DIGITAL CONTROL LOADING AND MOTION

THE FINAL WORD?

J.C. Cooper
Group Leader
Control Loading

M.L. Rutherford
Manager
Systems Engineering

G.M. McKinnon
Director
R & D

CAE Electronics Ltd.
Montreal, Canada

Summary

This paper reviews the essential elements in effective load unit design and introduces a novel approach to digital control loading and motion with extensive performance and logistics benefits. Performance of the digital system is superior to modern analog systems. A 3-KHz iteration rate provides the ability to model non-linear characteristics which are difficult to reproduce cost-effectively in an analog model. Maintenance and sparing of the digital controller is simplified by the use of a minimum number of different card types with built-in automated diagnostics which locate failures at the board level. Updates and maintenance adjustments are performed through user-friendly software utilities, with rigid configuration control of the system's state via software backups.

Introduction

The force levels and dynamic feel perceived by a pilot in control of an aircraft must be totally reproduced in an aircraft simulator to provide a realistic training environment. The loads felt by the pilot are a combination of forces due to such effects as friction, breakout or notch forces, viscous damping, non-linear spring gradients, deadbands, velocity limits, acceleration of masses, aero forces, etc. The modeling of these forces has traditionally been done using analog circuitry. Although the analog force modeling technique can produce a high quality system, there are some significant drawbacks for both the manufacturer and the purchaser:

(1) Since a unique analog model is required for each control, a spare analog circuit card is also required. Rigid control of the spare cards must be maintained to ensure that they are kept at the same state as the active cards. Also a new hardware design and manufacture cycle is required for each new simulator type. This approach does not lend itself to extensive self-testing features. While generic boards can be designed to fit a wide variety of applications, these, by nature, involve redundancy and extensive tuning and calibration.

(2) Maintenance personnel must develop specialized expertise in order to tune and maintain analog systems.

(3) During the acceptance and life of a simulator, new data for the control loading system often becomes available, due to updates in the aircraft manufacture's data package or due to measurements performed on the actual aircraft. During these updates, adjustments to the characteristics of an analog model may require extensive hardware changes. It is difficult to record and track the current state of the system. This often means that the simulator must be taken out of training until an update is complete. Further, there is no means to recall the previous state of the control loading system, making it difficult to compare the original and the recalibrated simulations.

(4) Analog circuits inherently drift with temperature and time. They therefore require periodic tuning.

The digital system can solve all the above problems. Our first digital system, produced in 1982, digitized only the aft section of the simulation, that is the masses and forces of the controls themselves were modeled by analog circuitry, but the cable drives and aerodynamic surfaces were modeled digitally. This proved so successful that we decided to take the final step and digitize the entire control loading and motion system. The resulting system, which runs at a 3-KHz iteration rate, simply receives force and position signals from the actuator unit, through A/D converters, and generates a current to the controlling servo valve via a D/A converter.

The design objectives were to produce a high performance system with the following characteristics:

(1) A fully digital system with full software control over all system parameters, requiring no hardware adjustments of any type. The goal was totally automated tuning and calibration procedures.

(2) Utilities developed from the onset of the program to reduce the amount of time required for setup, tuning and updates.

(3) Reduced sparing requirements by using common components throughout the entire range of simulated controls.

(4) Self-test hardware features designed into the system to improve maintainability. The system runs self-test programs which locate faults to the board level. The system then reports the nature of the fault to the operator and indicates the board to be changed by its slot location. The operator can then change the faulty board with the common spare and since the boards require no setup time, the system is operational after minimum downtime.

(5) Total configuration control. The data base for the control loading and motion system must be capable of software backup and restore. This allows the operator to instantly return to a previous state for training or for comparison purposes. He also has the ability to load various data bases on a single simulator, an essential feature when more than one aircraft type is to be simulated on a generic simulator.

(6) Capability of standalone operation. This allows integration and maintenance to be done on the control loading and motion system without the requirement of having a running host computer. It also allows the system to be used for retrofits to an existing simulator.

The digital system developed has achieved all the above objectives.

System Configuration Overview

Figure 1 shows the general layout of the digital control system. The heart of the digital system is the Digital Servo Controller (DSC). Each DSC card contains a high-speed processor which performs all of the control loading/motion modeling calculations for two channels. It also contains the electronics necessary to interface to two hydrostatic actuators, self-testing circuitry which allows the card to perform loop back tests, power level checks, calibration checks, memory checks and timer checks. Each DSC card is identical, contains no potentiometers, and requires no setup time. Packaging two channels per card could not normally be realized using conventional analog circuitry.

Each DSC card is connected to two buffer units located close to the hydrostatic actuators. The buffer unit interfaces the force and position transducers with the DSC card and contains the current amplifier for the servo valve drive. All signals between the DSC card and the buffer unit are differential, which eliminates electrical noise pickup on long cable runs (100 ft typically) between the control loading/motion cabinet and the actuators. The buffer units also contain a safety monostable watchdog, power sensing circuitry and a hardware standby mode which puts the control in a safe state if the DSC watchdog is lost. The buffer unit cards are identical and can be interchanged between channels. They also contain no potentiometers and require no setup time if interchanged. The buffer units can even be interchanged between control loading channels and motion channels. The buffer unit connector will define the type of standby mode which will be active if power or the watchdog signal is lost. The standby mode for control loading is a light, highly damped state. The standby mode for motion will slowly retract the actuator in a controlled fashion. Figure 2 shows the buffer unit housing which is located at the hydrostatic actuator.

The digital system also incorporates two Microprocessor Controller (DMC) cards. The first controller, DMC #1, controls data transfers between the host computer and the various DSC cards which occur via a high-speed RS-422 serial link. Data transfer between the DMC card and the DSC cards is via a 16 bit parallel C-BUS. DMC #1 also contains the utilities for updating control loading and motion system parameters. The second controller, DMC #2, is responsible for the logic necessary for the cabinet's push buttons, displays and motor/pump controls. The two DMCs are connected via an RS-422 serial link. The DMC card contains nonvolatile memory on which a son, father and grandfather version of the data base can be permanently stored. Using this approach, two previous calibrations can be protected while a third is being modified. Standalone operation of the system is possible without a running host.

The cabinet itself contains a master control panel which houses an electro-luminescent (EL) display (figure 3) and a motion test panel. The master control panel provides full control over the hydraulic motors, control loading system and motion system. The display, which has graphical capabilities, is used to indicate the status of the system and to describe any systems failures which occur. The display is also used to report the results of the self-test features of the system.

Modeling

Figure 4 shows the general software configuration of the control loading and motion system. The motion system is functionally identical to an analog motion system but is realized in a digital format. The objective in developing the control loading software and utilities was to develop a totally generic model applicable to all types of control loading systems. If a particular feature in the model is not required, its gain factor is simply set to its inactive state (ex. 0.0). This allows updates to the system not only without hardware changes but also without software changes! The various gain constants are simply changed via the DMC's utilities and then stored in the nonvolatile data base. Three different configurations are stored in the DMC itself and a large number of data bases can be stored and recalled from the host computer via the serial link.

As shown in figure 4, separate models have been developed for the forward, aft and cable systems as well as a servo driver which compensates for nonlinearities of the servo valve. The characteristics that can be modeled in the general control loading model include:

- nonlinear springs

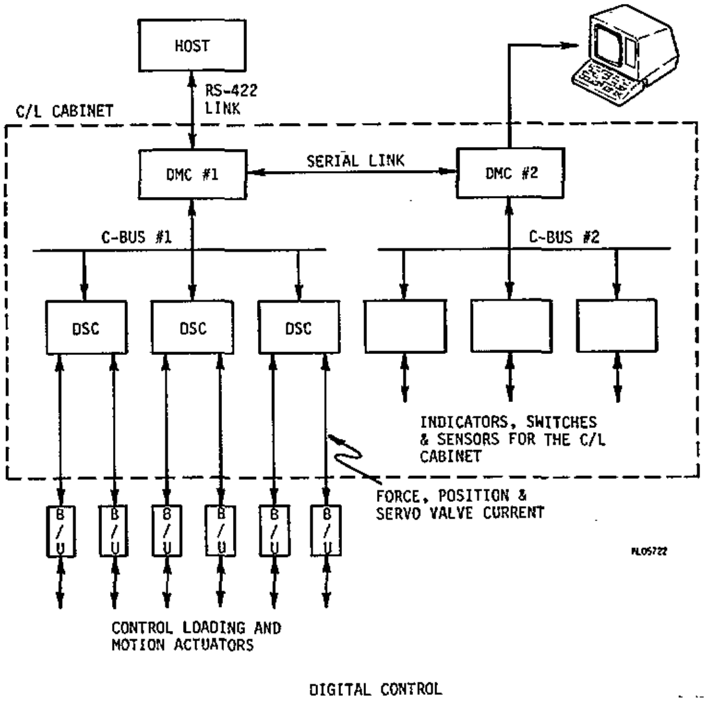

Figure 1. Digital Control System

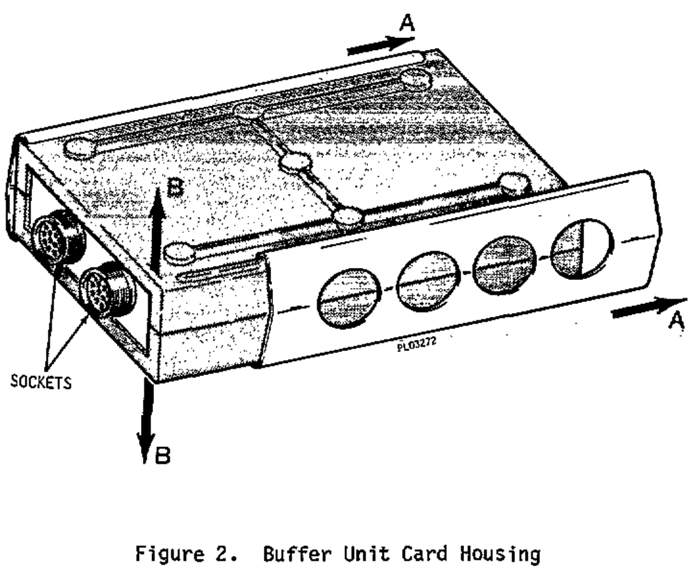

Figure 2. Buffer Unit Card Housing

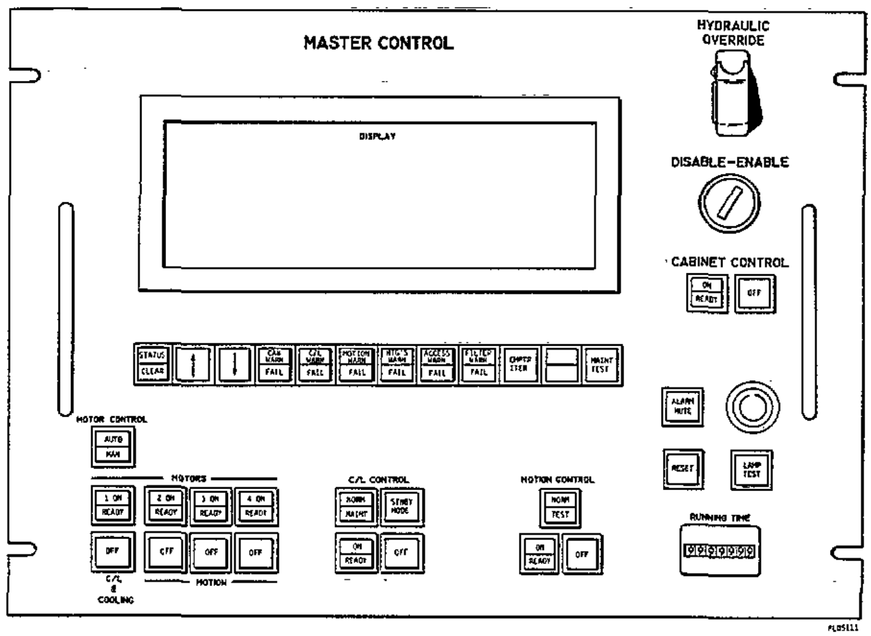

Figure 3. Master Control Panel

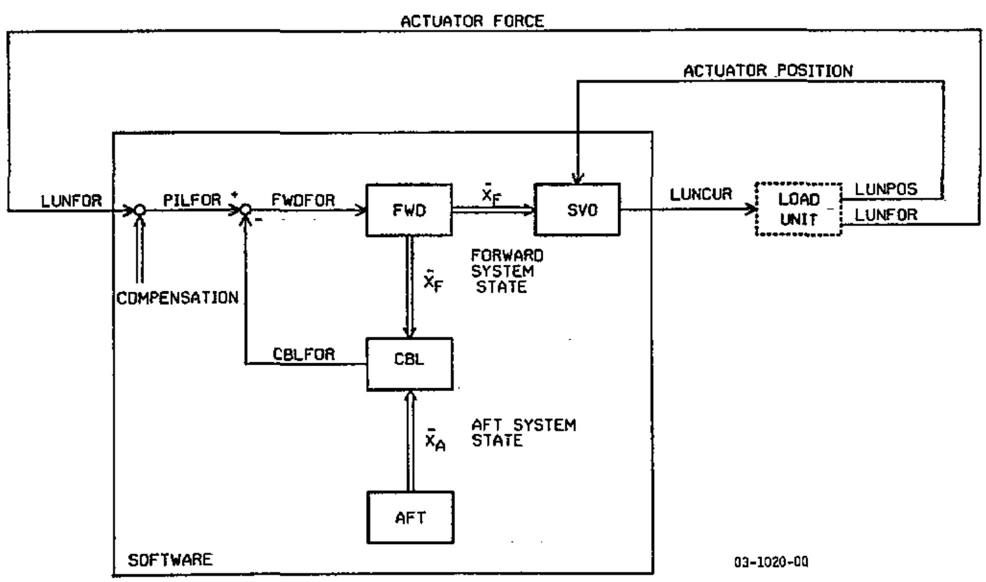

Figure 4. DFC System Block Diagram

- mass unbalance effects
- aft velocity limits
- forward velocity limits
- asymmetric velocity gains
- forward mass
- aft mass
- forward viscous damping
- forward friction
- aero springs
- aero damping
- aft viscous damping
- cable gradients
- notch stiffness
- compensation for mechanical friction in simulator linkages
- compensation for compliance
- compensation for nonlinear position and force gearing
- coupling of dual controls
- friction clutches
- forward jams
- aft jams
- cable breaks
- deadbands
- asymmetric notch or preload force
- aft limits
- backdrive
- current, force and position offsets
- test force inputs
- current limits

Of special note is the modeling of forward friction, a characteristic not modeled in existing analog systems due to problems associated with drift. We have found that such friction has a pronounced effect on surface centering and small displacement control of the aircraft. Modeling forward friction has a beneficial effect on handling qualities.

The various code options to select control loading, motion, g-seat and g-suit are stored on a single set of EPROMs on the DMC card. The user can then select the code option which will be downloaded to various DSC cards on power-up. This technique allows for painless expansion. The maximum number of channels in the current configuration is thirty-two.

The 3.0-KHz iteration rate was chosen after a series of subjective tests on a number of controls. These subjective tests included the feel of crispness of the notch forces, hardness of electrical stops, the ability to tune a light (low simulated mass, therefore high gain) control and the general realism of feel. It was found that no noticeable improvement was perceived above a 3.0-KHz iteration rate (up to 4.8 KHz was tried). However, below a 3.0-KHz iteration rate some degradation of the subjective performance was noticed. The high iteration rate of the DSC card allows high loop gains to be used which enables hard stops and low mass controls to be simulated. All calculations for both the forward and aft system are performed at the 3.0-KHz rate.

Mechanical Design

The design of the electromechanical components of control loading and motion systems is fundamental to system performance. These components are, with the possible exception of transducer types, essentially independent of the mode of control; however, drastic improvement in fidelity and maintainability can only be realized with sound mechanical design.

Effective simulation of non-linearities requires a wide bandwidth, generally more than 50 Hz. Such bandwidths can be achieved only with rigid mounts and direct linkages between actuators and controls. A direct linkage reduces compliance in simulator components between the actuator and control permitting reproducible force vs position characteristics.

The disadvantage of mechanical linkages is non-linearity between the actuator and pilot control which must be compensated for in the controller.

Table lookup for linkage compensation is a task for which a digital controller is ideally suited. In analog controllers, non-linearities pose a greater problem as complicated function generation requires complicated circuitry.

In order to achieve a wide bandwidth, it is essential to use force or acceleration feedback or compensation in the inner control loop. The resolution of the force servo is limited by friction or backlash in the mechanical configuration. It has been found that for effective control, actuators with minimal friction, such as hydrostatic cylinders, are required. This is true for both digital and analog systems.

The response and linearity of the servo valve used is also a limiting factor in load unit design. Factors such as lap, small signal characteristics, response and matching flow rates to valve port size must be considered. In our case this is done for each type of control loading, motion, g-seat, etc., and the controller coefficients are then selected appropriately.

In the case of dual controls, such as elevator controls which are linked by a torque tube, it has been found that the most efficient simulation technique is to provide an actuator for each stick and to simulate the torque tube in the digital model. The fact that this can be achieved is an indication of the response and fidelity of the system. In this manner, failure conditions, overrides and disconnects can be easily implemented and readily changed.

Utilities

Nine utilities are available to allow setup, tuning, configuration control and maintenance of the digital system. The utilities are run from the user's terminal, which is connected to the DMC card via a normal RS-232 cable. The first six utilities are designed for general use:

- Servo tuning
- Aft quadrant force vs position
- Transducer calibration
- Configuration control
- System definition
- Safety level calibration

The last three utilities are designed mainly for CAE's use for maintenance and debug of the digital system.

All the utilities display numerical parameters in floating point representation. They all are full screen, cursor driven, user friendly utilities. Each utility has a help function which instructs the operator on its operation and use.

The utilities allow the user to enter and modify a family of force vs position curves for each channel. The user can specify the functions relating forces and positions at the point of pilot input to those at the control loading actuator. He can also specify the population of DSC cards in the system, the address of each card, the type of code to be downloaded to it, and the name associated with each channel.

The utilities also allow the user to tune and examine all aspects of the control loading and motion systems. Such parameters include:

- gains controlling system mass and damping
- controller drive signal scaling and offset
- transducer offset compensation
- actual and demanded forces
- actual and demanded accelerations, velocities and positions
- actuator drive signal
- cable stiffness associated with the simulated mechanical system
- breakout (notch) force and stiffness
- autopilot force characteristics
- trim position
- position limits
- cable stiffness gain
- friction gain

The parameters can also be displayed graphically to further facilitate tuning and examination of system values. These utilities are designed to facilitate verification, morning readiness checks and other checks required by regulatory authorities.

Safety

No discussion of a control system would be complete without considering the safety features. A number of levels of safety have been designed into the system. The first level is on the buffer unit. The buffer unit receives a toggling input from the DSC card. If for any reason the buffer unit should lose this input, the control will go into a hardware standby mode. The buffer unit also senses the rising and falling of electrical power. If a power fail is sensed, the buffer unit will put the control into its standby state and remove hydraulic pressure from all the controls.

If the buffer unit receives a toggle input from the DSC, the DSC is assumed to be running. In the DSC the following parameters are checked:

excessive position error -
the system predicts where the control position should be and compares it to the actual position. If this difference is above the set threshold, the DSC will turn the control off.

excessive force*velocity -
this is a maximum power check to ensure that the control is operating within a safe range.

excessive force -
this level is set slightly above the maximum anticipated operational force.

excessive velocity -
this level is set slightly above the maximum anticipated operational velocity.

If any of these parameters exceed a set limit, the control will put itself into a standby mode, remove hydraulic pressure from the control and report the fault to the central control processor (DMC). The nature of the failure will be displayed on the EL display. The threshold level of the above parameters can be set with the safety utility. This utility also allows the recording of the maximum values reached by the parameters during operation.

A DMC card also receives a toggling input from the host computer and from other DMC's. If the signal from DMC #1 or the signal from the host computer is lost, DMC #2 will turn off control loading and motion in a controlled fashion and remove hydraulic pressure. If the signal from DMC #2 is lost, all power is removed from the system.

Conclusions

In review, the major advantages achieved with a digital approach for the simulation of control loading and motion are:

- *Improved maintainability* and long term stability.

- Added flexibility in matching aircraft data.

- Added ability to backup and retrieve configurations.

The objectives of producing a flexible, high performance controller for both control loading and motion, while eliminating the maximum amount of hardware, have been achieved. Also, the ease of maintenance, intial setup, calibration and control loading updates has been greatly improved by user friendly utilities and hardware self-test features. We are confident that the digital approach is indeed the last word.

BIOGRAPHIES

Jim C. Cooper graduated from the University of Waterloo with a B.Sc. in mechanical engineering in 1980. He joined CAE in 1980 as a systems engineer in the Motion and Control Loading Group. He currently holds the position of Senior Group Leader of the Control Loading and Motion groups.

Max Rutherford graduated from the Heriot-Watt University in Edinburgh with a B.Sc. in Electrical Engineering in 1971, followed by an M.Sc. in 1973 in Digital Technique in Communication and Control. He joined CAE in 1975 as a systems engineer and has held various design and management positions prior to his current appointment as Manager of Flight Simulator Systems Engineering.

Murdoch McKinnon received his B.E. in 1966 from Nova Scotia Technical College and his Ph.D. in 1970 from the University of Saskatchewan. He taught for three years at the University of Singapore before returning to Canada. After two years at Concordia University, he moved to CAE Electronics Ltd., where he has held various positions in engineering management prior to his current appointment as Director of Research and Development. In addition, Dr. McKinnon is currently Adjunct Professor of Mechanical Engineering at Concordia University.