visual cues. Motion cues greatly affect our sensation of the flight experience and the feedback of aircraft motion to the pilot will assist in his/her determination of an aircraft’s flying qualities. In the same way, the design process can benefit from the addition of a motion system, allowing the designer to more thoroughly experience the aircraft or system he or she is attempting to design.

In summary, the motion base is added to this system in order to enhance the simulation environment for the operator. It aids in the teaching and learning of flight mechanics and is itself a valuable research and teaching tool for control systems, hydraulic actuation systems, psychological and physiological analysis of flight.

Chapter 3

System Integration

3.1 Design Decisions

The 707 simulator that the Department received was initially constructed during the 1960s and at that time was state of the art. It was designed for operation by a Flight Training organisation (QANTAS) that had the capability to maintain such a large facility as necessitated by training requirements. As delivered, the system comprised a large amount of hardware:

- Simulator Cabin
- Analogue Flight Instruments (707)
- Engineer's Station
- Instructor Station
- Analogue / Digital Control Loading & Motion Base Control
- Flight Controls
- Power Supply Cabinet

- Junction Box Cabinet
- Two Digital Computer Cabinets
- Visual Computer Cabinet
- Visual Collimator’s (2)
- Visual Displays (2 CRTs)
- Several cabinets containing Instrument Synchro Resolver Drivers and Radio Aids Instrumentation
- Hydraulic Power Unit
- Interface Cabling (over 400 * 50 wire cables)

Prior to disassembly and removal of the simulator from QANTAS it was a fully accredited flight simulator being used for training of RAAF crews. If we had so desired it would have been possible to re-assemble the simulator at Sydney University and to operate it as it had previously .However, there were several reasons that this was not done

1. The Department was not intending to utilise the device for the training of 707 flight crews. The intent is to operate the facility as a teaching and research tool with no requirements for the simulator to be accredited as a flight training device.

2. It was not an aim of the project to create a dedicated 707 flight simulator, but rather to develop a re-configurable device capable of operating as any type of aerospace vehicle. The system in essence provides us with a 3 degree of freedom motion base with hydraulically loaded flight controls, visual hardware and an aircraft flightdeck facility. The fact that it was previously a 707 is only of historical interest.

3. A lack of resources existed with regard to personnel and funding with which to operate a large flight simulator. A system like the 707 simulator is very costly both in terms of manpower, parts and expenses. Even if it had been desired to operate the sim as a 707, it would have been prohibitively expensive to do so.

Providers of simulator training facilities operate with large numbers of specialist maintenance and engineering personnel to service, repair and upgrade their equipment. Many of the components in the Link 707 system are early generation analogue electronics that are very expensive to procure and difficult to maintain. Even if the systems were new, the large volume of equipment dictates a large budget for maintenance. For a University department, this is clearly impossible.

The new system installation is shown in **Figure 15**

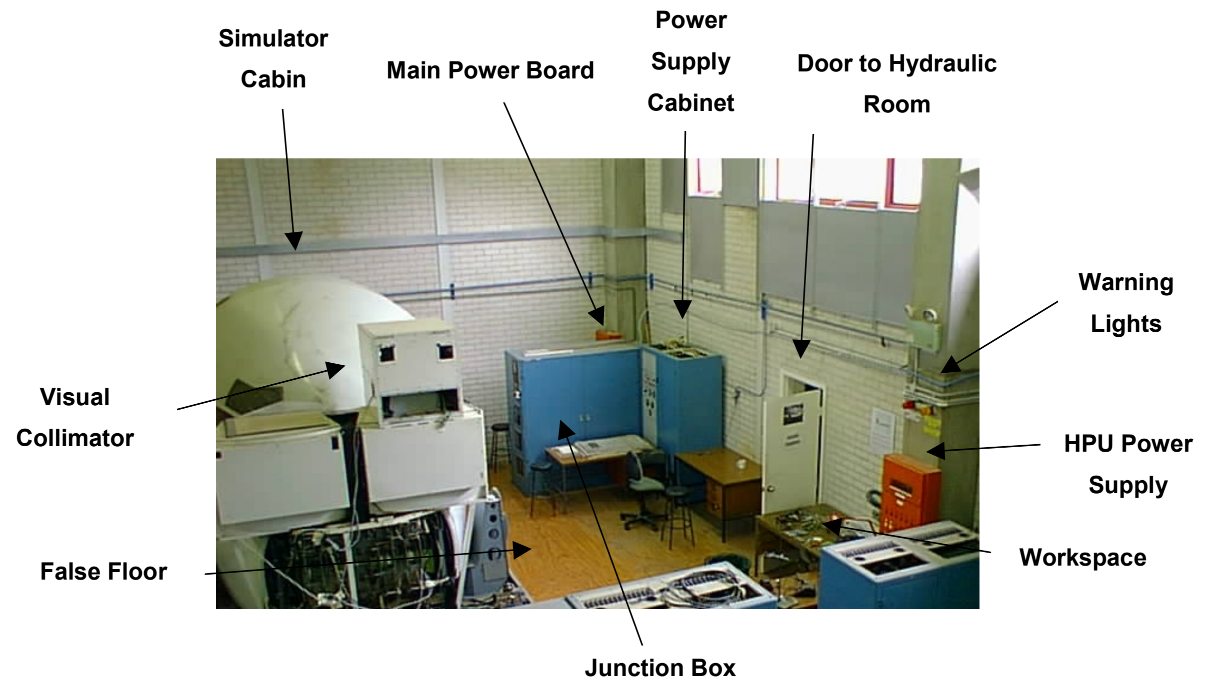


Figure 15 The Simulator

Having decided to modify the equipment substantially, decisions were made regarding Simulator components and architecture. The Simulator cabin contains several items of interest including the flight controls, flightdeck, motion base and parts of the visual hardware. These items will become the core of the new system. Surplus items include the Flight Engineer’s station, the Instructor Station in its previous guise, the analogue flight instruments, control loading and motion base analogue electronics, and the CRT visual displays.

3.1.1 Flight Controls

The flight controls are loaded hydraulically with control previously provided via analogue circuitry located at the control head. A new analogue electronic system is required to interface to a new PC based control algorithm. The servoamplifier has been replaced by modern control circuitry from the Moog company. Each flight control axis (3) runs through a mechanical linkage that terminates at a hydraulic actuator that provides the loading of the controls. Essential parts of each device that have been re-used include the servo-valves, the position potentiometers and force transducers that measures the force the pilot places on the controls.

The only other part of the original system reused is the interface panel shown in Figure 16. This has several heavy duty connectors that have been re-used as they interface with the potentiometer and force transducer and provide a mechanically strong connection for the new system.

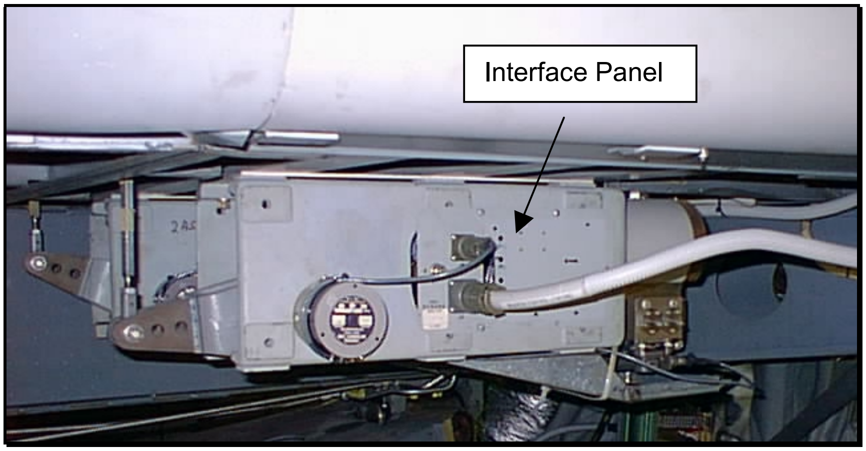


Figure 16 Control Loading Unit

3.1.2 Motion Base

The motion base is very important to the new system. As delivered the servovalves for each actuator were again run via extensive analogue circuitry. This has also been replaced with a Moog analogue position circuit interfaced with digital commands. There are several items on each of the three actuators (Figure 17 & Figure 18) that are desriable to re-use. Limit switches detect that an actuator has over-extended in either direction and provide an important safety mechanism in the event of a motion system problem and have been interfaced into the new system. Similar in operation is one 'Out of Settle' switch per actuator that determines movement of the motion base from its resting position. This is used to turn on several lights that warn people outside the sim that it is moving.

Each actuator also contains a Settle Valve. During normal operation, power (110V AC) is provided to this valve holding it closed. If the system is shutdown for whatever reason and power is lost to this valve, it opens and drains pressure from the actuator at a set rate allowing the simulator to 'settle' slowly to its resting position. Power supply to this valve is required for normal operation of the motion system.
Each actuator also has a position potentiometer that outputs the linear position of the actuator, an important part of the position feedback loop.

There is also a device on each actuator that monitors pressure differential between each side of the actuator. This was added to the simulator post manufacture to provide for increased motion bandwidth after the attachment of a new visual system. At this stage it is not required but wiring has been provided to it for possible future implementation.

Figure 17 Hydraulic Motion Actuator – Wide View

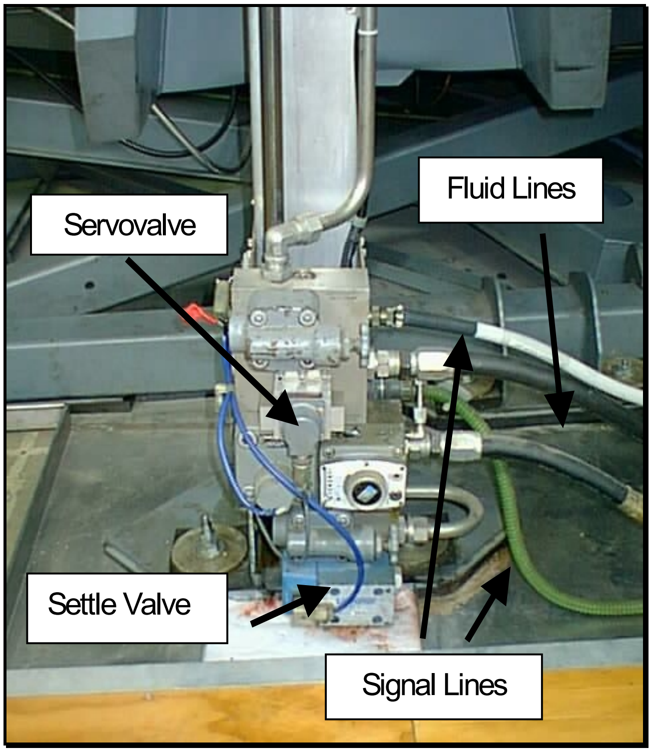


Figure 18 Hydraulic Motion Actuator

3.1.3 Hydraulic Power Unit (HPU)

Both the Motion Base and the Flight Control Loading require Hydraulic power to operate. This is provided by a Hydraulic Power Unit (HPU) located externally to the simulator and shown in Figure 19 & Figure 20.

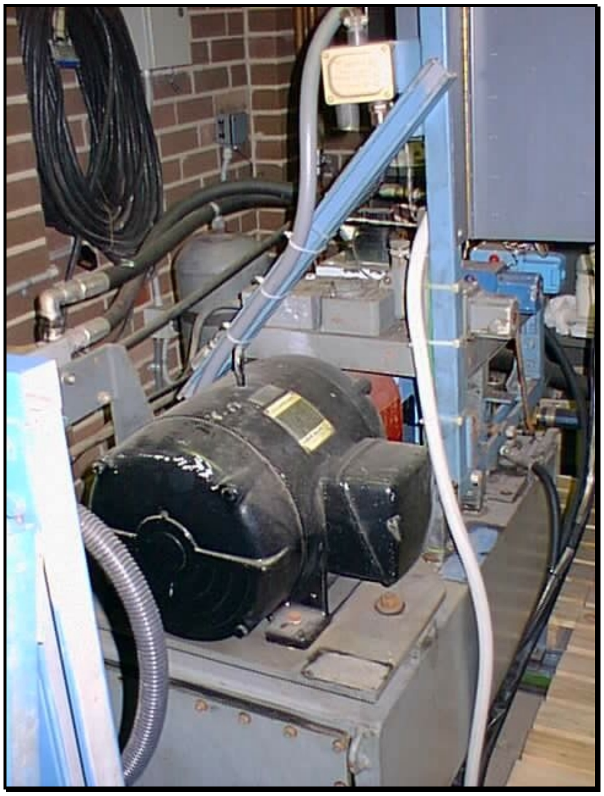


Figure 19 Hydraulic Pump Unit

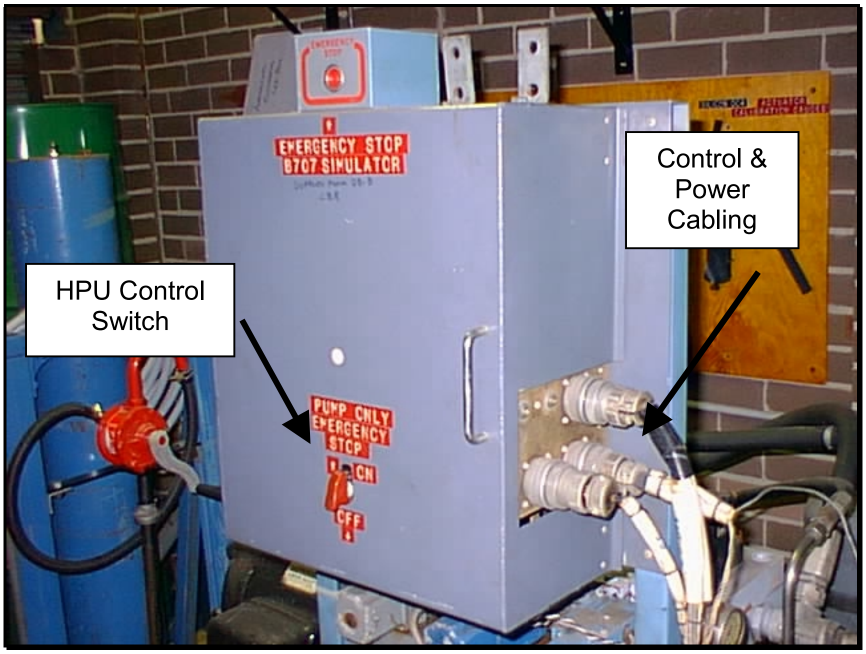


Figure 20 Hydraulic Power Unit Controls

Pressure and return lines run between the simulator and the HPU. An accumulator is also located in the pump room. it maintains hydraulic pressure during heavy demand periods and in effect dampens out pressure fluctuations caused by rapidly changing demands and is shown in Figure 21

Figure 21 Hydraulic Accumulator

The system has been housed in a new extension to the laboratory to isolate it due to the noise and requirements for hazard mitigation. The provision of a separate room also allows isolation of the device when it is running from a safety and environmental point of view. Should there be a failure of the pressure vessel or some part of the high pressure network, it is much safer to have the HPU in its own room. Small scale leakage of hydraulic fluid is easily contained by the concrete slab and absorption material around the edges of the room.

3.1.4 Electrical Power Supply

Electrical Power for the HPU comes from the Power Supply cabinet. This cabinet also supplies power to the Junction box to operate various control circuits and relays, and to the Simulator cab for lighting. It is shown in Figure 22.

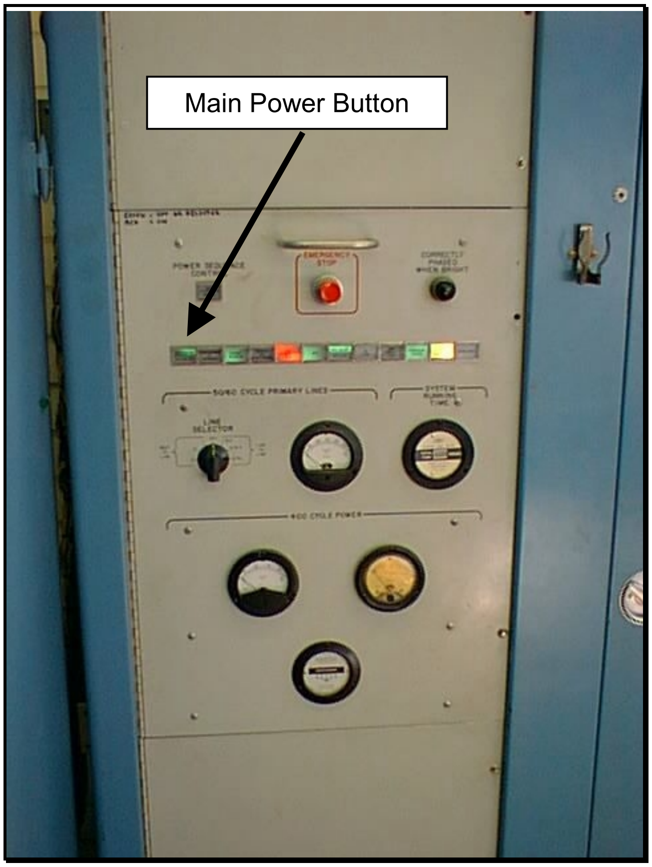


Figure 22   Power Supply Cabinet Front Panel

Indirectly the supply provides power to the Settle Valves through the HPU. Some modification has been necessary as it contains an interlock circuit that depends on the availability of other supplies in cabinets that that are no longer in use. An important fact about the power supply is that it is from the USA and relies on three 115 V AC phases for operation requiring a three phase 415V transformer shown in Figure 23.

Figure 23 Transformer

3.1.5 Junction Box

The Junction box cabinet forms the central point of both the old system and the new. Each cable from every system cabinet (including the simulator cab) was routed to the Junction Box (Figure 24) to be re-routed to its destination. For example, a cable from the simulator containing various flight control signals was connected to the Junction Box's front plane. The back plane contains wiring to re-distribute signals and or power from one connector on the front panel to another as described in a manual titled 'Junction Box Wiring' [46]. The various flight control signals can be split into several sections and routed to a new front panel connector, depending upon their final destination.

This cabinet is important in the new system as it still requires some interfacing to the simulator system through various cables. Some modifications have been necessary as components such as the HPU previously relied upon an interface to the now defunct digital computer and to other cabinets, new circuits have been created based upon the digital system but will still require access to several cables to interface with various systems.

Figure 24 The Junction Box

3.1.6 Interface Cabling

Interface cabling was extensively used in the device. The Junction box contains over 400*50 pin connectors for these heavy and long cables. A large number of these protrude from the rear of the simulator cab. Many of these cables are connected to pieces of hardware that are no longer required. Existing labelling has been critical in the circuit identification process. Unfortunately, due to their age much of the marking system has been erased from some cables making identification almost impossible. Identification of attached cables has been a predominately manual process.

The following sections will outline the hardware developments and modifications for the project.

3.2 Internal Modifications

This section deals with the conversion of a simulated 707 flight deck to a teaching tool / research simulator

As delivered, the simulator cabin, or ‘cab’ was fitted out to contain 5 occupants during a simulator training session. The aircraft itself required three crew members to operate it. They are the aircraft Captain, in the left hand seat, a Co-pilot/First Officer in the right hand seat and a Flight Engineer seated at his panel. Also, as per a 707 flight deck, there is a seat for an observer, or fourth crew member, located behind the Captain’s seat. Also present for the purposes of simulation is the simulator instructor, seated at the rear of the cab at his/her instructor panel.

A plan view of the original cabin is shown in Figure 25.

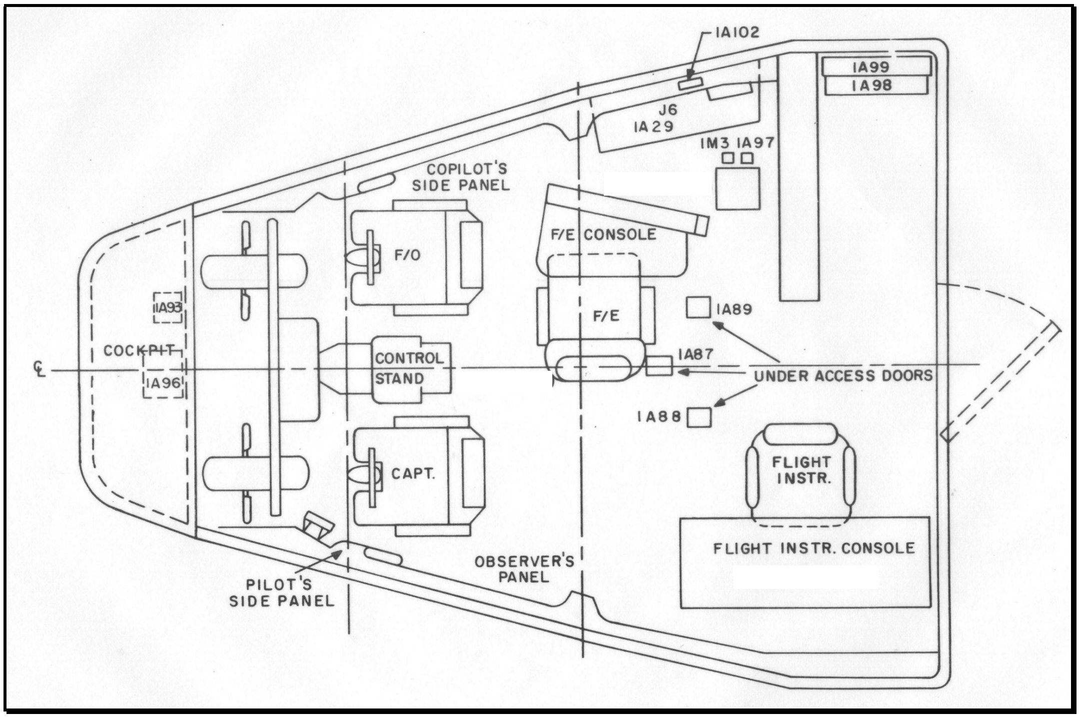


Figure 25 Plan View of 707 Cockpit Layout [22]

Figure 7 and Figure 8 show how the flight deck looked before its decommissioning.

Points of interest from the photos include:

- Flight Engineers panel,
- Analogue flight instrumentation,
- All flight displays specific to the 707

On the 707, the Flight Engineer was a crucial member of the crew. Unfortunately, for Flight Engineers, they are no longer required on modern flight decks. The first 'two man' aircraft, with crews consisting only of pilot crewmembers were the Boeing 737 and the Douglas DC-9, designed in the early 1960's. The two man flightdeck is now the norm, with Flight Engineers having gone the way of the Navigator and Radio Operator.

For this reason there was no valid reason to keep the Flight Engineer's panel: it was removed from the cabin and has provided a large amount of useable space.

3.2.1 Seating Installation

The original simulator contained five seats. Unfortunately, when the RAAF handed over the simulator, the flight deck seats (barring the observer's seat) were all missing, having been salvaged for use in a new simulator. Four modified car seats have been installed in the simulator. The two seats at the pilot locations are mounted on tracks for fore/aft movement. These two seats also have the capability to move up and down. The location of the two pilot seats both in terms of distance from the controls and pilot eye elevation is important for proper operation of the aircraft to be simulated. Proper seat position is essential in the final segment of an instrument approach so as to provide the pilot with the maximum visual segment, so he or she can see as much as possible from the forward windows.

As the original seats and their support structures were not present, it was necessary to recreate the required seat position. Located above each pilot is an ‘eye position indicator’, similar to an automotive antenna. It has a small ball located on the end. When the pilot is in the correct seating position with the eye position indicator extended, the small ball should sit exactly between the pilot’s eyes. Doing so will provide the appropriate eye position to obtain an optimal visual segment.

With the removal of the Flight Engineer’s panel, it is also possible to install two seats for student observer’s as shown in Figure 26.

Figure 26 Additional Observer's Seats

These are also modified car seats that have been installed at the rear of the flight deck , where the Flight Engineer’s panel was located. All seats are fitted with four point car racing harnesses to ensure occupant safety.

A photograph of the completed flightdeck is shown in Figure 27

Figure 27 Seating Installation

3.2.2 Flight Instrumentation

It was never the intent of the project to reproduce the flightdeck of a 707 aircraft with its extensive use of analogue instruments. Externally such instruments are identical to aircraft parts, however, the mechanism with which they are driven is different. The simulation we intended to install utilised computer Cathode Ray Tube (CRT) displays to display flight instrumentation. As such it was decided to remove the installed 707 flight instrument displays and replace them with CRTs.

The new simulation includes a computer generated flight instrument display, in front of the pilot. By adding a signal splitter cable, an identical instrumentation has been provided to each pilot. This is not an ideal situation, as in any large transport aircraft, each pilot's display receives data from separate sources to his partner's. This is to provide redundancy in the event of a subsystem failure providing erroneous information. During flight simulator pilot training, it is advantageous to be able to provide such conflicting inputs to flight crews to enable fault detection and isolation practices to be developed. Such events (differing flight instrument displays) have occurred in aircraft and have caused major accidents.

However, to provide such functionality would require a new module in the flight simulation. In the initial phases of development it is not necessary to allocate resources to such a project, but this could become the subject of future work.

Figure 28 shows the new flight instrument panel provided by the Cranfield flight simulation software suite.

Figure 28 New Flight Instrument Display

This display contains both flight instruments and engine instruments. On a large transport aircraft, the engine instruments are found on a separate display. A CRT has been installed between the Captain and First Officer’s instrument displays in place of the original engine instrument section. Currently this screen is not used for instrument display as the simulator software requires extensive modification to move the engine instruments from the above display to the new display. Instead the centre screen is used for operator and analytical data.

3.2.3 Instructor Station

The original instructor station in the simulator contained systems for controlling instructor inputs as well as displays of current aircraft parameters. The station was dominated by pushbuttons that allow the input of faults into various aircraft systems. Other inputs are provided for weather conditions, radio aids, visual scenarios as well as controls used to position the simulator at the intended training position.

This station will be used as the new instructor location as it provides desk space and a seating position at the rear of the simulator cabin so as not to interfere with the simulation. A thin LCD panel monitor has been installed along with a trackball mouse and keyboard. Interfaced with a multi-PC digital IO switch, this will allow full control of the simulation from inside the simulator..

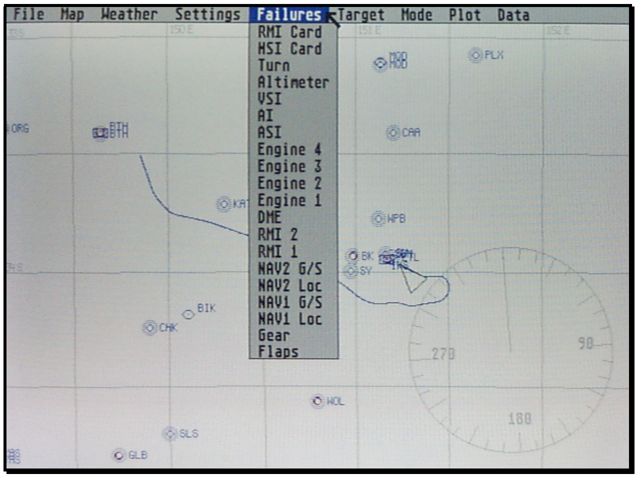


Figure 29 Instructor Operating Station Screen

3.3 Support Systems

Several systems were required to support simulator operation. These include the

- Electrical Supply
- Hydraulic power Unit
- Water Cooling System
- Air Conditioning

3.3.1 Electrical Supply

Cabinet 7 as delivered with the 707 simulator is the Power Cabinet shown in Figure 22. In the original system, the cabinet supplied power sources to all computers and instruments in the system, except for the HPU pump motor which is powered directly by an external three phase 415 volt 50 Hz supply.

The input to the simulator system is three-phase, 415/240 volt 50 Hz grounded neutral power supply. As the simulator was built in the USA, it directly requires 115v/208v power. A transformer is required to make this conversion as shown in Figure 23.

From the transformer the power is routed through the pumphouse wall into the power cabinet. The cabinet itself has several sections which are outlined below.

3.3.1.1 Main Circuit Breakers

This panel (Figure 30) controls power flow into the cabinet through the main 60A circuit breaker (CB, upper left), and from here through to the many power systems found in the cabinet. This cabinet contains 115V AC and 28V DC power supplies.

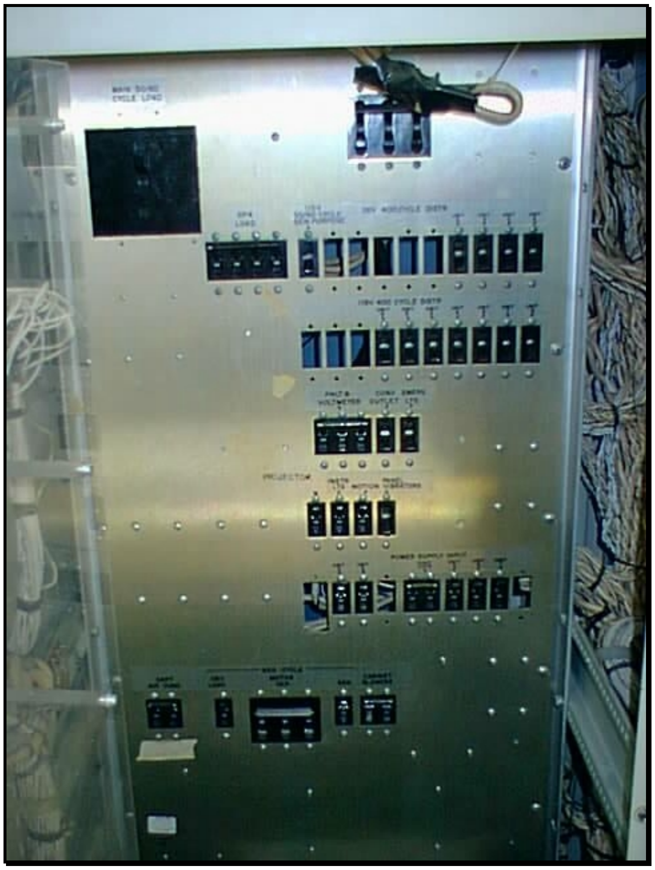


Figure 30 Main Power Supply Circuit Breakers

3.3.3.2 AC Power

50Hz power at 115V is used throughout the simulator as inputs to power supplies, power relay control circuitry as well as excitation to several systems such as blowers, air-conditioning (old) and convenience outlets which are no longer used. High frequency Power is produced by a 400Hz frequency converter.

This device is capable of a 20A current drain at 115 Volts, 400Hz. From here the power is reduced also reduced to 26V to be used throughout the simulator. This voltage is used as it is the same as actual aircraft power. As the old system utilised many actual components, this is a sensible way to power the simulator. Because all analogue instruments have been removed, the 400Hz supply is now used only for lighting.

3.3.3.3 DC Power

DC power is generated by regulated solid state power supplies shown in Figure 31. The upper supply is live at system start-up and provides 28V DC to the cabinet's control system. The second supply is activated when commanded by the DC power control circuitry. At this time, the second supply is not required as it currently provides no power. For this reason, the output of the first supply has been tied to the output of the second to provide power to its receivers.

Figure 31 DC Power Supply Controls

28V DC bussbars are found in the rear of the cabinet, currently supplied by 28V supply one. The bars supply power to relay control circuits, many of which are found throughout the simulator. As the system are no longer uses several of the older cabinets, it does not require nearly as much power from these circuits. Also produced is +/- 24 , 15 and 10 volts . These were all used throughout the simulator for various items including:

- Potentiometer power
- Peripheral components
- Servo devices

3.3.3.4 Power Sequence Control

To turn the power system on, first the three phase power must be turned on at the appropriate Power Board. This is located in the corner of the workshop, adjacent to the junction cabinet. This supplies power to the power cabinet's control circuitry. With the Power Sequence Control in AUTO and the System ON/OFF switch ON, the power sequence commences. This sequence is shown in Figure 32.

The section of the circuit that passed through the GP-4 was no longer present. As such, in order to get the outputs produced downstream of this step, a bypass circuit activated by the new supervisory computer system was created and will be detailed later.

3.3.3.5 28 VDC Supply to the Junction Box

Previously power was routed to the Junction box to various Busbars. From these, power was distributed throughout the simulator. Currently the three 28 V DC power busses are connected as well as the associated ground bus. This power is used throughout the new system for supervisory control signals.

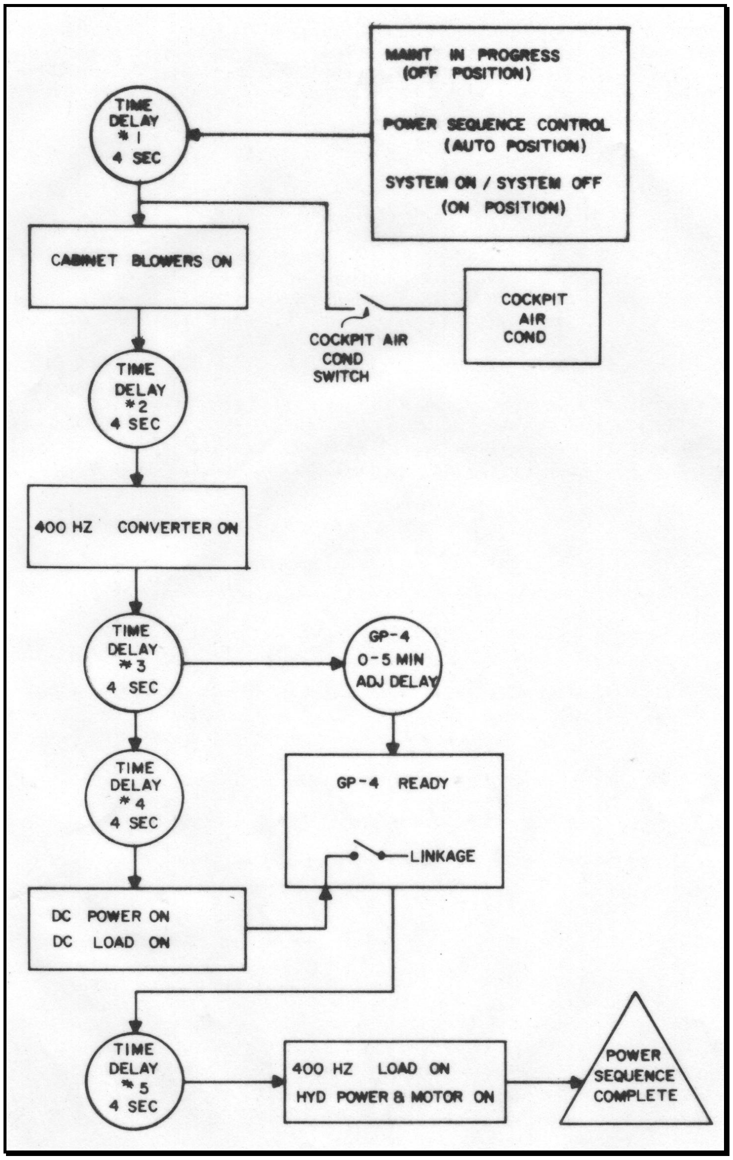


Figure 32 Power Supply Sequence Control [22]

3.3.2 Water Cooling

A water cooling system is required to cool the simulator’s Hydraulic Oil prior to returning it to the reservoir, [22] with specifications listed in Table 4

Maximum Flow Rate	15 gpm
Minimum Water Pressure	40 psi
Maximum Water Temperature	$29.5^{o}C$

Table 4 Hydraulic Power Unit Water Cooling Requirements

The cooling system was installed by Atlas Building Services Pty Ltd of North Ryde, NSW Australia. Documentation is provided in [47] and some excerpts from it follow.

3.3.2.1 System Control

1. Cooling system operation is automatic and is controlled via a relay in turn controlled by the Hydraulic system on/off switch.

2. Temperature of the inlet water is controlled via a thermostat which controls the cooling tower fan (Figure 33).

3. Hydraulic oil temperature is controlled via regulating the water flow through the oil to water heat exchanger based on LEAVING water temperature via a Danfoss AVTA-20 regulating valve (Figure 36). This temperature can be manually altered by adjusting the valves position.

Figure 33 Shinwa SBC10 Cooling Tower

The water tower (Figure 33) is located on the roof of the laboratory. Water is piped to and from the HPU via the copper pipes extending to the right.

Figure 34 Grundfos CR4-60 Condensor Pump

The condensor pump (Figure 34) drives the water through the system with the following specifications (Table 5)

Condenser Pump max flow rate	1.5 L/S
Condenser Pump output temperature	29.5^{o}C

Table 5 Condensor Pump Specifications

Figure 35 Aquarius 522MF Dosing System (provides water cleansing)

To ensure that the water used in cooling remains clean, a water cleansing system is used (Figure 35)

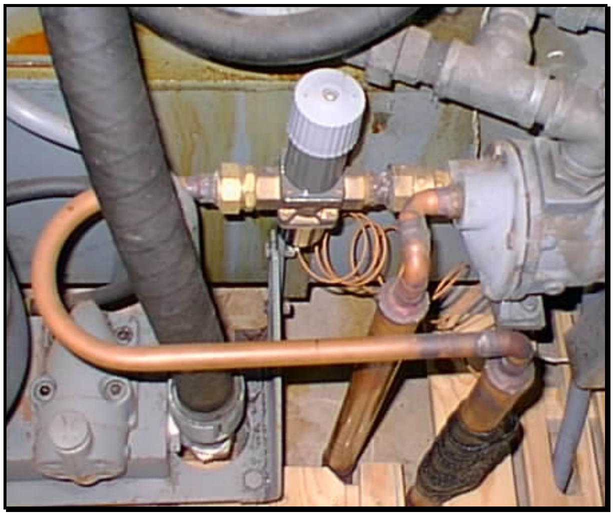


Figure 36 Danfoss AVTA-20 Temperature Regulating Valve

This valve (Figure 36) controls output water temperature by switching the cooling tower on and off. The output temperature target can be adjusted manually by turning the circular valve handle. Currently it is set at 38 degrees Celsius.

3.3.3 Simulator Visual System Hardware

Early simulators were intended to teach only instrument flight, where, by definition, there is nothing to see out of the cockpits windows and as such had no requirement for a visual system. The basic principle of instrument flight is to use only those visual cues presented to the pilot via his/her instrument display. It can be understood that the lack of a visual display in this instance would serve to reinforce that the pilot cannot fly by reference to visual cues obtained outside of the cockpit.

As the simulator has developed into an all round flight training device as opposed to a pure instrument flight trainer, the visual system has become an important and necessary part of the simulation experience. Initially, film based systems were designed to be used for takeoff and landing training. Subsequently closed circuit TV systems were developed to expand the amount of terrain that could be visualised. Since the late 1970's, computer generated imagery has become the most effective way to present visual displays in civil flight simulators.

Visual systems for simulation today employ projectors and a display screen in front of the pilot. The image is projected by several such projectors onto a wide angle, mirrored screen of up to 225 degrees field of view. As well as providing forward facing visual scenes, such a system adds many peripheral cues to the simulation experience. This is of particular importance when operating aircraft in close proximity to the ground in landing and or takeoff operations.

3.3.3.1 Depth of Field

Depth perception in simulation refers to the apparent 'depth' of the visual scene presented to the pilot. Depth can be defined as :

"distances measured along the line of sight to the object viewed" [31]

Stereopsis provides the major input to our ability to determine such a quantity. Stereopsis is a binocular operation (uses two eyes) and depends upon the angle subtended by an object as sensed by our eyes, similar to parallax. The further away an object is, the smaller the angle subtended by the object and our eyes and so the further away we determine the object to be.

There are also many monocular cues (one eyed) such as:

- Perspective,
- Distant objects appearing hazy
- Objects high in the field of view appear further away
- One object obscuring a second is seen as being closer.

Such monocular cues can be used in a Computer Generated Image (CGI) system with software modifications of images depending upon their distance. However, a Cathode Ray Tube (CRT) or Liquid Crystal Display (LCD) cannot reproduce the conditions required to utilise stereopsis.

A device known as a “beam splitter collimated display” can be used to create an illusion of depth of field using stereopsis. A diagram is shown in Figure 37. A full treatment of this device is found in [13].

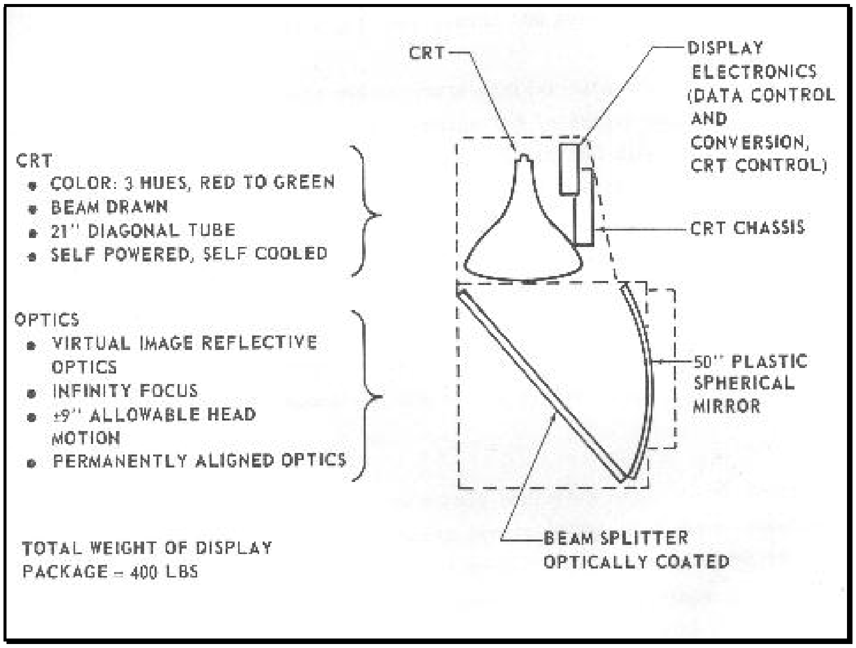


Figure 37 Collimator Optics

The Link 707 simulator was fitted with two collimators when delivered, one in front of each pilot location. The original displays have been replaced by 22 inch colour displays. The use of collimators has the following benefits over the use of uncollimated CRT displays

1. A collimator provides the depth of field discussed in the previous section, i.e. it makes the image appear approximately at infinity.

2. Use of a collimator provides a much greater field of view from a CRT display without having to position the display unacceptably close to the pilot.

3. With a collimator , the entire display system is mounted externally to the cockpit environment. This provides a better simulation by maintaining the correct cockpit environment

In a modern projector/screen configuration this depth of field is provided by the concave spherical mirror. In many ways this set-up is preferable, most notably so in that it provides a continuous field of view throughout the viewing area. Only one scene is generated and so each pilot sees the correct viewpoint out of his or her window. Such a system is desirable, but will be the subject of further developmental work.

3.3.3.2 The Vital IV System

The Vital IV is a product of the McDonnell Douglas Electronics Company of St. Charles MO and dates from the late 1970's. The simulator as delivered was equipped with this system. It provided forward visual scenes to both pilots. The scenes were for night operations only as shown in Figure 38

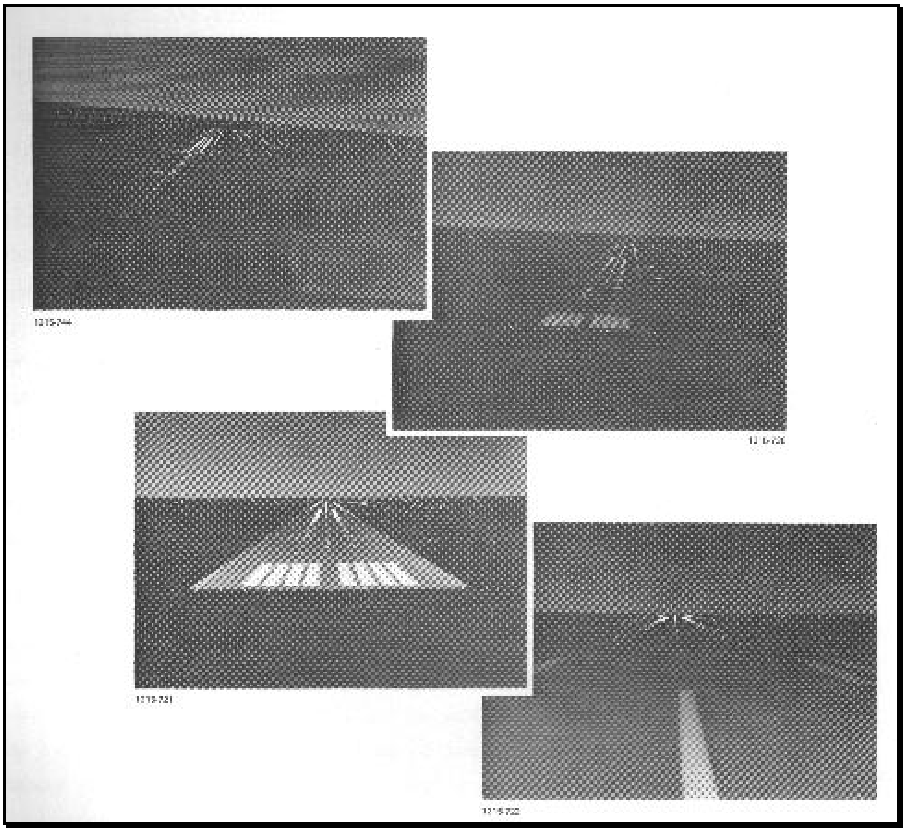
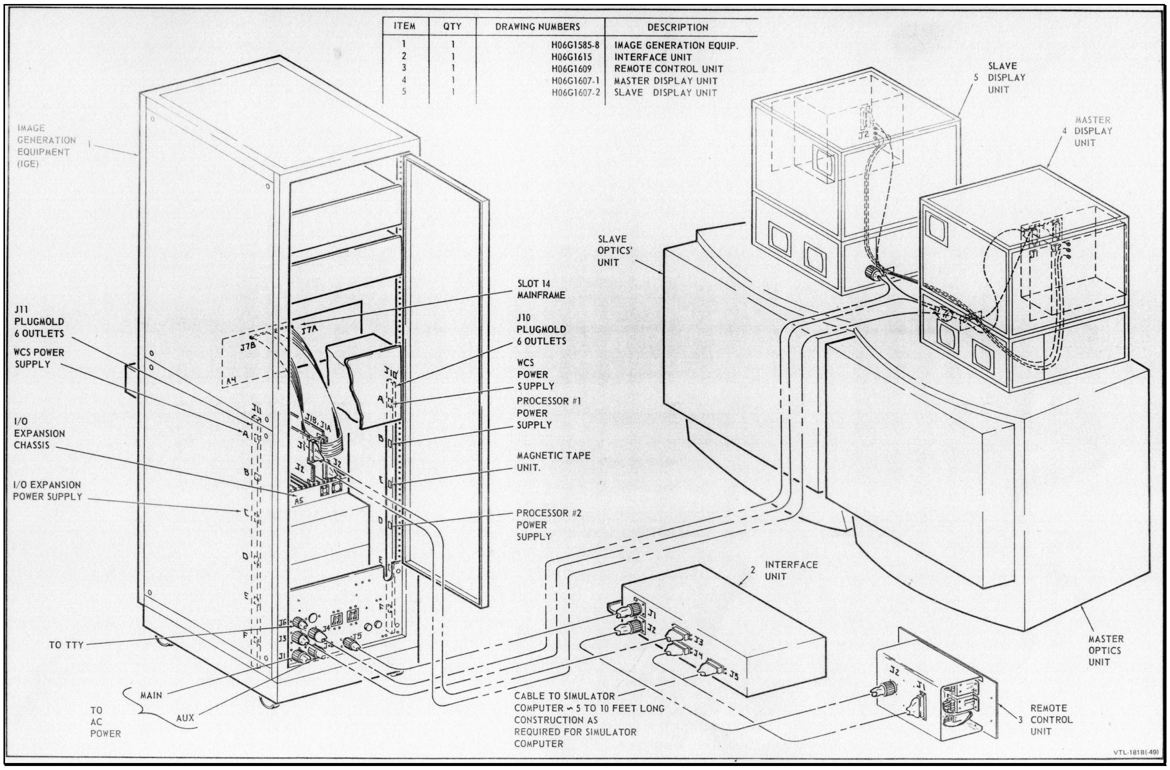


Figure 38 Vital IV Visual Picture

The scene presented to each pilot was identical and through the forward windows only. The side windows are covered by blackout curtains

The complete system is shown in Figure 39. On the left of the drawing is the main computer for the system. Data is routed through cabling and interface boxes to the two CRT displays (master and slave) which in turn project downwards into the Optics units.



ITEM	QTY	DRAWING NUMBERS	DESCRIPTION
1	1	H06G1585-8	IMAGE GENERATION EQUIP.
2	1	H06G1615	INTERFACE UNIT
3	1	H06G1609	REMOTE CONTROL UNIT
4	1	H06G1607-1	MASTER DISPLAY UNIT
5	1	H06G1607-2	SLAVE DISPLAY UNIT

Figure 39 Vital IV System Diagram

3.3.3.3 Optical System (Collimator)

The optical system consists of a spherical mirror used to provide collimation, a beam splitter, and support structure. The mirror itself has a radius of curvature of 127 cm. The system is located so as to place the pilot’s eye at roughly the center of the mirror’s curvature.

The optical system provides depth of field to the CRT’s image as well as expanding the field of view to 63cm (25in) high by 91cm (36in).

3.3.3.4 Display Device (CRT)

The CRT [14] is red-green phosphor, single gun magnetic deflection unit. Colour is adjusted via control of the anode voltage to provide red at low electron velocity to green at high electron velocity. Intermediate colours of orange and yellow can also be obtained.

The useable area of the CRT is 19 inches wide by 13 inches high (48cm by 33cm).

3.3.3.5 Re-Engineering Decisions

Whilst the hardware to drive this system was also provided with the simulator, the decision was made early on to install a new visual system for several reasons:

1. As for most of the hardware delivered with the simulator, the work involved in maintaining the system as delivered would have been prohibitive.

2. The night only scene, whilst suitable for aircrew training is limiting when compared to the performance of low cost visual systems available today.

3. A modern SVGA system is capable of daylight scene presentation to computer monitors. It was not possible to input this data into the original CRTs.

4. An SVGA system is re-configurable and expandable where the VITAL system is not.

The optimal solution (barring cost) was the installation of a wide angle projection type visual system as found on modern training simulators. Due to the high cost involved in purchasing such a system, it has been deferred until a later date.

The possibilities of constructing such a system in house were also investigated using Commercial off the shelf (COTS) projectors and a spherical screen constructed by the department's workshop. While promising, and possibly the subject of future research into low cost simulation, the decision was made to progress using large CRT computer monitors as the display device combined with the existing optics units.

3.3.3.6 New Visual Installation on the 707

Two large[13] CRT Colour monitors have been purchased for use in the new visual system. These have been installed in place of the original Display units, on top of the optics unit. A frame has been constructed to suspend each monitor, minus its outer shell, into the same position as the original monitor. This is important as the distance from the screen to the first collimator mirror is important. The height of the screen can be adjusted to provide the optimal field of view and focus. The new screen fits into the system above the collimator. The dimensions of the hole are shown in Figure 40.

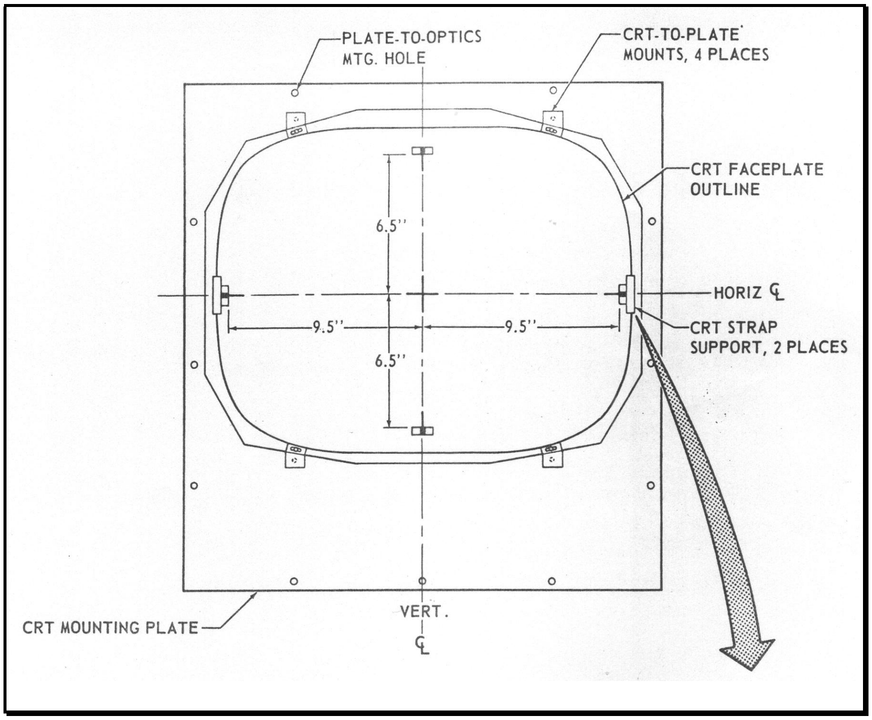


Figure 40 Visual System CRT Dimensions

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[13] **Panasonic 22 inch monitors**

The dimensions in Figure 40 [14] will accept a commercial 22 inch monitor although the aspect ratio is slightly different.

The area between the monitor and the flightdeck windscreen is darkened with the aid of blackout curtains and is painted with matt black paint to ensure optimal viewing conditions. The previous Vital IV system used only night displays and so the dark screen located above the collimator was not clearly visible. However, our new colour display has a much higher light output. If the pilot's seat is set too low, the monitor can be seen above the visual scene protruding into the field of view. It is very important to position the pilot seat properly to prevent this. Luckily it is also important when flying an aircraft to have correct seating to allow for optimal visibility over the flightdeck coaming.

3.3.3.7 The New Simulator Image Generation System

The new Image Generation (IG) system is produced by Primary Image. It consists of three Barracuda image generation cards running Tempest software . A diagram of the basic system is shown in Figure 41.

At system start-up, the Tempest Database is loaded onto each Barracuda card. Three Barracuda cards provide three different views. As originally configured, these views were straight ahead, as well as left and right peripheral views. The location of the monitor with respect to the Pilot's eye is programmed for each card, allowing it to determine the correct output. As discussed in Chapter 2, peripheral visual cues are important for piloted flight simulation.

The visual computer (VIS) provides graphics to the visual displays given aircraft position and orientation. It has the capability of displaying three independent displays, each with a different viewpoint. For example initially it was intended to have one display directly in front of the pilot with two displays placed laterally about the pilot's head to provide peripheral cues.

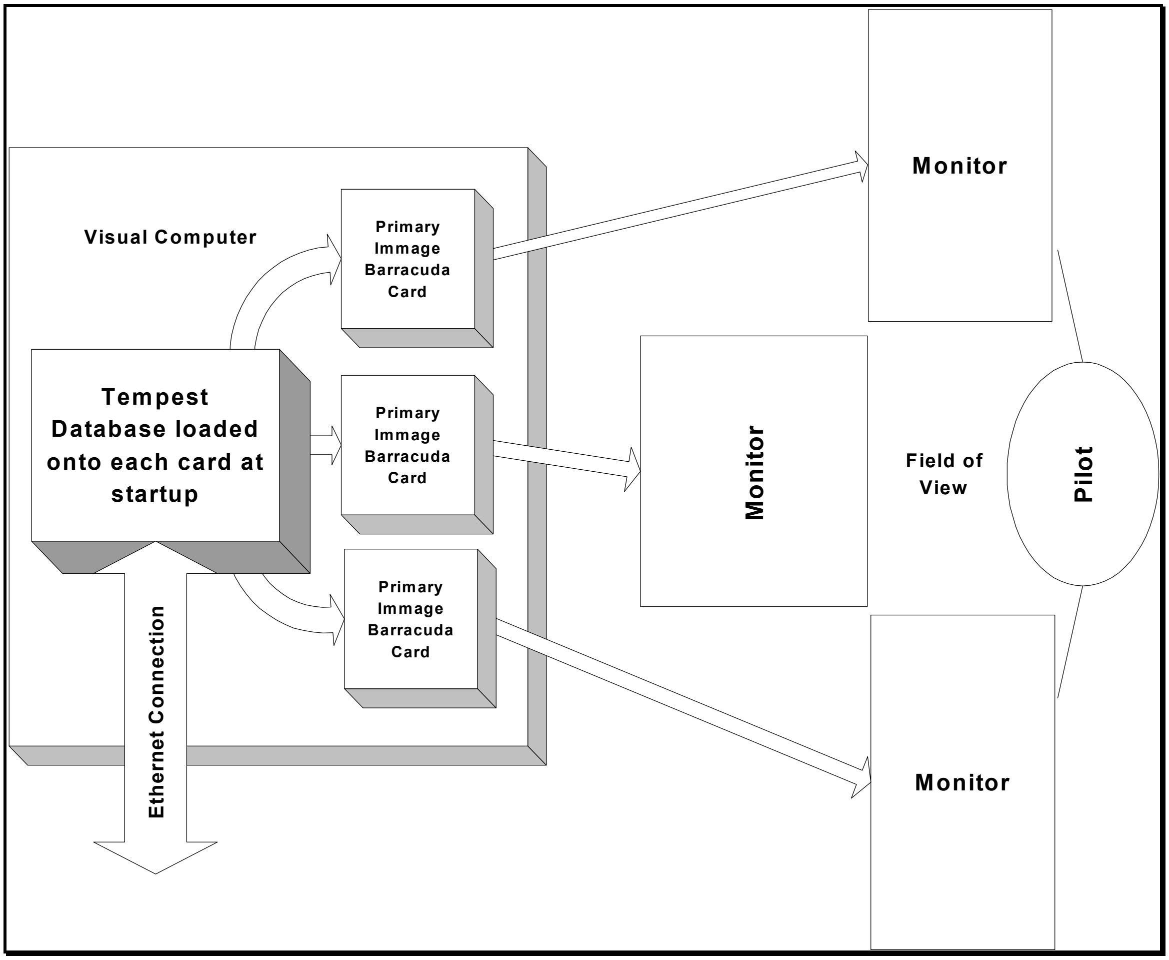

Figure 41 Piranha cards and three monitors around pilot's head

At this stage only the forward channel is used although it is duplicated via a cable signal splitter to the two forward displays. Control of the system at the operator level is confined to re-boots from the keyboard or via a reboot switch on the front of the device.

The forward display output is shown in Figure 42

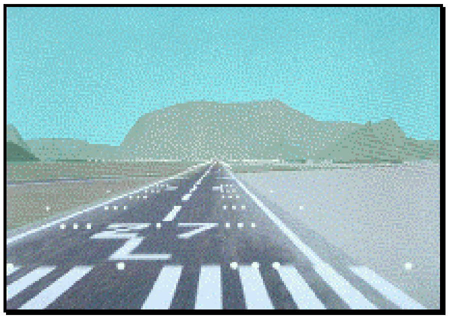

Figure 42 New Visual Display

3.4 The Cranfield Flight Simulation System

Early on in the simulator project, it was decided to base the system upon a flight simulator software suite developed by Professor David Allerton of the College of Aeronautics at Cranfield University in the UK. This section will outline the architecture of this system and outline the reasons for employing this system.

Older flight simulators such as the 707 utilise dedicated custom digital systems to provide computing power. These systems are by design highly specialised, expensive and difficult to maintain without an extensive budget and support structure. The Cranfield system negates these issues by using COTS technology. A full description of the system is found in both [2] and [3].

The hardware used in the simulation includes commercial Personal Computer (PC) technology, as well as SVGA graphics cards and Ethernet network cards. It is shown that such a distributed set-up can provide sufficient fidelity to operate as a real time simulation with a rate of 50Hz sustained throughout simulation. The system generates 1.5 Mbytes of data each minute that can be recorded and analysed off-line. The real-time nature of this system as well as the extensive graphics and flight instrument representation allow utilisation of the system as a training flight simulator as well as for its intended use as an engineering simulator.

A flight simulator has many software modules as shown in the Figure 43. The flight model is the center of the system and provides the focal point for module interactions. In most commercial flight simulators, many of the modules are combined into one computer system. Separate modules often include the visual system as well as the instructor station and the motion system.

In the Cranfield system, the modules are physically partitioned into separate PC computers linked by an Ethernet network. For real time simulation, all of the modules use a common frame rate of 50Hz. To achieve a proper real time simulation, each module must execute all of its code as well as accomplish any data transfer between modules in the allotted time frame. Some modules such as the visual system receive data that has been processed several times. First a control input is sensed, then processed by the flight model, then the resulting motion is passed to the visual system which must calculate the resultant visual picture. The output that this process produces must be made available to the projection system within one time frame to prevent noticeable visual lags.

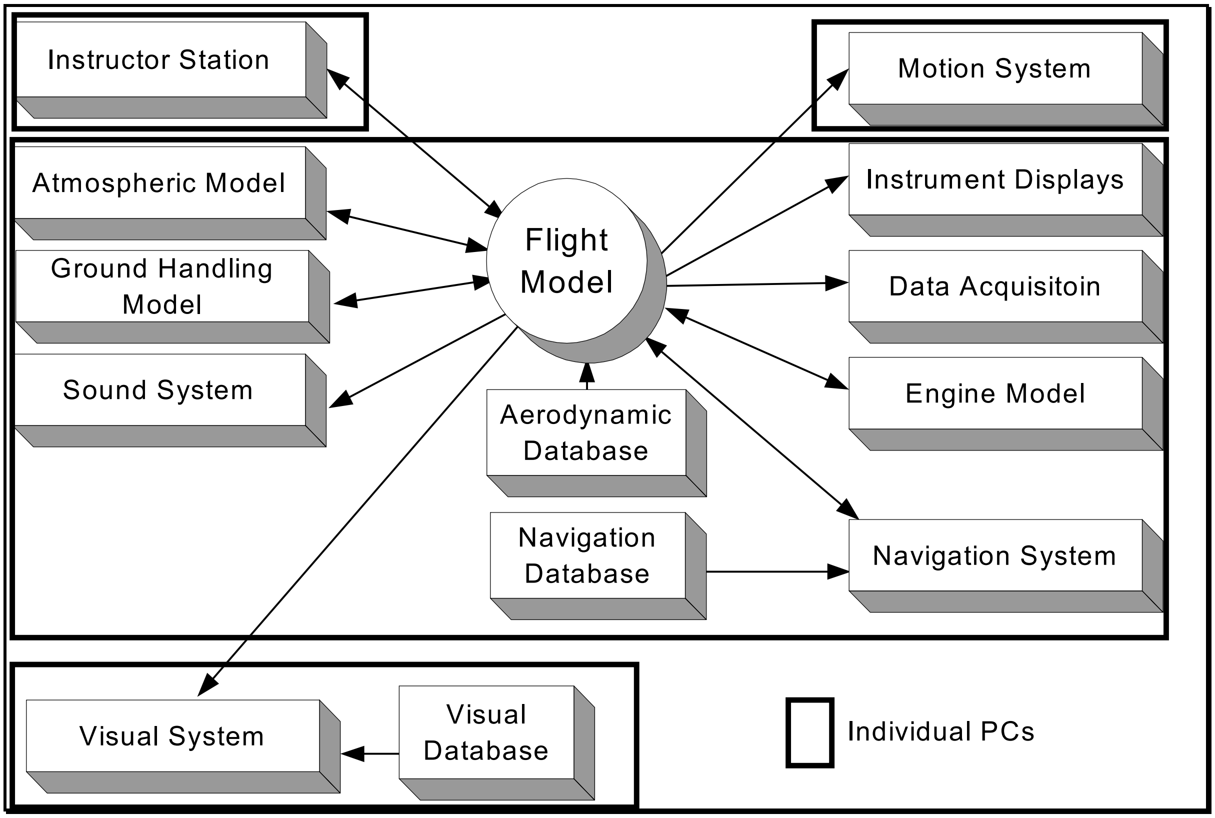

Figure 43 Simulator Data Flow

3.4.1 Ethernet Network

The Ethernet protocol used to transfer data between modules has been widely used for inter-computer communications for several years now and forms a Local Area Network or LAN. The basic set-up of a LAN is that a communications network is shared by several devices. A system known as *packet broadcasting* is used to transmit data. In this method, all devices on the network receive all the packets transmitted by the other devices [4]. Data is transferred in ‘packets’ of between 46 and 1500 bytes [3]. Each packet not only contains the transmitted information, it also contains ‘header’ information. This Header information outlines both where the data has come from and to where it is addressed. A basic diagram of the system is shown below. The Ethernet is shown here as extending beyond those modules already installed. The network can accommodate additional modules as required simply by attaching them to the Ethernet. **Figure 44** shows the communication architecture of the basic Cranfield Simulation System.

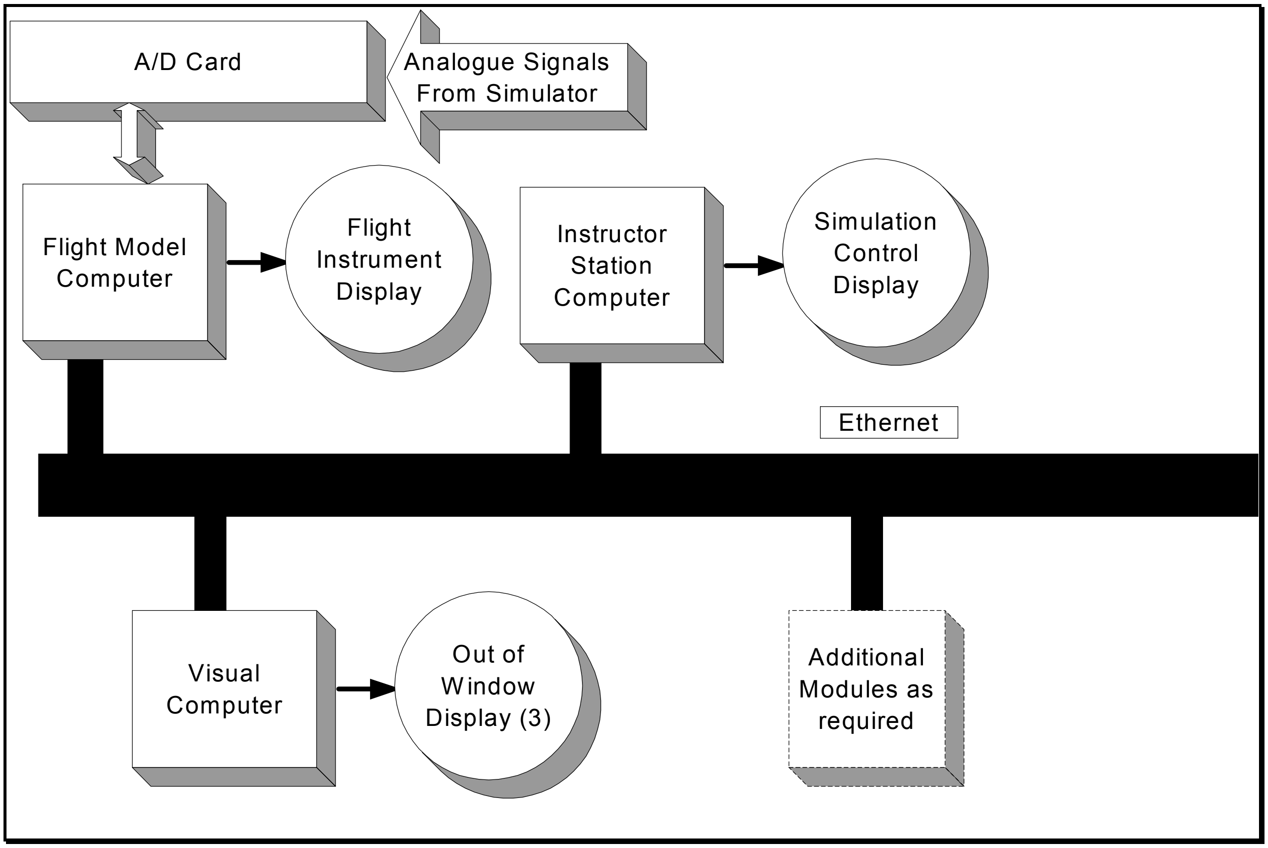

Figure 44 Cranfield Simulator Communication Architecture

The system does not focus on speed or timing of data transfer, rather it provides excellent data integrity. An Ethernet network works as an open system, in that many node on the network can transmit a data 'packet' at any time. With several nodes transmitting, this leads to collisions between packets with the resultant loss of data. The system compensates for this by detecting collisions and using one of several schemes to cause the sending nodes to resend their data. Different delays are used to try and ensure that the data is successful on their resultant tries.

Whilst this system is excellent at providing data integrity, it is has no method for ensuring that data packets arrive within a certain time period. Transfer speeds on an Ethernet network are usually given as 10Mbit/s or 100Mbit/s. This is the fastest speed that two adjacent systems can communicate with each other and does not represent an average of transfer times between multiple systems on a network. The Ethernet card itself provides collision detection and controls the re-try mechanism, isolating the software from the problem.

The Ethernet system does not provide an ideal data transfer protocol for real time flight simulation precisely because of the way it handles the transfers. On a network that is not operating at a high utilisation rate, collisions may occur infrequently and lost transmission time due to re-sending packets is a small percentage of the networks usage. On a highly loaded network, it cannot be guaranteed that the level of packet re-transmissions will not adversely affect the timing requirement[14].

What does help us in a flight simulation application is that the sequence of required packet transfers is regulated and repeated in every frame. If this sequence is outlined to the system, then the number of packet collisions is reduced considerably. Also, the small amount of data being transferred (compared to that amount permitted by the frame size and transmission speed) means that the operator can be reasonably assured of correct and timely data transmission.

The use of an Ethernet driven by a publicly available packet driver[15] allows for the following:

1. Low cost transmission
2. Excellent data integrity
3. High speed transmission, particularly with the small number of transmitting devices in this network
4. Addition of extra modules.

In this application it is desired to add a Motion base computer as well as a Variable Stability module. As the data on the network is in packet form, any Ethernet capable

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[14] In this case the timing requirement means completing all packet transfers within the 20ms frame.

[15] In this case the Crynwr public domain packet driver collection.

computer can access the data in each packet, even if it is not originally intended for that device.

3.4.2 Flight Modeling

The 50Hz iteration rate mentioned previously is required so as to provide sufficiently real simulation. That is, the calculations performed by the system as to aircraft motion must occur sufficiently rapidly so as to be transparent to the operator or pilot. The sequence of calculations for simulation is shown in simplified form in Figure 45.

The aerodynamic database contains information used to calculate forces and moments generated upon the aircraft. This data is typically available in tabular or graphical form [3]. Each variable itself may be the function of several other variables. Data is extracted by table access or polynomial fitting. First order or Euler integration is used and has been shown to offer acceptable system stability.

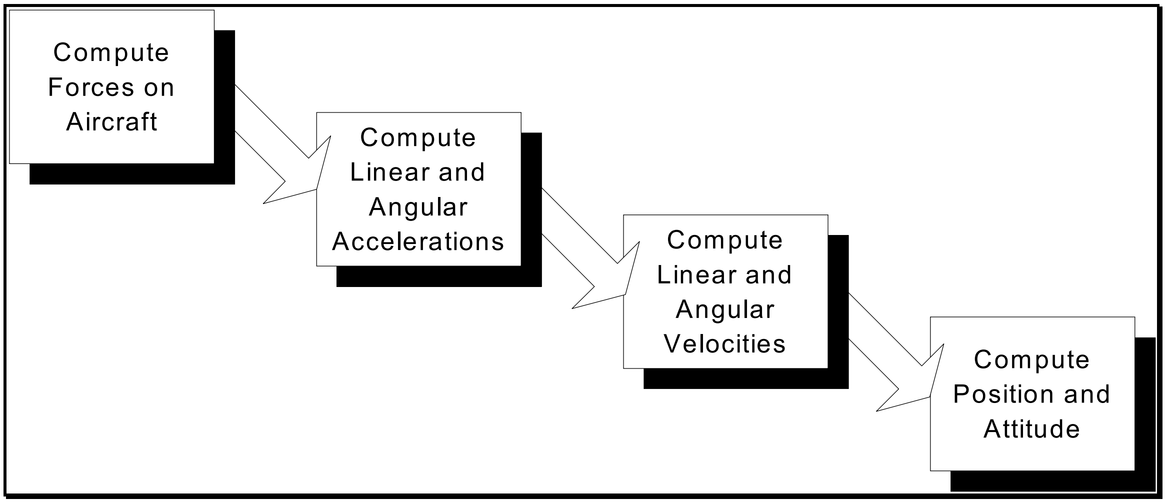

Figure 45 Sequence of Events in Simulation Run

Also required are the computations required to change from one axis system to another. In particular, as mentioned in [3], aerodynamic data is often specified in stability axes whilst for engine data, forces and moments are often calculated in body axes. The calculation of Euler parameters as well as Direction Cosines for conversion between earth and body axes also require computation time from the 20ms time frame.

The weather and navigation models in an ideal system would approximate a round earth. An acceptable approximation, particularly for an engineering simulator (the system's original intention), is a series of flat panels. As the aircraft moves across the surface of the earth, the closest runway system is chosen as the center of such a panel and the systems coordinate systems are transferred to this new origin.

3.4.3 Analogue to Digital Conversion

Pilot inputs to the flight model are introduced into the system via a 12 bit analogue to digital conversion process (ADC). The Advantech PCL-812PG card provides 32 digital and 32 analogue inputs with a sampling rate overall of 1600 Hz [3] . Each value is stored in a shared buffer that is accessed by the flight model when required. Interrupts are used to access the 32 analogue channels, with an interrupt time of 50µs for each interrupt, a total of 1.6ms of each frame is taken up by data acquisition.

3.4.4 Aircraft Instrument Displays

As the system does not specifically targeting a particular aircraft flight deck, and as the originally designed engineering simulator was not so designed, there is no requirement for an accurate replication of actual aircraft instrument displays. The displays must only be functionally correct and refresh at an acceptable rate, in the case of this system at a minimum of 50Hz. SVGA graphics provides suitable performance and is used in this system. SVGA does not provide for vector graphics, character generation, clipping or infilling of regions. These capabilities have been provided by the system's designer.

3.4.5 Instructor Station

The instructor station provided with Cranfield simulation provides functionality to change the following parameters on-line:

1. Weather and Lighting
2. System Settings
3. System Failures
4. Map and Data Displays

A sample screen is shown in Figure 46

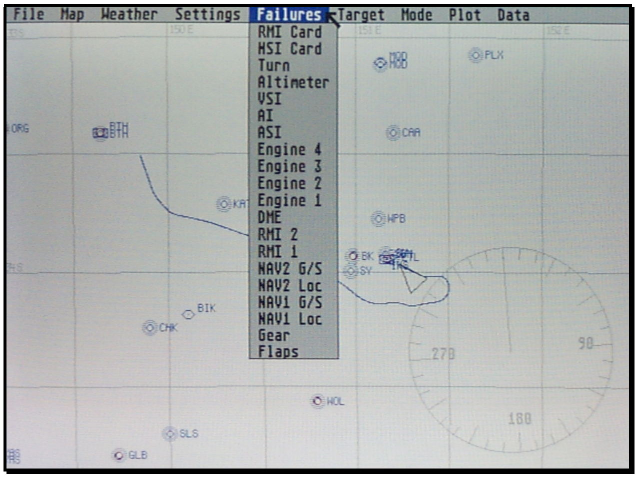

Figure 46 Instructor Station Example Page

3.4.6 Flight Test Environment

As the system was originally designed as an engineering flight simulator, it has the capability of capturing large amounts of data from the simulator. This data is recorded during a simulation run and can then be analysed either on line or off line after the session. The flight model generates a 512 byte data packet during each frame which contains the following:

1. Aerodynamic data
2. Engine data
3. Navigation data
4. Systems data

This generates 1.5Mbytes of data a minute. Extended memory is used to store the data packets directly.

3.4.7 System Performance

The basic system was benchmarked using three 486 computers. Real-time simulation was achieved at 50hz with a worst case time consumption of 15ms (compared to the available frame length of 20ms). The flight models used are full six degree of freedom non-linear state models. A propriety navigation database is incorporated as well as a commercial visual system. The system is implemented on Intel Celeron 300MHz computers, resulting in a 5 fold increase in performance [3].

3.5 System Structure

An outline of the system's overall structure is shown in **Figure 47**. There are seven main sections of the system:

1. Simulator Cabin
2. Junction Box
3. Hydraulic Power Unit
4. Electrical Power Supply
5. Computer Cabinet
6. Motion Actuator Assembly
7. Control Loading Assembly

The Simulator cabin is the center of the simulation and houses the flight deck, flight controls, motion base, visual system, sound system, instructor station and student seating. The Junction box was and still is the focal point for signal wiring in the simulator. It is here that signals are both received from and sent to the other parts of the system.

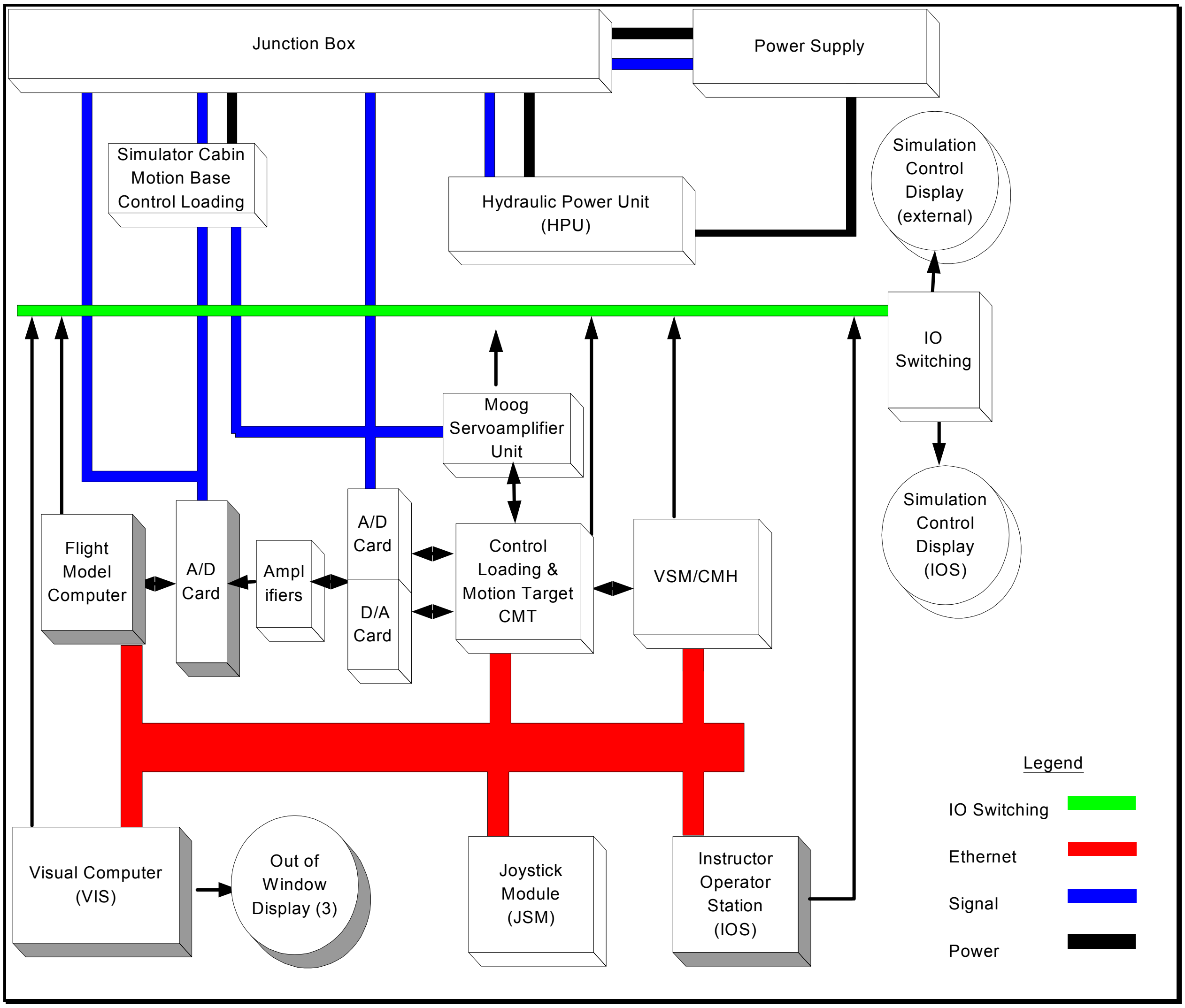

Figure 47 System Large Scale Setup

The Hydraulic Power Unit (HPU) provides hydraulic power at up to 3000psi and 10 Gallons per minute. It receives control signals from the Control Loading and Motion target (CMT) via the junction box and power from the Power supply cabinet.

The computer cabinet (Figure 48) is located behind the simulator and contains the following pieces of computer hardware

- Flight Model Computer (FMC)
- Flight Model A/D board and multiplexer
- Instructor station computer (IOS)

- Variable stability module computer / Control Loading and Motion Host (VSM & CMH)
- Control Loading & Motion Target (CMT)
- Visual Computer (VIS)
- Ethernet hub
- IO Switching hub
- Moog Servoamplifier Unit
- Motion/Control loading wiring (including CMT, A/D and D/A boards interfacing as shown).

Figure 48 Main Computer Cabinet

It is here that all the computation is done to drive the simulator.

The flight model computer contains the software to run the simulator flight model. Presently this is an executable with the source programmed in the Modula 2 programming language.

The Instructor station computer (IOS) houses the Instructor Station software described in section 3.4.5

The Variable Stability computer houses the variable stability module used to change aircraft aerodynamic, control, inertial and propulsive characteristics on line. It also houses the motion system host. This part of the system is where the Supervisory / Motion / control loading software is programmed and built for transfer to the CMT. This system also allows on-line adjustment of parameters via the Matlab Real-Time Workshop. The system display will be used for two purposes. The first is the variable stability control panels, the second is the Simulink host model that can be adjusted on-line, in turn adjusting whatever systems are running on the motion target.

The CMT runs in real time and provides supervisory control of the system as well as actuator position commands to the flight controls and motion base via the Moog Servoamplifier Unit. It runs as a dedicated real time system and can operate on its own or connected to its host in the CMH for on-line changes. It has a dedicated A/D and D/A system for the collection and distribution of signals. It collects data from the power supply, the HPU, the simulator cabin and Moog Servoamplifier Unit as shown in Figure 50. The computer display has two areas. The top section shows the system status including how long it has been operating, how close to frame capacity it is operating, the worst case frame usage[16] and Ethernet connection status.

The Visual Computer operates as described in section 3.3.3.7

The Ethernet hub (Figure 49) is simply a central location in which to plug the Ethernet cables from all of the computers. It can be connected to the wider Departmental network

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[16] The worse case observed during testing was a 7% frame usage.

to allow simple data transmission to and from the simulator. However this is not done when running the simulator as the system transmits a lot of data over its network and would greatly increase the department system load . This also prevents external transmissions interfering with the simulation system.

Figure 49 Ethernet and IO Switching

The Input/Output (I/O) switching hub allows one monitor/keyboard/mouse combination to operate up to eight computer systems although only one can be used at any one time. Each systems input and output cabling is routed to this device. Its output goes to the IOS control monitor/keyboard/mouse. Software in the hub allows for quick switching between the use of each computer[17]. Currently this system is used to control 5 computers. When the device is running operationally, the control console is the instructor station equipment in the simulator. This allows the operator to monitor all of the available systems, including the flight/engine instrument displays, as well as access them for changes as required through one keyboard and mouse.

The Moog Servoamplifier Unit houses the six Moog servoamplifier control cards. There are three for the flight control actuators and three for the motion actuators. Each takes a position command from the motion target as a 0 to 10V dc command. The card forms the control in a position loop for each actuator that includes a measurement of actuator position. Each card is individually configurable for a combination of Proportional,

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[17] Switching to another computer involves tapping the Ctrl key twice followed by the allocated number of the desired device.

Integral and/or Derivative control which is jumper selectable. Each card also provides Dither as required to prevent stiction[18] in the actuators. The Moog box also provides a 15 volt power supply which is used in the many amplifiers and sensors required.

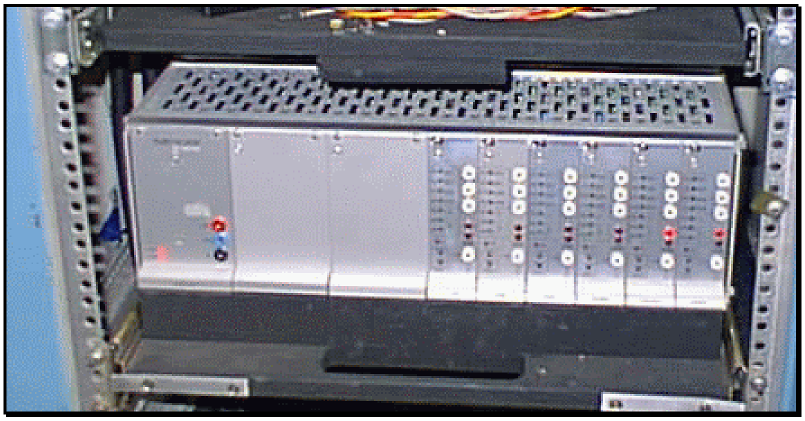

Figure 50 Moog Unit

The Moog wiring set-up will be investigated in the next section. Basically it involves signal conditioner information that regulates position signals from each actuator to produce a 0 to 10 V dc position signal for each card. A set of signal amplifiers facilitates flight control position and trim signal buffering, filtering and amplification to the FMC A/D card.

These amplifiers are detailed in Appendix four.

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[18] **Dither in effect superimposes a high frequency oscillation of a very small magnitude on the position signal, this keeps the servo valve/actuator constantly moving which in turn increases dynamic response.**

3.6 Electrical Integration

The heart of this system is the supervisory control system based in the CMT computer, operating as a real time Supervisory Control and Data Acquisition (SCADA) system from within the Matlab environment. It gathers external data from the simulator and generates outputs to it, all of which are interfaced via several devices:

1. Serial Ports
2. PCI-DAS1602 16 Analogue to Digital (A/D) card
3. PCI-DDA08 Digital to Analogue (D/A) card
4. Measurement Computing SSR 24 / DST Solid State Relay Board

The serial connection provides the SCADA system with the data it requires from the Flight Model computer. The following parameters are required for Motion cue generation, Flight Control Loading and general system operation

- Aircraft Translational Accelerations
- Aircraft Roll rates and Accelerations
- Aircraft attitude information
- Aircraft body axis velocities
- Current Atmospheric data

Although it is possible to use an Ethernet connection for this purpose, using the serial cable provides a dedicated channel for data transfer to ensure deterministic operation.

The A/D card provides a logical interface with the rest of the simulator systems via the Computerboards SSR 24/DST solid state relay board (Figure 51) that has been mounted in the side of the Junction box. This board allows connection of various circuits to the CMT to allow for control of the supervisory, Motion and Control Loading systems.

The D/A card facilitates eight channels of analogue output with 16 bit accuracy over a 0-10v range. These provide analogue position commands for the motion base and flight control position hydraulic actuators as well as reference voltages. It also provides 48 channels of digital I/O to be used in future for interfacing to a Boeing 747-400 Autopilot Mode Control Panel.

3.6.1 PCI-DAS1602 16 bit card

Analogue to Digital conversion is achieved through the use of the PCI-DAS1602 16 bit card manufactured by ComputerBoards. It has the following specifications.

Analogue Input

- 16 bit
- 8 Differential or 16 Single ended inputs
- 5 µs A/D conversion time
- minimum 200kHz throughput

Analogue Output

- 16 bit
- 2 channels

Digital I/O

24 channels configurable in banks of 8,8,4,4 as inputs or outputs.

Currently 7 digital inputs, 13 analogue inputs, 5 digital outputs and 2 analogue outputs are used. The Digital inputs and outputs interface with the simulator via a Measurement Computing SSR 24 Relay Board and will be described first. The Analogue inputs and Outputs interface via Measurement Computing SCR-50 breakout board.

3.6.2 PCI-DDA08 D/A Analogue Output Card

This card provides Digital to Analogue conversion and is also a 16 bit board manufactured by ComputerBoards. It currently is used to supply Analogue outputs via a Measurement Computer SCR 50 breakout board as outputs to the Moog system and the Flight Model computer.

It has the following specifications

Analogue Output

- 16 bits
- 8 channels

Digital I/O

- 4 banks of 8
- 4 banks of 4, programmable as input or output

3.6.3 Measurement Computing SSR 24 Relay Board

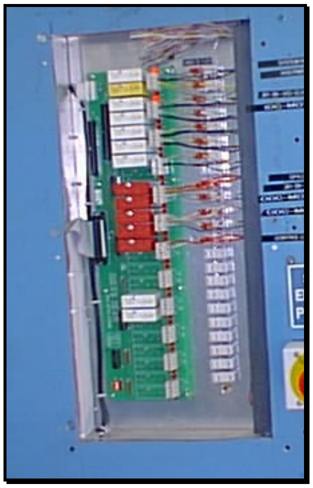

Figure 51 Measurement Computing SSR 24 Relay Board

On the left hand side of the board (Figure 51) are positions for input or output Solid State Relays (SSR). These are of types listed in Table 6

SSR Module	I/O Configuration
IDC 5 (white) IAC 5 (yellow) ODC 5 (red)	3 – 32 Volt DC Input 140 Volt AC Input 60 Volt DC Output

Table 6 SSR Components

There are 24 positions available in groups of 8, 8, 4 and 4. Each bank is configurable as an input or output operation. Currently the first 8 (Figure 52) have been configured as input terminals, the next 8 have been configured as output terminals (Figure 53), the next four as inputs while the last four are not as yet used. The data to or from these blocks is taken via ribbon cable to the Digital lines of the PCI DAS1602 16 card located in the CMT computer.

The Input/Output terminals in the center are the physical interface between SSR blocks on the left and the signal connection on the right. From Table 5, each standard IDC 5 has a maximum voltage input of 32V DC, as the power supply's 28 V DC power is used extensively this is more than adequate. The second SSR is yellow in colour to distinguish it as a 140 V AC device. It is used as part of the HPU to detect 110 V DC power application to the hydraulic cooling system an indication that the HPU has been turned on. Each terminal has 2 ports, + and -, as well as a red LED that indicates the logical status of the input signal.

3.6.3.1 PCI DAS1602 16 Digital Inputs (1 to 8)

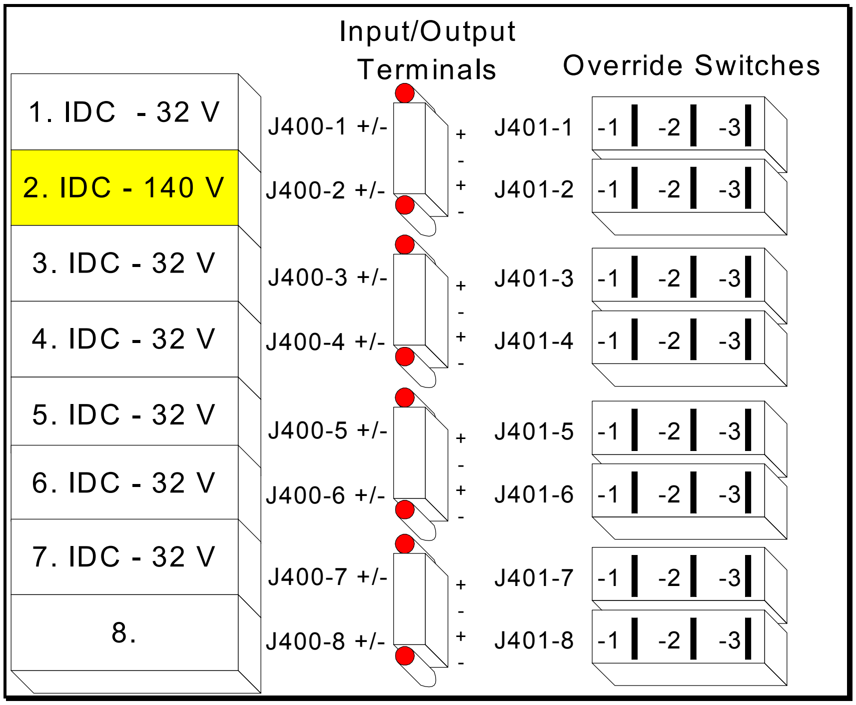

Figure 52 SCADA Input Terminal for PCI DAS1602 16

The Override Switches on the right provide a manual override[19] input to the SCADA system. Each IO module can be isolated from its circuit by positioning the switch in the override position. This breaks the circuit and allows us a final decision on the status of the signal. This has been used extensively during development and represents an important maintenance tool.

The elements of Table 6 comprise the basic systems the SCADA system monitors for control. Each signal in this instance is either on or off.

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[19] **We also have software override switches in the SCADA system**

SSR Input	***Name***
1	Power System Ready
2	Hydraulic System Ready
3	Control Loading Switch ON
4	Motion Switch ON AND Safety circuit complete
5	Left Limit Switch
6	Right Limit Switch
7	Rear Limit Switch
8	NC (not connected)

Table 7 Digital Inputs to SCADA PCI DAS1602 16 from IO Card Block 1

3.6.3.2 PCI DAS1602 16 Digital Output (9 to 16)

The second section of the IO board is shown in Figure 53.

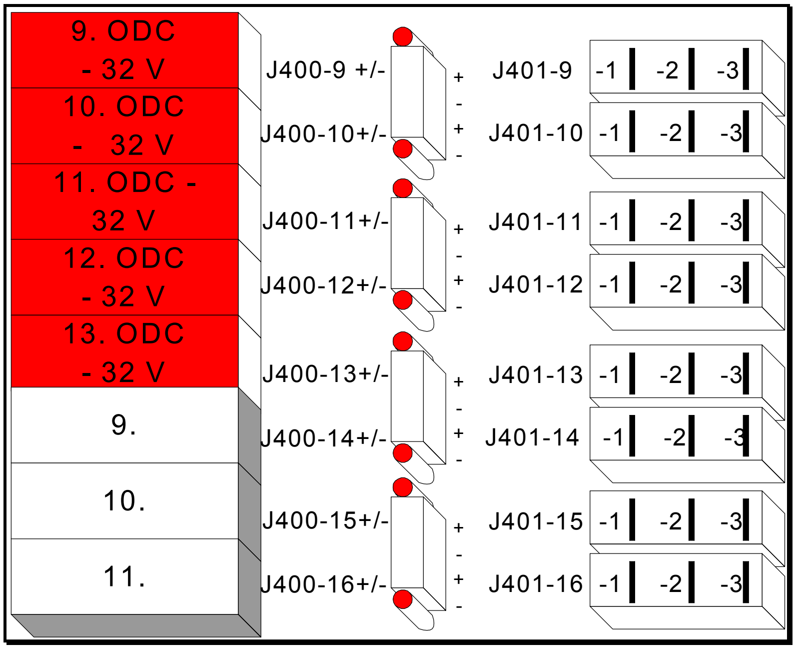

Figure 53 Group of Eight Digital Outputs

It currently contains 5 ODC 5 blocks with three spare positions. These blocks output the signals generated by the PCI-DAS 1602-16 card Digital Output section. Each circuit starts at the + terminal, a red LED indicates the signal is on. From here it proceeds to the center pin of its respective override switch. From here the signal can proceed to the simulator by two methods.

1. If the switch is in the Computer Controlled (CC) position, when the SSR closes the signal is directed through the SSR mechanism, giving the CMT control of the signal.

2. If the switch is in the middle position, the signal is isolated. This is particularly useful for isolating hardware such as the motion base or control loading hydraulic valves during testing, while still permitting software operation.

3. If the switch is in the override position, the input signal is connected to the output circuit. This allows manual activation of the system, again useful for testing and development (independent of software operation).

The five signals are shown in Table 8

SSR	***Name***
9	GP4 Signal
10	Control Loading ON
11	Motion Erect
12	Motion ON
13	Control Loading Full Pressure
14	NC
15	NC
16	NC

Table 8 SCADA Digital Outputs

3.6.3.3 PCI DAS1602 16 Digital Inputs (2)

The third section of the board (group of 4) is configured in the same way as the first section and in shown in Figure 54. Functionality is listed below.

The last group of four is not currently used.

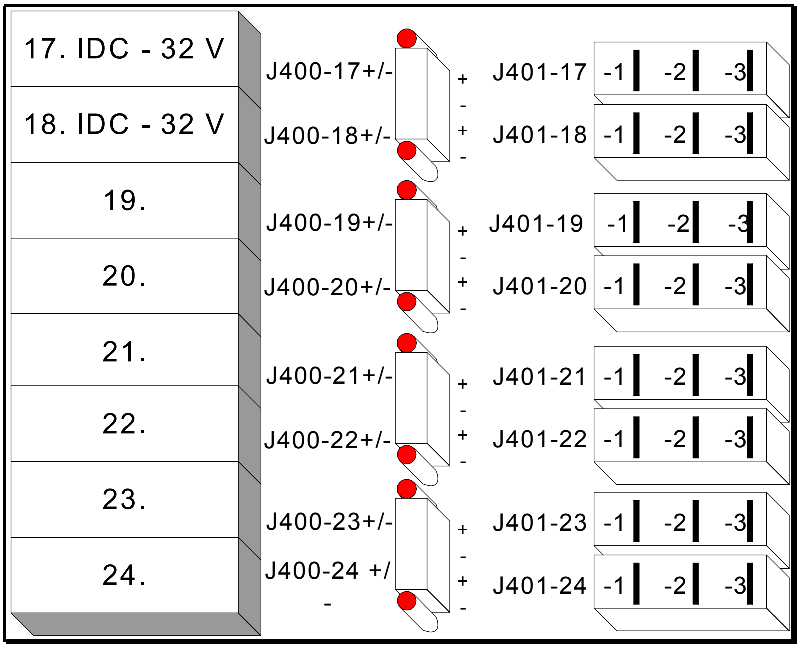

Figure 54 Digital Inputs to SCADA PCI DAS1602 16 from IO Card Block 3

SSR	***Name***
17	Elevator Trim nose UP
18	Elevator Trim nose DOWN

Table 9 SCADA Digital Input (2 of 4)

3.6.3.4 PCI DAS1602 16 Analogue Inputs (13)

This card also collects a large amount of data directly from the rest of the simulation. These analogue signals are shown in Table 10.

Input	**Name**
1	Aileron Force Measurement
2	Aileron Position Measurement
3	Elevator Force Measurement
4	Elevator Position Measurement
5	Rudder Force Measurement
6	Rudder Position Measurement
7	NC[20]
8	NC
9	Aileron Trim Position
10	Elevator Trim Position
11	Rudder Trim Position
12	NC
13	Rear Actuator Position
14	Right Actuator Position
15	Left Actuator Position
16	Moog Servoamplifier Unit Check Signal

Table 10 SCADA Analogue Inputs

The Moog Servoamplifier ready status signal (input 16) is the only signal that comes directly to the card.

The flight control force measurements are described in the Control Loading Wiring Section, as are the flight control and motion actuator positions

The flight control trim positions come from the simulator, then are routed via ground isolating amplifiers to the FMC. This is because the CMT and FMC both require trim positions. The CMT requires trim positions to account for control column neutral point changes due to trim wheel movements. The FMC also requires them to accommodate the aerodynamic effects of the trim controls. Although these inputs could have been communicated via the Ethernet connection between the CMT and FMC, this would have involved far more complexity due to packet transmission and collision avoidance concerns. Electrical integration was seen as a cleaner, more reliable solution.

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[20] The three NC or no connection inputs are provided for the motion actuator differential pressure measurements which are not in use at this time.

3.6.3.5 PCI DAS1602 16 Analogue Outputs

The two analogue outputs from this card (Table 11) are used as reference voltages in the control loading system. As will be explained in the following sections, there are several amplifiers in the Motion and Control Loading systems. These are used for

1. Ground Isolation
2. Amplification
3. Filtering

They are described in detail in Appendix 4.

On each control loading actuator there is a force transducer that measures the force applied by the pilot. The output of the transducer is bipolar having a range of –10 to 10 volts. To be used by the SCADA system it must be read as a signal in the range of 0 to 10V DC. Amplifiers are used to reference the voltage to this range by applying a gain and offset. For this to occur, the PCI DAS 1602 card produces analogue outputs that provide reference voltage offsets to the amplifiers.

Output	Name
1	Aileron and Rudder Zero Force Positions
2	Elevator Zero Force Position

Table 11 PCI DAS 1602 Analogue Outputs

3.6.3.6 PCI-DDA08 Card Outputs

Output	Name
1	Aileron Position Command
2	Elevator Position Command
3	Rudder Position Command
4	Rear Motion Actuator Command
5	Right Motion Actuator Command
6	Left Motion Actuator Command

Table 12 PCI-DDA08 Analogue Outputs

These six outputs are calculated by the Control Loading and Motion Target software as commanded positions for the Moog servoamplifier unit.

3.6.4 System Description

The simulator’s Junction Box has been described before. It is where connections are made to various circuits. It contains a large number of Junctions (J) and Terminal Blocks(TB). The Junctions are where each black cable from the simulator is attached to the front face of the Cabinet. At the back face of each Junction, cables route signals to other Junctions for distribution throughout the simulator. The Terminal Blocks are used to join several signals together. Typically these are used to distribute electrical power to various circuits. The TBs have been expanded to include the junctions on the SSR board.

3.6.4.1 HPU Power and Signals

Two cables run to the HPU system

Cable 345 runs from the Junction Box and carries signals and power to the HPU as listed in Table 13.

The main control signals are outlined in Figure 62 and are listed as follows:

1. 'd' Provides the initial 28V DC signal to commence motion operations and to operate the Motion Erect Valve.
2. 'D' Provides a second 28 V DC signal that maintains the motion base operation after the initial start-up period and to open the Motion ON Valve.
3. 'H' Provides a 28V DC signal to operate the Control Loading Valve that allows pressure to the CL system.

These valves are shown in Figure 55 HPU Control Loading and Motion Valves. They allow Hydraulic pressure to the Control Loading and Motion Systems.

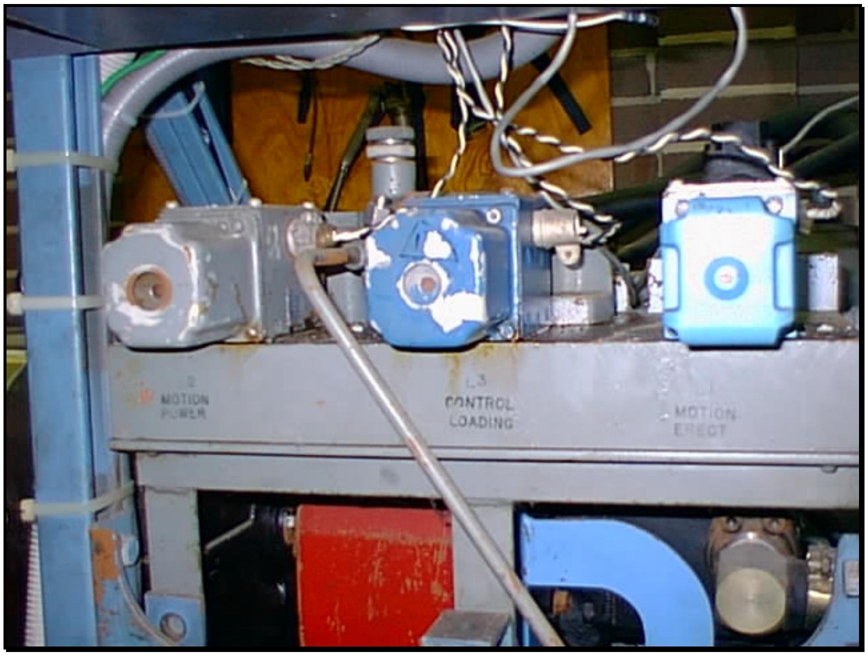

Figure 55 HPU Control Loading and Motion Valves

A	28 V dc for relay operation
p	NC
R	NC
a	NC
B	NC
T	NC
C	NC
U	NC
S	NC
b	NC
D	Motion ON Signal
E	Not used
G	Old Emergency Stop – Not used
H	Control Loading ON
J	Not used
K	Not used
L	GND
V	Not used
W	Not used
X	Not used
Z	Old Emergency Stop – Not used
n	Not used
d	Motion Start
M	Speaker Power – Not used
N	Speaker GND – Not used
J3 – G	Limit Switch Power IN
J3 – E	Limit Switch Power IN GND
J3 – H	Low Pressure Sensor – Not used
J3 – K	Low Pressure Sensor – Not used
J3 – J	Low Pressure Sensor – Not used
J3 – L	Low Pressure Sensor – Not used
J3 – M	Low Pressure Sensor – Not used

Table 13 HPU Connections

Another cable runs directly from the Power Supply cabinet to the HPU.

Power Supply P2 – A	28 V dc
Power Supply P2 – B	GND
Power Supply P2 – F	HPU Motor Power Relay Switching – 110 V
Power Supply P2 – D,E	HPU Motor Power Relay Switching – 110 V

Table 14 Power Supply to HPU

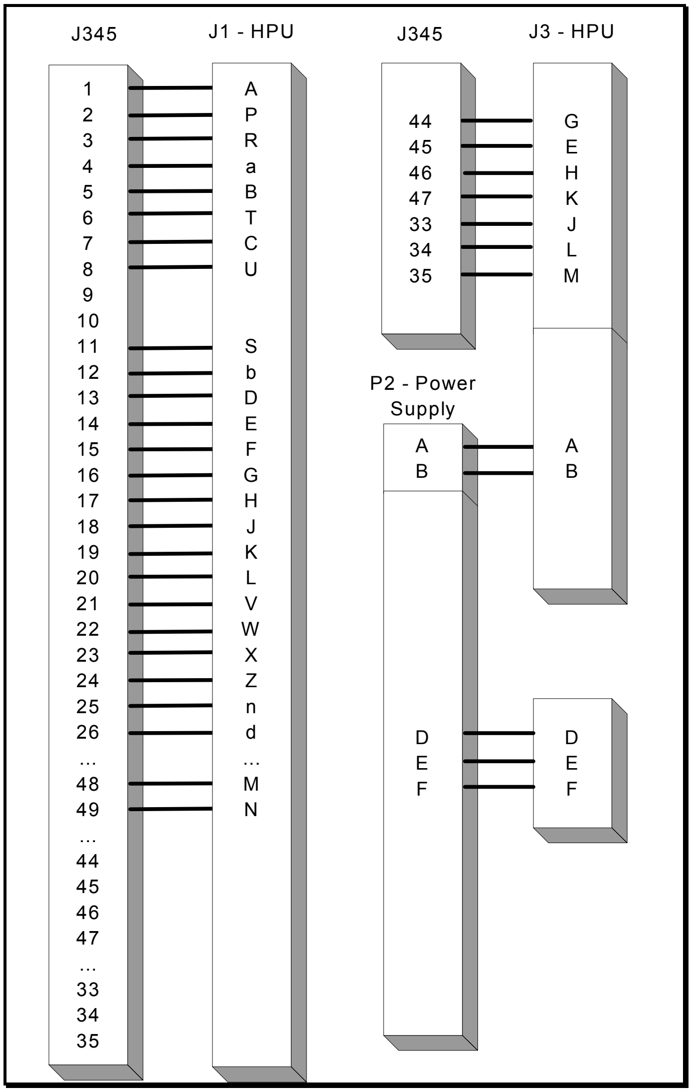

Figure 56 HPU Cabling

3.6.4.2 Power System Ready

This circuit is shown in Figure 57. This SSR receives a positive signal when the Power Supply is producing its 28 V DC power. As this is used extensively in control relays, this signal is used by the SCADA as a status signal indicating that the external system is ready for activation.

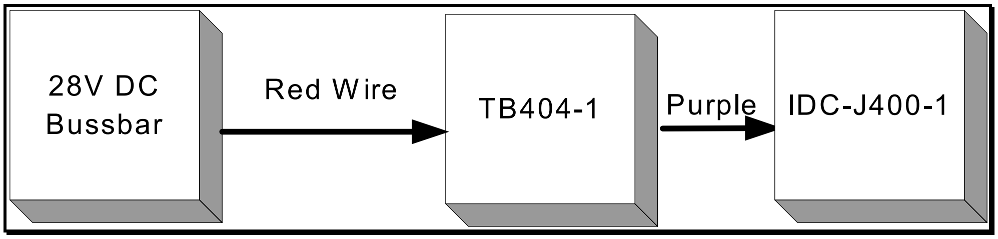

Figure 57 Power System Ready Circuit

3.6.4.3 Hydraulic System Ready

The hydraulic system ready signal is used to detect whether or not the HPU is operating. The main HPU manual on/off switch also controls a 110V circuit used to turn on the hydraulic water cooling circuit, which operates when the HPU main switch is activated. Since the HPU will not operate without the cooling system on, this circuit gives a reasonable indication of HPU operation.

Conversely, during testing it can be operated with HPU main power off to simulate the HPU operation without actually generating hydraulic power. As the SCADA system requires this signal to operate, it is helpful for system testing and development.

The interface circuit is shown in Figure 58

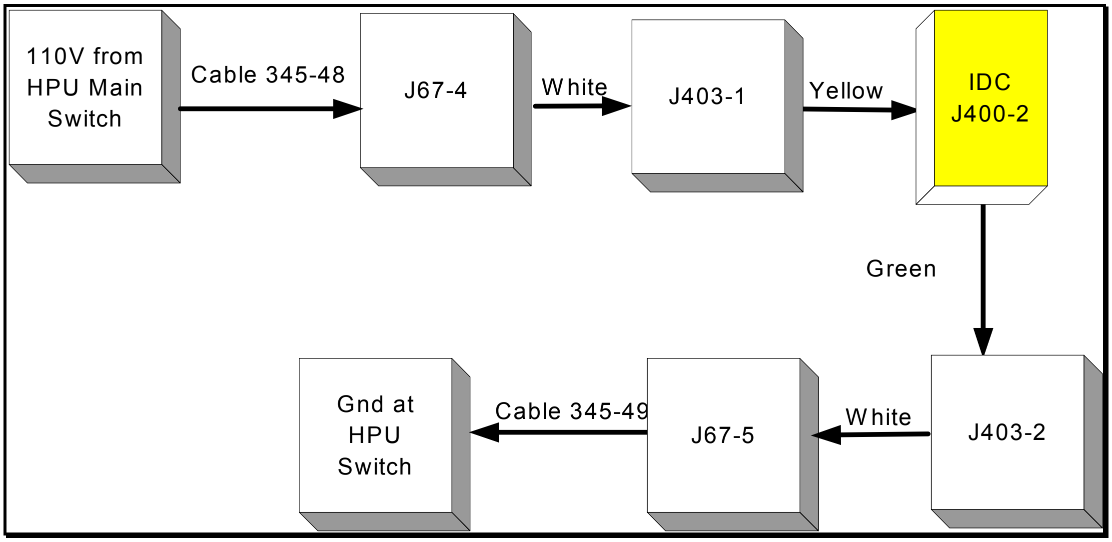

Figure 58 Hydraulic System Ready Circuit

3.6.4.4 Control Loading Switch ON and Motion Switch ON AND Safety circuit complete

This circuit is one of the primary safety features in relation to Motion system safety as well as providing information to the SCADA system on the status of the Control Loading and Motion Switches on the rear of the center console in the simulator. These switches provide operator control of the hydraulic systems.

The signal marked 'H'[21] (Figure 62) is the command to the valve controlling pressure to the Control Loading valve on the HPU. When activated by the SSR at TB400-10, opening of this valve allows pressure to flow to the control circuit. Initially most of this pressure bypasses the control circuit whilst the controls move to their neutral position, this is to provide a measure of safety to the pilot. After a 20s delay, a solenoid activates under the simulator that allows full pressure to be applied to the controls.

Logical signal H (and hence control loading) must be on before motion can be activated. From this point the signal passes through a 'safety circuit' before commanding the motion on.

The 'safety circuit' checks the following

1. Nose switch (under the simulator nose) is not closed (Fig. 57)
2. Simulator door is shut (Fig. 58)
3. Simulator door is locked (Fig. 59)
4. Simulator access gate is closed. (Fig. 60)

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[21] **Notation adopted from the original Link documentation [22]**

Figure 59 Safety Circuit Nose Switch

Figure 60 Safety Circuit Door Handle & Lock (In the locked position)

Figure 61 Safety Circuit Gate Switch

This circuit is used to make sure that the cabin is locked and secure before turning the motion on thus ensuring a safe condition. It will also shut down the motion should personnel approach the sim and attempt to enter, or if the occupants attempt to exit the simulator without turning off the motion.

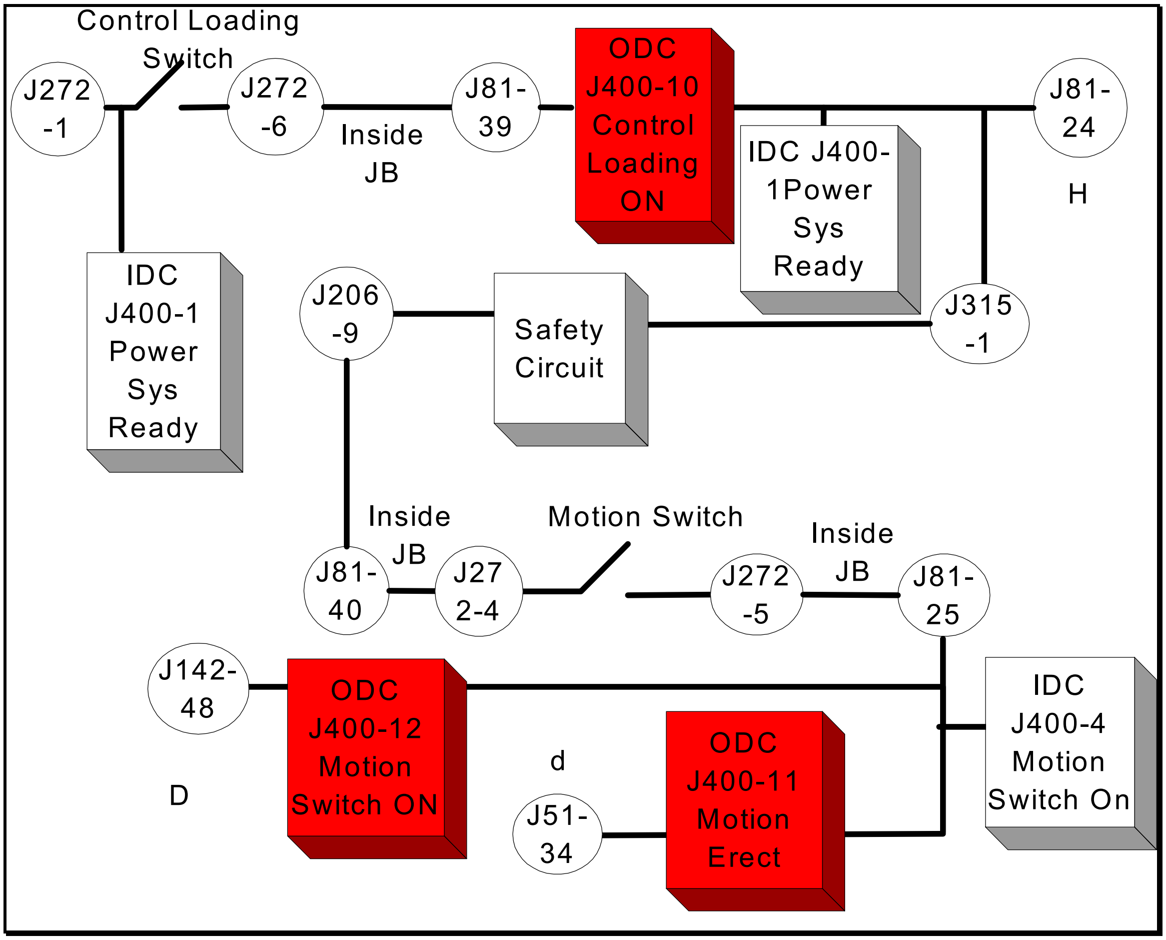

Figure 62 Control Loading switch, Motion switch and Safety Circuit

The control loading and motion switches are found on the rear of the aft pedestal in the flightdeck and are shown in Figure 63.

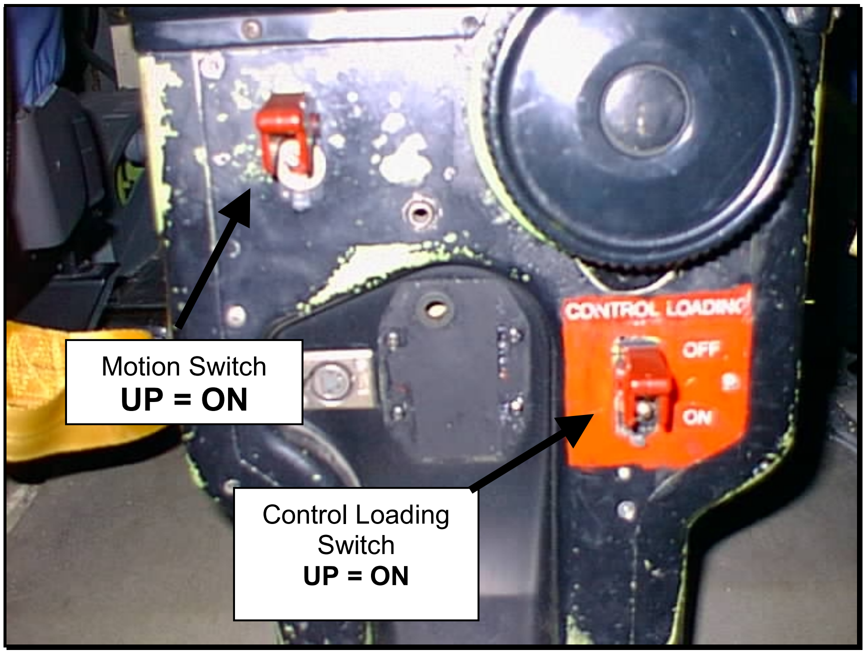

Figure 63 Control Loading and Motion Switches

The next stage is to pass through the Motion Switch on the rear of the center console. SSR 4 at J400-4 detects this signal for use in the SCADA system to activate the control algorithms.

The Control Loading ON signal (J400-10) has previously been documented. The Motion Erect signal (J400-11) is used to open the Motion Erect valve on the Hydraulic Pump Unit (HPU). This supplies pressure to the Motion Base to raise it from its resting position to its neutral position prior to the activation of simulator motion. This next step is activated by the Motion ON SSR which opens another valve at the HPU, allowing pressure to operate the motion base.

The interface for all three signals is shown in Figure 62. The function of SSR-10 has been explained previously. When the system has detected that the Control Loading is on, the Motion Switch is on and the rest of the system logic is satisfied, firstly SSR-12 (J400-12) activates. This commands the Motion Erect valve to open on the HPU to allow pressure for motion set-up to neutral. After a delay SSR 13 activates opening the Motion ON valve on the HPU to allow full motion pressure.

3.6.4.5 Limit Switches

There are six limit switches, two on each actuator. They detect when an actuator has extended to its maximum allowable displacement. The motion system is designed to operate within this band of extensions, however if the system does exceed its maximum normal extension, these switches detect this condition and trigger a motion shutdown as explained in Chapter 4.

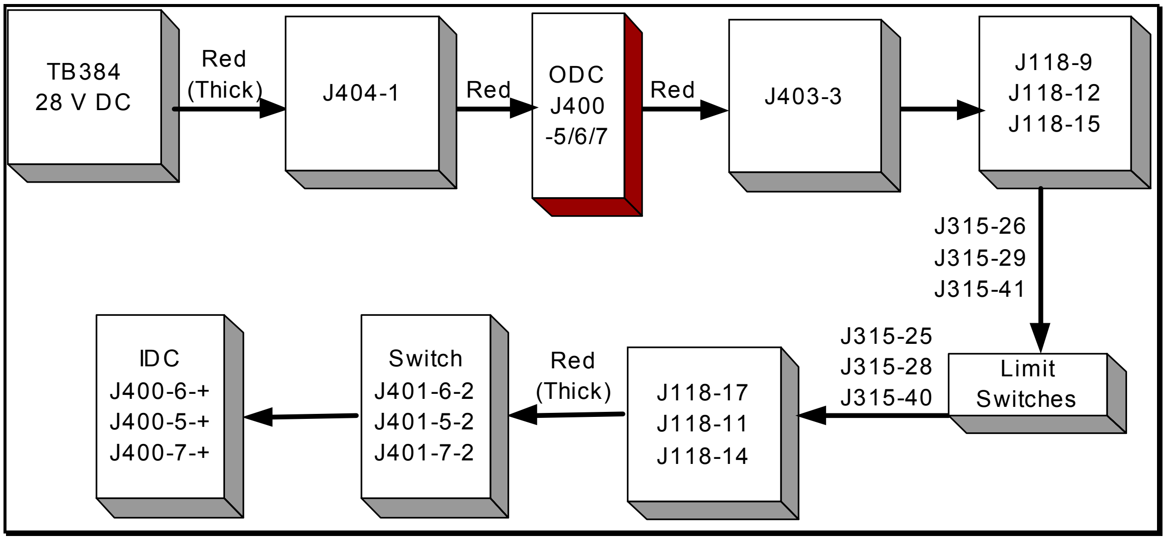

Figure 64 Limit Switch Detection Circuit

28 V DC is supplied from the Junction Box through the Limit switches and back to SSRs 5, 6 and 7. On each actuator the two switches are in series as shown in Figure 65.

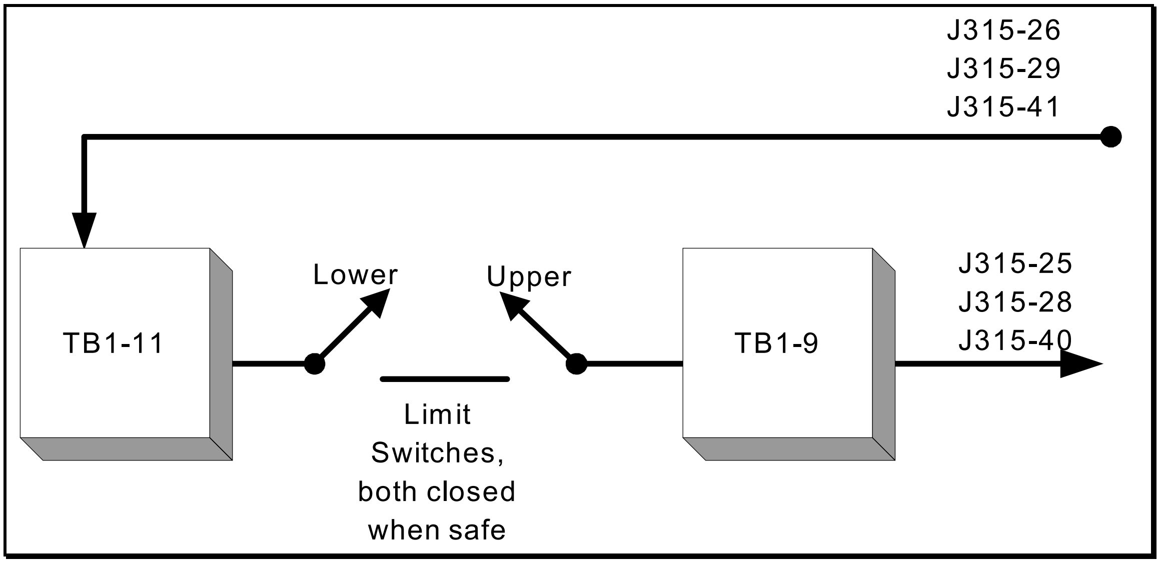

Figure 65 Limit Switch Circuit

3.6.4.6 Trim Switches

These two inputs come from the electric trim switches on each control column. A nose down trim input from either switch is detected by SSR 18 , a nose up from either column by SSR 17. The circuit for this interface is shown below. 28V is sent via cable 298 to the Control Column. After passing through the pilot and co-pilot trim switches in parallel, the nose up and down are sent back to the junction box and appear at J160 pins 23 and 26. From there they are taken to the two SSR's above.

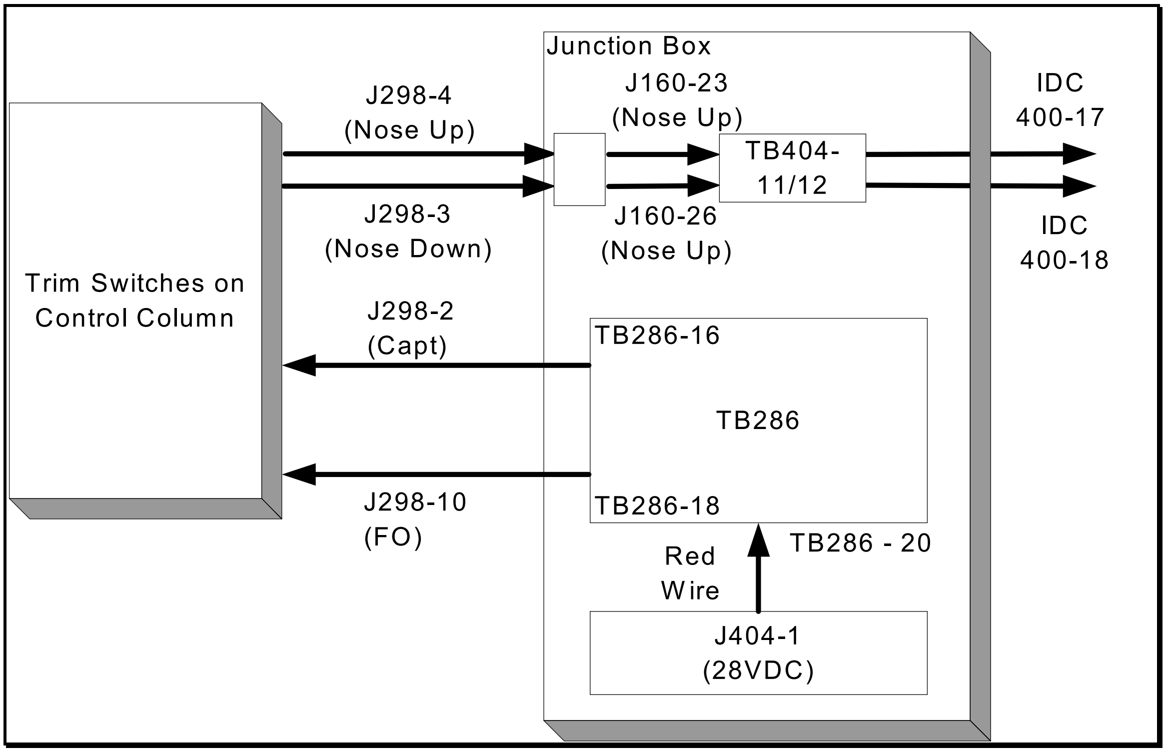

Figure 66 Trim Switch Circuit

3.6.4.7 GP4 Circuit

When 3 phase power is applied to the Power Supply cabinet, it can only turn on the initial stages of its power on sequence. In order for the system to activate the AC and DC supply regulator it previously required a signal from the Simulator's Digital Computer. When the computer, known as the GP-4 was ready, an internal relay was closed, allowing 28 V DC to flow back to the appropriate location in the power supply to complete start-up. A replacement circuit was needed to indicate the equivalent ready state of the CMT computer that has assumed the equivalent role of the defunct GP4 computer.

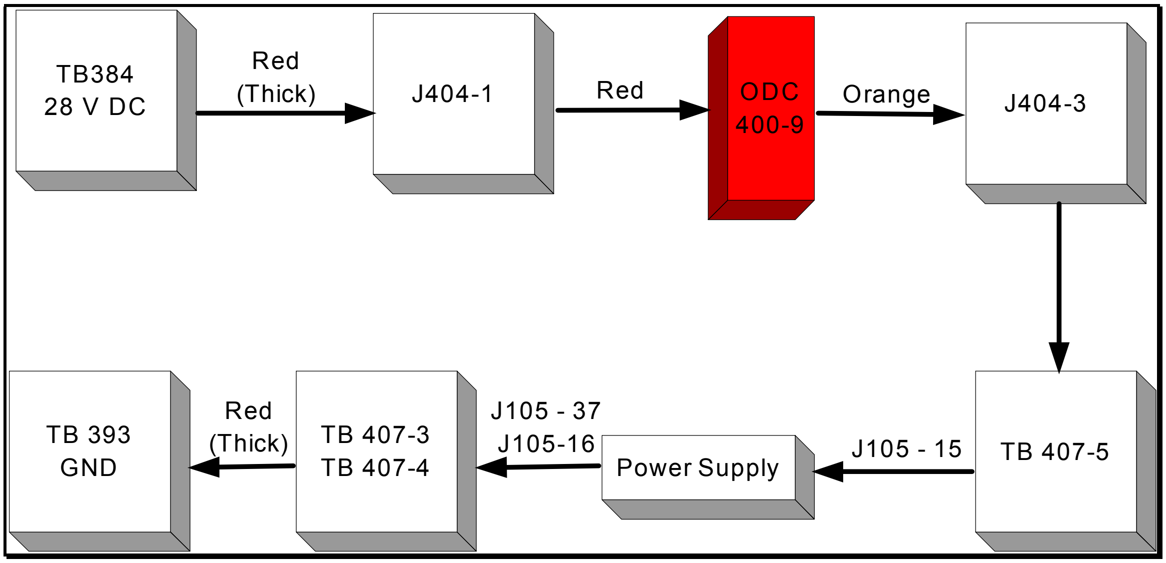

Figure 67 GP4 Interface Circuit

The signal originates at a 28 V DC supply point and is routed to the front of the junction box at J404-1. From here it proceeds through SSR-9 activated by readiness of the CMT PC through existing cabling to the Power supply, then back to the 28 V DC GND at TB393.

3.6.4.8 Control Loading ON, Motion ERECT and Motion ON SSR's

As described in Section 3.6.4.4

3.6.4.9 SSR 13 - Control Loading Full Pressure

When the Control Loading pressure is applied, it is at a reduced pressure while the system moves it to the neutral position. After a 20s delay, this SSR supplies 28 V DC to the solenoid to allow full pressure to flow to the control loading system.

3.6.4.10 Settle Switches

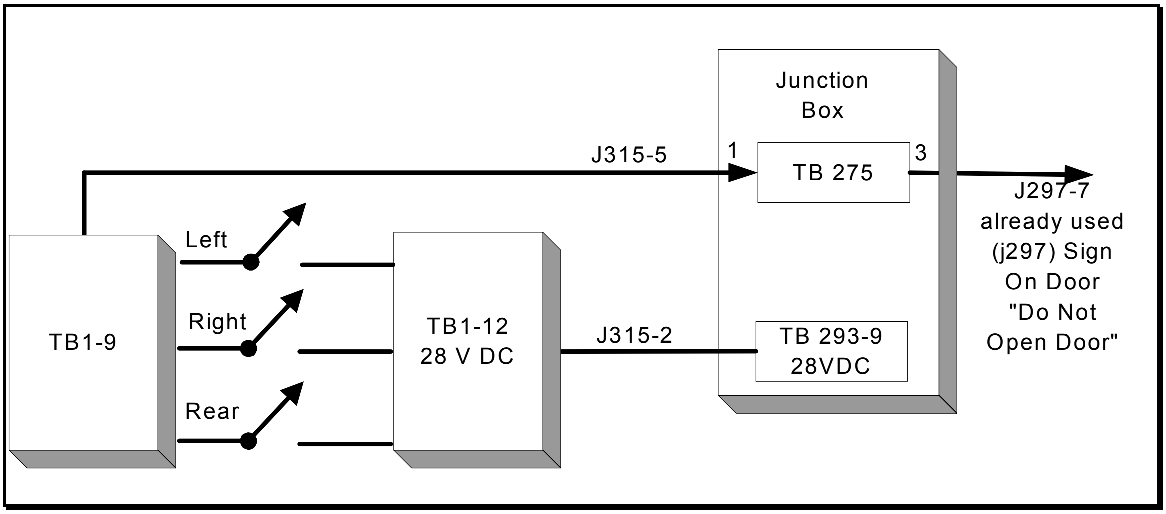

Figure 68 Settle Switch Circuit

Each actuator also has an ‘Out of Settle’ switch, also known as a Settle Switch which is identical to the Limit Switches. The three (one on each actuator) are wired in parallel and when activated indicate the applicable actuator is in motion. The parallel wiring allows the system to return a positive signal even if only one actuator is moving. A positive signal is used for several lights around the simulator that are used to warn people of motion activation.

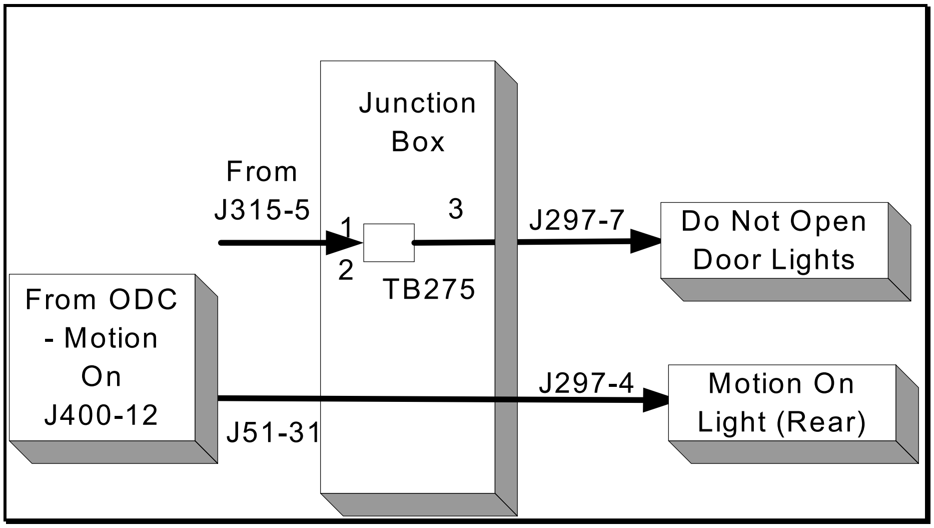

Figure 69 Motion ON Light Circuit

Figure 69 outlines two such lights. When the motion base begins to move, two small red lights inside the flight deck adjacent to the exit door illuminate. They are either side of a sign reading ‘Do Not Open Door’. The other light in Figure 69 is mounted on the rear face of the simulator on the right hand side of the door. This warns anyone at the development station that the sim is moving.

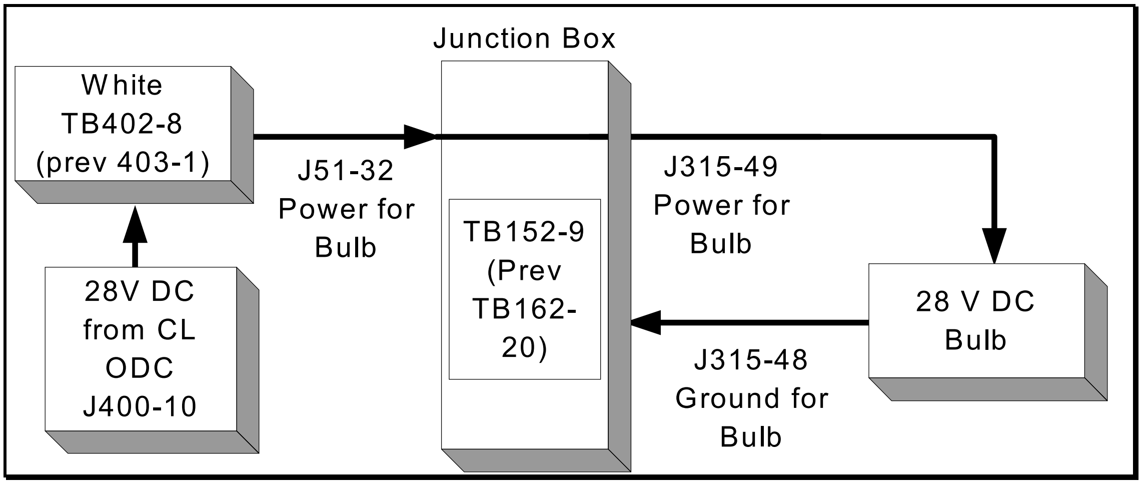

Figure 70 Motion ON Flashing Light Circuit

Figure 70 also shows the interface for the Motion Light system located under the nose of the simulator. Originally this was wired to accommodate a 110V AC bulb. It has been re-wired as shown to accommodate a 28 V DC flashing light, used to warn people approaching the simulator from the front that the motion is active.

3.6.5 Motion Wiring

There are three motion actuators and each one is identically wired.

Appendix 2 shows the complete wiring schematic for the Motion System and Control Loading. Figure 71 shows the wiring associated with each motion actuator. A diagram of Moog servoamplifier cards is included in Appendix 3.

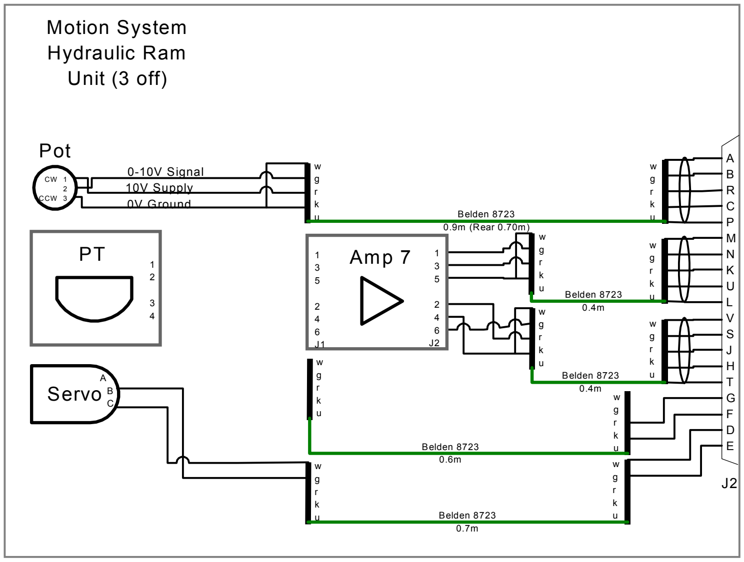

Figure 71   Motion Wiring - Actuator

There are four items of interest in Figure 71

1. The potentiometer (‘Pot’) is used by the Moog servo card as the position transducer. It connects through J3 (right hand side) eventually through to its respective Signal Conditioner.

2. The Pressure Transducer (‘PT’) is currently not used. It measures the pressure difference between each side of the hydraulic piston and is a measure of how hard the system is working. These were added previously to each actuator following the installation of the external visual system to increase the system bandwidth. This is detailed in [34].

3. The Servo valve (‘Servo’) controls fluid flow to the actuator. It receives its drive signal from its Moog servoamplifier card. The servo for each of the Motion actuators has its two coils connected in series.

4. ‘Amp 7’ is in place should the pressure transducer (pt) be required. It provides a power source to the PT as well as amplification of the signal.

This interface is found mounted at each actuator. It interfaces with a cable back to the Computer Cabinet through J2 at right.

Figure 72 shows the rest of the motion system wiring. The connector at left is again J2 , this interface is mounted on each actuator. The wiring for each actuator travels through conduit to the computer cabinet.

1. The two dashed lines represent the signal (upper) and power to/from the PT which has not been implemented at this stage.

2. The lower solid line has two sections. The lower signals from the Moog card are the two servo signal wires. The upper lines carry GND and 24 V DC for the PT as power from Moog pins 20 and 24.

3. The signal conditioner (SC) receives a 0-24 V DC power supply from the Moog servoamplifier card. This is regulated to provide a stable 0 to 10v supply to the potentiometer. The upper solid line carries the actuator position information from the Pot back to the signal conditioner (Position Feedback Signal). This is a 0 – 10V signal. The SC has zero and gain adjustments to create a position signal for the Moog that is in the correct range of 0 to 10 V DC to compensate for the potentiometer only covering a portion of its range.

4. The Moog card receives a 0 to 10 V command input via pins 3 and 22 from the CMT via the PCI DDA08 card.

5. Amp 3 buffers the actuator position and passes it to the PCI DAS1602 card for use in the SCADA system. It receives its power from the Moog servoamplifier at pins 22, 28 and 30.

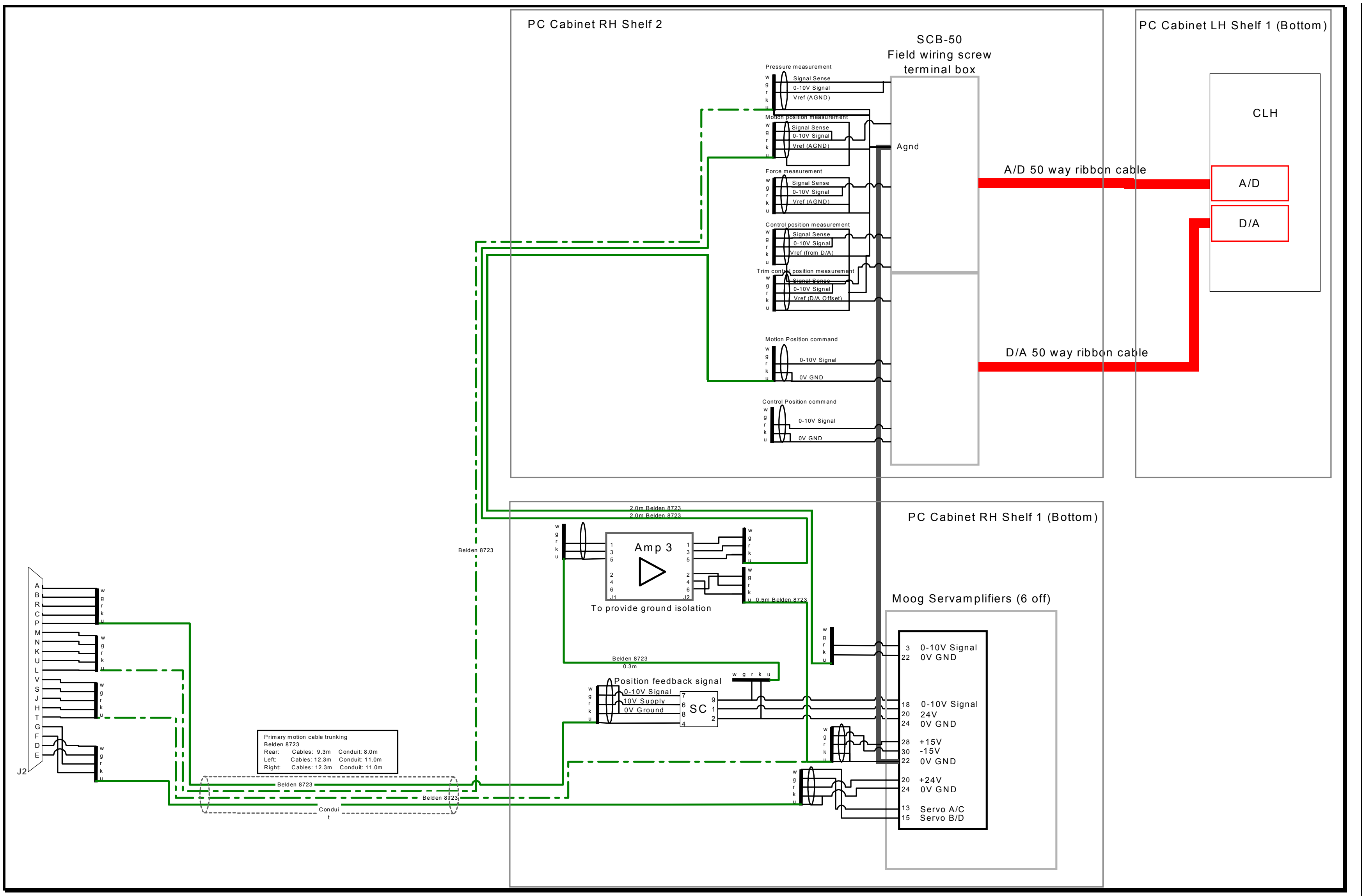

Figure 72 Motion System Wiring – Moog System & CMT

3.6.6 Control Loading Wiring

The wiring schematic for each flight control axis is identical. The circuit shown in Figure 73 is found mounted at each control actuator, with the Amp (4, 5 or 6) mounted on the reverse of the original servo card from the 707 simulator.

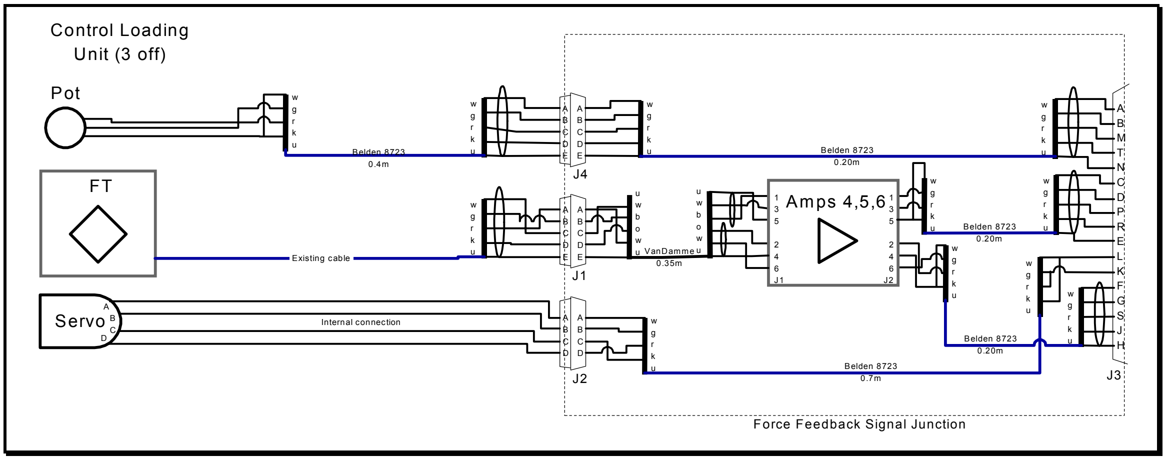

Figure 73 Control Loading Wiring at Actuator

1. Each axis has a servoamplifier similar to that of the motion system (listed in Appendix 4).

2. The potentiometer for the position loop is a rotary potentiometer.

3. The Force Transducer ('FT') is shown connected through Amps 4, 5 or 6[22] (to provide different amplification to each control channel due to different force ranges) to connector J3. Calibration data for this device is found in Chapter 5. It measures the force applied by the pilot into each control axis. It is a bipolar signal that requires significant amplification. The amplifier is driven by a +/-15V supply from the Moog servoamplifier card and regulates a +/-12V supply for the force transducer. The reference voltage input to the amplifier from the PCI-DAS 1602 together with amplification lifts the bipolar signal to the required 0-10v range.

---

[22] **See Appendix 4 for details**

Figure 74 shows the second part of the system. Again the signals travel from each control loading via individual conduits to the computer cabinet.

1. The servo drive signal comes from Moog pins 13 & 15.

2. The amplifier power (all amps) comes from 22, 28 & 30 (+/- 15 and GND)

3. Position information is measured by the signal conditioner, again as a 0 to 10V signal for the Moog servoamplifier card.

4. Amp 1 takes flight control data from the signal conditioner to the FMC's (flight model computer) A/D board. This amp is required to provide ground isolation and reduce the signal from a 10V signal to a 5V signal as required by the flight model A/D.

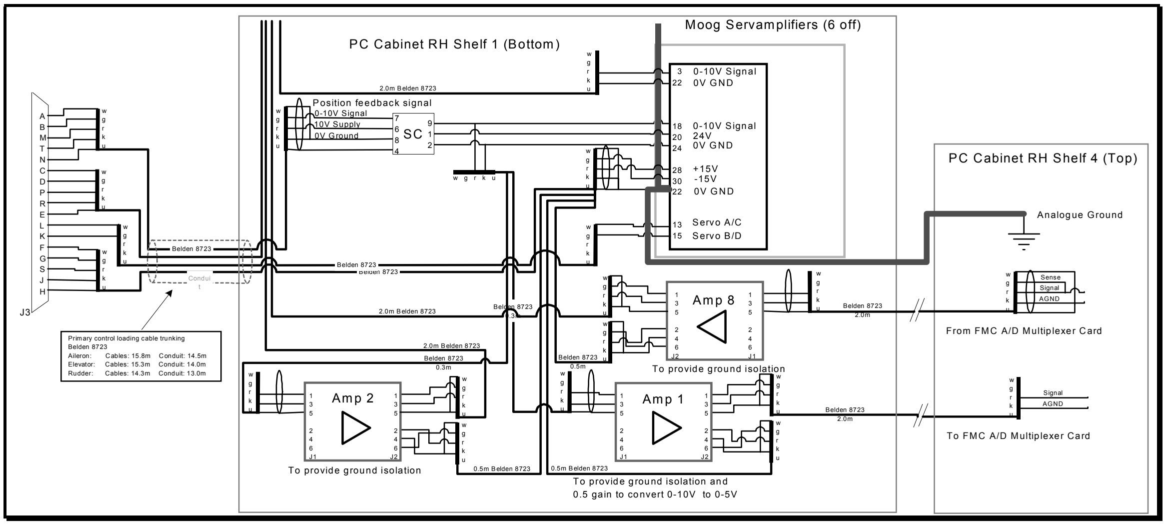

Figure 74 Control Loading Wiring – Moog System Wiring

5. Amp 2 provides ground isolation to take flight control positions from the signal conditioner to the SCADA system (Figure 75) for use on the control loading system.

6. Amplifier 8 takes trim control signal from the flight model computer A/D board and isolates them as well as boosting them from a 5 V signal to a 10 V signal for use in the SCADA system as shown in Figure 75.

7. The force transducer signal travels directly to the PCI DAS 1602 input card of the SCADA system.

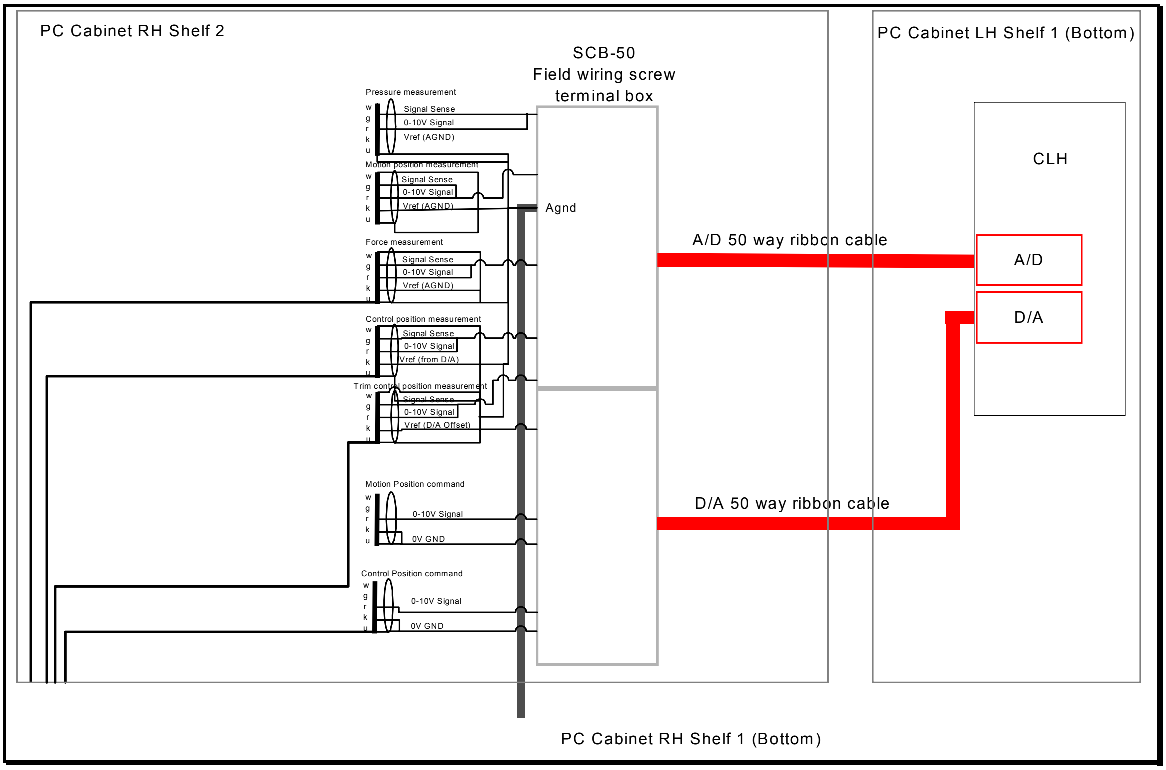

Figure 75 Control Loading Wiring – PC Cabinet

Chapter 4

System Safety and Supervisory Control

4.1 Safety Considerations

A ‘safety critical system’ is defined as one that can pose a threat to human life [21].

In our system we have several components that may be regarded as safety critical:

1. Control Loading
2. Motion Base
3. Electrical Supply
4. Hydraulic Supply

The hazards that these present need to be examined in the context of the following modes of operation:

- System failure modes
- Normal operating modes
- Maintenance modes

4.1.1 System Failures, Normal and Maintenance Modes

System failures that can impact on safety include:

- Hydraulic failure – This could cause extension of the flight controls towards the pilot.
- Incorrect position commands
- Supply line failure – Externally, a failure of the hydraulic supply line could result in the dispersal of hot hydraulic fluid throughout the complex.

The first two items are mitigated by a combination of the hardware safety features mentioned previously as well as the Emergency Stop switches at the instructor station. If this is pushed, hydraulic shutdown occurs in less than five seconds with pressure drop-off shortly thereafter.

In the case of a supply line failure, the open area surrounding the facility is to be un-occupied. This not only prevents human contact with the moving simulator but prevents injury in the case of an uncontained failure that results in fluid dispersal.

Normal Modes of operation can be dangerous if the system is not programmed to operate in a safe manner. It can also be dangerous if during the normal operation of the equipment, the proper operation of the system is capable of exceeding the strength or geometric constraints of the device. Such dangers are mitigated by careful design of the system.

Maintenance modes pose dangers to maintenance personnel when they work outside the normal operational requirements of the device. An example might be working in close proximity to the motion system when hydraulic pressure is present.

4.1.2 Emergency Stop Buttons

There are three Emergency Stop buttons installed at this time. One is mounted at the rear of the simulator cabin, one on the junction box and one adjacent to the Hydraulic pump room as shown in Figure 76,Figure 77 and Figure 78. Pushing any one of these shuts off three phase power to the Power Supply cabinet. As all hardware in the system eventually relies on power from this cabinet, this results in a system shutdown within 5 seconds.

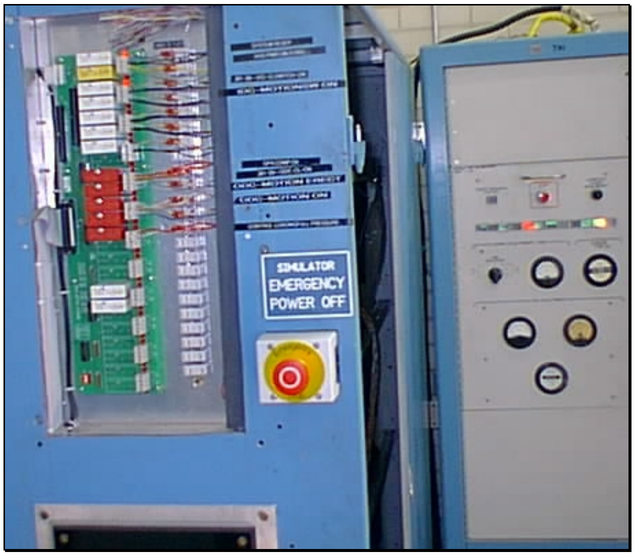

Figure 76 Junction Box Emergency Stop Switch

Figure 77 IOS Emergency Stop Switch

Figure 78 HPU Emergency Stop Switch

4.1.3 Control Loading

The hydraulic loading of the primary flight controls involves a pressure of 2000 psi. This pressure, even over the small area of the loading piston, represents a sizeable force which acts through the control column. In the longitudinal axis of the control column despite the existence of hardware stops, an uncommanded movement may cause the control column to come into to contact with the pilot. This is obviously an undesirable situation and one to be avoided.

The most important safety measure for this system is adherence to the correct procedures. In particular, ensuring that no-one is in the vicinity of the control loading pistons before operations commence, and ensuring that the occupants of the pilot seats are correctly seated so as not to be within the range of travel of the controls upon start-up.

This is equally valid for maintenance modes, however the control loading system can be disabled by switching the Control Loading Override switch to OFF at the Junction Box.

The Pitch axis of the control system is the more dangerous as it powers the flight control column, the largest item and the one with the largest range of motion.

When the Link simulator was delivered, the pilot seats had been removed. New modified automotive seats have been installed as outlined in Chapter 3. As such it was not possible to examine the original seats in situ to determine how close the flight controls came at full control extension. With the new installation, the control only comes into contact with the seat at full aft extension when the seat is positioned fully forward on its tracks. Through experience in the simulator in the new configuration, such a fully forward seat position sufficiently limits control displacement so as to prevent rotation of the aircraft nose on takeoff. If the seat is positioned correctly as determined by the pilot eye position indicator, the control column is physically prevented from contacting the seat.

Maintenance on the control loading system involves work both outside and inside the flight deck of the simulator. Working in the simulator involves the same hazards as in normal operation whilst outside more probably involves contact with the moving hydraulic actuator. These can be prevented by the following steps when performing hardware maintenance on the control loading circuit both inside and outside the simulator:

1. Ensure the HPU is OFF – wait at least 3 minute to allow pressure to dissipate from the accumulator
2. Ensure that the manual override switches that command the control loading valves open are in the OFF position. Override switches at J400 numbers 10 and 13 in should be in the center position.
3. Ensure that the control loading switch on the center console is OFF

4.1.4 Motion System

The Motion system is a hazard not only to the occupants of the simulator, but to anyone in the vicinity of the system whilst the simulator is moving. The fact that the simulator is close to human level poses a great risk to anyone coming into contact with it while it is in motion.

During normal operation with occupants in the simulator cabin, the most dangerous condition is a combination of actuator displacements that results in excessive tilt of the cabin for several reasons. The system is securely bolted to the floor of the workshop, however, we do not wish to test the strength of the fixtures under extreme dynamic conditions that may result in the simulator tipping over. Even if the system does remain attached to the floor, extreme dynamic motion could injure the occupants even if adequately secured. Each actuator is fitted with a limit switch at each end of its travel. If a actuator approaches its maximum extension, the activation of either limit switch will cause the motion system to initiate an immediate shutdown. The system will not restart until it has been reset following investigation into the cause.

The speed of the system is also a concern. Any sort of high frequency oscillatory motion would be dangerous to the occupants especially if not properly secured. Also, high frequency motion may shake loose simulator parts or panels inside or outside the simulator. This can be mitigated by proper use of controls in the software that limit commanded output frequencies to reasonable values.

The present system configuration has the Moog servoamplifier system powered from a source separate to the rest of the system. This was done to isolate the Moog servoamplifier system from the simulator power supply. In the event of an emergency stop button being used, it is advantageous to have the Moog servoamplifier system continued to be powered to provide a continuous safe position command signal for the motion and control loading systems. However, should this source fail, the servoamplifier output will decay to 0v. This would result in a rapid motion of the simulator and controls to their neutral position. To combat this an uninterruptible power supply (UPS) is being installed to ensure that in the event of a building power loss that the previously described situation does not occur.

Externally and during maintenance modes hazards exist for anyone who comes into contact with the motion base hardware whilst in motion. It is critical that no-one enters the area underneath the sim at any stage without taking the following precautions:

1. HPU OFF and power off
2. No pressure in the system , this can take up to 3 minutes to fully dissipate
3. Motion Control Software Off

When the system is running no-one will be allowed into the simulator area . If it is required to operate the development station (external to the simulator), the user must stay at the station at all times the motion is on. At present there is no facility to view the external area of the simulator from inside the cabin. However, the simulator compound entry door will be equipped with a safety switch that will be integrated into the safety circuit discussed in Section 3.6.4.4.

The system is equipped with several signs and lights that indicate the motion system is active. These are described in the next section. Flashing lights have been installed that can be seen from all areas of the workshop environment that indicate that the motion / control loading system is pressurized and in motion. When these lights are on, no-one will be permitted to enter the simulator compound.

4.1.5 Electrical Supply

The Electrical supply operates from three phase power at up to 415 Volts and is therefore a considerable hazard. The system is protected by standard over current protection both at the main power boards in the workshop as well as in the Power Supply cabinet itself. Activation of the Emergency Stop switches will also cause an immediate shutdown of the main power supply board, essentially isolating the simulator from the three phase supply.

4.1.6 Hydraulic Power Supply

The Hydraulic Power Unit (HPU) generates a flow of 40 L per minute at up to 3000psi (reduced to 2000psi for the control loading). An uncontained failure of one of the lines could result in the release of high pressure oil into the simulator environment. It is intended to surround the system with a containment screen that will protect anyone outside the sim from harm. Hydraulic shutdown is also actioned by using the Emergency Stop buttons.

As a secondary issue, the HPU itself generates a large amount of noise. At present this is markedly reduced by closing the door to the pump house, however, prolonged exposure to noise within the pumphouse could result in hearing damage. Personnel are prohibited from entering the pumphouse while the HPU is running unless required to do so for maintenance in which case suitable protective equipment will be worn.

4.2 Supervisory Control

The supervisory control system is responsible for the operation and control of several areas of the simulator as listed below:

1. Safety
2. System start-up / shutdown
3. Control of Electrical Power
4. Control of Hydraulic Power
5. Hydraulic Commands for Control Loading and Motion
6. Monitoring of the Motion Base movements.

The Supervisory system has been implemented in the Matlab Simulink environment, specifically using the Real Time Workshop and XPC Target real-time kernel. This environment provides a visual design structure which takes care of the real-time programming overhead that would accompany such a system if implemented in a real time high level language. The following pages outline the design of the system with reference to actual screen shots. The system is built and the resultant output runs on the CMT computer in real time.

4.2.1 Supervisory System Circuit Input Blocks

The entire system is shown in Appendix 6

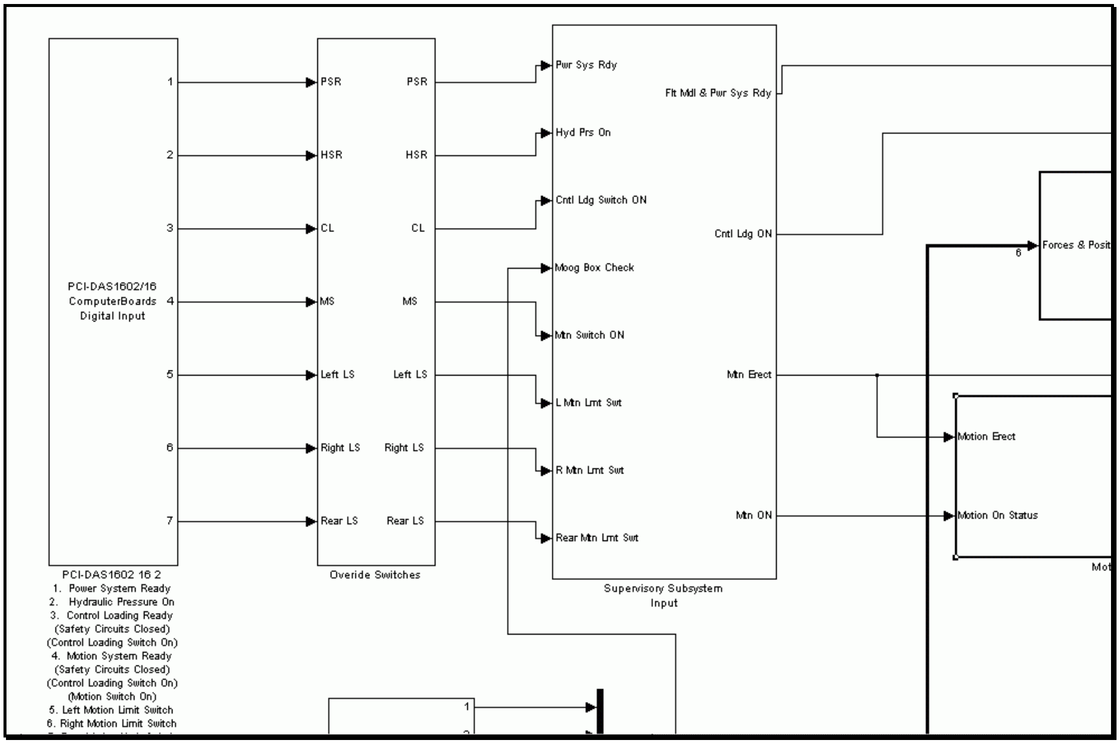

Figure 79 Part of the Supervisory System Circuit

4.2.1.1 PCI DAS 1602/16 Computer Boards Digital Input Block

Figure 79 shows the inputs to the supervisory control system. On the left is a block that receives Digital signals from the simulator to Computer boards SSR 24 I/O Board. The actual outputs of the block are Boolean with values listed in Table 15:

State	***Meaning***
0	ON
1	OFF

Table 15 Boolean Logic Table

These are opposite to our normal understanding of such signals where a high signal indicates a positive output. This has been dealt with by immediately passing each signal through a logical “NOT” operation, after which normal 1-ON, 0-OFF logic applies.

The outputs are listed in Table 16

Output	***Meaning***
PSR	Indicates that the power system is operating
CL	Indicates whether or not the Control Loading switch on the flight deck aisle stand is on
MS	This signal indicates two things: The Motion Switch in the aisle stand is on The safety circuit is closed
Rear, Right & Left LS	Indicate the status of the limit switches. Each of the three motion actuators has an upper and lower limit switch. If any of the actuators extends so as to activate these switches, these inputs cause a motion system shutdown, this will be examined further.

Table 16 Input Signals

The safety circuit is a 28 VDC series loop that contains the following

- Flightdeck door closed signal
- Flightdeck door lock closed signal
- Flightdeck Gate closed signal
- Contact switch signal (under the nose of the simulator cabin)

The first three items are there to ensure that no-one enters or leaves the simulator while it is in motion. The last item causes the motion to switch off if the nose of the simulator comes into contact with the ground. After the signal has successfully passed through this circuit , it is routed to the Motion switch on the aisle stand. This ensures that the Motion can only be on if the switch is on AND the safety circuit is complete.

4.2.1.2 Override Switches Block

This block allows the operator to manually override the inputs previously described for maintenance purposes. The internal structure is in Figure 80.

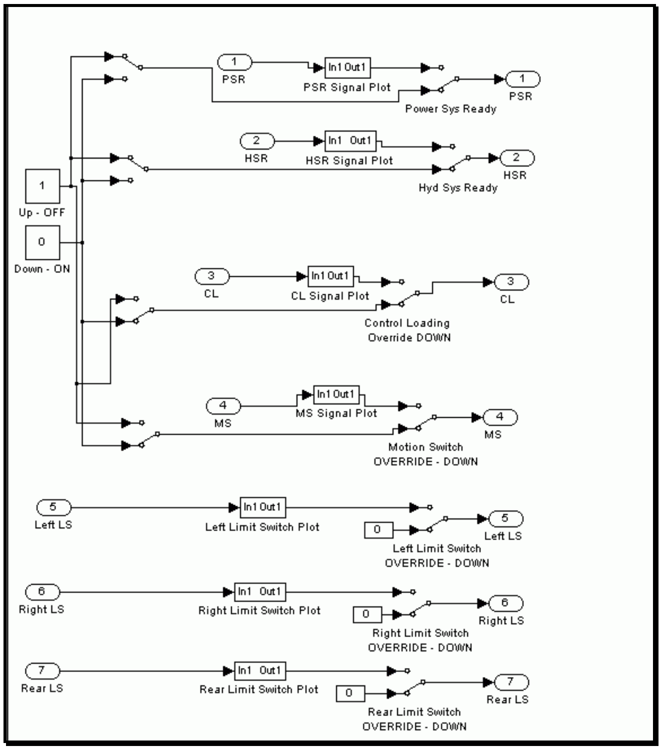

Figure 80 Override Switches Block

The seven previously described signals enter on the input blocks. Circuitry is provided to either allow the actual signal to pass through the block or to allow an operator input value for the selected parameter. By selecting the switch applicable to each circuit to the down position (by double clicking on it), the output is taken from the constant blocks (labelled Up-OFF or Down-ON). At this stage the inputs are still in the negative sense with a 0 as on and a 1 as off. This allows the operator to input values as required into the system.

With the PSR and HSR signals, we can run the real-time programme without having to turn on either the Power system or the HPU. As both systems are complicated and mechanical, having this capability reduces wear and tear on the system while testing system logic.

The next two signals are designed to manually override the Motion and Control Loading signals. Operating the system with reduced safety in this way after the system is completed would only occur for the specific purpose of tracking faults in the Motion system that cannot be identified without the Motion system active or to permit operation of the simulator from outside the flightdeck during development. We can use these override switches to simulate the switches inside the flightdeck as we did not wish to be in the simulator during initial motion testing. It also allows manipulation of the system from outside during maintenance and implementation of new software modules.

The last three signals are from the limit switches. During normal operations, these signals will shut down the motion system if an actuator limit is exceeded. During Maintenance and development override of these limits was necessary for calibration of actuator position sensors and stops. By overriding the signals automatic shutdowns are inhibited.

4.2.1.3 Supervisory Subsystem Input Block

This block provides the first logic decisions in the system and to enable standard logic to be used, the input signals are inverted to give a 1 for ON and 0 for OFF. It has seven inputs and four outputs. The inputs are as described previously. The outputs are as follows

- Flight Model & Power System Ready (Flt Mdl & Pwr Sys Rdy)
- Control Loading ON (Cntl Ldg On)
- Motion Erect (Mtn Erect)
- Motion ON (Mtn On)

The logic for these outputs is in Figure 81:

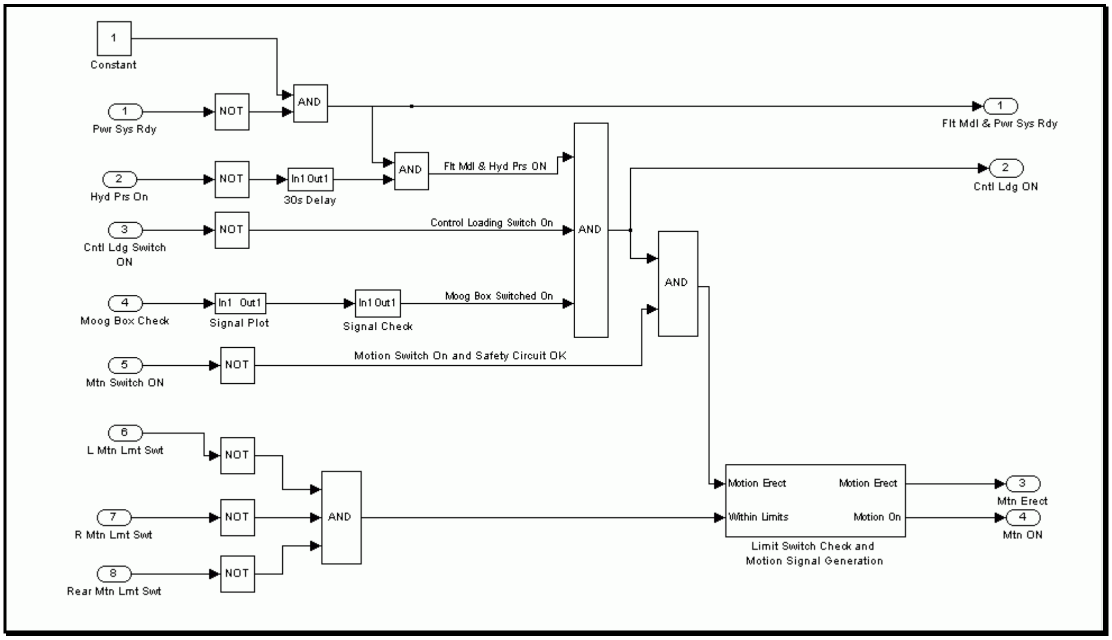

Figure 81 Supervisory Subsystem Input Block

Flight Model AND Power System Ready ON Logic

This signal has a value of 1 when the Flight Model is producing simulator flight data AND the Power system is ready. This signal is used later to provide power to the HPU for subsequent hydraulic operation.

Control Loading ON

This signal has a value of 1 when the Flight Model is on AND the Power System is ready AND the Hydraulic Pressure is on AND the Control Loading Switch is on AND the Moog Servoamplifier Unit is on. This signal is used later to allow hydraulic pressure to the flight controls. It is not desirable for the pressure to come on until all the above conditions are satisfied as all of them are necessary to provide effective and safe control of the loading system.

This signal AND the Motion Switch ON creates the two signals that allow motion base operation.

Motion Erect AND Motion ON

These two signals control motion base activation. This cannot be allowed to occur until all of the above conditions are met in order to operate safely. At this stage limit switch logic is introduced, the structure of which is shown in Figure 82. The ‘Within Limits’ signal is a ‘1’ if all the actuators are within limits.

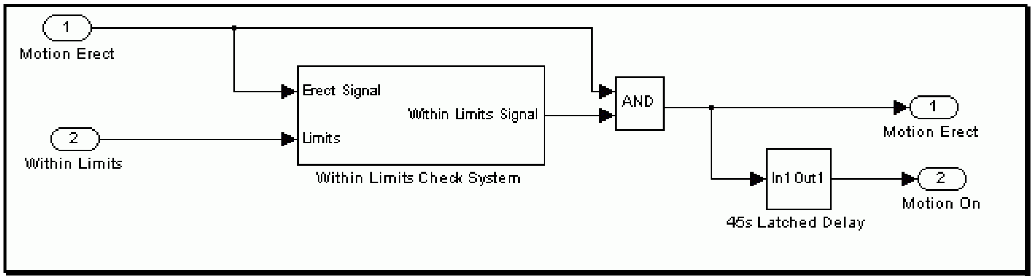

Figure 82 Motion Erect & Motion ON Signals

The block ‘Within Limits Check System’ (Figure 83) outputs a ‘1’ signal if the Motion actuators have not exceeded the displacement limits, the logic for this will be examined shortly. This signal AND the Motion Erect signal provide the final Motion Erect signal. This is used later to allow the hydraulic system to raise the motion base to its neutral position. This signal, delayed by 45 seconds is the Motion On signal, used later to allow the motion commands to drive the motion base.

The system below is the logic behind the ‘Within Limits Check System’ output. At system start-up the actuators are at their rest position, with the lower limit switches activated. These signals are not activated until the system has been raised into the operational range. Integrator1 is saturated at an output of ‘1’ at system start-up. If the input to switch3 is ‘1’, the ‘Integrator Step Up’ value of 0 will keep the Integrator1 at its value of ‘1’, indicating a safe system. If the input to switch3 is a ‘0’, the Integrator Step Down value of –10000 will take Integrator1 output to ‘0’ in 0.0002 of a second[23], i.e. an

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[23] The system operates at 500Hz and each time step is therefore 0.002 seconds.

'out of limits' signal. As the 'Integrator Step Up' values is '0', even if switch3 subsequently returns to its previous value, the Integrator output cannot increase.

Initially, the input to switch3 is a '1' from the 'Within Limits OVERRIDE' constant ('1'). When the input to switch1 becomes greater than 35, the input to switch3 becomes the actual value of the limit switch signal. This corresponds to a 35 second time delay implemented by the last part of the circuit after the 'Erect Signal' becomes a '1', i.e. when the Motion Switch is turned on. When the 'Erect Signal' becomes a '1', switch2 allows a value of 1 to the Integrator, which then increases to 36 in 36 seconds, the value being 1 higher than the 35 second delay required to ensure switch1 operates correctly.

Hence for 35 seconds after motion system is turned on, the system ignores the limit switch signals while the base moves to its neutral position. After this period, the system uses the limit switch signals. If a limit is exceeded, the output of the circuit is '0' and cannot be reset to '1'. This would require an 'Integrator Step Up ' value of greater than '0'.

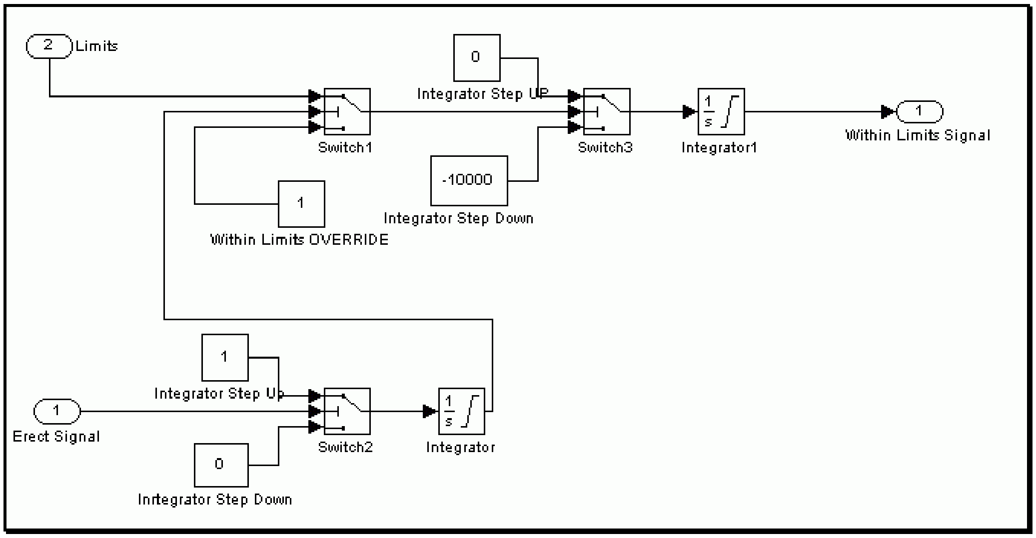

Figure 83 Within Limits Check System

The 'Latched Delay'

Figure 84 is known as a 'Latched Delay' and is used extensively throughout the supervisory system

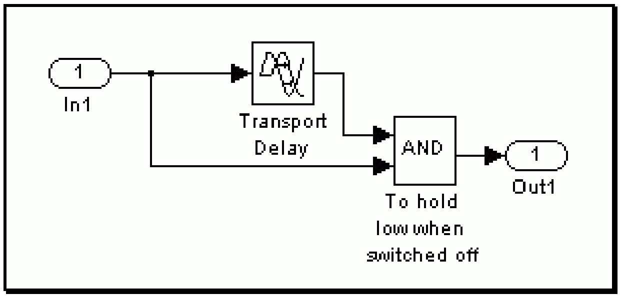

Figure 84 Latched Delay

The Transport Delay delays passage of the input signal by an amount set within the block. It is often necessary to delay an ON signal that occurs at system start-up. This could be achieved by the Delay block alone. However, if we wish to shut down the system immediately this delay block would of course delay a shutdown by the same amount. By using an AND block as shown above, the output is a '1' when both signals are '1', i.e. after the delay. However, as soon as the input becomes a '0', the lower signal is '0' and the output of the AND block is therefore '0'. Thus a change to a '1' is delayed and a change to a '0' is immediate.

4.1.2.4 'Signal Check' Block

This circuit outputs a '1' if the input is a '1' and a '0' if the input is a '0'. It is used to analyse the Moog system indication. It is necessary to use this block as the original signal cannot be used as an input to Boolean logic. This block does not alter the magnitude of the signal, but it does alter it in such a way to allow it to be used in Boolean logic. It is shown in Figure 85.

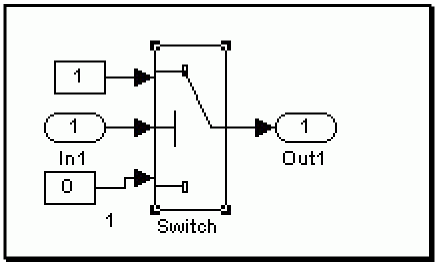

Figure 85 Signal Check Block

4.1.2.5 PCI DAS 1602/16 Computer Boards Analogue Input Block

This block acquires the Analogue data from the PCI DAS 1602/16 card. There are 16 single ended inputs available as indicated in Figure 86.

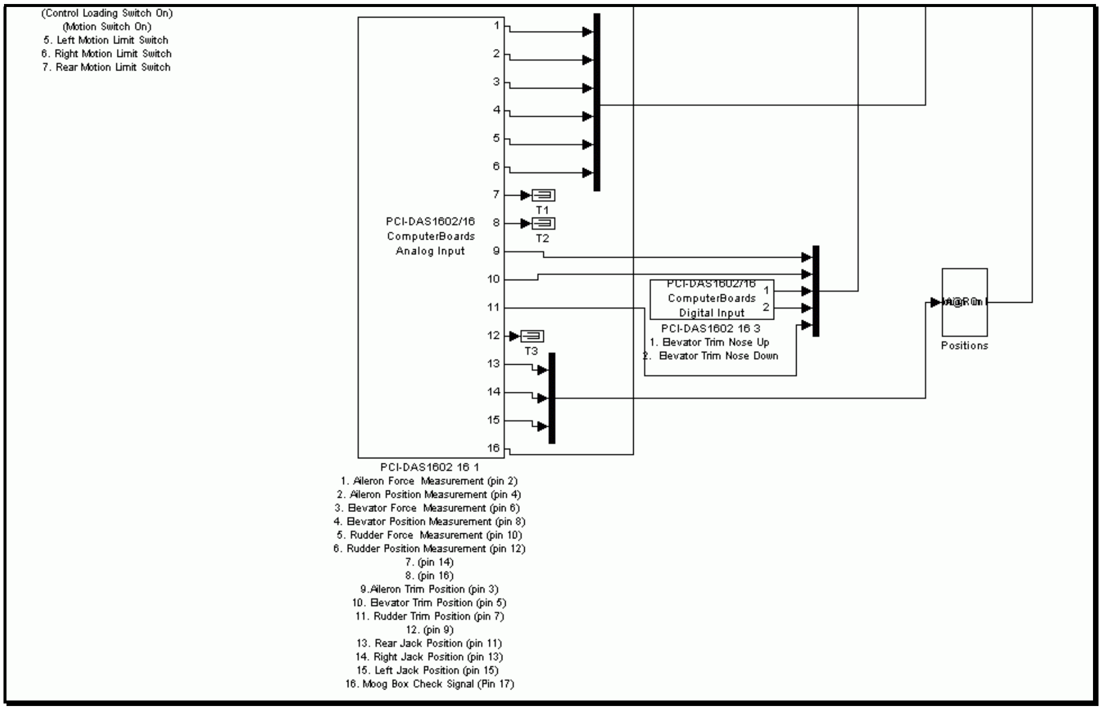

Figure 86 PCI DAS 1602/16 Computer Boards Analogue Input Block

The first six signals are the Flight Control Force and position measurements. These are used in the Control Loading block later in the system and are routed to this block.

The last signal is an input from the Moog Servoamplifier Unit. It is used by the supervisory input block to determine if the Moog system is available to control the hydraulics. The control algorithms will not commence until it is on.

4.2.2 Output Blocks

4.2.2.1 Analogue Outputs

The Control Loading and Motion Systems determine the commanded actuator positions for the motion base and control loading systems. The PCI DDA08/16 block represents a Digital to Analogue converter as shown in Figure 87. The six hydraulic actuator commands are directly transmitted for use in the Moog servoamplifier system. The signals output in the 0-10V range representing actuator position commands.

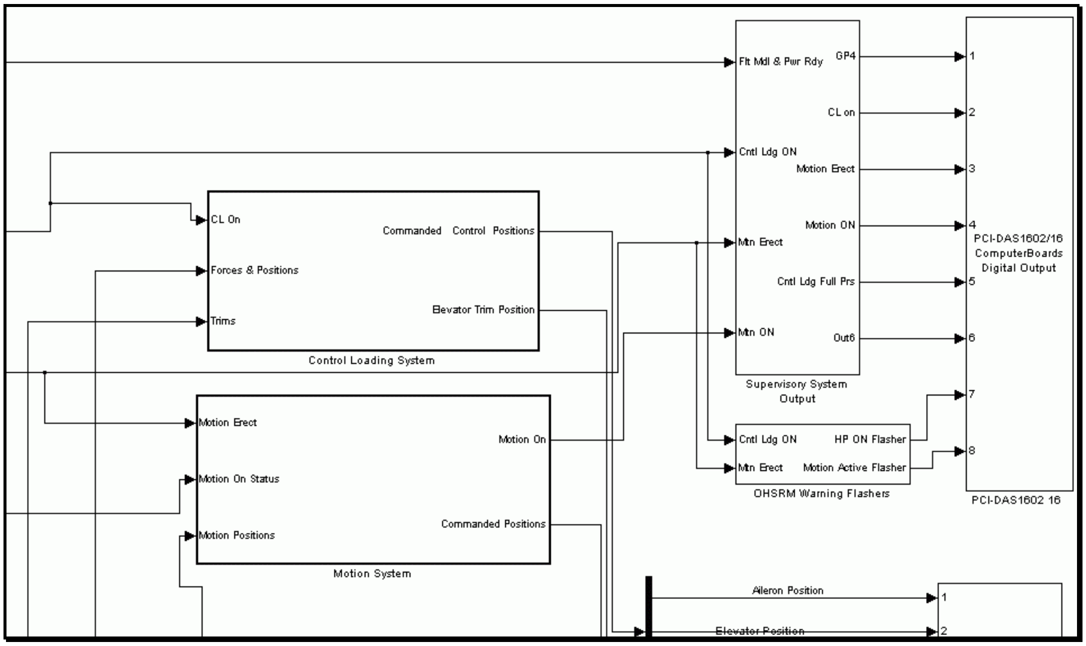

Figure 87 Output Blocks

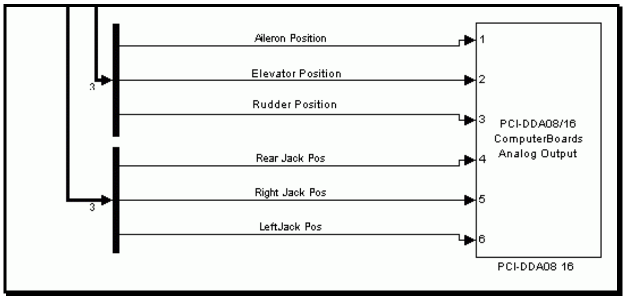

Figure 88 Output Blocks 2

4.2.2.2 Supervisory System Digital Output Block

This software controls the system logical output to the PCI DAS1602/16 Digital Output block as shown in Figure 87The logic for this system is shown in Figure 89.

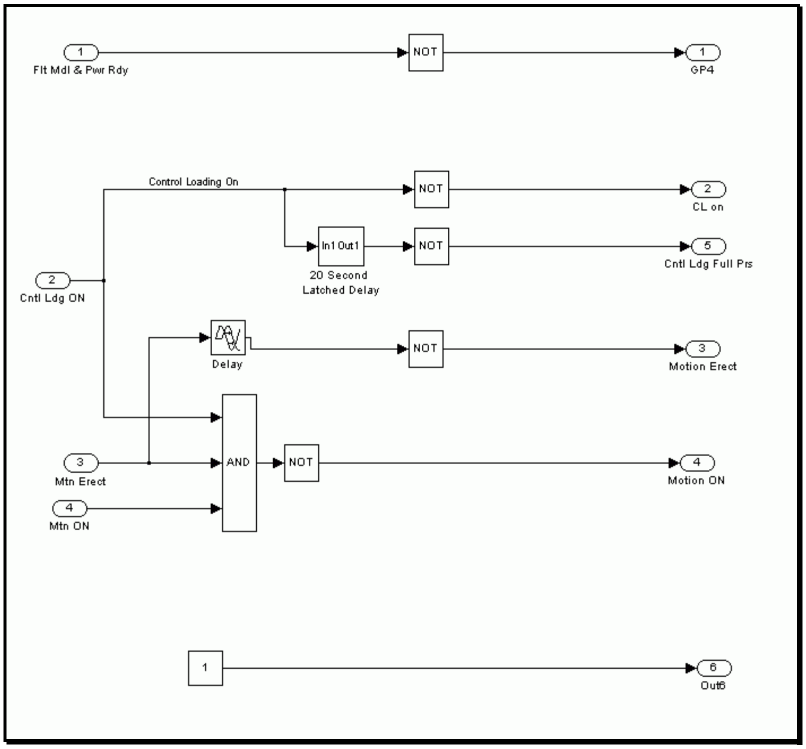

Figure 89 Supervisory System Output Block

The GP4 output signal mimics the previous systems signal that the controlling computer system is operating correctly. This previously defined[24] signal that indicates that the both the flight model and the power system is operating. Until this signal becomes a '1', the power system start-up is halted halfway. After this, the start-up completes and power is available to the HPU, allowing it to create hydraulic pressure.

The control loading on (CL on) signal comes directly from the input supervisory system. This output signal switches on the Control Loading Valve on the HPU, allowing pressure into the control loading system. This circuit is also delayed by a 'Latched Delay' of 20 seconds before the Control Loading Full Pressure (Cnt Ldg Full Prs) output is activated. Until this signal is activated a valve activated by a solenoid bypasses the fluid through a restricted orifice to reduce the pressure available to the flight control actuators. When activated, the solenoid allows full pressure to the system

The Motion Erect Signal comes from the input supervisory system and is sent directly to the Motion Erect Valve on the HPU after a delay. This allows pressure for the Erect process to occur which moves the simulator to its neutral position. When the control loading is on and the "motion erect" signal and the "motion on" signals are present, the Motion On output is transmitted. This opens the Motion valve on the HPU, allowing pressure and fluid flow required for full motion operation.

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[24] **Section 3.3.3.4**

4.2.3 Motion System

The supervisory section of the block ‘Motion System’ is shown in Figure 90. The block ‘Motion Drive Signal’ provides the actual motion base commands in accordance with the simulation and will be detailed in Chapter 6. The rest of the circuit provides the ‘Motion Erect/Shutdown’ and ‘Motion Envelope’ functions as well as output position and rate limiting.

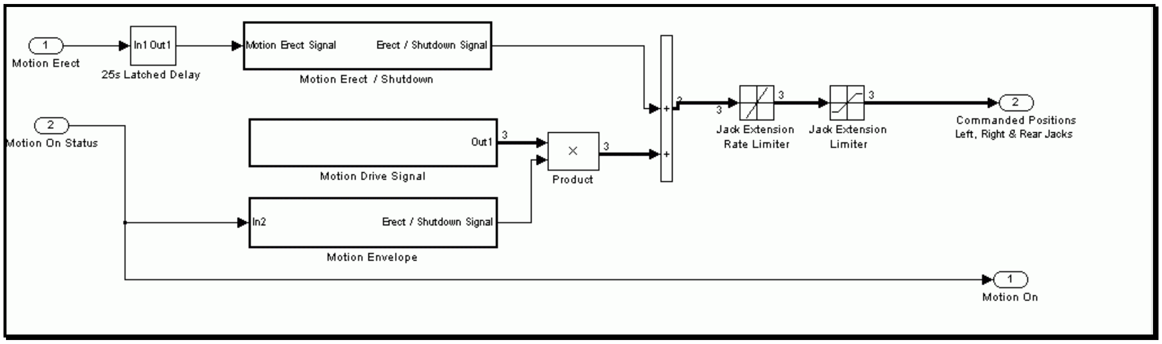

Figure 90 Motion System Block

4.2.3.1 ‘Motion Erect/Shutdown’ Block

The circuit in Figure 91 raises and lowers the motion base to/from its neutral position at the start and end of a motion session. Whenever the ‘Motion Erect Signal’ is a ‘1’, the switch passes a 0.2 Volts per second increase to the integrator which saturates at 4.5 V. At start-up, the base rises at this rate from the resting position to the neutral or erect position at 4.5 V. When the ‘Motion Erect Signal’ is turned off at the end of a motion session, the switch passes a 0.2 V per second signal to the integrator which then outputs a signal decreasing to 0 V, lowering the motion base to the rest position.

This neutral position provides the point about which the motion drive operates.

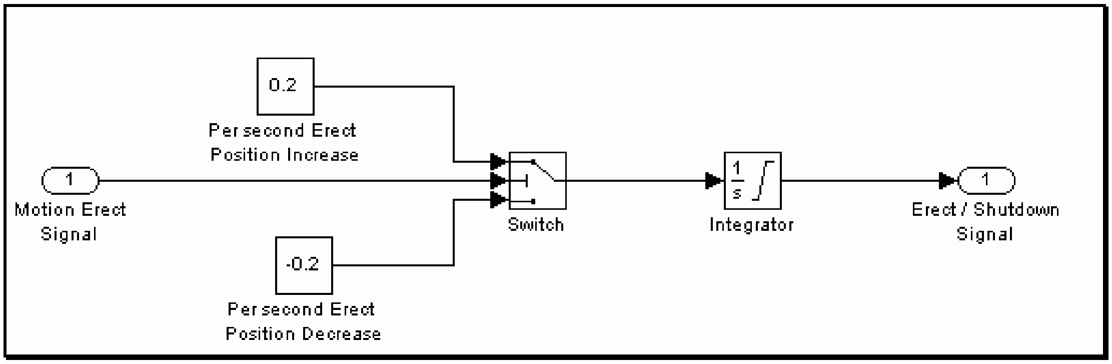

Figure 91 Motion Erect/Shutdown Block

4.2.3.2 Motion Envelope Block

The 'Motion Drive' system outputs data as soon as the flight model operates. However, this should not occur until the motion base has moved to the erect position. The circuit shown in Figure 92 gradually introduces the 'Motion Drive' signal on top of the Erect signal. At start-up the Integrator output is '0', multiplied with the 'Motion Drive' signal the output is 0' as required. 'When the 'Motion On' signal becomes '1', the Integrator counts upwards at 0.2 units per second saturate the Integrator at a value of '1' after 5 seconds. This value multiplied by the 'Motion Drive' signal allows the motion commands to be gradually added to the Erect position over a five second time period.

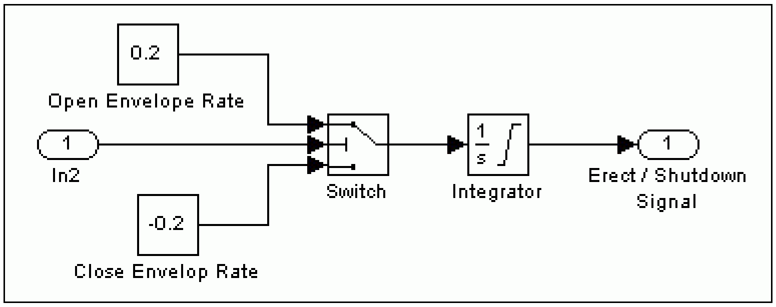

Figure 92 Motion Envelope Block

When the 'Motion On' signal becomes a '0' at the end of motion, the Integrator output decreases at 0.2 units per second, gradually diminishing the 'Motion Drive' commands. At the same time the Erect/Shutdown block is lowering the base to the rest position. The motion signals are removed after 5 seconds and therefore are not present when the simulator approaches the rest position.

4.2.3.2 Actuator Extension Rate Limiter and Extension Limiter Blocks

These blocks are standard Simulink blocks that simply limit the rate at which the actuator extension commands can change and also the maximum value of actuator displacement that can be commanded.

4.2.4 Control Loading System

This block (Figure 93) produces the commanded actuator positions for the control loading system as the previous block did for the motion system. It takes inputs of flight control force inputs (from the pilot) and control position from each of the three flight controls[25] as signals of 0 to 10 V. Each control has a separate block that computes required actuator length, these blocks are the subject of the Control Loading chapter.

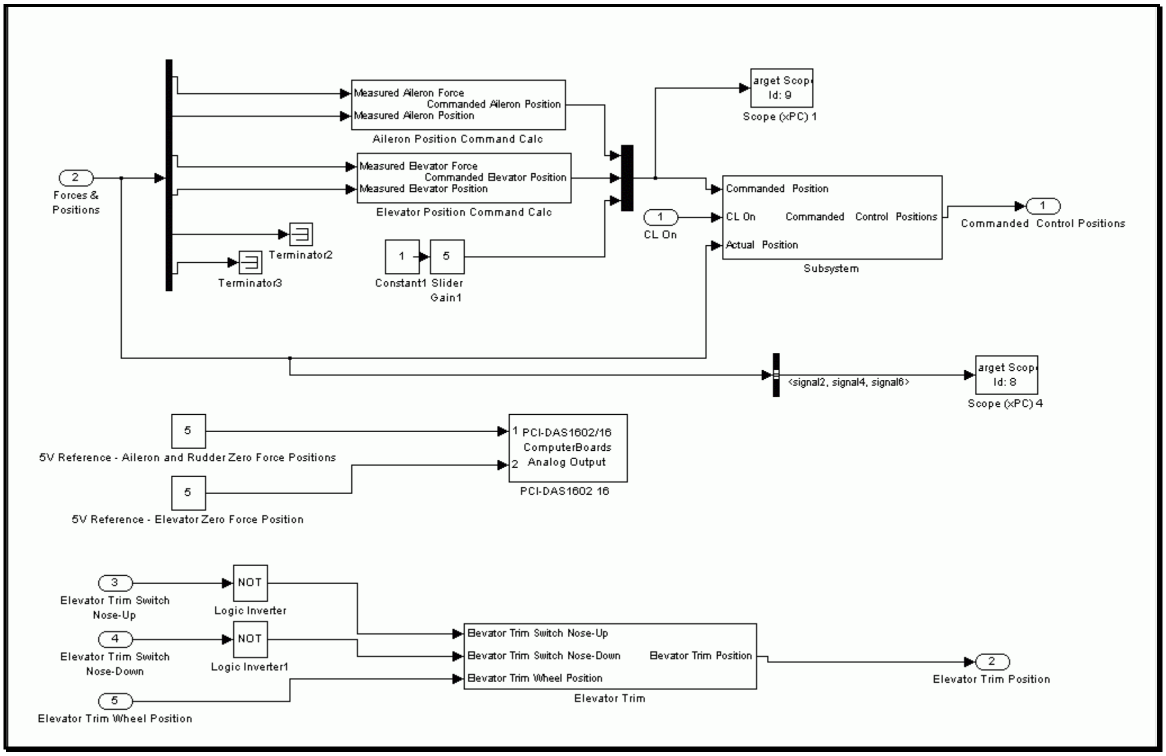

Figure 93 Control Loading System

The block 'PCI DAS 1602-16' outputs a 5V signal to the Digital to Analogue converter. This is used in the flight control force measurement circuit as a reference voltage. It converts the force transducer output on each control from a –5 to 5 V range to a 0 to 10 V range as required by the PCI DDA08 card

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[25] **Aileron, Elevator and Rudder**

Chapter 5

Flight Controls

5.1 Flight Controls Hardware

A major part of the project was the ability to interface the simulators flight controls to the new PC based simulation. The new simulator's computer is able to process analogue and several digital inputs through the attached multiplexer board designed and supplied by the Cranfield College of Aeronautics. Controls available on the simulator include;

Primary flight controls

- Elevator
- Aileron
- Rudder

Secondary Controls

- Thrust Levers (4)
- Elevator, aileron and rudder trims,

- Flaps
- Landing gear
- Wheel Brakes
- Speed Brake
- Engine Fuel Switches (4)
- Park brake

Tertiary Controls

- Radio and Navaid Frequencies
- Barometric Settings
- Navigation Instrument settings
- Heading Bugs

The secondary controls are connected directly to the Cranfield Simulation System as detailed in Appendix 5.

The tertiary systems are being developed as part of a current undergraduate thesis.

5.1.1 Primary Flight Controls

The primary flight controls include the Elevator, Aileron and Rudder. They control motion about the three aircraft axes. Initially information was required on the position of these controls for use in the simulators flight model. There is also a requirement to provide force feedback to the pilot through the flight controls if he is to adequately control the aircraft. Initially the flight controls were connected directly to the Cranfield Multiplexer Board to provide flight control position information to the Flight Model. As the system was developed, it became necessary to also make this information available to the CMT for use in the Flight Control Loading module. The system was redesigned as outlined in Chapter 3 to enable the information to be used by the CMT first before being used in the FMC.

All three of the controls are interfaced through mechanical linkages to identical hydraulic actuator arrangements. Each linkage is different and the three are shown in diagrams that follow.

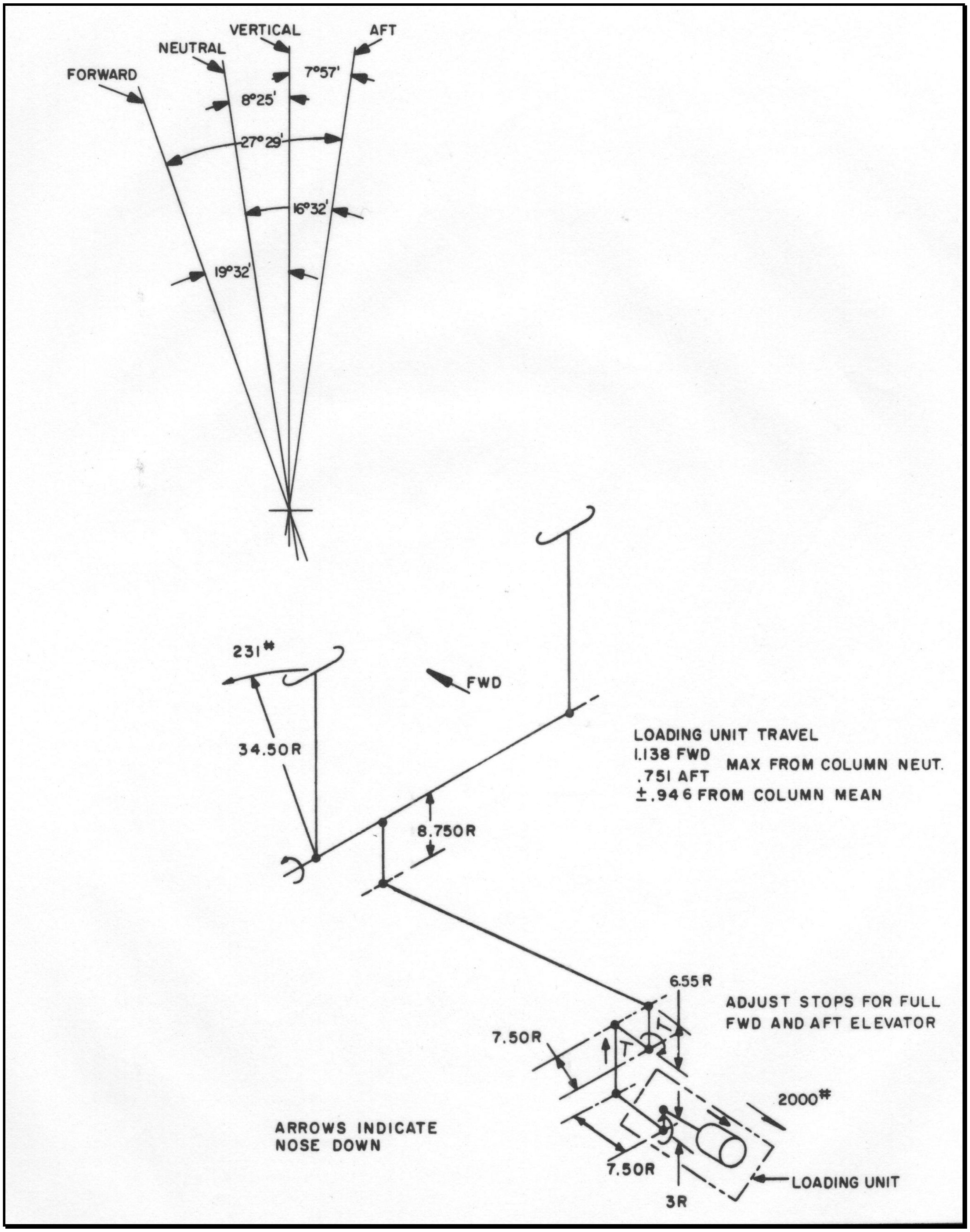

Figure 94 Column (pitch) linkage

Figure 94 shows the Pitch Control Linkage [22]. Of interest here is the geometry of the column in pitch with reference to neutral position. It is shown here as being forward of the vertical by over 8 degrees. There is just over 27 degrees of travel, from 11 degrees forward of neutral to 16 degrees aft of neutral. This asymmetric set-up reflects the fact that greater control inputs are generally required in the nose up sense (control column aft). When the controls are loaded hydraulically this will be reflected in the system's neutral point.

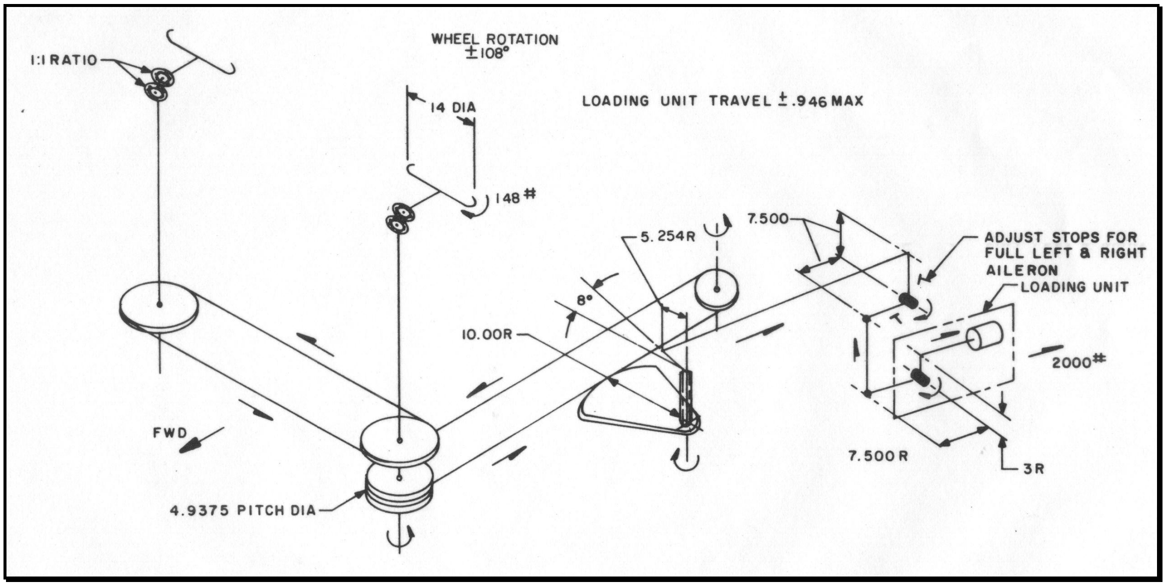

Figure 95 Wheel (aileron) linkage

The wheel linkage, shown in Figure 95 [22], is symmetrical with 54 degrees of rotation in either direction.

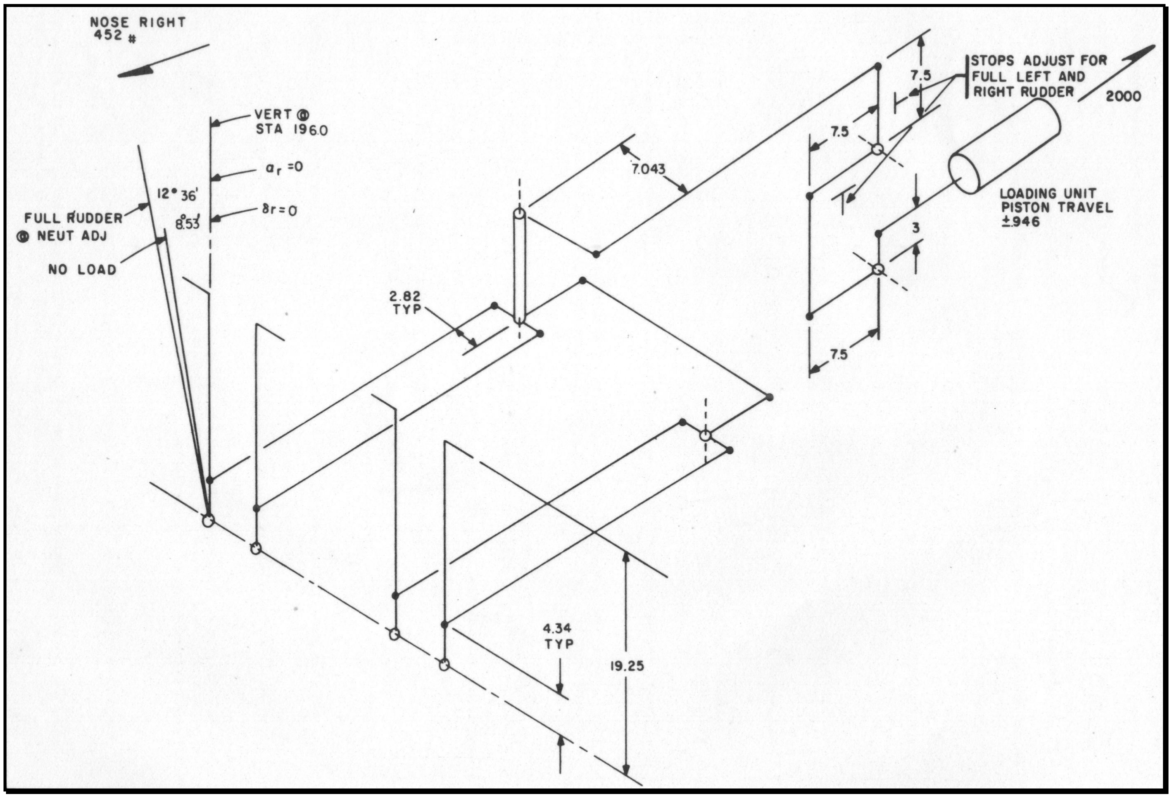

Figure 96 Rudder pedal linkage

The rudder linkage (Figure 96 [22]) is again symmetrical with 12 degrees of travel available in either direction giving a linear response.

Whilst each control axis has separate and different mechanical connections, each one terminates at an identical control loading unit. Three of these are mounted underneath the simulator cabin, two on the left hand side with aileron outboard and elevator inboard, and the rudder on the right hand side[26].

The gearing involved in each circuit from input at the pilot station to loading unit is different in each case. The amount of gearing is measured during the force transducer calibration.

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[26] Looking forward from the rear of the sim

5.2 Flight Control Loading

The flight controls of an aircraft in flight are affected by several factors. These include aerodynamic forces on the flight control surfaces as well as forces produced by various components of the flight control system, including centring springs, trim drives, autopilot drives, gearing and various sources of friction. It is the sum of these forces that the pilot 'feels' through his controls. The simulator must reproduce these forces in order to provide a proper simulation of the aircraft. This is especially so because the control system provides the pilot with a means to input commands into the closed loop control system of the aircraft, if the feedback provided to the pilot via the controls is not accurate, the training received in the simulator will not be of relevance.

The simulation of aircraft flight controls can be divided into two areas, inner and outer loop control [25]. The inner loop consists of the actuator which is linked to the flight control linkage, a potentiometer to provide feedback, and a device for measuring the force applied by the pilot into the system. The outer loop consists of computer hardware that computes the forces and the control loading position commands that should be apparent to the pilot for the current phase of flight.

It is not the pilot that physically moves the controls. The force he/she applies to the controls is measured by the inner loop's load cell and this force is provided to the outer loop. This force is divided by control inertia to determine the acceleration of the controls, this is integrated to give control velocity and position. This data is provided to the inner loop which then positions the control using the potentiometer as feedback. In aircraft control systems, control movements at frequencies of up to 50Hz have been documented [31]. To avoid aliasing, a frequency of at least 500Hz is required. This will ensure adequate dynamic response to control inputs by the pilot.

Traditionally, a dedicated analogue computer would be provided for each control axis to control the system. It would also receive digital inputs to its amplifiers from a host computer that corresponded to various simulated aircraft components such as the autopilot. This system is robust in that it utilises well known electronics, but it has limitations seen in any analogue system including:

- Drift
- No Self-checking or monitoring for safety
- Lengthy process of tuning the analogue components to fit aircraft data

Now that digital computers have matured sufficiently, they now provide high enough bandwidth to be used for outer loop control. In turn they provide self-monitoring and can utilise design tools developed for such a situation, as well as interactive programmes such as Matlab and Simulink.

5.2.1 The Original B707 System

Information describing the Aircraft Flight Controls Simulation is found in Reference [22]. At this stage the system is only concerned with the primary controls axes of Rudder, Elevator and Aileron. There is also provision for force loading of controls such as Thrust Levers, Stabiliser Trim and Nose Wheel Steering. Loading of these secondary controls is beyond the scope of the current project.

A basic system layout of the original set-up is shown in Figure 97.

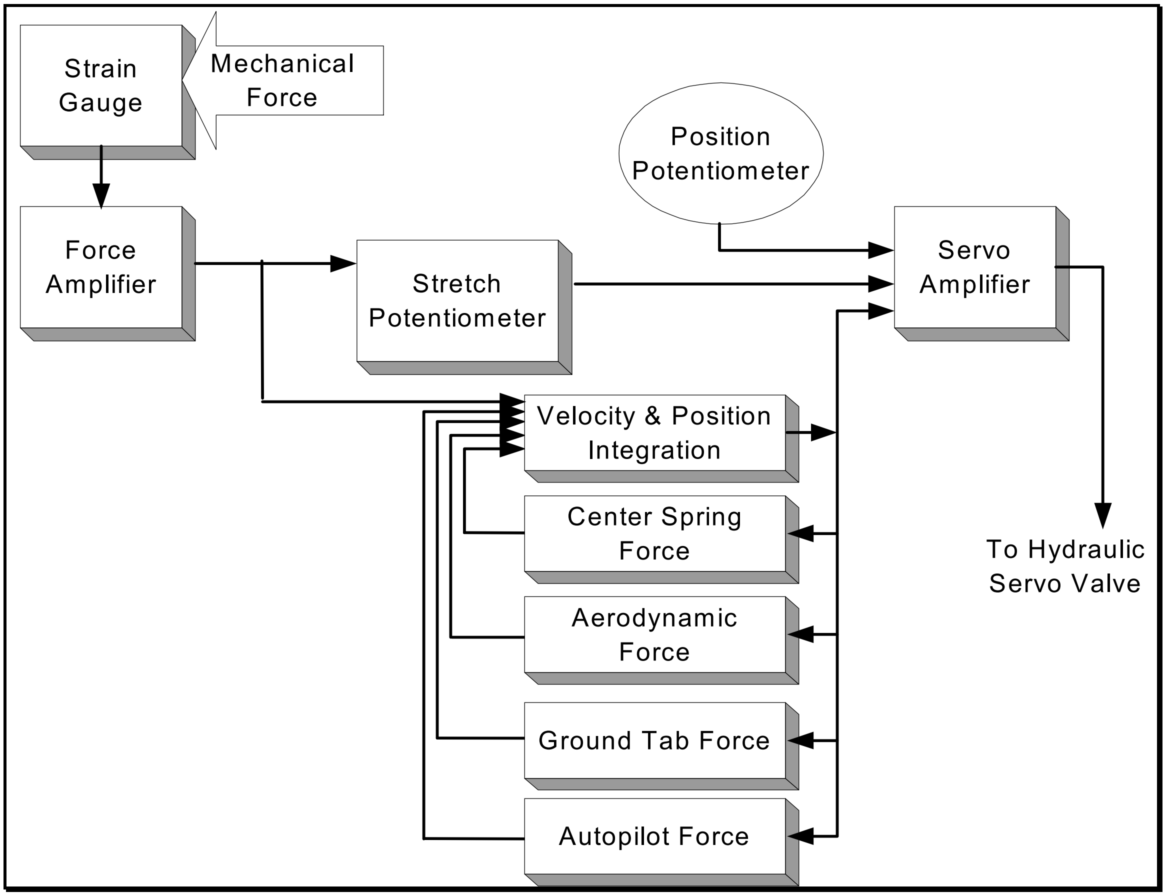

Figure 97 Original Control Loading Schematic

5.2.1.1 Inner & Outer Loop Control

The mechanical force applied by the pilot on either the control wheel (aileron), control column (elevator) or rudder pedals is measured by the force transducer and amplified to produce a usable signal. From here it passes into a integrator to produce values of Velocity and Position. This integrator also receives inputs from several modules simulating various aircraft specific forces. The output of this integrator, a scaled version of the actual force and a value of actual control position are sent to a servo amplifier card.

The inner loop is shown in Figure 98.

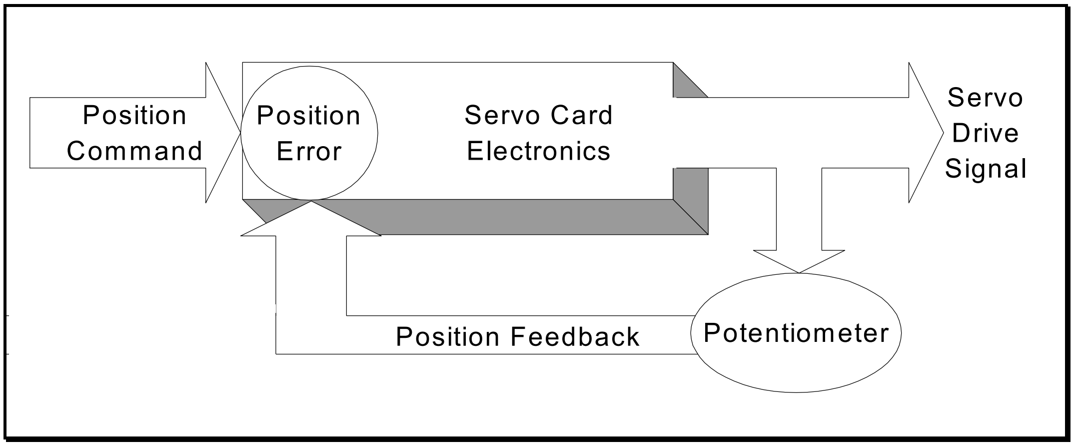

Figure 98 Control Loading Inner Position Loop

Each loading unit was equipped with an analogue electronic control loop physically located on the side of the unit. The servo amplifier card itself comprised two large operational amplifiers (op-amps - late 60’s early 70s vintage) as well as 20 resistors and 6 capacitors. Three potentiometers were provided for calibration. System gains and inputs were aimed at replicating the control feel of the target 707 aircraft and by nature not designed to be changeable or re-configurable.

Outer loop control uses pilot input force as well as several aerodynamic forces and aircraft dynamic forces to produce the required control position. The basic system is analogue again using several early series op-amps and potentiometers to produce a position command. Some of the inputs to the analogue circuitry were derived from the GP4 digital computer system.

Outer loop control circuitry was located in one of the several component cabinets.

5.2.2 The New System

In designing a flight control loading system for our application, it was necessary to move away from application specific electronics as used previously on the simulator for several reasons.

1. The system as delivered was designed to specifically replicate the flight control system of a Boeing 707-338 as delivered to QANTAS airways in the 1960s. It can be calibrated but only so as to produce the appropriate 707 control response.

2. The analogue inner loop hardware used, while functioning at the time of simulator delivery, was based around early vintage components. Such components are not readily available and replacement in the event of failure is difficult.

3. The outer loop analogue electronics are located externally to the simulator in one of several large component cabinets that we did not wish to re-commission.

4. The digital computer for the simulator has been scrapped and can no longer provide suitable inputs. The code from this computer is available but is extremely difficult to interpret even if we had wished to reproduce it.

It is easy to see that a new system of control loading control was required to produce a re-configurable, easily maintainable process of loading the flight controls. Having said this, all mechanical components of the original loading units are used. Position potentiometer and the force transducer are also used.

5.2.2.1 New Inner Loop

The first step in the process is to produce a new inner loop for position control. The only item needing replacement was the servo amplifier card. All the servo valves on the simulator are manufactured by Moog Hydraulics, listed in Appendix 3.

Consultation with Moog Australia produced a requirement for hardware to control six hydraulic servo valves. Three each for flight control loading and simulator motion. The system diagram for the servoamplifier card can be found in Appendix 3.

The servo amplifier card is capable of producing PID control. At delivery it is configured for purely proportional control. Integral and Derivative control is jumper selectable. Six of the cards are housed in a rack mountable unit that provides power supply outputs of +24V, -24V, +15V and –15V from a 240V supply. There is room in the unit for 4 additional cards for a total of 12.

Each card has provision for the adjustments detailed in Table 17.

Control	Purpose
P1 Zero	Sets the zero point to remove small errors in the system
P2 Gain	Adjust point for gain (prior to PID control)
P7 Scale	Allows scaling of the command signal to match the feedback signal
P9 Scale	Scales down high voltage feedback signals
P5 I	Adjust point for Integral gain
P6 D	Alters breakpoint frequency
P8 D	Alters derivative gain
Dither Freq[27]	Adjust point for Dither Frequency
Dither Level	Adjust point for Dither Level
V in3	Measure of input polarity
V in7	Measure of the input command
V R7	Measure of divided down input
+ & - LEDs	These LEDs show when the card is still driving the valve. If these flicker during a position motion, it indicates overshoot.
Isv	Used as a measure of drive voltage

Table 17 Moog Servoamplifier Unit Controls and Indications

The inputs to each card are as follows:

Command (0 – 10V)
Control Position (0 – 10V) , buffered by the signal conditioner
Power (+/- 24V & +/- 15V)

Outputs from each card are:

+24V and GND to the signal conditioner
Servo Valve drive current

---

[27] Dither is used in Hydraulic control to continuously provide a small signal changing position command to the hydraulic cylinder. This is to stop ‘stiction in the motion system. At delivery it is jumper selected off.

During initial testing of the closed loop circuit, the command signal was provided by a voltage source. When the outer loop control was added, this was replaced with the commanded flight control position.

5.2.2.2 Set-up & Initial Calibration

An inner loop was first established on the Aileron control unit. In the early stages, minimal consideration was given to shielding and cable lengths. The idea was to develop an understanding of system dynamics and whether or not there would be sufficient bandwidth and control authority over the system for our purpose.

To provide the necessary cabling of output potentiometer information to the Moog servoamplifier control card as well as to provide an input for servo valve inputs, the servo amplifier card installed previously on the control unit was removed and replaced with an amplifier card that provides filtering, amplification and reference voltage offset (detailed in Appendix 4) for force measurement.

Dedicated cabling has been established to connect the amplifier and potentiometer to the Moog signal conditioner and servoamplifier. A variable voltage source was used in testing as an initial position command as shown in Figure 99.

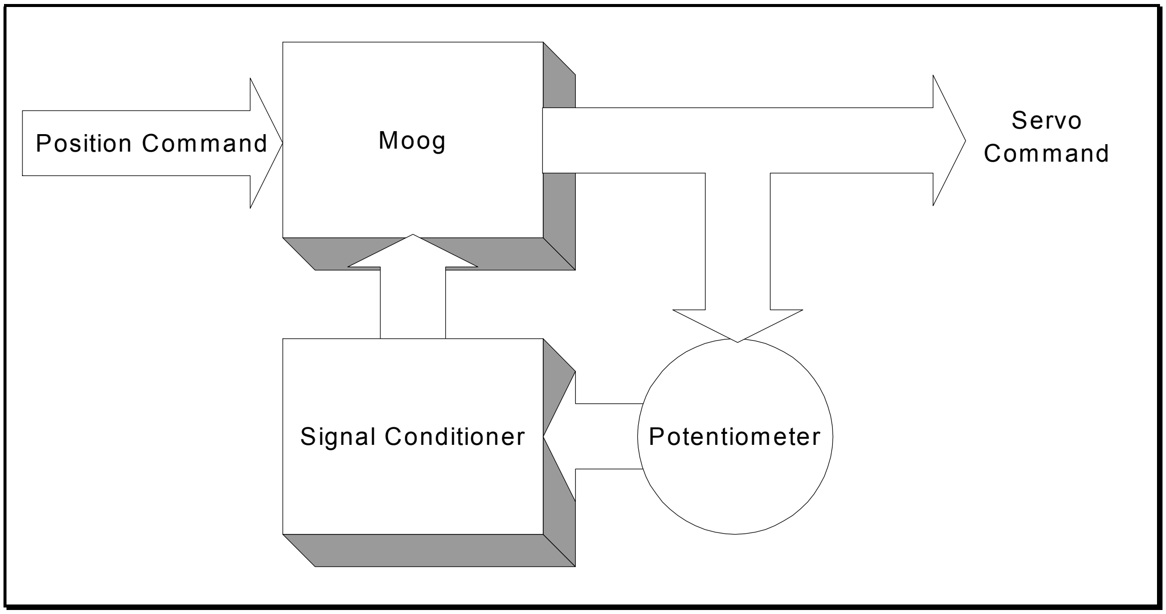

Figure 99 Force Transducer Test Setup

The first step was calibrate the signal conditioner so as to ensure that a full scale control deflection corresponded the full voltage range of the servoamplifier system. Each signal conditioner has configurable values of gain and offset, these were adjusted to produce a voltage reading of 0 to 10V corresponding to a full scale control deflection.

5.2.2.3 Initial Closed Loop Results

Initial qualitative results using the variable voltage supply input were promising with the control position tracking commanded position with good high frequency response. At this stage hydraulic supply pressure was not selected to a full value of operating pressure, which should increase system response.

One problem that quickly became apparent involved losing ‘lock’ of the control position. This means that if the commanded position signal exceeded the operating range of 0-10V, tracking of commanded position would be lost. The input voltage would have to be returned to the vicinity of the control position to re-acquire tracking.

It must also be emphasised that the position signal provided by the potentiometer via the signal conditioner must have a range equal to or greater than that of the commanded position. If this is not the case, once again the closed loop will not be able to correctly track input commands. Each circuit was re-calibrated to ensure that this was the case.

5.2.2.4 Outer Loop Control

To produce an outer control loop, we require the following

1. Force measurement
2. Control position determination
3. Output of position to the inner loop

Force measurement is achieved through use of the force transducers discussed previously. The gain of these transducers is very small and the output signal must be amplified to produce a useful signal. For this system a voltage range of 0 to 10 V DC is required (Appendix 4 details the amplifiers).

Once the system has sensed the force applied to the control it is used in the outer loop contained in the Target computer to calculate a new control position. This is sent to the control card which moves the control to the required position. This process is the subject of the next section.

5.2.2.5 Analogue Force transducer Gain Determination

An analogue calibration of the control loading force transducers was carried out to determine a rudimentary system gain.

Initial studies of a spare force transducer showed the gain to be very small, as expected. However, when the force transducer is in series with the mechanical connections of each control axis, the gain is increased through gearing. The mechanical set-up is shown in [22].

5.2.2.6 Calibration Set-up

For the test, 21.08 VDC was applied to the inputs of each gauge. The output was read by a multi-meter and the results recorded.

The force inputs were provided via a rope with a spring balance in series. Two balances were used, one a 20 kg balance, the other a 50 kg balance.

The inputs available from the smaller & lighter 20 kg balance were more accurate and more easily sustainable. Also, the smaller forces being applied through the 20 kg balance were easier to apply and maintain. Data from both inputs was recorded and the results examined.

Some difficulty was experienced in the application of the input force. Obviously, in order for the force recorded by the spring balance to be equal to the force applied through the control gearing to the force transducer, the rope would need to be connected to the control at the correct place at an angle of 90 degrees to the moment arm. In the case of the pitch response, whilst the attachment of the rope at the correct point was not a problem, achieving a constant 90 degree angle to the control column was. As can be seen in the plots of Pitch Response, a slightly different slope occurs from one of the inputs not being applied at exactly 90 degrees.

5.2.2.7 Calibration Results

Input Forces Required

Values of maximum input forces were determined [23,24,Table 18]. These forces were applied as discussed previously and the results recorded and plotted below for each axis.

Control Axis	***Maximum Force (lbs)***
Pitch	91 pull / 30 push
Roll	15
Yaw	115

Table 18 Maximum Forces Applied to Each Control Axis

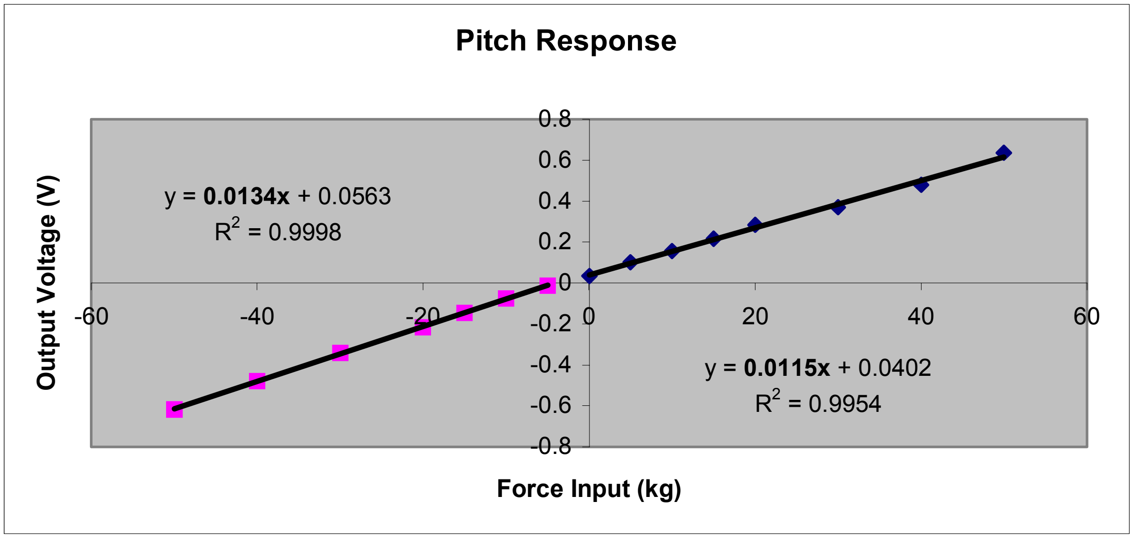

Figure 100 Pitch Force Transducer Calibration

Results were measured in both nose down and nose up. For the nose up force case (negative input and output), the gain is 0.0134 whilst for the nose down case the gain is 0.0115. The nose down case involved passing the force input rope through the nose of the simulator, and was by inspection not as close to 90 degrees as the nose up case. Therefore, the gain of 0.0134 is more realistic and will be used for calibration.

Roll Response

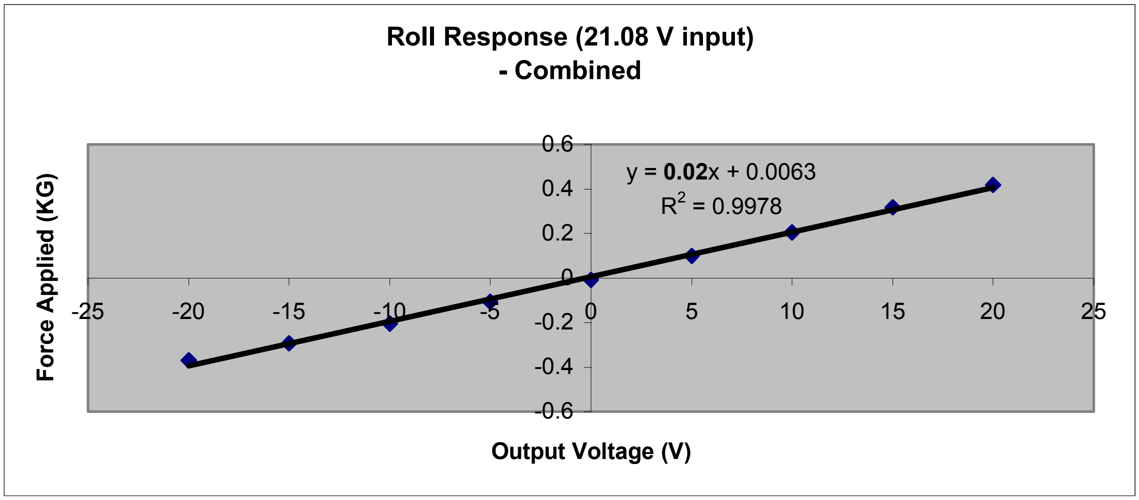

Figure 101 Roll Force Transducer Calibration

When data is combined from both directions as shown above, a gain value of 0.020 is apparent and reasonable.

Yaw Response

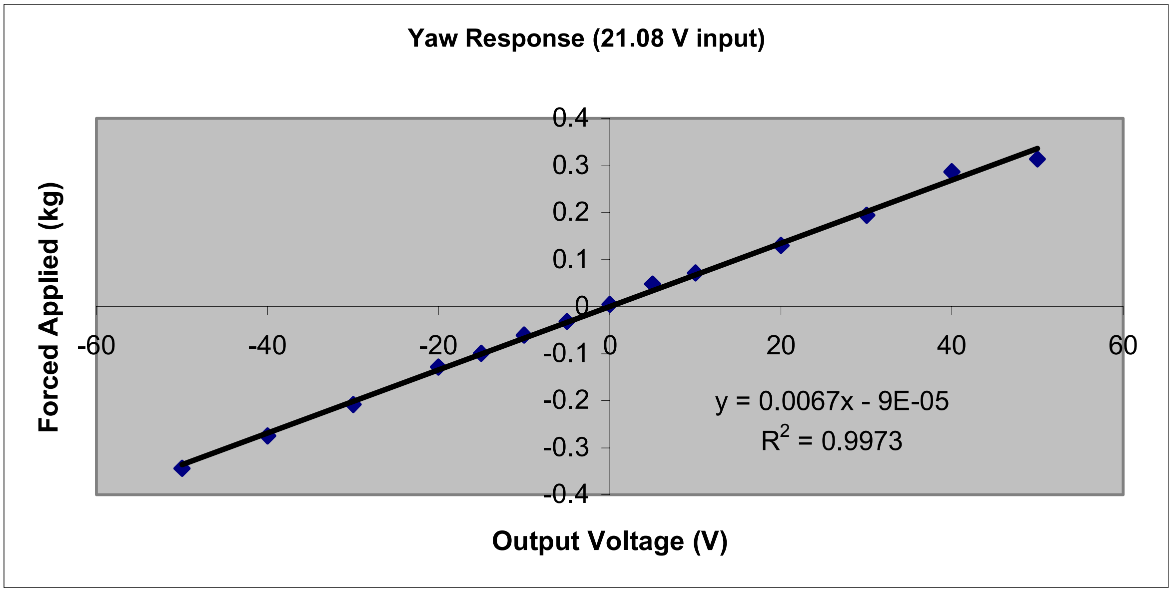

Figure 102 Yaw Force Transducer Calibration

Yaw calibration is excellent with a gain of 0.007.

5.2.2.8 Calculation of Amplifier Gains

Amplifiers are used as previously described to scale the measured control forces to a suitable range for use by the flight control system. It is necessary to receive these signals in the range of 0 to 10V. The force transducer produces low voltages outputs with 0v as the neutral. A 5V bias signal is produced from the Supervisory control system to bias the signals to a 5V zero position.

The following equation outlines the calculation required to give the correct amplifier gain:

$$\mathrm{Maximum\_Force\_Applied} \times \mathrm{Transducer\_Gain} \times \mathrm{Amplifer\_Gain} = 5\mathrm{V}$$

From this we determine the gains listed in Table 19.

Control Axis	***Gain Required***
Pitch	8.4
Roll	14.8
Yaw	6

Table 19 Amplifier Gains for Force Measurement

For the Pitch calculation, a maximum force of 45lbs in the nose-up case was used. Using the maximum 91 lbs force would have reduced the gain available for nose-down pitch. As it is a figure for a manual reversion scenario, its inclusion was not justified.

5.3 Control Loading Software

5.3.1 Simulink Implementation

The Simulink implementation of the control loading system is shown below.

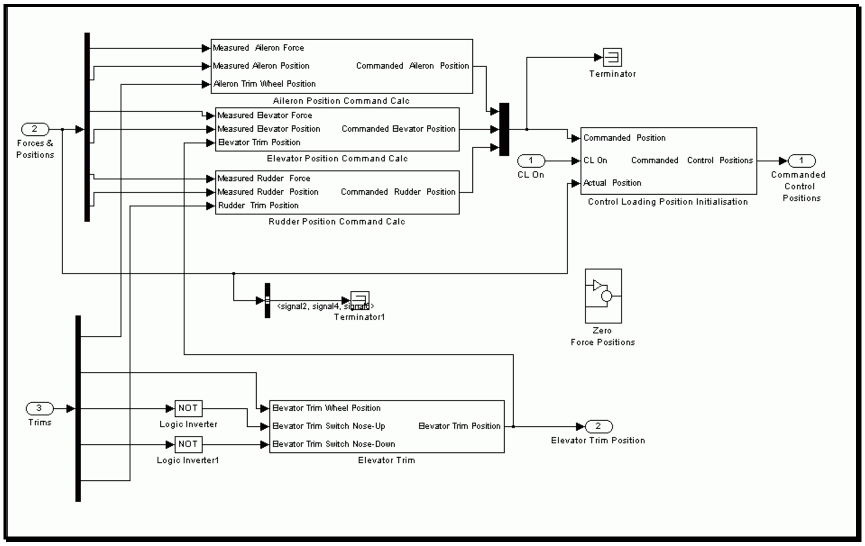

Figure 103 Control Loading System Overview

The top half of the system contains the control loading software for the three control axes with Aileron at the top, followed by Elevator and the yet to be commissioned Rudder. At right (labelled Control Loading Position Initialisation) is the subsystem that controls the commanded positions when the system is initially switched on. The inputs to this sections are forces applied to each control (3), the position of each control (3) and the Control Loading 'on' signal. In the middle is a small circuit (Figure 104) used as a reference voltage for the force transducer amplifiers in order to bias the force signals from a bipolar –5V to +5V to a 0 to 10V signal as read by the PCI-DAS 1602 card. The lower section is for elevator trim and combines the electric trim switches on the control yoke with the manual trim wheel at the pilot stations (2).

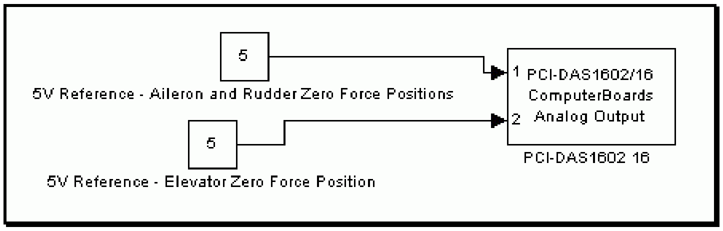

Figure 104 Bias Output for Force Amplifiers

The circuit for each axis is essentially the same as the aileron circuit is shown in Figure 105. The structure of the model is essentially taken from the original 707 schematic shown in Figure 97. At this stage the system roughly models the flight controls of a large jet transport aircraft. No attempt has been made to match the performance of the system with flight test data, nor has it been designed match any particular aircraft's flight control system. The tuning of gains and filter coefficients was undertaken subjectively by the author in an effort to produce a working system that would sufficiently represent a large transport aircraft. It is understood that more work can be done in this area to produce a 'better' simulation of such a system as required by the applicable user of the simulator.

The circuit has two inputs:

1. Measured Control Force
2. Measured Control Position

Both are signals from 0 – 10V DC as read by the A/D card.

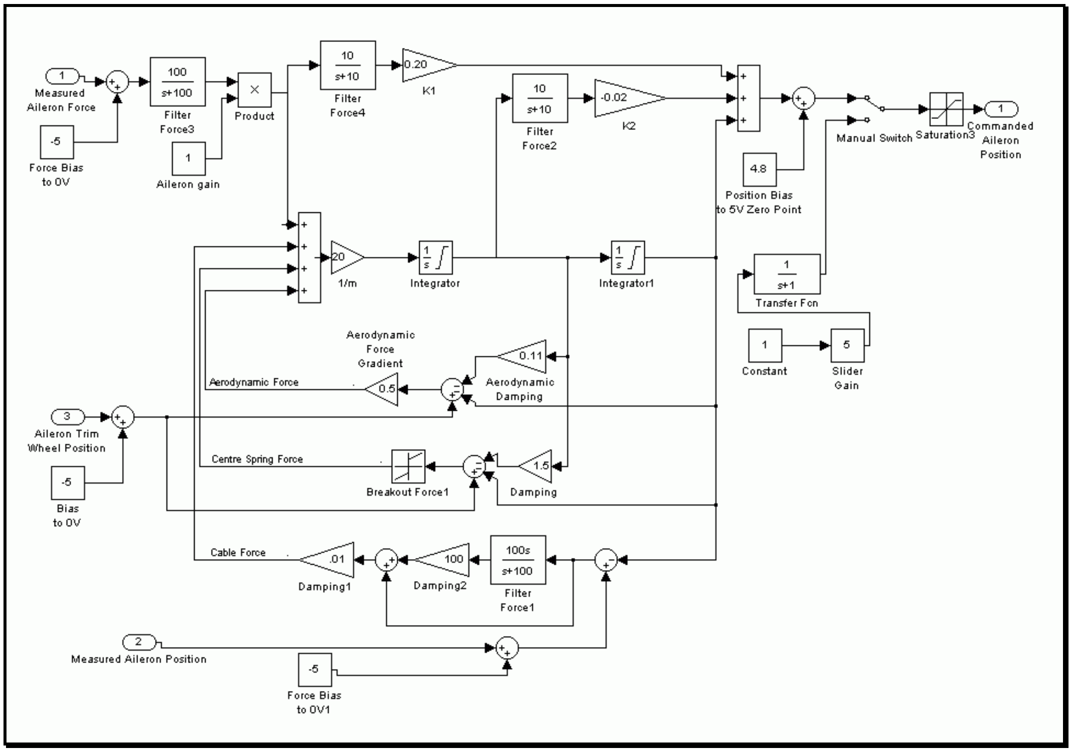

Figure 105 Flight Control Software

The output of the main block is a commanded position voltage in range of –5 to 5V. This is biased to a 0 to 10V signal by the block ‘Position Bias to 5V’. Here the actual value is 5 volts due to some non-linearity in the system.

The output before this biasing is a sum of filtered control force, filtered control velocity and filtered control position.

The control velocity is an integration of the sum of the following

Force – This is the force that the pilot inputs into the system. It is measured at the hydraulic actuator and so has the flight control’s gearing between it and the pilot. The signal is measured by a force transducer whose output is in turn amplified by an amplifier mounted next to each force transducer. This is done so as to amplify the signal before transmission to the Target to avoid later amplification of noise.

Cable Force – This term models the force applied when the aircraft's flight control system, which is connected by cables on the 707, is stretched. This stretch is calculated by looking at the difference between the control position and the actual position.

Center spring force – The flight control system contains a spring loaded device that centres the flight controls. This combined with the Cable Force provides the system feel when the aircraft is on the ground and not affected by aerodynamic effects.

Aerodynamic force – This module simulates the Aerodynamic force as applied to each control surface. This force is dependant upon dynamic pressure.

The system has been tuned subjectively through an iterative process of parameter adjustment. At this stage aerodynamic data from the FMC has not yet been included.

5.3.2 Control Loading ON Subsystem

Unlike the motion base which rests at the zero position when unpowered, the flight controls can assume any position. If the position commanded by the software is significantly different from the actual position, initial application of hydraulic power to each axis will cause a rapid movement of the controls to the commanded position, even with the reduced pressure at system start-up. Particularly with the column but also with the wheel, this condition is unacceptable. Figure 106 outlines the solution to this problem.

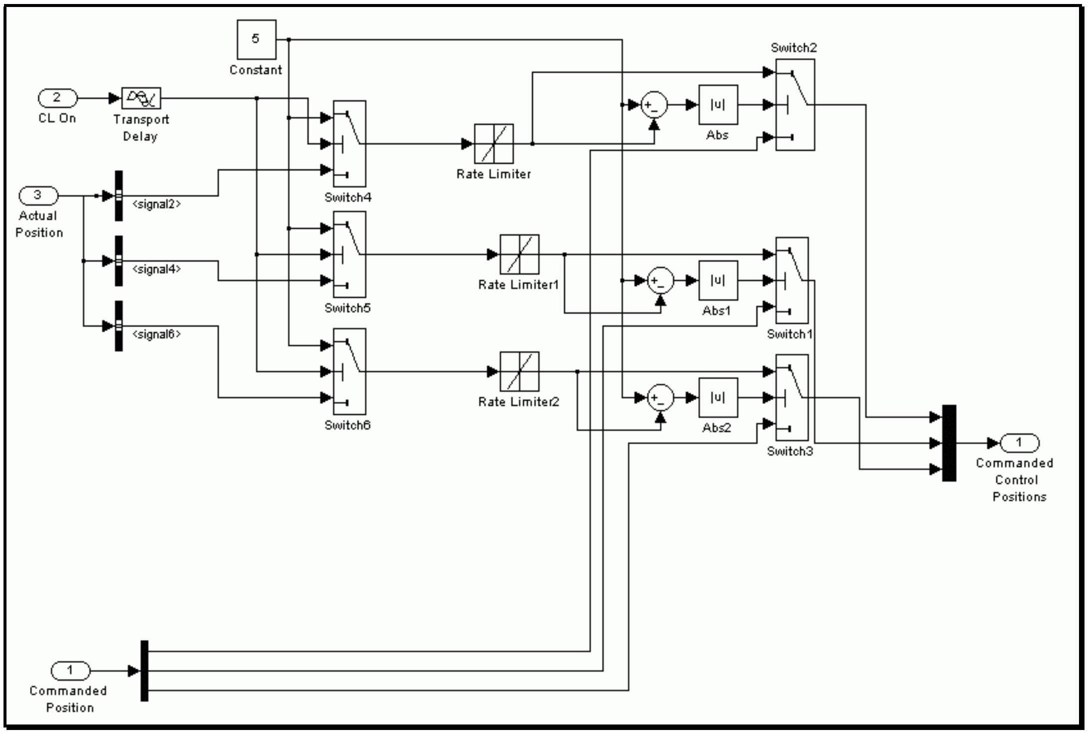

Figure 106 Control Loading Position Initialization

When no force is applied to the controls, the neutral commanded position has a measured position of 5 volts, corresponding to a half scale signal at the mid position. The circuit above commands one of two positions as determined by Switches 1, 2 and 3.

The actual position information is divided throughout the system by use of the ‘<Signal>’ blocks. These demultiplex the original signal to produce individual signals for use in the rest of the circuit. Initially the output of the block, ’Commanded Control Positions’ comprises the outputs of Switches 4 through 6 which are a measurement of the actual positions. This means that when the system is energised, the controls remain in this current position. When the Control Loading ON signal (CL On) is powered, it is delayed by ‘Transport Delay’ for a short period (2 secs) before activating Switches 4 through 6. When this occurs, the outputs of Switches 4 through 6 change to 5V instantly, however the Rate Limiter blocks only allow the new commanded position to change from the actual position to 5V at a reduced rate of 1V per second. This has the effect of slowly raising the controls to their neutral position.

When each actual position is within a specified distance from the commanded 5V position, the absolute value of their difference falls below a threshold value. The output of this value causes Switches 1 through 3 to operate, allowing the Commanded Position as determined by the previous Control Loading block to become the Commanded Control Positions.

This block is used only for start-up of the Control Loading system. If the system is turned off, it will revert to its start-up condition, subsequently turning the Control Loading ON will cause the controls to raise slowly to the neutral position again.

5.3.3 Elevator Trim Circuit

Each axis has a trim circuit as outlined in Chapter 3. The Elevator is different from the Aileron and Rudder in that there are two ways to alter trim position, a trim wheel and electric trim buttons. In the original system, the trim switches caused movement of the trim wheels by activating a hydraulic servo valve under the simulator. As trim systems no longer work in this fashion in modern aircraft it is no longer necessary or desirable to replicate this mechanism. Instead the desire for generic simulation motivates a system in which the trim wheel or switches or both will operate the pitch trim. The new architecture is shown in Figure 107.

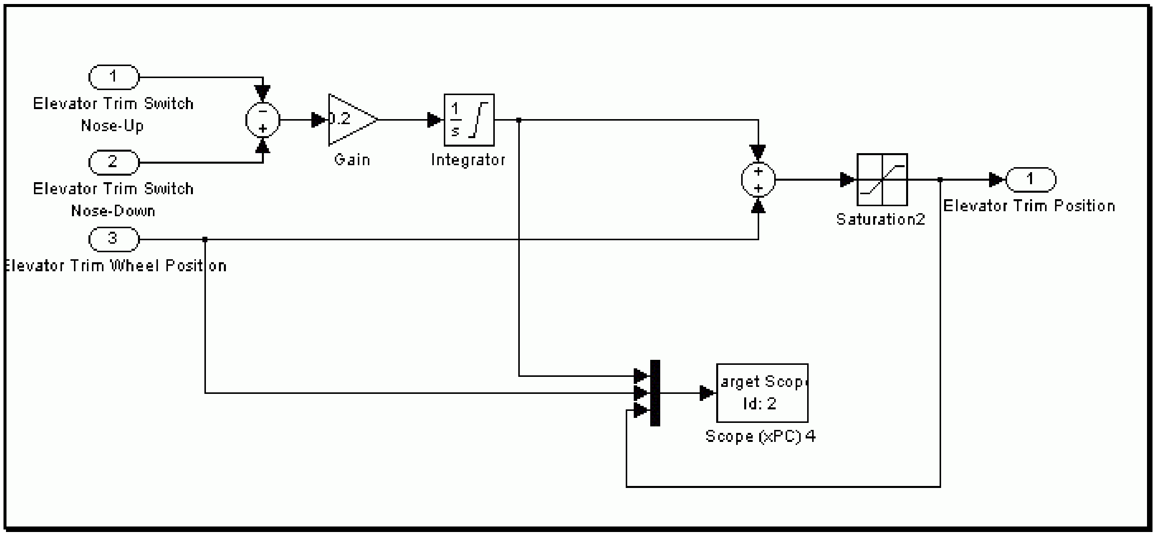

Figure 107 Elevator Trim Circuit

Turning the trim wheel from the forward trim position to the aft position moves the output 'Elevator Trim Position' as it would in any aircraft. Superimposed on top of this signal is the Electric Trim signal, input via the Nose-Up and Nose-Down switches on each control column at the pilot stations.

At start-up, the output of the integrator is 0 and the trim position output is the trim wheel position. When a Nose-up or Nose-Down signal is received, it inputs a positive (nose-down) or negative (nose-up) signal of value 0.2 via the Gain block to the integrator. This represents a trim change speed of 0.2 V/S or 50S for a full range of travel. It has a maximum output range from –10 to 10, this allows the Electric trim to command a full scale trim change regardless of wheel position.

The sum of the two becomes the Trim Position Output, the saturation block limits the output to 0 to 10 for output via the PCI-DDA08 card to the Flight Model Computer. It also passes through an amplifier with an attenuation gain of 0.5 providing the Flight Model A/D card with a 0 to 5V trim signal.

To use the circuit at start-up, the trim position begins at the current wheel position. It can be changed using either the wheel or the switches or a combination of the two. The actual trim position is shown on the instrument display in front of the pilot.

Chapter 6

Motion System

This chapter details the development of the Simulator's Motion System. Much of the influence on the design of the system comes from the work of Reid and Nahon [26, 27 and 28] of the University of Toronto Institute for Aerospace Studies.

It begins with an analysis of the system as delivered with the B707 simulator to determine what dynamics can be expected from the system based upon supplied specifications. This is followed by the design of the Motion system control software in a manner closely following that of references [26, 27 and 28].

Section 6.3 outlines the results of performance testing of the system. Having designed the control system, a series of tests were carried out to determine the actual performance available from the system. This is followed by Section 6.4 which outlines an analysis of the filter coefficients required to properly provide motion cues.

Section 6.5 outlines how the system has been tuned and subsequently analysed. The system tuning was carried out both subjectively and objectively. Subjective assessment has been carried out by the author[28]. Objective analysis is again based upon the work of Reid and Nahon.

6.1 Motion System Analysis

It is necessary to determine the dynamic characteristics of the hydraulic motion system in order to be able to exploit it to the maximum possible range of accelerations, velocities and positions. The usual practice in flight simulator motion system development is to tailor the motion performance to the aircraft being simulated. Although the basic idea of a simulator motion platform is to provide a 'washed out' version of an aircraft's motion, it is still important that it provide to the pilot some representation of the applicable translational accelerations and rotational rates.

Motion system specifications for flight simulators typically contain figures as shown in Table 20:

Translational Degrees of Freedom	Maximum translational acceleration (multiples of 'g')
	Maximum translational velocity
	Maximum displacement from a nominated neutral position
Rotational Degrees of Freedom	Maximum rotational acceleration
	Maximum rotational rates
	Maximum angular displacement from a nominated neutral orientation (usually zero degrees pitch, yaw and roll).

Table 20 Motion System Specifications

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[28] **The author is a Flight Simulator Evalution Pilot with QANTAS Airlines as well as an operating First Officer.**

Unfortunately, there is no specific data available for our motion system. Reference [32] documents this and provides motion plots developed by QANTAS Simulator Services to provide a baseline against which to analyse motion system performance. It was not intended to design a motion system for a specific aircraft. Instead, a generic system is sought that will be able to simulate a variety of aircraft, as such we are more interested in the capabilities of the motion base so as to be able generate motion cues for aircraft with widely different motion frequency spectra[29].

The system as delivered produced motion cues suitable for flight simulation of a large transport aircraft, in this case the Boeing 707. As such, without modification it would have been possible to use the system for aircraft with similar or more sedate motion. However, without data it is not possible to quantitatively define a set of maximum rates and accelerations that are possible with this equipment.

Reference [34] does contain Bode plots of actuator response. One of these is reproduced as Figure 108 [22]. The plots show that the hydraulic actuators have a low pass frequency response with a corner frequency[30] of approximately 0.2 Hz or 1.26 rad/s.

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[29] The Motion frequency spectrum is defined here as the range of frequencies of rates and accelerations of a specific aircraft. A large transport aircraft spectrum will have a low maximum frequency of rotational rates and translational accelerations. In comparison, a fighter type aircraft has a much larger spectrum containing larger frequencies as it can manoeuvre at much higher rotation rates and translational accelerations.

[30] Corner Frequency is defined as that frequency where the gain is –3dB, or approx 70% less than the pass-band gain. Also, the phase angle is –45 degrees.

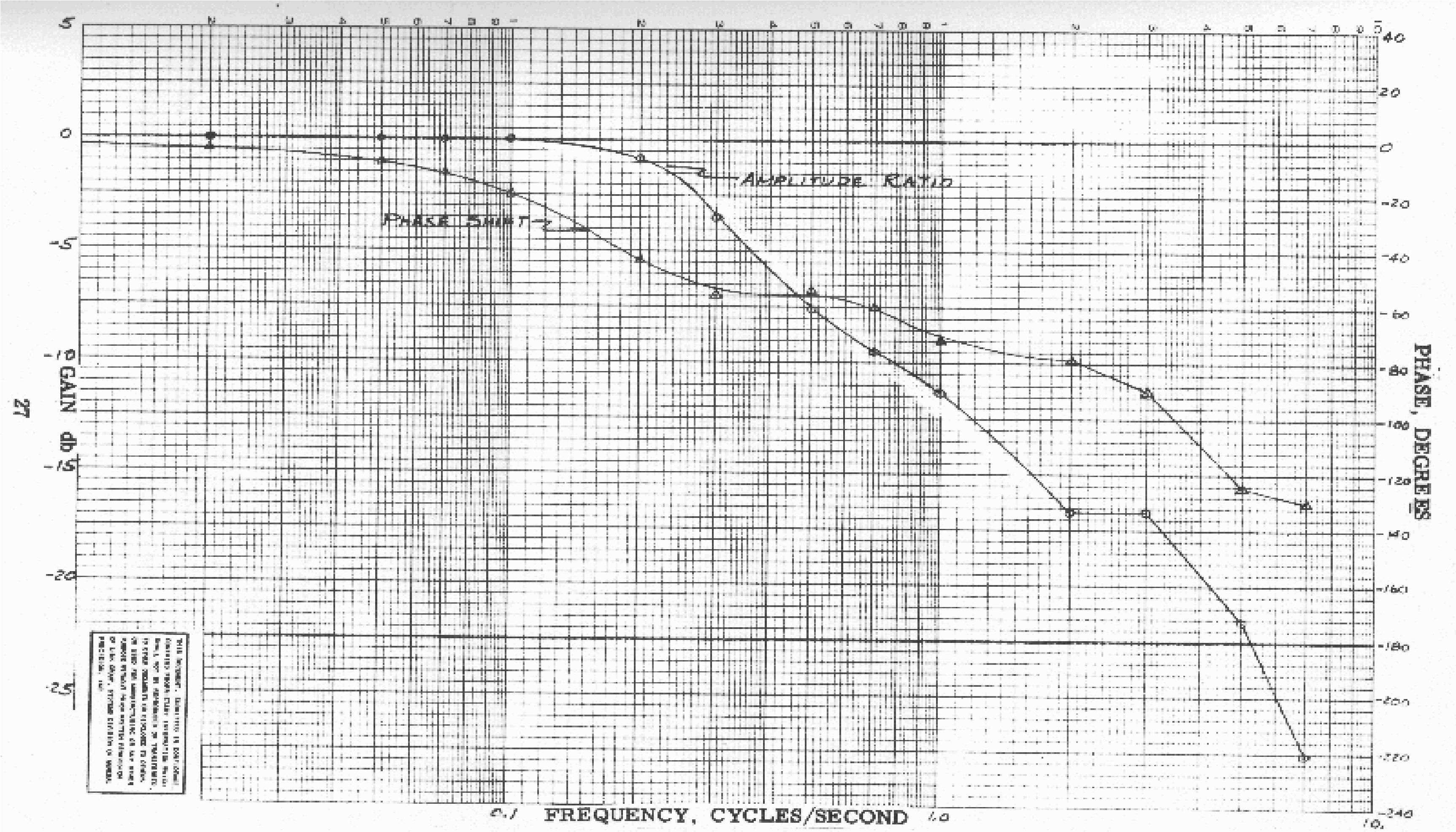


Figure 4-16 FREQUENCY RESPONSE, PITCH, COMPENSATED

Figure 108 Original Motion System Frequency Response

6.1.1 Motion System Forces, Accelerations and Speeds

Drawing 828480 from the Simulator Drawing File outlines the Simulator's hydraulic system. It does contain some figures, listed in Table 18 that allows calculation of values of system performance.

	Left Cylinder	***Right Cylinder***	***Rear Cylinder***
Bore (inches)	2.5	2.5	2.5
Full Stroke (in)	36	36	26
Normal Stroke (in)	34	34	24
Cushions (both ends) (in)	11/16	11/16	11/16
Area 1 (sq. in)	4.9	4.9	4.9
Area 2 (sq. in)	2.5	2.5	3.4
Flow Rate (gpm)	10	10	10

Table 21 Motion System Parameters

Where

- Bore is the inner diameter of the actuator cylinder.
- Full Stroke is the absolute range of extension available
- Normal Stroke is the useable actuator extension
- 'Cushions' is the amount of cushioning at the end of each cylinder to prevent hard stops. Nominally, such an event will not occur as the software should not command actuator extensions in excess of the Normal Stroke. However, they are provided for system protection.
- Area 1 is the area of the end of the actuator upon which the fluid acts, i.e. the area of the cylinder.
- Area 2 is the smaller area corresponding to the area of the cylinder minus the area of the actuator rod. This smaller area is the area upon which the fluid acts to return the actuator after extension (refer Figure 109).

Linear Hydraulic Actuators

A basic diagram of a linear hydraulic actuator is shown in Figure 109.

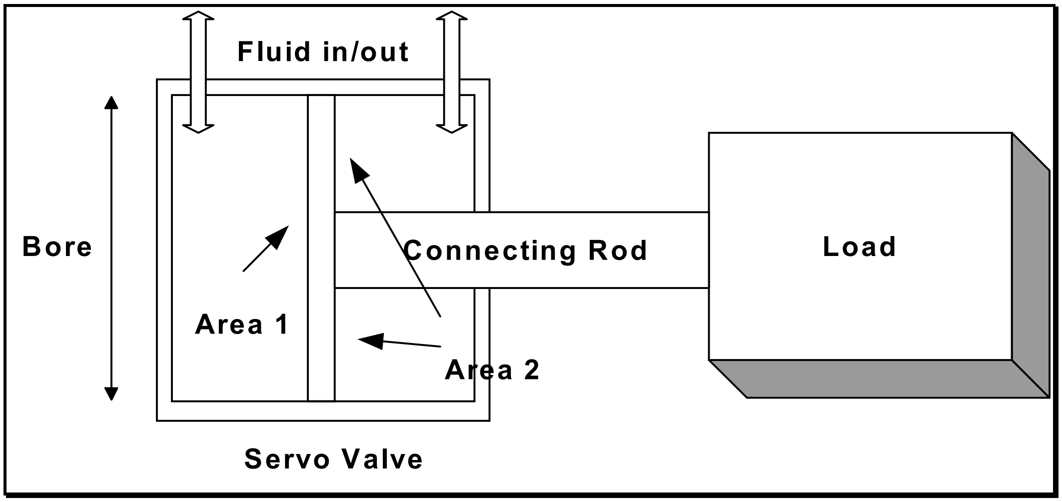


Figure 109 Unbalanced Linear Hydraulic Actuator

From the preceding definitions:

$$\mathrm{Area1} = \pi \times r^2 = \pi \times \left(\frac{\mathrm{Bore}}{2}\right)^2$$

$$\mathrm{Area2} = \pi \times \left[\left(\frac{\mathrm{Bore}}{2}\right)^2 - \left(\frac{\mathrm{Rod\_Diameter}}{2}\right)^2\right]$$

From [35], Force, Pressure and Area are related by the following equations:

$$\mathrm{Force} = \mathrm{pressure} \times \mathrm{area}$$

Relationships for Flow rate, speed and area are also given as:

$$\mathrm{Speed(V)} = \frac{\mathrm{FlowRate}}{\mathrm{Area}}$$

For the actuator shown in Figure 109, the area upon which the hydraulic fluid works is reduced on the side of the rod by the rod's cross sectional area. This will give differing rates and forces when the actuator is retracting. The actuators are unbalanced due to the need to support the static weight of the cockpit as a bias, but otherwise the driving capability is about the same. The actuators for the flight controls are balanced as they have no such bias requirement.

From equations (1.1) through (1.4) it is possible to determine the values of motion system performance.

6.1.1.1 Extension and Retraction Forces

Left & Right Actuator Force

The left and right actuators are identical and will have the same values of force and speed.

From (1.2)

$$\begin{aligned}\text{Force(extension)} &= \text{Area1} \times \text{pressure} \\ &= 4.9\text{in}^2 \times 3000\text{psi} \\ &= 14{,}700\text{lbf} \\ &= 63{,}385\text{N}\end{aligned}$$

similarly for retraction

$$\begin{aligned}\text{Force(retraction)} &= \text{Area2} \times \text{pressure} \\ &= 2.5\text{in}^2 \times 3000\text{psi} \\ &= 7500\text{lbf} \\ &= 33{,}360\text{N}\end{aligned}$$

The retraction force is almost half that of the extension force, to be expected as we will see later.

Rear Actuator Force

The Rear actuator has the same Area1 as the Forward actuators. This gives an extension force of 14,700lbs or 65,386N. For retraction however, it has a larger Area2 corresponding to a smaller diameter actuator rod.

$$\begin{aligned}\text{Force(retraction)} &= \text{Area2} \times \text{pressure} \\ &= 3.4\text{in}^2 \times 3000\text{psi} \\ &= 10{,}200\text{lbf} \\ &= 43{,}370\text{N}\end{aligned}$$

6.1.2 Vertical Acceleration

The weight of the entire simulator is given as 12,000lbs or 5,500kg. If it is assumed that most of the weight is in the simulator cab with some in the motion base, an estimate of the mass of the simulator cab is 5,000kg.

Looking at the system when it is accelerating in the Inertial Z axis, i.e. up and down with no roll or pitch:

$$\begin{aligned}\text{Acceleration(upwards)} &= \frac{\text{Force} - \text{mg}}{\text{mass}} \\ &= \frac{(3 \times 63{,}385\text{N}) - (5{,}000\text{kg} \times 9.81\text{ms}^{-2})}{5{,}000\text{kg}} \\ &= 28\text{ms}^{-2}\end{aligned}$$

When added to acceleration due to gravity of 10ms^{-2} this gives a 4G vertical acceleration as felt by the pilot. This is only an instantaneous value.

For retraction we have

$$\begin{aligned}\text{Acceleration(downwards)} &= \frac{\text{Force} + \text{mg}}{\text{mass}} \\ &= \frac{(2 \times 33{,}360) + 43{,}370 - (5{,}000\text{kg} \times 9.81\text{ms}^{-2})}{5{,}000\text{kg}} \\ &= 32\text{ms}^{-2}\end{aligned}$$

an acceleration value almost identical to that of the extension case. This equates to a negative 2g acceleration being available, once again an instantaneous value.

The 3 DOF motion base simulates longitudinal and lateral translational accelerations with simulator tilt with only vertical acceleration coming from direct motion. Of more relevance then is the speed with which the actuators extend and retract, as this is what determines roll rates of the simulator cab.

6.1.3 Extension and Retraction Speeds

Calculation of actuator extension and retraction speeds utilises equation 6.1 [35].

$$\text{Velocity} = \frac{\text{Flowrate}}{\text{Area}} \qquad 6.1$$

The flow rate from Table 21 is given as a maximum of 10GPM. This equates to 0.00063 $m^3\ s^{-1}$. Results are tabulated in Table 22. The first three entries examine the resultant output when each actuator moves individually, the last two examine the results when all three are moving. When all three actuators move at the same time as is the case for the heave motion, the effective area is the sum of all three actuator areas.

Actuator Combination Under Study	***Linear Velocity (ms^{-1})***
Left, Right & Rear Actuator Extension Speed	0.28
Left & Right Actuator Retraction Speed	0.54
Rear Actuator Retraction Speed	0.41
Combined Extension Speed	0.09
Combined Retraction Speed	0.17
Roll Motion (left & right differential motion)	0.18
Pitch Motion	0.1

Table 22 Extension and Retraction Speeds of Motion Base Actuators.

6.1.4 Flight Simulator Geometry

Figure 110 shows a diagram of the LINK motion base system as installed on the simulator [22]. The geometry of the simulator cab is shown in Figure 111.

From these diagrams and calculated actuator extension rates, simulator cab rotational rates can be determined .

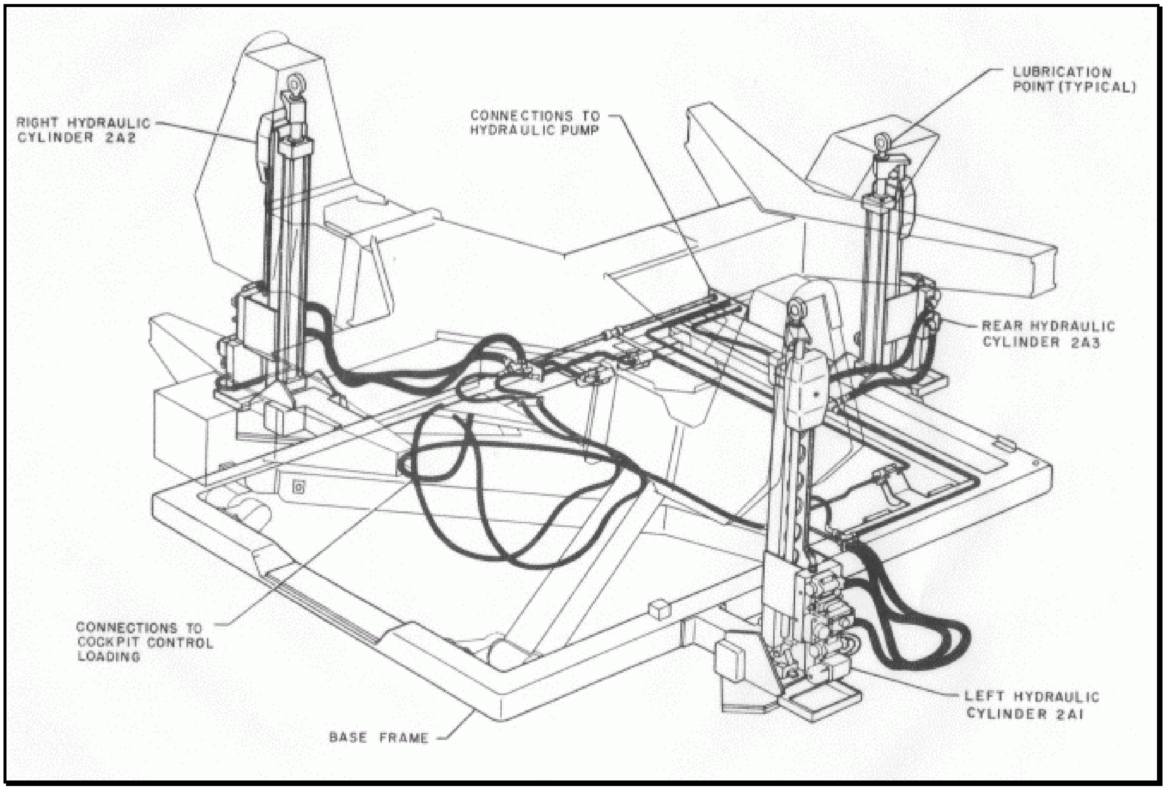
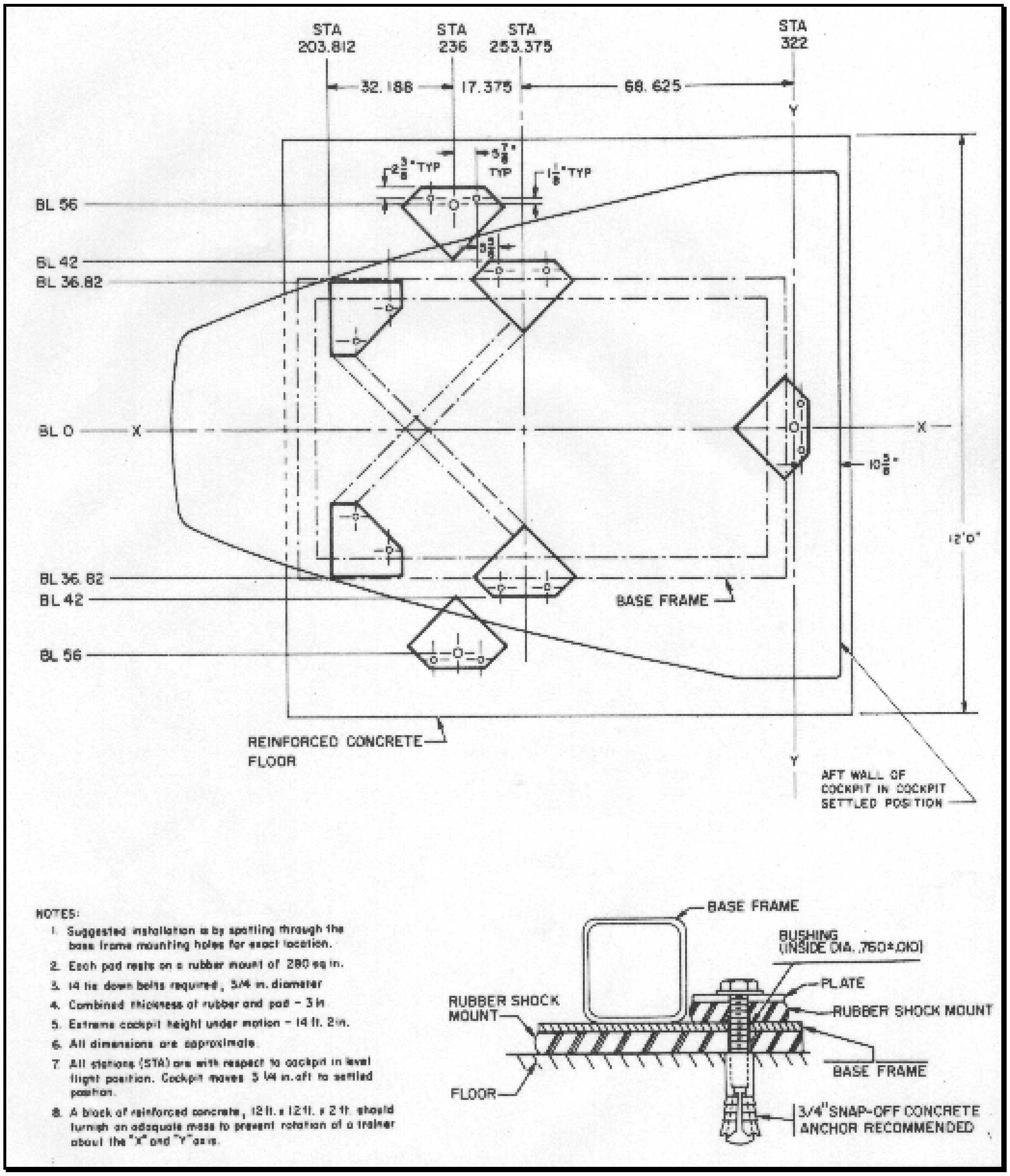


Figure 110 The Link Motion System



NOTES:

1. Suggested installation is by spotting through the base frame mounting holes for exact location.
2. Each pad rests on a rubber mount of 280 sq in.
3. 14 tie down bolts required, 3/4 in. diameter
4. Combined thickness of rubber and pad – 3 in
5. Extreme cockpit height under motion – 14 ft. 2in.
6. All dimensions are approximate.
7. All stations (STA) are with respect to cockpit in level flight position. Cockpit moves 3 1/4 in. aft to settled position.
8. A block of reinforced concrete, 12 ft. x 12 ft. x 2 ft. should furnish an adequate mass to prevent rotation of a trainer about the "X" and "Y" axis.

Figure 111 Link Motion Base Dimensions

The lateral baseline which is the distance between left and right actuators is 112 inches or 2.8 meters.

The Longitudinal Baseline is 86 inches or 2.18 meters.

The maximum actuator stroke is given in table is 0.9m (36 inches) for the forward actuators and 0.65m (26 inches) for the rear. This stroke is reduced by the positioning of the limit switches giving useable values of 0.8m for and 0.6m respectively.

6.1.5 Simulator Maximum Roll Angle & Rate

The maximum roll rate will be achieved by differential motion of the left and right actuators. I.e. for left roll (-ve) we require to extend the right actuator while retracting the left. Whilst both can retract at 0.4ms$^{-1,}$ extension occurs at half that rate. In order to produce only rotational motion, the extension rate of one must be matched with the retraction rate of the other. Otherwise vertical motion will be induced.

Working from a neutral position of 0.4m from bottom and an max extension of 0.4m in either direction, a left roll is shown in Figure 112.

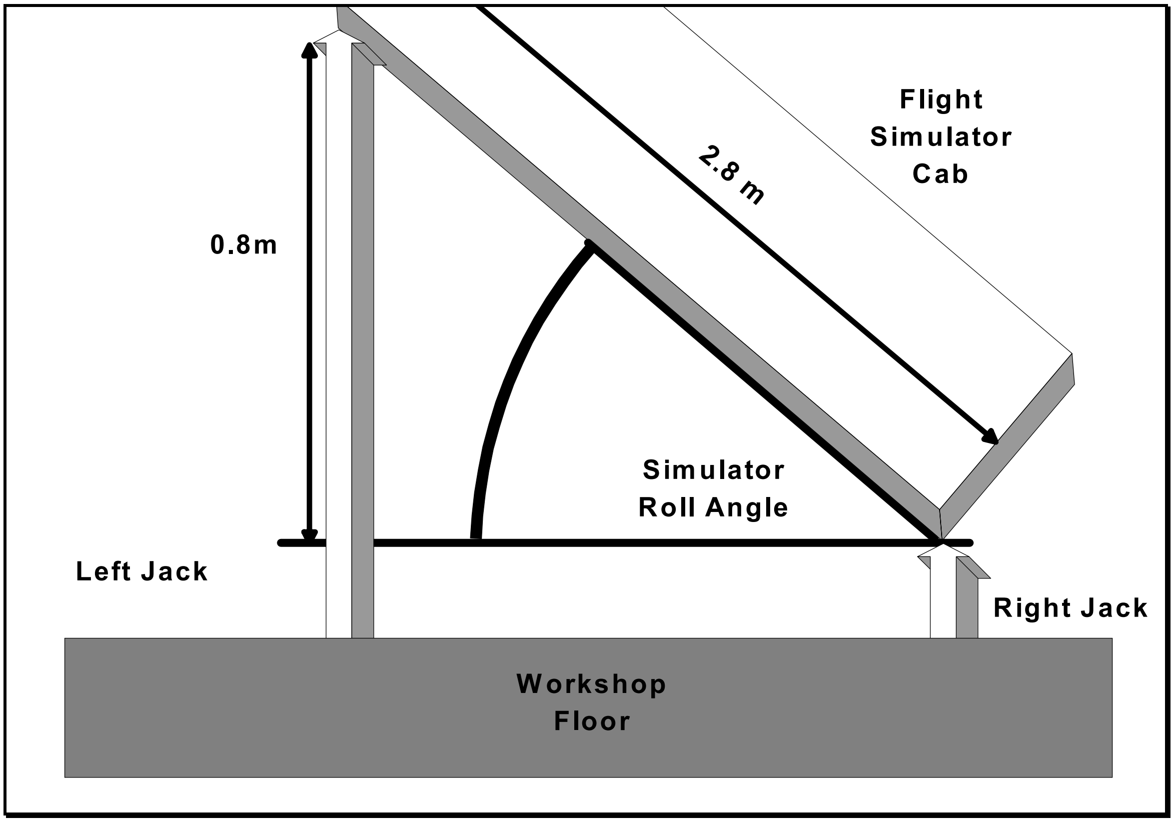


Figure 112 Simulator Cabin Maximum Roll Angle Determination

The roll angle shown here is the maximum achievable angle.

The roll angle is given by:

$$\phi = a\tan\left(\frac{x}{b/2}\right)$$

where

ϕ = roll angle

x = actuator extension

b = baseline

therefore

$$\begin{aligned}\phi_{max} &= \tan^{-1}\left(\frac{0.8}{2.8}\right)\\ &= 16\deg = 0.29\text{rad}\end{aligned}$$

To determine roll rate:

Average[31] Actuator extension speed = 0.18 ms-1

with a formula and value for roll rate p_{max} of

$$\begin{aligned}p_{max} &= a\tan\left(\frac{\dot{x}}{b/2}\right)\\ &= 0.13\text{rad}/\text{s}\end{aligned}$$

---

[31] To achieve roll motion without inducing linear acceleration it is necessary to examine roll using simultaneous opposite direction actuator motion.

6.1.6 Simulator Maximum Pitch Angle & Rate

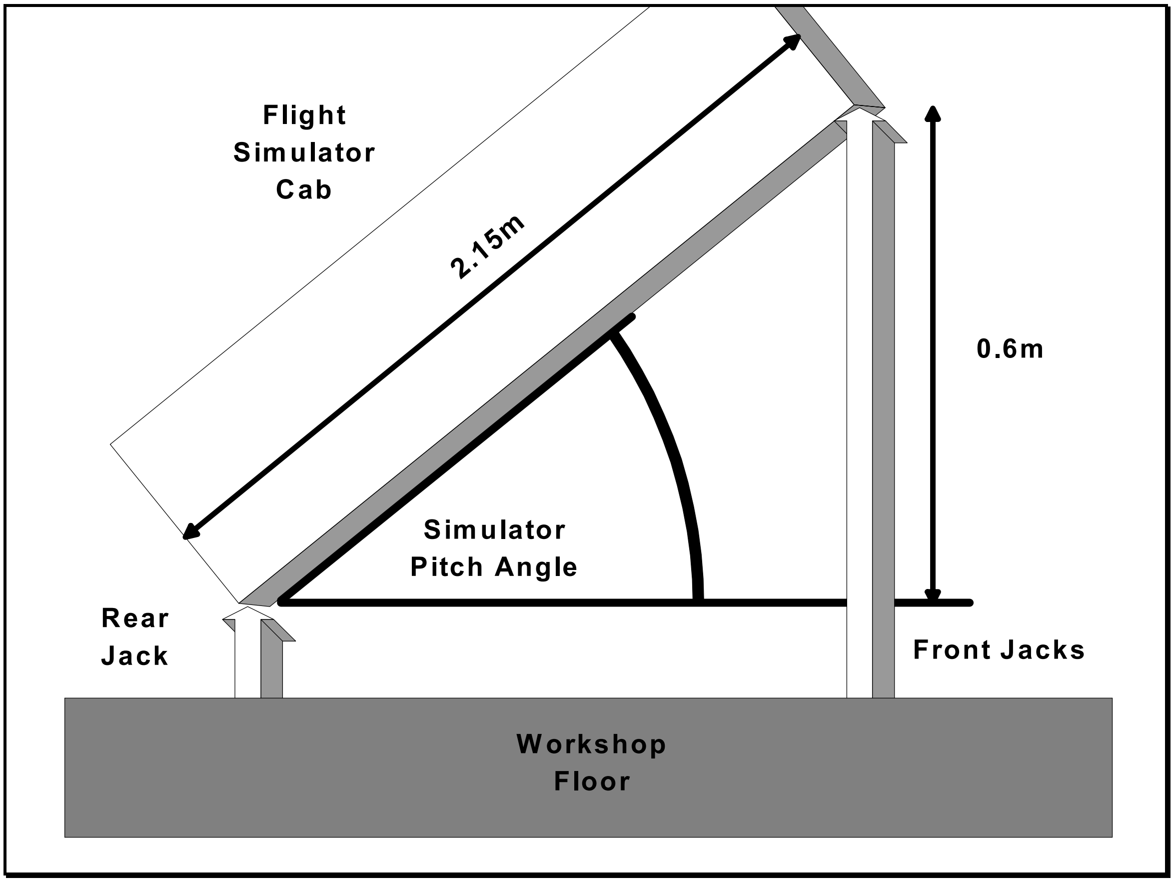


Figure 113 Simulator Maximum Pitch Angle

The maximum pitch angle is given by

$$\theta_{\max} = \tan^{-1}\left(\frac{0.6}{2.15}\right)$$
$$= 0.28\text{rad}$$

For a pure pitch motion about the centroid of the motion base, maximum pitch rate will occur with rear actuator retraction coupled with actuator extension. Assuming now that all actuators are moving at an average rate of 0.1ms^{-1} with a baseline of 2.18m, the following result is obtained:

$$q_{max} = a\tan\left(\frac{\dot{x}}{b/2}\right)$$
$$= 0.09 rad/s$$

6.1.7 Summary of Simulator Motion Capabilities

For the 3 degree of freedom simulator motion base data listed in Table 23.

	Max Rate (rad/s)	Max Angle (rad)	Max Acceleration (Multiples of $9.81ms^{-2}$)	Max Velocity (ms^{-1})	Max Vertical Position (m)
Roll	0.13	0.29	N/A	N/A	N/A
Pitch	0.09	0.28	N/A	N/A	N/A
Heave	N/A	N/A	+4g / -2g	+0.1 / -0.17	+0.3m / -0.3

Table 23 Simulator Motion Capabilities

6.1.8 Pressure Compensation

Reference [34] also details the purpose of the pressure transducer located on each hydraulic actuator.

As originally designed, the simulator was not fitted with the Vital III visual system. The Vital system comprises a sizeable attachment external to the simulator cabin. As it provides the visual picture, it must be rigidly attached to the simulator cab. If it is not, any oscillations produced by the motion system will appear as visual aberrations to the pilot. The location of the attachment, well displaced from the original C of G of the motion base both vertically and longitudinally, as well as the weight of the attachment, caused excessive oscillations in the motion system and reduced dynamic response.

Pressure feedback is used to provide compensation to reduce oscillation and allow increased gain, increasing dynamic response. This may be important in the design of the motion algorithm. Initial designs do not incorporate this compensation. It will only be required if the frequency response of the system is inadequate.

6.2 Motion System Design

6.2.1 Motion Drive Block

This block produces the actuator length commands. Figure 114 shows the set-up of the circuit. The output consists of three commanded actuator lengths for the motion base system, each from 0 to 10 V. The switch allows the operator to use one of two signals as the output, one from the Washout Filter block and one from the Alternate block.

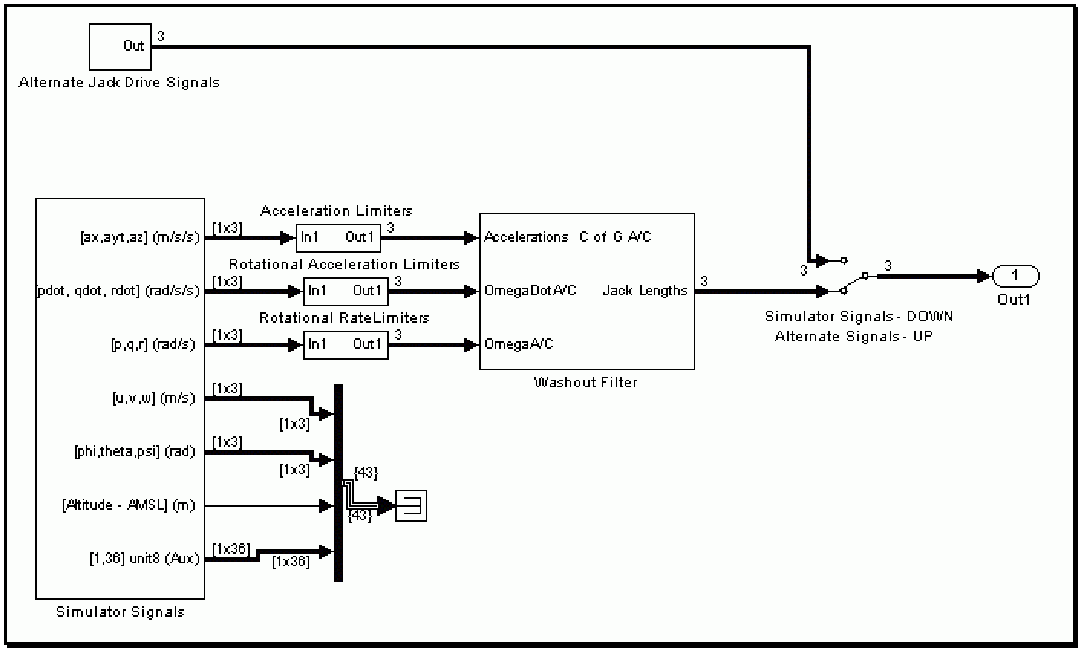


Figure 114 Motion Drive Block

The inputs to the washout filter come from the Flight Model via the Ethernet. The block ‘Simulator Signals’ takes Ethernet packets from the network and extracts data from them. Additonal data can be sent from the flight model simply by altering the construction of the output packet as defined in the flight model. At present:

- ax,ay and az which are the aircraft body axis accelerations [ms^{-2}]

- pdot,qdot and rdot which are the aircraft body axis rotational accelerations [rad/s]
- p,q and r which are the aircraft body axis rotation rates [rad/s]
- u,v and w which are aircraft body axis velocities [ms^{-1}]
- phi, theta and psi which are aircraft Euler angles (roll, pitch and yaw) [rad]
- Dynamic Pressure as required by the control loading system.

Limiters are used on the linear and rotational accelerations as well as the rotational rates. These provide protection from excessive rate/acceleration signals as generated by the flight model, following an aircraft crash and/or flight model abnormal software termination as appropriate. Whilst the washout filter is designed to limit motion base displacement with normal values of rates/accelerations, spurious values may cause a limit to be exceeded, hence the limiters.

6.2.2 Alternate Drive Signals Block

This block provides the second output of actuator lengths and was used extensively during development. It will also be an important maintenance tool as it allows the operator to position the motion base in any position he/she chooses directly.

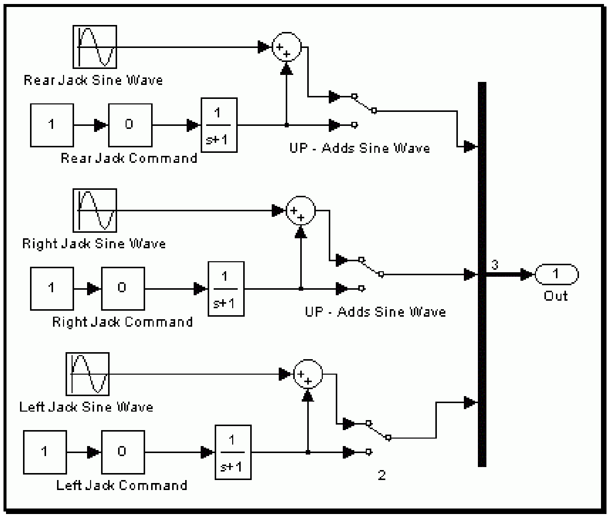


Figure 115 Alternate Drive Signals Block

The circuit Figure 115 has a channel for each actuator. For each channel, the operator can select a straight numerical value, or can use that value added to a sine wave output block which can be adjusted online for frequency and amplitude. The constant (1) enters a slider gain block. This block when opened provides the ability to adjust its output from a minimum value to a maximum value (which can be change online), either by entering that value, or sliding a graphical 'button' along a slide that moves the output form the minimum value to the maximum. The low pass filter on the output provides a smooth signal when the slider is moved. If it is not present, any change in the output is a step input that induces extreme accelerations that may damage the simulator.

6.2.3 Washout Filter / Motion Commands Block

This block produces the washed out motion resulting from the flight model motions. Its content is shown in Figure 116.

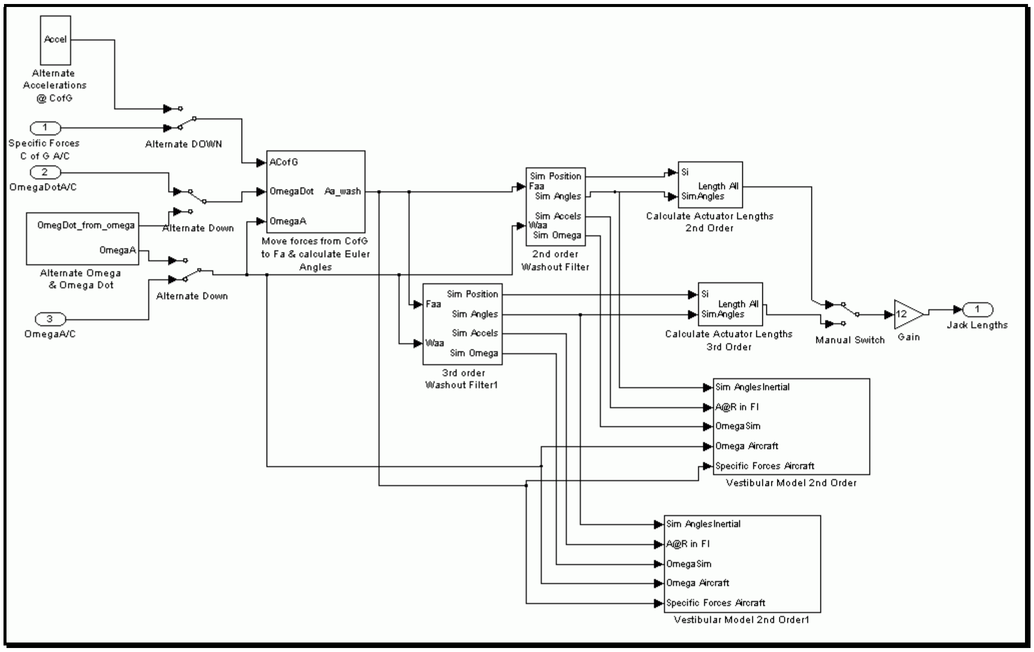


Figure 116 Motion Commands

Inputs on the left are selectable between the actual rates and accelerations calculated in the simulator Flight model or alternate signals used for testing and development. From here the chosen translational acceleration inputs are moved from the C of G of the aircraft to the location that has been chosen for washout calculations, in this case at the pilot’s head. The rotational rates are the same for every part of the vehicle and pass directly into the washout filter. After the inputs have been filtered, the outputs are Simulator position and rotational position both in Inertial axes. These are used by the block ‘Calculate Actuator Lengths’ to calculate the length of the three motion system actuators, at this stage calculated in meters about the neutral position created by the Motion Erect function. The final gain is used to scale the output displacement in meters to volts as required by the Moog servoamplifier system.

6.2.4 Alternate Accelerations @ CofG and Alternate Omega and OmegaDot Blocks

These signals can be used as substitutes to simulator data. Figure 117 shows the translational accelerations, available as constants processed by a variable gain block. This block consists of a slider block that varies the input to the transfer function. It has been used extensively in the development of the both due to the absence initially of the simulator data and as a developer controllable source of data.

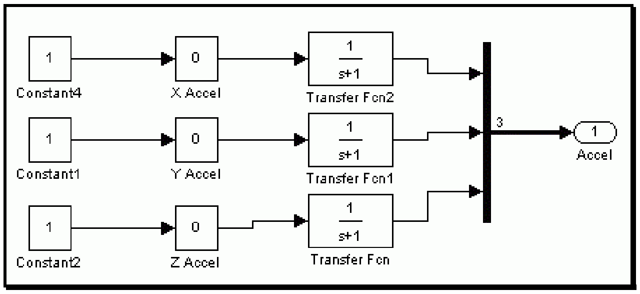


Figure 117 Alternate Accelerations Block

Figure 118 shows the block used to create alternate values of rotational accelerations and rates. The desired rate is created by the Signal Generator, with various outputs available including Sinusoids, Square and Sawtooth functions available. Again the signal is passed through a slider gain that allows quick magnitude adjustment.

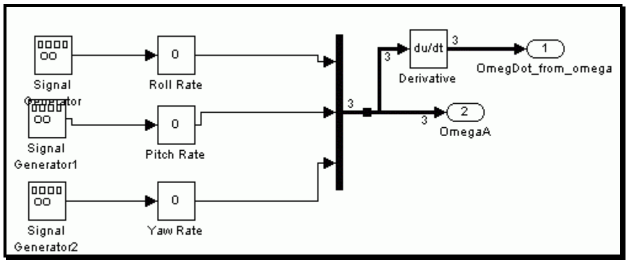


Figure 118 Alternate Rotational Rates

The rates are differentiated to produce values of rotational accelerations, these are required to compute translational accelerations induced by rotational accelerations that occur away from the C of G.

6.2.5 Move Forces from CofG to F_A and calculate Euler angles Block

Translational and rotational accelerations are calculated at the simulator's center of gravity. It is necessary to replicate the components of linear acceleration that occur at points away from the C of G, for instance at the flight deck, that result from rotational accelerations about the C of G. We must therefore determine the motion at the desired location caused by the motion of the aircraft at and around the CofG. As examined in the washout filter section, this location is given by the reference frame F_a. Rotational information is the same for all points of the aircraft and does not require a transformation.

Figure 119 shows this block that transforms rotational accelerations to linear acceleration components at a point

$$\text{Washout Location - } \vec{P} = \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix}$$

relative to the C of G.

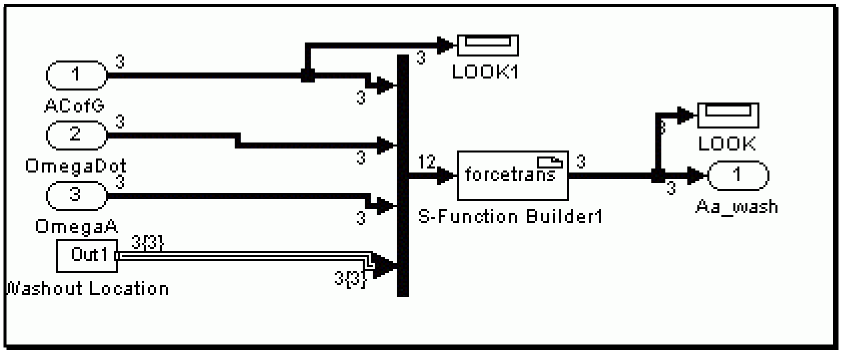


Figure 119 Block used to transfer accelerations from CofG to Washout Location

Washout Location

This block is used to supply the vector from the CofG to the location of the washout (FAA). For example, for a 747, Fa can be given as the Captain's head. An approximation to this position from the CofG is

Px = 20m
Py = -0.5m
Pz = -5m

This indicates that the captain, and the location of the desired washout is 20m forward of the CofG, 0.5 m to the left and 5m above the CofG.

ACofG

This input receives acceleration data from the simulator as determined at its CofG.

OmegaDotA & OmegaA1

These inputs receive the rotational accelerations and rates as determined at the aircraft's CofG:

OmegaDotA = $(\dot{p}, \dot{q}, \dot{r})$

Similarly,

OmegaA1 = (p, q, r)

The data to be used depends upon the inputs to be used. It is therefore possible to output the rates to the filter directly. With a non-constant rate, i.e. an acceleration, OmegaDot is used as the input and integrated to determine the rates for the washout filter. The choice is made by the manual switch.

6.2.6 Forcetrans Block

This s-function has four inputs and one output. It receives translational (linear) accelerations at the CofG, rotational rates and accelerations at the CofG and the aforementioned position vector from the CofG to Fa. It produces translational accelerations at Fa via the following method.

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}_{Fa} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} + \begin{bmatrix} 0 & P_z & -P_y \\ -P_z & 0 & P_x \\ P_y & -P_x & 0 \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix}$$

6.2.7 Calculate Actuator Lengths Block

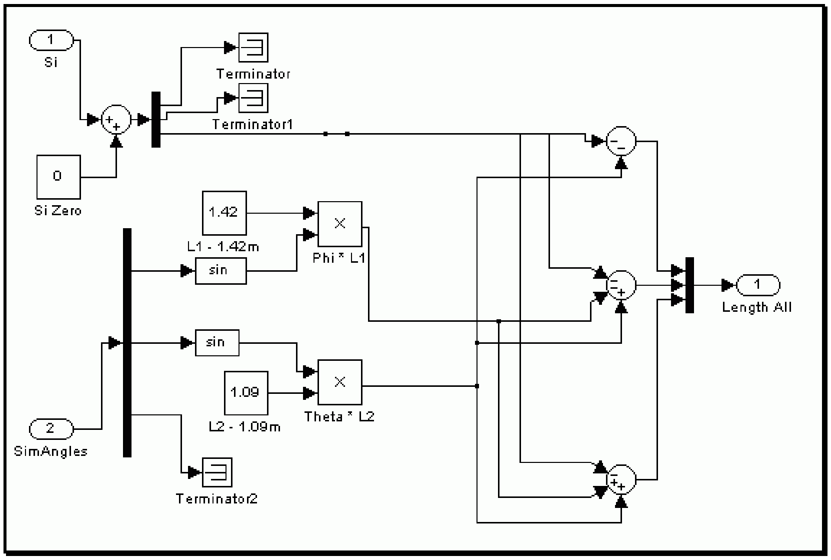


Figure 120 Calculate Actuator Lengths Block

This block has inputs of simulator motion base position “Si” and “Simulator Euler angles”. Si is the simulator position in the inertial frame. There are three motion inputs that require integration. These are:

1. Vertical Position
2. Roll Angle
3. Pitch Angle

The length of each actuator is the sum of inputs from the rotational channels and the translational channel.

Vertical Motion

The data from Si consists of vertical axis motion base movement. Essentially in this axis, all three actuators will extend or retract the same amount in response to a z axis motion. Each actuator has a maximum extension of 0.3m either side of the neutral position. The neutral position itself is 0.3 m above the zero point. The constant term “Si Zero” inserts the neutral position into the system.

Roll and Pitch Angles

Roll motion is caused by differential extension of the left and right actuators. The distance between these actuators is 2.84m. Initially the calculation of roll actuator commands used the arc approximation as shown below:

$$\text{Length} = \text{L1} \times \text{Sin}\phi$$

where

Length = length of Actuator extension
L1 = baseline length (half of the full baseline of 2.84m)
ϕ = roll angle in radians

As the motion does not occur with movement of one actuator, but occurs differentially between the left and right actuators, we divide the motion between the two. In the system , this is done by making the baseline length half of its actual value and feeding the signals with opposite signs to each actuator as shown in Figure 120.

Pitch extensions are calculated in the same way using the baseline of 2.18m

$$\text{Length} = \text{L1} \times \text{Sin}\theta$$

where

Length = length of Actuator extension
L1 = baseline length (half of the full baseline of 2.18m)
θ = roll angle in radians

6.2.8 Washout Filter Blocks

Initial work on the motion system washout filter centred on the publication "Flight Simulation Motion Base Algorithms: Part 1 –Developing and Testing the Equations" by L D Reid and M A Nahon at the UTIAS. In turn, this work builds on earlier work by Schmidt & Conrad [33] and Baarspul [40]. The document outlines the development of three different types of washout filter

1. Classical
2. Optimal Controller
3. Coordinated Adaptive

Classical Washout – A Brief Summary

- Most widely used.
- Linear high and low pass filters. The break frequencies and damping ratios are adjusted off line.
- Tilt coordination used to produce low frequency position accelerations longitudinally and laterally.
- 3rd order filters required for translational high and low pass filters to return platform to neutral
- 2nd or 3rd order for rotational.

The classical method is that used in the majority of commercial flight simulators and will be used.

6.2.8.1 Specific Forces

The total specific force acting on the aircraft is the sum of all non-gravitational forces acting on the aircraft per unit mass. These forces are developed by the aircraft simulation from the sum of Aerodynamic forces, Propulsive forces etc and are those forces sensed by both a linear accelerometer aligned with the aircraft body axes and the human Vestibular system (via the Otolith).

The force equations are listed below for a non-rotating flat earth [41]:

$$X - mg\sin\theta = m(\dot{u} + qw - rv)$$

$$Y + mg\sin\theta\cos\phi = m(\dot{v} + ru - pw)$$

$$Z + mg\cos\theta\cos\phi = m(\dot{w} + pv - qu)$$

The following equations outline the required data:

$$\frac{X}{m} = g\sin\theta + \dot{u} + qw - rv$$

$$\frac{Y}{m} = -mg\sin\theta\cos\phi + \dot{v} + ru - pw$$

$$\frac{Z}{m} = -mg\cos\theta\cos\phi + \dot{w} + pv - qu$$

6.2.8.2 Angular Motion

Reference [42] Examines the functions of the semi-circular canals of the human ear, that is that part of the body that senses rotational motion:

"...their function is more analogous to that of rate gyroscopes. For most of the frequencies involved in normal daily activity, the semi-circular canals adequately signal the angular velocity of the head about any axis." [42]

However, the report then explains that below 0.1 Hz (0.63rad/s) the system more closely indicates measurement of angular acceleration. This frequency is well in excess of the motion system's maximum angular rate of 0.4rad/s and suggests that our system should use angular acceleration rather than rate as inputs to the washout filter as shown below (in body axes):

$$\dot{\omega} = [\dot{p}, \dot{q}, \dot{r}]^T$$

This is supported by Baarspul in [40].

Reid and Nahon ulitilise values of Angular rate as shown below in their rotational channels:

$$\omega = [p, q, r]^T$$

This is first suggested by Schmidt & Conrad [33]. They do so for the following reason:

"Although rotational acceleration is sensed by the pilot we can also consider rotational rate as an equally valid quantity in mathematical development. That is, if rotational rates are the same in the motion generator as they were in an aircraft then the rotational accelerations would also be the same"[33]

The purpose of the rotational channel is the reproduction of high frequency angular accelerations. Long term rate sensing is provided by the visual system. If it is possible to reproduce correct angular accelerations in the motion system the angular rate associated with the input angular accelerations can be used. Analysis of the motion system's output accelerations can then be compared to those of the simulated aircraft.

6.2.8.3 Reference Frame Locations

Reference frames are defined in [26] for both the simulator and the aircraft .

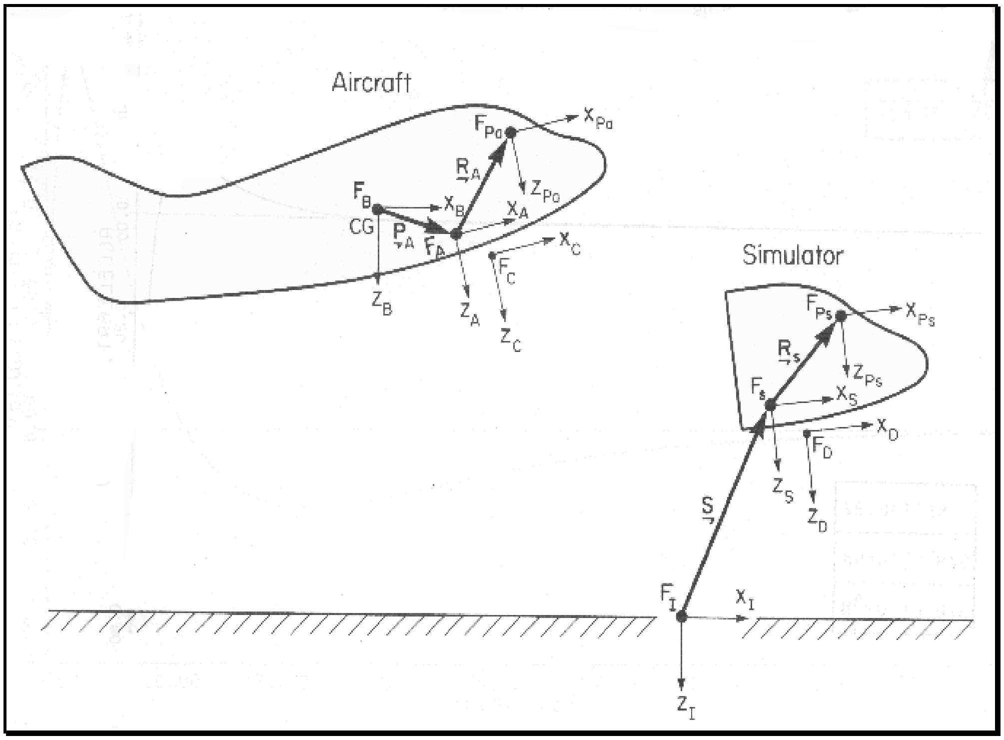


Figure 121 Flight Simulator Reference Frames (Reproduced from [26])

Frame F_D	Origin at the centroid of the Motion Base's upper frame actuator attachment points. The x-y plane is parallel to the simulator motion cab with the z-axis pointing downwards.
Frame F_C	Located in the same relative position as F_D but in the aircraft.
Frame F_S	F_S is attached to the simulator frame and is parallel to F_D. It is selected as required for the motion algorithm under study.
Frame F_A	F_A is analogous to F_S but once again in the aircraft, it is also parallel to F_C.
Frame F_{PS}	This frame is attached to the Captains head. Its' exact origin is midway

	between his left and right vestibular systems. We will assume that F_{PS} is parallel to F_D with the Z-axis down the Captains spine.
Frame F_{PA}	Analogous to F_{PS} but once again located in the aircraft. It is parallel to F_C.
Frame F_B	Located at the aircraft's center of gravity as a conventional Body Axis frame
Frame F_I	Inertial frame with z-axis aligned with the gravity vector.

Table 24 Reference Frame Location

The specific forces and angular velocities are derived from the flight simulation, generated at the CofG of the simulated aircraft. These values must be transformed to the origin of the appropriate reference Frame for the filter to begin its calculations. Initially they are transformed to an F_A Frame location corresponding to the centroid of the motion base. From here, the values are transformed to the chosen location for F_S.

Once correct forces and velocities have been calculated, the washout process commences at F_S . After the washout has been completed, output are sim cab acceleration, sim cab position, sim Euler angles, sim rotational rates and accelerations (aSI, SI, BetaS, WSS, and WdotSS.)

6.2.8.4 Choosing the Location for F_S

Several choices of location for F_S are available when designing the filter. The choice of F_S is an important one as it impacts on several areas [26]. These include;

1. Actuator extension
2. Correctness of Motion Cues
3. Ability of filter to wash out all motion in the long term.

4. Where exactly in the simulator cab we want the sensed forces and velocities to be sensed by the occupants.

1. Centroid of the Simulator Cab frame (i.e. $F_S = F_D$)

Using $F_S = F_D$ minimises actuator extension [29]. The center of rotation in this instance is the centroid of the actuator attachment points and so reduces their extension when creating rotations about this location.

This is obviously important for any flight simulator motion base using a Stewart platform[32]. In our case, using a Heave-Pitch-Roll (HPR) platform , the range of movement of the motion platform is even more limited and so minimising actuator extension becomes even more important. This is the usual convention used in many commercial flight simulators.

2. Center of Gravity of the Simulator Cab Frame

Having F_S at the CofG of the simulator minimises dynamic actuation forces as off center rotations are not generated. The analysis carried out of the motion system's dynamics indicates that for the simulation this is less limiting than the minimisation of actuator extensions.

3. Pilot's Head (F_S coincident with F_{PS})

Having F_S coincident with F_{PS}, the desired result of creating our desired forces and rotations at the pilot's head is created. This is of course one of the main aims of a washout filter. However, this configuration does create larger peak actuator extensions than using the $F_S = F_D$.

---

[32] **A 'Stewart Platform' refers to a conventional modern six degree of freedom motion base.**

In this case, there will be several students in the cab at one time, only two can be in the pilot seats, with others seated behind. It may be possible to extend this case by moving the washout location to a position approximating the centroid of the student's heads.

In order to achieve our previously stated aim of producing acceptable motion cues for several students located in the simulator cab, the washout location can be altered to be the centroid of the students head positions. From the simulator seating layout, it can be seen that this approximates a position above the simulator motion base centroid. However, in the initial stages of development, scheme 1 was chosen so as to allow maximum sim cab motion about the centroid of the motion base.

6.2.8.5 Filtering in F_I or F_S

A decision must also be made as to where to actually carry out the high pass filtering associated with the washout process. Appendix C of Reference [26] provides a detailed analysis. In summary, the logical points at which to high pass filter the motion are either in the inertial frame or simulator cab frame.

If the washout process is carried out only in the inertial frame F_I, cross-coupling of forces can occur. This leads to incorrect motion cues being generated for the pilot.

If the washout is carried out in the simulator cab frame F_S only, the result can be an inability of the washout filter to return the simulator cab to a neutral position. In other words, actuator offsets can develop over time.

It is also possible to filter part of the signal in the F_I frames with the rest filtered in the F_S frame, as is done in some commercial simulators. Doing so provides the individual benefits of each frame whilst restricting the motion system to its limits.

As the designer is concerned with what is sensed in the simulator cab frame and it is undesirable to generate incorrect motion cues, it seems logical to filter in F_S. However, the generation of low frequency offsets in the motion base actuators is very undesirable for long term simulation.

By Filtering in F_I this problem is removed, but as noted there is the possiblity of generating incorrect motion cues for the pilot.

In a simulator used for pilot training, the simulator must be required to run properly (i.e. without running out of actuator extension) for periods of up to several hours. In this case it is unacceptable to filter only in F_S. Doing so will eventually lead to the actuators becoming saturated at an extremity, destroying the motion simulation. However, the purpose of our simulation is the demonstration of motion phenomena to students in a simulator. Here there is no real requirement for long term simulation in many cases. In this instance it may be very acceptable to filter only in F_S. However, it is more important to ensure that the motion system is fully constrained. As such the filtering in this system is carried out in the Inertial (F_I) frame only although the system provides the capability to filter in both or a combination of the two.

6.2.8.6 Filter Design

The design of the filter is taken from a design developed by the University of Toronto Institute for Aerospace Studies [26]. The reader is referred to this reference for an in depth treatment of the development of the various channels and signal paths. Two washout filters have been implemented. The block ‘2nd order washout filter’ has a second order filter in its rotational channel whilst the corresponding filter in ‘3rd order washout filter’ is a third order filter. A manual switch provides the capability to select either output. Inputs to the filter are specific forces and angular velocities. These accelerations and velocities are computed at the applicable location in the F_S frame from the values derived at the CofG of the simulated aircraft.

The complete washout filter is shown in Figure 122

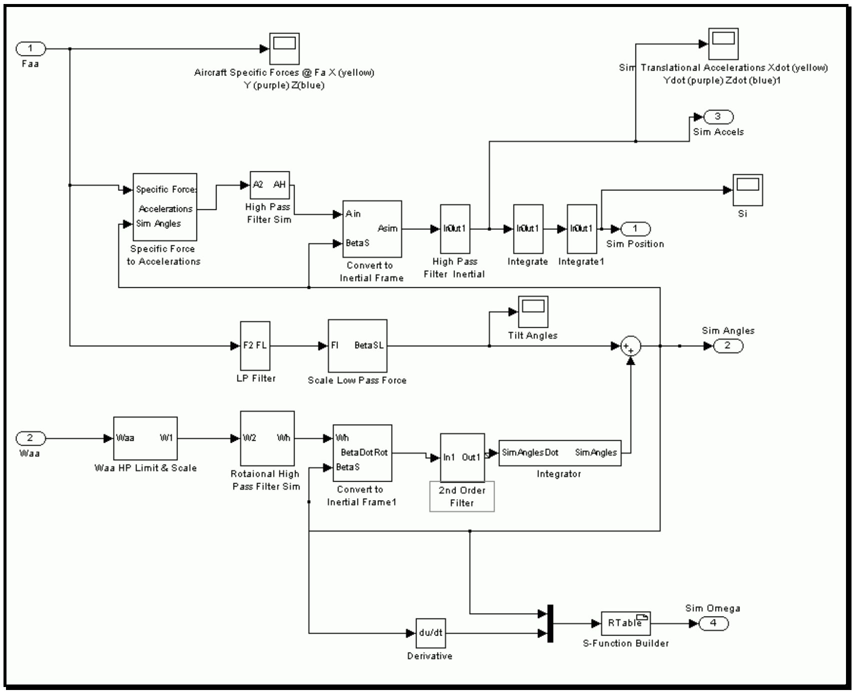


Figure 122 Washout Filter Structure

The system comprises three channels. As this part of the software has been adapted from a design developed by the University of Toronto Institute for Aerospace Studies, the reader is referred to [26] for an in depth analysis of the operation of each channel. A brief summary of this work follows:

Translational Channel (high pass filtered)

This channel takes inputs of translational accelerations and conducts the following operations to produce the simulator cabin's translational position. The inputs are first converted to accelerations (from specific forces (section 6.2.8.1)) that the motion base will experience by the block 'Specific Forces to Accelerations' . These can be high pass filtered in the simulator frame or can be passed through to be converted straight to an inertial frame. After this conversion, the accelerations can again be filtered, this time in the inertial frame before a double integration to produce a value of simulator position in the inertial frame.

The filtering creates washout which in turn restricts the motion base movement. A linear acceleration causes the system to move in the same sense as the aircraft would. However, to prevent the system saturating at its limits this motion must be stopped and eventually reversed to bring the cabin back to its neutral position. High pass filtering is used to accomplish this and it must be done without the occupants knowledge. This means that the deceleration of the motion cue must be at a sufficiently low value so as not to be perceived by the pilot or induce motion sickness through his proprioceptive system. Filtering is conducted in only the inertial frame to ensure the simulator motion is adequately restrained.

Translational Channel (low pass filtered)

The first channel reproduces only the high frequency components of aircraft translational accelerations in order to limit the motion of the simulator cabin. We can reproduce the low frequency components by ‘borrowing’ a small component of the gravity vector. By tilting the cabin in response to an acceleration input, the gravity vector is no longer aligned with the vertical, as the occupant is not aware of this tilt (the visuals do not reflect it, and it occurs at a rate below the detection threshold), he or she perceives this tilt as an acceleration.

This is most readily seen from the outside of a simulator taking off. The initial acceleration is reproduced by a linear forward translation, as this motion washes out, the simulator cabin tilts backwards and remains there during the acceleration. To the pilot this is sensed as a continuous acceleration down the runway.

Rotational Channel (high pass filtered)

The rotational rates are processed in a similar manner to the translational accelerations. They can be filtered in either the simulator frame or the inertial frame or both, again this system will filter in only the inertial frame. The output is fed to the translational channel to be used in the calculation of the simulator gravity vector for addition to the specific force to calculate system accelerations as well as in the conversion from simulator to inertial frames. The output are values of simulator roll and pitch angles (in inertial frames) for use in the calculation of actuator lengths.

6.3 Motion Performance

6.3.1 System Frequency Response

Sinusoidal inputs are used to test system frequency response. Chapter two mentions the following frequency response requirements [12]:

13.4.4.3 The system shall possess a linear frequency response to a sine wave input with a tolerance of +1 dB amplitude performance up to a corner frequency of 3 Hz where it may be no more than 3 dB down.

When testing the system at 3 rad/s (0.5Hz) with the 1V input results in the system being incapable of tracking the command as a result of the HPU's inability to pump oil into the system fast enough. This is characterized by increasing noise from the actuators as the fluid flow reaches its maximum value. Better frequency response is obtained at a lower input frequency.

Rear Actuator Only Testing

The system lacks sufficient fluid flow at frequencies above 3 rad/s when the amplitude is greater than 0.5V (1Vpeak to peak) while testing all three actuators in a simulation of heave motion (all three actuators with the same input). To extend the range of frequencies analysed, one actuator was excited at a time.

Table 25 contains the results:

Frequency (rad/s)	Input Amplitude (V)	Right dB	Right Phase (rad)	Left dB	Left Phase (rad)	Rear dB	Rear Phase (rad)
3	0.2	-0.46	-0.57	-0.99	-0.64	-0.57	-0.54
6	0.2	-2.80	-1.12	-2.73	-1.07	-2.54	-1.05
9	0.2	-5.93	-1.51	-6.16	-1.51	-4.99	-1.47
12	0.2	-8.17	-1.77	-8.38	-1.78	-7.22	-1.71
15	0.2	-9.02	-1.90	-8.78	-1.92	-8.71	-1.86
18	0.2	-10.86	-2.08	-10.17	-2.10	-10.46	-2.01
21	0.1	-12.22	-2.30	-9.99	-2.29	-13.07	-2.29
3	0.5	-0.51	-0.57	-0.67	-0.54	-0.54	-0.52
3	1	N/A	N/A	N/A	N/A	-0.41	-0.34
3	1.5	N/A	N/A	N/A	N/A	-0.53	-0.50
3	2	N/A	N/A	N/A	N/A	-1.15	-0.63
6	1	N/A	N/A	N/A	N/A	-3.63	-0.95

Table 25 Motion System Frequency Response

Matlab produces a Bode Plot of these results for all three actuators operating shown in Figure 123

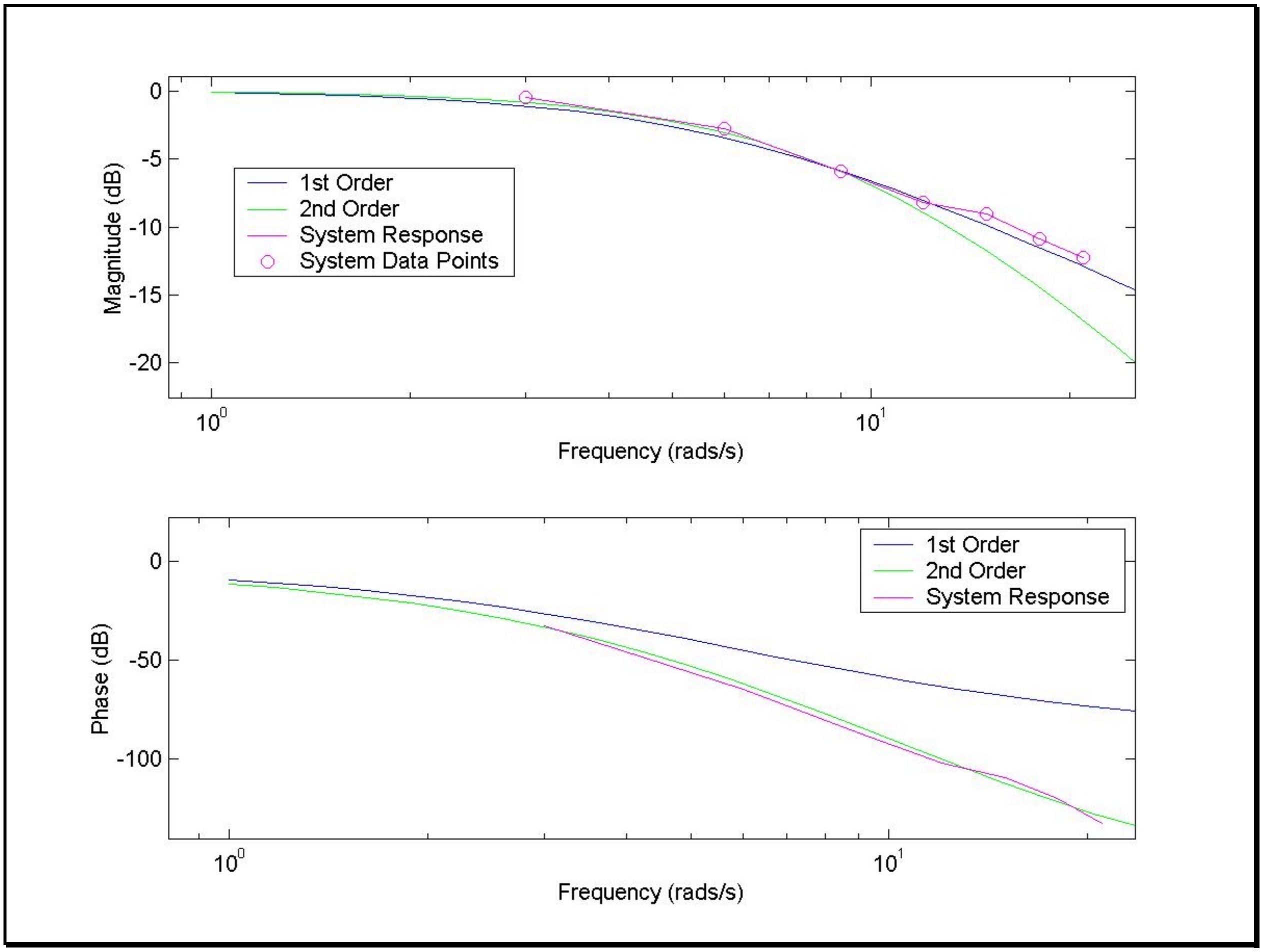


Figure 123 Right Actuator Bode Response

From the chart the 3dB point occurs at a frequency of 6.1 rad/s which corresponds to 0.97 Hz. This is approximately one third of that required by the statement above. Also plotted are ideal low pass 1st and 2nd order responses with a 6.1 rad/s corner frequency. From this it is apparent that the system is representative of a 2nd order system.

6.3.2 Determination of Maximum Flow rate from System Response

At an input of 3 rad/s and amplitude of 1V with all three actuators in motion, the system was noticed to run out of oil pressure after a short period (10secs). This suggests that this inputs exceeds the system's ability to provide enough hydraulic oil. Flow rate is related to system speed and piston area by the following equation

$$\mathrm{FlowRate}(V) = \mathrm{Speed} * \mathrm{Area}$$

The units of Speed are Vs^{-1} and for Area are m^2.

Flow rate is given in m^3s^{-1}, therefore a conversion factor of K mV^{-1} is required to convert Speed*Area to Flow rate.

Therefore   Flow rate = K*Area*Speed

To calculate K we need to determine how many cubic metres of fluid are required to move the system by 1V.

A movement of 1V corresponds to a movement[33] of 0.08m. This results in a conversion factor of

$K = 0.08mV^{-1}$

The input signal is of the form

$$\dot{P} = A\omega\cos\omega t$$

---

[33] **The full 10V range is equal to a displacement of 0.8m**

where $\dot{P}$ is the derivative of the Position and is therefore the velocity.

The areas of the three pistons combined are at their maximum during extension when the combined area is 14.7in ^{2} or 0.0091m^2

This results in

Flow Rate $= 0.08\ mV^{-1} * 0.0091m^2 * A\ \sin\omega t *$
$= 0.000728 * A\ \omega\sin\omega t\ m^3s^{-1}$

As the input is a sinusoid, this is an instantaneous value of flow rate. To determine the Fluid flow over a period of one minute, the absolute value of the Flow Rate[34] is integrated to give the amount of fluid that flows in a minute. For each case, the value of A is the output amplitude as this determines how hard the system was actually working during the test. The value of ω is the output frequency which is the same as the input frequency.

This is achieved by using

$$\mathrm{FluidFlow}\left[m^3\ \min^{-1}\right] = \frac{60\omega}{2\pi} * 0.08 * 0.0091 * A\omega * 2 * \int_0^{\pi/\omega} \cos\omega t dt$$
$$= 0.028 * A * \omega[m^3\ \min^{-1}]$$

For the simulator's limiting case of 3 radians per second with 1 volt amplitude, this give a Flow Rate of 0.084m^3/minute, equal to 84 litres per minute or 20 Gallons per Minute. The Simulator Maintenance Manual lists the HPU output as 10 Gallons per Minute or 0.04m^{3}min^{-1}. Every other flow rate Table 26 for all three actuators

---

[34] We are interested in the total magnitude of the fluid flow which flows in both directions, giving a net flow of zero at any chosen point. Therefore we must integrate the absolute value of the sinusoid.

operating is less than this figure. This suggests that the figure of 10 GPM was used by the manufacturer as the operating system flow as it is achievable in many cases.

Frequency (rad/s)	Input Amplitude (V)	Right Output (V)	Right Flow m^3min^{-1}	Left Output (V)	Left Flow m^3min^{-1}	Rear Output (V)	Rear Flow m^3min^{-1}
3	0.2	0.189	0.016	0.178	0.015	0.187	0.016
6	0.2	0.145	0.024	0.146	0.025	0.149	0.025
9	0.2	0.101	0.025	0.098	0.025	0.113	0.028
12	0.2	0.078	0.026	0.076	0.026	0.087	0.029
15	0.2	0.071	0.030	0.073	0.031	0.073	0.031
18	0.2	0.057	0.029	0.062	0.031	0.060	0.030
21	0.1	0.024	0.014	0.032	0.019	0.022	0.013
3	0.5	0.471	0.040	0.463	0.039	0.469	0.039
3	1					0.95	0.080
3	1.5					1.41	0.118
3	2					1.75	0.147
6	1					0.66	0.111

Table 26 System Flow Rates

6.3.3 System Performance Maxima (Translational)

The input position signal is given as

$$P = A\sin\omega t$$

where P is the position command.

This gives corresponding forms of velocity and acceleration as[35]

$$\dot{P} = A\omega\cos\omega t[Vs^{-1}]$$
$$\ddot{P} = -A\omega^2\sin\omega t[Vs^{-2}]$$

---

[35] In the following analysis, the units are in volts as this is the signal derived by the motion software. The full range of 10V corresponds to full deflection of the actuator and is more representative of performance.

The value of Aω is the maximum system velocity which occurs at the mid point of the actuator extension.

The value of Aω^2 is similarly the maximum value of system acceleration which occurs at the actuator‘s maximum extension for the applicable input.

These outputs are shown in Table 27

Frequency	***Number of Actuators Operating***	***Input Signal***	***System Response (dB)***	$\dot{P}_{max}$ ***Vs-1***	$\ddot{P}_{max}$ ***Vs-2***
3	3	0.2	-0.57	0.56	1.68
6	3	0.2	-2.54	0.89	5.36
9	3	0.2	-4.99	1.02	9.15
12	3	0.2	-7.23	1.04	12.53
15	3	0.2	-8.72	1.1	16.43
18	3	0.2	-10.46	1.08	19.44
21	3	0.1	-13.08	0.46	9.70
3	1	0.5	-0.55	1.41	4.22
3	1	1	-0.41	2.85	8.55
3	1	1.5	-0.53	4.23	12.69
3	1	2	-1.15	5.25	15.75
6	1	1	-3.64	3.96	23.76

Table 27 System Maximum Accelerations and Velocities (P is position)

6.3.3.1 Maximum Actuator Velocity

With three actuators operating at the –3dB point at approximately 6 rad/s, a maximum velocity of 0.89Vs^{-1} occurs.

A maximum velocity of 1.1Vs^{-1} occurs at 15 rad/s with a 0.2V input. Figure 124 shows that the maximum speed of the system with three actuators operating is in the range of 1 to 1.1 Vs^{-1} from approximately 8 rad/s up to 18rad/s with a 0.2V input signal. The system response in this region varies from –5db to –13dB. This maximum velocity equates to 0.06ms^{-1} for the rear actuator and 0.08ms^{-1} for the front actuators based upon strokes of 0.6m and 0.8m respectively.

Section 6.1.3 tables the theoretical corresponding values of 0.09 for extension and 0.17 for retraction. These figures suggest that the system is operating in the vicinity of its velocity limits in these tests.

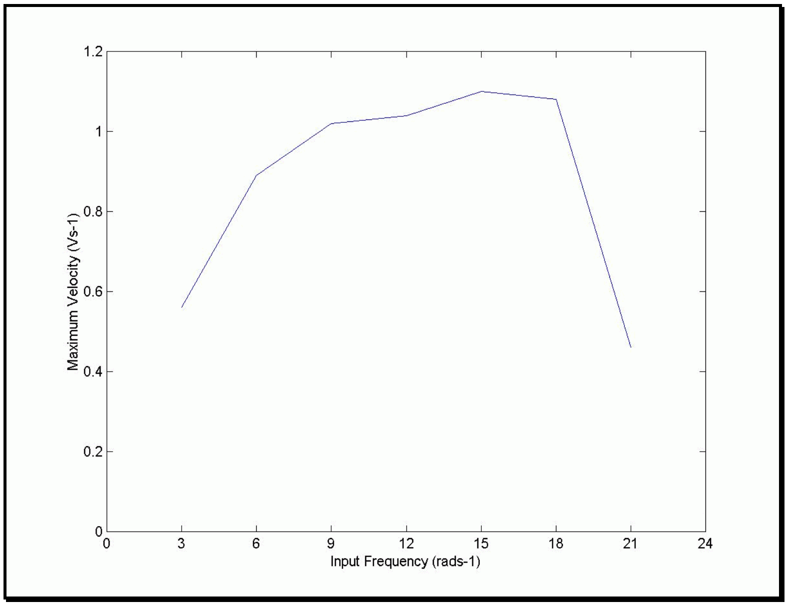


Figure 124 Maximum System Velocity – 3 Actuators Operating

6.3.3.2 Maximum Acceleration

The system acceleration is shown in Figure 125 The maximum value displayed is approximately 20ms^{-2} with all three actuators operating. The theoretical values of 28ms^{-2} and 32ms^{-2} suggest that there is more acceleration capability available to the system.

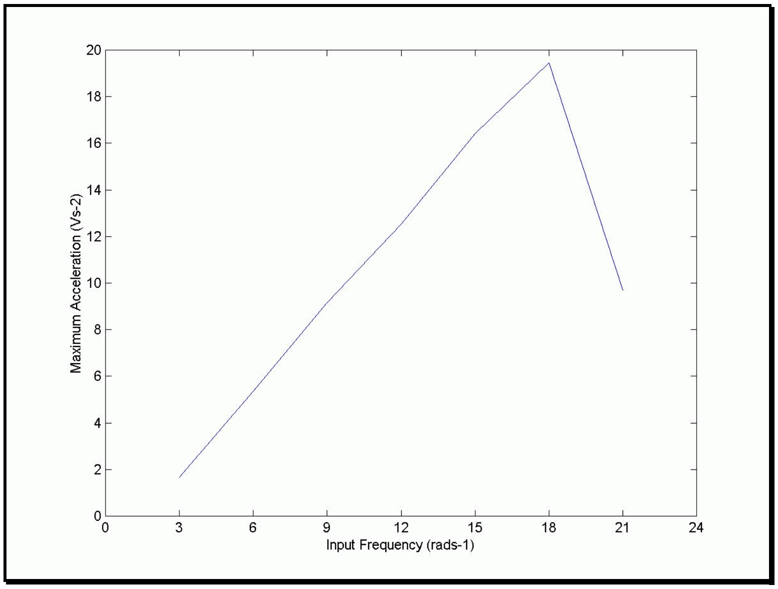


Figure 125 Maximum System Acceleration – 3 actuators operating

6.3.3.4 Comparison of Theoretical and Measured System Performance Maxima

Table 28 outlines a comparison of the measured system performance maxima as determined in Section 6.3 against those predicted in Section 6.1.3. From this table it is evident that the system is not yet running at full output. However, the motion cues generated have been subjectively assessed as being useful for simulation.

	Theoretical	Measured
Velocity – Forward	0.17 ms^{-1}	0.08 ms^{-1}
Velocity – Rear	0.09ms^{-1}	0.06 ms^{-1}
Acceleration	28 & 32 ms^{-2}	20ms^{-2}

Table 28 Comparison of Theoretical and Measured System Performance maxima

6.4 Determination of Filter Coefficients

The general layout of the system has been outlined previously. One translational and two rotational channels require filtering. What remains is to determine coefficients for the high pass filters in the washout filter. For an aircraft specific project, this would involve selecting parameters that produce the correct motion cues for a particular aircraft. In this case, of more interest is the maximum performance available from the motion system so that the limits are known, within which parameters can be set to match the dynamic characteristics of the aircraft under study. e.g. an F16 fighter aircraft will require higher filter frequencies that a Boeing 747 so that the higher rates wash away faster to keep motion within limits.

It is possible to input aircraft body axis accelerations in the z axis as well as pitch and roll rates to the filter system and examine the output produced by the filter. This is done to determine what filter coefficients are required to control the motion base within its limitations. This section analyses 2nd and 3rd order high pass filters. By changing various parameters in the filters, it is possible to determine the resultant effect this will have in the motion system.

The system can produce motions up to its maximum physical limits, as determined in Section 6.3.3, in position, rate and acceleration. This means that it is desired to attenuate the motion signals only as much as necessary so as to prevent the system reaching a limit. By experimenting with various sets of filter coefficients, the resultant output signals can be examined to determine whether or not each filter set sufficiently restricts simulator motion. Firstly, an analysis of a 2nd order high pass filter as used by the rotational channel. This is followed by a similar analysis of a 3rd order high pass filter as used in the z axis ‘Heave’ channel. The effects of two coefficients will be examined, filter gain and cut-off frequency, to determine their effects on filter output.

The following work is found in [26] and is included here for a more thorough understanding of the use of high pass filters in a flight simulator washout filter.

6.4.1 Rotational Channel High Pass Filter

The Transfer Function for a high pass filter takes the following general form[36]:

$$\mathrm{TF} = \mathrm{T(s)} = \frac{\overline{\alpha}_o}{\overline{\alpha}_i} = \frac{s^n \mathrm{Num(s)}}{\mathrm{Den(s)}}$$

where

Num(s) is of order l
Den(s) is of order m

α_o is the filtered angular output

α_i is the input angle rate

For any transfer function,

$m \geq l + n$

Additionally, for a high-pass transfer function

$n \geq 1$

The worst case for this channel is a constant angular rate ($\dot{\alpha}_i$)

---

[36] **$\overline{R}$ indicates the Laplace transform of the applicable signal.**

$$\dot{\alpha}_i = \text{const.} = \kappa$$

$$\overline{\alpha_i} = \frac{\kappa}{s}$$

The output of the filter is therefore

$$\begin{aligned}\overline{\alpha_o} &= \overline{a_i} \times \frac{s^n \text{Num}(s)}{\text{Den}(s)} = \frac{\kappa}{s} \times \frac{s^n \text{Num}(s)}{\text{Den}(s)} \\ &= \kappa \times s^{n-1} \frac{\text{Num}(s)}{\text{Den}(s)}\end{aligned}$$

The Final Value Theorem determines the steady state response.

$$\begin{aligned}\lim_{t \to \infty} \alpha(t) &= \lim_{s \to 0} s\overline{\alpha_o} \\ &= \lim_{s \to 0} \kappa \times s^{n-1} \frac{\text{Num}(s)}{\text{Den}(s)}\end{aligned}$$

If the desired steady state output is zero, it is necessary that

$$n \geq 2$$

A second order high pass filter should be capable of washing out the angular displacements and so return the motion system to a neutral position as desired. This means that even if a worst case input of a constant angular rate is applied, the channel output will not exceed the maximum allowable angular position, and will also washout, or return to a zero steady state angular position.

The following basic transfer function will be used to illustrate this point

$$TF = \frac{Ks^2}{s^2 + 2\zeta\omega_n s + w_n{}^2} \tag{6.1}$$

where

K = Gain

ζ = Damping Ratio

ω_n = Corner Frequency

Bode Analysis of a 2nd Order High Pass Filter

Using the transfer function described above, The response shown in Figure 126 is obtained

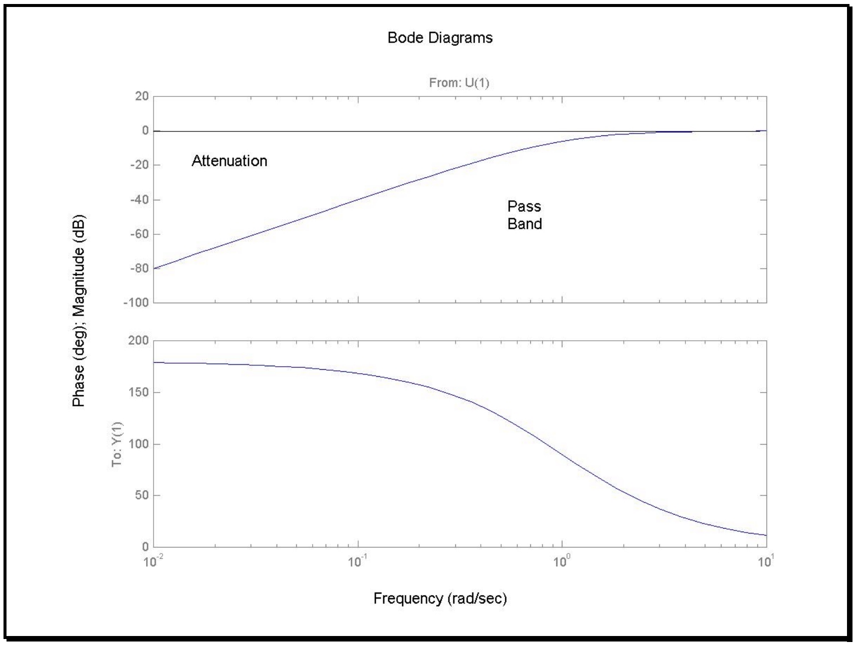


Figure 126 Bode plot of Eq 6.1 with $\zeta = 1$, $K = 1$, $\omega_n = 1$rad/s

There are two areas of importance in the above figure, the Pass Band and the Attenuation area.

The Pass Band gain is as expected 0 db meaning there will be no attenuation of the signal. This means that any component of the signal with frequencies above the corner frequency (here 1 rad/s) will pass through the filter without change (except for minor phase alteration near the cut-off frequency).

In the attenuation region however, there is an increasing attenuation as the input frequency decreases from the corner frequency. Such a response is known as a high pass response, as it allows higher frequency signals without attenuation, while attenuating low frequency signals.

This high pass response can be displayed by running the following Simulink™ model

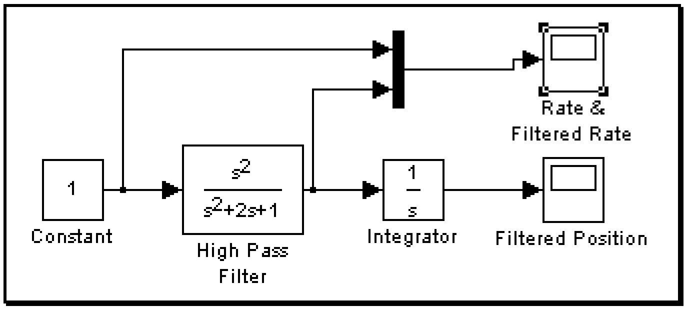


Figure 127 High Pass Filter

The constant input here represents a constant angular rate input. Without the filter, the output of the integrator from such a signal will increase linearly with gradient of 1. For an aircraft subject to a constant angular rate (i.e. constant roll rate), this is evident as an increasing pitch, roll or yaw angle. However, as we have discussed, the simulator motion must be contained, and in fact the resulting position output 'washed out' to zero.

Figure 128 plots the Input Rate and the Filtered Rate. The input rate is displayed as the constant value of 1. The filtered value of angular rate is plotted below. It begins at the initial value of 1 rad/s and decreases below 0 rad/s after 1 second.

The integrated value of the Filtered Rate is shown in Figure 129. It can be seen that the integrated output does return to zero even with a constant input. One of the impacts of washout filtering is seen in this figure. The filter is attempting to return the motion system to its neutral position. To do this it creates motion opposite to that of the simulated aircraft (in acceleration, rate and position). The rate at which it does this is controlled by the corner frequency of the filter. The next section will outline how the magnitude of the filter affects the perceived response.

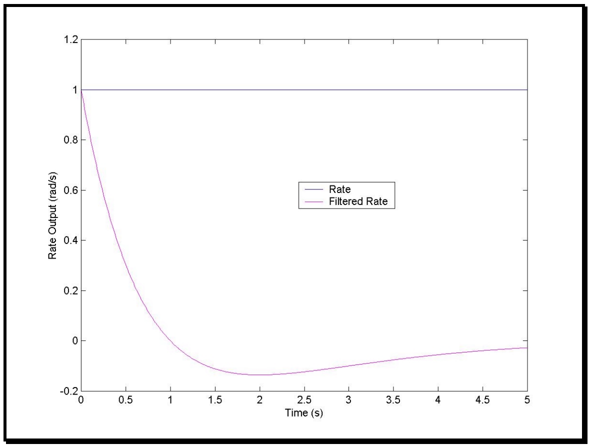


Figure 128 Rate and Filtered Rate

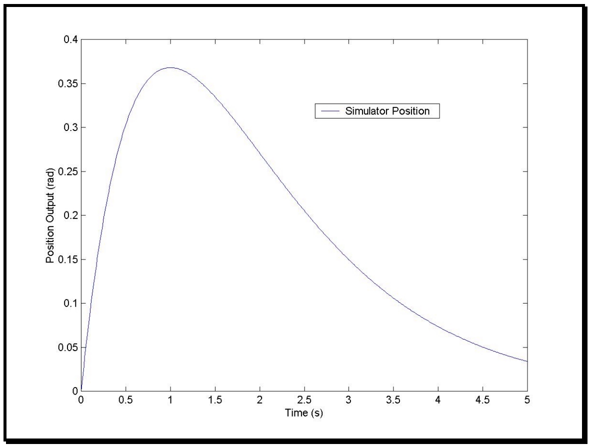


Figure 129 Filtered Position

The high pass filter in the roll channel accepts inputs of inertial axis rotation rates, converted from body axis rotation rates. At this stage under consideration are purely rotational rates with no input from either translational channel.

From the Section 6.2.6, The system displays a maximum roll rate of 0.06rad/s and a maximum roll angle of 0.31rad. The maximum roll angle of 0.31rad can only be obtained with full extension of left and right actuators, with no additional vertical inputs being concurrently feasible. These values can be used when analysing pure roll motion. If translation and/pr pitch inputs are to be added, then possibly only half of this roll response will be available.

The worst case for the roll channel is a constant roll rate as without filtering, this will cause the simulator to exceed its maximum 0.31rad roll angle in 2 seconds from neutral. There is a need to filter the input roll rate so as to achieve a maximum angular displacement of 0.31 rad. To do so it is necessary to determine suitable values of K,ζ & ω_n.

6.4.1.1 Effect of Different Corner Frequencies

This analysis will examine a constant roll rate input of 0.16 rad/s which was determined to be representative of the motion system's maximum roll rate. The Simulink Model shown in Figure 130 will be used. The parameters are listed in Table 1. The corner frequencies are chosen to represent a spread of frequencies around the maximum input rate, in this example 0.18rad/s.

For each transfer function, analysis of the response of both the filtered roll rate as well as the maximum roll angle achieved after integration determines the suitability of the parameters under study.

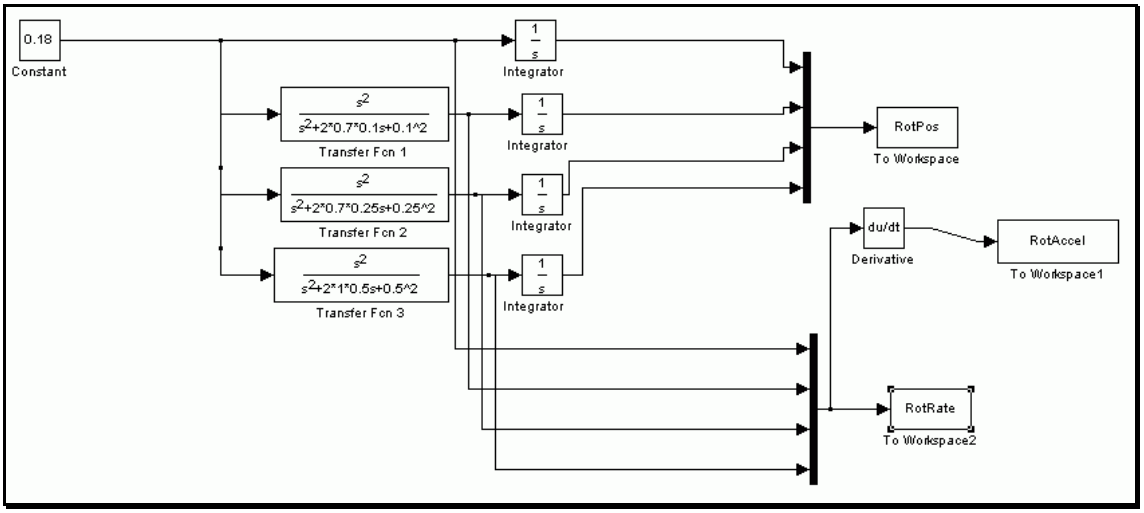


Figure 130 Roll Channel Transfer Function

	Gain – K	Damping Ratio - ζ	Corner Frequency - ω_c rad/s
Transfer Fcn 1	1	0.707	0.1
Transfer Fcn 2	1	0.707	0.25
Transfer Fcn 3	1	0.707	0.5

Table 29 Roll Channel Test Cases

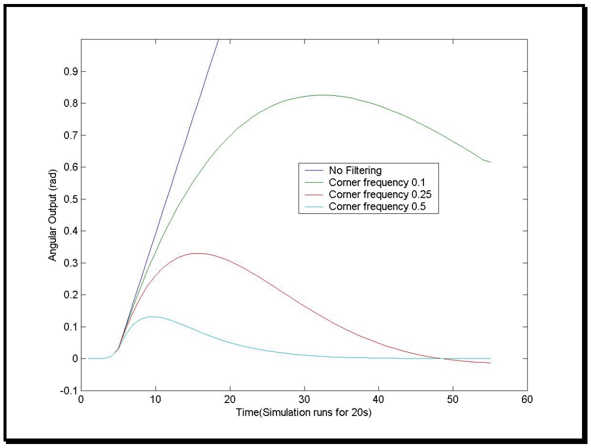


Figure 131 Angular Outputs

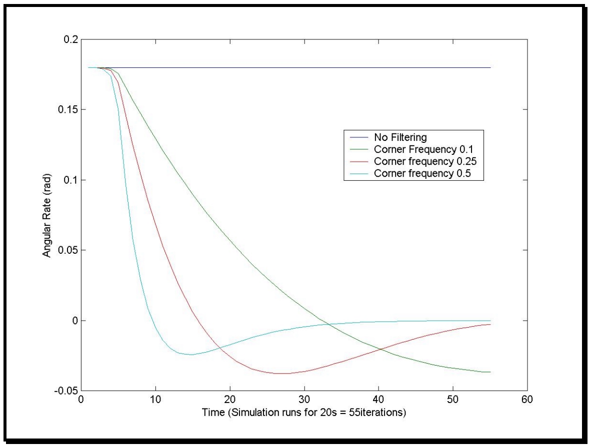


Figure 132 Filtered Rates

As the corner frequency increases, the amount of rate attenuation increases. The non-filtered input increases at 0.25 rad/s, as the aircraft roll angle would if a constant roll rate was applied. The next signal (corner frequency 0.1) is filtered at a rate of approximately 15% of the input signal. It does not increase as sharply as the non-filtered signal but is not contained within 0.31 rad.

The next two signals (corner frequency's 0.25 and 0.5) are filtered enough to remain within the set limit. The fastest filter (Transfer Fcn 3), set at approximately three times the input rate restricts the output to 50% of that allowed. Transfer Fcn 2 allows almost exactly the required output signal. It is apparent that in this system a second order filter with a corner frequency of similar magnitude to the maximum input rate will sufficiently restrict the position of the motion system.

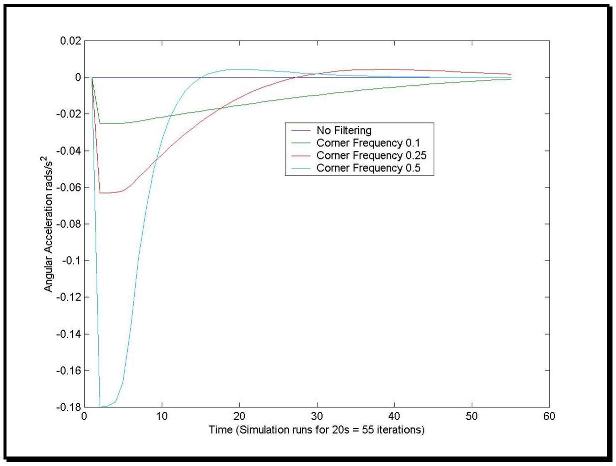


Figure 133 Filtered Angular Accelerations

Shown in Figure 133 are the accelerations associated with the Model output. With a constant rate input, it is a preferable to prevent the pilot from sensing accelerations in the opposite direction. The previous analysis of motion cues shows that the Vestibular system can sense accelerations in the frequency band of approximately 0.03 rad/s^2 to 0.16 rad/s^2. This would indicate that the two Transfer Functions (TFs) using the faster frequencies create excessive acceleration cues in the wrong sense. The two slower Transfer Functions create a maximum negative acceleration that is less than the Vestibular threshold for the Semicircular Canals.

Whilst analysis of the rate outputs led to a choice of corner frequency of approximately the same value as the input rate, analysis of the acceleration outputs trends towards choosing a slower filter frequency in order to limit the production of accelerations opposite in direction to those desired. This is important in re-creating the flight environment. What is important is for realistic recreation of motion cues in the correct direction over a time period of up to several seconds, after which the visual system will take over as the dominant creator of motion cues.

From these results, it can be seen that increasing the corner frequency of the filter has several effects, A faster filter:

1. Better restricts the maximum roll angle

2. Increases opposite direction accelerations, i.e. accelerations that are opposite to those experienced in the aircraft. If they are of sufficient magnitude, the simulator pilot will perceive them.

Increasing the corner frequency helps in that it more severely restricts the resultant roll angle after integration. However, it decreases the amount of time that a roll rate with the correct sign is available. The ‘faster’ the filter, the faster the forward rate that is produced is ‘washed out’. To start using rate output it is necessary to use a sufficiently fast filter. Such a filter may also wash out that rate fast enough to create opposite direction acceleration cues.

6.4.1.2 Effect of Changing the Forward Gain

By reducing the forward gain of the filter, the output of the filter is reduced accordingly. If the filter output is restricted in this way, it should be possible to use a correspondingly slower corner frequency to restrict the rotational output of the simulator. In this way the output signal will be restricted without producing motion cues in the opposite direction.

The circuit in Figure 130 is used but with only Transfer Functions 1 & 2 being examined. The values shown in the table below are used. The Gain value of Transfer Function 1 is reduced to 0.4 in order to restrict the output signal to 0.3 rad.

	Gain – K	Damping Ratio - ζ	Corner Frequency - ω_c rad/s
Transfer Fcn 1	0.4	0.707	0.1
Transfer Fcn 2	1	0.707	0.25

Table 30 Roll Cases – Different Gains

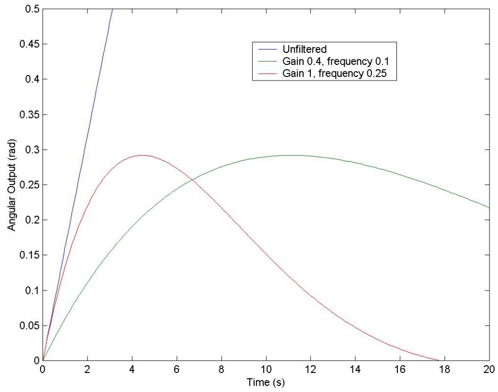


Figure 134 Angular output – Changing Gain

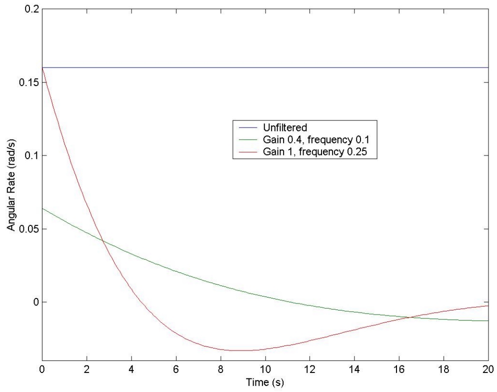


Figure 135 Angular Rate Output – Changing Gain

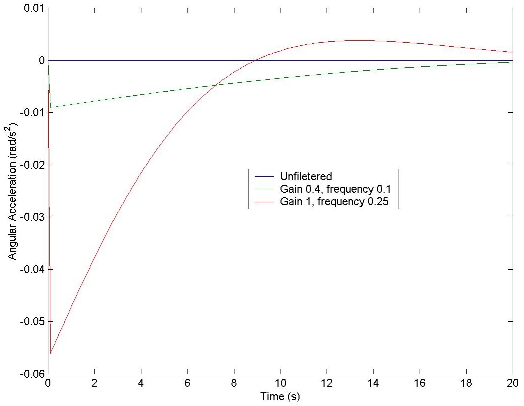


Figure 136 Angular Acceleration – Changing Gain

This time the angular output from TF1 is restricted to the same value as that of TF2, 0.3 radians.

What is more important is the acceleration output as shown in Figure 136

Here the TF with the slower corner frequency has an opposite direction acceleration at a value lower than the threshold of the Vestibular system

Reduction of the forward gain of a slow transfer function allows it to effectively restrict the angular output of our system. Reducing the gain reduces the output as required. It also allows for a slower corner frequency that in turn results in lower values of opposite direction acceleration created during the ‘washout’ process.

6.4.1.3 Effect of Changing Damping Ratio

Figure 137 shows the effect of changing the damping ratio of filters with identical gains and cut-off frequencies on the resultant angular output.

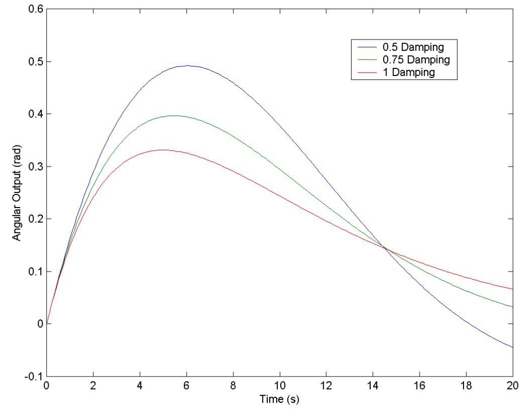


Figure 137 Angular Output – Changing Damping Ratio

Lowering the damping ratio in this figure increases the resultant angular output. A reduced damping ratio also increases the amount of time taken to wash out the simulator rotational angle. This is evident in Figure 137 where it is apparent that the filter with the lower damping ratio gives a lower washout rate.

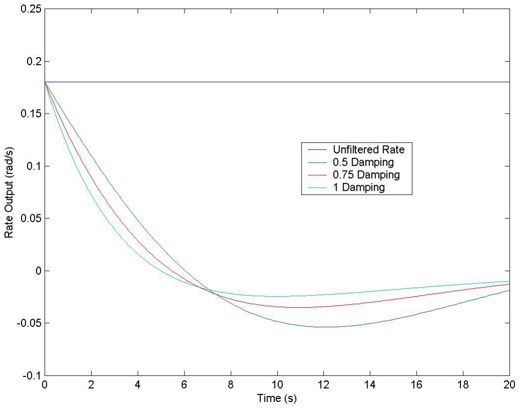


Figure 138 Angular Rate Output – Changing Damping Ratio

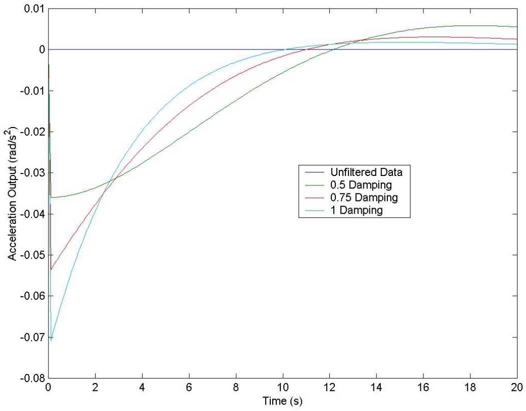


Figure 139 Angular Acceleration Output – Changing Damping Ratio

Figure 139 shows the angular acceleration output of the filter. Again, the filter with the lower damping ratio produces lower values of acceleration. When examining washout acceleration, the sign of the cue is opposite to that of the cue experienced in the aircraft. This is because the simulator can no longer track the aircraft input and is instead washing out the signal to prevent the simulator reaching its motion limits.

In summary, lowering the damping ratio of the washout filters has the following effect

- Higher angular displacement
- Faster angular rates
- Lower opposite sense acceleration

6.4.1.4 Summary of the Effect of Changing Various Filter Coefficients

A faster filter (higher corner frequency):

1. better restricts the maximum roll angle
2. Allows more initial acceleration in the correct direction
3. Increases opposite direction accelerations

Increasing the corner frequency helps in that it more severely restricts the resultant angular output after integration. However, it decreases the amount of time that an angular rate can be produced with the correct sign. The 'faster' the filter, the faster the forward rate the simulator is trying to produce is 'washed out'. To start with rate output requires a sufficiently fast filter. Such a filter may also wash out that rate fast enough to create misleading opposite direction acceleration cues. The higher the rates produced by the aircraft's flights model, the higher the desired corner frequency so as to more accurately produce the higher frequency rates for the pilot. Section 6.4.1.1 showed that selecting a corner frequency of the same order of magnitude to that of the maximum input signal sufficiently constrained the motion.

It is also possible to reduce the forward gain of a slower transfer function to allow it to effectively restrict the angular output of our system. Reducing the gain reduces the output as required, it also allows for a slower corner frequency that in turn results in lower values of negative acceleration created during the 'washout' process. Modern simulators use values of gain down to 0.5 [26] to provide adequate restriction of motion system movement. This has been evaluated as not detracting from the simulation experience.

Lowering the damping ratio of the washout filters has the following effects

- Higher angular displacement
- Faster angular rates
- Lower opposite sense acceleration

However, the resultant change from alteration of the damping ratios is minor when compared to the effects of the corner frequency and forward gain.

6.4.2 Translational Channel

The translational channel uses a third order filter as outlined in Section 6.2 The response of such a filter is similar to that of the second order filter as outlined in the previous section. The requirement for the extra pole and zero arises from the differing nature of the input. For the rotational channel with rate inputs, a 2nd order filter is required to ensure the resultant angular output is restricted. The rotational channel is different in that it has an acceleration input. A 2nd order filter would restrict the simulator's translational rate but not its translational position.

6.5 Motion System Tuning & Analysis

The Washout Filter must be tuned to achieve the following

1. Constraint of Motion Base Travel
2. Constraint of Motion Base Speed
3. Constraint of Motion Base Acceleration
4. Creation of ‘realistic’ Motion Cues

There are three main variables that we can alter to achieve this

1. Washout Filter input Scaling (Gain Changing)
2. Washout Filter Frequency
3. Washout Filter Damping Ratio

The Flight Model outputs translational acceleration as well as rotational acceleration. By flying the simulator maximum values of these variables can be obtained.

Subjective tuning of the three channels (roll, pitch and yaw) was carried out. During the subjective test, filter coefficients suggested by previous work were used. An objective test of the roll channel using the Vestibular model identified in Chapter Two was also carried out. The objective testing of the roll channel is by no means exhaustive and is presented as an extension.

6.5.1 Roll Channel Coefficient Selection

Three parameters have been identified as having an effect upon the motion system. These are corner frequency, gain and damping ratio.

Corner Frequency

Three values of corner frequency have been evaluated. These values are 1, 1.5 and 2 rad/s.

Gain

The gain was set at 1 for the analysis. As described in Section 6.4.1.4 this could be reduced to as low as 0.5.

Damping Ratio

Three values of damping ratio were tested, 0.7, 0.85, 1.

It was felt that although it was shown that damping ratio has a mush lesser effect upon motion base output, it was important to subjectively and objectively asses its effect on simulator motion.

The test cases for assessment are shown in Table 31

	Filter Frequency (rad/s)			
Damping Ratio		1	1.5	2
	0.7	Fig. 140-143	Fig. 148-151	Fig. 160-163
	0.85	N/A	Fig. 152-155	N/A
	1	Fig. 144-147	Fig. 156-159	Fig.164-167

Table 31 Objective Roll Test Parameters

6.5.2 Roll Channel Motion Objective Analysis

Objective tests were conducted on the roll channel to asses the effect of alteration of filter frequency and damping ratio on the resultant motion system output.

The input sequence in each case was identical and involved:

1. Left roll input of 50% of aileron
2. Hold
3. Right roll input to 0% aileron
4. Hold
5. Right roll input of 50% of aileron
6. Hold
7. Left roll input to 0% aileron
8. Hold
9. Left roll input of 50% of aileron
10. Hold
11. Right roll input to 50% of aileron
12. Hold
13. Left roll input to 0% of aileron

Figure 140 through Figure 167 outline the results of the tests.

6.5.2.1 Roll Rate Comparison

As the filter frequency increases, the simulator maximum roll rate decreases . With a damping ratio of 0.7, the change is approximately proportional to filter frequency, (I.e. at 1rad/s, the initial roll rates are 0.05 rad/s (Fig. 140) while at 2 rad/s (Fig. 160) the initial roll rates are 0.025 rad/s).

Damping ratio does affect the roll rates of the simulator. For the 1.5rad/s filter, changing the damping ratio from 0.7 to 0.85 and then to 1 (Figure 148, Figure 152, Figure 156) has the effect of reducing the maximum output roll rate by a factor of approximately 20%. This effect can also be seen in comparing the 1 and 2 rad/s filters with damping ratios changing from 0.7 to 1.

In no case did the system reach a maximum velocity in roll. Calculations in Section 6.2 did produce a figure of 0.16rad/s for maximum roll rate (in isolation). The highest rate achieved was in the order of 0.1 rad/s.

6.5.2.2 Roll Accelerations Comparison

When examining roll accelerations, there are two important results. The first is that the simulator should produce as much acceleration as possible in the correct direction. Secondly but just as important is that the acceleration caused by the washout, i.e. in the opposite direction should be below the thresholds of angular acceleration detection established in Chapter 2.

All of the filters show that the simulator will track the correct direction accelerations well. Figure 141 shows that with a low filter frequency, the simulator acceleration is almost identical to the aircraft. As the filter frequency increases from 1 to 2 rad/s (Figure 141,Figure 149, Figure 161), the simulator rotational acceleration output reduces to approximately 50% of the aircraft values.

However, in Figure 141, the washout accelerations do have an absolute value in excess of 0.05 rad/s^2. This is greater than the lower roll acceleration threshold of 0.022rad/s^2 and comparable to the upper value of 0.055rad/s^2. As the filter frequency increases, the magnitude of the opposite direction washout accelerations increases as detailed in section 6.4.1.1. At a filter frequency of 2 rad/s^2 and damping ratio of 0.7, (fig 161), the values have an absolute value of approximately 0.07, this time well in excess of both angular acceleration detection thresholds.

The effect of damping ratio in this case is greater. For the 1.5 rad/s^2 filter, increasing the damping ratio from 0.7 to 1 significantly reduces the amount of washout acceleration.

These results suggest using a lower corner frequency with a higher damping ratio to create correct motion cues.

6.5.2.3 Perceived Roll Acceleration Comparison

Section 6.5.2.2 analysed the simulator accelerations before application of the vestibular model and showed that the higher the filter frequency, the larger the magnitude of the opposite direction washout acceleration cues. The 2rad/s filter exceeded (Fig 161) the detection threshold and should therefore perceive more cues in the wrong direction. Analysis of the perceived roll acceleration figures shows that in fact it is the slower filter that produces more ‘perceived’ opposite direction accelerations.

This is due to the fact the faster filter, while creating an initially larger motion cue in the opposite direction, also removes that washout cue faster than the slower filter. In effect, the time derivative of the acceleration for the faster filter is larger, creating an initially larger ‘bump’ as the motion is washed out. However, the opposite direction cues are also removed faster. With the lag involved in the vestibular model, this fast removal of the washout acceleration (as it is in turn washed out) leads to the perceived angular acceleration being less both in the correct direction as well as the in the washout direction for the faster filter.

This suggests that a higher frequency than that called for in Section 6.5.2.2 may be warranted.

6.5.2.4 Actuator Length Comparison

As the filter frequency is increased from 1 rad/s^2 to 2rad/s^2, the maximum actuator displacement decreases by approximately 15 to 20% (Figure 143, Figure 151, Figure 163). The maximum actuator displacement observed was 6.2V to 2.7V. With the neutral position set at 4.5 V, this 1.8V displacement in the downwards direction represents 40% of maximum displacement. Clearly none of the cases were restrictive in this isolated case.

However, the view must be taken that the motion system also produces cues in Heave and Pitch and must therefore be able to accommodate all three without exceeding a displacement limit.

6.5.2.5 Summary of Results

Comparison of the Roll Rate outputs for varying corner frequencies and damping ratios did not demonstrate a clear influence on the choice of parameters. Analysis of actual roll accelerations showed that a lower frequency with a higher damping ratio would be appropriate to reduce the creation of misleading opposite direction motion cues. However, the analysis of perceived roll accelerations displayed that in fact a higher corner frequency can in fact reduce the creation of opposite direction cues. The trade off is that the time derivative of acceleration for the output from the faster filter may be more. At no stage was actuator length a concern, indicating that the lower frequency filter's are still capable of sufficeintly resticting the simualtor motion when operating as a 747 aircraft. This case is only for roll motion analysed and when pitch and heave are added there will be increases in the motion envelope.

From this analysis and from the subjective assessment, the values listed in Table 32 have been chosen.

Corner Frequency	1rad/s
Damping Ratio	0.7
Gain	1

Table 32 747 Roll Filter Parameters

These results have been for a simulated 747 aircraft. Had the simulated aircraft exhibited higher frequencies of motion, the previous analysis would call for a higher corner frequency to better restrict the roll motion of the simulator. Again, although intially analysis infers that this increases the creation of opposite direction motion cues, the higher frequency filters have shown a tendency to not produce excessive amounts of such motion. For such a system, a corresponding increase in damping ratio would reduce the creation of opposite direction cues.

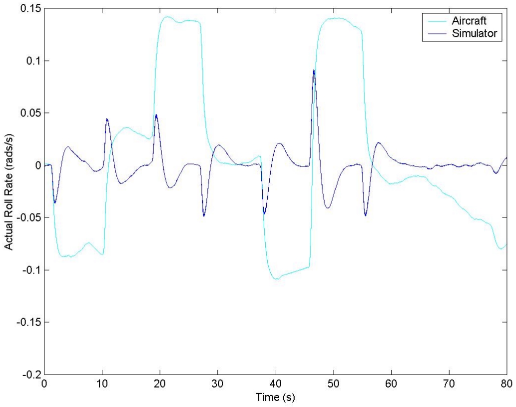


Figure 140 Roll Rates

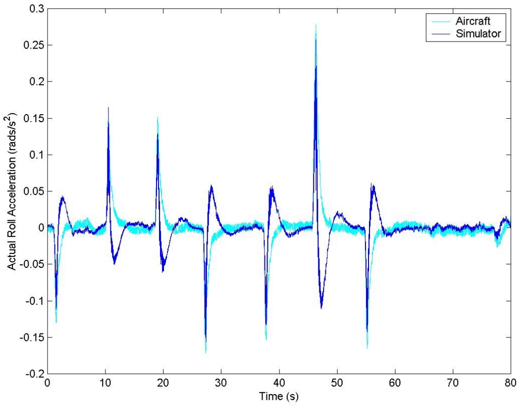


Figure 141 Roll Accelerations Actual

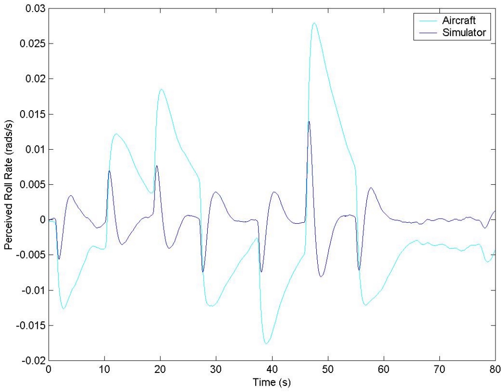


Figure 142 Roll Accelerations Perceived

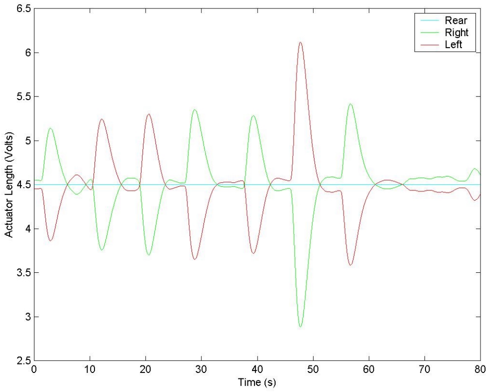


Figure 143 Actuator Lengths

Corner Frequency	1rad/s
Damping Ratio	0.7

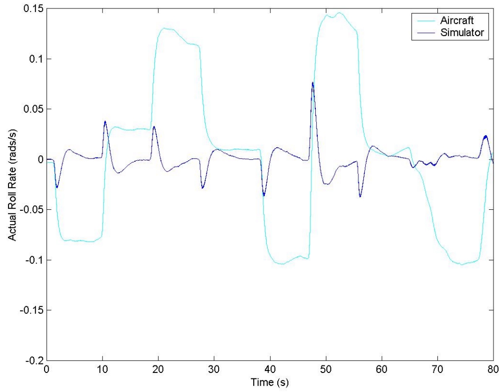


Figure 144 Roll rates

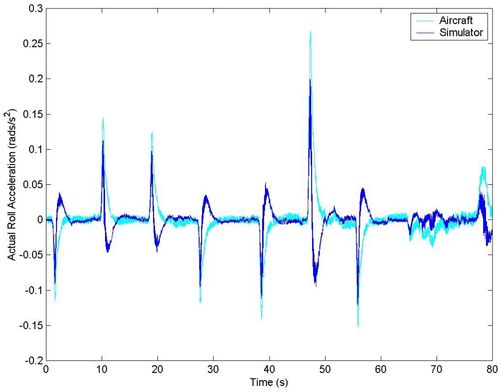


Figure 145 Roll Accelerations Actual

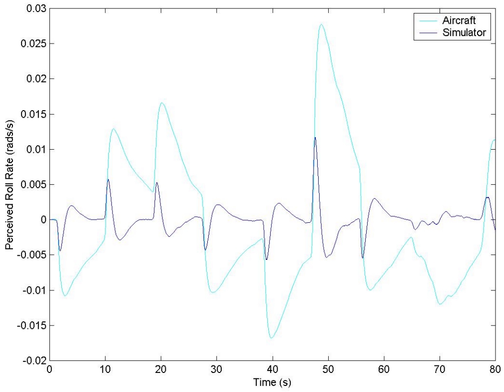


Figure 146 Roll Accelerations Perceived

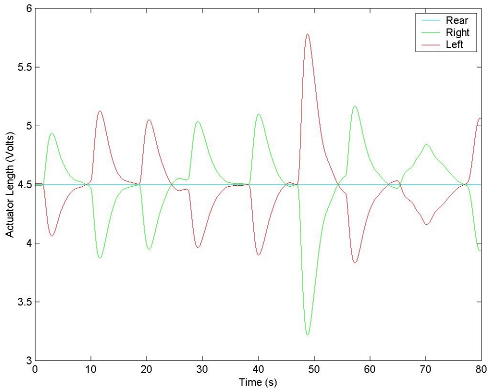


Figure 147 Actuator Lengths

Corner Frequency	1rad/s
Damping Ratio	1

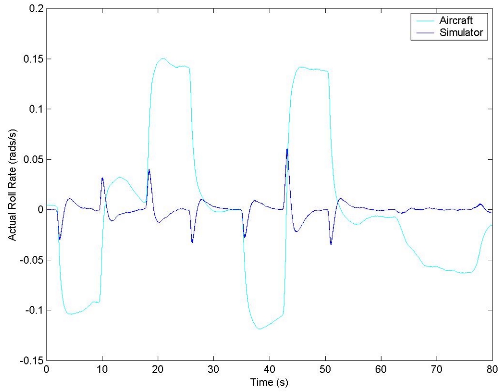


Figure 148 Roll Rates

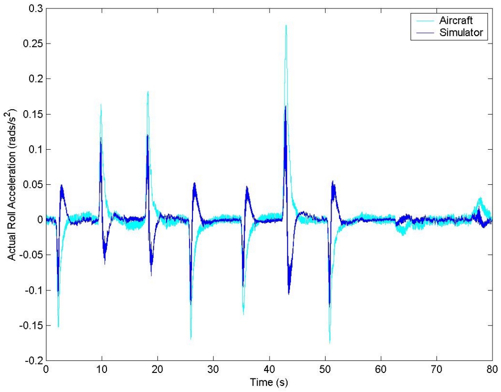


Figure 149 Roll Accelerations Actual

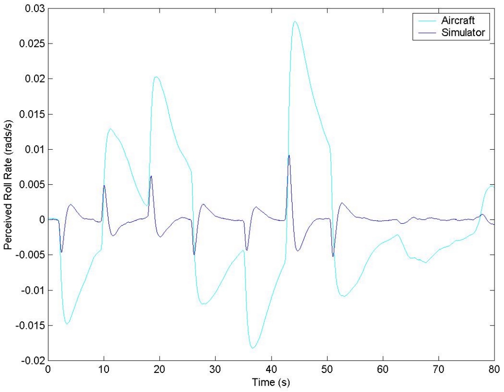


Figure 150 Roll Accelerations Perceived

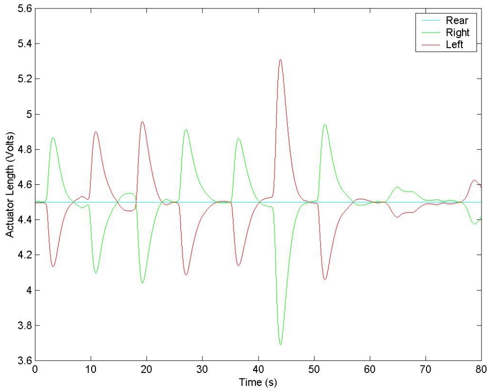


Figure 151 Actuator Lengths

Corner Frequency	1.5rad/s
Damping Ratio	0.7

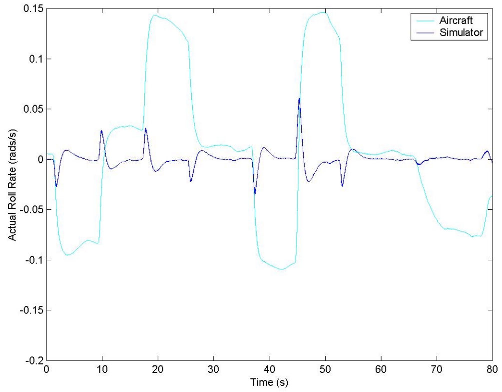


Figure 152 Roll Rates

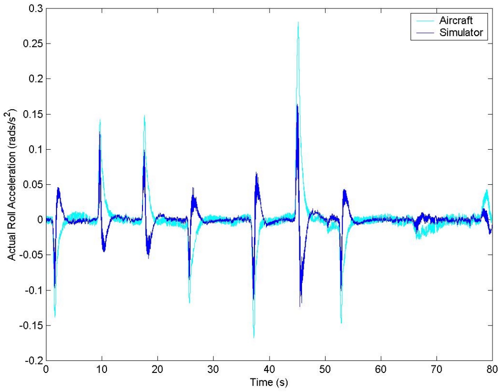


Figure 153 Roll Accelerations Actual

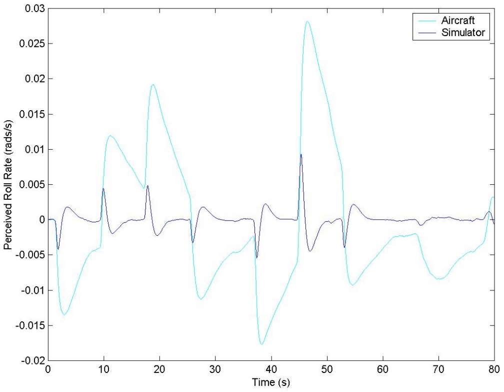


Figure 154 Roll Accelerations Perceived

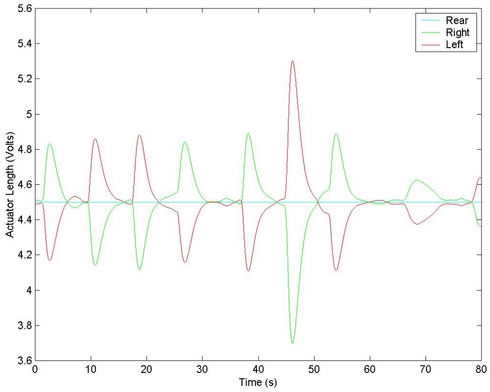


Figure 155 Actuator Lengths

Corner Frequency	1.5rad/s
Damping Ratio	0.85

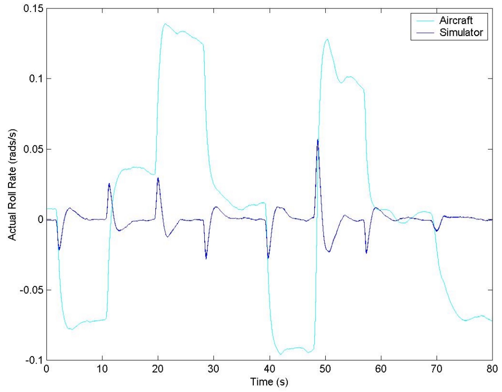


Figure 156 Roll Rates

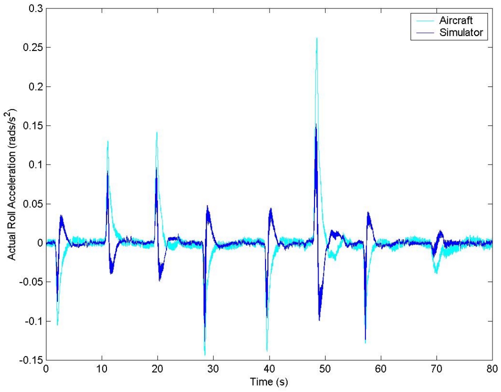


Figure 157 Roll Accelerations Actual

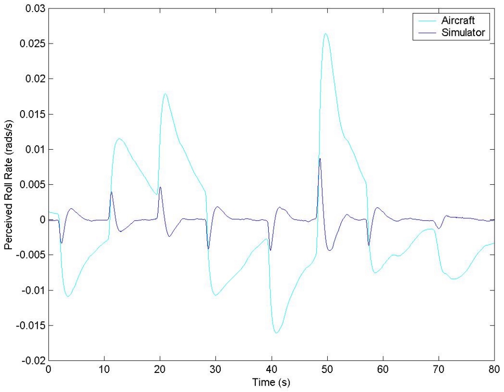


Figure 158 Roll Accelerations Perceived

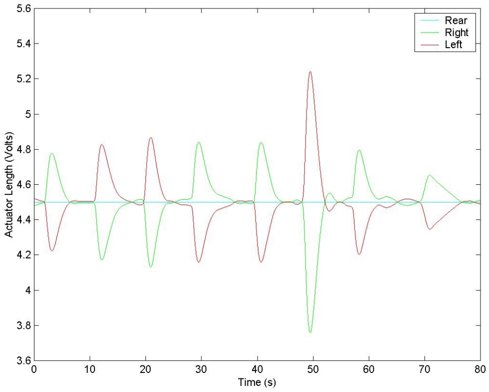


Figure 159 Actuator Lengths

Corner Frequency	1.5rad/s
Damping Ratio	1

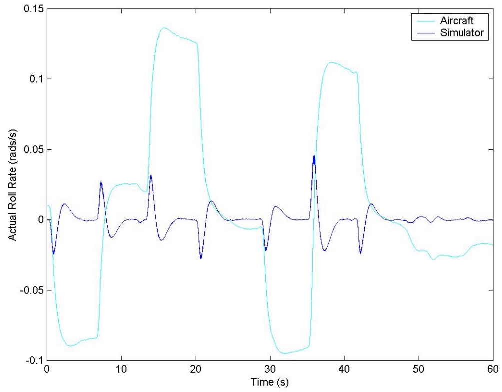


Figure 160 Roll Rates

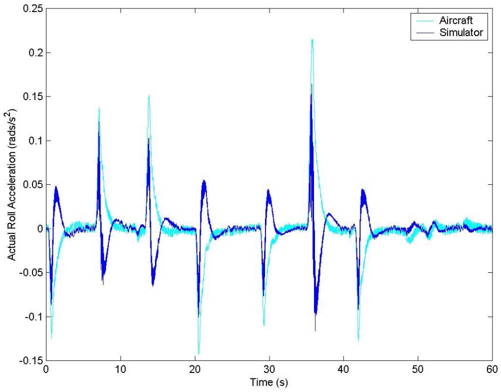


Figure 161 Roll Accelerations Actual

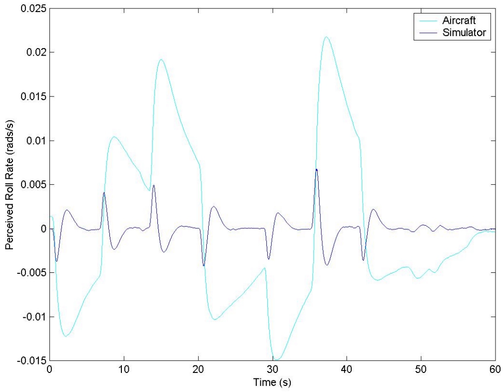


Figure 162 Roll Accelerations Perceived

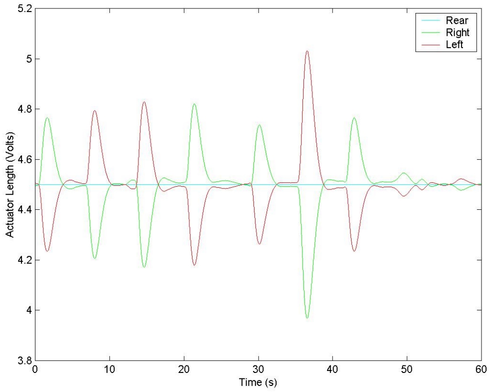


Figure 163 Actuator Lengths

Corner Frequency	2 rad/s
Damping Ratio	0.7

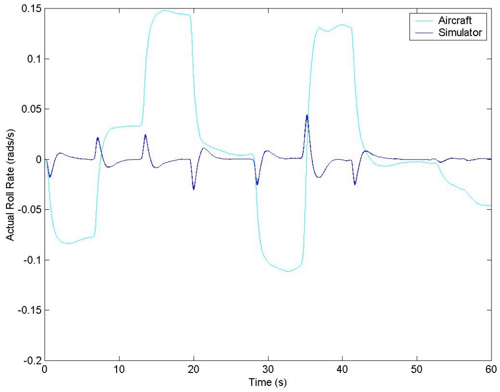


Figure 164 Roll Rates

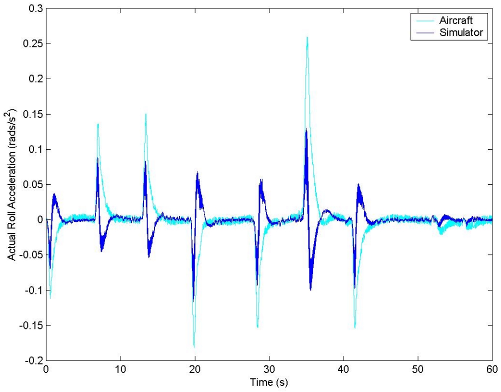


Figure 165 Roll Accelerations Actual

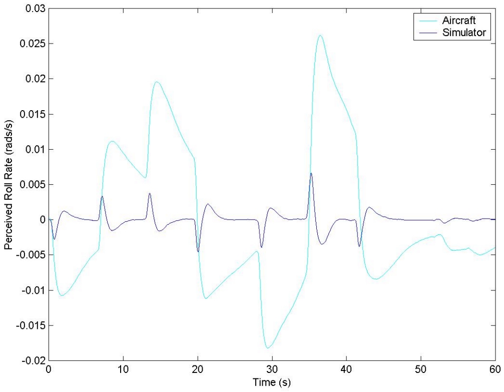


Figure 166 Roll Accelerations Perceived

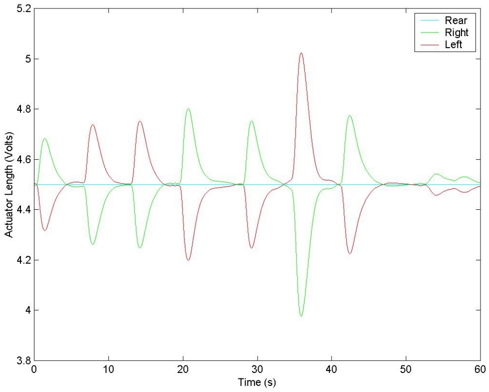


Figure 167 Actuator Lengths

Corner Frequency	2 rad/s
Damping Ratio	1

Chapter 7

Conclusions & Future Work

7.1 Conclusions

A flight simulator has been developed at the University of Sydney for use as a teaching and research tool. The device is now ready to accept Flight Mechanics students who can use the device as a simulator.

A flight simulation system from Cranfield University in the UK has been used as the core of the facility. This system has proven to easily interface with the new simulator’s control system. At present it is only capable of simulating an early generation 747 aircraft but with simple modifications will simulate several types of aircraft including light pistons and turboprop aircraft. The system runs several PCs connected via Ethernet to provide a modular simulation. Extra modules can be added as is intended for the Variable Stability module and as has been done for the Control Loading and Motion module.

A 707 simulator provides a flightdeck environment as well as flight controls and motion. The acquisition of this device has allowed the creation of a large simulator facility. Initial studies in the department focussed on small scale devices without an enclosed cockpit. The use of the 707 flightdeck provides a much more appropriate environment for both teaching and research. The interior of the simulator has been extensively reengineered to provide a generic reconfigurable system. This has involved removal of much of the original flight instrumentation which has been replaced with computer driven monitors. This allows the simulator to be highly generic and rapidly reconfigurable.

The laboratory has been modified to accommodate the device with the addition of several support systems. A three phase power supply provides power to the system as well as the Hydraulic Power Unit. Airconditioning, water cleansing and an Ethernet network are also present.

The performance of the motion system has been analysed. The measured performance is comparable to that predicted by theory. The system is capable of producing 3 positive ’g’s and two negative ‘g’s although for only a very short time. Although 3 degree of freedom systems are becoming obsolete, they are still in use in several training centres.

A new instructor station has been built at the rear of the simulator cabin. This station is capable of controlling all aspects of the simulation. A digital switch has been included in the system that allows control of any of the system’s computers from one single station. This allows the instructor to interface with the entire simulation system including giving him or her direct control of the flight control loading and motion system. This means that the capability exists to conduct on line modification and testing of different control algorithms without extensive coding.

A Supervisory Control and Data Acquisition system has been implemented to provide overall control of the simulator's control loading and motion as they are potential hazards. This includes several safety circuits and warning lights. This system is also responsible for safe activation of the simulator's hydraulic motion and control loading system. The system runs at 3000psi and is very mobile. The SCADA system protects the system and operators from damage by controlling the position commands to the system to prevent large amplitude inputs.

This system has been programmed with a 2nd order classical motion washout algorithm as well as software for controlling all three primary flight control axes hydraulically. The washout system also has provision for a 3rd order filter in the rotational channel should it be required. Washout filtering takes place currently at the centroid of the motion platform. This location can be moved by altering parameters in the simulation, again this can be done on-line.

As this system has been built as a Variable Stability Simulator that incorporates a motion base, it is important that the motion system be capable of interfacing with different magnitudes of motion as inputs from the flight model. The system has been tuned to operate as a 747 heavy jet simulator. However, the variable stability interface is capable of altering the flight model sufficiently to produce motion cues of such variation as to require re-configuring. For example, relaxing the lateral stability of the simulated aircraft may result in increased roll motion that could exceed the capability of the motion base to restrict its own motion. As the motion control software is reconfigurable in real time, it is possible to alter the washout filter via its gain, frequencies and damping to ensure a realistic motion environment.

The system's flight controls as well as the three degree of freedom motion base have been subjectively tuned with some basic objective analysis of the roll channel. The objective analysis has been presented as an extension to the work. It is felt that much more can be done in this area, however, at this stage the subjective analysis has proven that the system can operate as a motion based flight simulator which is sufficient for the Department's needs at this time.

Achievements of the objectives listed in chapter one are detailed as follows:

1. Re-engineer the systems to provide hydraulically loaded flight controls

An updated flight control loading system has been implemented to accommodate a new analogue inner loop with commanded position for each axis generated in software in the CMT computer. The software used to derive the commands to the hydraulic actuators is a generic model based upon the original 707 layout. The software's parameters have been subjectively tuned by the author. There is scope for further refinement of the system although at this stage the flight controls are a good simulation of the controls of a heavy jet transport aircraft.

2. Re-engineer the systems to provide a 3 Degree of Freedom motion base

This system has also been implemented with an analogue inner loop with digital outer loop control. The system has been modelled upon a system designed in Toronto by the UTIAS whose work is heavily referenced. This system has been tuned subjectively also. In addition, an attempt has been made to provide an objective analysis of the motion performance. The motion system software can be modified in real-time in the Matlab environment.

3. Create a collimated, daylight colour visual scene

A Primary Image software and hardware system has been implemented to provide such a scene. At this stage, each pilot views the same single channel out of the forward windows through a collimating mirror system. There is provision for the addition of two more peripheral displays although this has not been implemented at this time.

4. Install a "Glass Cockpit" to replace custom 707 analogue displays

All of the original displays have been removed and new CRT displays have been installed. These provide a re-configurable capability as well as the ability to view overall simulator control data from the pilot positions.

5. Provide seating for multiple occupants – including two observers

The original flight engineers location has been removed and two new observers' seats have been installed. For safety, all seats in the simulator are equipped with four point racing harnesses. In addition, there is one internal and two external emergency stop switches that remove all electric and hydraulic power from the system upon activation.

6. Create a "Safe" system with full supervisory control

Such a system is required to provide overall control and safety monitoring. This system has been implemented in the Matlab environment and also contains the software for the operation of the flight control loading and motion systems. The system monitors several safety parameters including motion base position, door status and power/hydraulic/flight model status signals to ensure that all hardware is operating correctly prior to the use of hydraulics in the flight control loading and motion systems.

7.2 Future Work

The Variable Stability Module is being developed and will soon be ready for inclusion in the simulator. This module will allow the full capability of the device to be used in the teaching and research environment.

Conversion of the flight instruments display will allow use of the centre CRT in the flight deck and reduce the amount of information displayed to the pilots on their displays. At this stage, each of the pilot's have an identical display that duplicates engine and radio data.

The last section of this thesis contains a basic objective analysis of flight simulator motion. It is felt by the author that this area has much potential. Presently most commercial flight simulator motion is tested subjectively by an experienced pilot. It is felt that by creating a purely objective test of simulator motion, much variation could be removed from flight simulator motion with a corresponding increase in training and testing effectiveness.

7.3 Summary

The completion of these objectives results in an operational flight simulator that can readily incorporate enhancements such as a Variable Stability Module. The operational system achieved is representative of a typical large jet transport aircraft in its production of flight control and motion cues. The simulator is now functional with the motion and control loading systems operating as designed. A significant outcome of this project has been to create a safe, easily maintainable, re-configurable flight simulator from a large, complex, legacy system. The facility now forms a significant research and teaching tool in areas such as flight mechanics, propulsion, aircraft handling qualities and human factors.

Appendix 1

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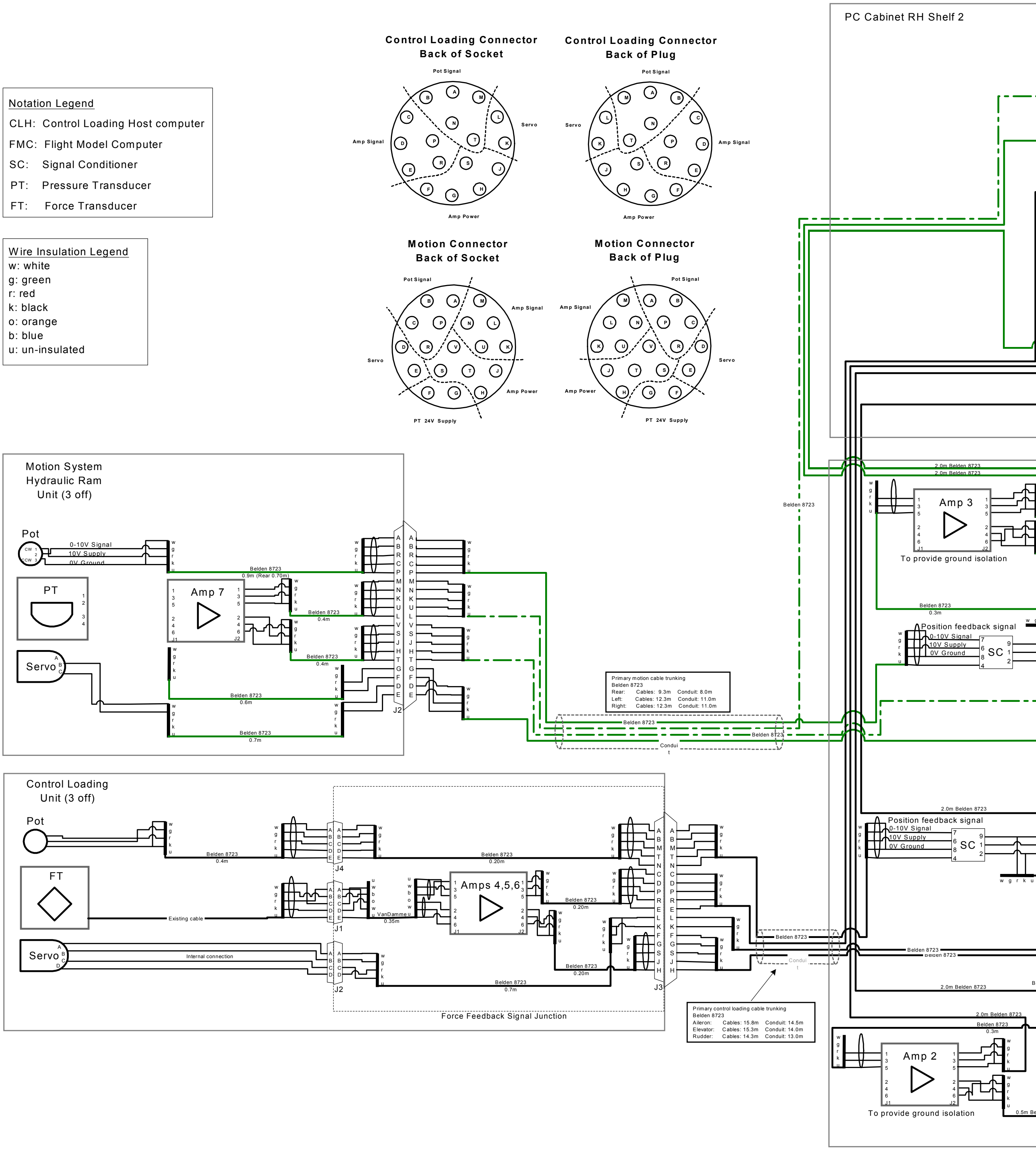
Appendix 2

Control Loading and Motion Wiring Diagram



Notation Legend

CLH: Control Loading Host computer

FMC: Flight Model Computer

SC: Signal Conditioner

PT: Pressure Transducer

FT: Force Transducer

Wire Insulation Legend
w: white
g: green
r: red
k: black
o: orange
b: blue
u: un-insulated

Appendix 3

Moog Servoamplifier System Schematics

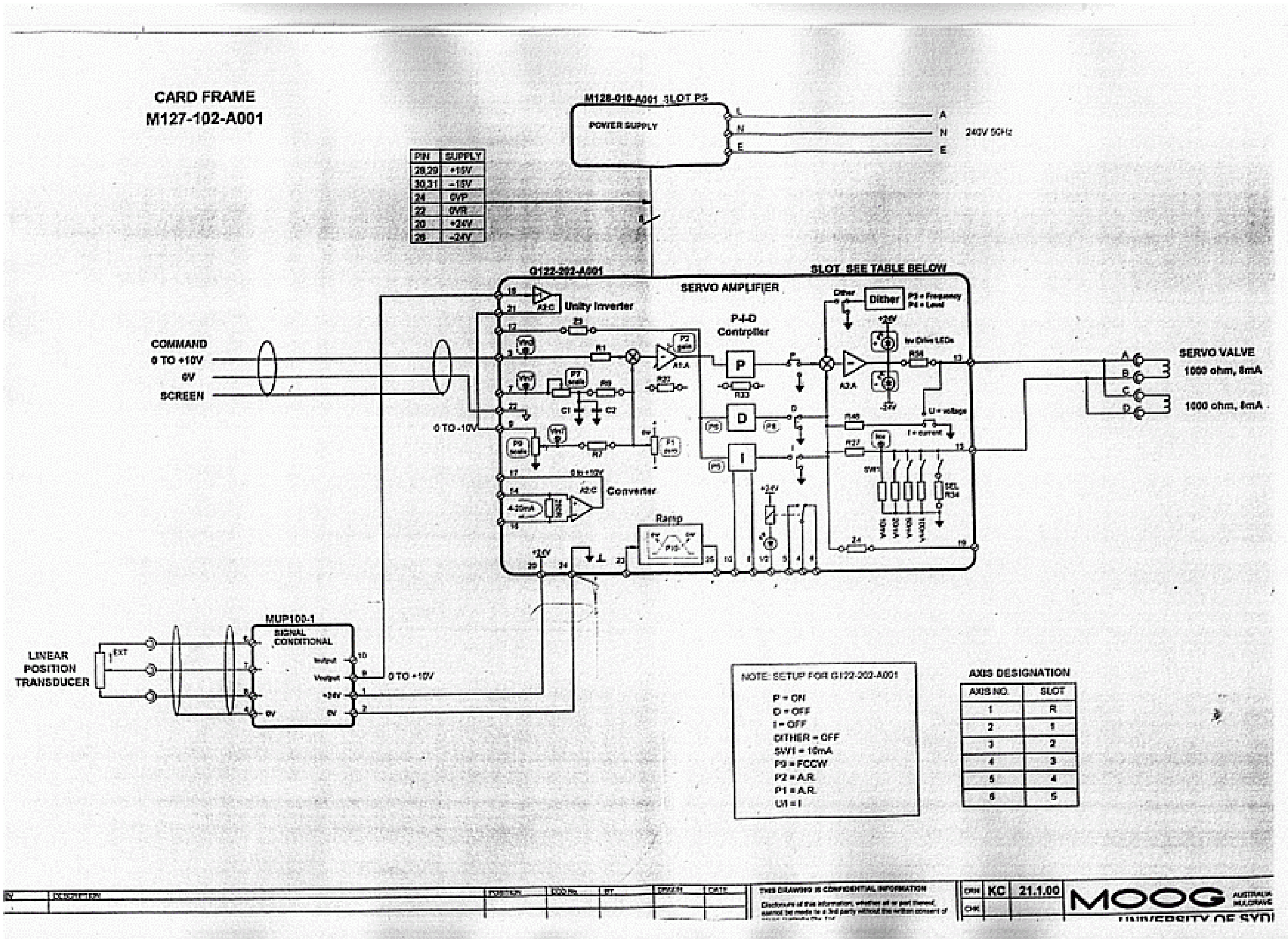


Figure 168 Moog Servoamplifier Card Schematic

Simulator Hydraulic Part Numbers

All valves are Moog Valves

Motion Jacks

Left Hand Front

Mod 772-220
Ser 109

Right Hand Front and Rear

PN 010 – 24503
Mod 2214 – A

Nose Wheel Steering

PN A – 01430-1
Mod 31 – 154A

Remaining Control Loadings

Mod 31 – 154
PN 010 22996

Appendix 4
Amplifier Schematics and Data

Flight Simulator Amplifier Specifications

Amplifier 1 (3):

Purpose:

To interface control positions signals to existing Cranfield multiplexer card.

Characteristics:

Filter Corner Frequency: 50 Hz
Gain: 0.5

Optional Component Values:

R5 = 10 kΩ,   R6 = 10 kΩ,   RG = ∞

C5 = 47 nF,   C6 = 10 nF

Cable:

J1 pins 1,3,5: 0.3m Belden 8723 connected as per system diagram
J1 pins 2,4,6: Not connected
J2 pins 1,3,5: 2.0m Belden 8723 connected as per system diagram
J2 pins 2,4,6: 0.5m Belden 8723 connected as per system diagram

---

Amplifier 2 (3 off):

Purpose:

To interface control position signals to CLH primary A/D card.

Characteristics:

Filter Corner Frequency: 50 Hz
Gain: 1.0

Optional Component Values:

R5 = ∞,   R6 = ∞,   RG = ∞
C5 = 47 nF,   C6 = 10 nF

Cable:

J1 pins 1,3,5: 0.3m Belden 8723 connected as per system diagram
J1 pins 2,4,6: Not connected
J2 pins 1,3,5: 2.0m Belden 8723 connected as per system diagram
J2 pins 2,4,6: 0.5m Belden 8723 connected as per system diagram

---

Amplifier 3 (3 off):

Purpose:

To interface motion position signals to CLH primary A/D card.

Characteristics:

Filter Corner Frequency: 50 Hz
Gain: 1.0

Optional Component Values:

R5 = ∞, R6 = ∞, RG = ∞
C5 = 47 nF, C6 = 10 nF

Cable:

J1 pins 1,3,5: 0.3m Belden 8723 connected as per system diagram
J1 pins 2,4,6: Not connected
J2 pins 1,3,5: 2.0m Belden 8723 connected as per system diagram
J2 pins 2,4,6: 0.5m Belden 8723 connected as per system diagram

---

Amplifier 4 (1 off):

Purpose:

To interface aileron force sensor signals to CLH primary A/D card.

Characteristics:

Filter Corner Frequency: 50 Hz
Gain: 14.8

Optional Component Values:

R5 = ∞, R6 = ∞, RG = 3.6 kΩ
C5 = 47 nF, C6 = 10 nF

Cable:

J1 pins 1-6: 0.4m Van Damme connected as per system diagram
J2 pins 1,3,5: 0.2m Belden 8723 connected as per system diagram
J2 pins 2,4,6: 0.2m Belden 8723 connected as per system diagram

---

Amplifier 5 (1 off):

Purpose:

To interface elevator force sensor signals to CLH primary A/D card.

Characteristics:

Filter Corner Frequency: 500 Hz
Gain: 8.4

Optional Component Values:

R5 = ∞, R6 = ∞, RG = 6.8 kΩ
C5 = 47 nF, C6 = 10 nF

Cable:

J1 pins 1-6: 0.4m Van Damme connected as per system diagram
J2 pins 1,3,5: 0.2m Belden 8723 connected as per system diagram
J2 pins 2,4,6: 0.2m Belden 8723 connected as per system diagram

---

Amplifier 6 (1 off):

Purpose:

To interface rudder force sensor signals to CLH primary A/D card.

Characteristics:

Filter Corner Frequency: 50 Hz
Gain: 6.0

Optional Component Values:

R5 = ∞, R6 = ∞, RG = 10.0 kΩ
C5 = 47 nF, C6 = 10 nF

Cable:

J1 pins 1-6: 0.4m Van Damme connected as per system diagram
J2 pins 1,3,5: 0.2m Belden 8723 connected as per system diagram
J2 pins 2,4,6: 0.2m Belden 8723 connected as per system diagram

---

Amplifier 7 (3 off)

Purpose:

To interface motion jack differential pressure signals to CLH primary A/D card.

Characteristics:

Characteristics:

Filter Corner Frequency: 50 Hz
Gain: TBA

Optional Component Values:

R5 = ∞, R6 = ∞, RG = ∞
C5 = 47 nF, C6 = 10 nF

Cable:

J1 pins 2,4,6: TBA
J2 pins 1,3,5: 0.4m Belden 8723 connected as per system diagram
J2 pins 2,4,6: 0.4m Belden 8723 connected as per system diagram

---

Amplifier 8 (3 off):

Purpose:

To interface trim signals from Cranfield Multiplexer card inputs to CLH primary A/D card.

Characteristics:

Filter Corner Frequency: 50 Hz
Gain: 2.0

Optional Component Values:

R5 = ∞, R6 = ∞, RG = 51K1
C5 = 47 nF, C6 = 10 nF

Cable:

J1 pins 1,3,5: 2.0m Belden 8723 connected as per system diagram
J1 pins 2,4,6: Not connected
J2 pins 1,3,5: 2.0m Belden 8723 connected as per system diagram
J2 pins 2,4,6: 0.3m Belden 8723 connected as per system diagram

---

BUILD TOTAL 21 AMPLIFIERS (18 above + 3 Spares)

Appendix 5

Cable & Pin Allocations for Secondary Flight Controls

The secondary flight controls use the existing connections from their respective position transducers. Using existing dicumentation and a manual search process, the required cables were identified and reconnected into the Junction Cabinet. Each required signal was tapped from the rear of each junction block and routed to the A/D breakout card assosciated with the Cranfield Simulation System. Five such cables are used and they are listed below.

Cable 1 – Thrust Levers 1 & 2

Thrust Lever 1 16 +
tap (1k)
Thrust Lever 2 12 +
tap (1k)

Cable 2 Speed Brakes ,Toe Brakes and Flaps

Speed Brakes 1 +
tap (5k)
Flaps 26 +
tap (5k)
Left Brakes 29 +
tap (5k)
Right Brakes 7 +
tap (5k)
Elevator Trim Output 46 tap (1k)

Cable 3 – Thrust Levers 3 & 4, Start Switches 1 thru 4

Thrust Lever 3 8 +
tap (1k)
Thrust Lever 4 31 +
tap (1k)
Start Switch 1 39 +
tap (2k)
Start Switch 2 35 +
tap (2k)
Start Switch 3 4 +
tap (2k)
Start Switch 4 27 +
tap (2k)

Cable 5 – Landing Gear

Landing Gear 18 +
tap (5k)

Cable 6 – Rudder & Aileron Trim
Rudder Trim 20 +
-tap (1k)
Aileron Trim 20 +
-

Appendix 6

Supervisory Control Software

```
43      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/Rotaion
44      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/Scale L
45      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/Subsyst
46      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate  Accelerations @ CofG
47      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate Omega & Omega Dot
48      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate Omega & Omega Dot/Cons
49      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate Omega & Omega Dot/Cons
50      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate Omega & Omega Dot/Sawt
51      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate Omega & Omega Dot/Sawt
52      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Calculate Jack Lengths 2nd Order
53      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Calculate Jack Lengths 3rd Order
54      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Move forces from CofG to Fa & ca
55      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Move forces from CofG to Fa & ca
56      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order
57      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/Omega
58      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/Omega
59      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/Omega
60      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/Omega
61      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/Speci
62      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/accel
63      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/accel
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73      Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order1/Tran
74      Motion_System_13_Vest/Motion System/Motion Drive Signal/Rotational Acceleration Limiters
75      Motion_System_13_Vest/Motion System/Motion Drive Signal/Rotational RateLimiters
76      Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1
77      Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Control System
78      Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232
79      Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232/For
80      Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232/Rec
81      Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232/Sen
82      Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232/Set
83      Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232/Set
84      Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232/Set
85      Motion_System_13_Vest/Motion System/Motion Envelope
86      Motion_System_13_Vest/Motion System/Motion Erect  // Shutdown
```

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 87      Motion_System_13_Vest/OHSRM Warning Flashers
 88      Motion_System_13_Vest/OHSRM Warning Flashers/40 Second inverse Latched Delay
 89      Motion_System_13_Vest/Overide Switches
 90      Motion_System_13_Vest/Overide Switches/CL Signal Plot
 91      Motion_System_13_Vest/Overide Switches/HSR Signal Plot
 92      Motion_System_13_Vest/Overide Switches/Left Limit Switch Plot
 93      Motion_System_13_Vest/Overide Switches/MS Signal Plot
 94      Motion_System_13_Vest/Overide Switches/PSR Signal Plot
 95      Motion_System_13_Vest/Overide Switches/Rear Limit Switch Plot
 96      Motion_System_13_Vest/Overide Switches/Rear Limit Switch Plot/Subsystem6
 97      Motion_System_13_Vest/Overide Switches/Right Limit Switch Plot
 98      Motion_System_13_Vest/Overide Switches/Right Limit Switch Plot/Subsystem5
 99      Motion_System_13_Vest/Positions
100      Motion_System_13_Vest/Supervisory Subsystem Input
101      Motion_System_13_Vest/Supervisory Subsystem Input/30s Delay
102      Motion_System_13_Vest/Supervisory Subsystem Input/Limit Switch Check and  Motion Signal Generation
103      Motion_System_13_Vest/Supervisory Subsystem Input/Limit Switch Check and  Motion Signal Generation/45s L
104      Motion_System_13_Vest/Supervisory Subsystem Input/Limit Switch Check and  Motion Signal Generation/Withi
105      Motion_System_13_Vest/Supervisory Subsystem Input/Signal Check
106      Motion_System_13_Vest/Supervisory Subsystem Input/Signal Plot
107      Motion_System_13_Vest/Supervisory Subsystem Input/Signal Plot/Subsystem2
108      Motion_System_13_Vest/Supervisory System Output
109      Motion_System_13_Vest/Supervisory System Output/20 Second  Latched Delay
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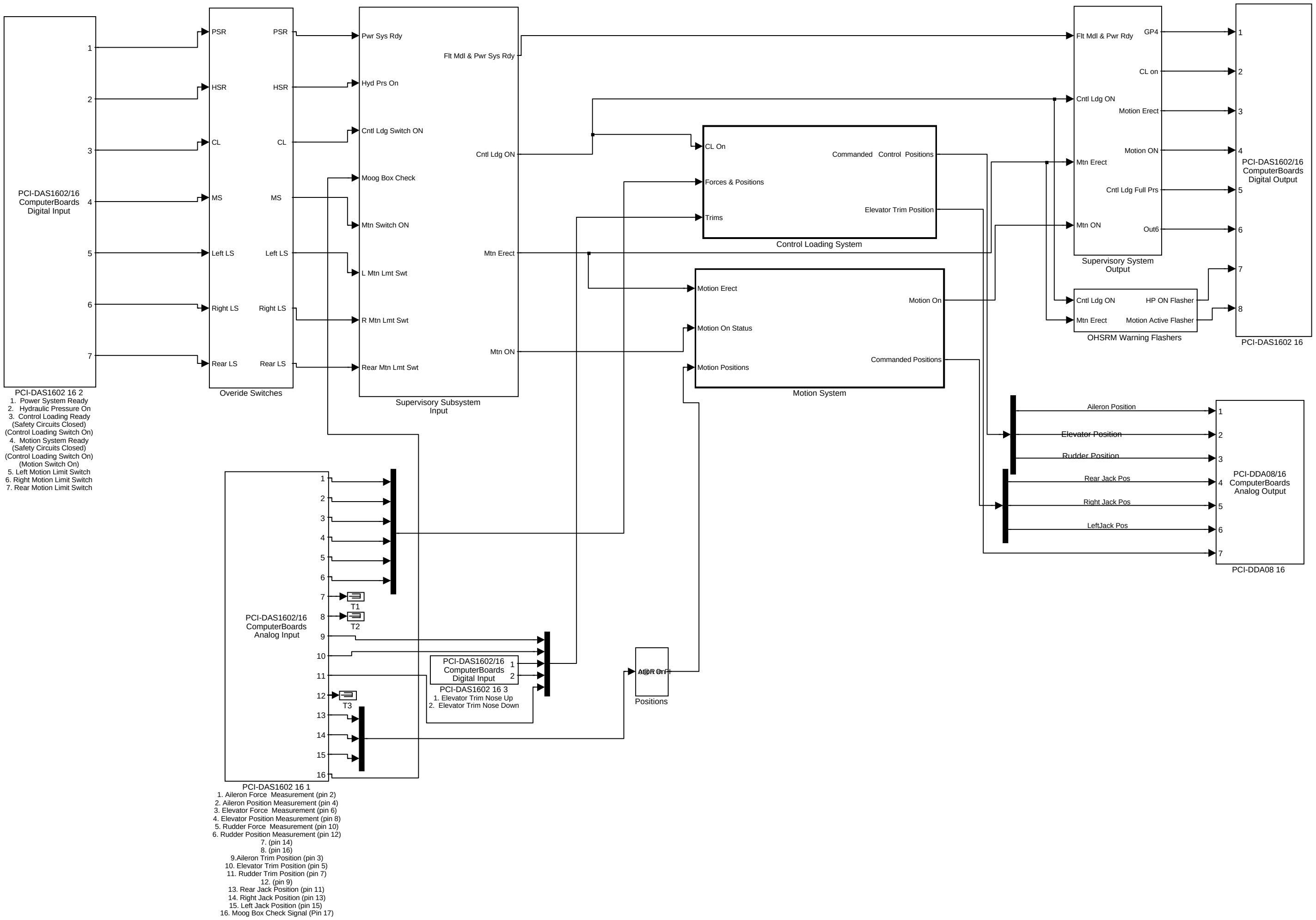
Motion_System_13_Vest



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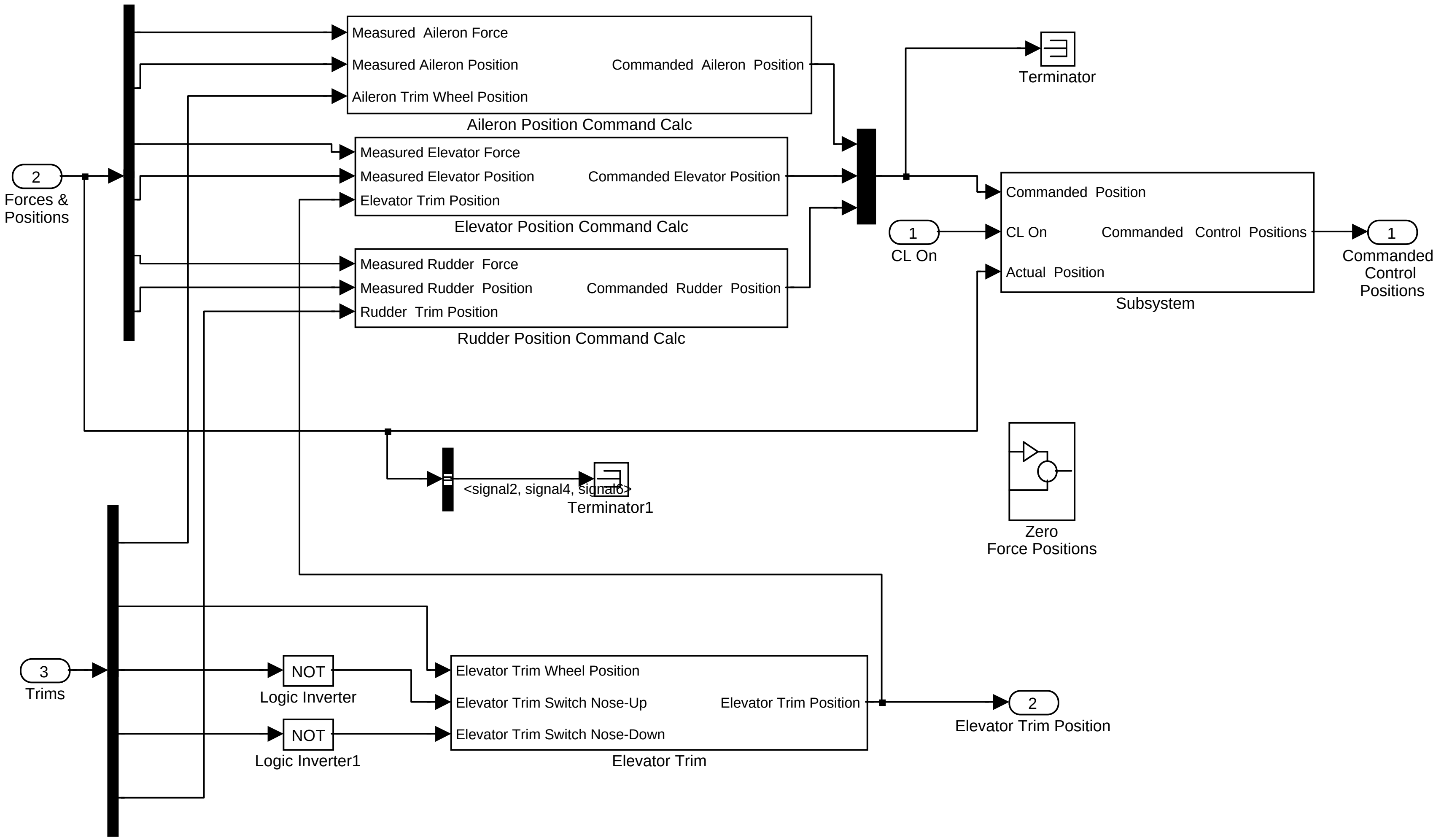
Motion_System_13_Vest/Control Loading System



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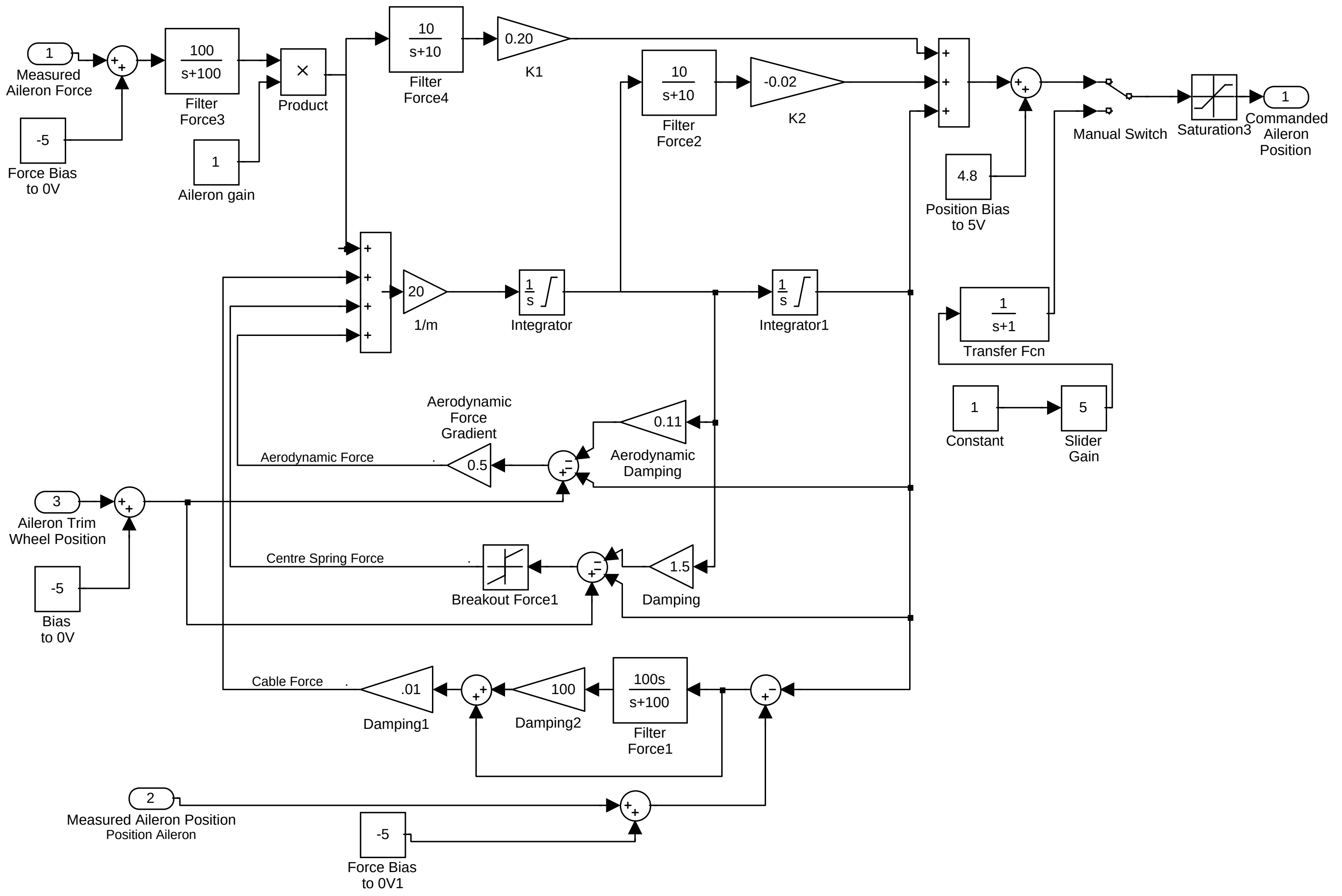
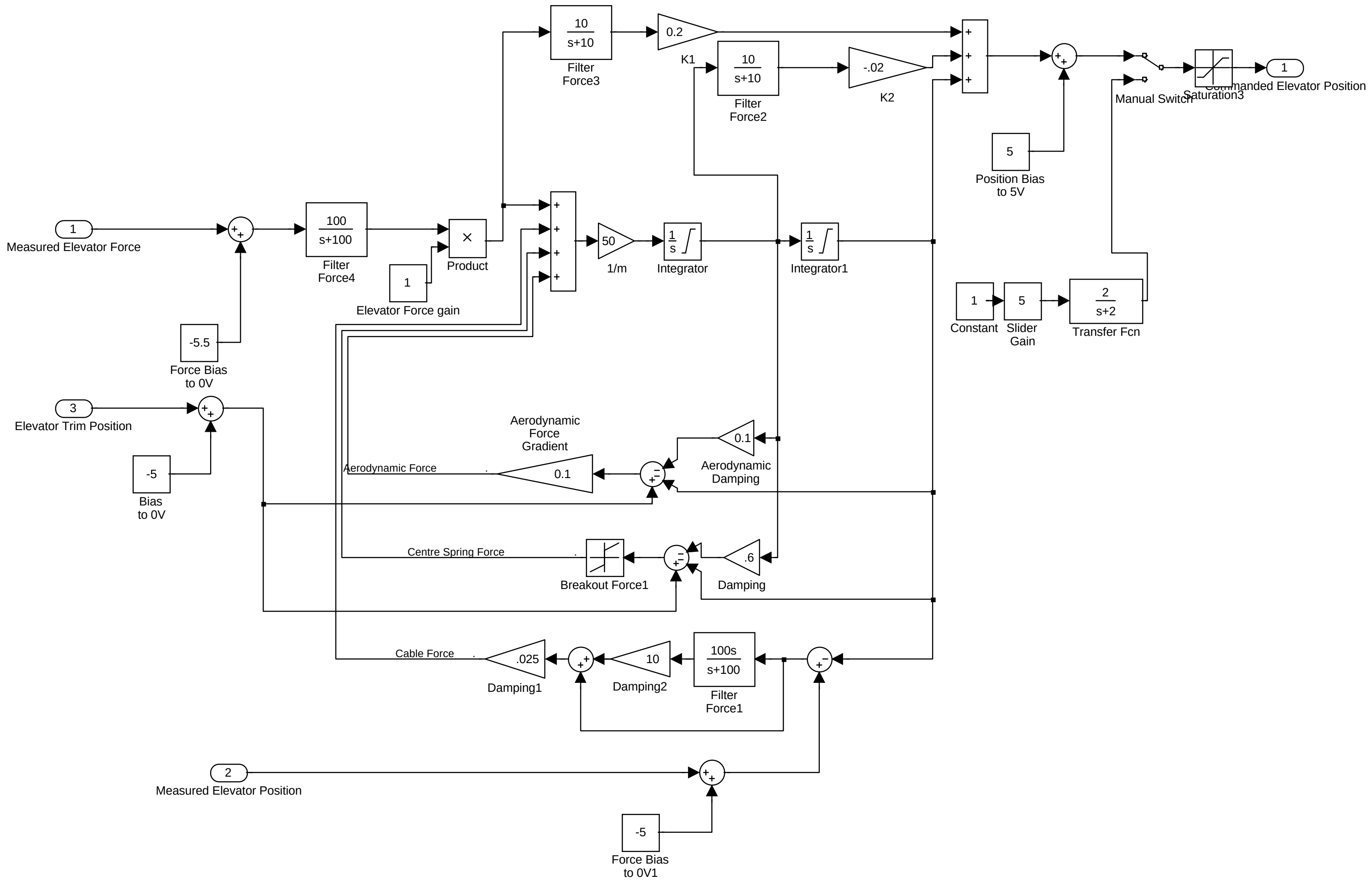
Motion_System_13_Vest/Control Loading System/Aileron Position Command Calc



Motion_System_13_Vest/Control Loading System/Elevator Position Command Calc



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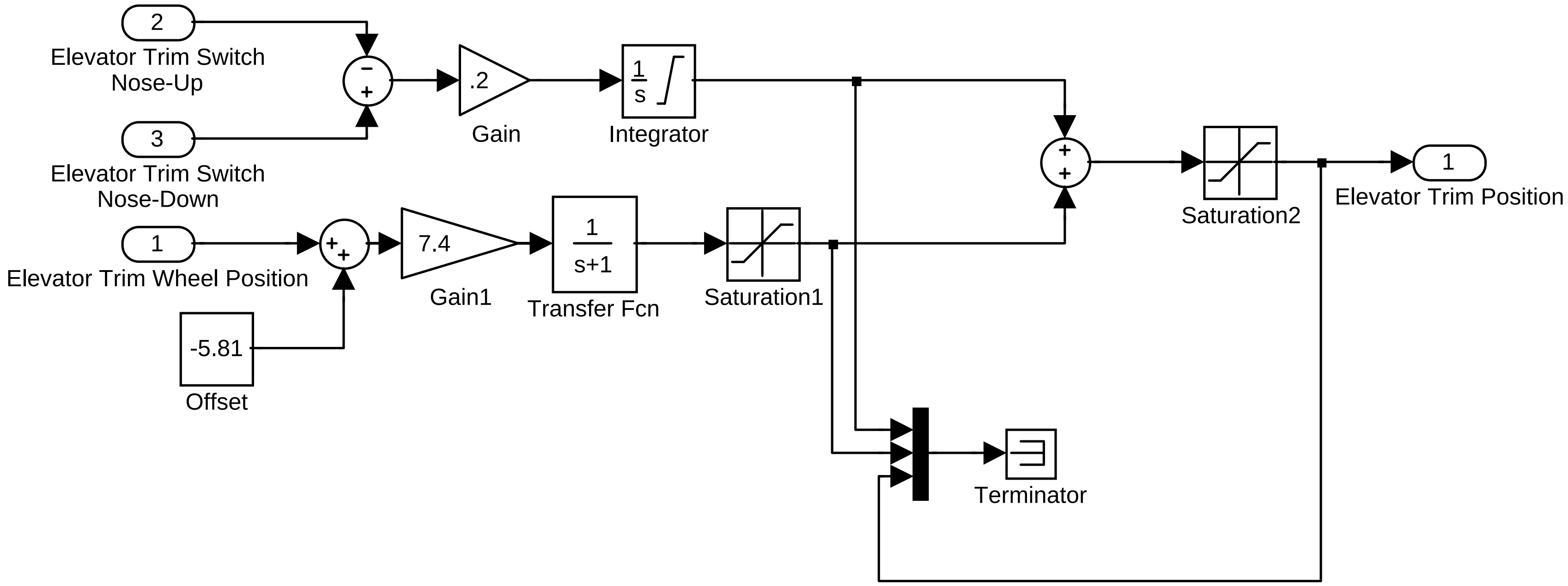

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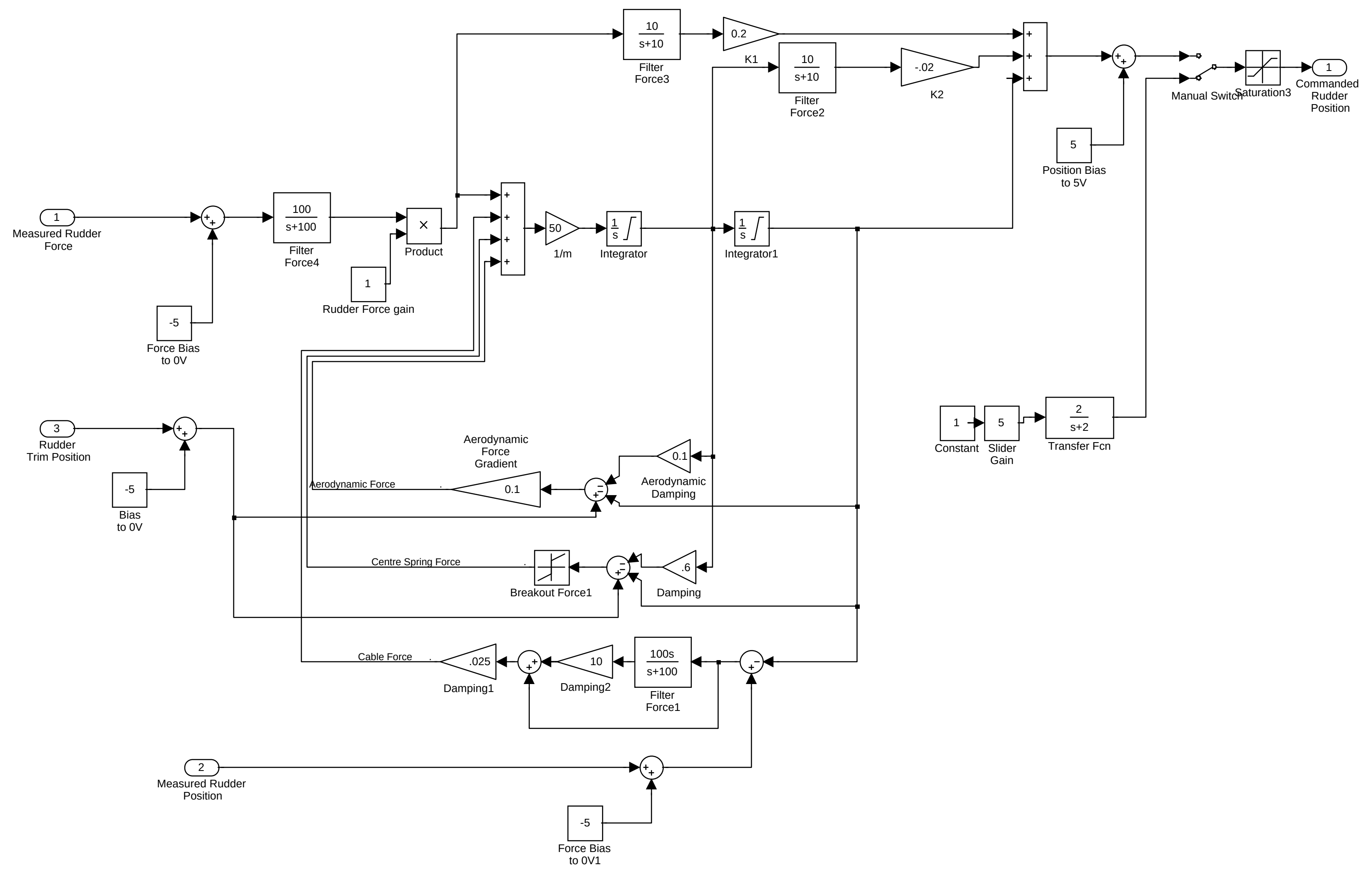
Motion_System_13_Vest/Control Loading System/Rudder Position Command Calc



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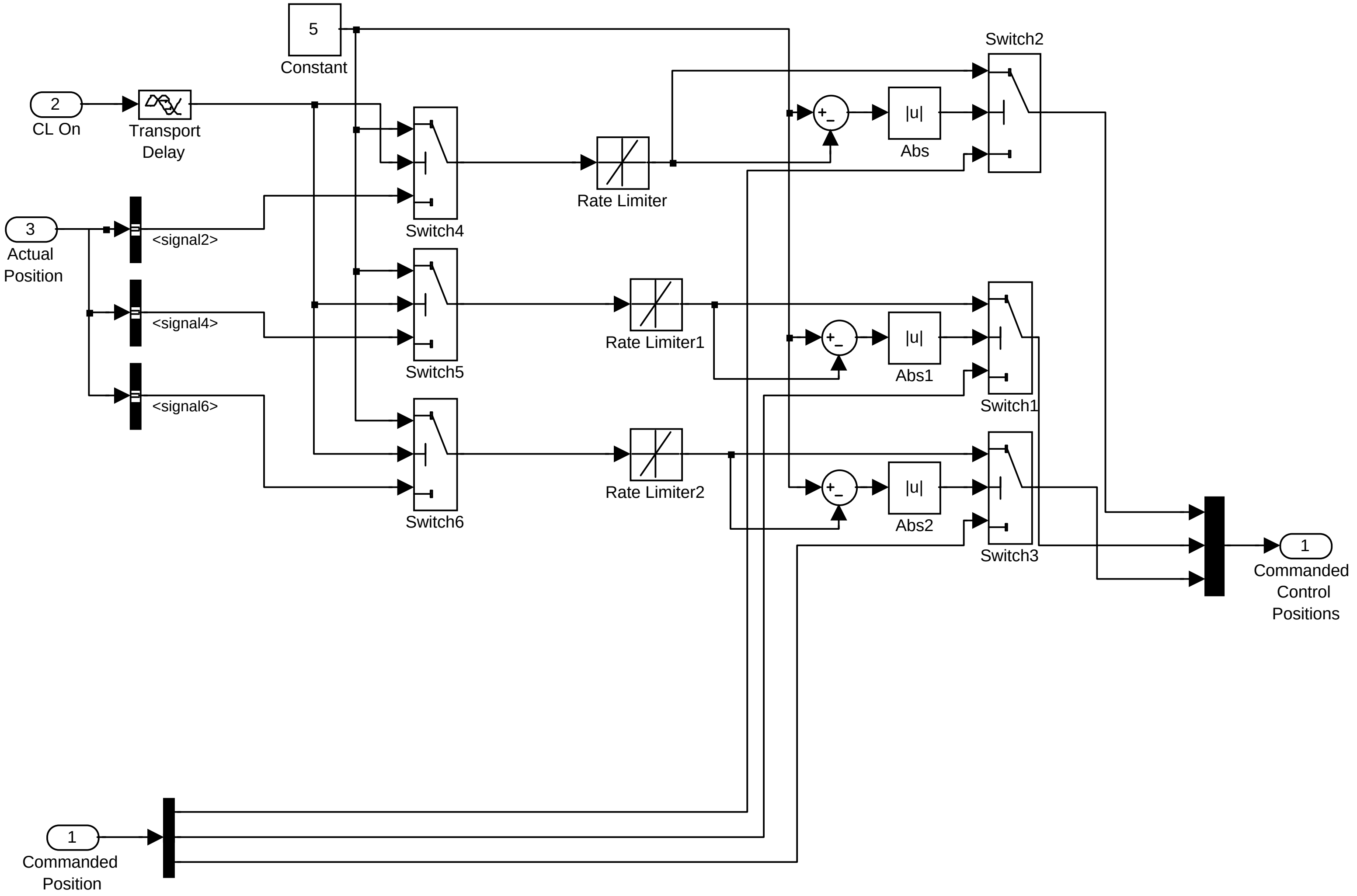

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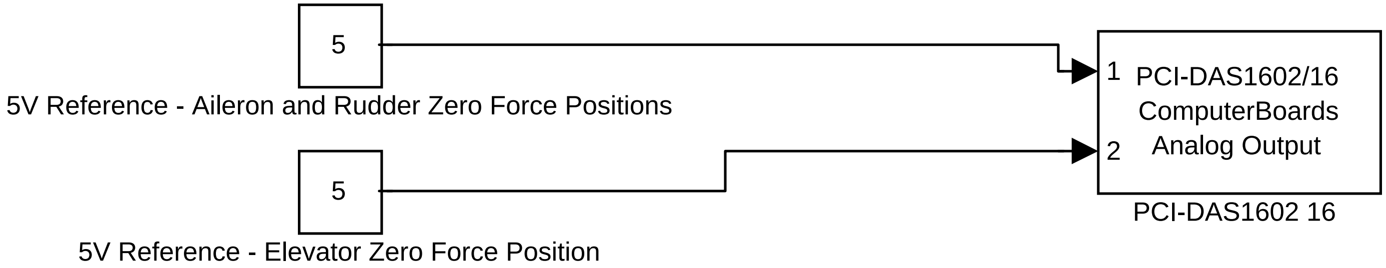
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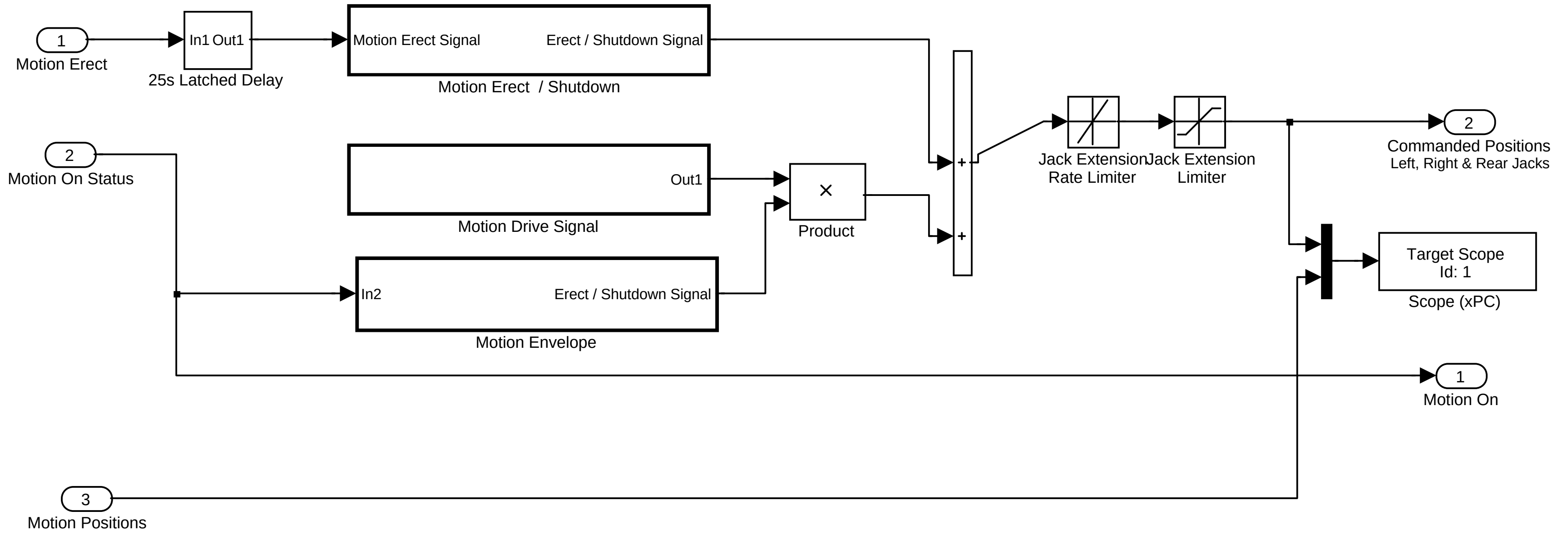
5V Reference - Aileron and Rudder Zero Force Positions
5
5V Reference - Elevator Zero Force Position
1
2
PCI-DAS1602/16
ComputerBoards
Analog Output
PCI-DAS1602 16

Motion_System_13_Vest/Motion System



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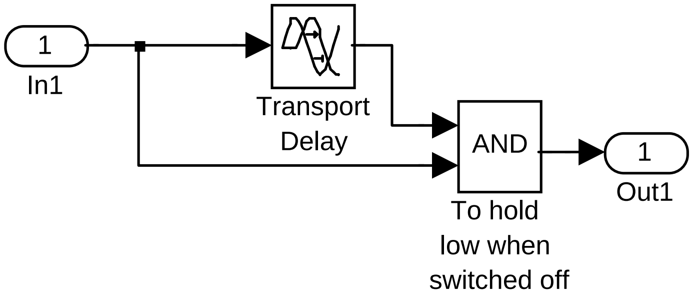

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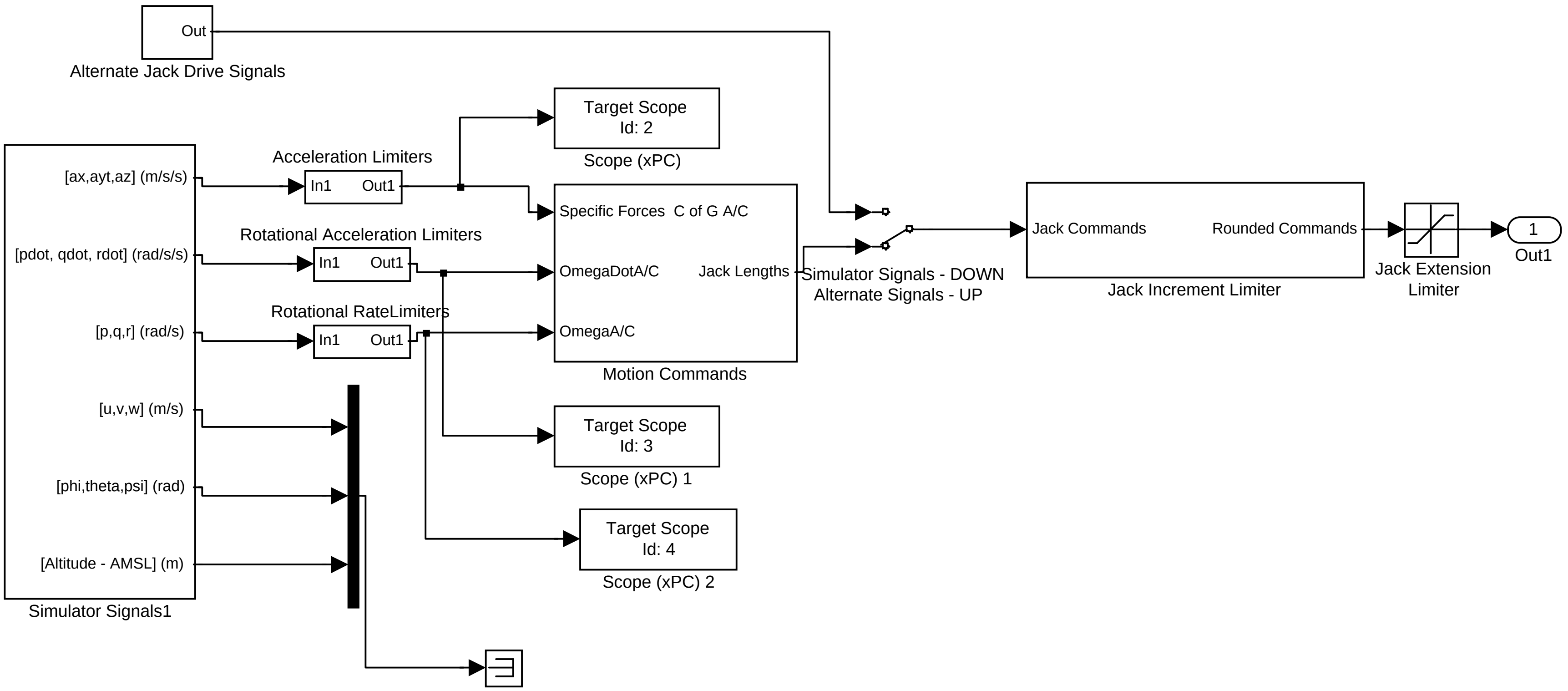

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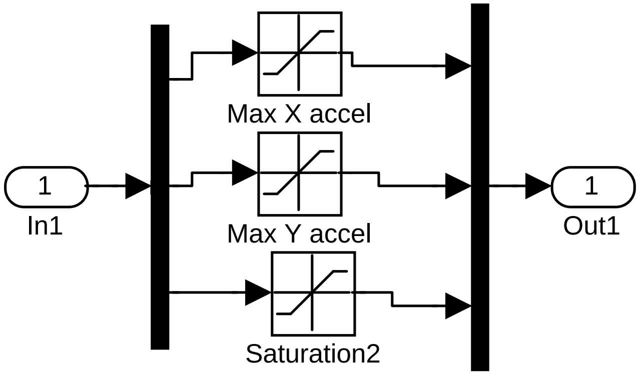

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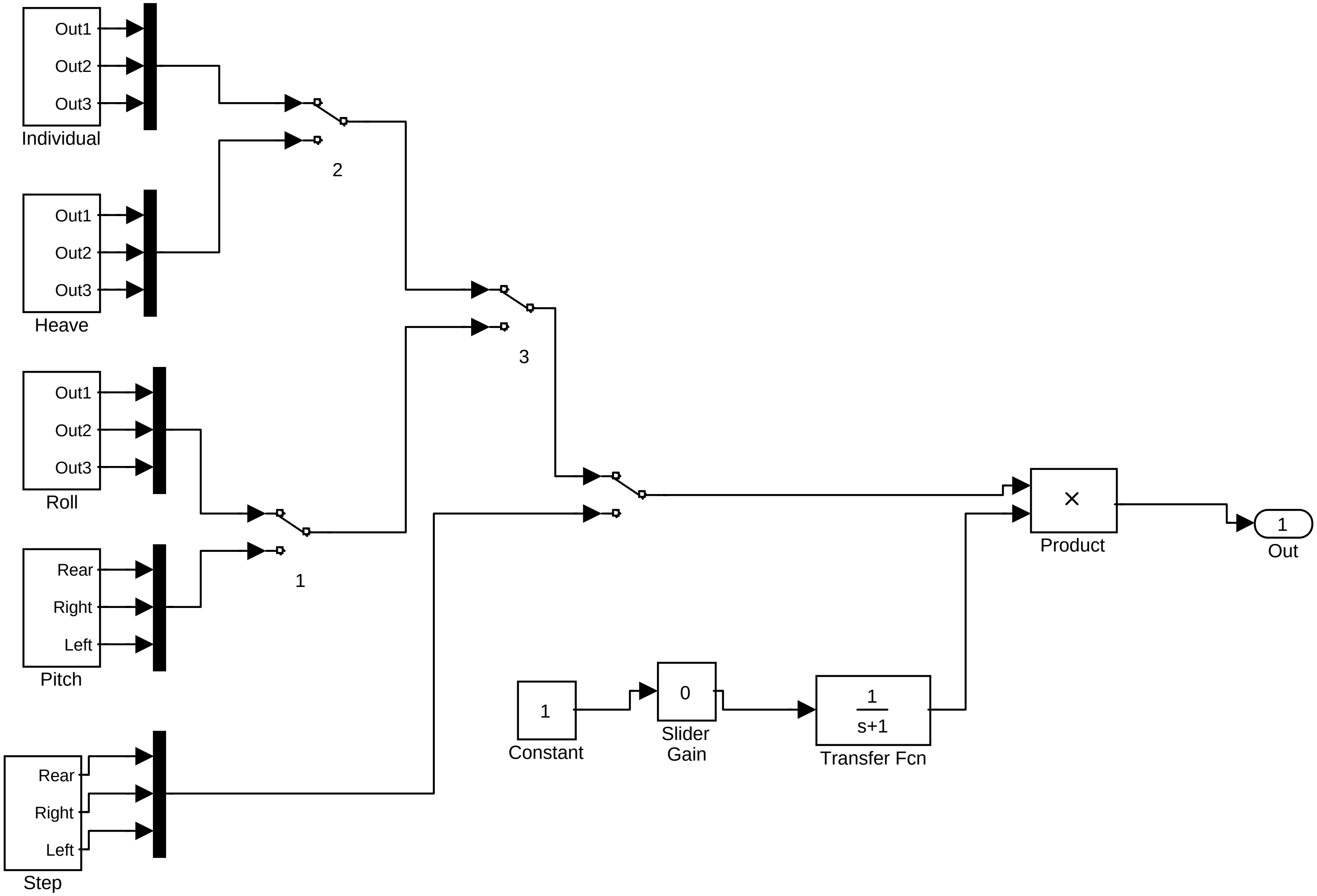

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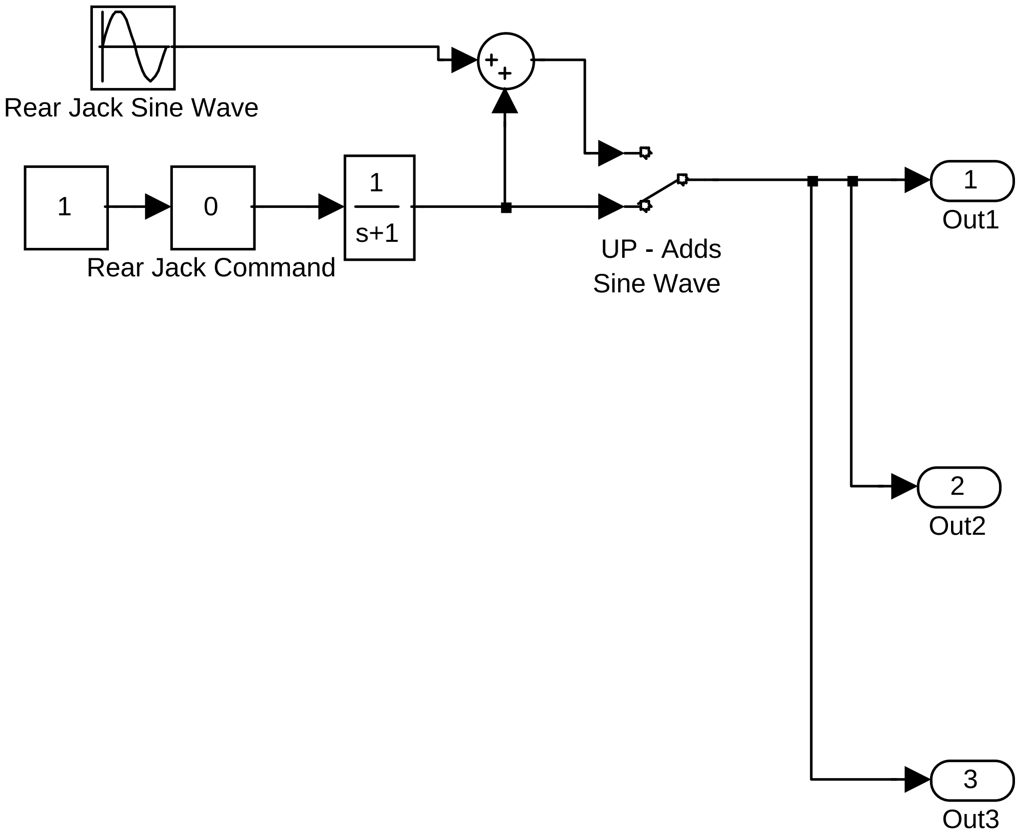

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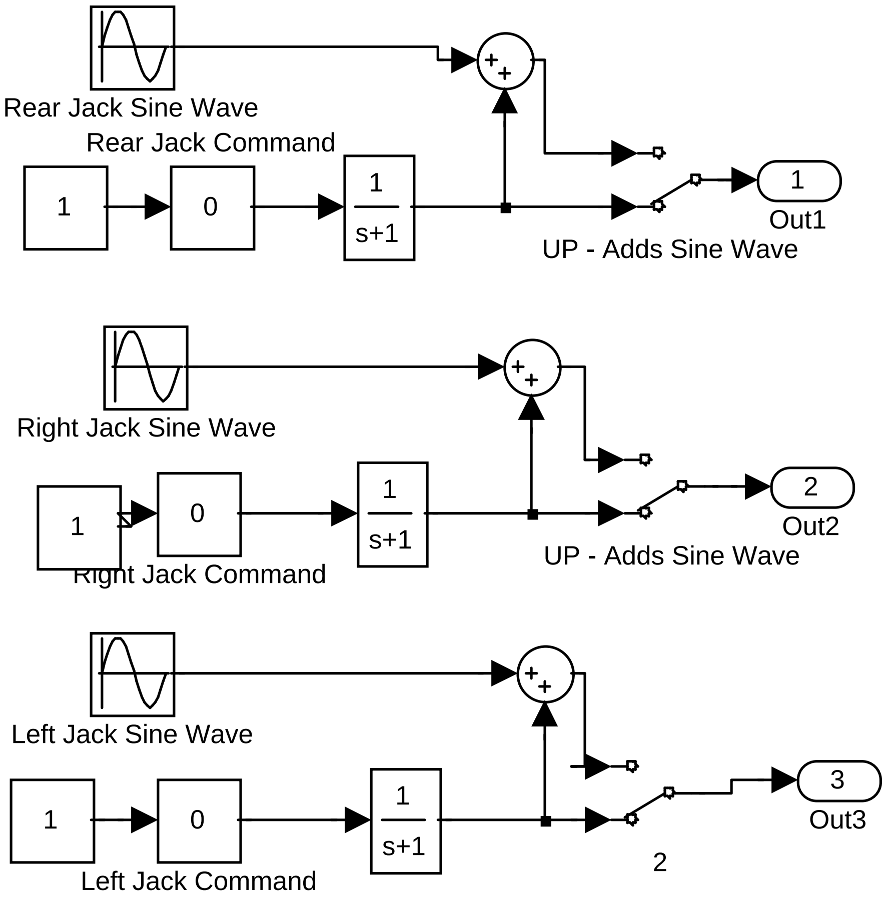

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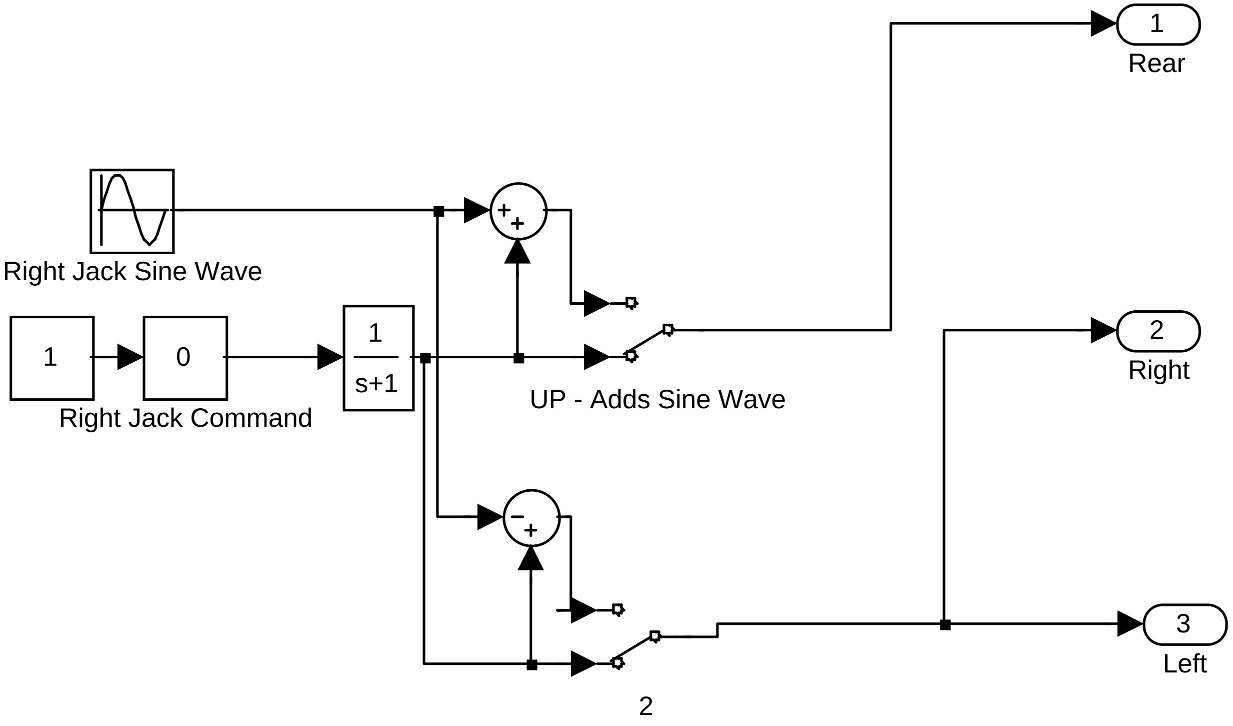

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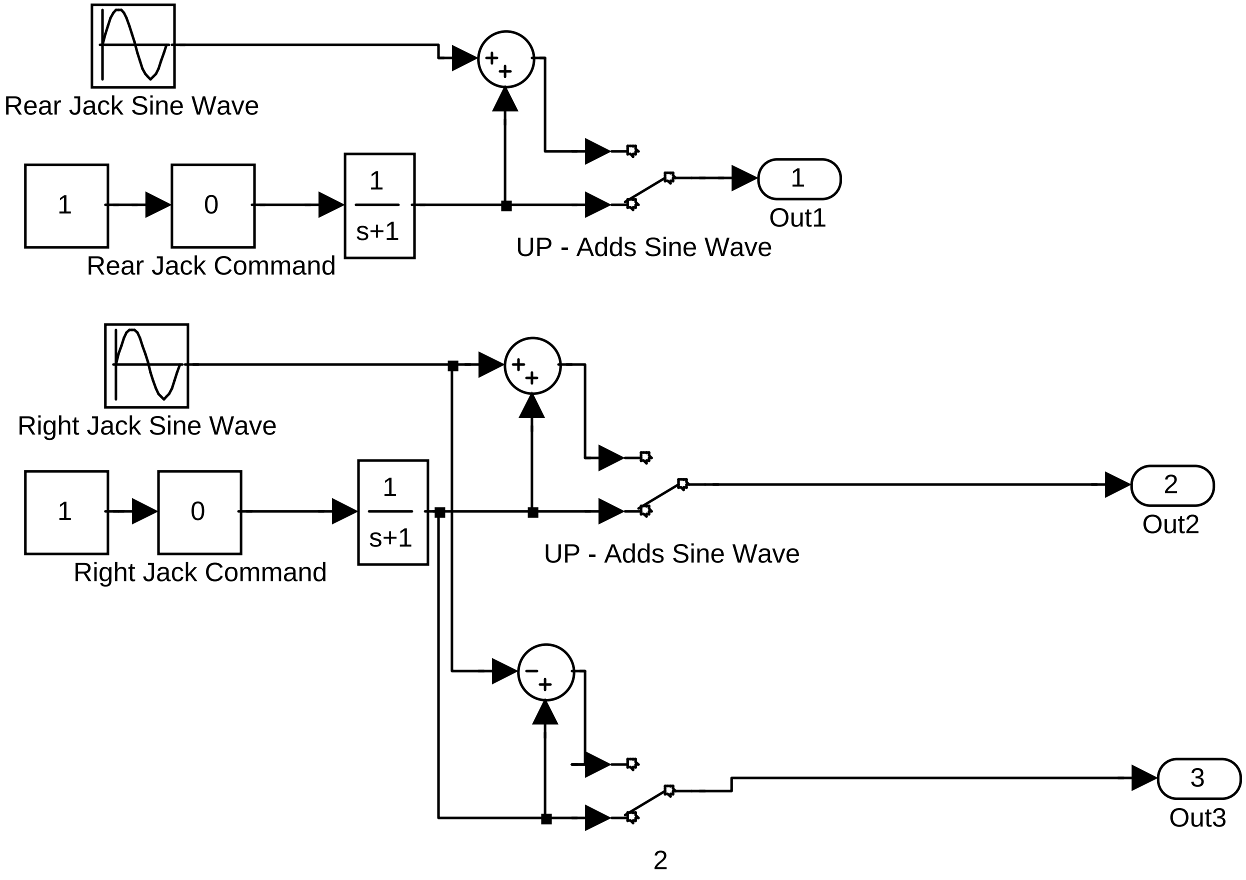
Motion_System_13_Vest/Motion System/Motion Drive Signal/Alternate Jack Drive Signals/Roll



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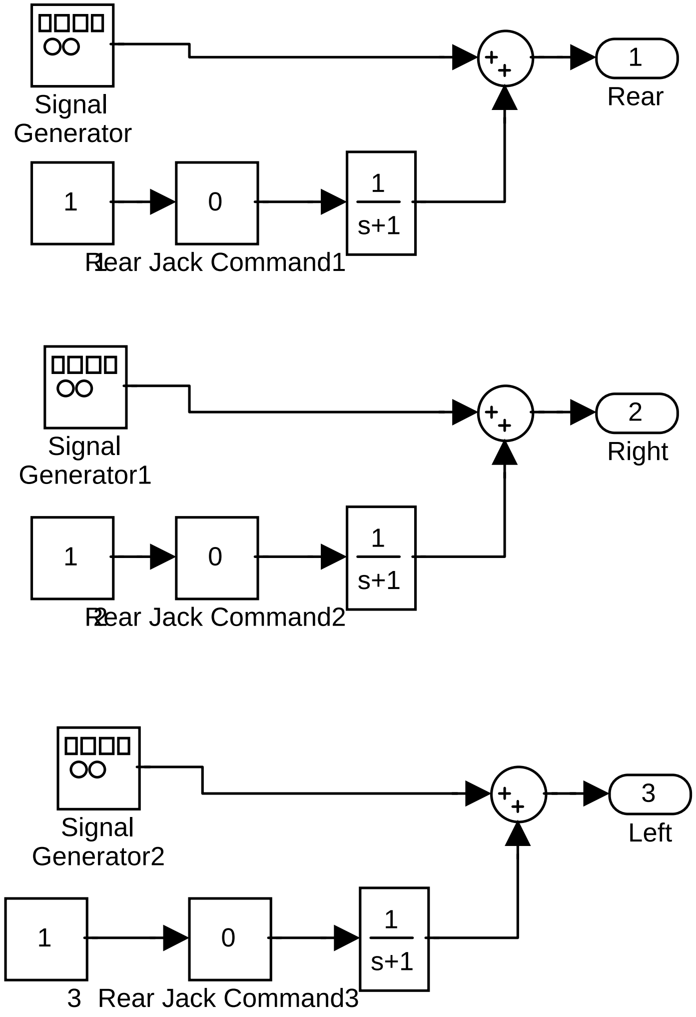
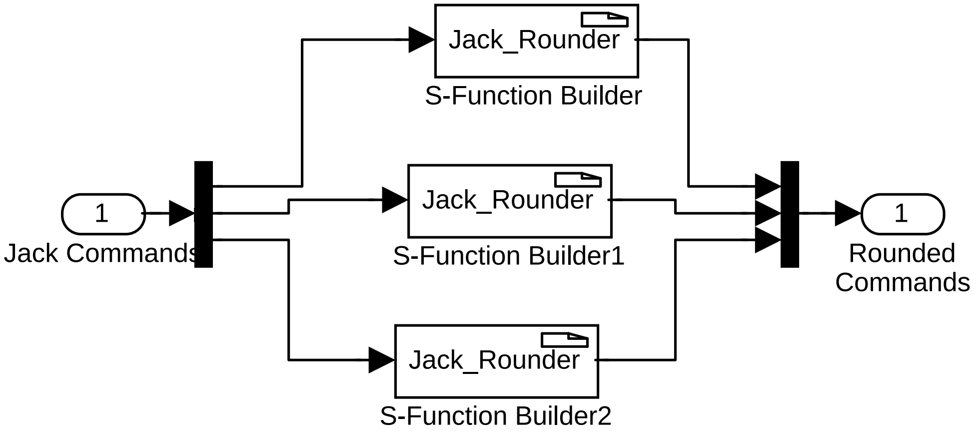
Motion_System_13_Vest/Motion System/Motion Drive Signal/Alternate Jack Drive Signals/Step



Motion_System_13_Vest/Motion System/Motion Drive Signal/Jack Increment Limiter



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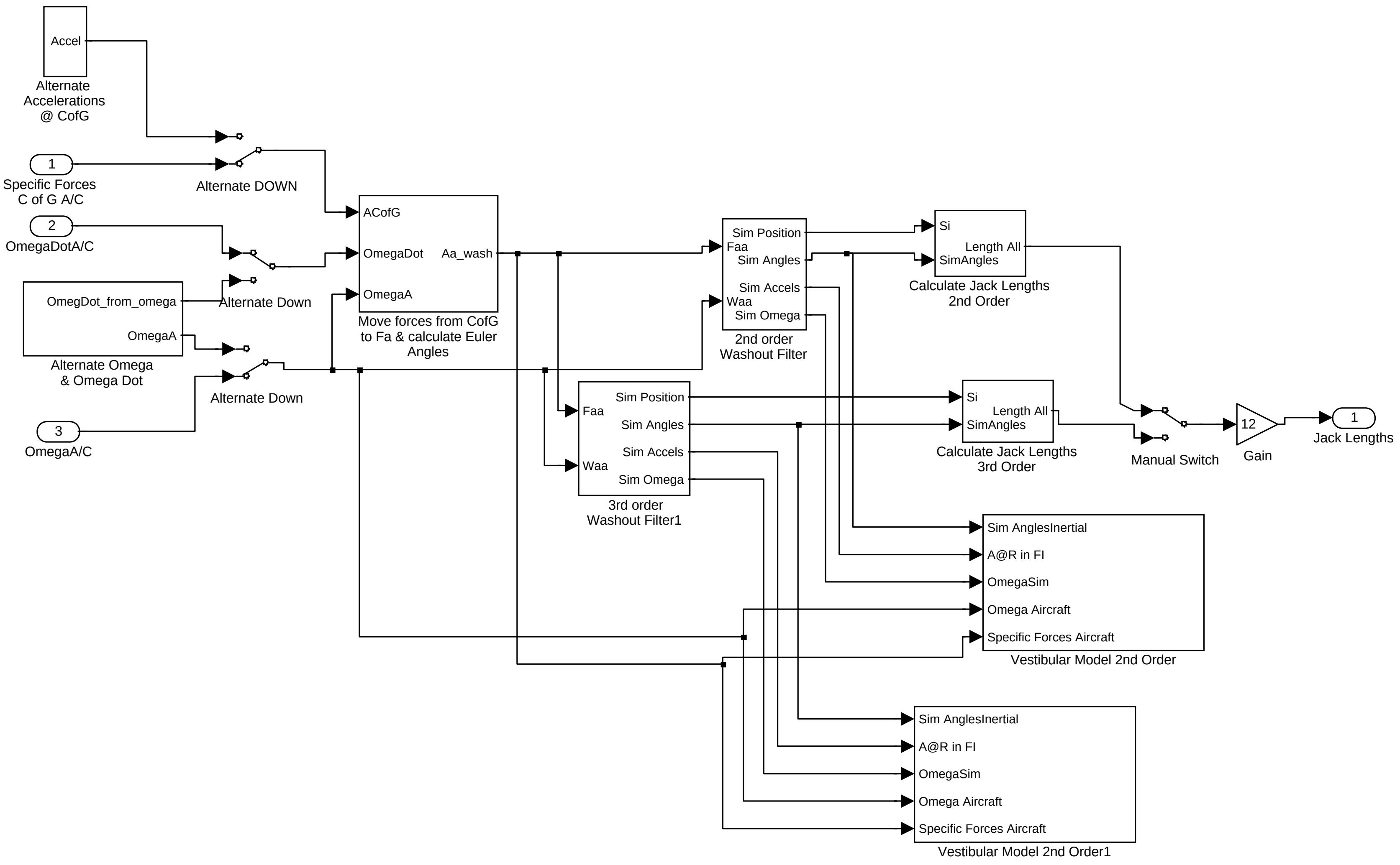
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

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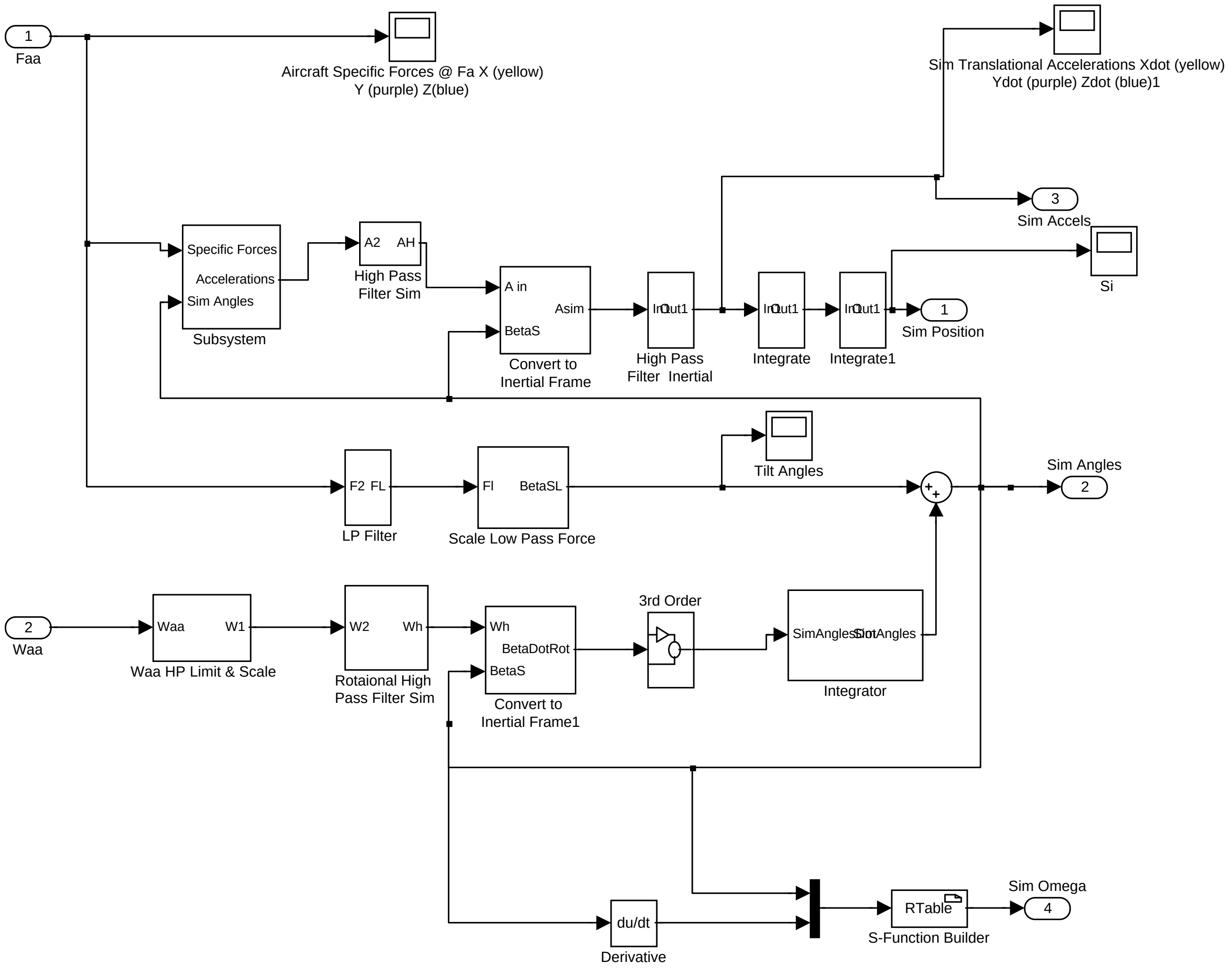
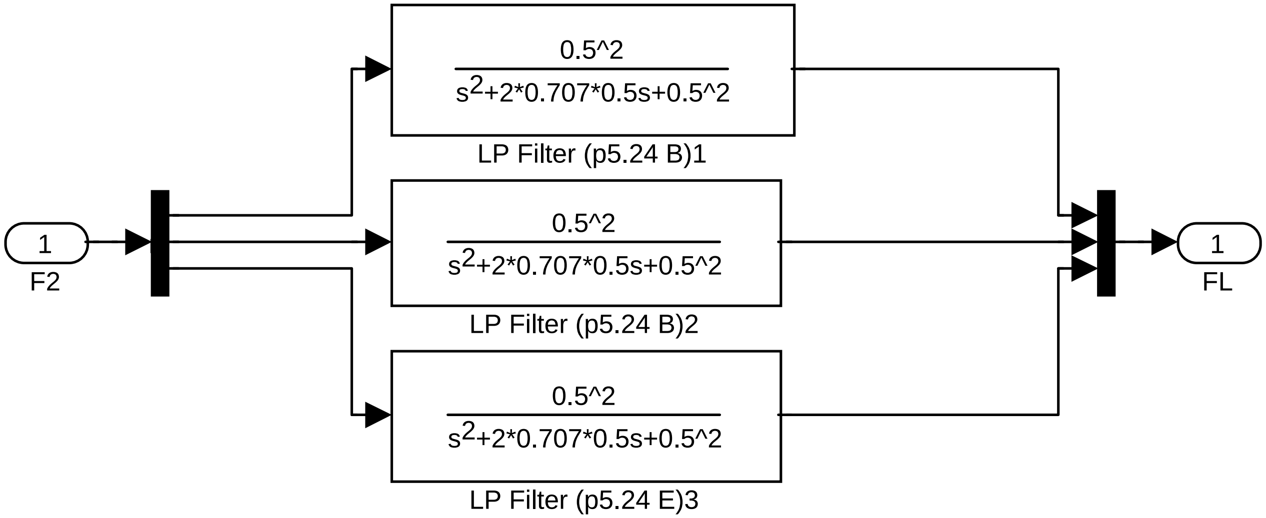
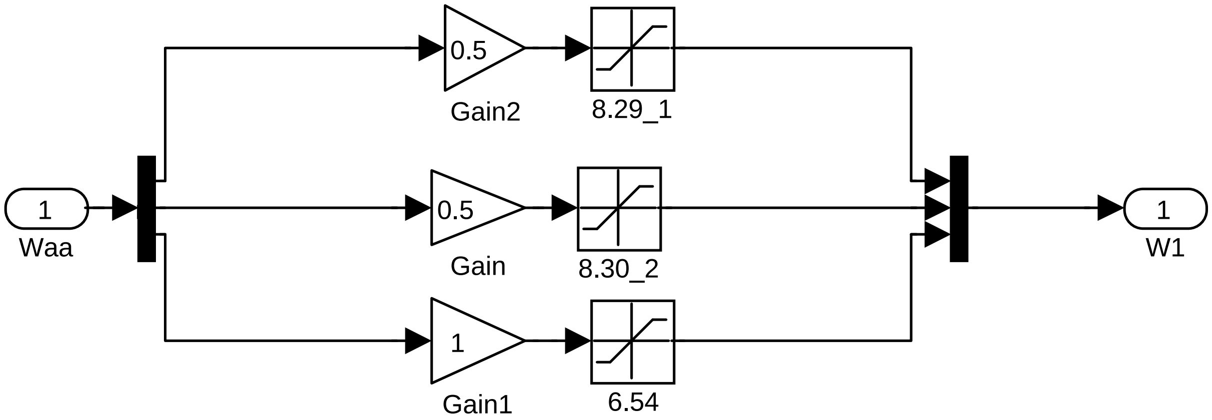
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/ 3rd order Washout Filter1



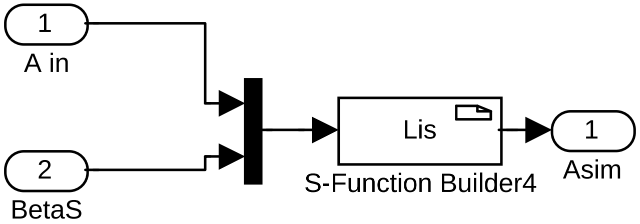

1
F2
0.5^2
s^2+2*0.707*0.5s+0.5^2
LP Filter (p5.24 B)1
0.5^2
s^2+2*0.707*0.5s+0.5^2
LP Filter (p5.24 B)2
0.5^2
s^2+2*0.707*0.5s+0.5^2
LP Filter (p5.24 E)3
1
FL

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/ 3rd order Washout Filter1/ Waa HP Limit & Scale



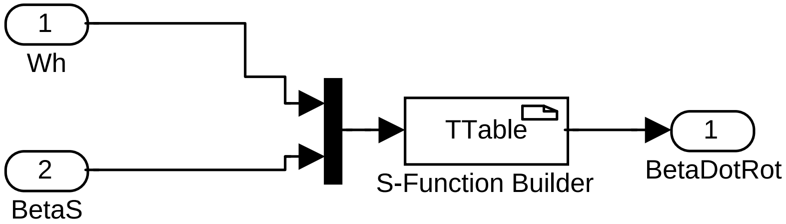
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/ 3rd order Washout Filter1/Convert to Inertial Frame



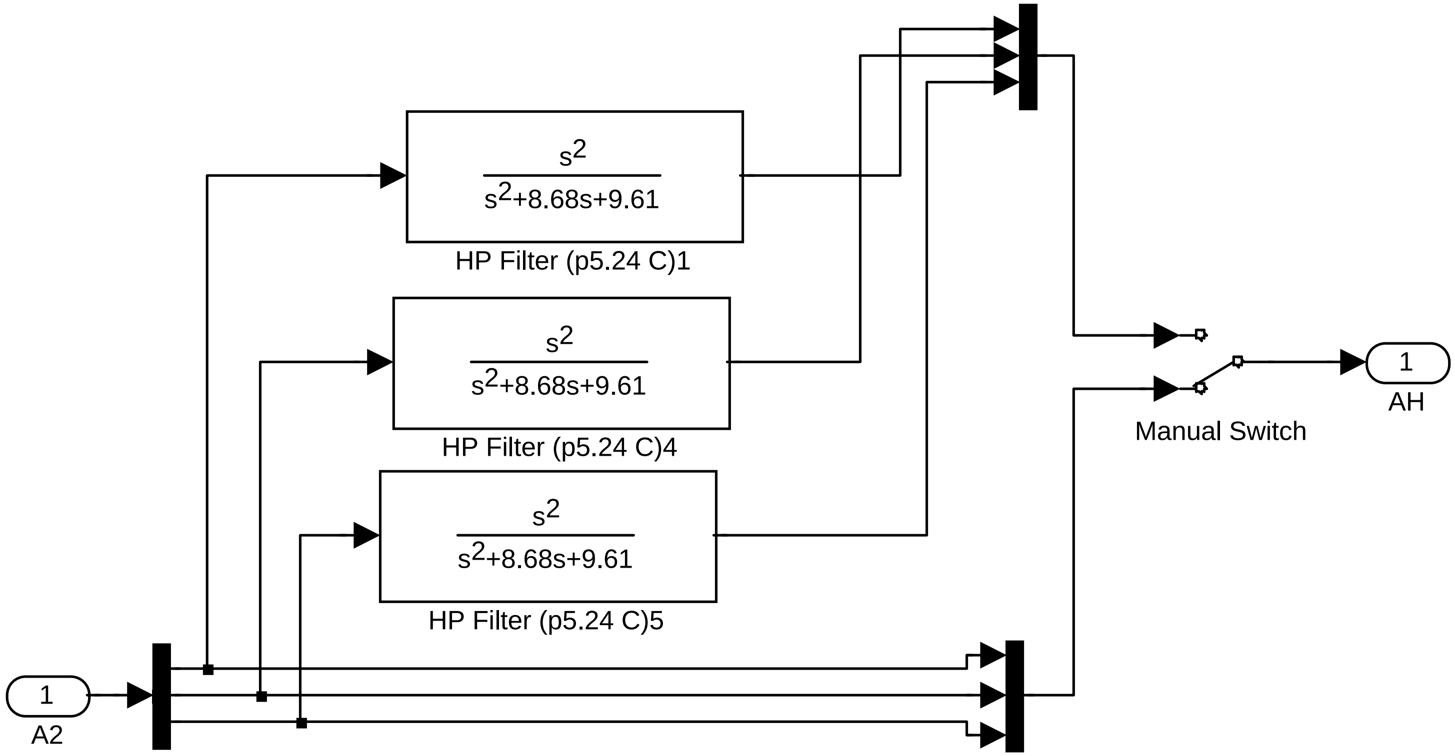
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/ 3rd order Washout Filter1/Convert to Inertial Frame1



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/ 3rd order Washout Filter1/High Pass Filter Sim



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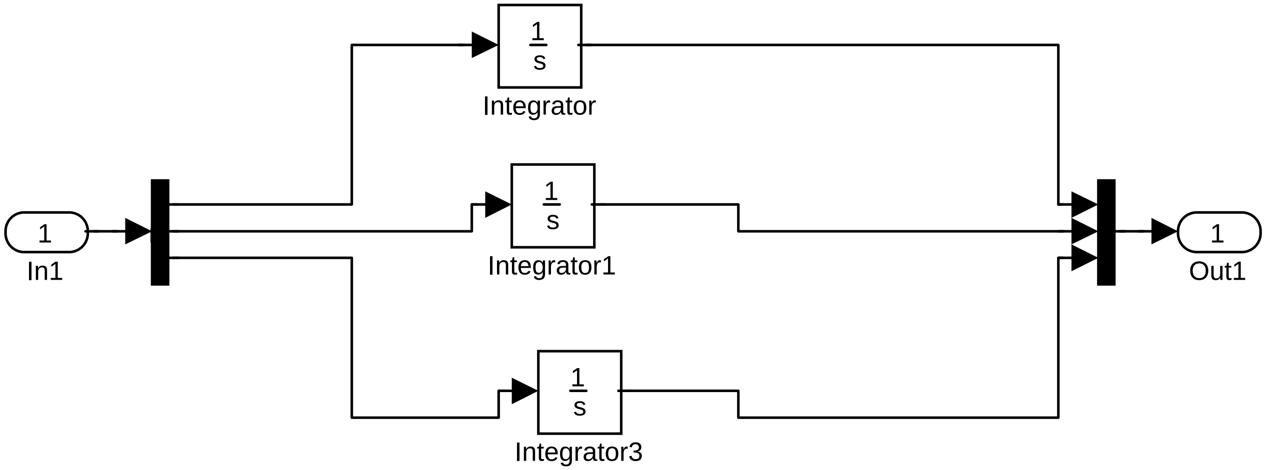
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/ 3rd order Washout Filter1/Integrate



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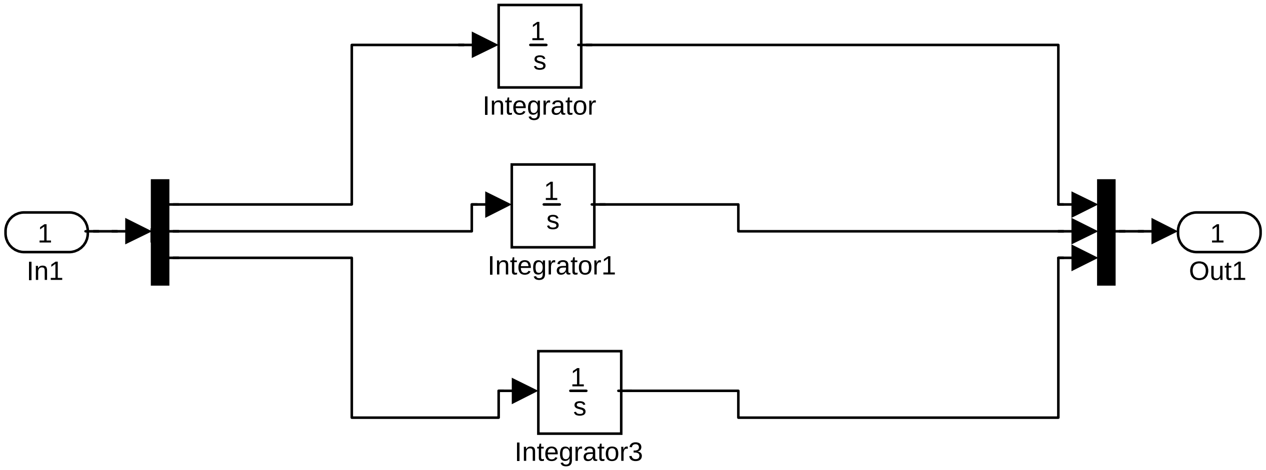
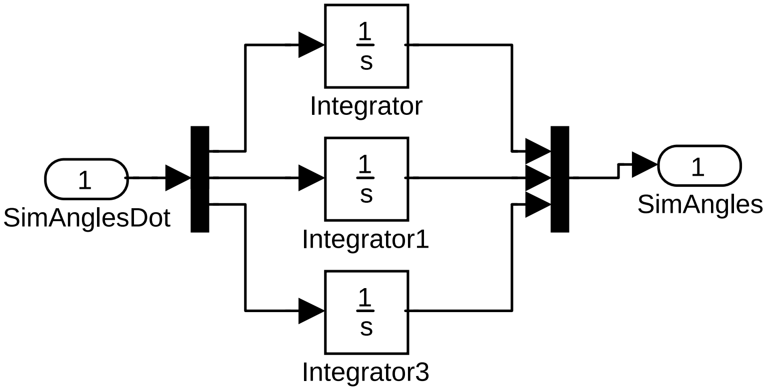
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/ 3rd order Washout Filter1/Integrate1



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/ 3rd order Washout Filter1/Integrator



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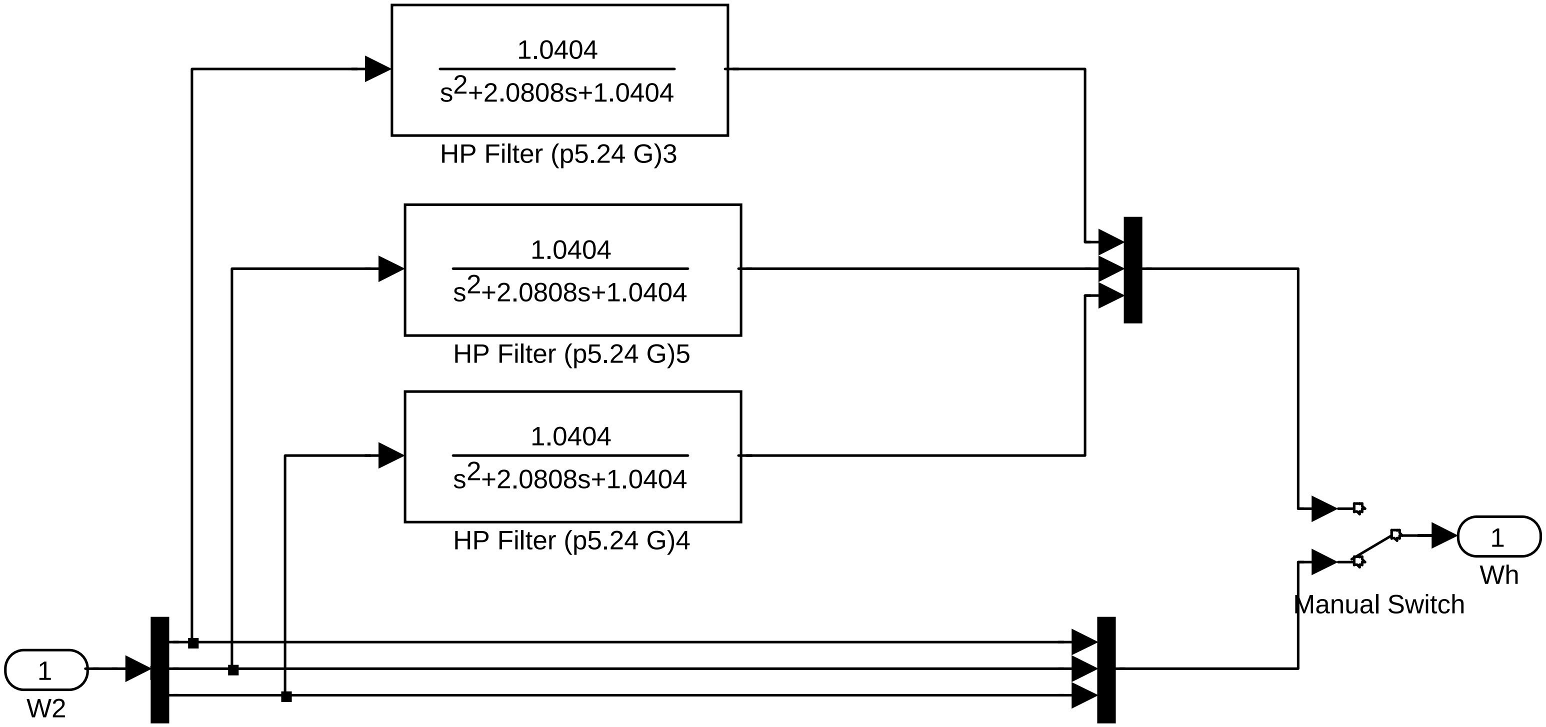
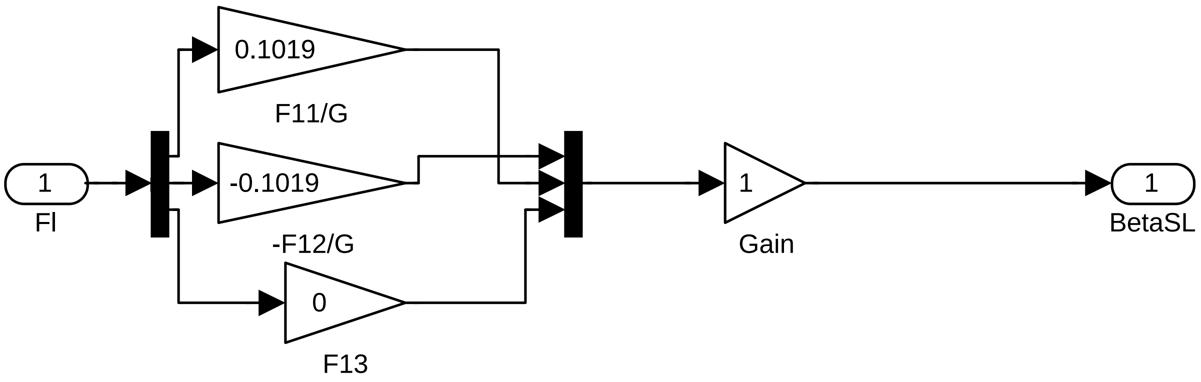
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/ 3rd order Washout Filter1/Rotaional High Pass Filter Sim



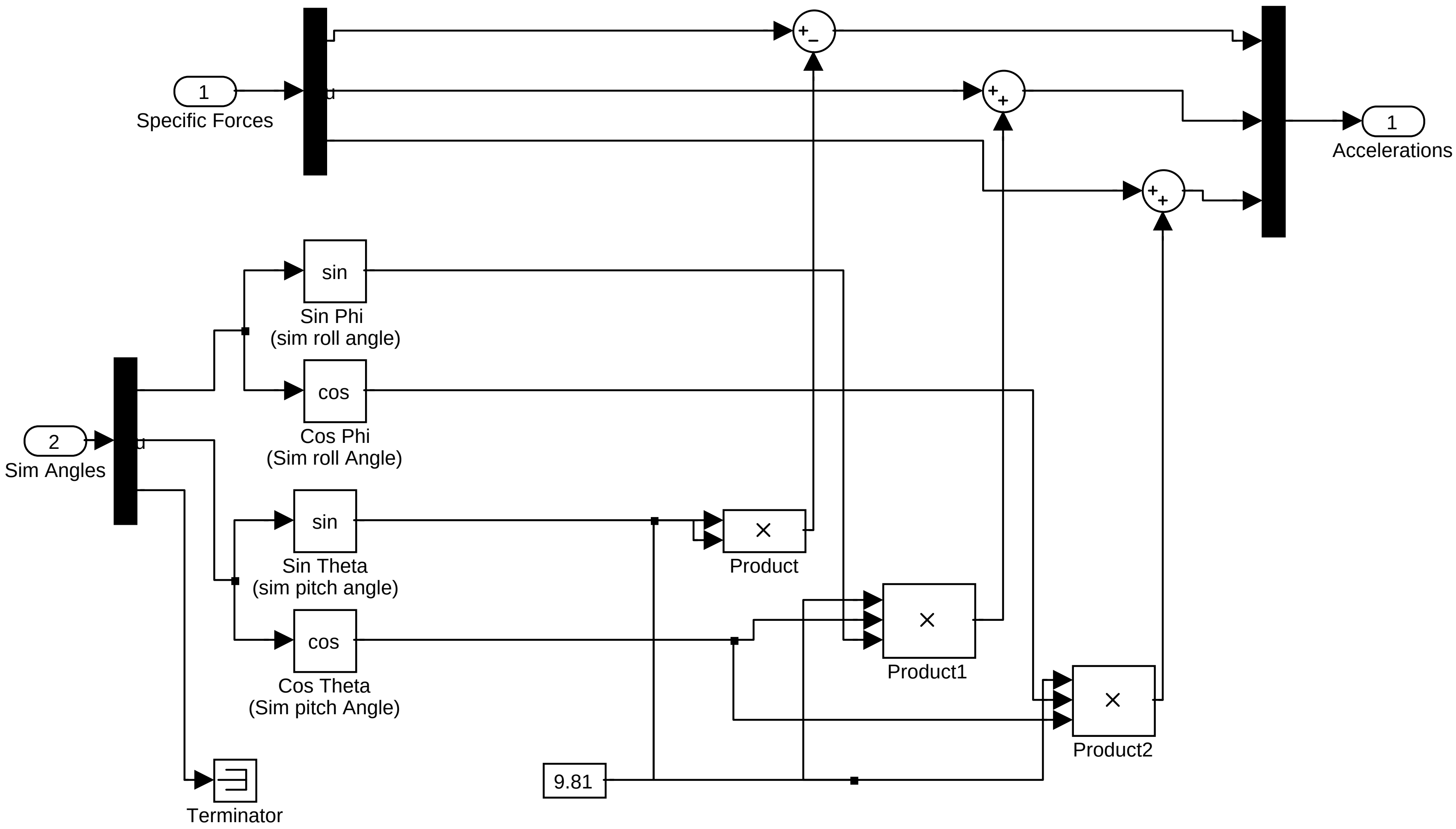
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/ 3rd order Washout Filter1/Scale Low Pass Force



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/ 3rd order Washout Filter1/Subsystem



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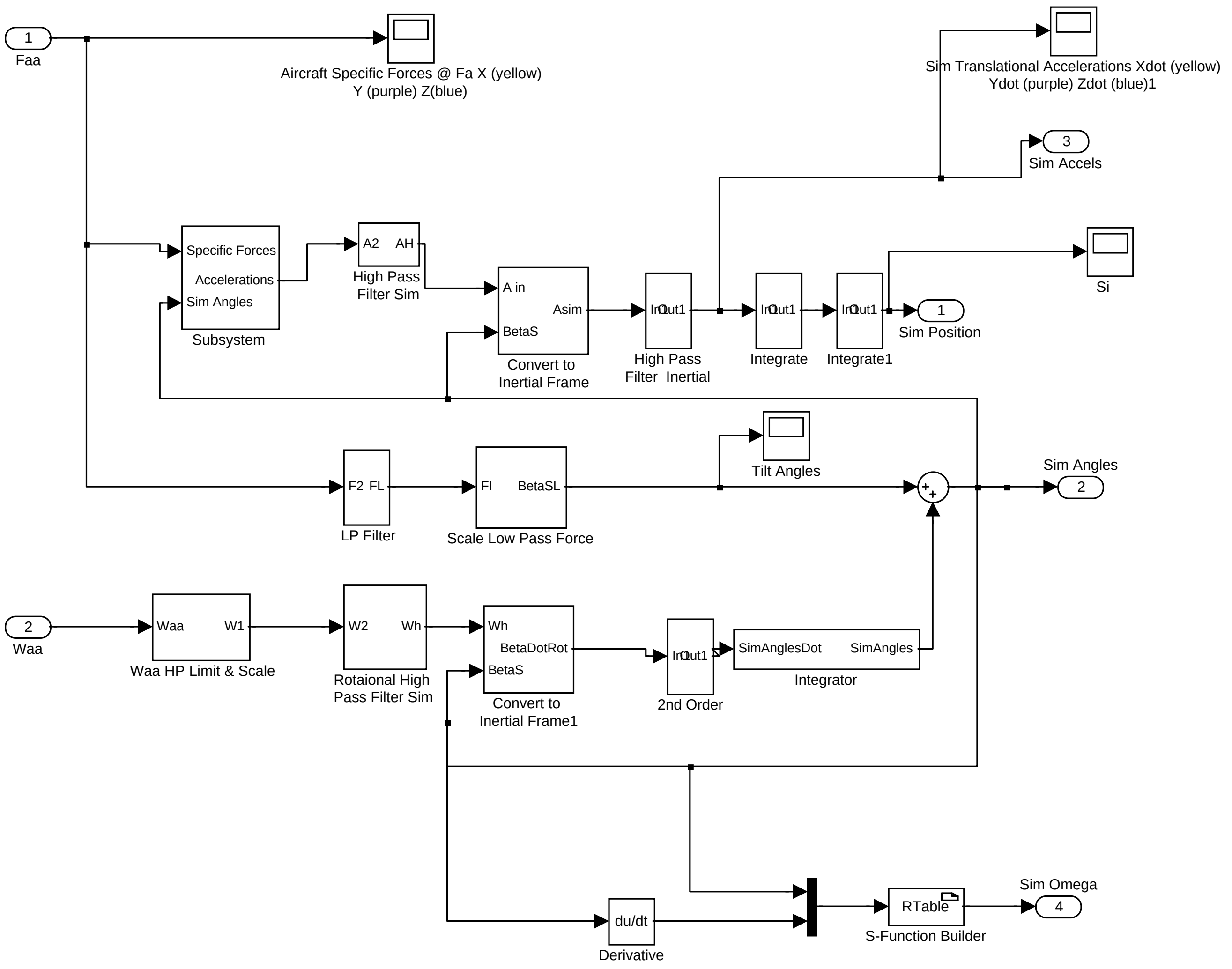
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter



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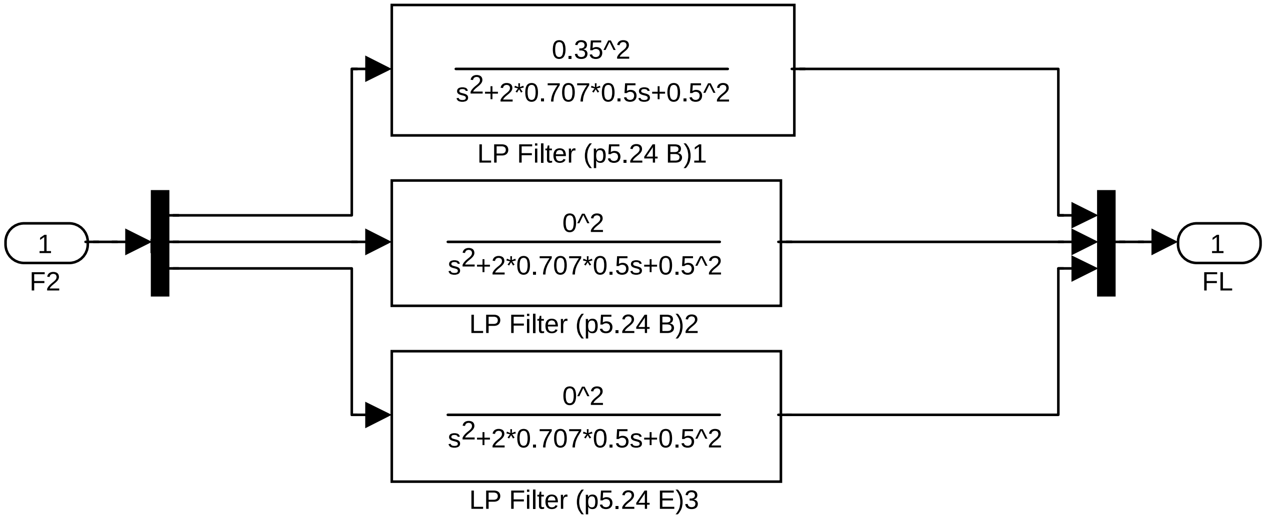
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/ LP Filter



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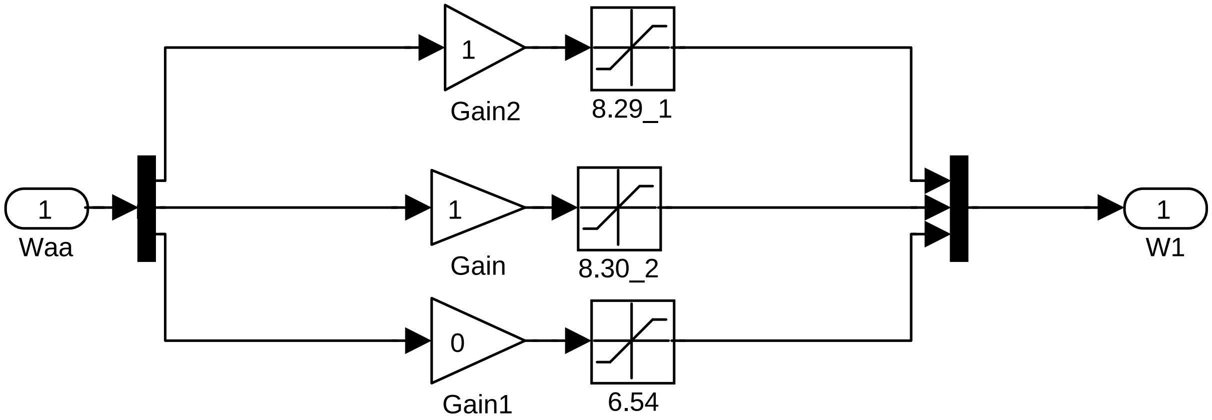
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/ Waa HP Limit & Scale



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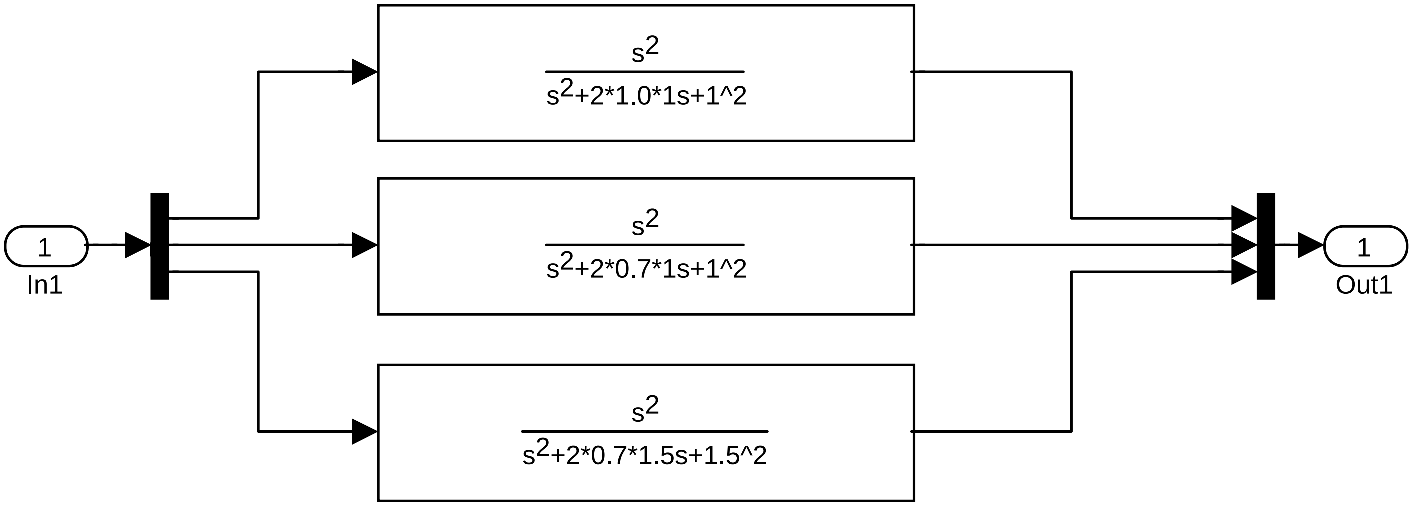
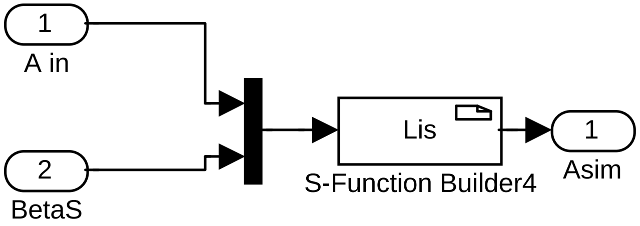
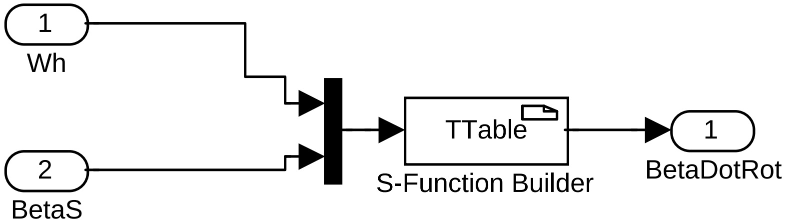
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/2nd Order



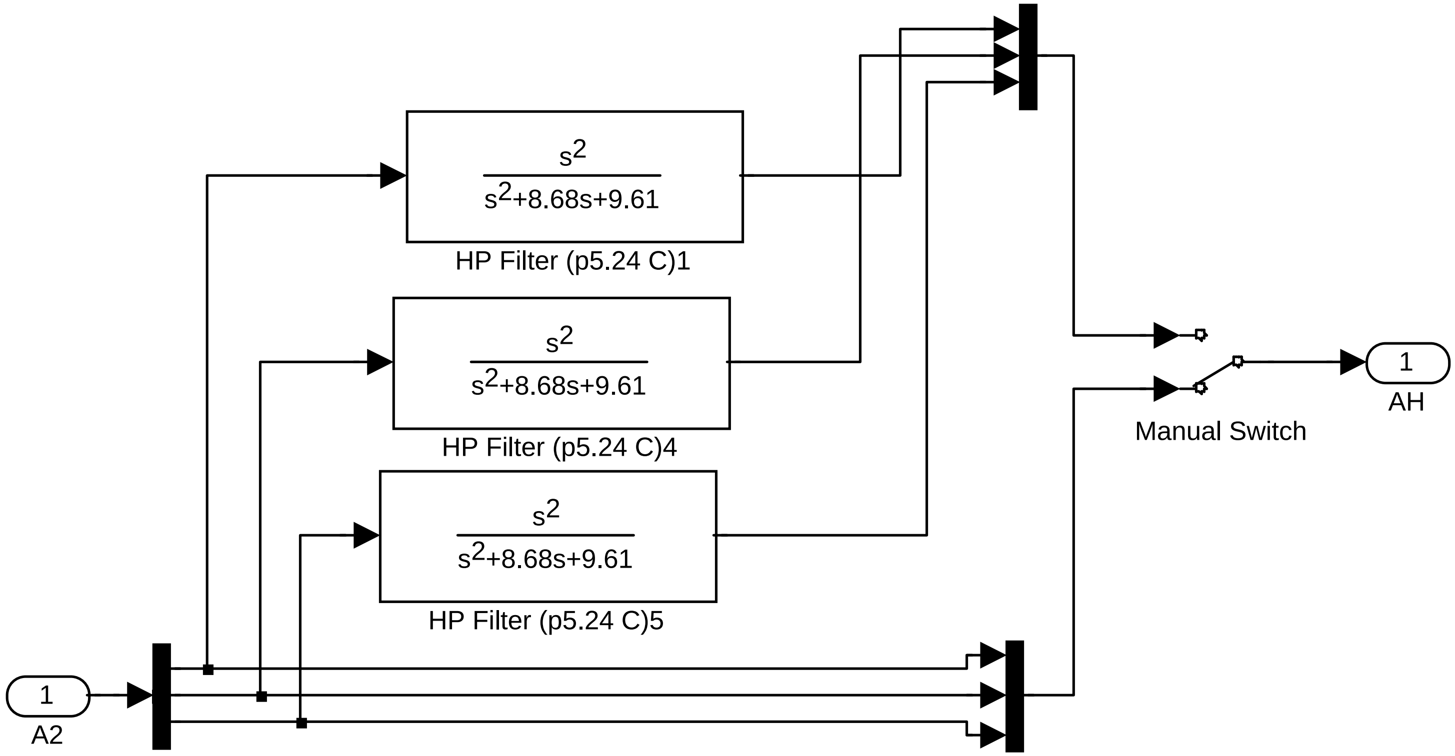

1
A in
2
BetaS
Lis
S-Function Builder4
1
Asim

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/Convert to Inertial Frame1



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/High Pass Filter Sim



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

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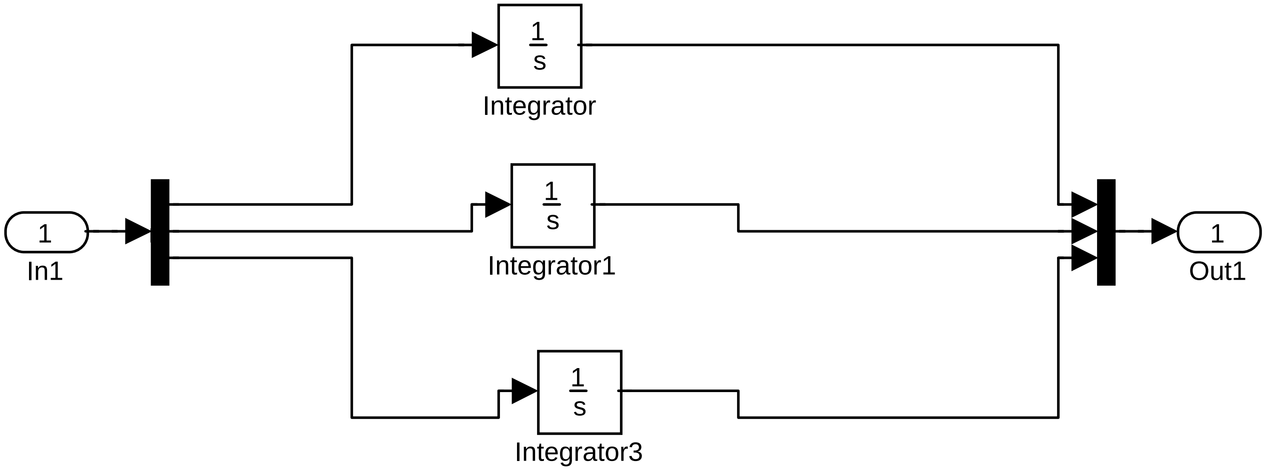
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/Integrate



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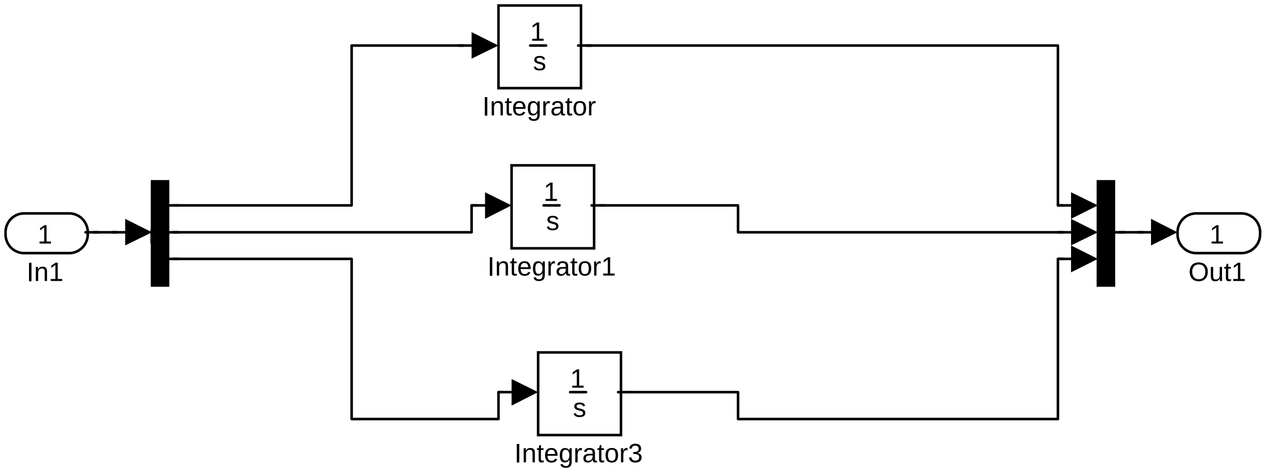
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/Integrate1



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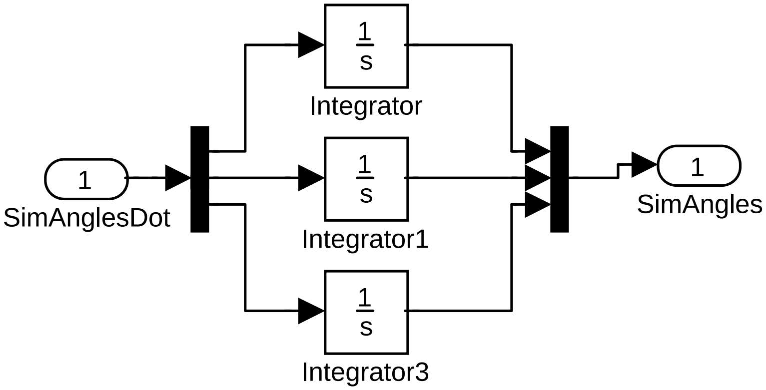
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/Integrator



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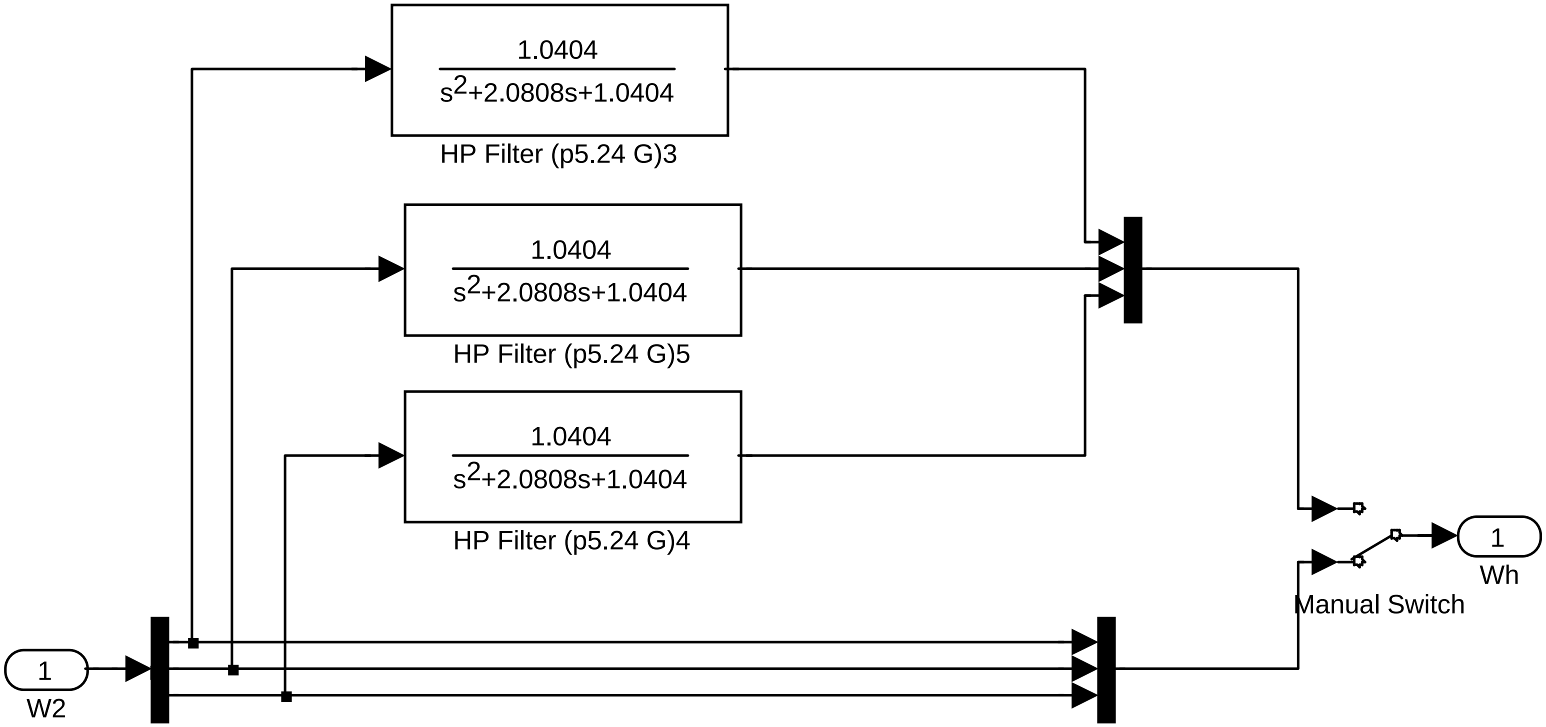
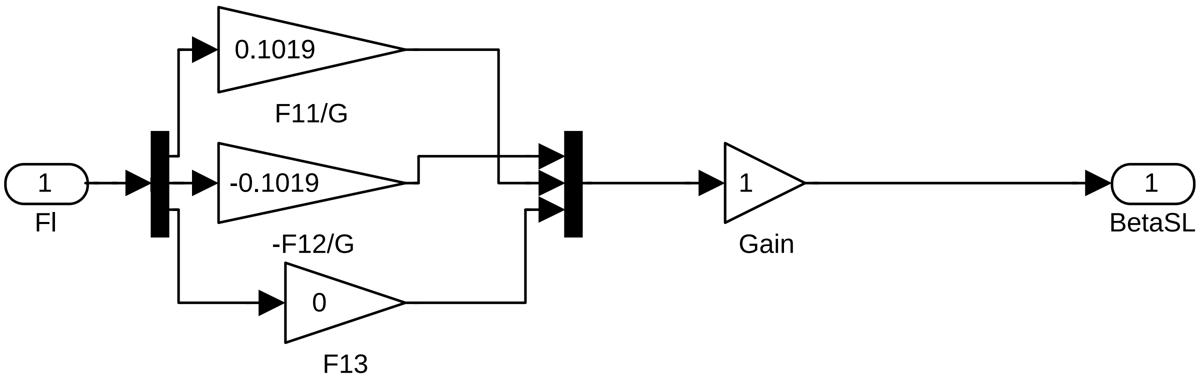

1.0404
s^2+2.0808s+1.0404
HP Filter (p5.24 G)3
1.0404
s^2+2.0808s+1.0404
HP Filter (p5.24 G)5
1.0404
s^2+2.0808s+1.0404
HP Filter (p5.24 G)4
1
W2
1
Wh
Manual Switch

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/Scale Low Pass Force



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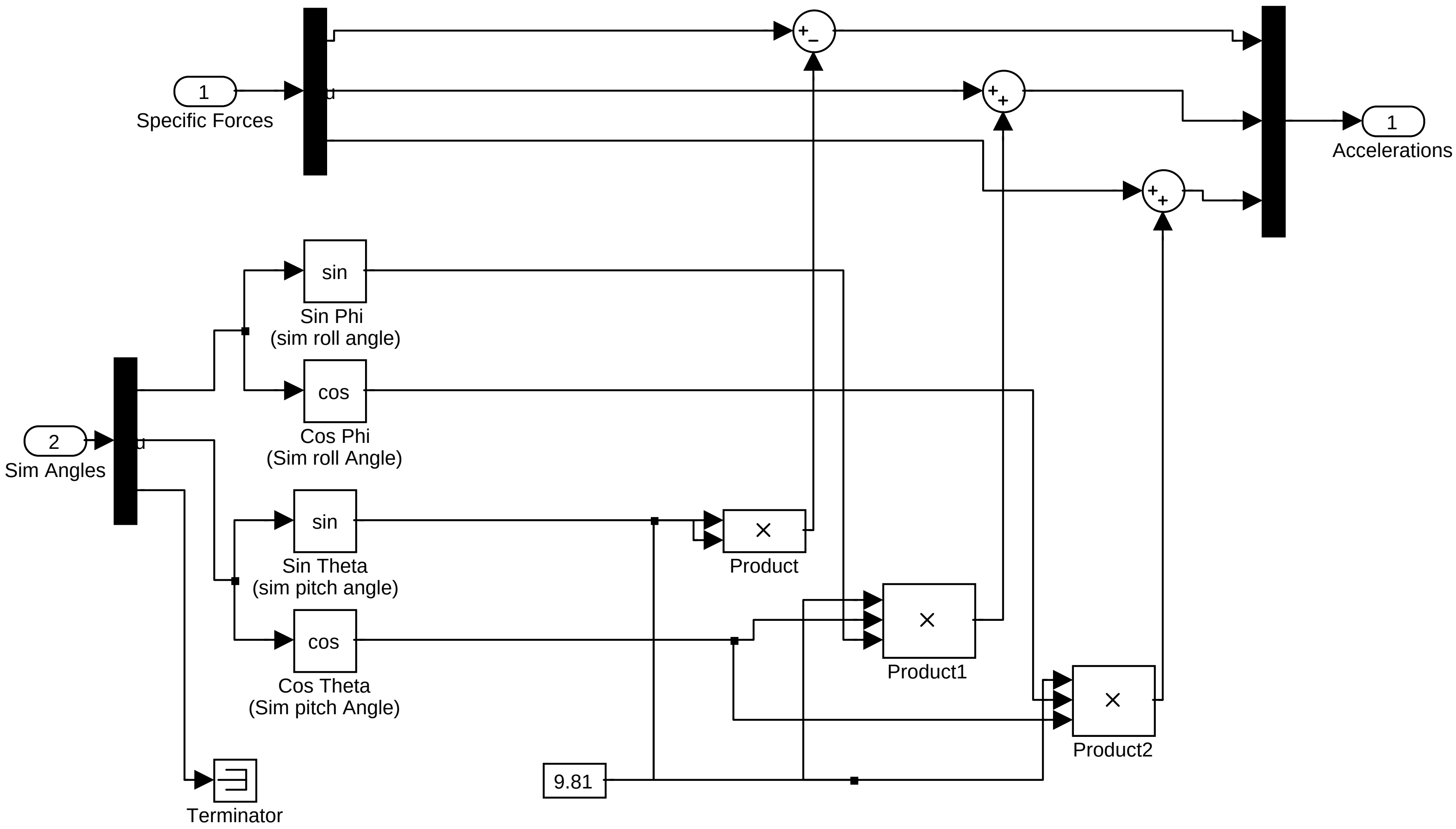
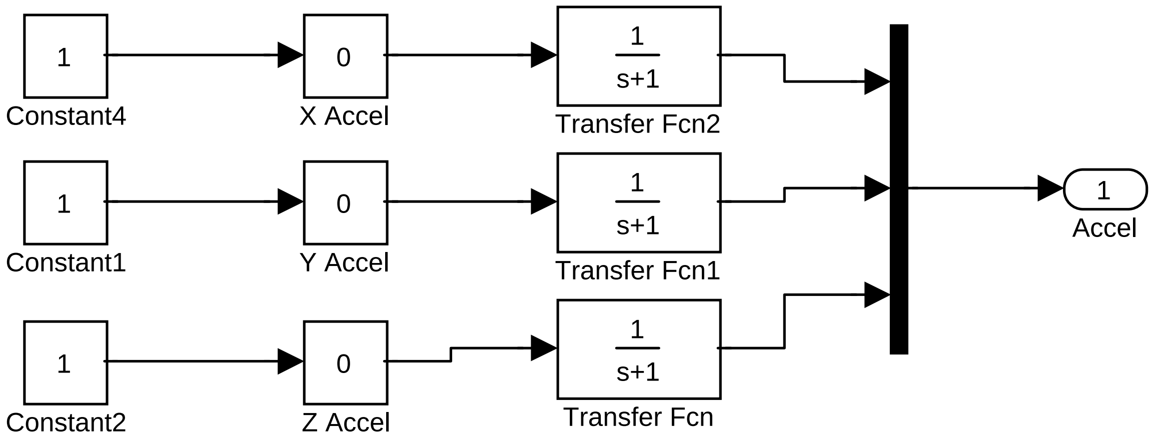
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/2nd order Washout Filter/Subsystem



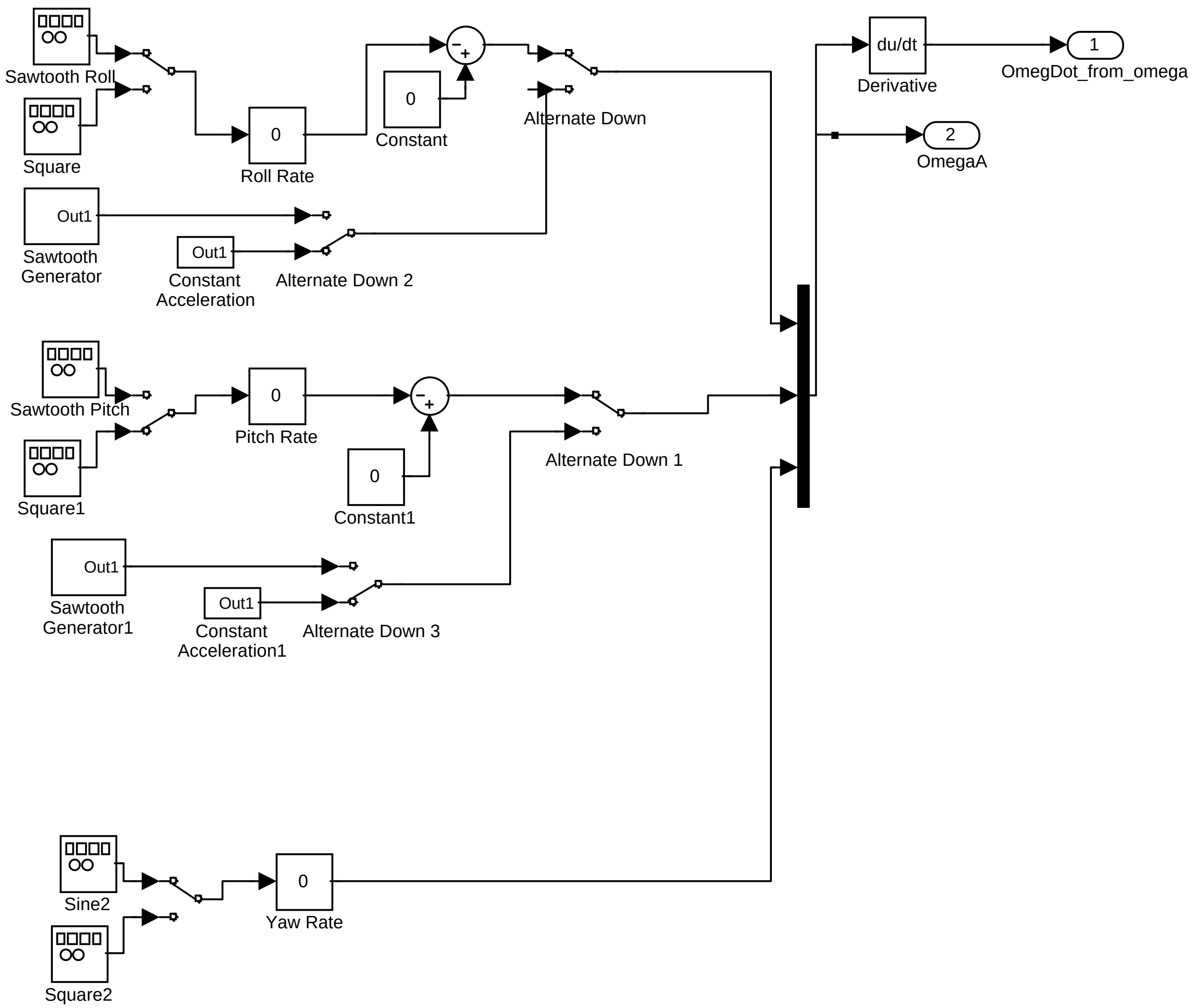
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate Accelerations @ CofG



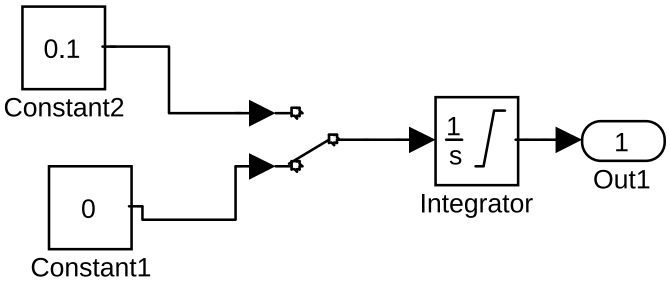
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate Omega & Omega Dot



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate Omega & Omega Dot/Constant Acceleration



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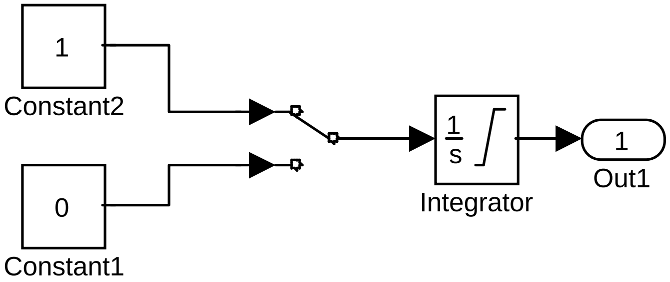
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate Omega & Omega Dot/Constant Acceleration1



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

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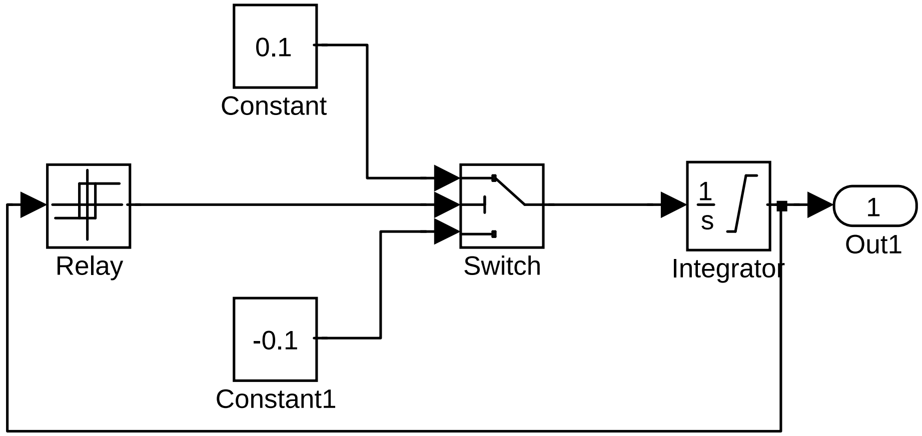
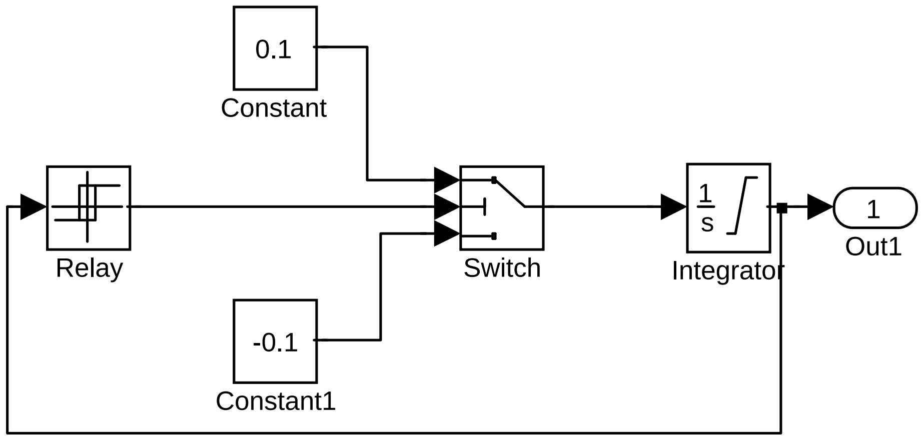
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate Omega & Omega Dot/Sawtooth Generator



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Alternate Omega & Omega Dot/Sawtooth Generator1



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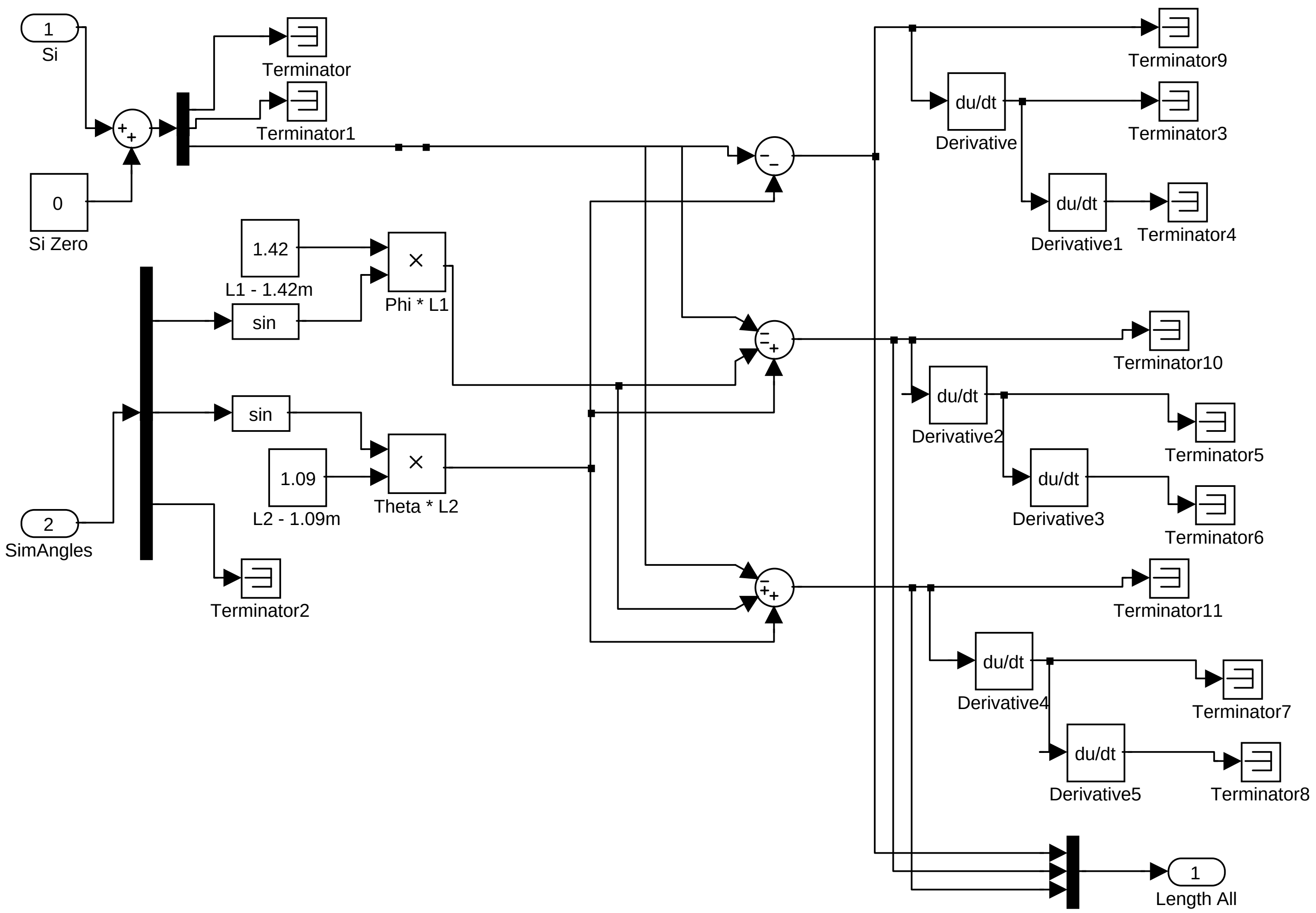
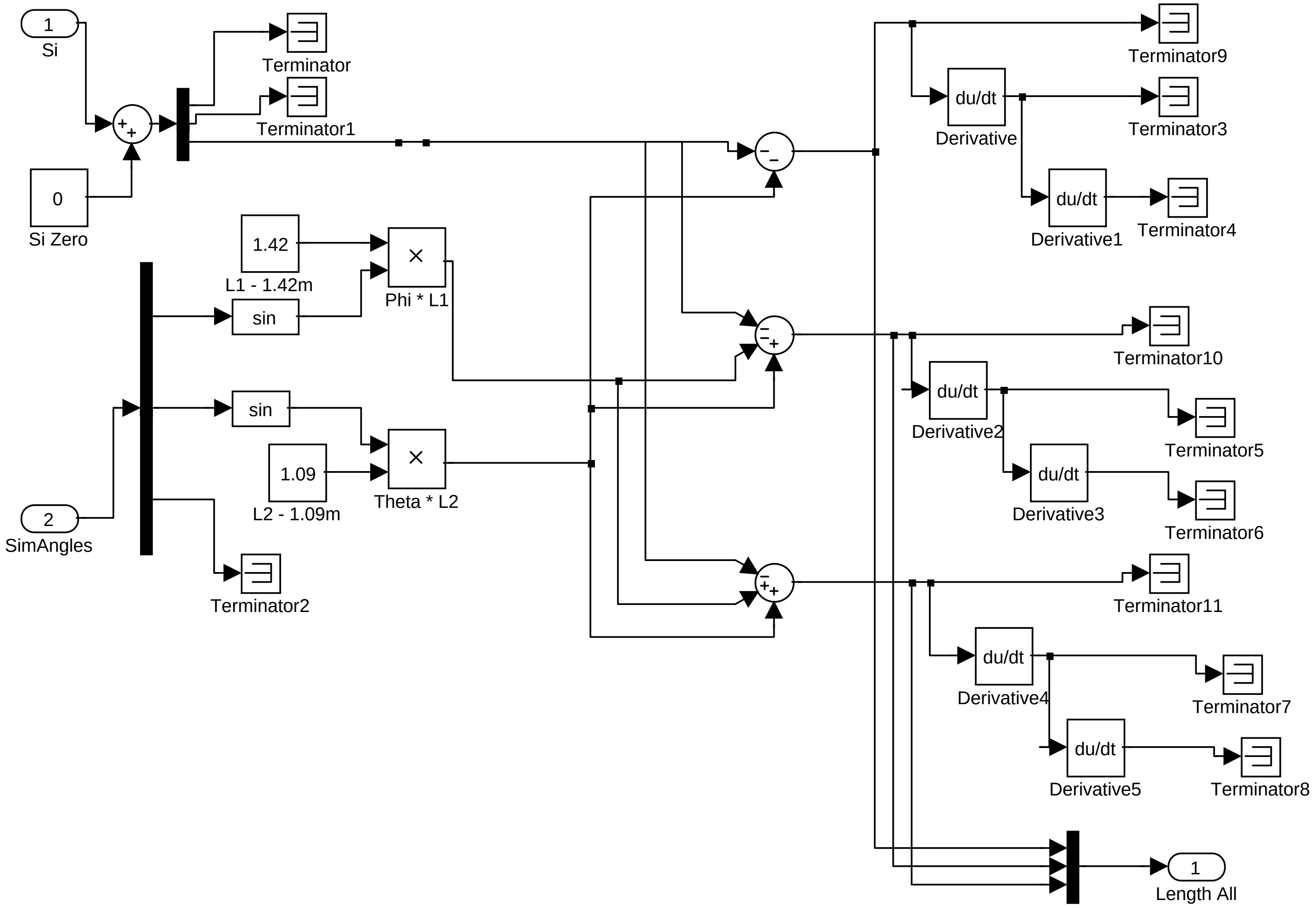

1
Si
Terminator
Terminator1
0
Si Zero
1.42
L1 - 1.42m
sin
Phi * L1
sin
1.09
L2 - 1.09m
Theta * L2
2
SimAngles
Terminator2
Terminator9
du/dt
Derivative
Terminator3
du/dt
Derivative1
Terminator4
Terminator10
du/dt
Derivative2
Terminator5
du/dt
Derivative3
Terminator6
Terminator11
du/dt
Derivative4
Terminator7
du/dt
Derivative5
Terminator8
1
Length All

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Calculate Jack Lengths 3rd Order



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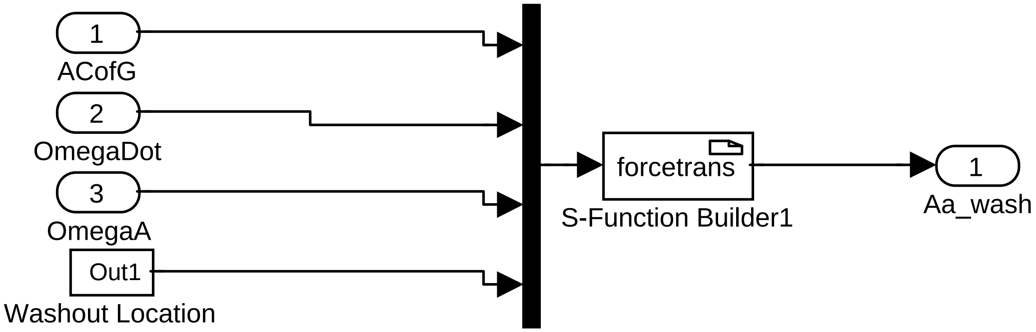
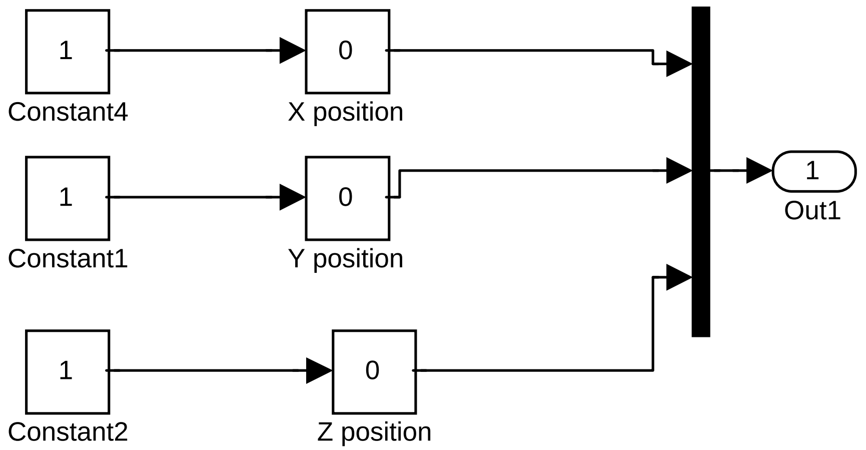
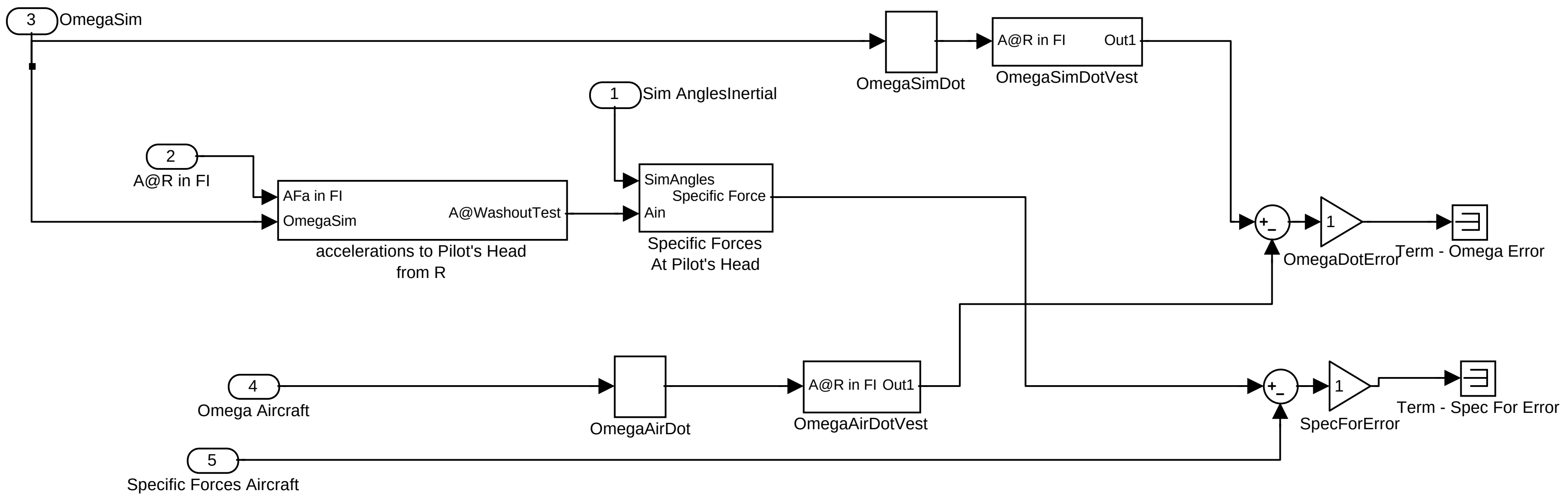

1
ACofG
2
OmegaDot
3
OmegaA
Out1
Washout Location
forcetrans
S-Function Builder1
1
Aa_wash

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Move forces from CofG to Fa & calculate Euler Angles/Wa

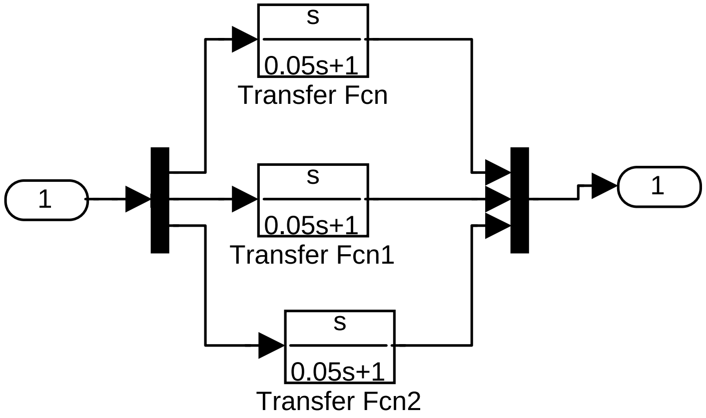


Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order



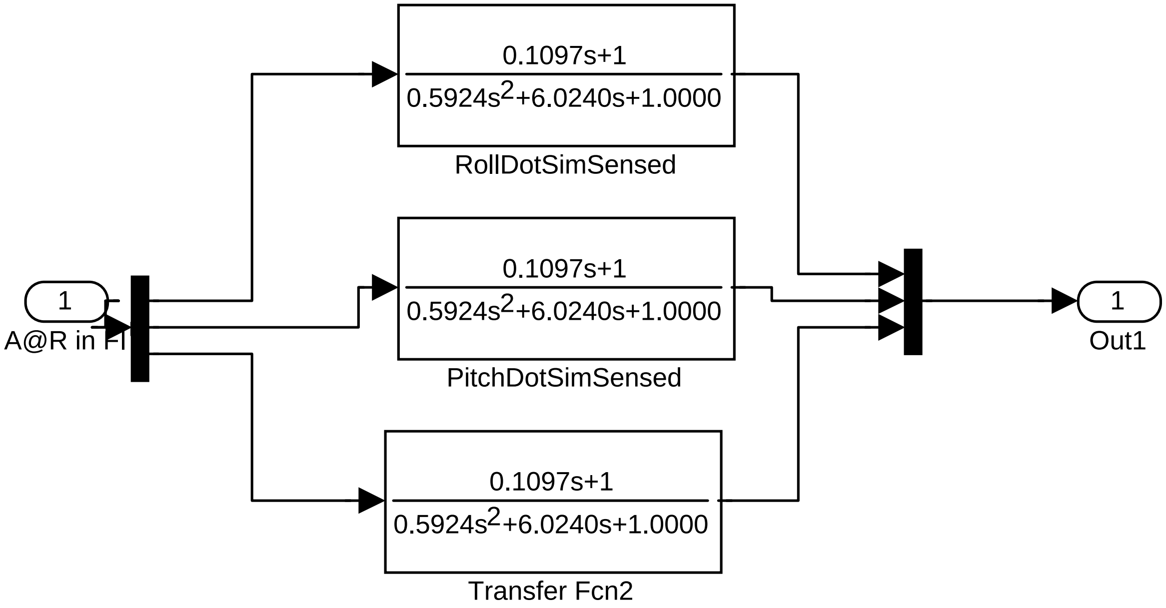
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/OmegaAirDot



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/OmegaAirDotVest



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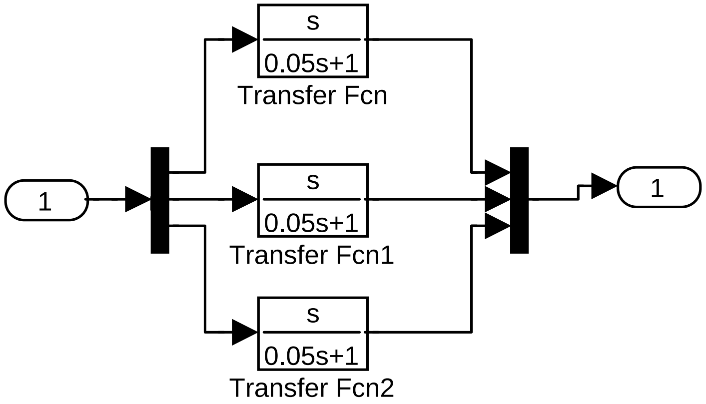
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/OmegaSimDot



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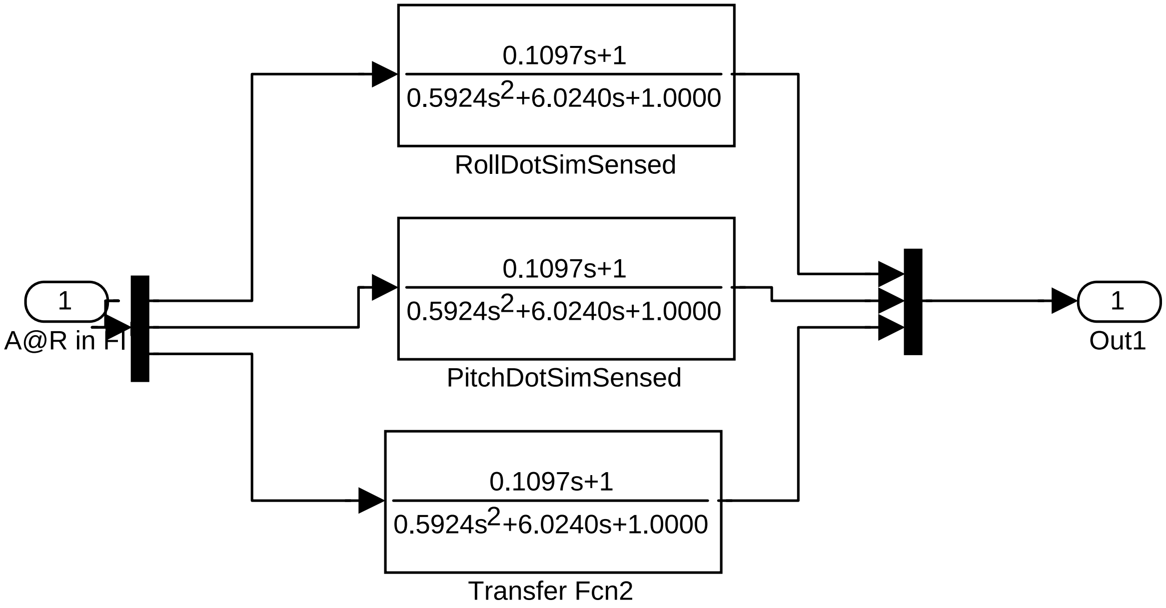
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/OmegaSimDotVest



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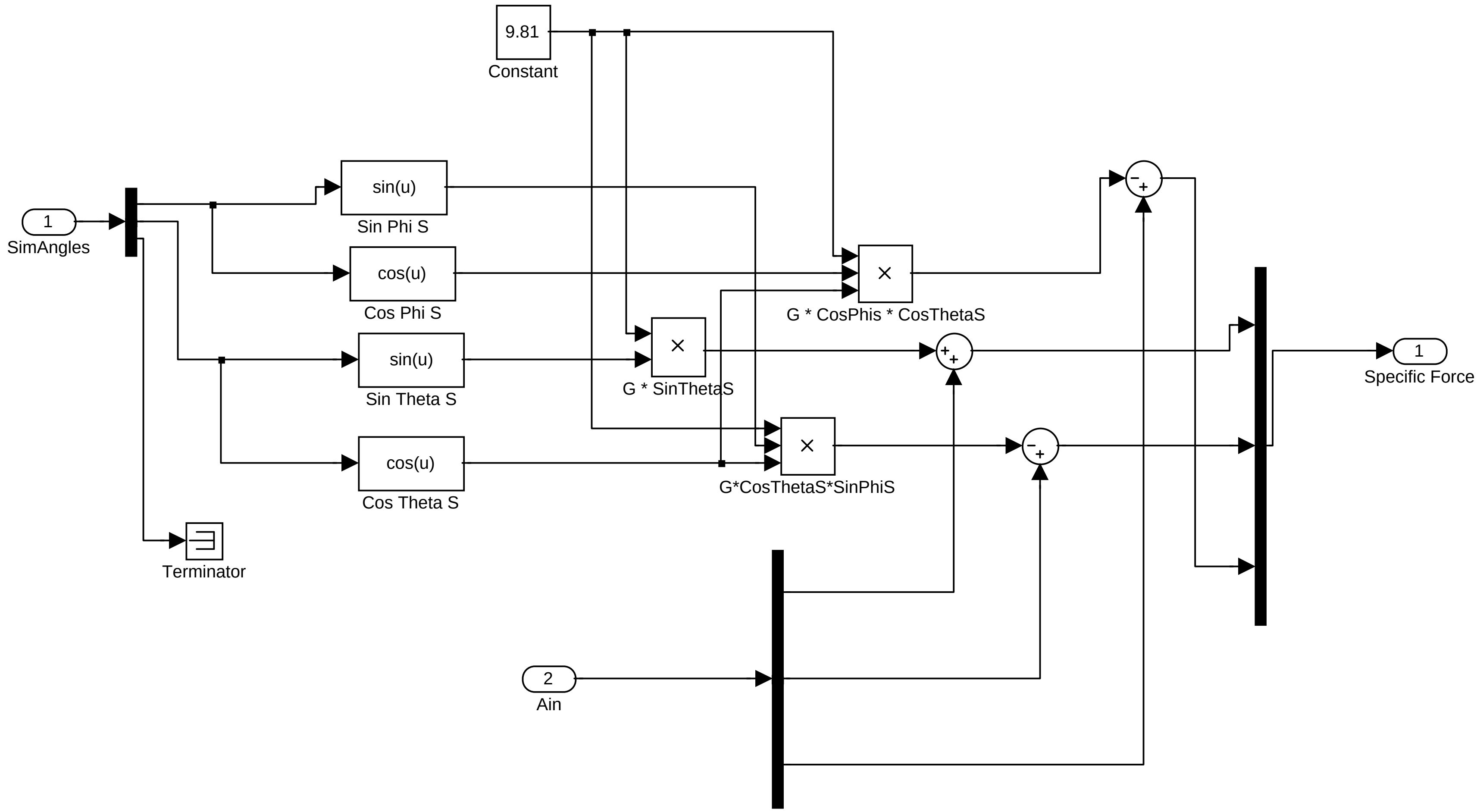
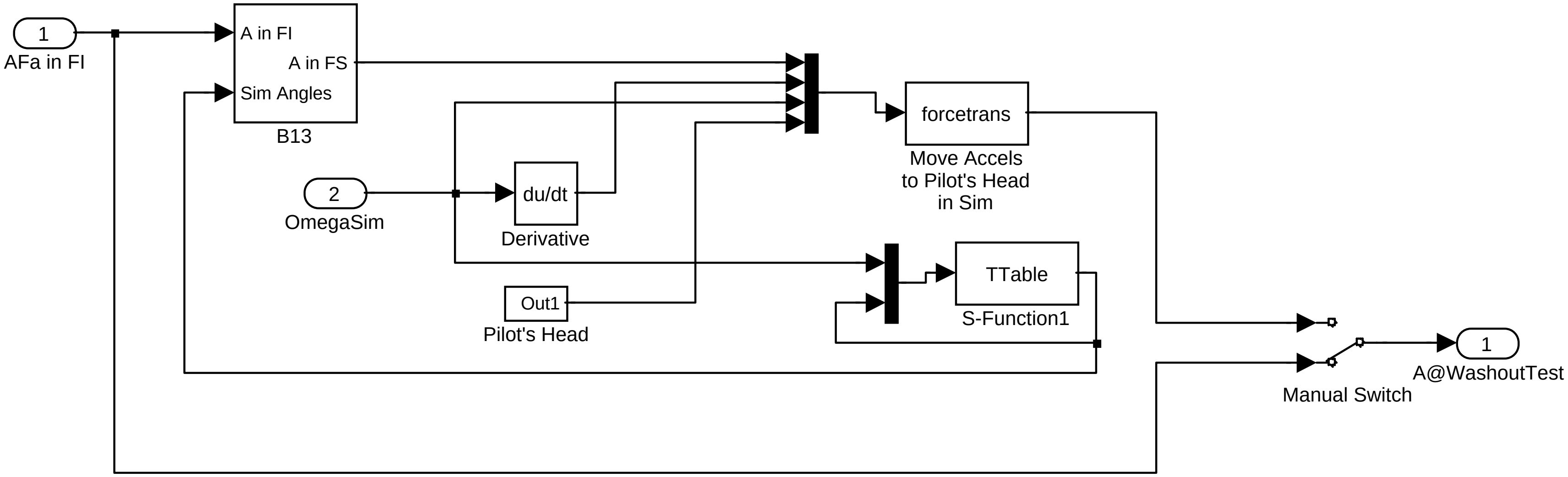
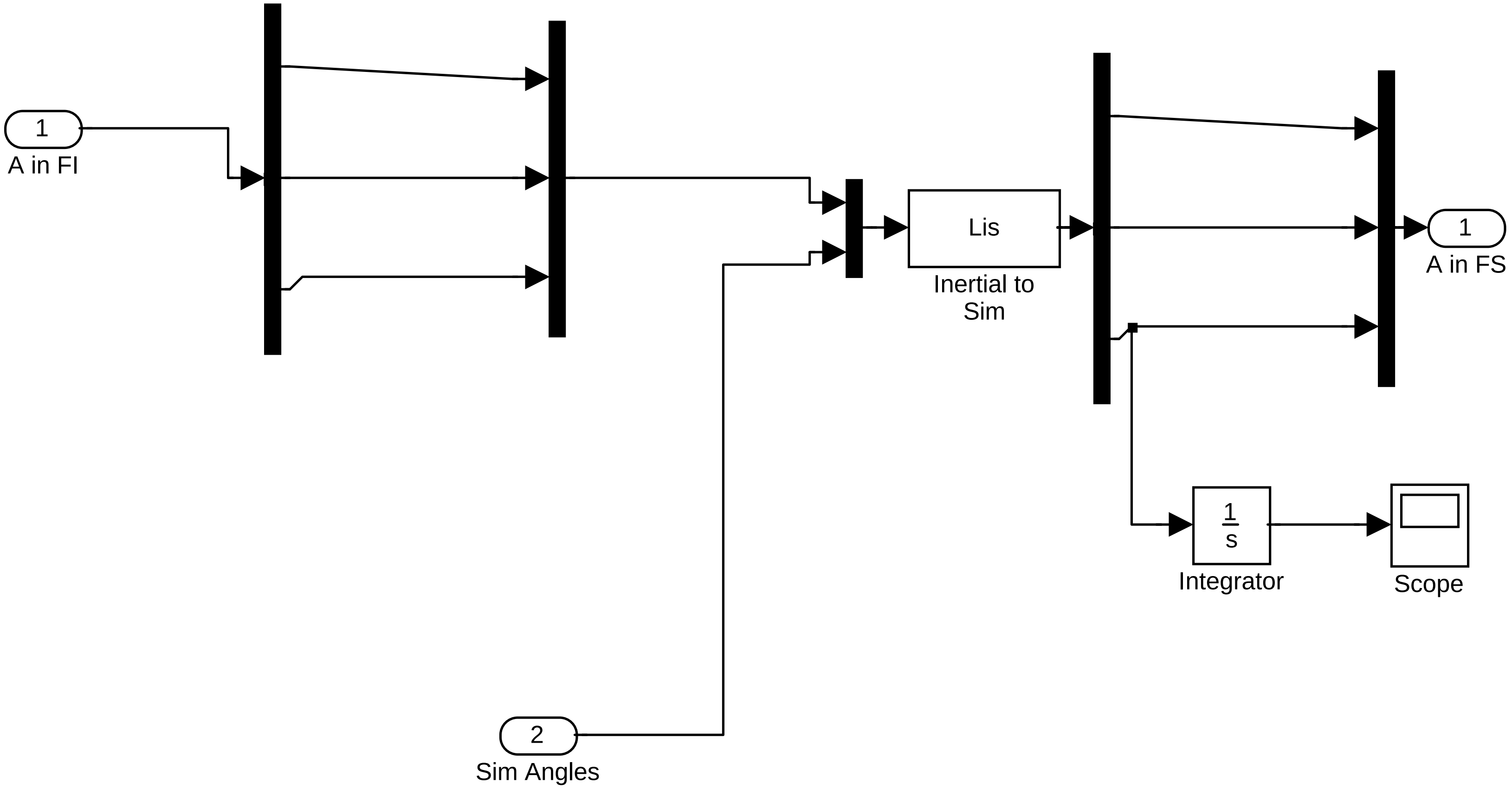

9.81
Constant
1
SimAngles
sin(u)
Sin Phi S
cos(u)
Cos Phi S
sin(u)
Sin Theta S
cos(u)
Cos Theta S
Terminator
×
G * CosPhis * CosThetaS
×
G * SinThetaS
×
G*CosThetaS*SinPhiS
2
Ain
1
Specific Force

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/accelerations to Pilot's Head



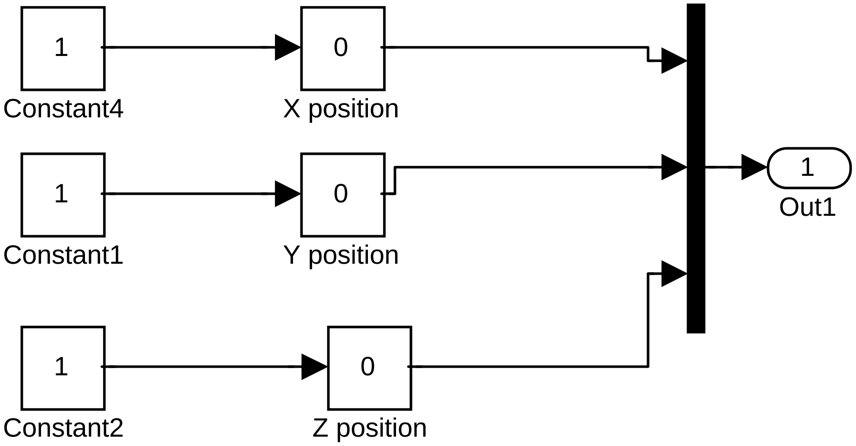
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/accelerations to Pilot's Head



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order/accelerations to Pilot's Head



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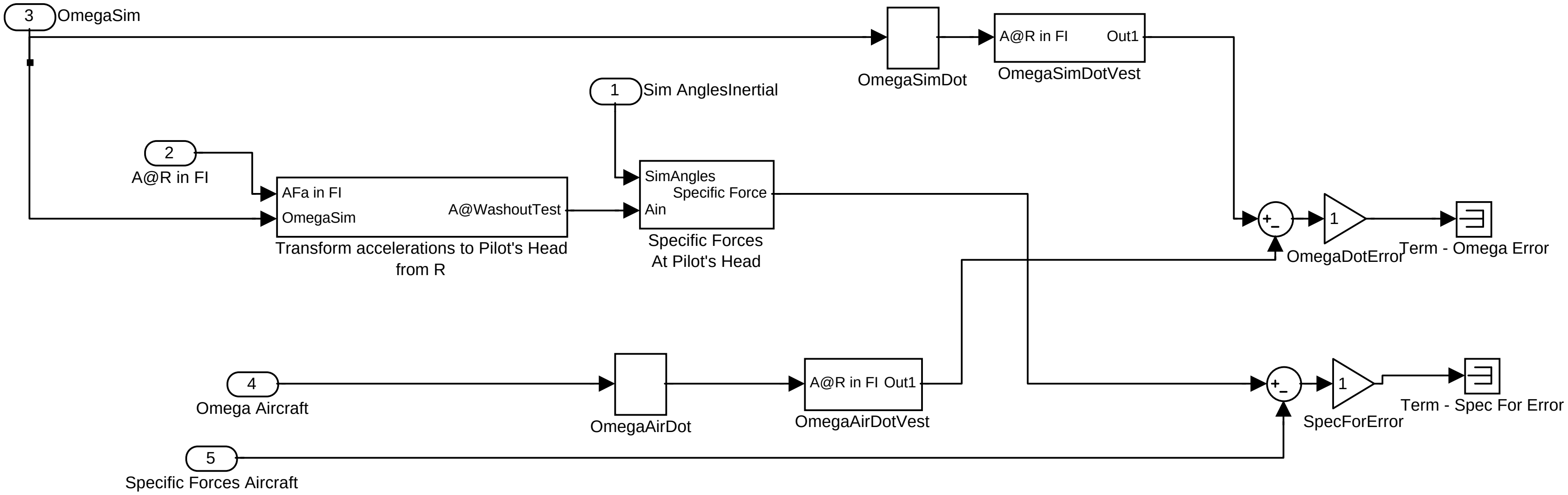
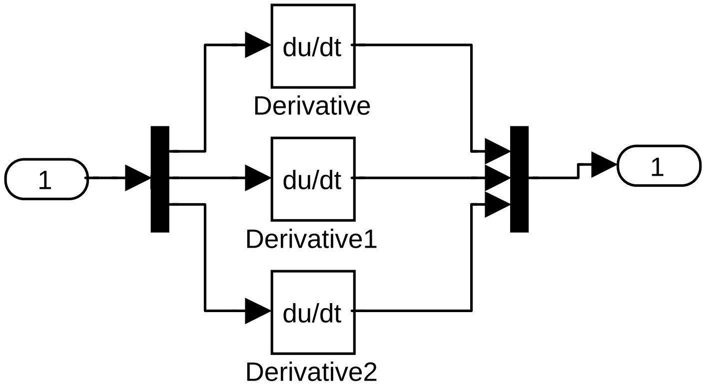
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order1



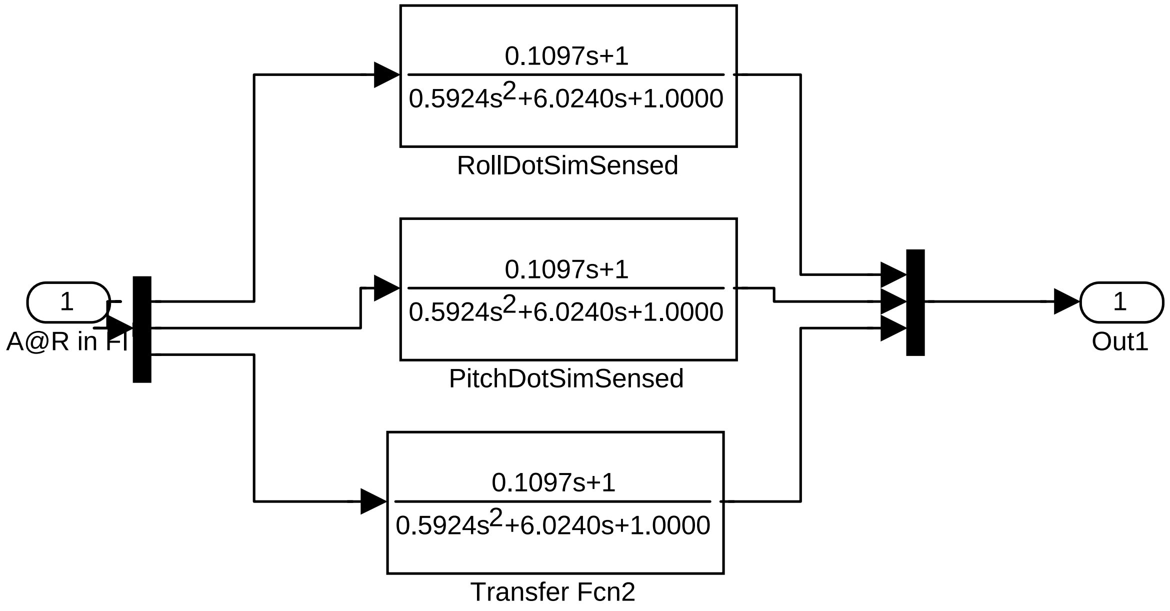
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order1/OmegaAirDot



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order1/OmegaAirDotVest



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

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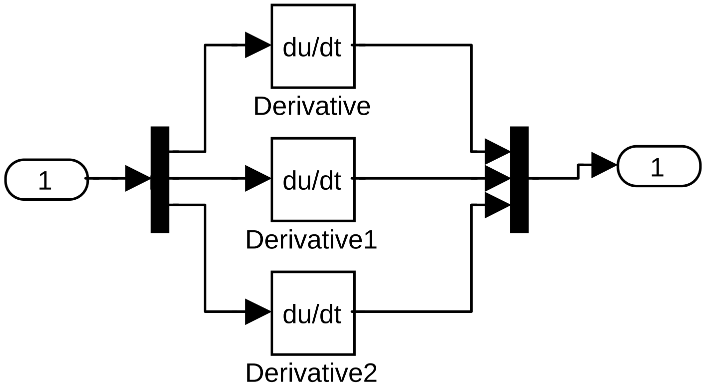
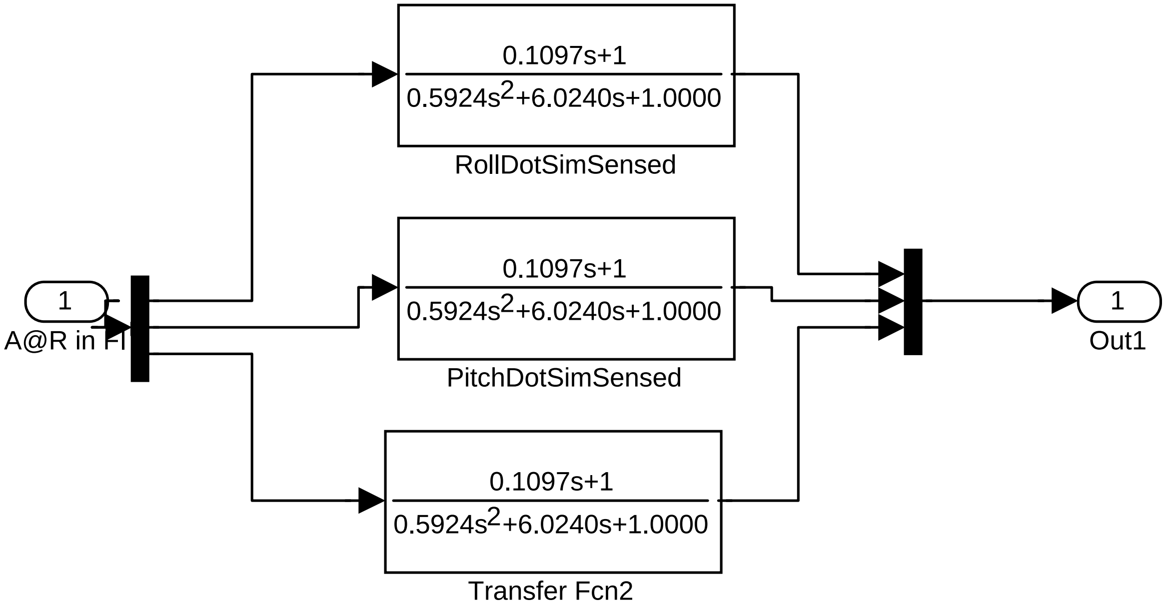
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order1/OmegaSimDot



Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order1/OmegaSimDotVest



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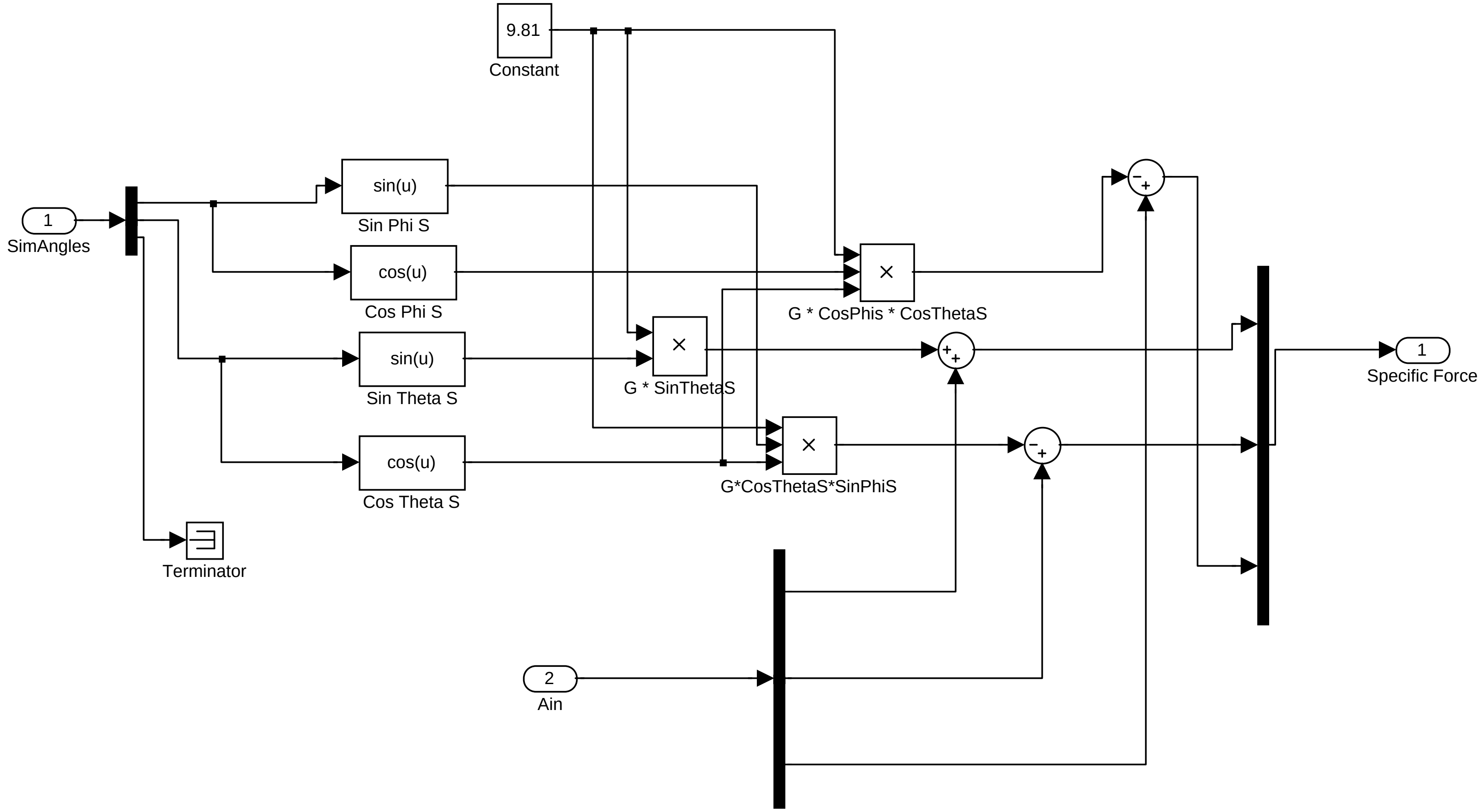
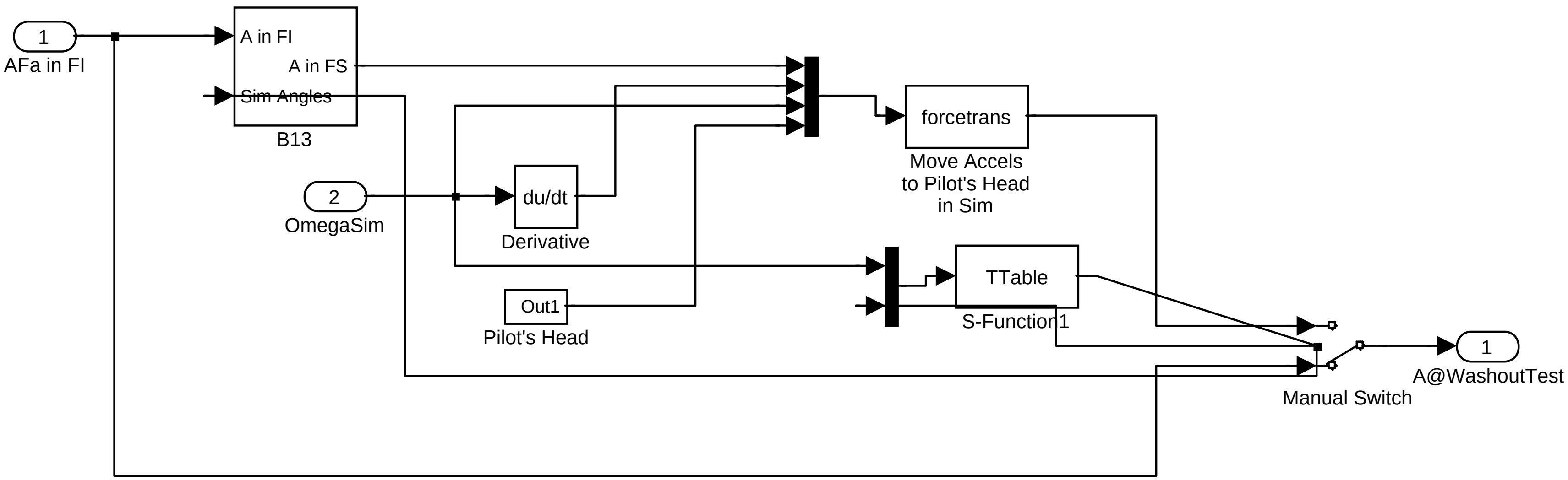
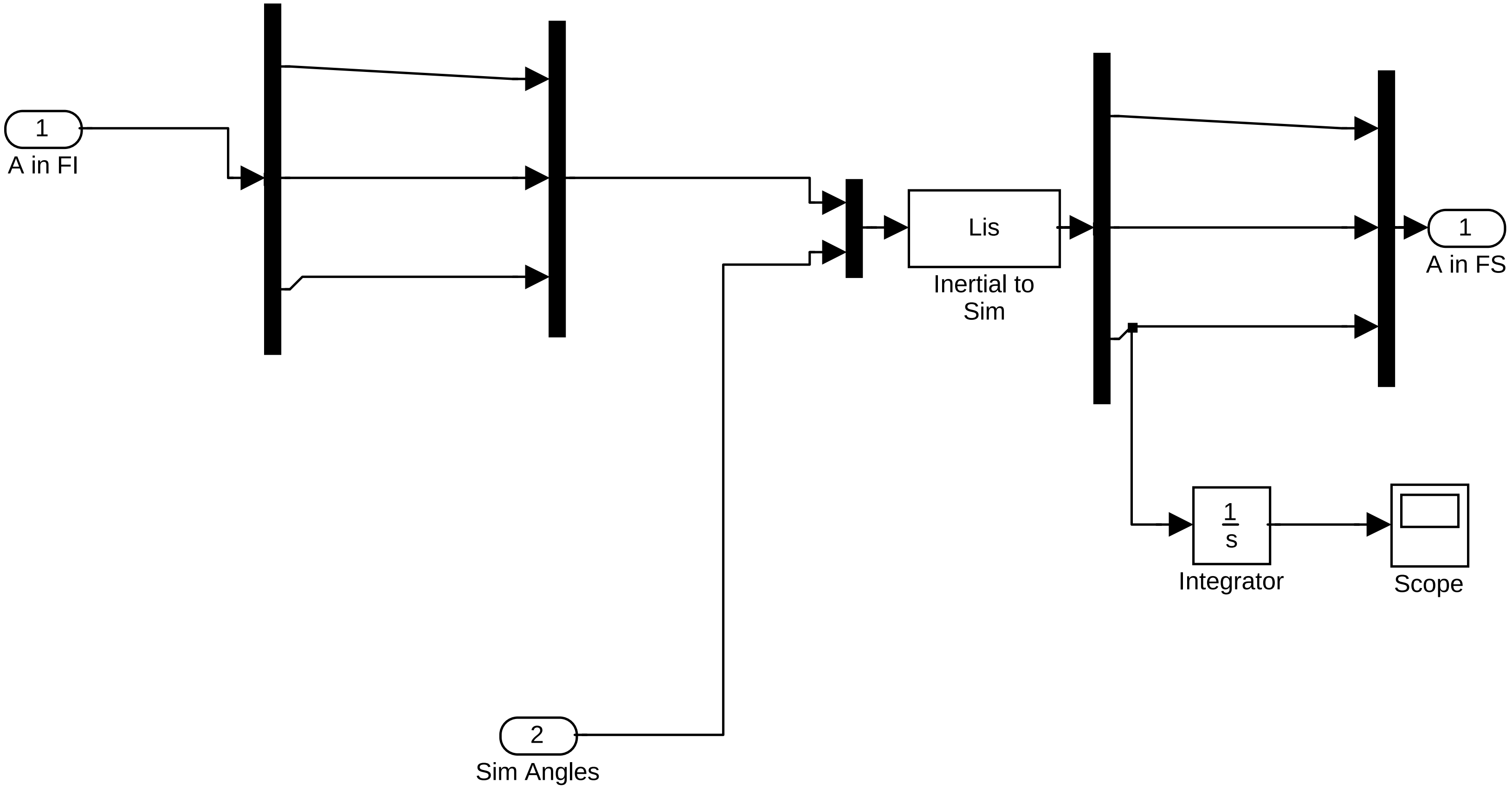

9.81
Constant
1
SimAngles
sin(u)
Sin Phi S
cos(u)
Cos Phi S
sin(u)
Sin Theta S
cos(u)
Cos Theta S
Terminator
×
G * CosPhis * CosThetaS
×
G * SinThetaS
×
G*CosThetaS*SinPhiS
−
+
+
+
−
+
1
Specific Force
2
Ain

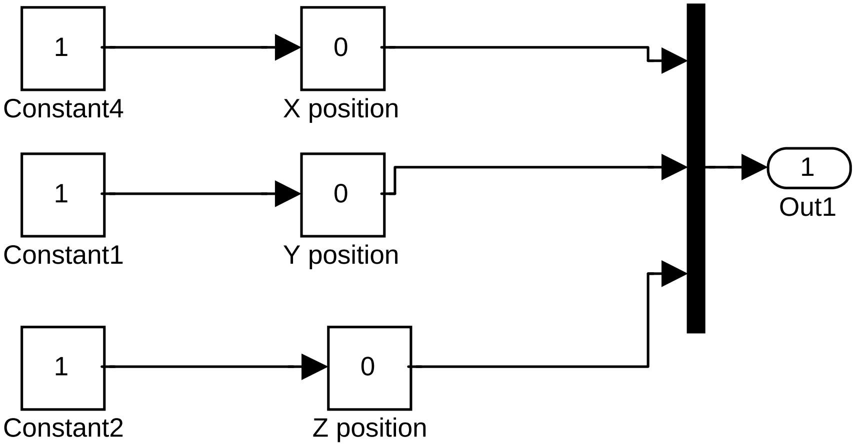
Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order1/Transform accelerations to



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

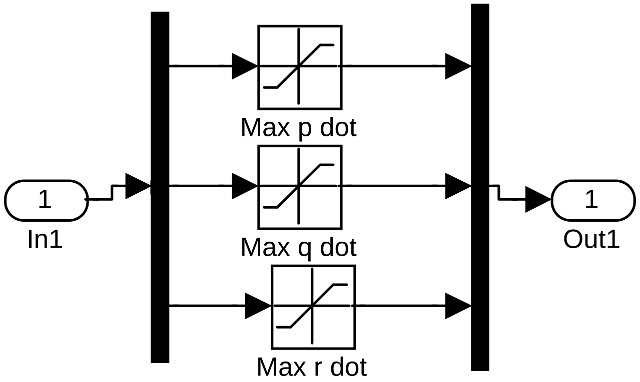

1
A in FI
Lis
Inertial to
Sim
1
A in FS
1
s
Integrator
Scope
2
Sim Angles

Motion_System_13_Vest/Motion System/Motion Drive Signal/Motion Commands/Vestibular Model 2nd Order1/Transform accelerations to

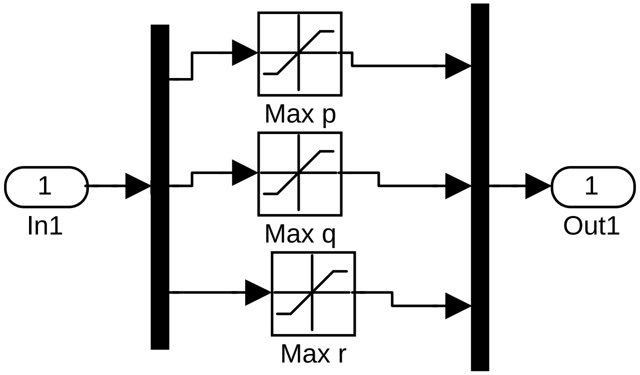


C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Rotational Acceleration Limiters



Motion_System_13_Vest/Motion System/Motion Drive Signal/Rotational RateLimiters



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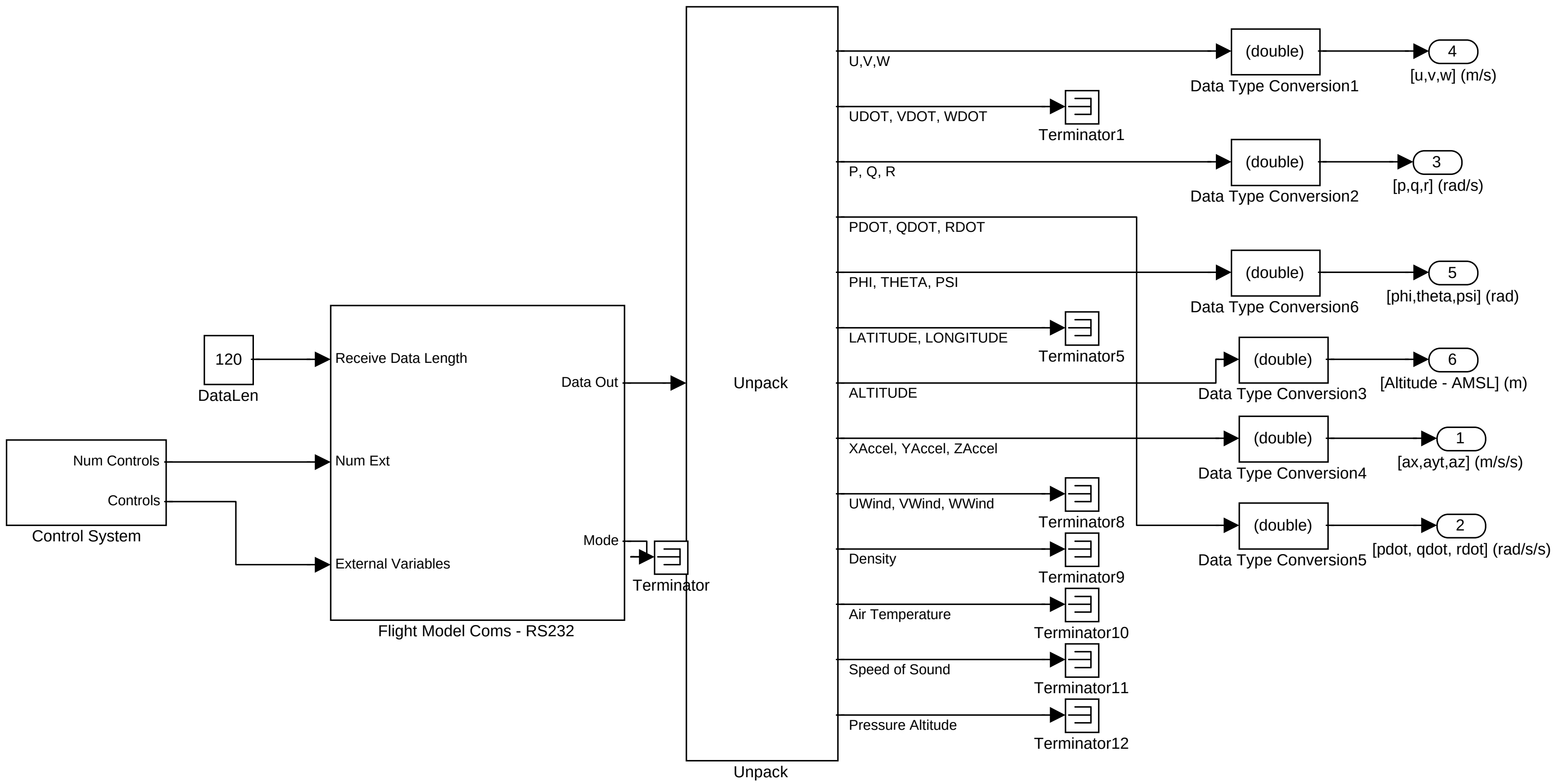
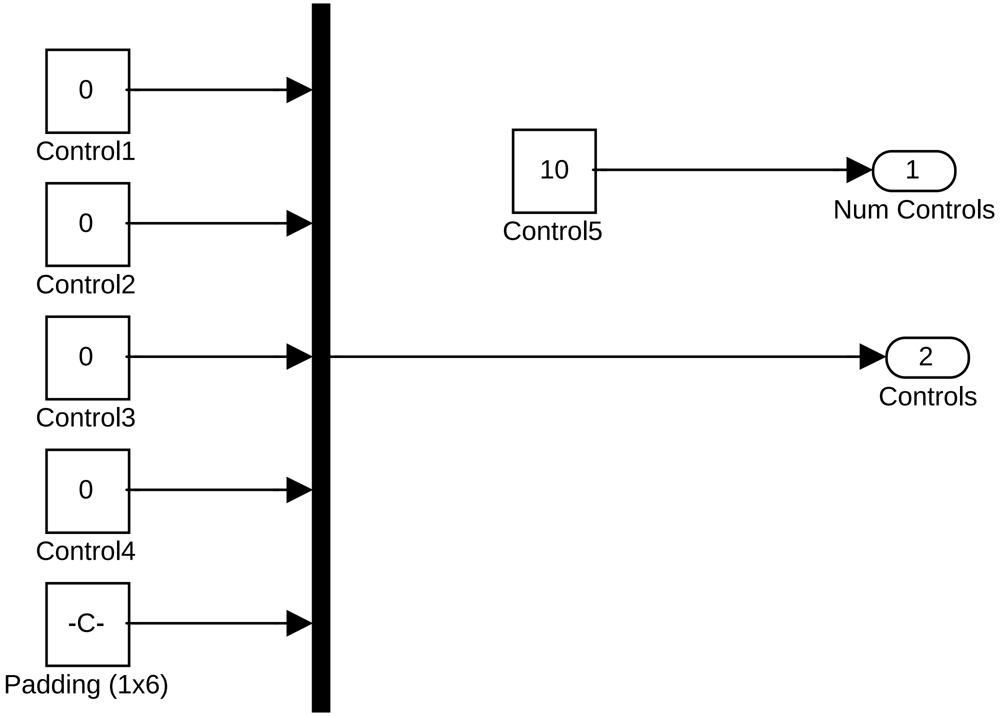
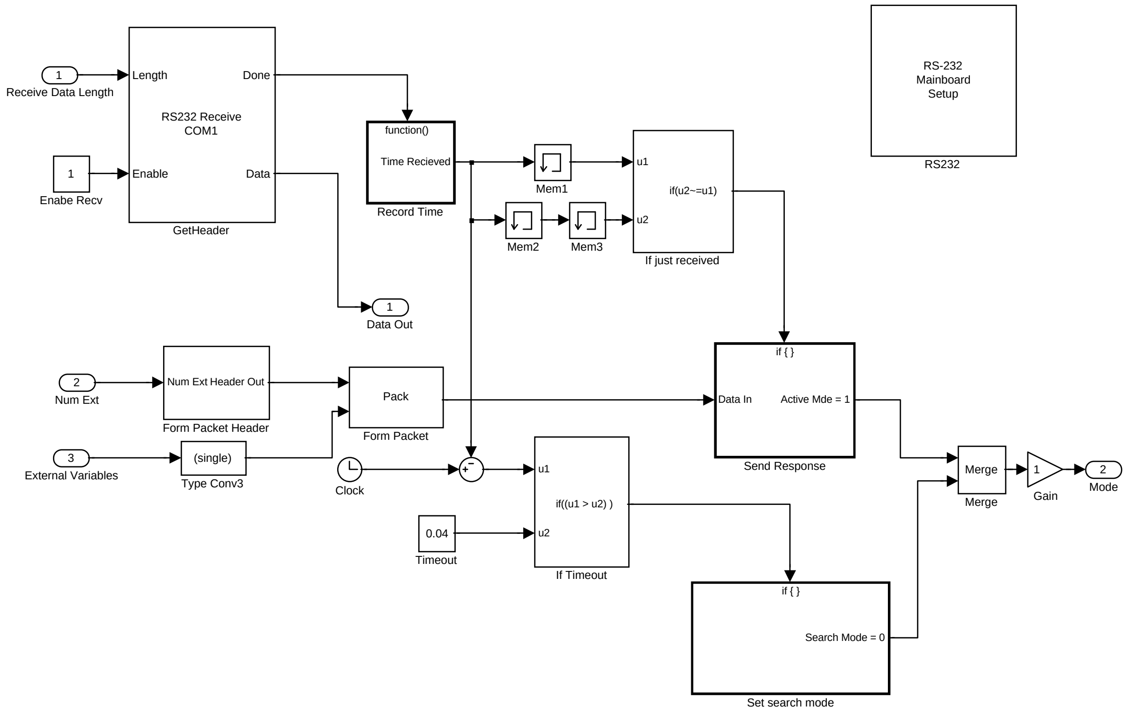
Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1



Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Control System



Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232



SPECIFICATIONS:

Port : COM1
Baud : 115200kBits/s
Max Receive Buffer : 100Bytes
Tranmit Buffer : 100Bytes
"Data In" : [1xn] of unsigned integer
  where n = "Receive Data Length"
"Data Out": [1x100] of unsigned integer

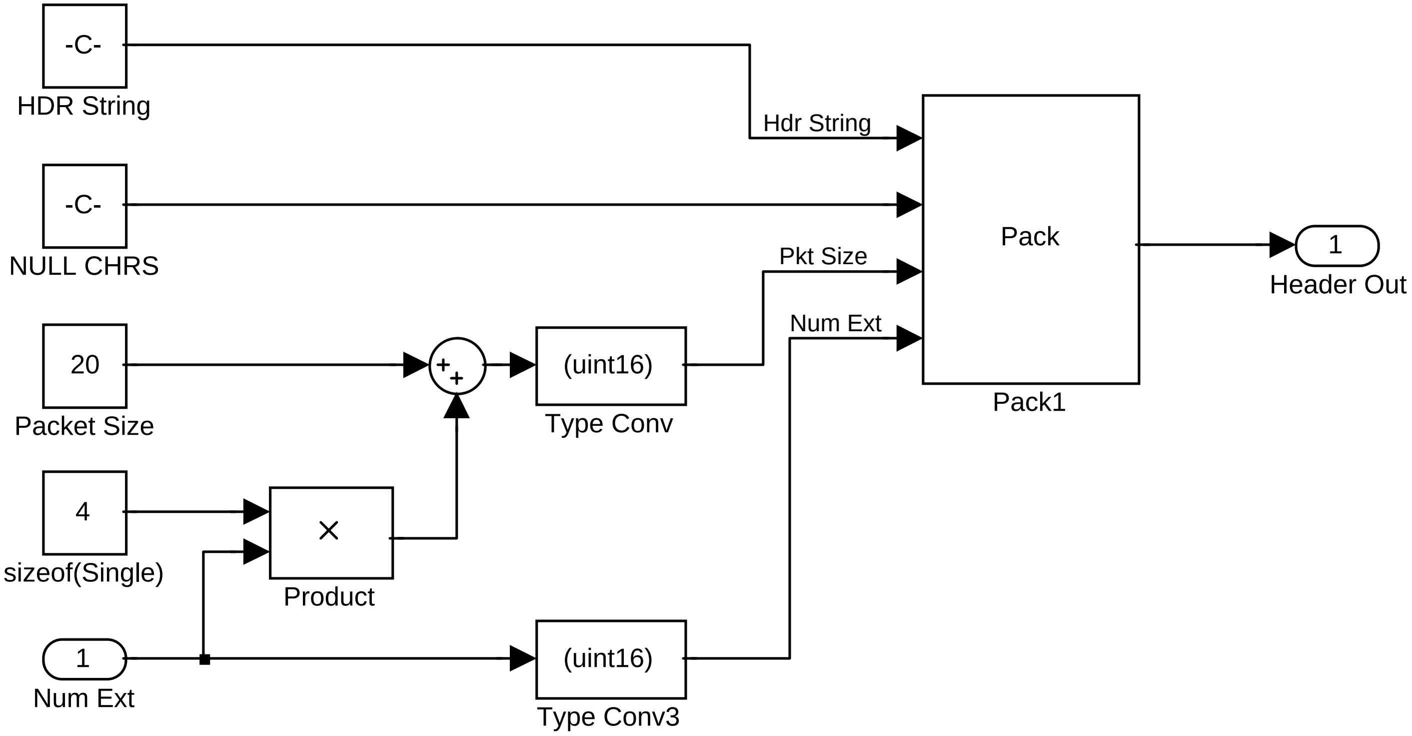
NOTES:

(1) Data out will only be updated when n bytes have been received
(n = "Receive Data Length")

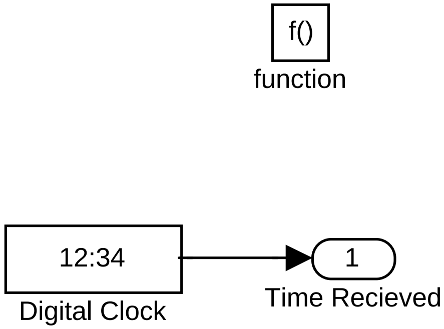
(2) When in search mode, data is transmitted at a sample rate defined
by the TimeOut constant block

(3) When in active mode, data is transmitted upon receiving n bytes of data
from the flight model computer. (n = "Receive Data Length")

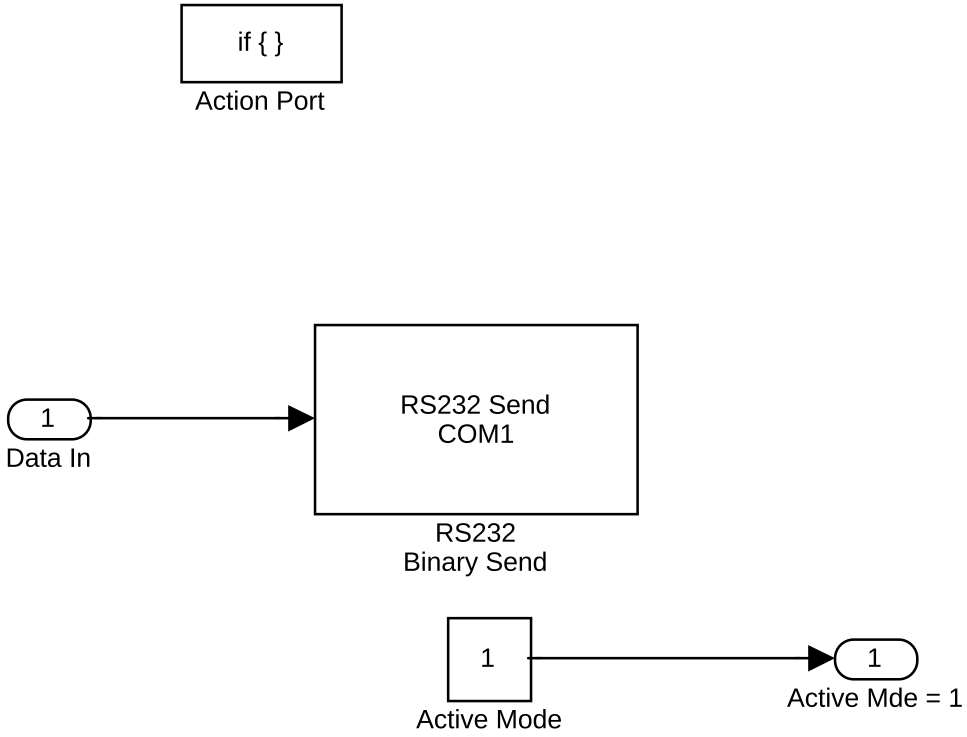
Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232/Form Packet Header



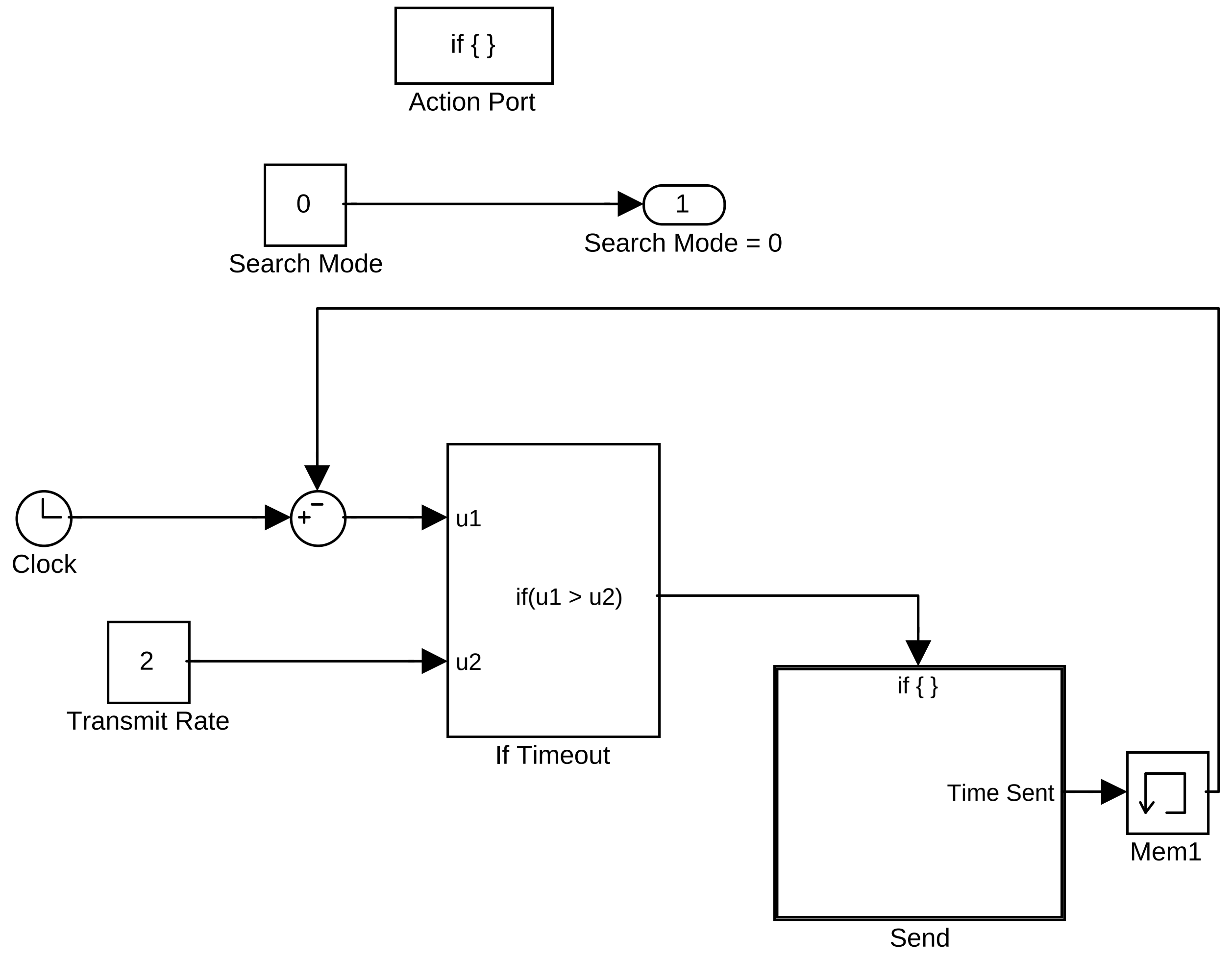
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl


f()
function
12:34
Digital Clock
1
Time Recieved

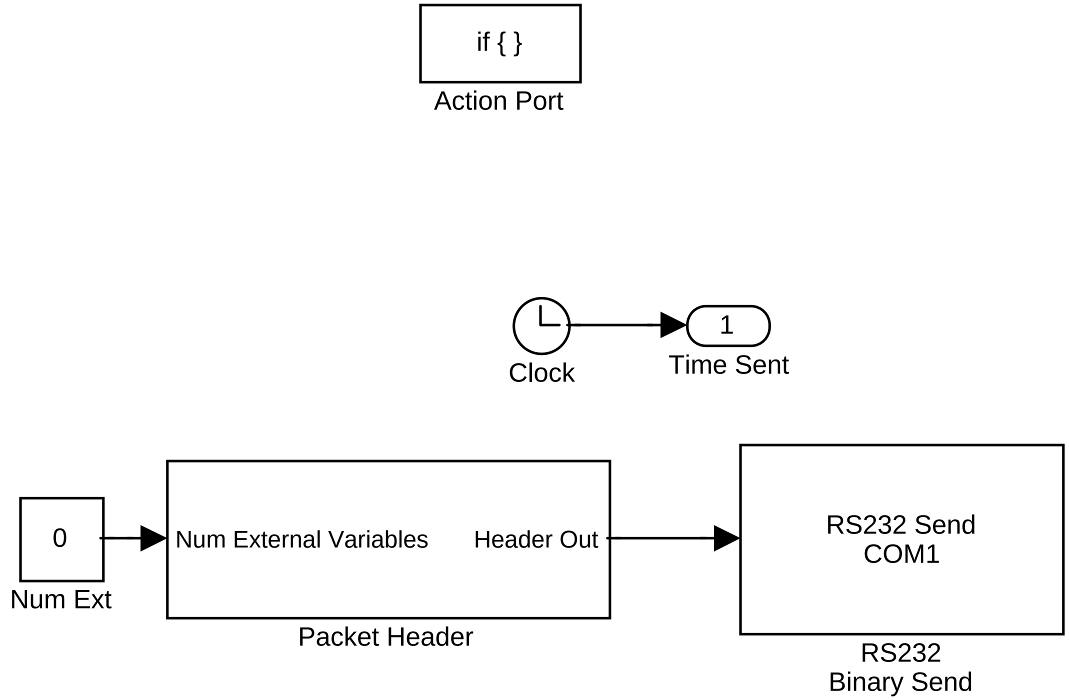
Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232/Send Response



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

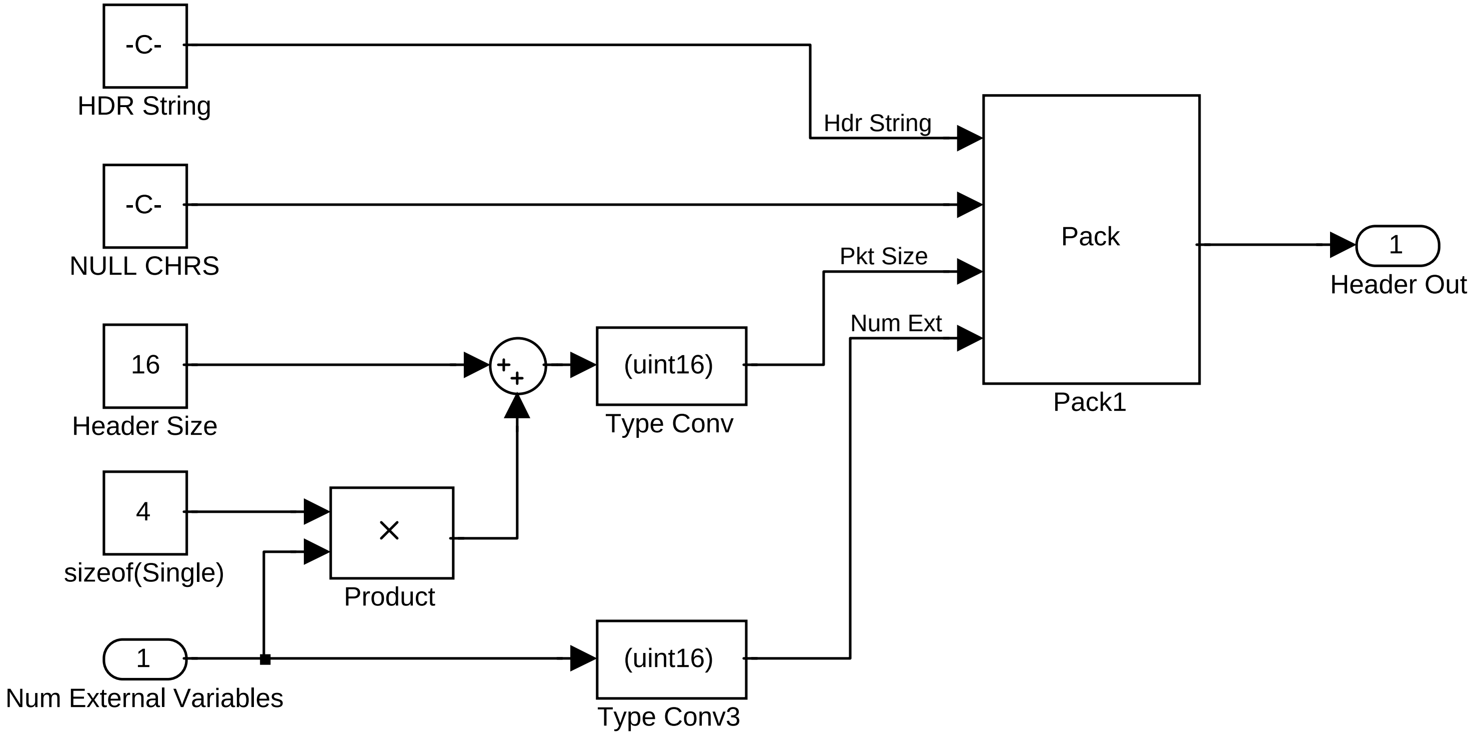

if { }
Action Port
0
Search Mode
1
Search Mode = 0
Clock
+
−
u1
u2
if(u1 > u2)
2
Transmit Rate
If Timeout
if { }
Time Sent
Send
Mem1

Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232/Set search mode/Send

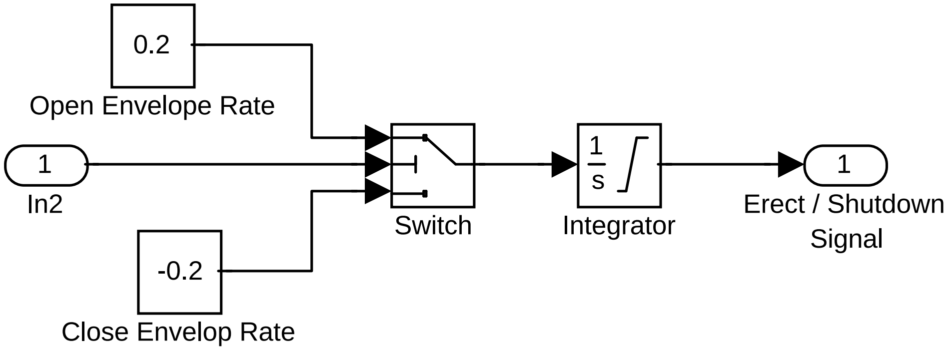


C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Motion System/Motion Drive Signal/Simulator Signals1/Flight Model Coms - RS232/Set search mode/Send/Packe



Motion_System_13_Vest/Motion System/Motion Envelope



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

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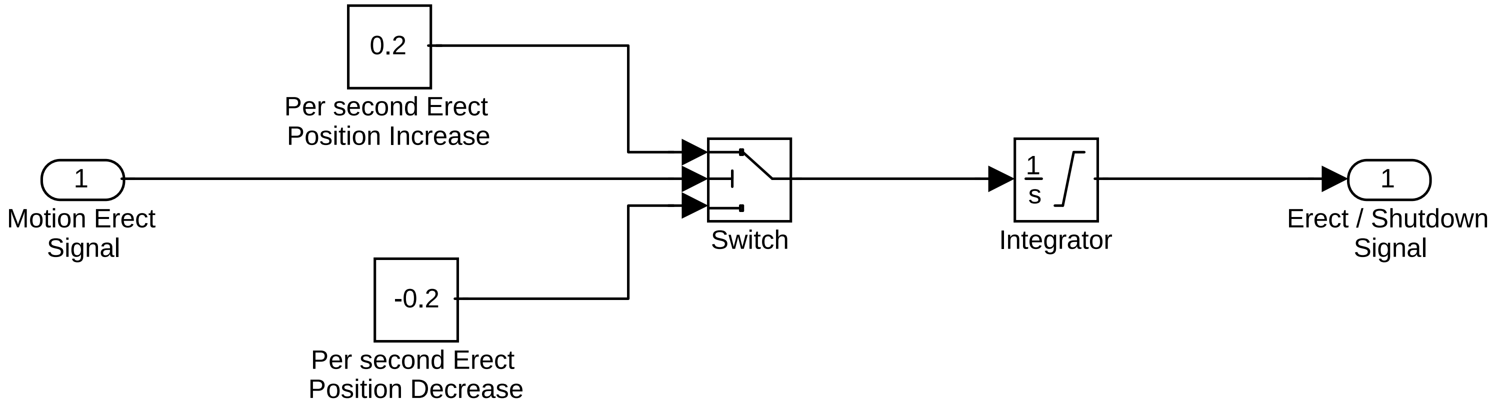
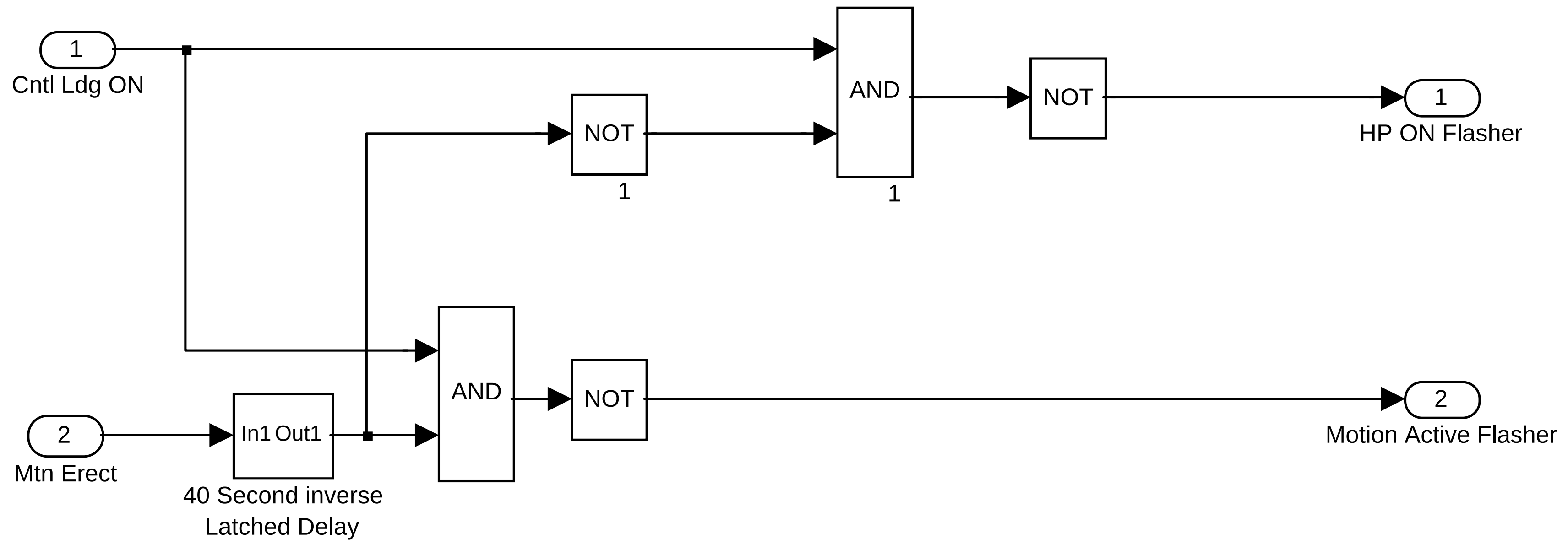
Motion_System_13_Vest/Motion System/Motion Erect // Shutdown



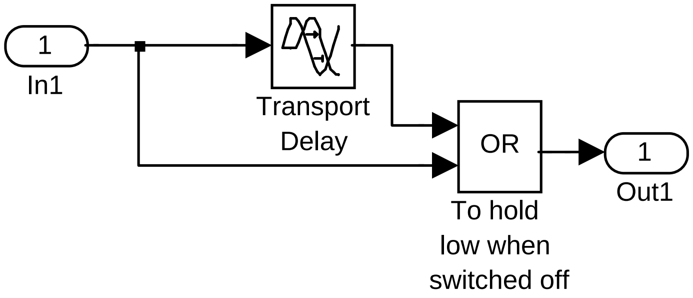
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/OHSRM Warning Flashers

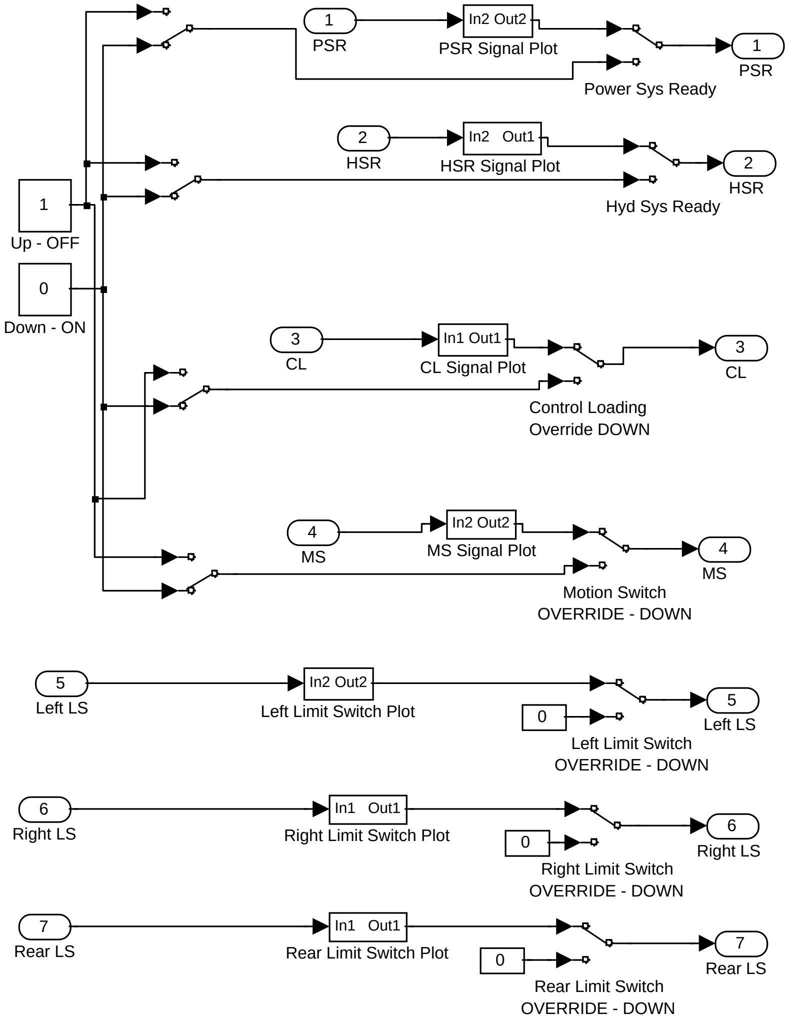


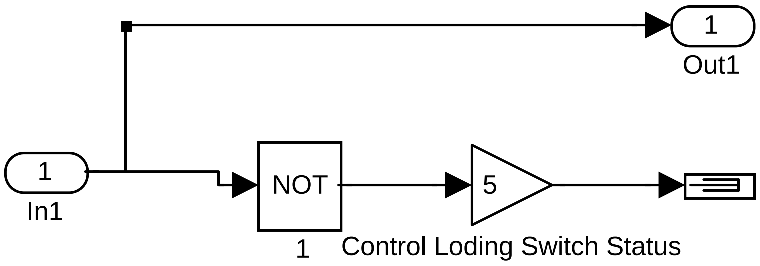
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/OHSRM Warning Flashers/40 Second inverse Latched Delay

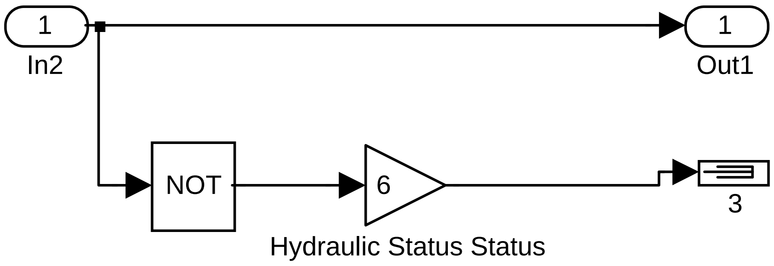


Motion_System_13_Vest/Overide Switches



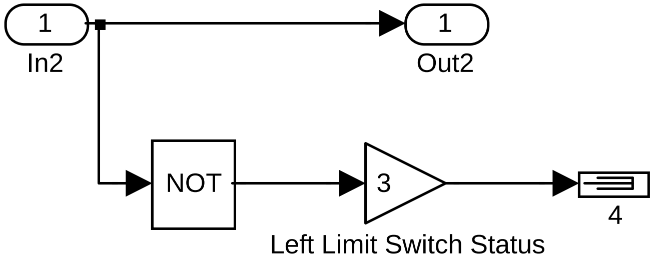

1
Out1
1
In1
NOT
1
5
Control Loding Switch Status

Motion_System_13_Vest/Overide Switches/HSR Signal Plot



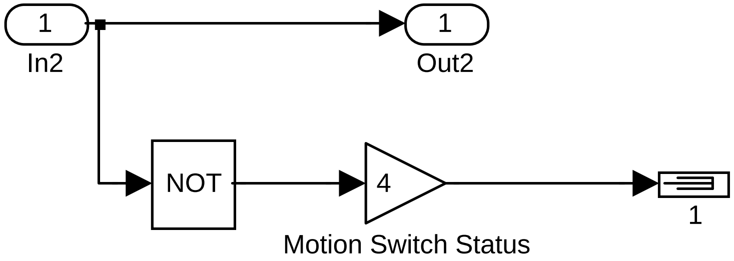
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Overide Switches/Left Limit Switch Plot



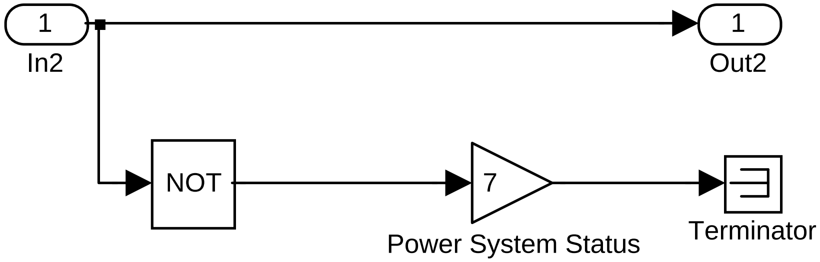
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Overide Switches/MS Signal Plot



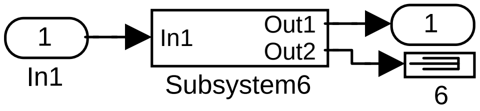
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Overide Switches/PSR Signal Plot



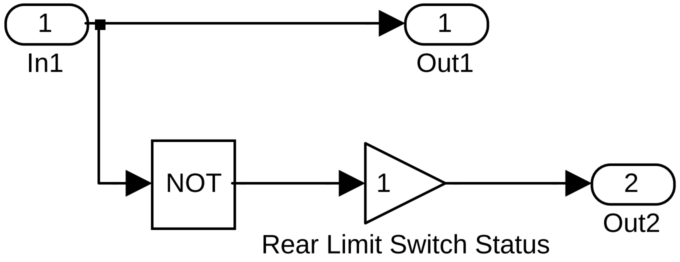
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Overide Switches/Rear Limit Switch Plot



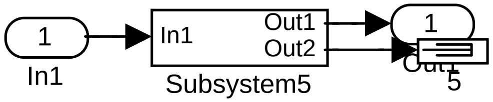
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Overide Switches/Rear Limit Switch Plot/Subsystem6



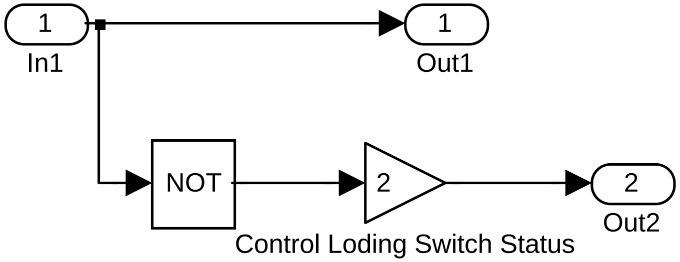
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Overide Switches/Right Limit Switch Plot



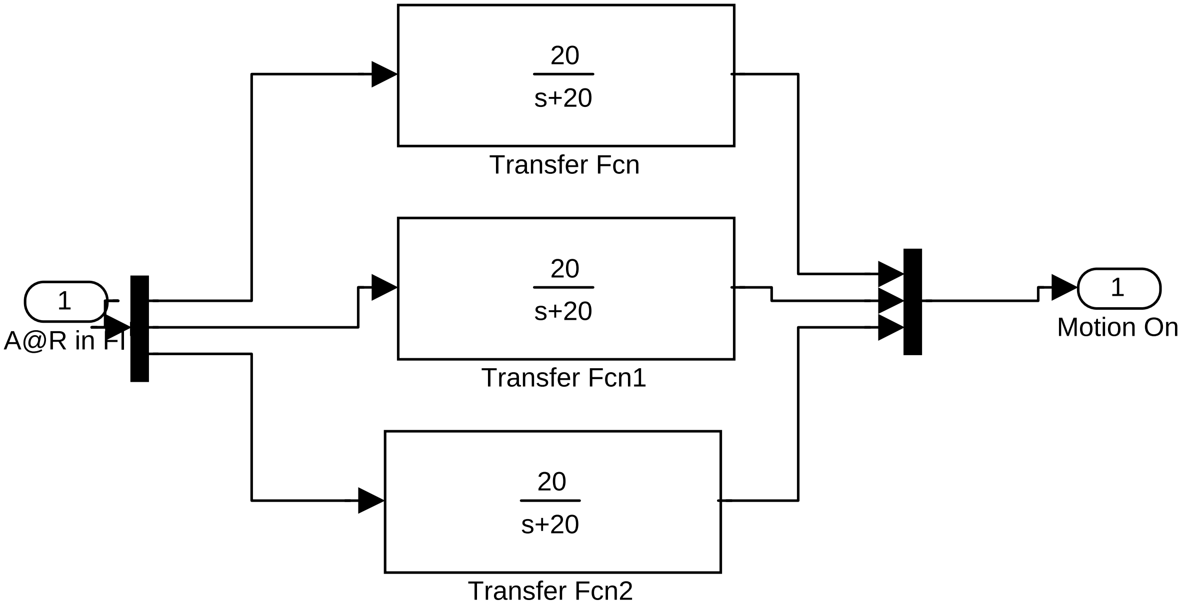
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Overide Switches/Right Limit Switch Plot/Subsystem5

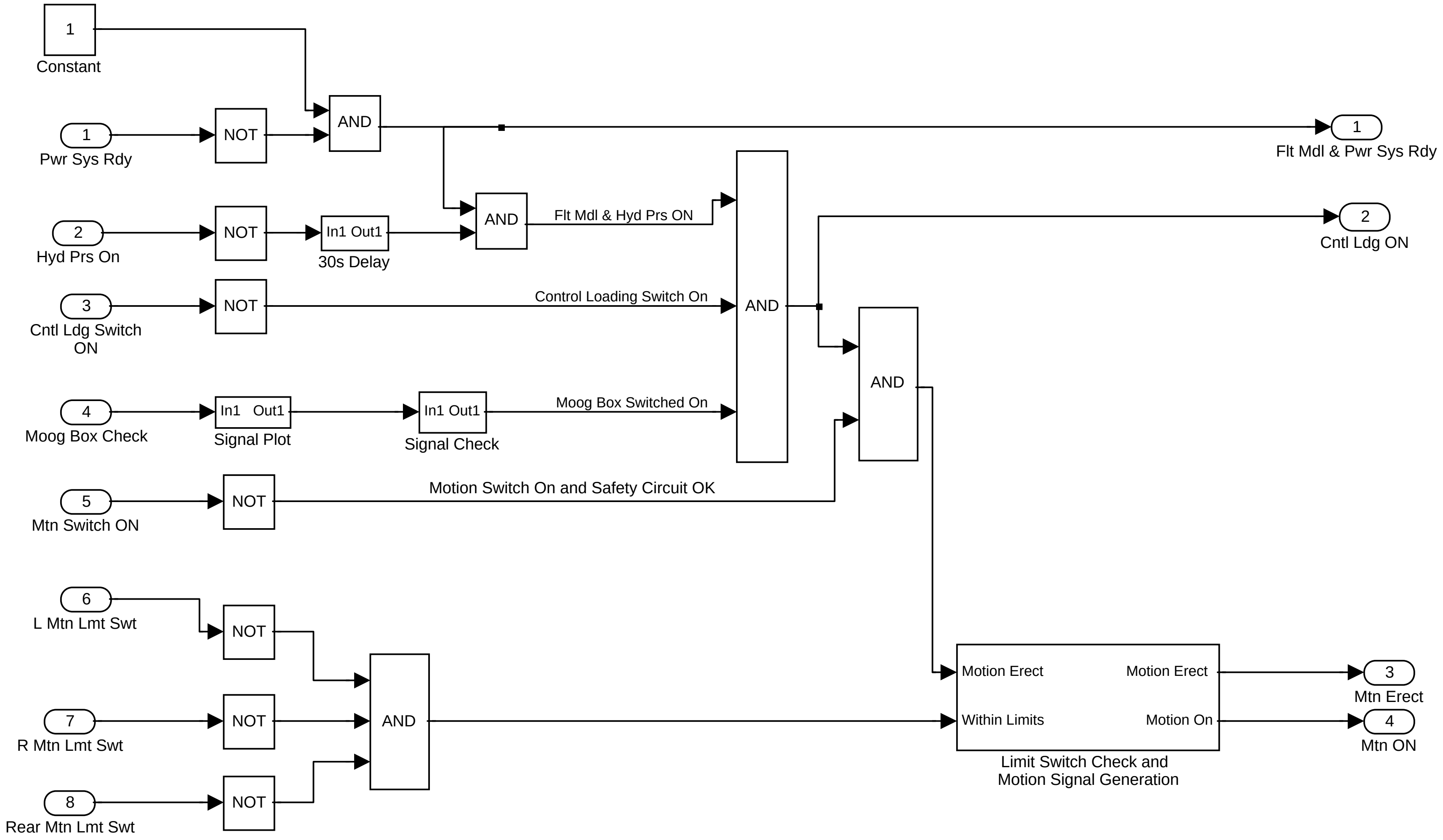


C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Positions

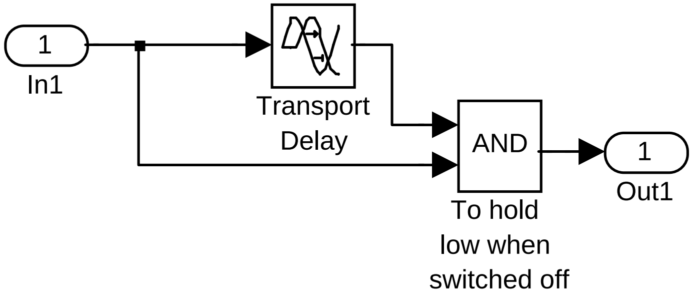


Motion_System_13_Vest/Supervisory Subsystem Input



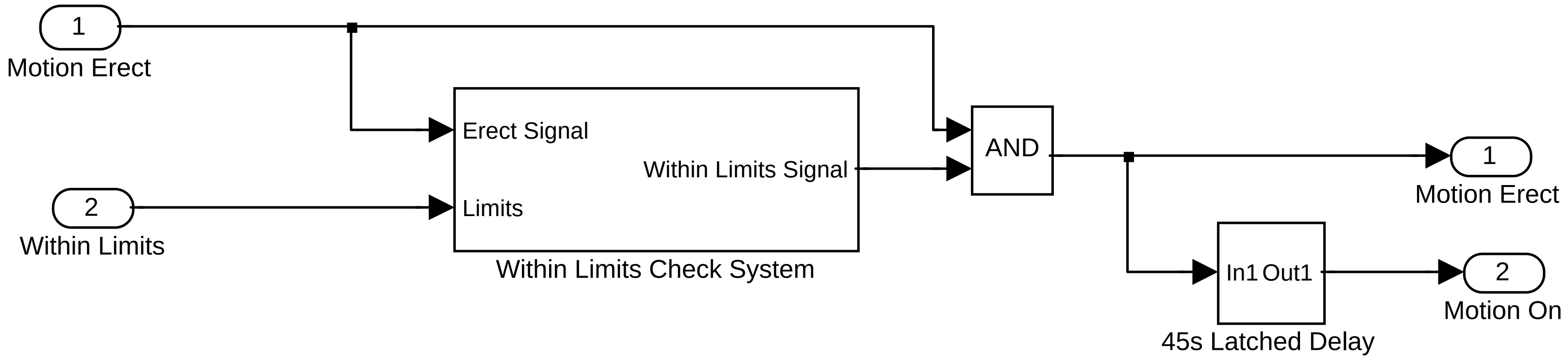
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Supervisory Subsystem Input/30s Delay



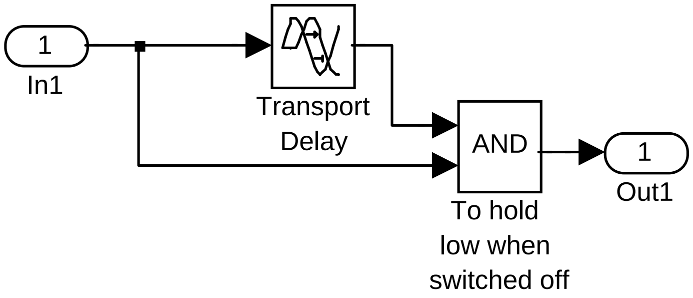
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Supervisory Subsystem Input/Limit Switch Check and Motion Signal Generation



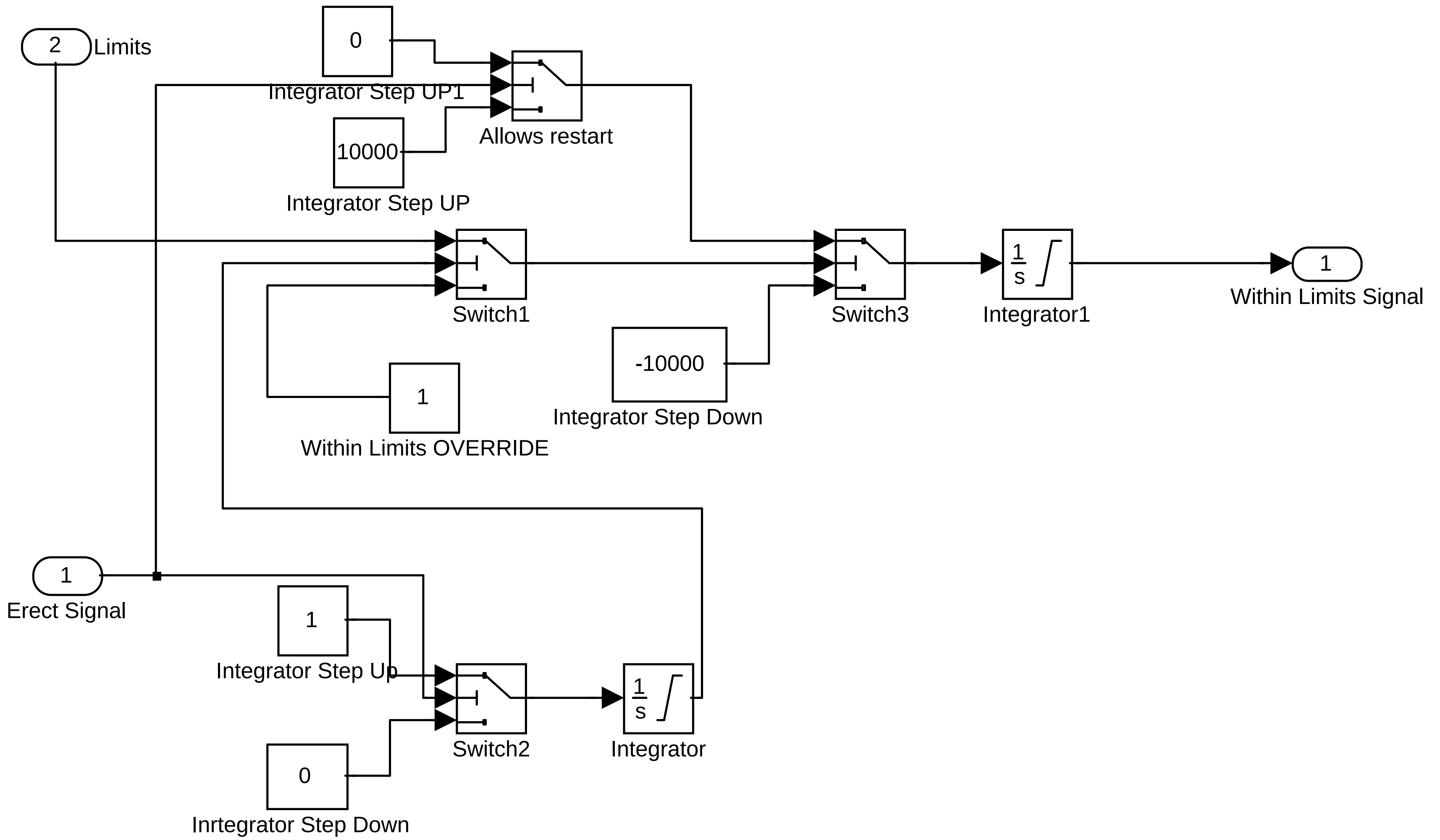
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Supervisory Subsystem Input/Limit Switch Check and Motion Signal Generation/45s Latched Delay



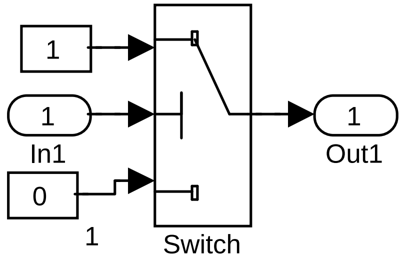
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Supervisory Subsystem Input/Limit Switch Check and Motion Signal Generation/Within Limits Check System



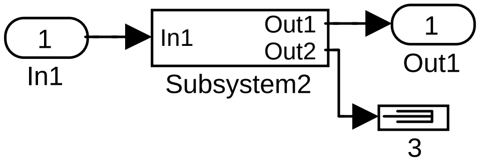
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Supervisory Subsystem Input/Signal Check



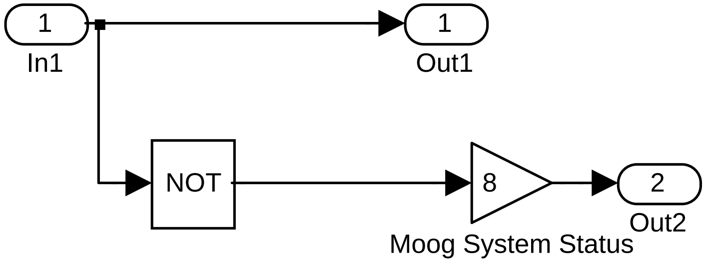
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Supervisory Subsystem Input/Signal Plot



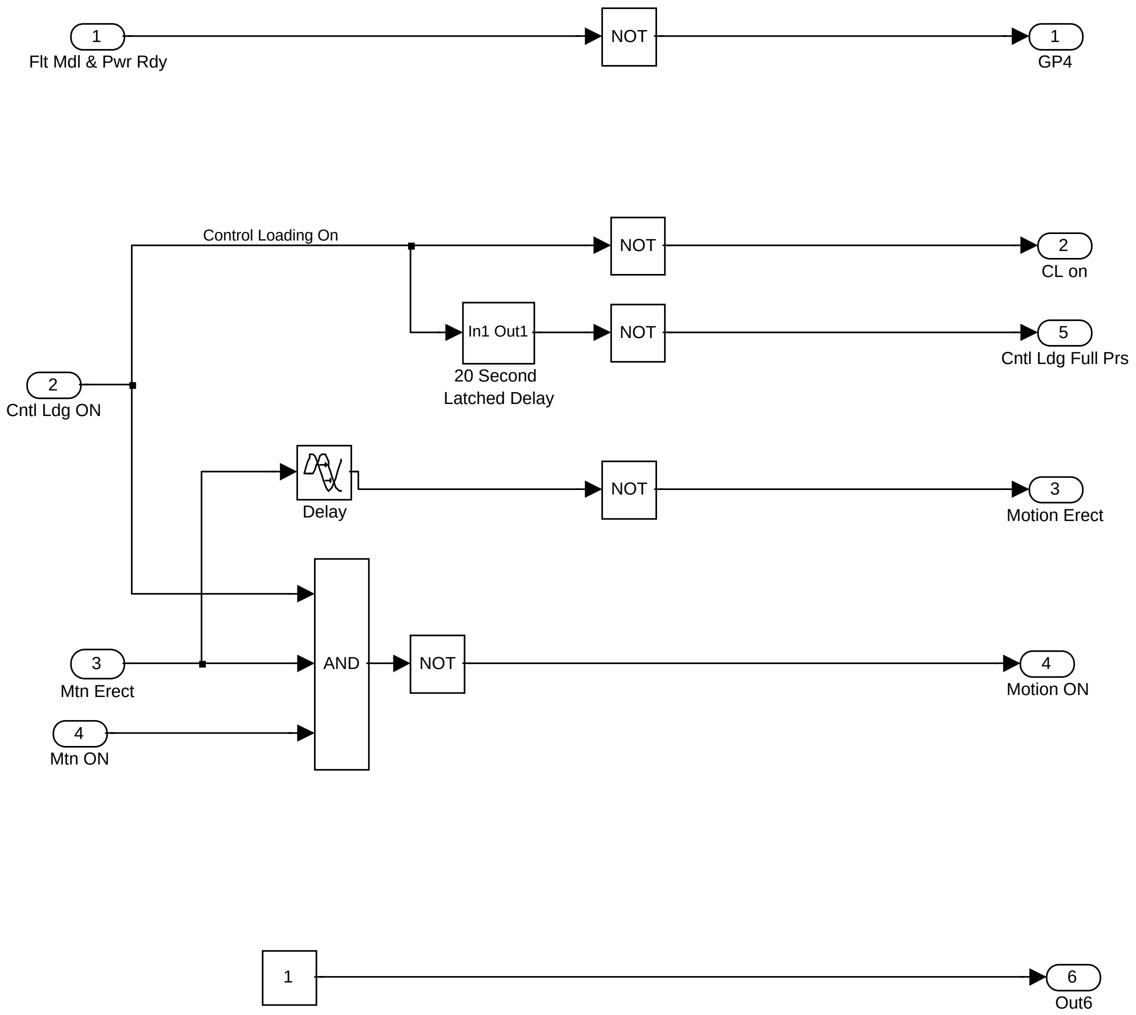
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Supervisory Subsystem Input/Signal Plot/Subsystem2



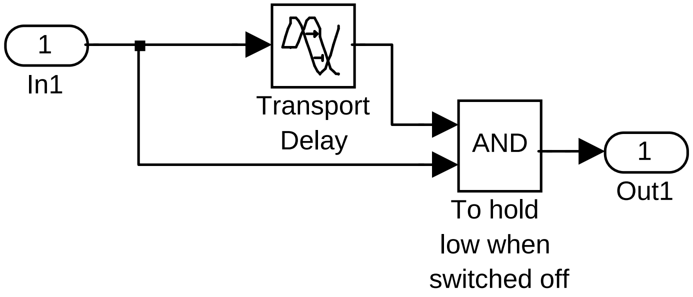
C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Supervisory System Output



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl

Motion_System_13_Vest/Supervisory System Output/20 Second Latched Delay



C:\MATLAB6p1\work\Motion_System_13_Vest.mdl