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Evolution of a Simulator Pilot Force-Feel System

Rodger A. Mueller
NASA Ames Research Center, Moffett Field, CA, 94035

Accurately reproducing pilot force effects on cockpit pilot controls is critical for meeting flight simulation requirements. Using high-performance pilot control loaders (pilot control force) simulators and a computer Pilot Force Program (force-feel program), the Vertical Motion Simulator at NASA Ames Research Center continues to meet this challenge. The Pilot Force Program creates the pilot force-feel effects and has undergone, from its first inception, continuous improvements to meet simulation requirements. Real-time digital systems that use object-oriented programming languages, virtual instrumentation, high throughput I/O, and fast processors are now practical and cost-effective. This paper describes the evolution of the Pilot Force Program, from its beginning using analog computers, to the successful digital computer replacement, that provided a significant improvement in responding to customer requirements.

Nomenclature

F_A	=	force due to acceleration, lb
F_{FB}	=	force balance, lb
F_G	=	force due to gravity. lb
F_P	=	pilot force, lb
F_T	=	differential pressure transducer output force, lb
F_{TB}	=	differential pressure transducer output force bias, lb
m	=	actuator mass, (lb-s^2)/in
s	=	Laplace operator, 1/s
G_0	=	force gradient (spring constant) for linear segment through origin, lb/in
G_n	=	force gradient (spring constant) for linear segment n, lb/in
X	=	pilot control position, in
X_n	=	pilot control position breakpoint for start of linear segment n as measured from origin, in

I. Introduction

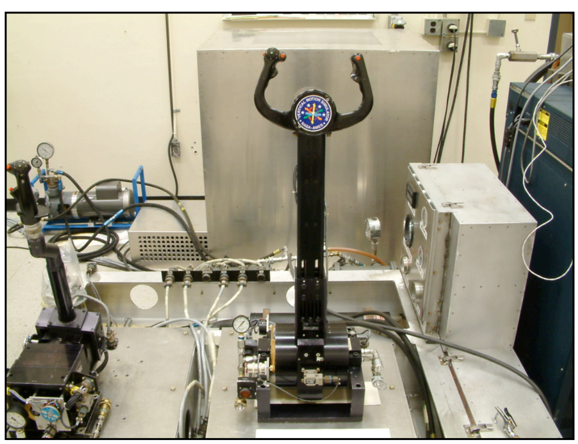


Figure 1. McFadden pilot control loader inceptors mounted on a test platform (Testbed).

The Vertical Motion Simulator (VMS) at NASA Ames Research Center uses McFadden System Inc. electro-hydraulic rotary pilot control loader (PCL) systems, as shown in Fig. 1, almost exclusively. These systems, first developed in the early 1960s (prior to the VMS, which came on-line in 1980), are capable of high forces, high frequency response, low damping factor, and very low friction. The VMS has a total of thirty-one cockpit pilot control assemblies including wheel and columns, cyclics (fighter sticks), collectives, pedals, seat shakers, hand controllers, and custom devices that work with the McFadden PCL systems. The force-feel characteristics of a PCL system are developed using a Pilot Force Program. The first Pilot Force Program at NASA Ames was developed in the late 1960s on an Electronics Associates, Inc. ±100 volt EAI 231R analog computer and was used to support McFadden PCL systems installed in the large six-degree of freedom and hexapod simulators being used at the time. The first Pilot Force Program implementation on an analog computer patchboard is shown in Fig. 2 along with an EAI 231R computer. This analog computer met simulation requirements at the time, but the patchboard was so densely packed with patch cords that it sometimes required a flashlight to view patch connections. By the mid 1970s, EAI 231R analog computers were becoming too expensive and difficult to maintain and were replaced by ±10 volt EAI 2000 analog computers. An EAI 2000 analog computer, which was used in the VMS Laboratory, is shown in Fig. 3. By the late 1990s, the EAI 2000 analog computers were also becoming too expensive and difficult to maintain. In addition, research simulation requirements for PCL system performance, driven by modern aircraft configurations and flight control systems, were exceeding the capabilities of the Pilot Force Programs. It became obvious by the mid 1990s that the EAI 2000 analog computers were nearing the end of their useful life and that a new solution was required to provide PCL capabilities required for research simulations on the VMS.

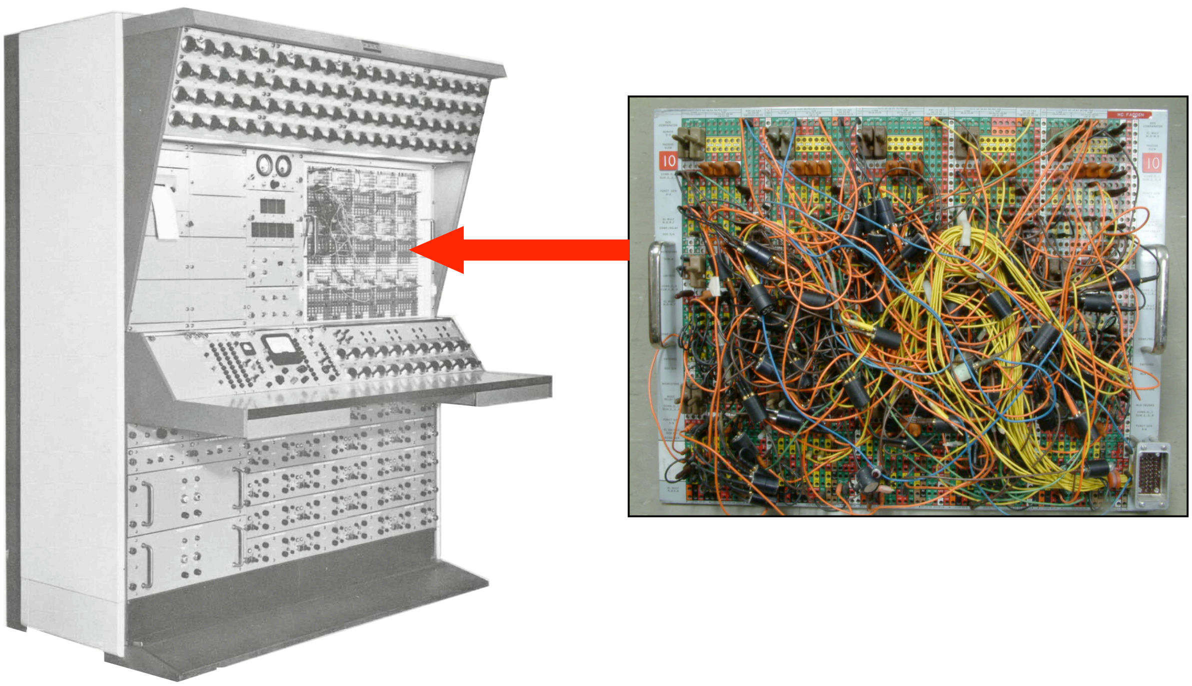


Figure 2. EAI 231R analog computer and Pilot Force Program patchboard.
EAI 231R illustration from bulletin No. AC 6007 courtesy of Electronic Associates, Inc.

The most promising solution was to replace the analog computer based Pilot Force Program with a digital version. Prior to beginning development, the performance requirements for using a digital computer were investigated by simulating digital operation on an analog computer. Quantizing circuits were added to an analog computer Pilot Force Program to simulate frame time delay and analog-to-digital converter (ADC) and digital-to-analog converter (DAC) resolution (quantization effects). The study examined the effects of these parameters on pilot control loader operational “smoothness” and stability and showed that either long frame times or low ADC and DAC resolution imparted a rough or granular feel to the pilot control. The study’s conclusion was that minimum requirements for a digital system included one-millisecond frame times and 16-bit ADCs and DACs.

This paper details the progressive development of the Pilot Force Program at the VMS from its initial analog to its current digital implementation. Section II describes the force feedback type control system model used by McFadden pilot control loaders and explains how the Pilot Force Program computer is interfaced with this model. Section III describes the development of the analog and digital versions of the Pilot Force Program and uses the implementation of the Friction and Nonlinear Force functions to illustrate the differences between these two versions. Section IV explains the current digital computer hardware and software as well as its primary features. Section V provides the conclusions.

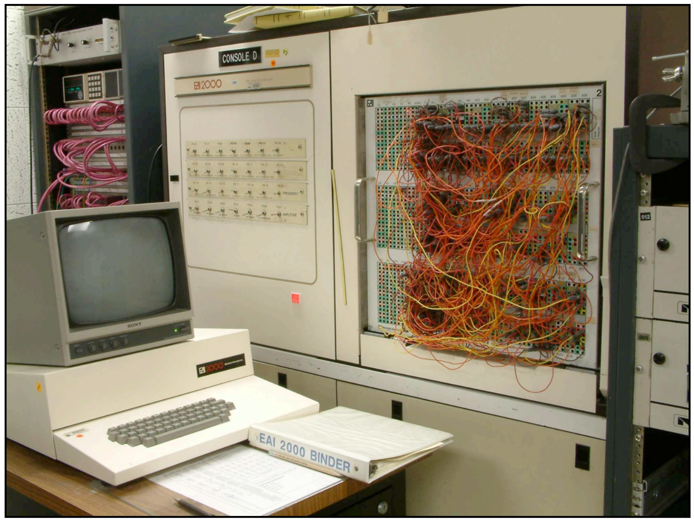


Figure 3. EAI 2000 analog computer with terminal.

II. The Force Feedback McFadden Pilot Control Loader

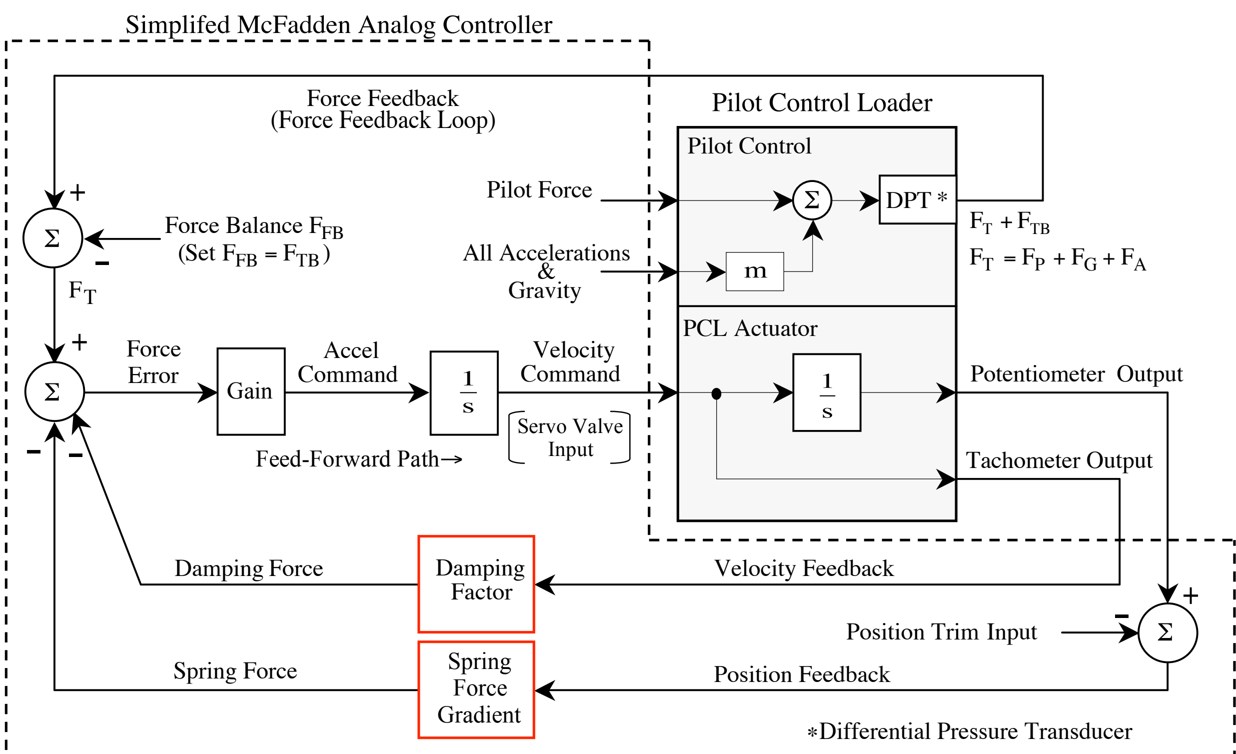


Figure 4. Simplified PCL force feedback model for a single axis.

The simplified 2nd order model shown in Fig. 4 for the PCL force feedback system represents one axis of a pilot control without the Pilot Force Program computer. When the pilot force-feedback loop is optimized, this model holds very well for frequencies up to 10 hertz[1]. Everything outside the Pilot Control Loader block in Fig. 4 is included in the McFadden Analog Controller unit. The front panel of the McFadden Analog Controller has potentiometers for adjusting force balance, position trim, damping factor, and spring force gradient. The McFadden Analog Controllers at the VMS were modified to bring the *Gain* block, which is normally a trim potentiometer located on a printed circuit board, to a front panel potentiometer labeled *Mass*. Varying this gain has the same effect as changing mass.

The model shown in Fig. 4 can only simulate a simple spring force gradient and damping factor. Figure 5 illustrates a PCL force feedback model that is modified to incorporate a computer for implementing the Pilot Force Program. While this illustration shows the basic inputs and output for the Pilot Force Program computer, the final version has both force feedback connections and an interface to the Flight Simulation Computer. This computer manages the overall simulation including the cockpit pilot interface, visual displays, and motion system. The Pilot Force Program computer, which can be analog or digital, only needs pilot control velocity and position feedbacks, in addition to the Flight Simulation Computer, to simulate the pilot control force characteristics.

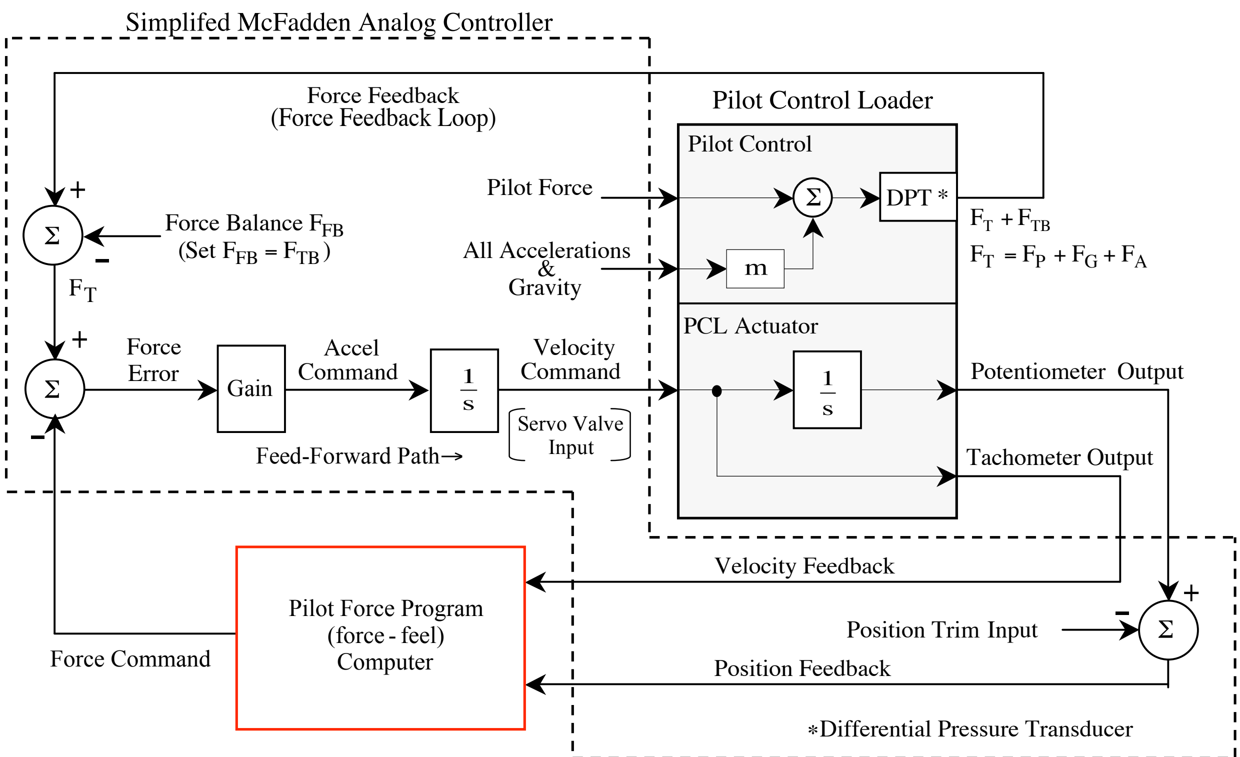


Figure 5. Simplified PCL force feedback translational model for a single axis modified for a Pilot Force Program computer.

III. The Pilot Force Program

The minimum force-feel characteristics that must be simulated by the Pilot Force Program are spring force gradient, damping factor, breakout force, breakout force gradient, independent stops, stop force gradient, and friction. These force functions are a fundamental requirement for a Pilot Force Program regardless of its implementation on either an analog or digital computer. If there are sufficient extra components (e.g. amplifiers, potentiometers, multipliers, etc.) in the analog computer or sufficient processing speed in the digital computer, then additional force functions can be implemented. Characteristics such as stiction, deadzone (free play), deadzone friction and stiction, nonlinear force gradient, pilot force limits, external force, inertia and gravity compensation, and others may be added if computational capacity allows. The implementation of inertia and gravity compensation is discussed in Ref. 2. However, if inertial compensation is not required, then the Gravity Compensation function in the Pilot Force Program can be substituted.

There are four subsections A through D in this section that explain the development of the Pilot Force Program. Section A illustrates all the Pilot Force Program force functions except gravity compensation. Sections B and C explain the development of analog and digital computer versions respectively. Friction Force and Nonlinear Force Gradient functions are used in subsections B and C to illustrate the differences between analog and digital approaches. The last subsection D provides a comparison between the features provided by both systems. This comparison makes the advantages of the digital computer approach clear.

A. Force Functions

Figure 6 illustrates a force versus position graph of force functions that are implemented in the Pilot Force Program. All force characteristics shown can be programmed locally at the analog or digital computer or remotely from the Flight Simulation Computer. The analog or digital implementation of the Pilot Force Program allows dynamic control of all force characteristics during simulation run time through an interface with the Flight Simulation Computer. For example, the pilot controls can be "back driven" through the Flight Simulation Computer or from the cockpit using the pilot trim control. The pilot control force characteristics may also be modified as a function of the simulated aircraft flight condition. This kind of versatility is critical to meeting all research simulation requirements at SimLabs.

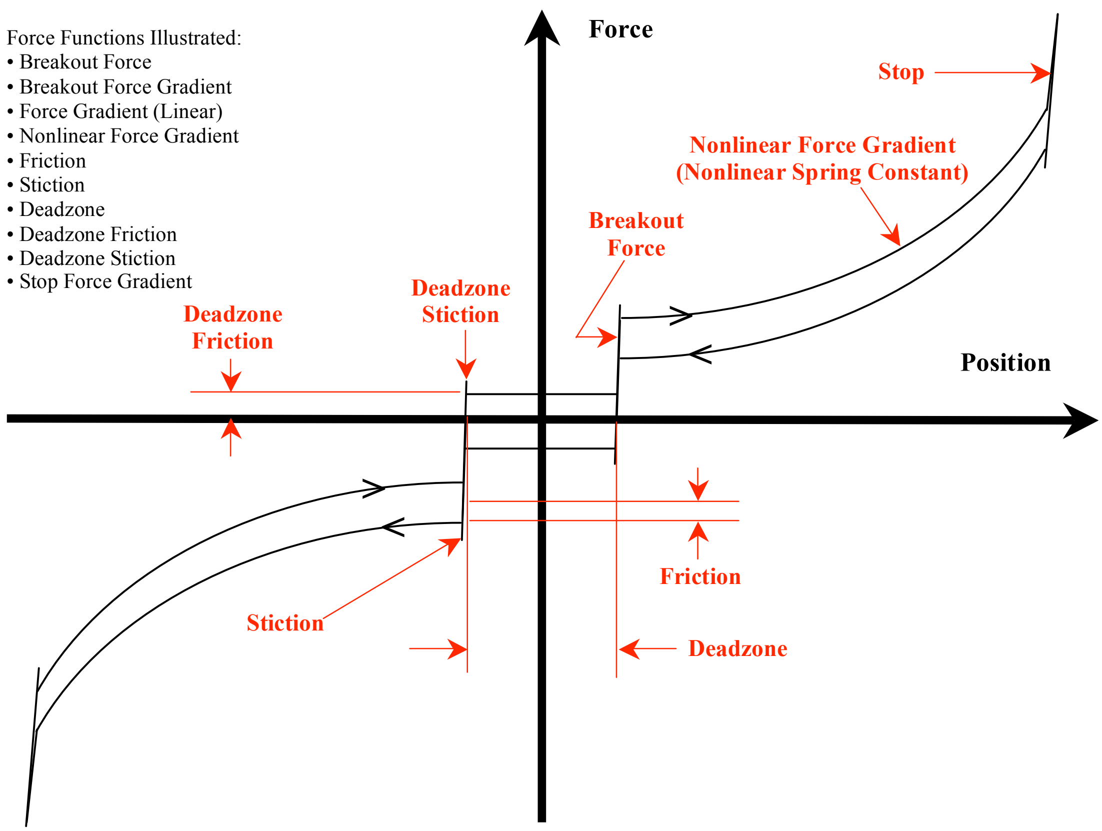
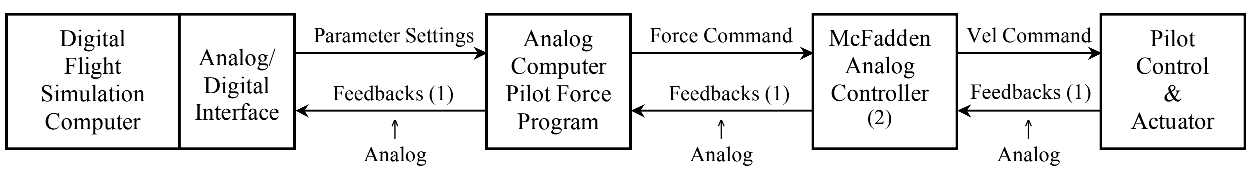


Figure 6. Pilot force example plot.

B. The Analog Computer Pilot Force Program



(1) Feedbacks are force, velocity, and position.
(2) Spring gradient and damping factor on the McFadden Analog Controller are set to zero.

Figure 7. Analog computer pilot force-feel simulation system.

The Pilot Force Program was first programmed on ±100 volt EAI 231R vacuum tube analog computers in the late 1960s. Analog computers were chosen for their high frequency response and because they do not become slower with larger programs. However, a fixed component layout patchboard required careful planning in assigning components to avoid the overuse of long patch cords and the resulting heavy patchboard. Removable patchboards made the analog computers quite versatile, but as useful as these machines were, they also had serious limitations. A fixed number of potentiometers, amplifiers, multipliers, and so on, meant that program size was limited. Setup times were required to set potentiometers and perform program static and dynamic checks. External control of parameters required the installation of switches. In addition, maintenance cost and calibration time were relatively high. The replacement of ±100 volt analog computers with ±10 volt solid-state computers reduced the maintenance cost, but calibration time was still required.

The functional diagram in Fig. 7 illustrates the analog Pilot Force Program implementation at the VMS. A pilot force input to the pilot control generates a force feedback signal that is fed to the McFadden Analog Controller, which drives the pilot control in the direction of the applied force. Position and velocity feedback signals sent to the Pilot Force Program are used to create the opposing force characteristics called the Force Command, which is fed back to the McFadden Analog Controller (also see previous Fig. 5) and compared to the pilot force feedback. The difference between the two signals becomes the "force error" term. After integration, this term becomes the servo valve input or Velocity Command signal. The Flight Simulation Computer receives all feedback signals, including pilot force, as input to the aircraft dynamic model. The Flight Simulation Computer also controls all force function parameter settings for the Pilot Force Program and allows all force functions to be dynamically changed during simulation runs.

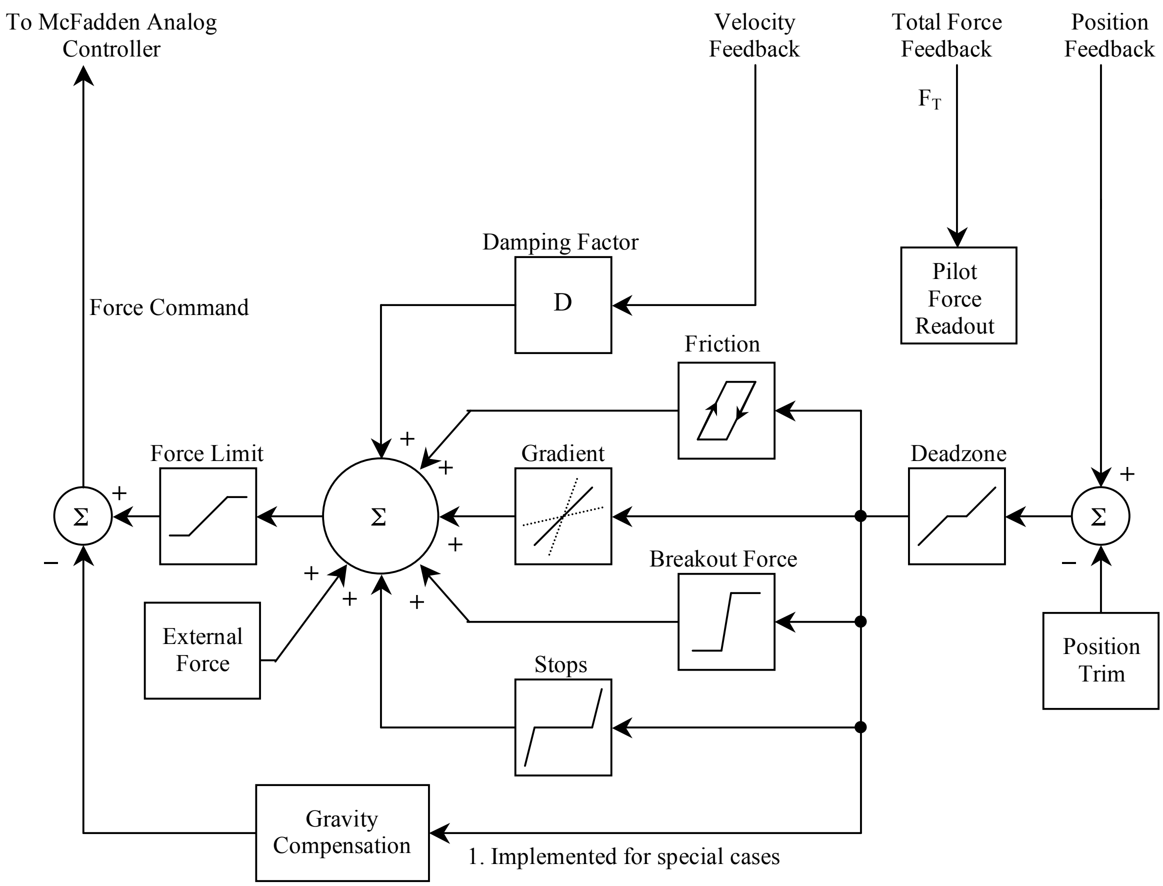


Figure 8. Analog computer Pilot Force Program functional diagram.

Figure 8 illustrates the analog computer Pilot Force Program. The McFadden Analog Controller provides all feedback signals and receives the Force Command as input. A DAC interface allows the Flight Simulation Computer to set parameters in the Pilot Force Program. Toggle switches are used to allow any parameter to be set locally (at the analog computer) or by the Flight Simulation Computer via DACs. The Pilot Force Readout block is used only for providing pilot force feedback to the Flight Simulation Computer since the Pilot Force Program does not require force feedback.

As previously mentioned, Friction Force and Nonlinear Force Gradient functions, are used to illustrate the technical differences that can arise when switching between analog and digital computer systems. For example, the Friction Force function was initially difficult to implement in the digital computer version, but it was just the opposite for the Nonlinear Force function.

1. The Analog Friction Force Function

The Friction Force function illustrated in Fig. 9 provides a good example of the problems that can occur when switching from an analog to a digital computer system or from an analog computer to another analog computer. The problem is that the friction value must exhibit a constant value without any drift in the pilot control position. An example would be a helicopter collective controller, which is typically held in place by friction. When the pilot moves the collective to a new position and then releases the grip, it is expected that the collective will hold its position. Also, the friction spring gradient determines the friction force stiffness and should be as high as practical without causing vibrations or instabilities.

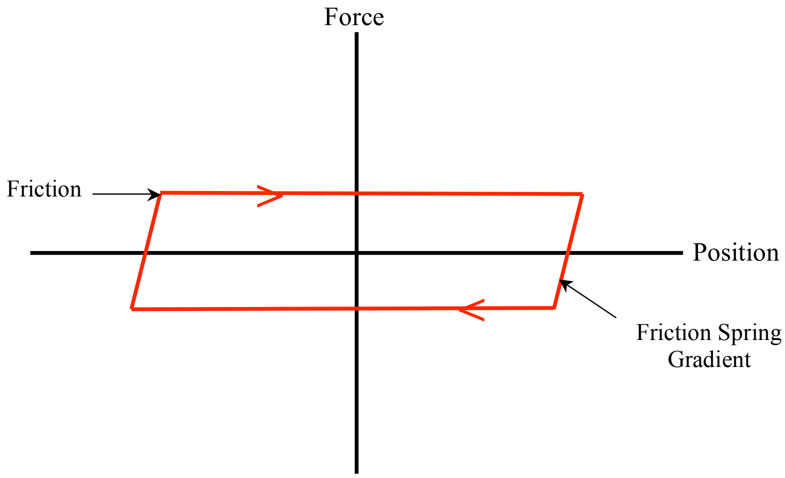


Figure 9. Friction Force function.

The analog computer Friction Force function circuit has been around for a very long time[3]. The basic design consists of a tracking circuit with a high loop gain. The tracking integrator follows the position input, but with a friction force set by the friction value. The tracking circuit loop gain must be at least 5000 or a noticeable artificial viscous damping will be created that can be felt by the pilot that is most notable when the friction value and other force characteristics are set to zero

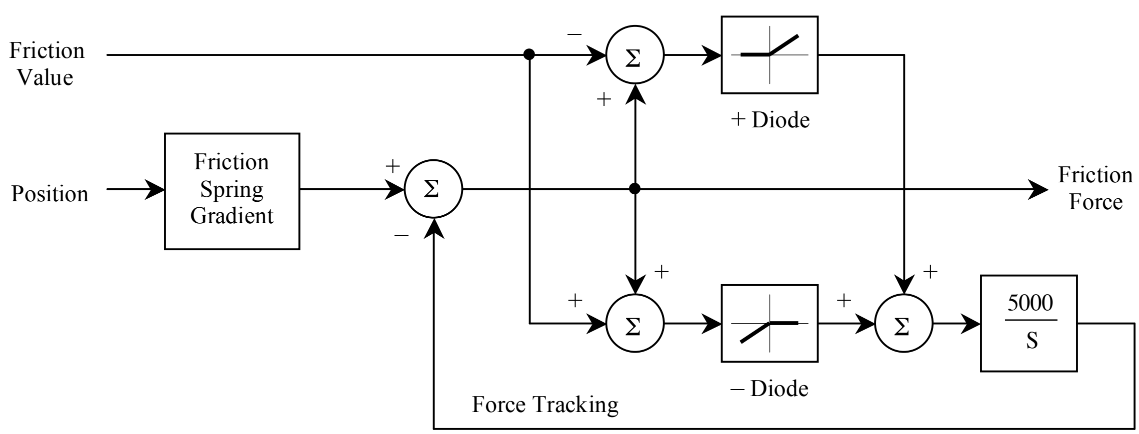


Figure 10. Analog computer Friction Force function circuit.

The ±100 volt EAI 231R analog computers were replaced by ±10 volt EAI 2000 analog computers in the late 1970s. However, the EAI 2000 integrators drifted significantly causing pilot control position drift. This problem was overcome by designing a friction circuit using low-drift operational amplifiers. The complete assembly or component tray was designed to fit into an amplifier slot on the EAI 2000 analog computer. A trim potentiometer, located close to the patch cord contacts and accessible from the front panel was used to zero integrator drift. This worked very well as the trim adjustment also took into effect any amplifier voltage offsets. Available additional space on the component tray was used to house a Stops function, which simulates a mechanical stop as previously illustrated in Fig. 6. The resulting Friction/Stops function tray is shown in Fig. 11.

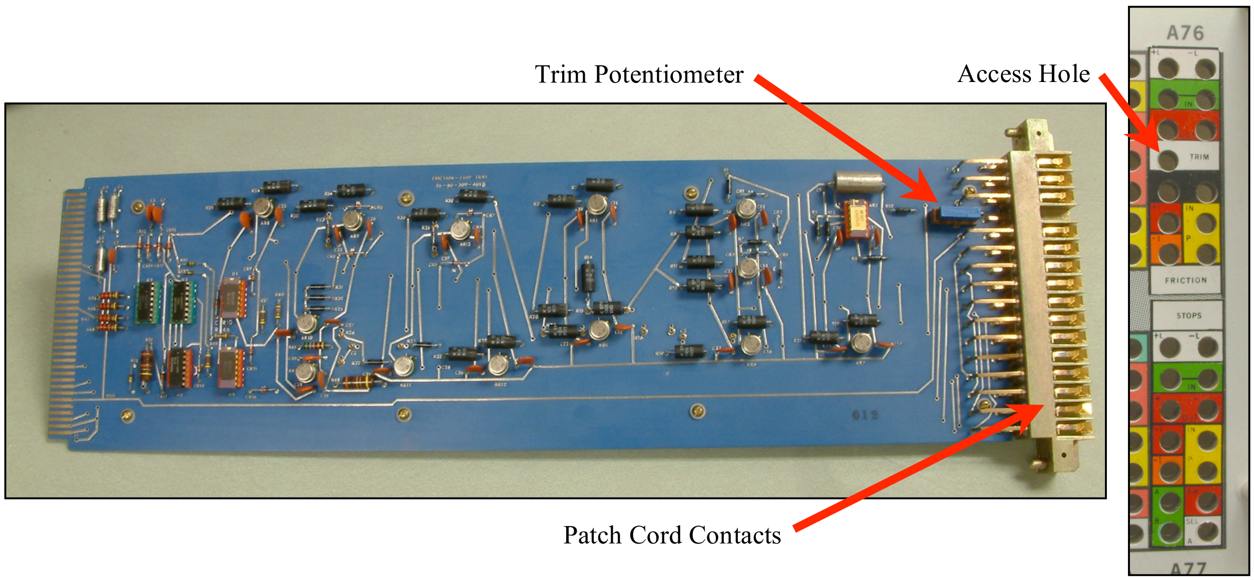
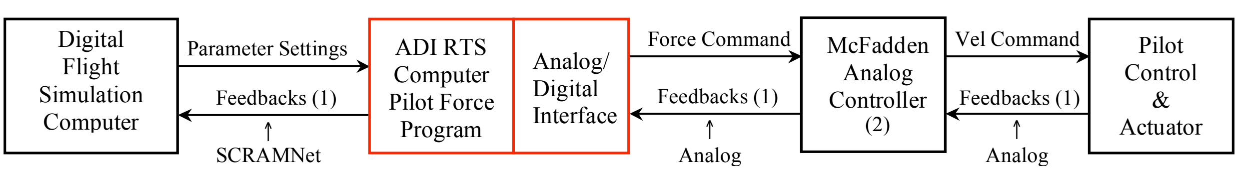


Figure 11. Friction/Stop tray and patchboard decal.

2. The Analog Nonlinear Force Gradient Function

Nonlinear curves are typically implemented on an analog computer using diode function generators This implementation uses diode networks to approximate nonlinear curves in a technique called piece-wise linear approximation. An example is illustrated in *The Digital Nonlinear Force Gradient Function* section. While 20- and 21-segment function generators were available for the EAI 231R and EAI 2000 analog computers respectively, these were never considered practical for Pilot Force Program applications as they were tedious to set and change and not externally programmable. The EAI 231R 20-segment function generator had position breakpoint and slope (force gradient) potentiometers that are manually set. Furthermore, changing any breakpoint or gradient potentiometer affected all breakpoint or gradient potentiometer settings that followed. On the other hand, the EAI 2000 function generator was easily set through a terminal, but it was limited to fixed position steps. The 21-segment breakpoints were fixed evenly spaced intervals and each of these breakpoints could be assigned a coefficient that was proportional to the reference voltage. This proved unusable as the fixed evenly spaced position breakpoints did not provide the position precision required for nonlinear force gradient applications in the Pilot Force Program.

C. The Digital Computer Pilot Force Program



(1) Feedbacks are force, velocity, and position.
(2) Spring gradient and damping factor on the McFadden Analog Controller are set to zero.

Figure 12. Digital computer pilot force-feel simulation system.

The first effort to replace the analog computer with a digital computer equivalent involved using a Personal Computer (PC) based real-time system. However, problems arose when developing the Friction and Stiction Force functions (see previous illustration Fig. 6). One problem was discussed earlier – the loop gain requirement – but the most critical problem was that the Stiction Force function would occasionally drop out. The result was that the Stiction Force function would sometimes re-engage when it should not, causing a force “bump” effect on the pilot control. The problem was that the PC based real-time system was not exactly real-time. A DAC channel was set up to output a square wave with a period equal to two frame times or two milliseconds and examination of the square wave output showed that timing froze for least two frame times approximately every forty-four milliseconds. This pseudo real-time effect was confirmed by the manufacturer and was considered by them to be acceptable for most applications. As a result, the PC-based system was replaced by an Applied Dynamics International Real Time System (ADI RTS) computer in 2001. The ADI RTS incorporates MatLab/Simulink, Altia FacePlate, high-speed processors, and high-speed 16 bit DACs and ADCs.

Another problem discovered was that a full four-axes simulation could not be achieved in the one millisecond frame time requirement. In fact, no system tested using object oriented programming, software-based virtual instruments, and 16 bit DACs and ADCs could meet this requirement, but the technology was rapidly changing. Meanwhile, development of the Pilot Force Program continued and in 2004 a high-speed processor was available that achieved frame time requirement.

The functional diagram in Fig. 12 illustrates the pilot force-feel system using an ADI RTS and operation is similar to the analog computer system previously shown in Fig. 7. The link between the Pilot Force Program and the Flight Simulation Computer changed from analog cables to optical fibers using SCRAMNet, and the Analog Digital Interface (DACs and ADCs) moved from the Flight Simulation Computer to the ADI RTS computer. There was no attempt to replace the McFadden Analog Controller, as the force feedback loop frequency requirements could not be provided by any practical digital system[4]. For example, it would not be possible to meet the tuning requirements[5] of the force feedback loop using the Pilot Force Program frame time of one millisecond.

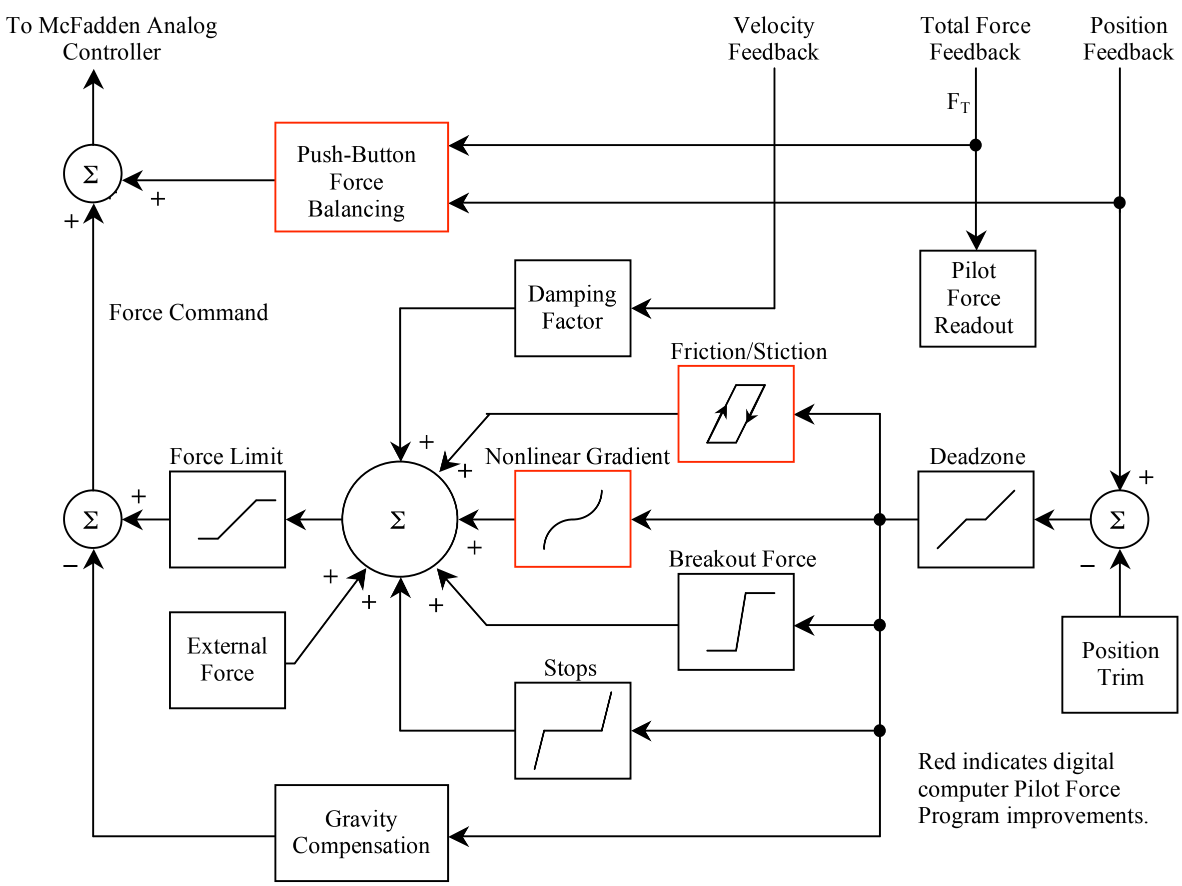


Figure 13. Digital computer ADI RTS Pilot Force Program functional diagram.

Figure 13 illustrates the digital computer Pilot Force Program, which is very similar to the analog computer version previously shown in Fig. 8. The Force Command is an input to the McFadden Analog Controller as it was with the analog version. Not shown is the SCRAMNet interface that allows the Flight Simulation Computer to set parameters in the Pilot Force Program and read feedback signals. Total force feedback is fed to the Pilot Force Readout block and the push-button force balancing block that are used to provide pilot force feedback to the Flight Simulation Computer and force balancing respectively. Push-button force balancing is a real benefit in switching to the digital computer Pilot Force Program and is used to compensate for force biases in the pilot control electronics, especially the differential pressure transducer (see previous Fig. 5). Other benefits of the digital computer approach include not having to convert parameter values into analog potentiometer coefficients and interpreting scaled amplifier voltages. The Flight Simulation Computer now communicates with the Pilot Force Program digital computer with physical parameters instead of voltages.

The next two sections explain the Pilot Force Program digital program implementation of the Friction Force and Nonlinear Force Gradient functions. As previously mentioned, these two force functions illustrate the differences between analog and digital computer Pilot Force Programs.

1. The Digital Friction Force Function

The Friction Force function is an example of the difficulties that can occur in transitioning from an analog to a digital computer Pilot Force Program. Modeling the Friction Force function using a digital equivalent of the analog computer model previously illustrated in Fig. 10 resulted in instabilities. As it turns out, digital computer programs are unstable if the frame time is not less than the reciprocal of any feedback loop gain when using standard integration algorithms. This implies a frame time of 200 microseconds or less for the feedback loop gain of 5000 used in the analog Friction Force function circuit. As previously mentioned, a minimum feedback loop gain of 5000 is necessary to avoid generating a noticeable viscous damping effect, but it was not possible to achieve frames times smaller than one millisecond using the available software and hardware. This means that the loop gain would have to be no greater than 1000 for the digital equivalent circuit, which would result in a noticeable artificial viscous damping factor. Therefore, accurate simulation of this function required the development of a different type of Friction Force function that did not require an integrator in a high-gain feedback loop.

To meet these requirements, the digital Friction Force function, shown in Fig. 14, was developed and uses a tracking circuit that incorporates a frame time delay unit. This tracking circuit allows the Friction Force function to limit the friction force to the input parameter *Friction Value*. But, most importantly, this Friction Force function implementation does not create an artificial damping factor or allow pilot control position drift.

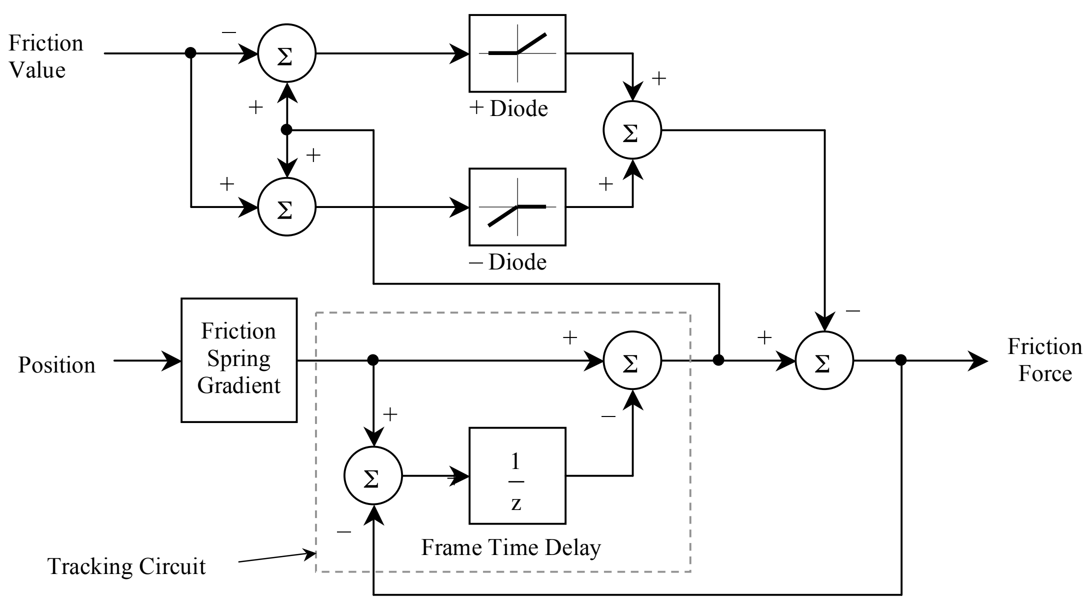


Figure 14. Digital computer Friction Force function circuit.

2. The Digital Nonlinear Force Gradient Function

In contrast to the Friction Force function, the Nonlinear Force Gradient function shows why it was advantageous to switch from an analog to a digital computer. The most common approach to simulating nonlinear curves is the "linear segment" or "piece-wise linear approximation" technique. The linear segment force curve consists of short linear segments that are defined by a position breakpoint and force gradient. An example of a nonlinear pilot force graph (nonlinear spring constant) is illustrated in Fig. 15. In this example, the nonlinear force curve is shown in black and the linear segment force curve is shown in red. An initial linear force gradient segment is used for the gradient through the origin G_0 with ten additional segments each for Quadrants I and III.

A general linear segment force curve for Quadrant I is defined as:

$$X_n \le X \le X_{n+1} \qquad F = XG_0 + (X - X_1)(G_1 - G_0) + (X - X_2)(G_2 - G_1) + \ldots + (X - X_n)(G_n - G_{n-1}) \tag{1}$$

A general linear segment force curve for Quadrant III is defined as:

$$X_{n-1} \le X \le X_n \qquad F = XG_0 + (X + X_{-1})(G_{-1} - G_0) + (X + X_{-2})(G_{-2} - G_{-1}) + \ldots + (X + X_{-n})(G_{-n} - G_{-n+1}) \tag{2}$$

where n is the segment number as measured from the origin.

The parameters in Eqs. (1) and (2), which consist of breakpoints X_n and gradients G_n, are independent of all other breakout and gradient settings. The segment through the origin is segment *0*. A negative n would be a segment or position breakout in Quadrant III. When applied to a breakout, n is the start of a linear segment as measured from the origin.

For the example shown in Fig. 15, the piece-wise linear equations for Quadrant I would be:

$$0 \le X \le X_1 \qquad F = XG_0 \tag{3}$$

$$X_1 \le X \le X_2 \qquad F = XG_0 + (X - X_1)(G_1 - G_0) \tag{4}$$

$$X_2 \le X \le X_3 \qquad F = XG_0 + (X - X_1)(G_1 - G_0) + (X - X_2)(G_2 - G_1) \tag{5}$$

$$X_3 \le X \qquad F = XG_0 + (X - X_1)(G_1 - G_0) + (X - X_2)(G_2 - G_1) + (X - X_3)(G_3 - G_2) \tag{6}$$

The last segment ($X_3 \le X$) extends indefinitely. The equations for Quadrant III are identical except that the sign for X_n is positive. The general Eqs. (1) and (2) were implemented using MatLab/Simulink summers, multipliers, and precision "diode" circuits. Parameters can be set locally or externally via SCRAMNet from the Flight Simulation Computer. This gives the researcher the capability to dynamically change the shape of the force curve for the pilot control during simulation run times. Equations (1) and (2) were implemented so that only positive values of X_n are entered for both Quadrants I and III.

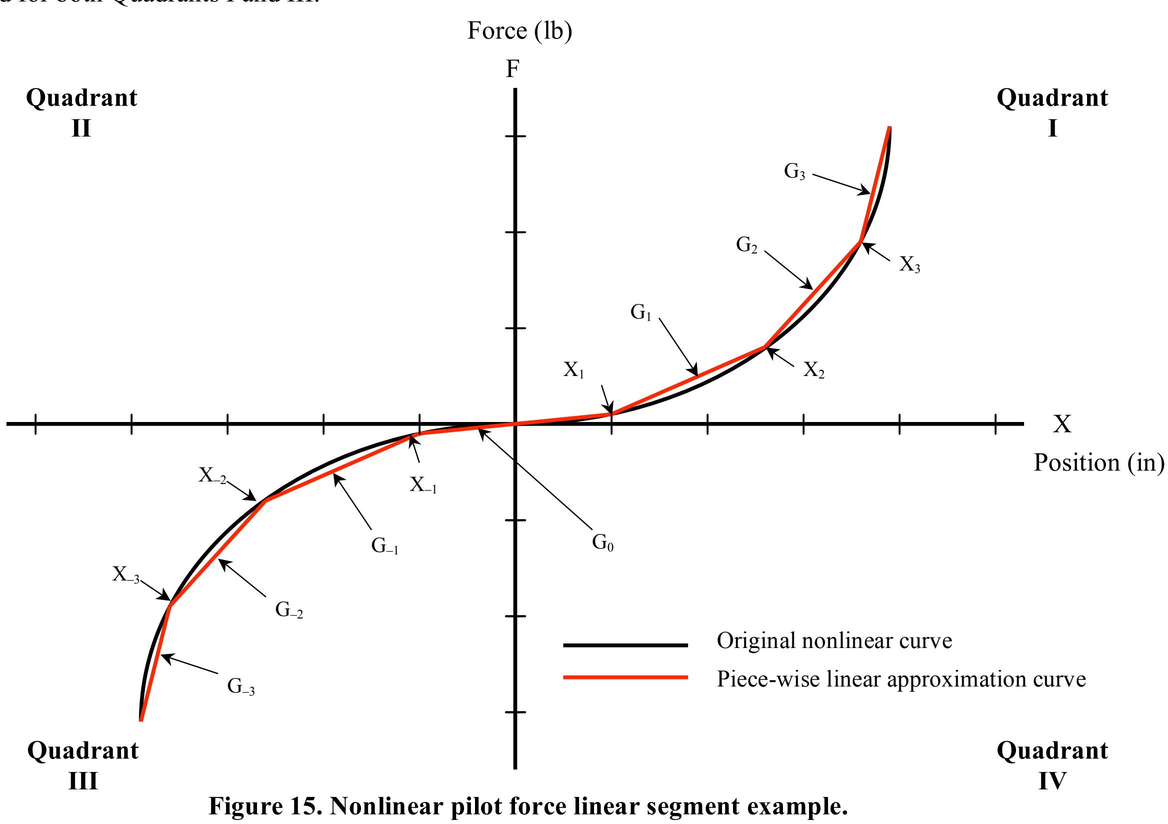


Figure 15. Nonlinear pilot force linear segment example.

D. Comparing the Analog and Digital Pilot Force Programs

Table 1 provides a comparison between the analog and digital computer program features. To keep this comparison in perspective, recall that the digital computer Pilot Force Program could not match the analog computer Pilot Force Program minimum requirements until 2004.

Parameter	Analog	Digital	Parameter	Analog	Digital
Damping Factor	Yes	Yes	Position Plus Stop	Yes	Yes
Gradient (Initial)	Yes	Yes	Position Minus Stop	Yes	Yes
Nonlinear Gradient	[1]	Yes	Position Stops Gradient	Yes	Yes
Breakout Force	Yes	Yes	Position Trim	Yes	Yes
Breakout Force Gradient	Yes	Yes	External Force	Yes	Yes
Friction	Yes	Yes	Gravity Compensation	[1]	Yes
Stiction	No	Yes	Damping Factor Compensation	[1]	Yes
Variable Friction/Stiction Gradient	No	Yes	Automatic Force Balancing	No	Yes
Deadzone	Yes	Yes	Slow Program Turn-On	No	Yes
Deadzone Friction	[1]	Yes	Program Off Damping	No	Yes
Deadzone Stiction	No	Yes	Force Command Limit	[1]	Yes

[1]: Only by special request due to insufficient components for programming all axes.

Table 1. Analog and digital computer Pilot Force Program features.

IV. The Digital Pilot Force Program System

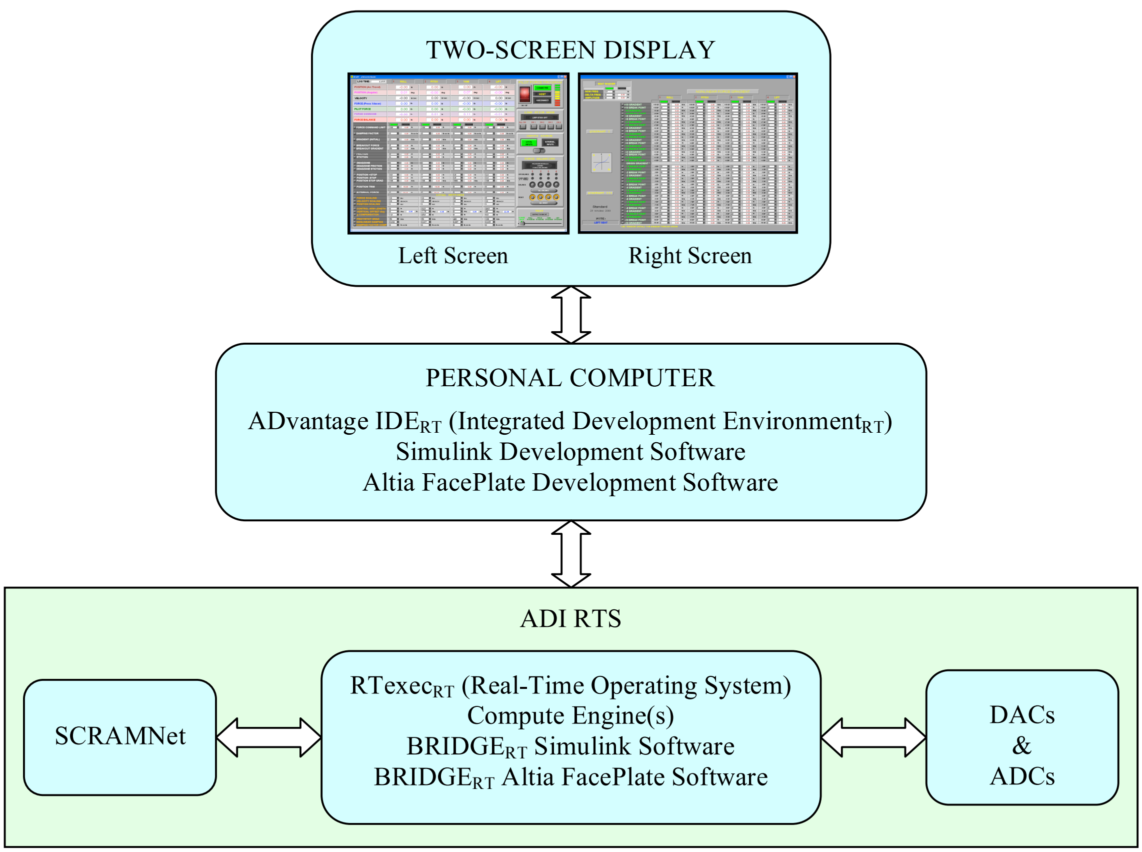


Figure 16. Digital computer four-axes Pilot Force Program system.

This section explains implementation of the final version of the Pilot Force Program for the VMS digital computer system. This is followed by a more detailed description of the Pilot Force Program virtual instrument two-screen display. These displays are a significant improvement in the interface between the Pilot Force Program, the Flight Simulation Computer, and the researcher. A brief description is given for each screen display.

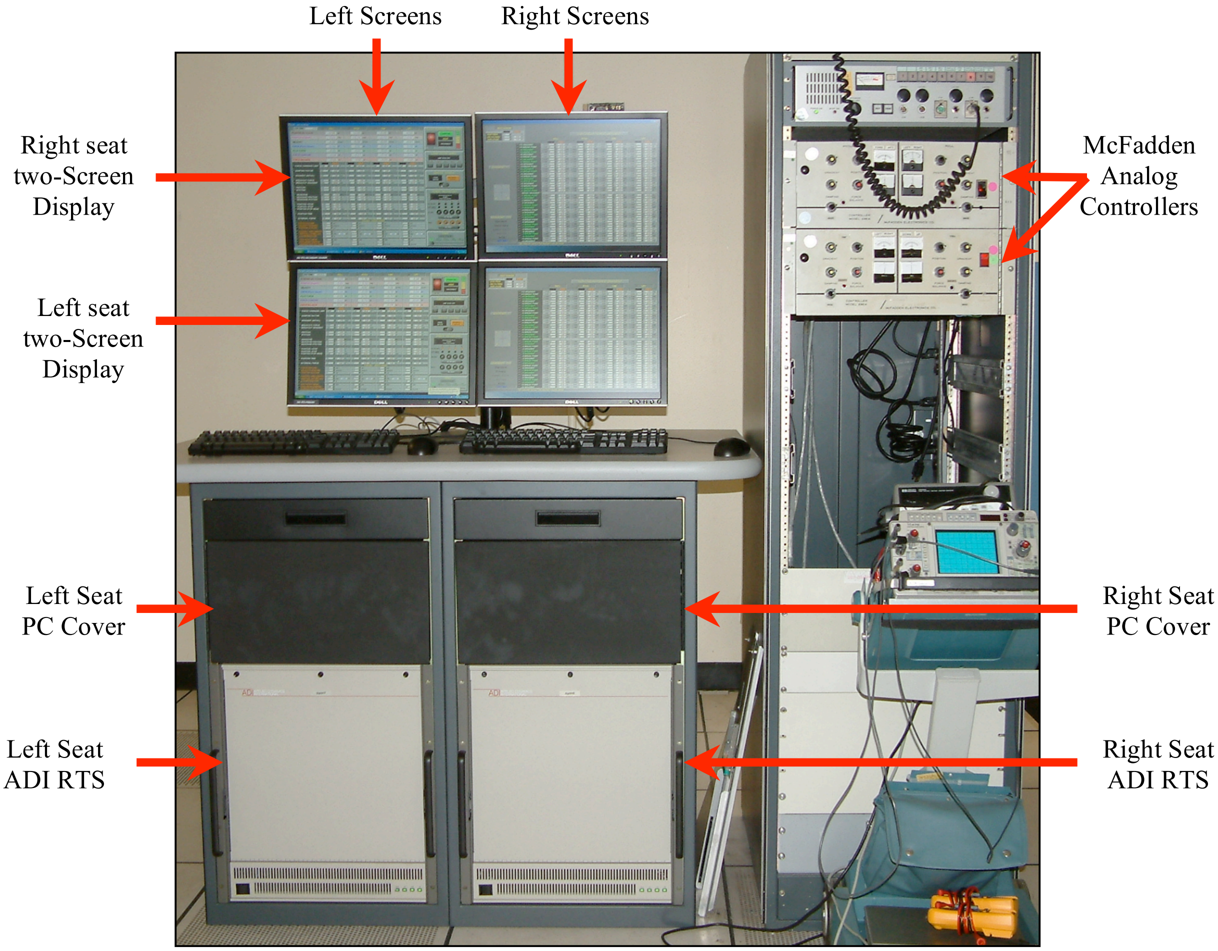


Figure 17. Two seat ADI Pilot Force Program system.

A. The ADI Real Time System

The Applied Dynamics International Real Time System (ADI RTS) computer is a hardware/software platform that was used to develop the digital computer Pilot Force Program replacement for the analog computer version. A functional diagram of the final digital system for four axes of pilot controls is illustrated in Fig. 16. The ADvantage IDE_{RT} (Integrated Development Environment) links the users various software programs (Simulink and Altia FacePlate) and hardware (DACs, ADCs, and SCRAMNet) into what appears to the user as a single software/hardware system. There is no requirement for the user to develop interface software. All software programs are linked through proprietary ADI $\text{BRIDGE}_{\text{RT}}$ software ($\text{BRIDGE}_{\text{RT}}$ Simulink and $\text{BRIDGE}_{\text{RT}}$ Altia FacePlate). The Pilot Force Program SCRAMNet provides a link to the Simulation Flight Computer for pilot control feedbacks and to set Pilot Force Program parameters (e.g. force gradient, damping, friction, etc.). The DACs and ADCs are used to interface the ADI RTS with the pilot controls and include all feedbacks and Force Command as previously illustrated in Fig. 12.

Figure 17 shows the hardware for an eight-axes pilot control force-feel system and is generally used to configure a two-seat simulator cab with four axes per seat. The cabinets for all systems were fabricated in-house and consist of two 19-inch racks bolted together to form a single unit. The racks house both the Personal Computers and ADI RTSs. The Altia FacePlate virtual instrument panel displays are mounted on stands for easy viewing. The keyboards can be stored in compartments located just below the cabinet top. A third 19-inch rack just to the right of the ADI RTS cabinet is used to hold the McFadden Analog Controllers. Shown are two McFadden Analog Controllers that are sufficient for 4 axes [e.g. roll, pitch, yaw, and lift (thrust)] of pilot controls. Two more McFadden Analog Controllers would be required to support the second ADI RTS system shown. Both the ADI RTSs and McFadden Analog Controllers have cable interface panels mounted on the rear of each 19-inch rack. Analog cables are used to interface the McFadden Analog Controllers to the ADI RTSs and optical cables are used to interface the ADI RTSs to the Flight Simulation Computer.

A development station or Testbed (see previous Fig. 1) is equipped with a complete ADI RTS system and is the only system with Simulink development software. Satellite ADI RTS systems without the Simulink development software are located in simulator cab development labs and motion simulators. Simulink and Altia Faceplate program designs for the Pilot Force Program are done on the Testbed Personal Computer (see Fig. 16) and then compiled. Copies of the compiled program are then installed in each satellite system and downloaded to their respective ADI RTS computer where real-time computation takes place through RTexec$_{RT}$, a real-time executive. A single development station assures that all satellite systems will have the same Pilot Force Program configuration.

B. Pilot Force Program Altia FacePlate Instrument Panels

The Pilot Force Program virtual instrument panels for eight axes of pilot controls consist of two sets of two 20-inch screen displays as shown in Fig. 17. All parameters are displayed so that researchers and simulation engineers can view or set parameters without having to manipulate the screen displays. While the screen displays are busy, the use of LCD technology gives for a sharp display with easy to read alphanumerics.

The Altia FacePlate virtual instrument panels are made up of various objects or widgets that are taken from a library of widgets provided by Altia FacePlate. Each of the widgets can be reshaped and given characteristics, which, for example, can be anything from color, shading, text, and so forth. Readout widgets can only display numerics. Input widgets are used for entering numerics or parameters and can easily be identified by the increment arrows just to the right of each widget. Virtual switches, buttons, and indicators are used for logic operations.

1. Left Screen Display

Figure 18. Left screen virtual instrument panel display.

Refer to the left screen shown in Fig. 18. The top left side of the screen lists seven readout widgets per axis or column. Displayed are all feedback signals and Force Commands to the McFadden Analog Controller. Parameter headings shown in white, on the left side of the screen are associated with two columns of widgets for each axis. The column on the left, headed by a green indicator, has input widgets for local settings while the other column on the right display external inputs from the Flight Simulation Computer. Parameters headings, shown in orange on the lower left side of the screen and under "Local Settings," are only set at the station (cannot be set by the Flight Simulation Computer) and include DAC and ADC scale factors, gravity compensation parameters, and other miscellaneous settings.

There are five Altia Faceplate virtual instrument control panels on the right side of the screen as shown in Fig. 18. The top panel or *Pilot Force Program* panel provides a slow turn-on connection to the McFadden Analog Controller. This is an important safety feature that prevents violent transients during Pilot Force Program connection to the McFadden Analog Controllers. When the program is in Disconnect mode, heavy damping is applied to the pilot control loader to minimize pilot control transients during hydraulic system power-up. The second panel, or *Limp Stick Mode* panel, allows putting any or all axes into limp stick or zero force mode. This is a condition where the McFadden Analog Controller, for the selected axis, is completely isolated (i.e. no Force Command signal) from the Pilot Force Program. But, the force loop still has closure through the McFadden Analog Controller. Limp stick mode is used for testing purposes such as hand testing the pilot control for servo valve smoothness and no turn-around bump. The *Inputs Source* panel selects either local inputs from the virtual instrument panel or external inputs from the Flight Simulation Computer. Indicators at the top of each column show which column is selected. If the parameters are switched while the Pilot Force Program is in "Connected" mode and running, the Pilot Force Program will immediately disconnect and slowly reconnect, providing another important safety feature. The *Force Balancing* panel provides push-button widgets to automatically and accurately force balance a selected axis or all axes at once. As previously mentioned, force balancing compensates for force offsets in the differential pressure transducer and associated electronics. The *Test* panel at the bottom of the screen provides for either a square wave output or a position output for a selected axis. The square wave output is used to test for frame time consistency and active program operation. The position outputs can be used for oscilloscope or X-Y plotter displays of the Command Force versus pilot control position for a given axis and, again, are only used for testing purposes.

2. Right Screen Display

The right screen consists of all parameter settings for Nonlinear Force Gradient functions for four axes and Seat Shaker and uses the same type of input and readout widgets found in the left screen. This screen display provides for a 21-segment piece-wise linear approximation curve. The initial force gradient, [*Gradient (Initial)*] in the left screen shown in Fig. 18, provides the force gradient through the origin. There are ten linear segments each for Quadrants I and III in the right screen. All parameters can be set locally or from the Flight Simulation Computer.

A small panel in the upper left corner of the right screen provides settings for a Seat Shaker. The Seat Shaker is an in-house design that incorporates a McFadden collective rotary actuator. Settings for the Seat Shaker include a nominal frequency, delta frequency, and seat amplitude. The nominal frequency is set locally for safety reasons. The delta frequency is the frequency range, but within limits. The amplitude is the vertical displacement of the seat platform. The delta frequency and amplitude can be set locally (at the station) or externally (at the Flight Simulation Computer).

V. Conclusion

Converting from analog computers to digital computers for The Pilot Force Program became practical at the VMS facility when the software environment, instrument panel displays, and frame time requirements all met stringent requirements that were determined by prior experience and investigation. The result was a significant improvement in precision pilot control force-feel simulation. For example, a recently completed simulation study[6] on rudder control would not have been possible with previous Pilot Force Programs due to the level of precision and variation in force-feel characteristics required.

The digital Pilot Force Program added many more features to the PCL systems at the VMS. These include:

- Additional safety features
- Friction function with zero drift and viscous damping effects
- Stiction
- Easy to program nonlinear force gradient
- Easy to set parameters
- Push button force balancing
- Display of all feedback signals

• No requirement for interpreting voltages

• No requirement for scaling ADCs and DACs in the Flight Simulation Computer

Most important, however, is the cost reduction that was realized due to lower maintenance and parts replacement. The digital computer system replaced an aging, costly, and difficult to maintain analog computer system.

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