DIGITAL CONTROL LOADING -- A MICROPROCESSOR-BASED APPROACH

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ABSTRACT

This paper reports on a multi-year development effort to provide exact simulation of aircraft primary control systems under all conditions of aircraft control and operation for all regimes of flight and environment conditions. The development demonstrated the ability to develop realistic models and provide for their exact solution via digital computation while integrated with a highly responsive control force simulation system. Digital quantization effects are eliminated by very high rates of computation achieved by using dedicated microprocessors within the control loop, resulting in no degradation of control "feel," smoothness, or response. Further improvements in long-term stability, calibration, and measurement are also achieved. The paper discloses the results of various comparative analyses between digital and analog, for various force and position servo loops, leading to the development of a microprocessor-based digital control loading system. Trace comparisons are made between the final breadboarded system versus actual aircraft control measurements for force/displacement and dynamic stick response tests to demonstrate the fidelity achieved by the system.

INTRODUCTION

The control loading system of a flight simulator provides one of the prime feedback elements to the trainee. The fidelity of forces at the controls is very important in the training role, and while quantitative data is available and used for design of such systems, it is an area where subjective "feel" also provides important criteria. Today's advanced level of simulation reached in flight simulators in areas such as flight dynamics, visual display systems, and general system simulation requires that the control loading system be designed to the same level of fidelity. The unique problems of this system present a challenge to the design engineer who has usually had to make substantial compromises to achieve an acceptable solution.

The "feel" of the controls experienced by the pilot results from a number of different forces. These are characterized as spring, breakout, damping, Coulomb friction, etc., some of which are a function of velocity. The complex nonlinear functions of the above, together with usual design parameters of low cost, low maintenance, and high reliability, form the basis of the problem. The principal components of a control loading system are shown in Figure 1.

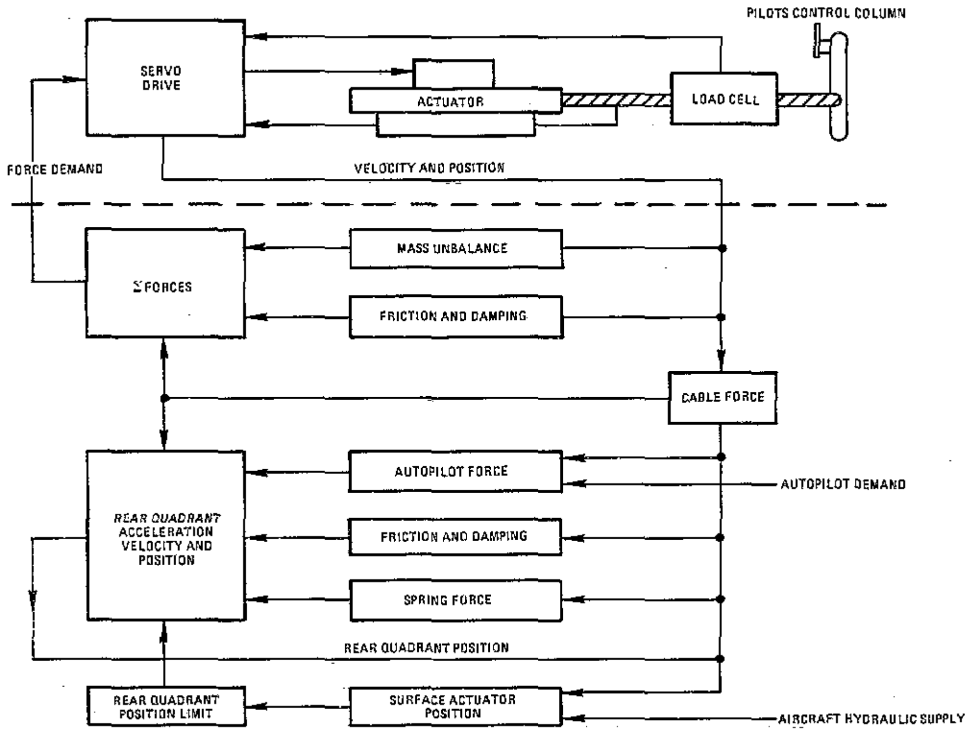

Figure 1 PRINCIPAL COMPONENTS OF CONTROL LOADING MODEL

The traditional solution is to employ a special-purpose analogue computer to solve these complex functions and second-order differential equations with sufficient frequency response to achieve the necessary smooth response. This type of system provides adequate performance but has inherent limitations. First, there is the long-term drift associated with any analogue computation which, if not corrected, affects the calibration of the system. The inability to provide adequate self-check or performance monitoring increases the problem associated with lack of general stability. The calibration of non-linear functions against associated aircraft data is also a time-consuming task with little possibility of applying automatic techniques and other aids within an analogue design.

Also, the system design for each type of aircraft is unique and consequently leads to a schedule problem and high recurring design costs. Each circuit card contains a part of the analogue computation and, while the basic design is common for most aircraft types, the non-linear functions, time constants, and other parameters associated with aircraft performance have to be designed into the resulting unique circuit card. The use of variable potentiometers offsets some of these problems, but this in turn leads to complicated calibration methods. The impact of this problem is exaggerated further if data associated with the aircraft being simulated is not available until late into the contract.

The recent revisions to the U.S. Federal Aviation Administration regulations for the evaluation and approval of flight simulators have also complicated the design task. Under the new rules it is no longer sufficient to compare the simulator characteristics with the aircraft manufacturer's engineering data for the control system. The simulator now has to be compared directly with measurements made on one of the customer's aircraft. As the differences between individual aircraft of a particular type, together with the tolerances on the measurement procedure, can easily exceed the tolerances allowed on the simulator, this can result in the necessity to modify the mathematical model for each application. In addition to this, the aircraft measurements are not always available before the simulator design is due to be completed. These two factors now make it essential that the mathematical model be easily modifiable up to the time of simulator acceptance.

The performance of minicomputers generally used for flight simulators is obviously powerful enough to achieve the required iteration rates, but they are too expensive to be dedicated to the control loading system. It is the advent of powerful microprocessors which can offer the price/performance to apply to such systems. Therefore, it was decided from the outset that microprocessors would be used in the final design.

OBJECTIVES

The objective of this development program was to produce a microprocessor-based digital control loading system which would interface with existing simulator configurations. The final design, however, also had to be compatible with possible future simulator configurations which may not be dependent on a central computing complex.

The hardware had to be configured in such a way that it would be cost-effective when applied to a large range of simulator types. The anticipated applications range from helicopters to wide-bodied commercial aircraft. The use of powered actuators to simulate aircraft control systems is not limited to the primary flying controls (elevator, aileron, and rudder). This technique is also useful in the simulation of some secondary flight controls such as speed-brake handles and toe brake pedals. In these cases, the servo actuator may well be a simple positional device with a much lower output than is required for a primary control system. It was therefore a requirement that the computing elements should be capable of controlling a number of different servomechanisms.

In order to accommodate the large range of simulators, it was also a requirement that the number of computing channels could be expanded in a modular fashion from a minimum of two up to a maximum of fourteen.

DESIGN CONCEPTS

The simulation of the correct feel of a control system can be conveniently broken down into two parts. First, there is the inner loop which comprises the actuator mechanically connected to the pilot's control, together with the servo system necessary to drive it. The outer loop contains the computing elements necessary to make the actuator reproduce the particular feel characteristics of the aircraft system.

In the case of a primary flight control system the inner loop will contain a hydraulic actuator and a force loop servo system, but in other applications it could well be a hydraulic position servo or even an electric torque motor. Whatever inner loop is chosen, the outer loop can use the same microprocessor board and digital-to-analogue conversion equipment. The use of an independent microprocessor in each channel allows the computer cycling time to be adjusted to suit each application.

It is also important that the interface between the microprocessors and the Host computer be handled in a flexible manner so that it can easily be adapted for use with any simulator computing system.

HARDWARE

Inner Loop

The most critical control loading applications on a flight simulator are the three primary flight controls plus the nosewheel steering system. For these systems the inner loop will normally consist of a hydrostatic hydraulic actuator coupled to the pilot's control through a force sensing load cell. The position of the actuator is measured with a linear position transducer (LVDT) and an analogue, force-feedback servo system provides the control signal to the servo valve. This arrangement has been used on control-loading systems for some years and has been shown to produce a sensitive, high-bandwidth, but stable system.

In addition to controlling the hydraulic actuator, the inner loop circuit must also fail safe to prevent any malfunction in the components causing damage to the simulator or harm to pilot. This is achieved by monitoring power supplies, actuator force, actuator velocity, etc., and deactivating a fast-operating hydraulic safety valve when any of the parameters exceed predefined limits.

Outer Loop

The digital outer loop for each channel one CPU card, and one I/O card as shown in Figure 2.

The CPU card employs the Intel 8 MHz 8086 processor with 4 K bytes of RAM and 32 K bytes of EPROM. Two DCL channels may be closely coupled and run in synchronism through the card's FIFO interface, giving communication between the two at 512 Hz. This facility would be used in a simulator for an aircraft which has dual control runs from sticks to control surfaces. Normally, the two controls would be used to move as one, but, in the event of a jam, the controls may be split and would then have to operate independently of each other.

The CPU has its real-world interface on the associated I/O card. This comprises a 16-channel multiplexed analogue-to-digital converter plus four channels of digital-to-analogue conversion. Although the A-to-D has 16 input channels, only eight are for conversions from the outside world. The remainder are used for wrap-around tests of the analogue outputs and power supply level checks.

For each simulator's control loading subsystem, an interface is required between the 20 Hz or 30 Hz Host tasks and DCL's specialized 512 Hz routines. For a typical SEL 32/77 Host Computer the High Speed Data (HSD) and compatible interface card is used. This contains a 1 K-word buffer RAM which interfaces to the final card in the system, the crosstalk CPU (CPUX).

The main function of CPUX, on interrupt from the Host, is to transfer data between the buffer RAM on the HSD interface card and the double-buffered RAM's on each channel's I/O card. On completion of this task, CPUX flags the double buffered RAM's which, then, in synchronism with each channel's real-time clock, swap the RAM areas over. Other functions of the card include the updating of a data entry panel and control of a multi-channel RS232 link which may be reallocated to any of the CPU's in the system entirely under software control. When a VDU is not available, the data entry panel provides a single location look-and-enter facility to any of the channels. The card again uses the 8086 with 4 K RAM and 16 K EPROM plus standard LSI to interface with the data entry panel components.

The iteration rate of 512 Hz was chosen to produce the smooth response required. It can easily be shown that such computational rates are required to achieve bandwidths of around 100 Hz. This was supported by qualitative assessments; iterations of 256 Hz produced a detectable noise level, while performance at 1,024 Hz,

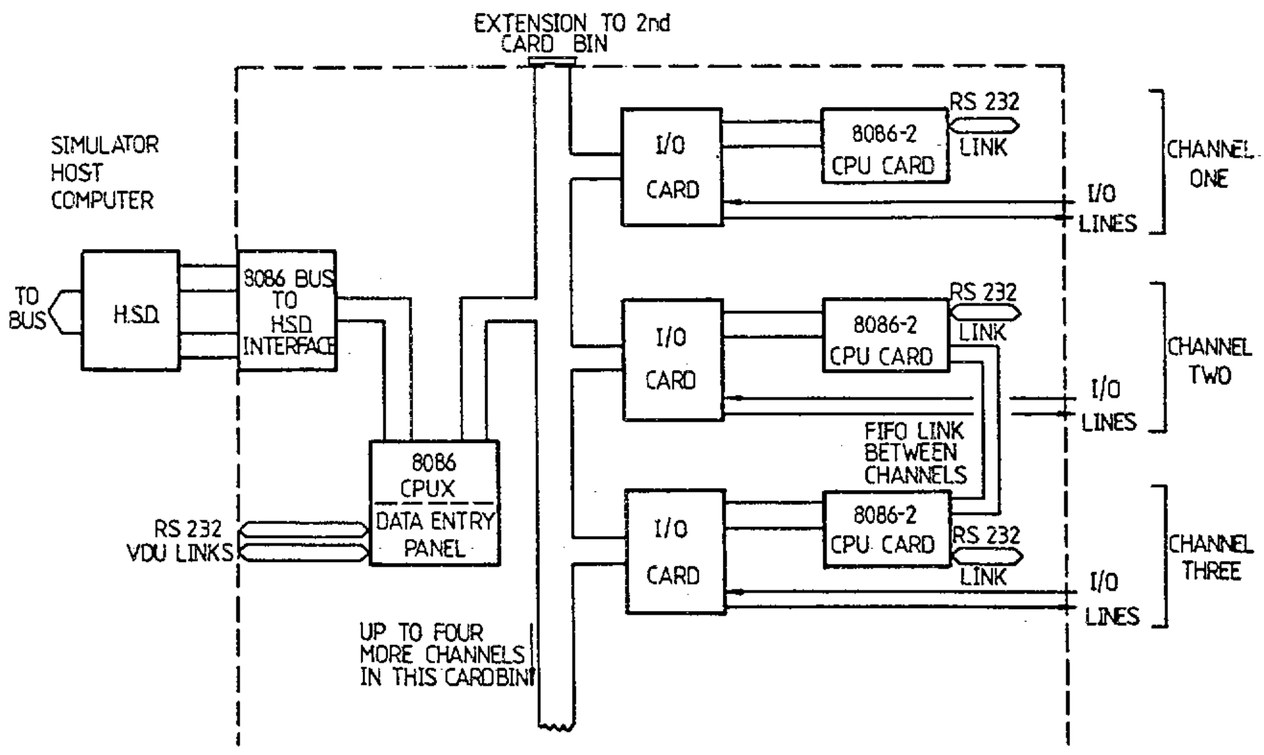

Figure 2 MULTI-CHANNEL DIGITAL CONTROL LOADING HARDWARE - BLOCK SCHEMATIC

made possible by coding certain routines in assembler rather than PLM, did not give an improvement over 512 Hz. All these tests used a complete math model for a primary 747 control channel. Each channel can be assigned an unique iteration rate, and the real-time executive and debug in each CPU and I/O can support multiple programs, say for small secondary control functions.

SOFTWARE

One of the advantages of the digital approach is that it provides a cost-effective method of implementing a detailed mathematical model of the aircraft system. A typical aircraft primary flight control system contains a number of distinct elements. On the flight deck there is the pilot's control column, torque tube, and drive mechanism to the forward cable drum. These components contribute mass, out-of-balance forces, and friction to the overall feel of the system. The next item is the cable run connecting the forward cable drum to the components in the rear of the aircraft. The primary contribution of this is a spring effect plus friction and viscous damping. Situated at the rear of the aircraft is the artificial feel system which usually comprises one or more springs, possibly with a means of adjusting the mechanical advantage so that the spring rate, as seen by the pilot, can be varied with the aircraft speed. These items largely determine the static force/displacement characteristics experienced by the pilot but they also contribute to the mass, friction, and viscous damping in the system. The aircraft-powered surface actuators are situated in this area and these also contribute to the feel of the system as they generally impose a velocity limit on components at the rear of the aircraft as a function of the flow available from the aircraft hydraulic supplies. The final component which needs to be considered is the autopilot actuator, as this usually has the ability to apply forces to the aircraft actuator input mechanism.

In addition to simulating the components of the aircraft system, the mathematical model programmed into the microprocessor must also take account of any non-linearities which exist in the simulator installation. These non-linearities, which usually occur as a result of using aircraft parts in the flight deck area, affect the relationship between pilot force and the force measured at the load cell and the control position and the position measured by the LVDT.

Once the mathematical model for a particular system has been developed, it is programmed in a high-level language. During development, the software is downloaded from a Microprocessor Development System to RAM within the DCL system and then programmed in EPROM when verified. The design of the software, due to individual processors for each channel, helps in the task and also decreases the life cycle cost of the total software.

The simulation module is run effectively as an interrupt task every 1.95 ms. Depending on the complexity of the task, this generally takes about 1 to 1.3 ms and, on completion, the CPU returns to its background program. This background routine consists, firstly, of updating information on the debug page, and secondly, of running diagnostic tests and reporting back the status of the channel to the Host in real time. In addition to these tests, the channel CPU's, at power up, pass through "Morning Readiness" checks which exercise the I/O components, perform RAM and EPROM tests and ensure that the system is in a fit state to operate control loading.

Any fault condition flags are passed back to CPUX and thence to the Host. Thus faults can easily be traced from system level to channel level to board level and, within certain constraints, to component level from the simulator's main computer.

Channels passing Morning Readiness checks automatically proceed with their simulation tasks, requiring only the manual 'hydraulics on' switch to be pressed before full simulation commences.

BENEFITS OF DIGITAL CONTROL LOADING

The digital approach to control loading systems has eliminated the need for unique analogue circuit cards in the simulator system. This, coupled with the inherent long-term stability of a digital system, should yield a significant reduction in the simulator maintenance effort. The absence of unique hardware is also important to the simulator manufacturer, as it means that the various mathematical models required can be verified and evaluated on a standard test rig before the simulator construction is complete.

With the digital approach, the mathematical model is much more easily modified to account for aircraft characteristics which were not identified during the initial analysis. This is important as sometimes these characteristics only become apparent when a pilot who is experienced on the particular aircraft type has the opportunity to assess the simulator. This added flexibility results in improvements in the standard of simulation. This has been demonstrated by programming our test facility to represent the elevator channel of a Boeing 747 aircraft. The degree of agreement achieved between this facility and a set of measurements made on a particular aircraft was excellent, with typical results shown in Figure 3. The adjustments normally required to tune a control system performance to match a set of measurements made on a specific aircraft are provided from the main simulator computer. It is anticipated that some 30 parameters per channel will be defined within the main computer data base. These parameters will allow the rapid and accurate adjustment of terms like friction levels, rate dampings, breakout forces, etc.

Digital control provides a very powerful means of implementing self-test and diagnostic features. In our standard simulator package, we include a Test Guide Driver facility to set up the initial conditions and automatically run the required force/displacement and dynamic response tests. The results of these tests may be recorded directly by connecting the output of

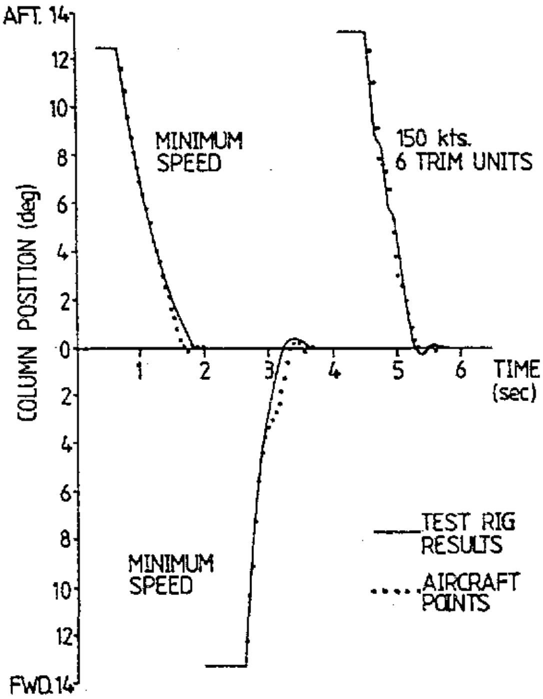

Figure 3 DYNAMIC RESPONSE CHECK - B-747 ELEVATOR

the control loading unit force and position transducers to a suitable chart recorder. Alternatively, the same results may be displayed as a graphical plot on the instructor's station visual display unit, from which a permanent copy can be made by means of a line printer.

The same instructor's VDU can be used to display warning messages should a malfunction be detected in any of the following areas:

1) The hydraulic fluid supply
2) Operation of any of the channel CPU's
3) Operation of the data link between the control loading microprocessors and the main simulator computer.

In the event of the safety circuit for a particular control loading channel tripping, then information on the status of that channel will be recorded at the instant of the failure and will be available for subsequent display. The recorded information will include power supply voltages, analogue-to-digital and digital-to-analogue converter status, control loading actuator force, velocity, velocity error, and position error.

ABOUT THE AUTHOR

Mr. David Parkinson is a Technical Development Manager with Singer UK Link-Miles and is responsible for all Research and Development Programs undertaken at Link-Miles. He holds an honours degree in Electronic Engineering and is a Member of the Institute of Electrical Engineers.

His early experience, having joined Link-Miles in 1971 as an Electronic Development Engineer, was mainly in circuit design using a variety of analogue and digital techniques. After being responsible for a number of new designs associated with simulators, he became a Group Leader in 1977 supervising the staff of the Development Department. During the last few years he has been involved in the introduction of advanced technology and associated development. Major programs which have recently been undertaken include an Electronic Warfare Simulation System, a Computer Generated Visual System, a Distributed Microprocessor Computing System for a Flight Simulator and a Digital Control Loading System.