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SYSTEMS DEVELOPMENT OF A STALL/SPIN RESEARCH FACILITY USING REMOTELY CONTROLLED/AUGMENTED AIRCRAFT MODELS

VOLUME I
SYSTEM OVERVIEW

Contract NAS1-14638

Prepared for

NASA

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

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VOLUME I

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By

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ABSTRACT

A partial systems development of the NASA-Langley Research Center stall/-spin research facility is conducted as a first step in obtaining an upgraded testing facility that uses remotely controlled/augmented aircraft models as recommended by a previous study (NASA CR-145182).

A ground-based, general-purpose, real time, digital control system simulator (CSS) is specified, developed, and integrated with the existing instrumentation van of the testing facility. This CSS is built around a PDP-11/55, and its operational software is developed to meet the dual goal of providing the immediate capability to represent the F-18 drop-model control laws and the flexibility for future expansion to represent more complex control laws typical of control-configured vehicles.

Also, a ground-based, real time, analog CSS dedicated to the F-18 drop-model control laws is designed, fabricated, and integrated with the existing instrumentation van. This analog CSS is developed to be used as a ready backup system during the F-18 drop-model program.

In this report (Volume I), overviews of the two CSS's developed under this contract and of the overall system after their integration with the existing facility are presented. Under separate covers (Volumes II, III, and IV for the digital, and V and VI for the analog), the details of the digital CSS and analog F-18 drop-model CSS are presented. These latter documents were supplied to NASA-Langley personnel as user-oriented documents needed to operate the particular system developed, and, as such are not of general interest.

Also in this report (Volume I), the latest version of the F-18 drop-model control laws (REV D) is described and the changes needed for its incorporation in the digital and analog CSS's are discussed. The implementation of REV D in the digital CSS is detailed in an addendum to Volume III. The implementation of a compromise version of REV D in the analog CSS is detailed in an addendum to Volume V.

ACKNOWLEDGEMENT

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For the designs and developments described in this report, work has been closely coordinated and discussed with personnel at Langley Research Center. Mr. William P. Gilbert, Mr. Luat Nguyen, and Mr. Charles Libbey of the Spin Tunnel Simulation and Analysis Section, Dynamic Stability Branch, under the direction of Mr. J. R. Chambers, have contributed heavily to the definition of systems whose designs are described herein. Mr. Larry B. Hall and Mr. George Turner of the Telemetry Instrumentation Section, Spacecraft Instrumentation Branch, Flight Instrumentation Division, have also collaborated extensively in the integration of the analog and digital control system simulators with the existing instrumentation.

RTI staff members participating in the study were:

C. L. Britt, Jr., Project Manager
R. J. Montoya, Project Leader and Systems Engineer
A. R. Jai, Systems Engineer
C. D. Parker, Systems Engineer
R. Stilley, Technician
L. Wiegand, Secretary

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LIST OF ACRONYMS

ACSS	analog control system simulator
ADC	analog to digital converter
AGC	automatic gain control
ANSI	American National Standards Institute
ARI	Aileron to rudder interconnect
BNC	standard coaxial connector
CCV	control configured vehicle
CMMD	command
CRT	cathode ray tube
CSS	control system simulator
DAC	digital to analog converter
DC	direct current
DCSS	digital control system simulator
DEC	Digital Equipment Corporation
DLK	downlink
DVM	digital voltmeter
EFP	external frame pulse
ENC	encoder
EXT	external
FBW	fly-by-wire
FID	Flight Instrumentation Division
FORTRAN	formula translator
GCU	ground control unit
IC	initial condition
IFP	internal frame pulse
INT	internal
KW	kilo words
LRC	Langley Research Center
MPX	analog multiplexer
MW	mega words
NASA	National Aeronautics and Space Administration
PCM	pulse code modulation
PDP	parallel digital processor

LIST OF ACRONYMS
(Concluded)

PPM	pulse position modulation
RCVR	receiver
RDTI	rudder to differential tail interconnect
RGC	remote ground cockpit
RTI	Research Triangle Institute
SAS	stability augmentation system
SM	spin mode signal (high)
$\overline{\mathrm{SM}}$	spin mode signal (low)
SRI	roll stick to rudder interconnect
SW	switch
TCS	terminal control system
TMTR	transmitter
TMY	telemetry
TTL	transistor-transistor logic
ULK	uplink
sync	synchronization
D/D	digital-to-digital
F/B	foreground/background
FM/FM	frequency modulation/frequency modulation
I/O	input/output
S/J	single job

LIST OF SYMBOLS

RF_Q	radio link quality signal (into interface box), volts
RF'_Q	radio link quality signal (into digital CSS), volts
$SYNC_{EXT}$	external synchronization signal, volts
$SYNC_{INT}$	internal synchronization signal, volts
V_D	downlink dropout detector output voltage, volts
V_{D1}	hardware downlink dropout detector output voltage, volts
V_{D2}	software downlink dropout detector output voltage, volts
α	angle of attack, degrees [volts]
α_{CAL}	calibration angle of attack, degrees [volts]
α_{COND}	conditioned angle of attack, degrees [volts]
α_{FB}, α_f, α_{fb}	feedback angle of attack, degrees [volts]
α_{SEL}	angle of attack selection control signal, volts
α_0	zero degree/zero volt angle of attack, degrees [volts]
δ_d	differential horizontal tail deflection, degrees
δ_h	average horizontal tail deflection, degrees
ε_S	digital CSS system error discrete, volts
$\dot{\psi}$	yaw rate, degrees/second

Mathematical Symbols

$\dot{f}$	time derivative of f
$\lvert\ \rvert$	absolute value of
$\leq$	less than or equal to
$\geq$	greater than or equal to
Σ	summation

1.0 INTRODUCTION

This report summarizes the work performed under contract NAS1-14638 entitled Systems Development for the Upgrading of a Stall/Spin Research Facility. The objective of this program is to take the first steps towards the upgrading of the drop-model, stall/spin research facility of the Langley Research Center recommended by the results of contract NAS1-14406 and documented in NASA CR-145182 (ref. 1).

To this end, the program calls for the design, development, and integration with the existing instrumentation van of the facility of a programmable, ground-based, real time, digital control system simulator (CSS) which will provide the immediate capability to represent the F-18 drop-model control laws and the flexibility for future expansion to represent more complex control laws typical of control-configured vehicles.

In addition, the program calls for the design, fabrication, and integration with the instrumentation van of an analog hardware unit as a dedicated representation of the F-18 drop-model control laws to be held as a ready backup for the digital CSS.

Under this contract, six volumes of documentation were provided to the government. This report is taken from Volume I and includes an overview of the work performed and of the capabilities provided in the upgraded facilities. The other five volumes were provided as user-oriented documents relating to the specific systems application at Langley and are therefore not being extensively published. These latter volumes present details of the digital CCS (Volumes II, III, and IV) and of the analog CSS (Volumes V and VI).

1.1 Background

The Langley Research Center (LRC) of the National Aeronautics and Space Administration (NASA) operates a drop-model, stall/spin testing facility in support of the center's research on the stall/departure/spin characteristics of high performance aircraft. The data derived from tests in this facility complements that obtained from tests in the free-flight wind tunnel and the spin tunnel.

Under a previous contract (NAS1-14406), the Research Triangle Institute (RTI) conducted a systems analysis of the drop-model facility to determine the characteristics of the elements necessary to support a change in the model control technique from the existing open-loop/visual feedback to one in which the models are remotely controlled/augmented using feedback from the model state.

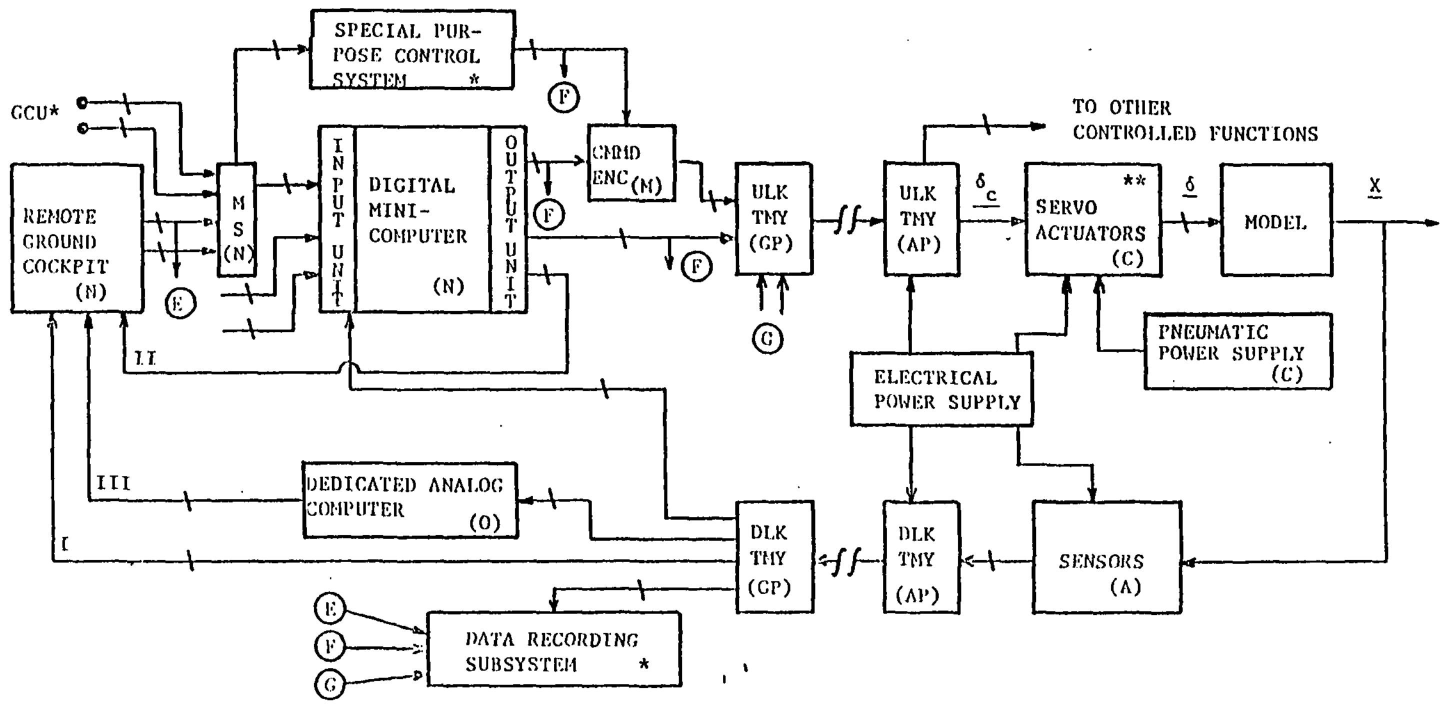
The thrust behind this study was the lack of capability in the facility to simulate sophisticated control laws and to close the control loop with the pilot in order to fly the model more precisely into the flight regimes of interest. This capability is essential for stall/spin research because, with the advent of control-configured vehicles (CCV) and the application of fly-by-wire (FBW) technology, many high-performance vehicles exhibit stability and control characteristics which are highly dependent on their automatic control system.

The systems analysis work has been documented in NASA CR-145182 (ref. 1). The main results were the recommendation of a system configuration and the specification of the operational characteristics of its constituitive elements. As shown in Figure 1-1, the system consists of a simple ground cockpit, a general-purpose digital control system simulator (CSS) based on a DEC PDP-11/45 and its associated peripherals, PCM command and data telemetry links, high-performance, miniature, electro-pneumatic servo actuators, and a complement of sensors which include a three-axis, 360^{o}-attitude gyro. The dedicated analog computer shown in the figure is included as an alternative (to the digital computer) for the ground-derivation of the Euler angles in the event that these cannot be sensed directly on-board the models.

Another important result of the systems analysis work was the recommendation of an approach to the upgrading of the facility. The approach was developed under two critical guidelines: minimum facility down-time and maximum gradual familiarization with the new elements of the facility for the personnel involved with the facility.

1.2 Scope of the Present Work

The results of the systems analysis work andthe planned F-18 drop-model test program have provided the impetus for the present systems development work. The goal of the program is to provide the first steps towards the long-term upgrading of the research facility while at the same time supporting the upcoming F-18 drop-model test program in a more



*Indicates compatibility with existing element
**Includes command decoder and control surface

A: additions
C: changes
M: modifications
N: new
O: optional

—/—▷ Indicates several analog and/or discrete lines

AP: Airborne Portion
GP: Ground Portion

Figure 1-1. Functional block diagram of recommended upgraded facility.

efficient and flexible manner. The activities under this program and related activities ongoing at LRC correspond in scope to the areas outlined in Figure 1-2.

To achieve this goal, RTI is to design, procure, and develop a programmable, ground-based, real time, digital control system simulator and the electronic interfaces necessary to integrate it with the existing instrumentation van. In addition, RTI is to design and fabricate an analog hardware unit, as a dedicated representation of the F-18 drop-model control laws, which is to be integrated with the existing instrumentation van and held as a ready backup for the digital CSS.

The specific tasks necessary to achieve the objective of this program are:

- Specify and procure a digital minicomputer and peripheral equipment necessary to provide a ground-based, real time control system simulator having a flexible operating system, the capability for handling the high frequencies associated with the dynamically-scaled drop-models, and the potential for representing complex control laws typical of control-configured vehicles.
- Specify and procure a modular input/output electronic interface capable of inputting the present drop-model downlink telemetry signals and pilot control signals to the control system simulator, capable of outputting the computed command control surface positions from the control system simulator to the present drop-model uplink telemetry system, and capable of future expansion to support additional input/output requirements such as driving a ground-based pilot cockpit and possible future conversion of downlink telemetry to Pulse Code Modulation (PCM).
- Determine, specify, and procure any additional hardware that will be needed to integrate the new ground-based control system simulator into the existing drop-model facility, assuming that the existing downlink telemetry will be unchanged, the existing uplink telemetry system will provide double the present uplink frame rate using 12-bit words instead of the present 8-bit words, and the present method of generating pilot control signals will be unchanged. Define requirements for operation of developed

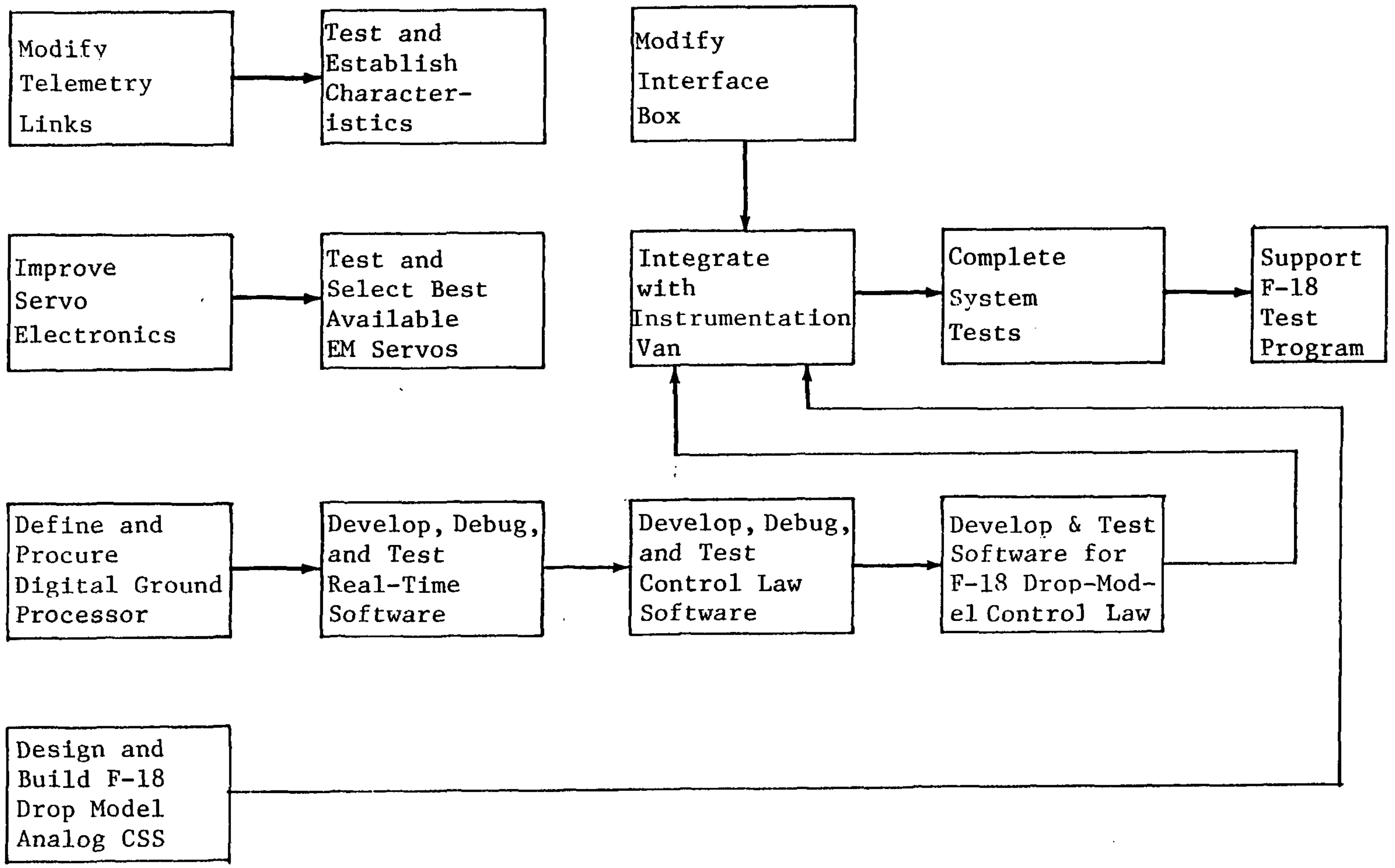


Figure 1-2. Areas of activities under the systems development program.

system using PCM downlink telemetry which may be incorporated at future date after the F-18 program.

- Design, fabricate, and validate, to the fullest extent possible at the contractor's site, an alternate, dedicated analog hardware implementation of the F-18 drop-model control law as defined in schematics supplied by the government, and insure compatibility with existing drop-model ground-based equipment.
- Integrate the hardware procured for the control system simulator into an operational computing subsystem at the contractor's site for use in development and validation of the real time control system simulator.
- Develop master executive program software (in high-level language) to support computer implementation of control laws, including provision to handle modular control law software to allow future expansion, provision to monitor input and output from control law modules, including capability to output critical control system variable to an analog recording device, and to provide backup control mode(s) for safety of flight in case of control system failure, and provisions to allow easy expansion of executive program to handle additional feedback parameter inputs and control system command outputs. Also provide capability to conduct pre-flight status check of control system simulator (printout of output for known pilot input).
- Develop, implement, and check out to the fullest extent possible the specific modular software needed to represent the F-18 drop-model control law as defined in schematics supplied by the government.
- Integrate the validated real-time control system simulator and associated input/output interface electronics module(s) with the existing drop-model facility ground-based equipment at the Langley Research Center.
- Perform the necessary static and/or dynamic tests to demonstrate that the upgraded drop-model facility provides the correct control system simulation, instruct designated government personnel in operation of new equipment, provide operational manuals describing use of control system simulator, and provide software listings, source tapes, object tapes, and equipment manuals and supporting software.
- Install, check out, and give instruction in the operation of the analog hardware module backup system for representing the F-18 drop-model control law.

1.3 Organization of the Report

The report of the work performed under the system development contract is contained within six (6) volumes. Reasons for this organization are the various audiences (managers, system engineers, system operators, and system programmer) to which this report is addressed and the need to provide disjoint access to information which is of particular interest to any of these audiences.

The work described in this report was performed jointly by R. J Montoya and A. R. Jai for the digital control system simulator and by R. J. Montoya and C. D. Parker for the analog control system simulator. Although all six volumes of the report are co-authored by all three individuals, the responsibilities for the preparation of these volumes were as follows: Volume I (R. J. Montoya); Volumes II, III, and IV (A. R. Jai); and Volumes V and VI (C. D. Parker and R. J. Montoya).

This volume (Volume I) presents an overview of the work performed and of the upgraded facility resulting from the integration of the two control system simulators and other modifications into the existing facility. Volume I is directed towards program managers and can be viewed as the contractor report in the traditional sense of the term.

Volumes II, III, and IV present detailed description of the configuration, operation, troubleshooting, and development of the hardware/software associated with the general-purpose digital control system simulator. Volume II is the digital CSS system's manual, which is addressed to the system engineers. Volume III is the digital CSS user's manual, which is addressed to the system operators. Volume IV is the digital CSS software manual, which is addressed to the system programmer.

Volumes V and VI present detailed description of the configuration, operation, "programmability," and troubleshooting associated with the F-18 drop-model analog control system simulator. Volume V is the analog CSS system's manual, which is addressed to the system engineers and operators. Volume VI is the analog CSS user's manual, which is addressed to the system operators and "programmers."

The following sections of this volume provide a general description of the configuration and operation of the general purpose digital control system simulator of the F-18 drop-model analog control system simulator, and of the modifications incorporated into the existing instrumentation van to facilitate the integration of the two control system simulators. The next section of this volume provides an overview of the upgraded research facility. The volume is concluded with a set of recommendations for further upgrading of the drop-model, stall/spin research facility.

2.0 GENERAL PURPOSE, DIGITAL CONTROL SYSTEM SIMULATOR

The purpose of this section is to present an overview of the definition, design, and development of the general purpose, ground-based, real-time, digital control system simulator for the drop-model, stall/spin research facility.

The section begins with a review of the operational requirements of the digital CSS determined during a previous study (reference 1) and a discussion of the specific operational requirements associated with the F-18 drop-model program. The next subsection contains a general description of the hardware/software that make up the digital CSS. The section concludes with a general discussion of the capabilities of the digital CSS.

2.1 Operational Requirements

The systems analysis (reference 1) recommended the use of a digital minicomputer for the ground processor of the upgraded stall/spin research facility. This recommendation was based on extensive trade-offs among the computational capability, programmability, and cost of comparable digital, analog, and hybrid processors.

This subsection considers the operational requirements of the digital control system simulator. The subsection also includes a discussion of the operational requirements specific to the F-18 drop-model program.

2.1.1 General. - The general purpose, digital control system simulator consists not only of a digital processor but of a complete real-time computing subsystem which includes an appropriate set of peripherals and I/O devices. The computing subsystem also requires a set of special purpose, real-time software packages to operate as a digital control system simulator.

The digital processor (a minicomputer) has two basic operational requirements: One is that its computational speed and accuracy be compatible with the high frequency (due to the size of the models) and stability characteristics of the real time control loop of which it is a part; and the other is that its computational capacity be sufficient to accomodate the computational requirements of complex control laws, the ground derivation of the Euler angles, and possibly some digital data recording.

The peripherals provide an enhancement of the computing capability of the processor and flexibility and ease of programming. The thrust behind the selection of the peripherals for the digital computer is to facilitate the development and operation of the operational software. For example, a floating point processor avoids the need for variable scaling prior to computations, a cartridge disk system simplifies the development and utilization of the software, and a teleprinter terminal is essential for interactions between the operator and the computer.

The I/O subsystem provides the means for data exchange between the external world and the computer. This is a very important hardware feature of the digital control system simulator because it provides the means to integrate the digital processor into the real time control loop of the application. The main requirement for this unit is a growth capability (through modularity) sufficient to accomodate extensive I/O data exchange in the future (see section 6.0, reference 1).

The operating software is the tool by means of which the system's users will configure and control the operation of the digital CSS in a given application. As pointed out in section 5.3.2 of reference 1, the operational software package consists in general of an executive program and the control law programs. The former performs supervision functions (timing, sequencing, et al.) during a test whereas the latter implements the control laws associated with the particular aircraft model being tested.

An important requirement of the executive software is the performance of certain monitoring and control functions which are based on external events. The monitoring functions are: The detection and timing of a downlink telemetry dropout and the selection of the source for angle of attack (between α and α_{CAL}) depending on the value (0,1) of the α_{SEL} signal. The control functions are: The generation and output of a dropout discrete indicating the occurrence of a downlink dropout whose duration exceeds a specified criterion, and the generation or acceptance of a sync pulse for synchronization of the operation of the computer and the uplink telemetry encoder.

The main requirement for the control law programs is that they be developed around a core of basic control law modules that can be selectively linked to obtain a desired configuration. The basic control law modules could be provided in a library of function oriented subprograms to maximize the programming flexibility.

A basic set of control law modules is presented in Appendix A of reference 1. These modules provide the following control system functions: Nonlinear function generator (1), gain schedule as a function of one or two variables (2), fixed limiter (3), first-order lag filter (4), lead-lag filter (5), integrator (6), second-order lag filter (7), washout filter (8), and actuator model (9).

The manner in which these functions would be used in simulating control systems of aircraft models in the facility is shown in Figures 2-1 and 2-2. These figures also provide an example of the range of complexity of the control laws to be implemented in the digital control system simulator. System A in Figure 2-1 is a conventional mechanical system with SAS about all three of its axes. System B in Figure 2-2 is an advanced stability and control augmentation system which incorporates such concepts as reduced static stability, α-limiting, direct lift control, direct side force control, et al.

2.1.2 F-18 drop-model. - The control laws for the F-18 drop-model are shown in Figures 2-3a and 2-3b. The symbols used in these control laws are defined in Table 2-1. Basically, the simulated control system required to support the F-18 drop-model tests is a modal, gain-scheduled mechanical system with yaw rate ($\dot{\psi}$) the mode parameter and angle of attack (α) and symmetric stabilator deflection (δ_h) the scheduling parameters. In addition, there are several interconnections between channels such as roll stick and rudder pedal to differential stabilator, rudder pedal to aileron, and roll stick to rudder; and, also, there is one interconnect between control surfaces (from the aileron to the rudder).

The F-18 drop-model control system has three pilot inputs, pitch stick deflection (δ_{SP}), roll stick deflection (δ_{SR}), and yaw pedal depression (δ_{PED}); two "feedback" variables, angle of attack (α) and yaw rate ($\dot{\psi}$); and four control surface deflection outputs, right stabilator (δ_{S_R}), left stabilator (δ_{S_L}), aileron (δ_a) and rudder (δ_r). The effective pitch control

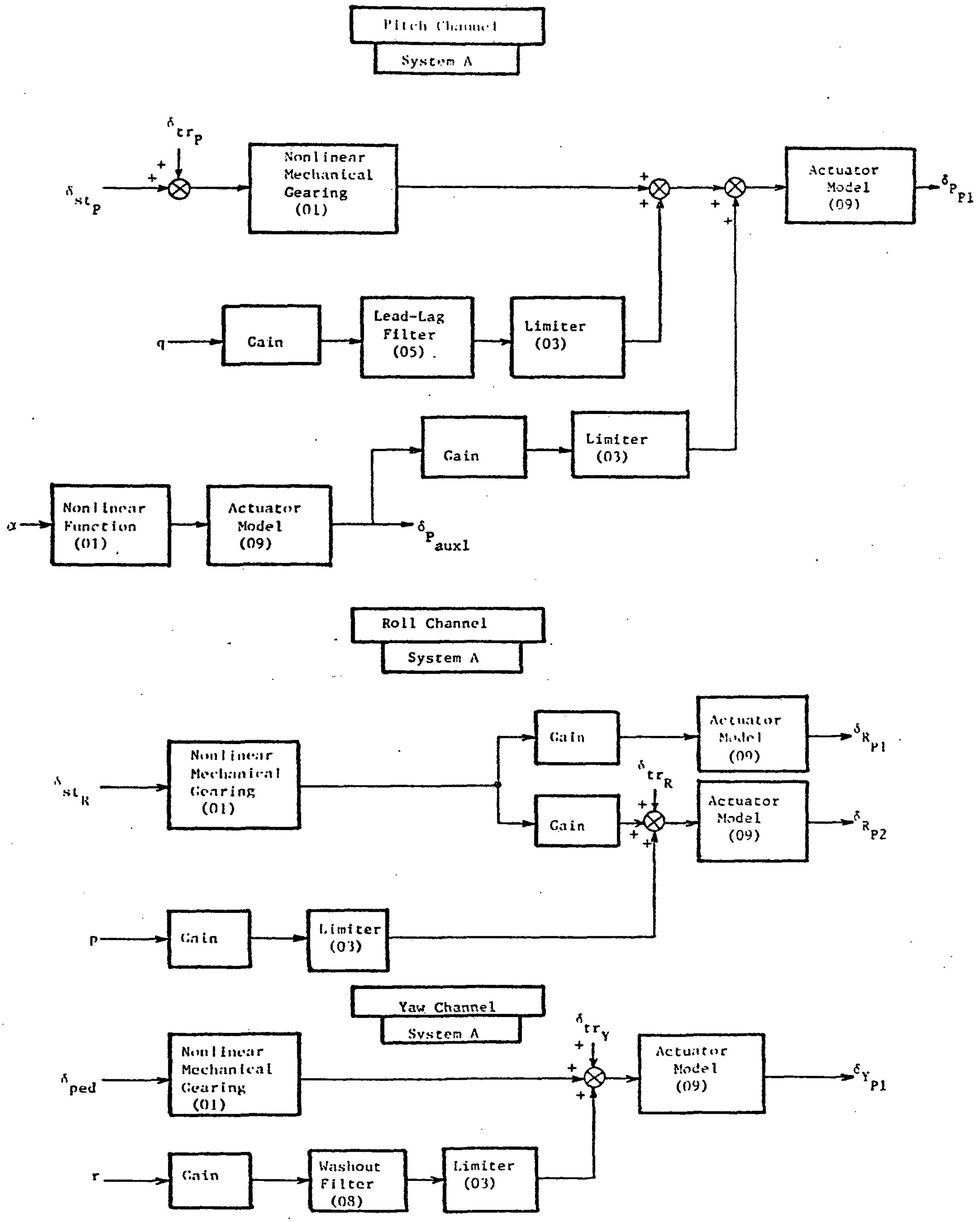


Figure 2-1. Schematics of control system A.

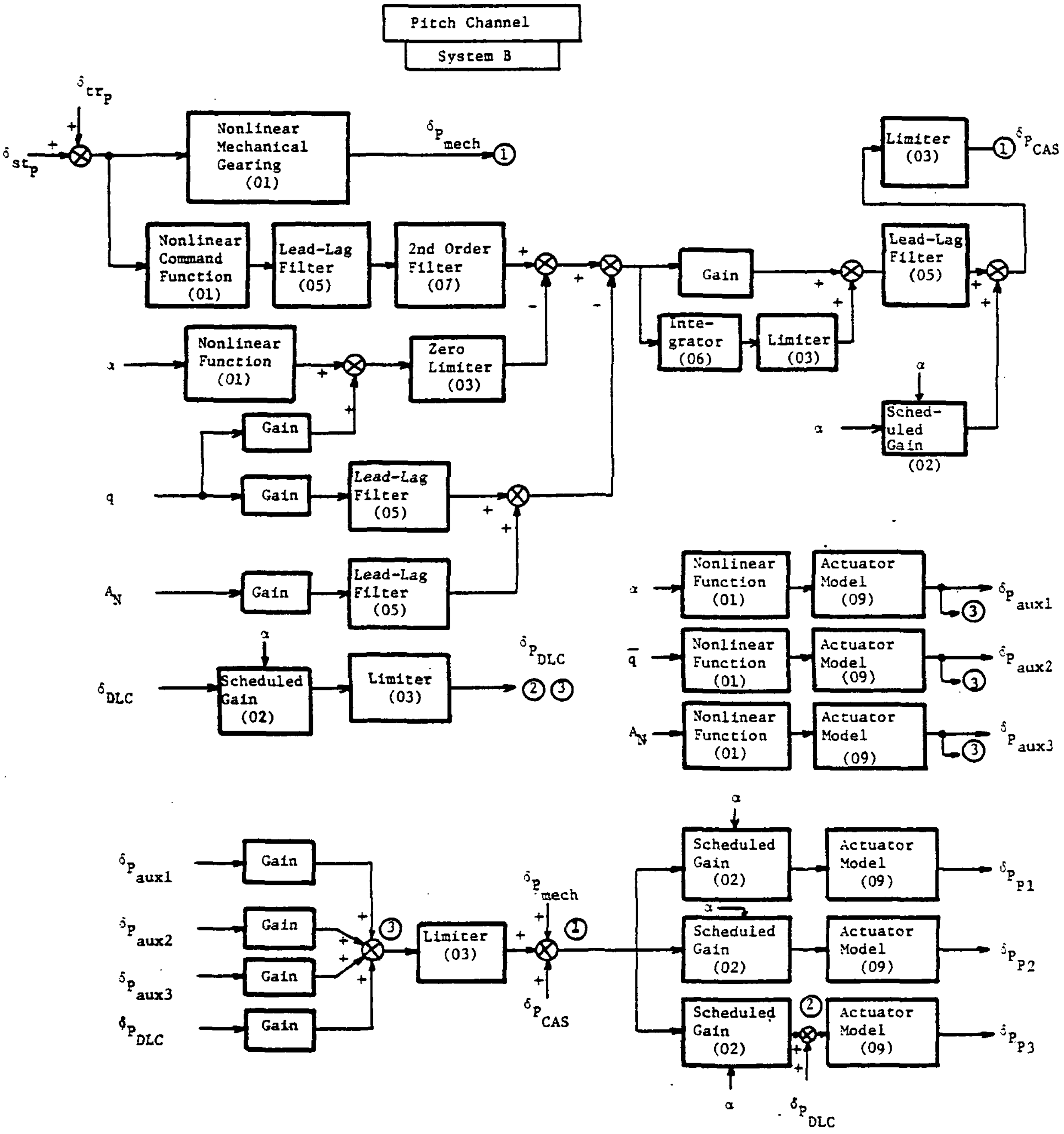


Figure 2-2. Schematics of control system B.

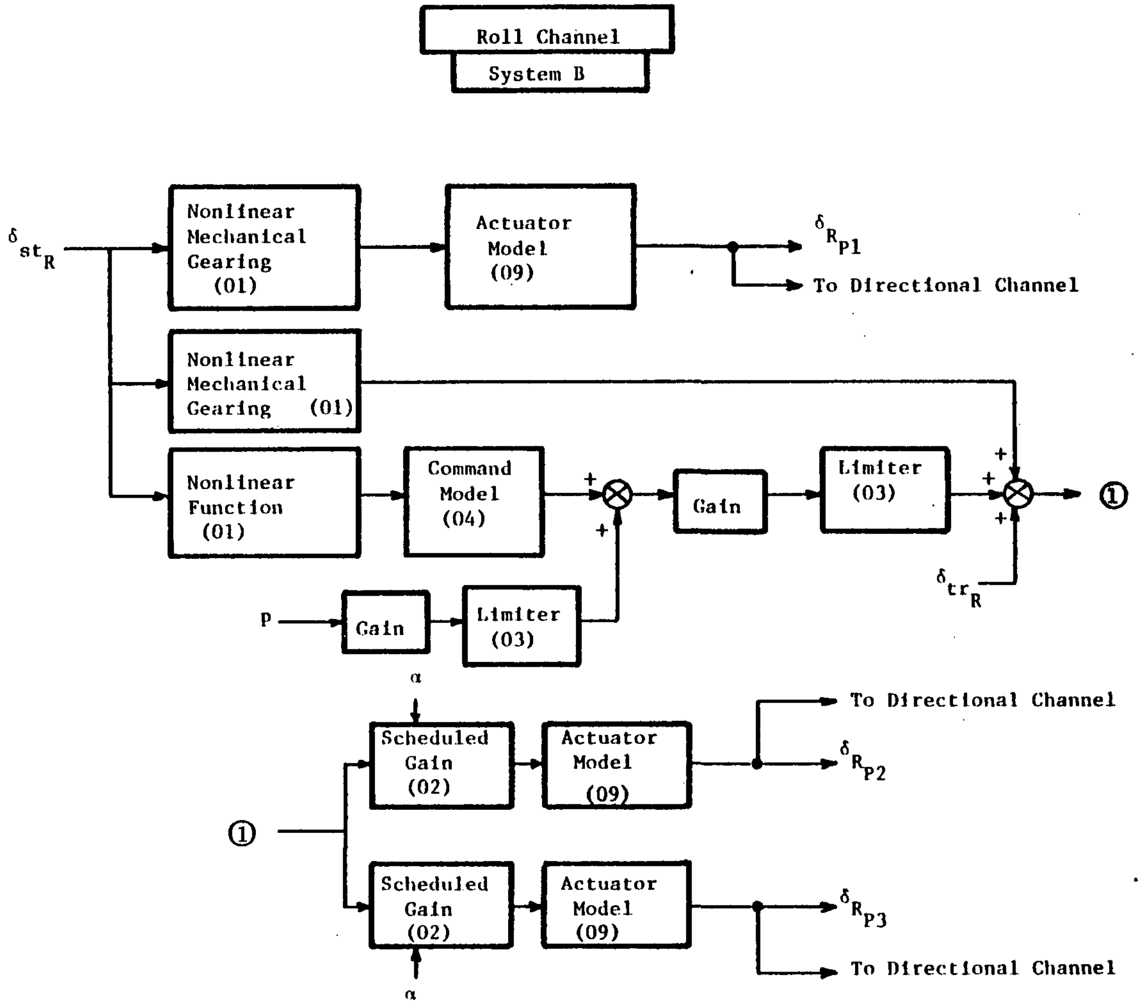
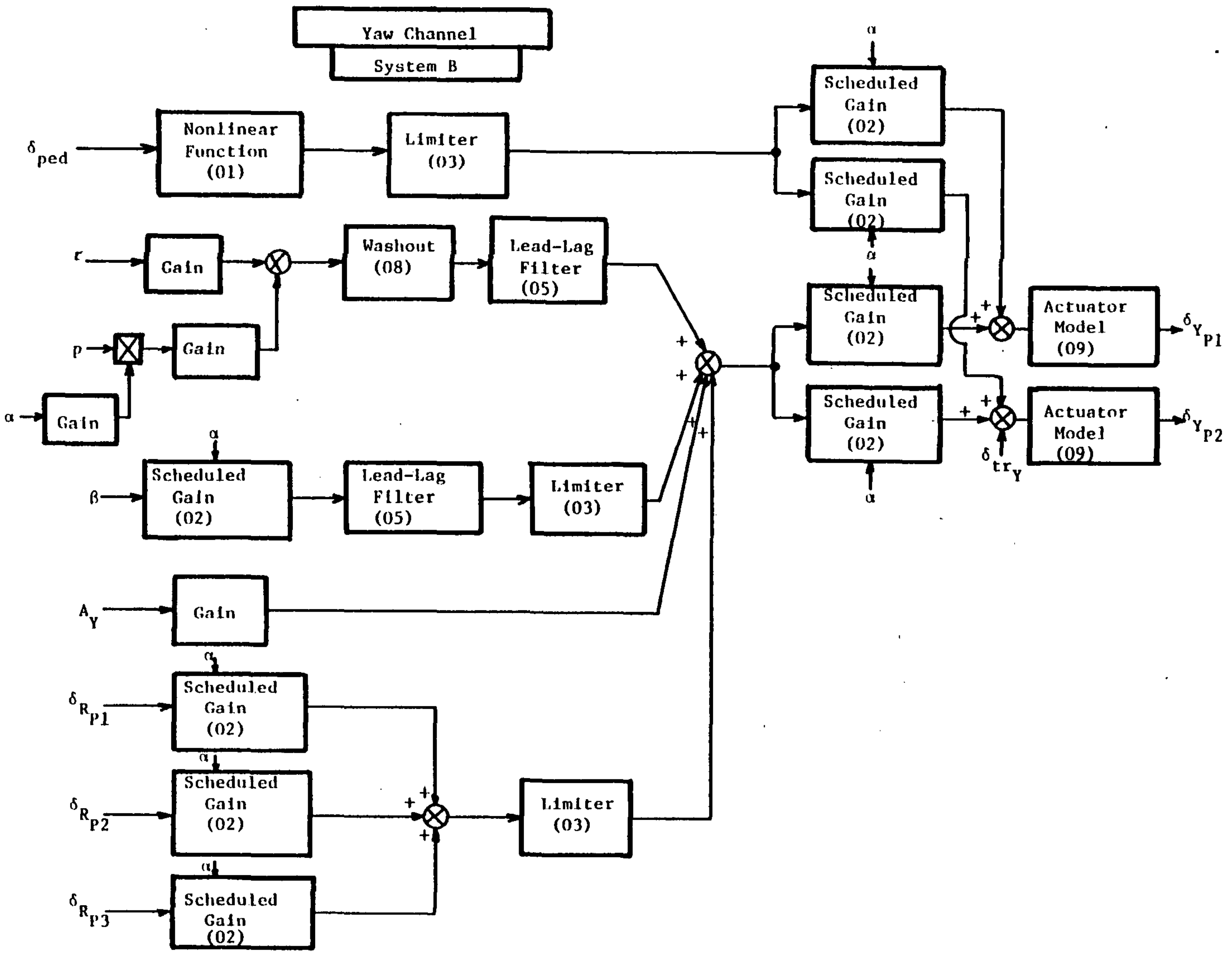


Figure 2-2. Continued.



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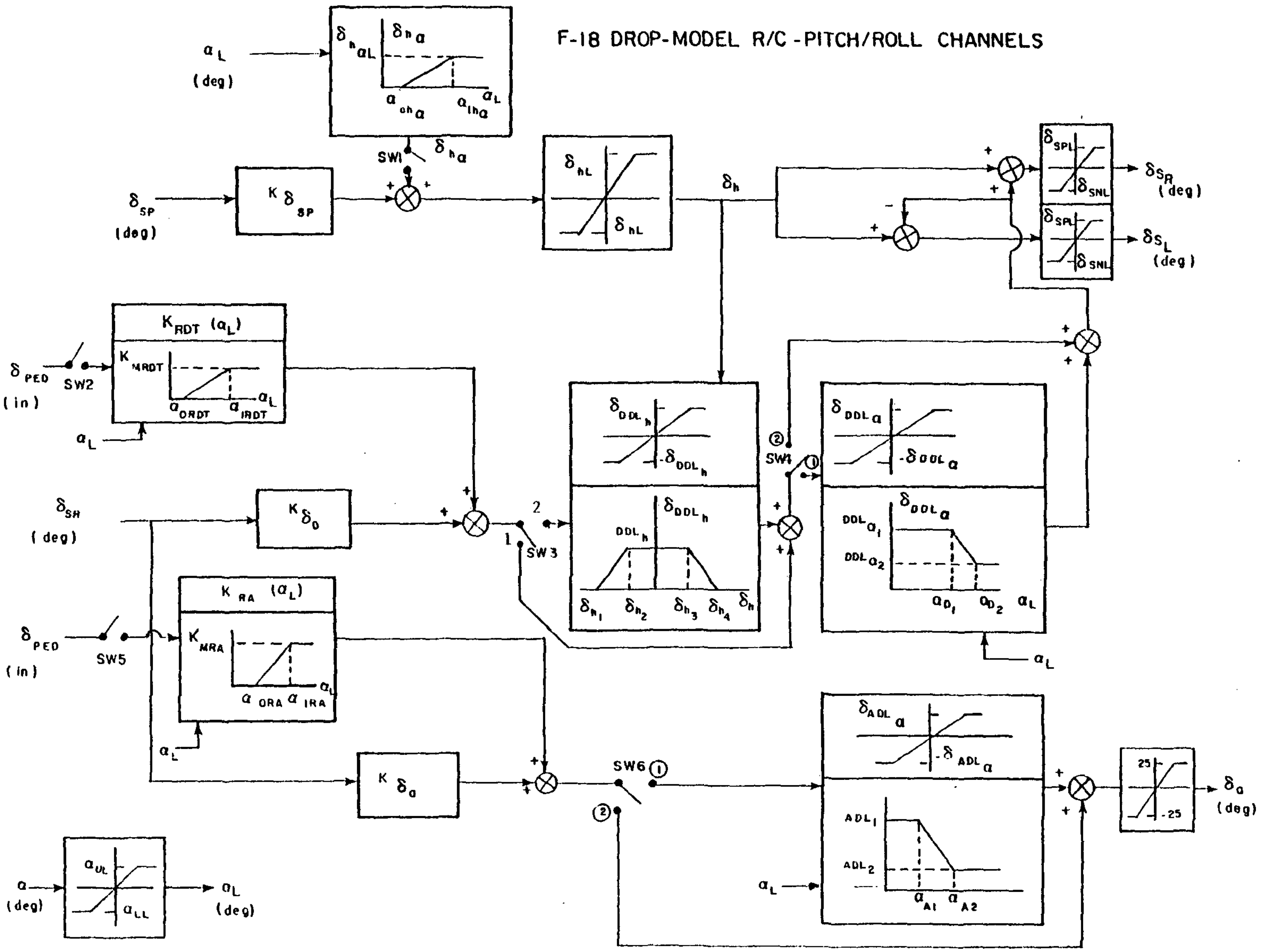

Figure 2-3a. Control laws for the F-18 drop model (pitch/roll channels).

F-18 DROP MODEL R/C - YAW CHANNEL

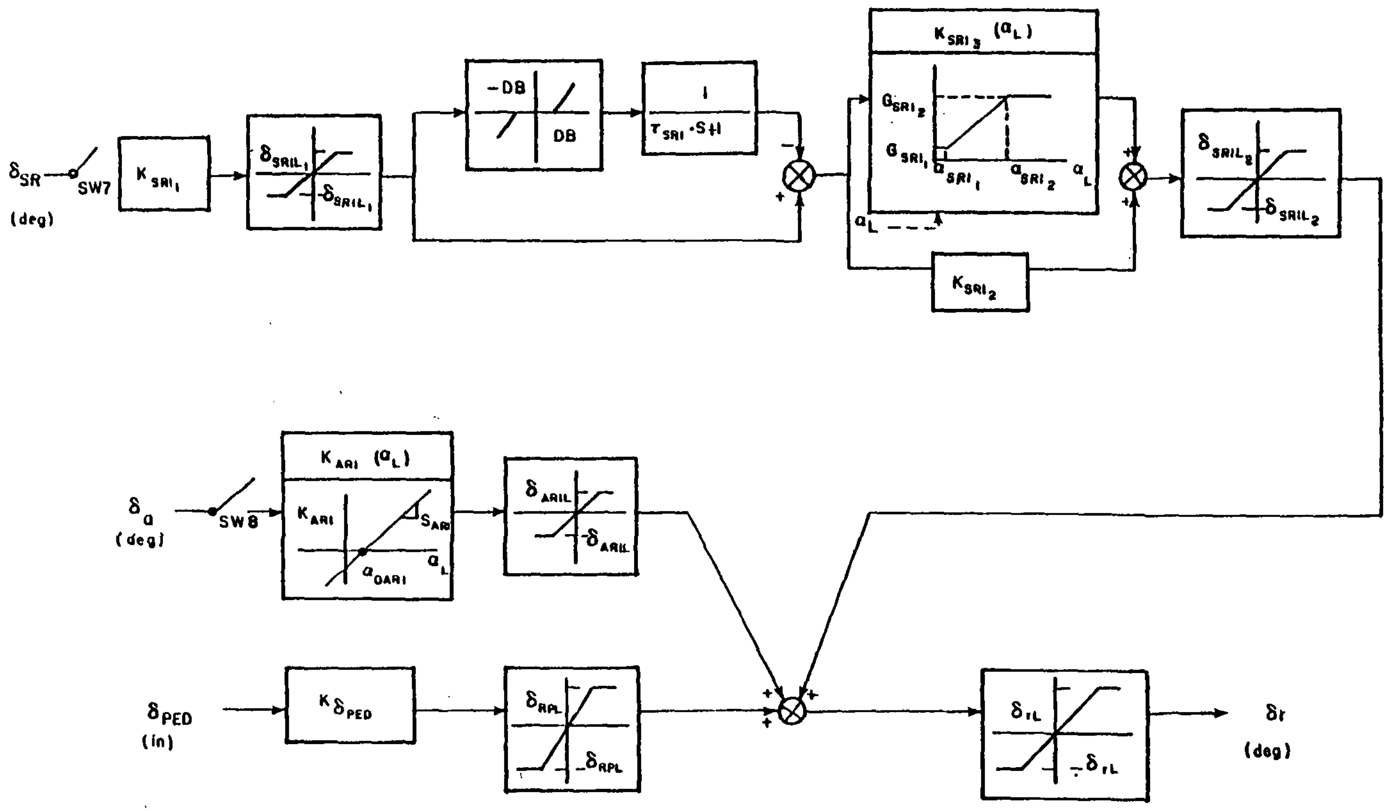

Figure 2-3b. Control laws for the F-18 drop model (yaw channel).

Table 2-1. DEFINITION OF SYMBOLS USED IN THE F-18 DROP-MODEL CONTROL LAWS OF FIGURES 2-3a AND 2-3b.

SYMBOL	UNITS	DEFINITION
δ_{SP}	deg.	pitch stick deflection, positive for aft deflection.
δ_{SR}	deg.	roll stick deflection, positive for right deflection.
δ_{PED}	in.	pedal deflection, positive for right pedal down.
δ_{S_R}	deg.	right stabilator deflection, positive for trailing edge down.
δ_{S_L}	deg.	left stabilator deflection, positive for trailing edge down.
δ_a	deg.	aileron deflection, positive for left roll (right aileron down).
δ_r	deg.	rudder deflection, positive for trailing edge left.
$K_{\delta_{SP}}$	deg./deg.	pitch stick to stabilator gearing.
δ^+_{hL}, δ^-_{hL}	deg.	positive and negative symmetric stabilator deflection limits.
δ_h	deg.	symmetric stabilator deflection.
K_{δ_D}	deg./deg.	roll stick to differential stabilator gearing.
δ_{DDL_h}	deg.	differential stabilator deflection limit versus symmetric stabilator deflection.
DDL_h	deg.	maximum differential stabilator deflection limit versus δ_h.
δ_{h_1}, δ_{h_2}, δ_{h_3}, δ_{h_4}	deg.	δ_h breakpoints for δ_{DDL_h} schedule.
δ_{DDL}	deg.	differential stabilator deflection limit versus α.
DDL_{α_1}	deg.	maximum differential stabilator deflection limit versus α.

Table 2-1. CONTINUED.

SYMBOL	UNITS	DEFINITION
DDL_{α_2}	deg.	minimum differential stabilator deflection limit versus α.
α_{D_1}, α_{D_2}	deg.	α breakpoints for δ_{DDL_α} schedule.
K_{δ_a}	deg./deg.	roll stick to aileron gearing.
δ_{ADL_α}	deg.	aileron deflection limit versus α.
ADL_1	deg.	maximum aileron deflection limit.
ADL_2	deg.	minimum aileron deflection limit.
α_{A_1}, α_{A_2}	deg.	α breakpoints for δ_{ADL_α} schedule.
ARI	N/A	aileron-rudder interconnect.
K_{ARI}	deg./deg.	ARI gain.
S_{ARI}	deg./deg./deg.	slope of K_{ARI} function.
$\alpha_{0_{ARI}}$	deg.	α bias in K_{ARI} gain schedule.
δ_{ARIL}	deg.	ARI authority limit.
SRI	N/A	roll stick to rudder interconnect.
K_{SRI_1}	deg./deg.	roll stick to SRI gain.
δ_{SRIL_1}	deg.	roll stick to SRI signal limit.
DB	deg.	SRI deadband.
τ_{SRI}	sec.	SRI lag time constant.
$K_{SRI_3}(\alpha_L)$	deg./deg.	SRI gain versus α.
G_{SRI_1}, G_{SRI_2}	deg./deg.	$K_{SRI_3}(\alpha_L)$ breakpoints.
α_{SRI_1}, α_{SRI_2}	deg.	$K_{SRI_3}(\alpha_L)$ breakpoints.

Table 2-1. CONCLUDED.

SYMBOL	UNITS	DEFINITION
K_{SRI_2}	deg./deg.	constant SRI gain.
δ_{SRIL_2}	deg.	SRI authority limit.
$K_{\delta_{PED}}$	deg./in.	pedal deflection to rudder gearing.
δ_{RPL}	deg.	pilot rudder authority limit.
δ_{rL}	deg.	rudder deflection limit.
α	deg.	measured angle of attack.
α_L	deg.	limited angle-of-attack signal.
α_{UL}	deg.	α_L upper limit.
α_{LL}	deg.	α_L lower limit.
δ_{h_α}	deg.	α-limiter stabilator command.
$\delta_{h_{\alpha L}}$	deg.	maximum value of δ_{h_α}.
α_{oh_α}, α_{1h_α}	deg.	breakpoints for α-limiter schedule.
RDT	N/A	rudder to differential tail.
K_{RDT}	deg./in.	rudder to differential tail interconnect gain.
K_{MRDT}	deg./in.	maximum value of K_{RDT}.
α_{ORDT}, α_{1RDT}	deg.	breakpoints for K_{RDT} versus α schedule.
K_{RA}	deg./in.	rudder to aileron interconnect gain.
α_{ORA}, α_{1RA}	deg.	rudder to aileron breakpoints.
K_{MRA}	deg./in.	maximum value of K_{RA}.
δ_{SPL}	deg.	positive stabilator deflection limit.
δ_{SNL}	deg.	negative stabilator deflection limit.

signal is the limited arithmetic average of the two horizontal tail deflections whereas the effective roll control signal is the limited value of one-half the difference between right and left horizontal tail deflections. The aileron deflection also provides a roll control signal.

In addition to its function as a scheduling parameter, the angle of attack produces a stabilator command (δ_{h_α}) through the function generator in the upper left hand corner of Figure 2-3a. This constitutes the only feedback loop in F-18 drop-model application. The value of α used through the control system is a limited version of the variable sensed on board the model and downlinked to the control system simulator. This limited angle of attack (α_L) is obtained by passing the telemetered α through the limiter shown in the lower left hand corner of Figure 2-3a. It is for this reason that δ_{h_α} is also referred to as the α-limiter stabilator command.

The F-18 drop-model control system is both configurable and modal. The configuration of the system can be changed through a whole spectrum of complexity by means of the configuration switches. These switches permit the selective introduction (or elimination) of the various channel interconnects, coupling of control surface deflections, and of the α-produced stabilator command (δ_{h_α}). Also, another configuration switch (SW3 in the figure) allows for a change in the manner in which the differential tail deflections are generated. The system is in a roll priority configuration with SW3 in position 1 whereas it is in a pitch priority configuration with SW3 in position 2. The difference between the two configurations is that in the roll priority the differential tail command (from δ_{SR} and/or δ_{PED}) are not scheduled by the symmetric stabilator deflection (δ_h). A summary of the configuration switches and their functions are presented in Table 2-2.

The F-18 drop-model control system has two modes: A normal mode and a spin mode. The spin mode is a subset of the normal mode in which all of the α_L -scheduled gains and limiters are either bypassed or their inputs disconnected by means of the spin mode switches. Examples of these are SW4 and SW6 which in position (2) bypass the α_L-scheduled limiters for the differential tail channel and the aileron channel respectively. With the exception of SW3, the configuration switches also play the roll of spin mode switches. The by-pass switches and the double purpose configuration

Table 2-2. CONFIGURATION AND MODAL SWITCHES IN THE F-18 DROP-MODEL CONTROL LAWS AND THEIR IMPLEMENTATION IN THE DIGITAL AND ANALOG CSS'S.

CHARACTERISTICS	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8
SWITCH TYPE								
CONFIGURATION	X	X	X		X		X	X
MODAL (SM) /1	X	X		X	X	X	X	X
SWITCH OPERATION	MANUAL & AUTO /2	MANUAL & AUTO	MANUAL	AUTO	MANUAL & AUTO	AUTO	MANUAL & AUTO	MANUAL & AUTO
SWITCH FUNCTION CONTROL OVER	δ_{h_α} (α_L) /3	δ_d/δ_{PED} (α_L) /3	PRIORITY ROLL (1) PITCH (2)	δ_d VAR. LMT. (α_L) /3	δ_a/δ_{PED} (α_L) /3	δ_a VAR. LMT. (α_L) /3	δ_r/δ_{SR} (α_L) /3	δ_r/δ_a (α_L) /3
SWITCH STATES								
MANUAL	ON/OFF	ON/OFF	1/2	N/C /4	ON/OFF	N/C /4	ON/OFF	ON/OFF
AUTOMATIC /5	$\overline{SM}$: IC SM : OFF	$\overline{SM}$: IC SM : OFF	N/A	$\overline{SM}$: ON SM : OFF	$\overline{SM}$: IC SM : OFF	$\overline{SM}$: IC SM : OFF	$\overline{SM}$: IC SM : OFF	$\overline{SM}$: IC SM : OFF
DIGITAL CSS	← PROGRAMMABLE SWITCHES →							
IMPLEMENTATION								
ISWOUT(1)=0 ($\overline{SM}$)	ISWPRG(1): 1=ON 0=OFF	ISWPRG(2): 1=ON 0=OFF	ISWPRG(3): 1=ON 0=OFF	DOES NOT EXIST	ISWPRG(4): 1=ON 0=OFF	DOES NOT EXIST	ISWPRG(5): 1=ON 0=OFF	ISWPRG(6): 1=ON 0=OFF
ISWOUT(1)=1 (SM)	OFF	OFF	IC		OFF		IC	OFF
ANALOG CSS								
IMPLEMENTATION								
FRONT PANEL								
SWITCH NUMBER	2	5	4	NOT /6 AVAILABLE EXTERNALLY	6	NOT /6 AVAILABLE EXTERNALLY	7	3
SWITCH LABEL	δ_{h_α}	$\delta_{PED_{\delta_d}}$	PRIORITY ROLL (UP) PITCH (DN)		$\delta_{PED_{\delta_a}}$		$\delta_{SR_{\delta_r}}$	δ_{a_r}
SM	OFF	OFF	IC	OFF /7	OFF	OFF /7	OFF /8	OFF
$\overline{SM}$	IC	IC	IC	ON /9	IC	ON /9	IC	IC

/1 Depends on spin mode (SM) signal

/2 AUTO = Automatic

/3 Generating or scheduling parameter

/4 N/C : noncontrollable

/5 $\overline{SM}$: not in spin mode; SM : in spin mode; IC : initial conditions prior to first entry into spin mode

/6 In the analog CSS these are internal, non-programmable switches

/7 Variable limiter is bypassed

/8 Disconnected at the input to the rudder limiter

/9 Variable limiter is in the loop

switches are activated by the spin entry/spin recovery signal generated by a yaw rate magnitude timer (not shown in the figures). The timer produces a spin entry (SM) signal when $\dot{}$ exceeds a specified magnitude for a specified length of time. The timer also generates a spin recovery ($\overline{SM}$) signal when $\dot{}$ is below a specified magnitude for a specified length of time. The spin recovery ($\overline{SM}$) signal returns all switches to the conditions they were at prior to the occurrence of the first SM signal, i.e., it returns the system to the initial conditions (IC) of the normal mode configuration. A summary of the spin mode switches and a description of their functions are presented in Table 2-2.

The table also presents a description of the implementation of these switches in both the digital and analog control system simulators. The description provides a focal point of reference for future discussions involving the mechanization of the two control system simulators.

A comparison of Figures 2-1 and 2-3 (a and b) shows that the control laws for the F-18 drop model are of similar complexity to that of system A used in the analysis study. The F-18 control laws do not have as many feedback channels as system A does but it has more channel interconnects than system A does. The recommended digital control system simulator should be able to handle the computational and operational requirements of the F-18 drop-model control laws with an ample margin for growth.

A particular requirement of the F-18 drop-model control laws is the implementation of a yaw rate magnitude and duration detector. This software based detector will be used to determine when the model is in a spin or, if in a spin, when it recovers from the spin. This additional software requirement can be easily handled by the recommended digital control system simulator.

2.2 Digital Control System Simulator Configuration

This subsection presents an overview of the hardware and software configuration of the digital control system simulator. The present hardware configuration differs somewhat from the one recommended in the previous work and the rationale for this change will also be explained.

2.2.1 Hardware. - The digital control system simulator recommended by the systems analysis work (reference 1) was configured around a Digital Equipment Corporation's (DEC's) PDP-11/45 minicomputer with 16K words of memory and a hardware floating point processor. The PDP-11/45 mainframe was selected after a nominal control law program written in FORTRAN-IV was comprehensively benchmarked in a group of candidate minicomputers (see section 5.3, reference 1). The selection criterion was the high throughput rate characteristic of the real time application at hand.

The peripherals recommended for the PDP-11/45 were: a cartridge disk system, a high speed paper tape reader/punch, a teleprinter terminal, a programmable real time clock, and modular digital and analog I/O subsystems. An alpha-numeric CRT graphics display terminal and a companion hard copy unit were also recommended as peripherals for the minicomputer.

Since this hardware configuration was recommended, the Digital Equipment Corporation (DEC) has developed and started marketing a PDP-11/55 minicomputer which is basically an upgraded version of the PDP-11/45 designed primarily for FORTRAN-based calculations with heavy floating point content in a real-time environment. On the basis of the performance criterion used to select the PDP-11/45 (instruction execution times), the performance of the PDP-11/55 is superior to that of the PDP-11/45. The same peripherals are available with both minicomputers except for the analog and digital input/output modules which differ in layout and mounting techniques. However, the modules have similar characteristics and provide the same capability for expansion.

The price of the system is also an attractive feature of the PDP-11/55. DEC offers a discount on the PDP-11/55 computer system when purchased as a package. The company does not offer such a discount in the PDP-11/45 computer system.

Because of the superior performance and lower cost of the PDP-11/55, RTI decided to configure the digital control system simulator around the PDP-11/55 minicomputer instead of around the PDP-11/45 minicomputer as previously recommended. RTI purchased one of DEC's standard PDP-11/55 system packages (PDP-11/55-BC) modified to meet the application under consideration. Purchase of this computing system as a package resulted in net savings of about $6,000.*

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* The net cost of the PDP-11/55 package is $60,500 - $7,000 (discount) = $53,500 whereas the cost of an equivalent PDP-11/45 system is $59,475.

The digital control system simulator specified, purchased, and developed by RTI is shown in Figure 2-4. The figure includes a description of the main hardware features of the computing system (a more detailed description is presented in Volume II: System's Manual).

The PDP-11/55 mainframe consists of a 16-bit processor, 32KW of memory, a memory management unit, a hardware floating point processor, a 1.2MW disk drive and controller, and a paper tape reader/punch. Interactions between the operator and the minicomputer occur through the DECwriter II keyboard/printer and its DL11-W* interface. Hard copies are obtained from the latter through the Tektronix hard copy unit. Interactions between data sources/sinks and the computer occur through the analog-to-digital converter (ADC), the digital-to-digital converter (D/D), and the digital-to-analog converters (DAC's) all of which operate under the control of the programmable real time clock.

The 32KW of memory consist of 16 KW of bipolar memory (300 nsec. execution time) and 16 KW of core memory (980 nsec. execution time). The memory management unit provides the capability for the expansion of the system memory up to 124 KW.

The AD11-K and AM11-K combine to provide 32 differential analog input channels. The analog to digital conversion has a resolution of 12 bits. The AA11-K provides 12 analog output channels (3 modules with 4 channels/module). The digital to analog conversion is performed with a 12-bit resolution. The DR11-K provides a 16-bit digital input/output channel (or 16 discrete I/O channels).

The digital control system simulator integrates with the existing drop-model facility as shown in Figure 2-5. The block diagram shows that the digital CSS receives inputs from the pilot (through the interface box) and the downlink telemetry receiver; and provides outputs to the uplink telemetry transmitter (through the uplink telemetry encoder in the interface box) and to the strip chart recorder. Outputs from the digital CSS (other than the control surface commands) can be recorded in the data recording sybsystem through the interface box. A detailed discussion of the interactions between the digital CSS and the rest of the facility is presented in the System's Manual (Volume II).

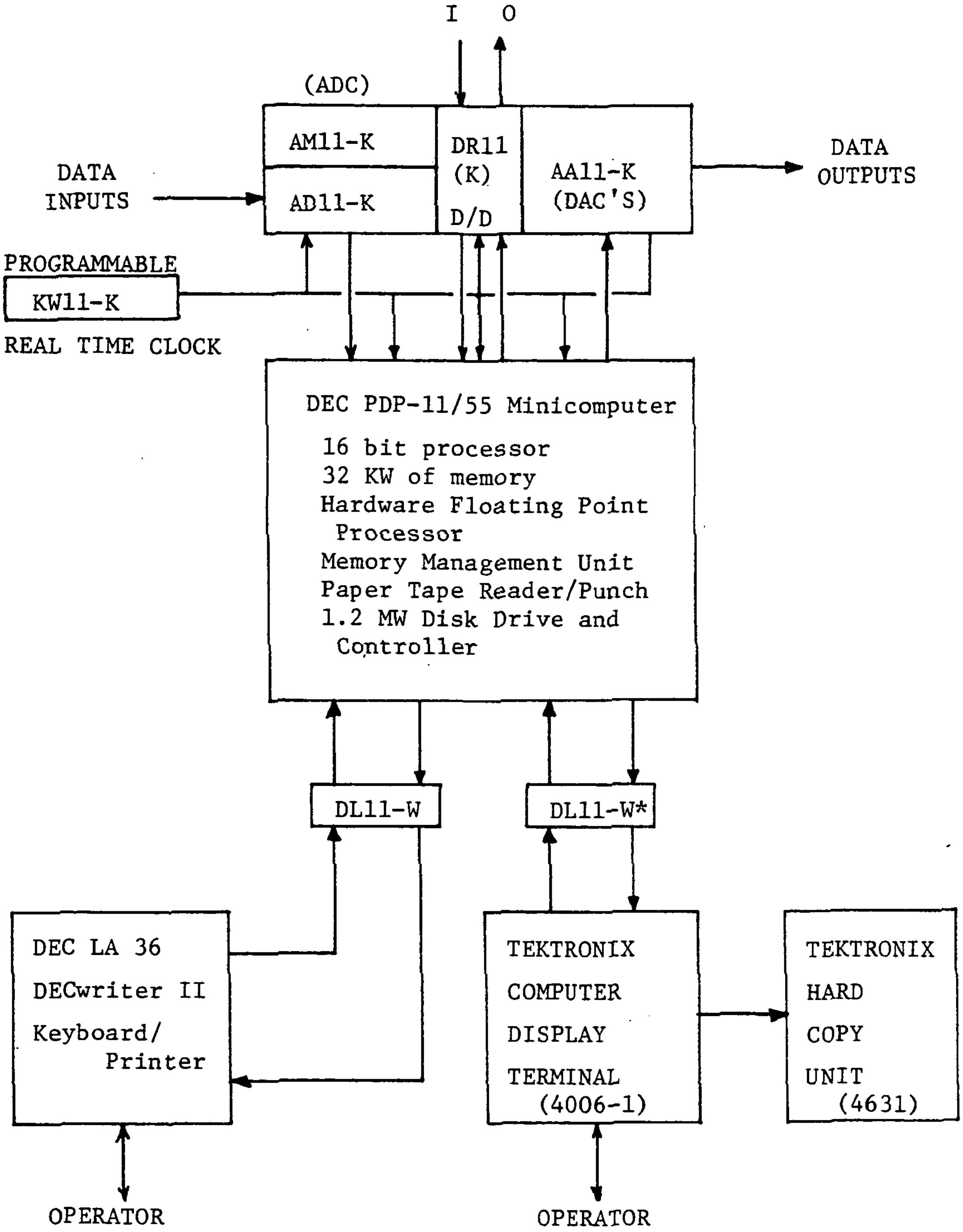


Figure 2-4. Hardware configuration of the PDP-11/55 based digital control system simulator.

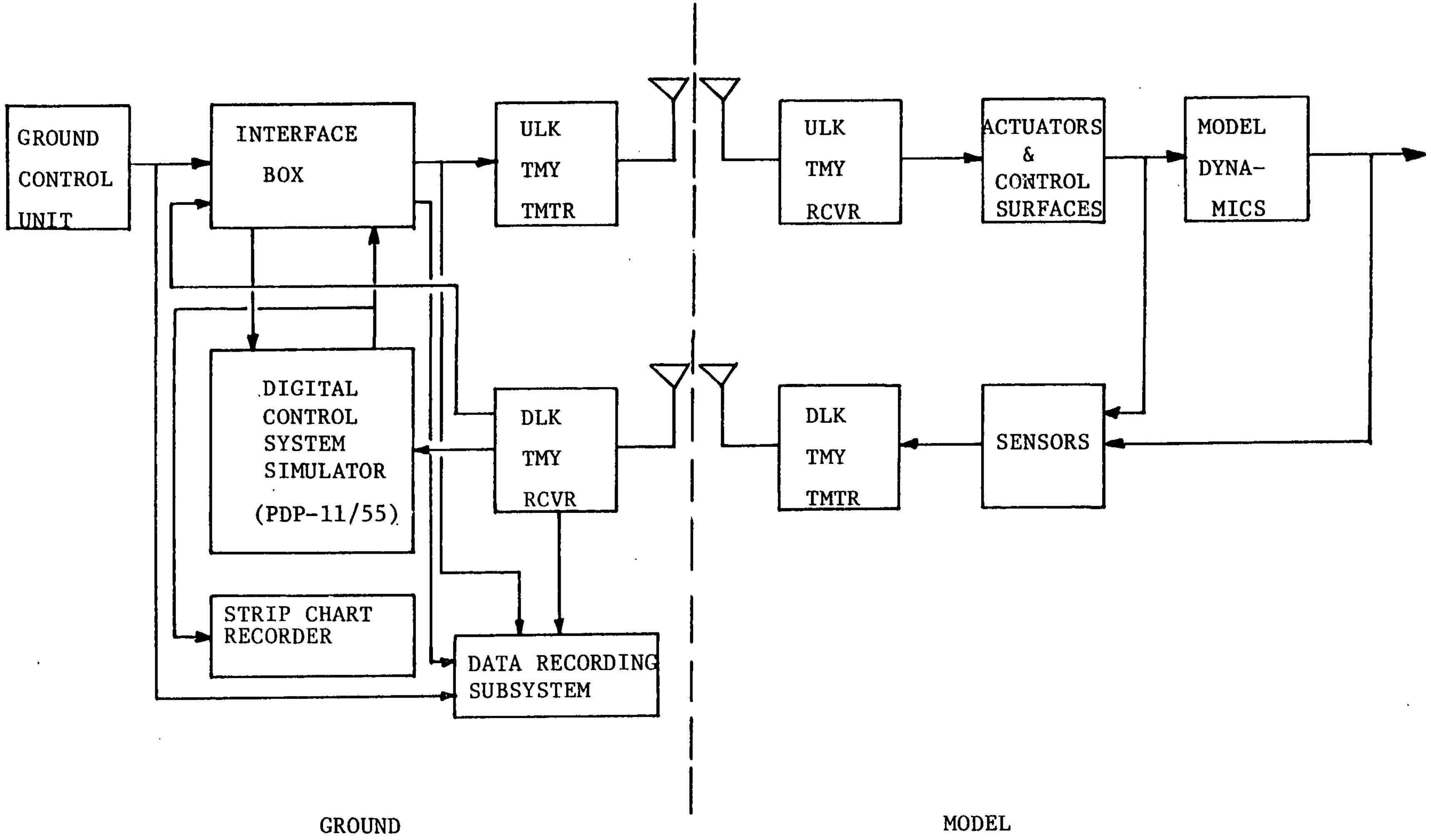
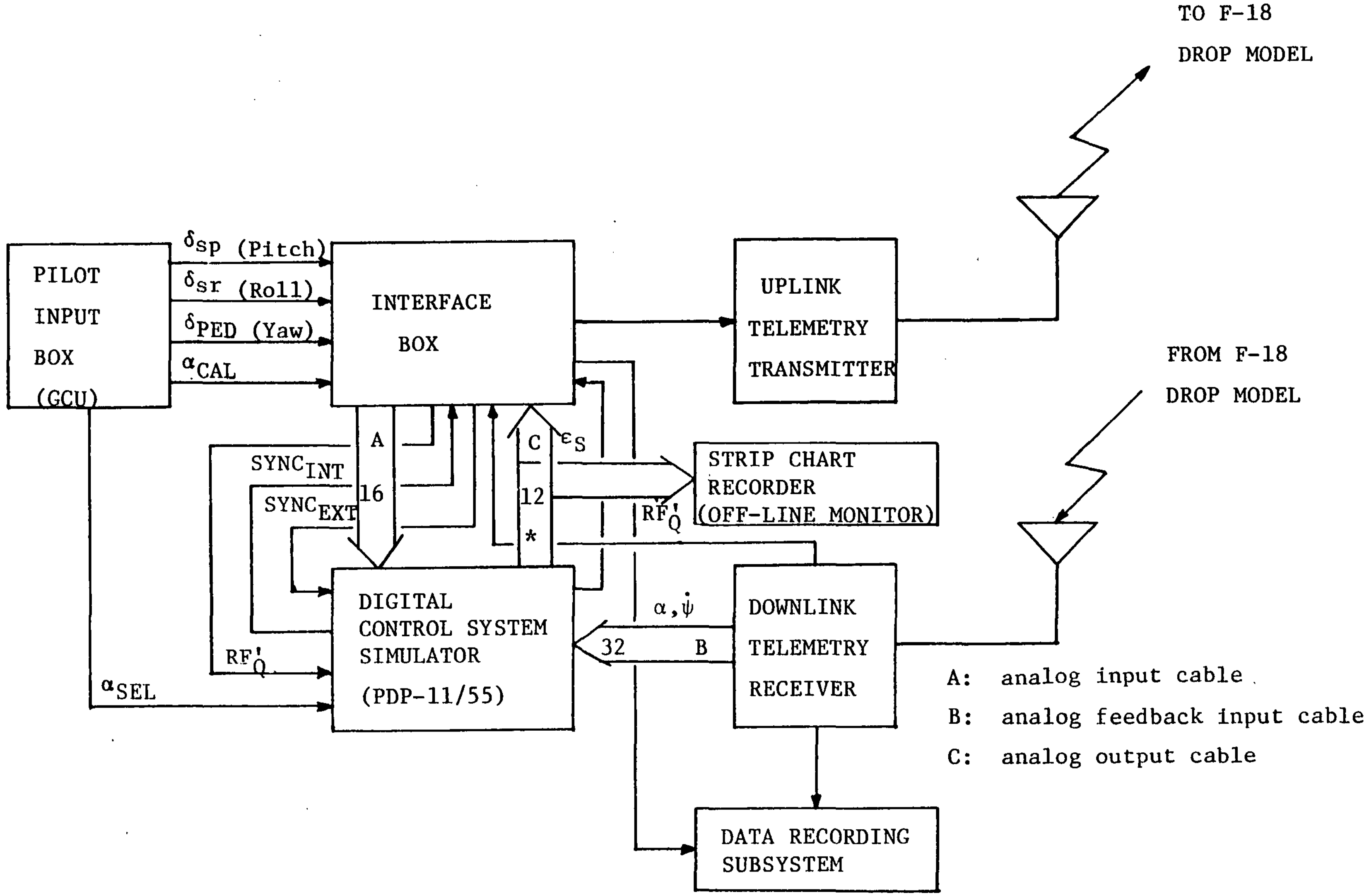


Figure 2-5. Block diagram of drop-model, stall/spin research facility with general purpose digital control system simulator

The block diagram of Figure 2-6 shows the configuration of the upgraded drop-model, stall/spin research facility needed to support the F-18 drop model tests. Although the cabling between the digital CSS and the interface box, the downlink telemetry receiver, and the strip chart recorder is a general feature of the upgraded facility, the block diagram illustrates the particular utilization of this configuration in the F-18 drop model tests.

The commands (δ_{SP}, δ_{SR}, and δ_{PED}) to the F-18 drop-model control laws implemented in the digital CSS are generated in the pilot input box of the ground control unit (GCU) and input to the digital CSS through the analog input cable (16 twisted-pair wires). Also generated in the GCU is a calibration signal for angle of attack (α_{CAL}) which is input to the CSS through the analog input cable. The feedback variables (α and $\dot{\psi}$) are received from the model by the downlink telemetry receiver and input to the F-18 control laws through the analog feedback input cable (32 twisted pair wires). The outputs of the F-18 drop-model control laws (δ_{S_R}, δ_{S_L}, δ_a, δ_r, and any other (up to 8) internal variables of the control laws) are sent to the interface box through the analog output cable (12 twisted-pair wires). These outputs are also connected to the strip chart recorder and can also be recorded in the data recording subsystem through the interface box.

Discrete inputs to the digital CSS are α_{SEL}, RF_Q', and $SYNC_{EXT}$. These inputs are fed through individual twisted pairs to selected discrete input channels (α_{SEL} and RF_Q' and the sync in channel ($SYNC_{EXT}$). The α_{SEL} signal (level change) allows the pilot to select between α_{CAL} and α as the feedback variable to the control laws during system checkout in a pre-drop, airborne environment. The RF_Q' (downlink telemetry dropout) signal (level change) is used by an algorithm in the executive software to determine the occurrence and duration of a downlink telemetry dropout. The RF_Q' signal is generated in the interface box by a threshold detector which monitors the AGC signal from the downlink telemetry receiver (RF_Q in the figure) and outputs a TTL-compatible level once this signal exceeds a preset value. The $SYNC_{EXT}$ (external synchronization) signal (pulse) allows for the optional enslaving of the operation of the digital CSS to that of the uplink telemetry encoder. This TTL-compatible pulse is generated by the uplink telemetry encoder at the beginning of each uplink telemetry frame.



* δ_{SR}, δ_{SL}, δ_a, δ_r, plus up to eight more internal control system variables

Figure 2-6. Block diagram of the upgraded stall/spin research facility configured to support the F-18 drop-model tests.

Discrete outputs from the minicomputer are the $SYNC_{INT}$ pulse and the system error signal level (ε_S in the figure). These outputs are fed to the interface box through individual twisted pairs from the sync-out terminal and one of the discrete output channels respectively. The $SYNC_{INT}$ (internal synchronization) pulse allows the optional enslaving of the operation of the uplink telemetry encoder to the computational cycle of the control laws in the digital CSS. The ε_S signal level alerts the external world of the occurrence of one or more of the following system errors: an error in the analog to digital conversion process, an out of synchronization condition, and a downlink telemetry dropout exceeding a preset value. The ε_S signal results from the logical OR of these three tests and activates a bank of relays at the interface box which disconnects the analog inputs coming from the computer and connects the pilot inputs directly to the uplink telemetry encoder. Thus, the ε_S signal is the mechanism whereby the computer can automatically switch itself out of the loop. Once this signal activates the relays, the computer remains out of the loop for the rest of the test run.

2.2.2 Software. - The real time software designed, developed, and validated by RTI under this contract converts the digital hardware described above into the programmable, real time, digital control system simulator for the drop-model, stall/spin research facility. This software is referred to in this report as the stall/spin system software.

The philosophy upon which the design of the stall/spin system software was based is dictated by two practical guidelines: The usage of a high level programming language (such as FORTRAN) wherever possible and the modularization of the key elements of the control law programs. The former guarantees a simple interaction between the software and system personnel whereas the latter facilitates future expansion of the digital CSS.

The development of the real time stall/spin system software is based on a group of DEC-supplied software packages which were specified and purchased in conjunction with the hardware. The group consists of the RT-11 real time operating system, RT-11 FORTRAN-IV with extensions, and a scientific subroutine package. Also, a set of diagnostics programs for the hardware was specified and purchased from DEC.

The RT-11 real time operating system is a single user, disk (or DEC-tape) based system which is very powerful and easy to use in real time programming applications (see reference 2). The system has two separate, independent monitors (a single job (S/J) monitor and a foreground/background (F/B) monitor) and a complement of program development utilities such as a relocating assembler, a linker, editor, debugger, and file interchange program.

The RT-11 FORTRAN-IV is an extended version of ANSI standard FORTRAN. The compiler for this programming language is optimized for fast compilation and the generation of highly efficient code. Signal processing (input/output of real time data) and graphics data are handled through routines in the FORTRAN extension library.

The scientific subroutine package consists of a host of mathematic functions commonly used in scientific applications. This package facilitates the programming tasks by providing the user with a library of FORTRAN-callable subroutines.

The diagnostic software package consists of a host of test programs which operate independently of the RT-11 operating system. The programs are designed to exercise the system hardware and detect errors or malfunctions in the constituitive elements of the system. They are intended primarily as an aid to field service personnel in the maintenance and calibration of the hardware.

In addition to the above mentioned software packages, a Tektronix-developed software package was purchased. The Terminal Control System (TCS), as this software package is known, provides the capability of generating graphic information for display in the Tektronix Graphics Terminal.

The stall/spin system software is a real time application program package that operates under the RT-11 operating system. The package consists of two main programs - the real time executive program and the system configurator program - and a host of support programs and program libraries. There is also a system test program that operates in a non real time environment. A more detailed description of the stall/spin system software is presented in the Systems Manual (Vol. II) and in the Software Manual (Vol. IV).

The real time executive program sequences and controls the operation of the application software during a test. This program is responsible for initializing the application software (a non real time task), maintaining synchronization with an external device, inputting data to the control law programs, monitoring critical external/internal events, sequencing the computation of the control laws, and outputting the outputs of the control law program.

The control law program and the library of control law modules are the basic elements for the development of the control system simulation for a particular aircraft model. The control law program is a description (in FORTRAN-IV language) of the various channels of a control law with their concatenation of functional blocks and configuration and/or modal switches. The control law program draws upon the library of control modules. This library consists of a set of subroutines coded in FORTRAN-IV and representing a wide cross section of functional blocks commonly used in control systems.

The modules available in the modules library are: a bi-directional limit, an integrator, a first order lag filter, a lead-lag filter, a second order lag filter, a washout filter, a deadband simulator, function generators with one, two, three, and four break points, a slow response actuator model, a fast response actuator model, a single-pole-single-throw switch, a single-pole-double-throw switch, and a mode switch. The integrator and various filters are implemented based on Tustin's transformation.

The system configurator program is the tool by means of which the users specify the configuration of the control law simulation for a particular run. Once the control laws have been programmed, the user uses this program for the assignment of the I/O channels, the range of the I/O data, the value of the parameters of the control laws, the initial conditions of the internal variables of the control laws, and the state of the configuration switches.

The system test program is a non real time program that aids the system operator in validating the operation of the digital system's I/O modules prior to a test. This program simply accepts manually supplied inputs to the various input channels of the system and transfers them to the various output channels. Together with a subset of the DEC supplied, hardware diagnostic program, the system test program provides the operator with a tool to check the operation of the digital control system simulator during the pre-flight checkout procedure.

The procedure for the utilization of the digital control system simulator in a drop-model test program is as follows:

1) Decompose the block diagram of the given control laws into a set of elementary functional blocks;
2) Check the control modules library for availability of all the functions identified;
3) Generate, test, and time any new module needed;
4) Generate the control law program from the block diagram;
5) Use the data configurator program to create a data file (I/O structure, position of the configuration switches, values of control law paremeters, et al.) for the control law;
6) Test and time the control law program;
7) Modify, if necessary, the control law data file;
8) Perform pre-flight checkout of the digital CSS, and;
9) Perform flight test.

The digital CSS has been configured to support the F-18 drop-model stall/spin tests following the procedure outlined above. The functional needs of the F-18 drop-model control laws are adequately satisfied by the elements of the control modules library since the control laws only require (see Figure 2-3a and 2-3b) bi-directional limiters, function generators, a deadband simulator, a first order lag filter, various configuration switches, and a modal switch.

A data file for the F-18 drop-model control laws was created based on the information available to RTI at the time the work was being done about the configuration and parameter values of the control laws. Modification of this data file (change in configuration and/or parameter values) can be easily accomplished through an interactive session with the system configurator program.

The control law software for the F-18 drop-model actually simulates two control laws: A normal mode and a spin mode. These control laws are implemented in parallel and differ in that in the spin mode all the α_L-scheduled limiters and function generators in the normal mode configuration are by-passed.

The decision as to which branch to execute in a given computational cycle is based on the output (0,1) of the modal switch. The modal switch has $\dot{\psi}$ as its input and its output remains at 0 (normal mode) as long as $|\dot{\psi}| < 87.5°/\text{sec}$. Once $|\dot{\psi}|$ exceeds 87.5 /sec, the module output changes to 1 (spin mode) if this magnitude persists for more than 2 seconds. The output of the modal switch returns to 0 if $|\dot{\psi}| \leq 37.5°/\text{sec}$ for more than 2 seconds.

The configuration switches are implemented through the single-pole-single-throw module of the modules library. These switches are binary variables with a value of 1 representing the switch in the closed position and a 0 value representing the switch in the open position. There are six configuration switches in the digital implementation of the F-18 control laws. The relationship of these switches to those used in the block diagram supplied to RTI (see Figures 2-3a and 2-3b) is described in Table 2-2. Note that SW4 and SW6 are not implemented. This is so because with the two control law modes there is no need to implement these switches. The binary value of the configuration switches are initialized through the system configurator program.

In addition to the configuration switches, the digital implementation has an input switch which allows for the selection of the source of the α signal. This input switch is implemented through the single-pole-double-throw switch module and its binary value can be set "manually" (through the configurator program) or automatically by the α_{SEL} signal level generated external to the computer. A binary value of 1 connects the software to a calibrated source of α (α_{CAL}) whereas a binary value of 0 connects the software to the downlinked α.

Also implemented in software as part of the real time executive program is the monitoring of downlink dropouts. The interface box generates, by means of a threshold detector, a TTL-compatible signal level when the AGC signal strength of the downlink telemetry falls below -8 volts. The software times the duration of this level and if it exceeds 500 msecs. the software generates a system error discrete which is used in the interface box for the automatic disconnect (bypass) of the digital CSS. The threshold level and the downlink dropout cutoff time are hardware and software programmable respectively.

It is important to note that as presently implemented the system error discrete does not go down even if the downlink dropout ceased to exist after say 501 msecs. In other words, once the computer switches itself out of the loop it cannot return automatically to the loop even if the condition that caused the generation of the system error discrete disappeared.

2.3 System Integration and Performance

The work associated with the definition, procurement, and configuration of the digital computing system and the design, development, and validation of its real time operating software was conducted at RTI over a period of twelve months.

Each element of the digital computing system was tested to verify its operation and to enhance our knowledge of the full extent of their capabilities. The programs and subprograms developed at RTI were also tested, first by themselves and then at various levels of software integration. Finally, the digital CSS was subjected to extensive validation tests at RTI for the purpose of verifying the compliance of the system operation with the needs of the real time application. These tests certified the proper operation of the digital CSS in a stand-alone, laboratory environment.

The digital CSS was then transferred to NASA-LRC where it was integrated with the drop-model instrumentation van (NASA trailer NA1044) that supports the stall/spin research facility. The system took its place alongside a set of rack-mounted cabinets already existing in the instrumentation van. Except for some minor modifications in the van (to support the computer cabinets, to provide the special power outlets required by the computer, and to route the I/O cables), the integration of the digital hardware with the instrumentation van took place without difficulties.

Once integrated with the instrumentation van, the digital CSS was subjected to a series of acceptance tests. These tests can be broadly classified into hardware and software.

The hardware tests were conducted to ascertain if the hardware had been effected during the shipment and having done this, to verify the proper operation of the hardware in its operational environment.

The hardware was exercised first with the diagnostics software package (DEC/X11) under the supervision of a DEC field service technician (the hardware is under a service maintenance agreement with DEC through June 8, 1978) and certified to be in good operating condition. Later on, during the software tests, a hardware problem developed in the I/O modules. The problem resulted from an out-of-calibration condition in the I/O modules brought about by the unnecessary application of input voltages which exceeded the normal range of the I/O modules (±10 volts). The problem was solved by recalibrating the I/O modules and limiting the input voltages to be within ±10 volts.

The hardware was exercised next with the test program developed by RTI. This verified the acceptance of inputs from the interface box by the computer and the output of the appropriate values by the computer to the interface box. This test completed the hardware portion of the acceptance tests.

The software tests were conducted to verify the operation of the stall/spin system program in its operational, real-time environment. Pilot inputs (δ_{SP}, δ_{SR}, and δ_{PED}) and the feedback variable α were generated in a control box and fed into the digital CSS through the interface box. The outputs of the digital CSS were fed to the interface box and plotted selectively on an X-Y plotter. The operation of the software-based $|\dot{\psi}|$ spin mode detector and the downlink dropout detector were also checked during this test.

The acceptance tests also subjected the F-18 drop model control law software to extensive tests. These were designed to check, in a hierarchical order of complexity, the operation of each of the channels of the control laws in response to their respective inputs. To facilitate the interpretation of some of the tests the calculation of the average horizontal tail deflection (δ_h) and the differential horizontal tail deflection (δ_d) were added to the control law software and their results were made available as outputs of the digital CSS.

The conditions under which the F-18 drop-model control law software was tested are summarized in Table 2-3. The table shows for each run the value that the input and feedback variables take on, the position of the configuration switches, and the output studied.

Thus, for example, run 1 checks the operation of the α-limiter (α_L function generator). Runs 2 through 7 check the travel and linearity of δ_h (2 and 3), δ_a (4), δ_d (5 and 6), and δ_r (7). Similarly, runs 10 through 13 check the response of the horizontal tail to pitch stick inputs

Table 2-3. Summary of conditions for acceptance tests of the F-18 drop model control law software.

Run No.	INPUTS			FEEDBACK		CONFIGURATION SWITCHES						OUTPUTS			
	δ_{SP} (deg.)	δ_{SR} (deg.)	δ_{PED} (in.)	α (deg.)	$\dot{\psi}$ (°/sec)	ISWPRG(k), k = 1→6. 0=Closed 1=Open						$\delta_{S_L}^{**}$	$\delta_{S_R}^{**}$	δ_a	δ_r
						1	2	3*	4	5	6				
1	0.	0.	0.	-30.→60.	0.	1	1	1	1	1	1	CHECK ON α-LIMITER			
2	-30.→30.	0.	↓	0.	↓	↓	↓	↓	↓	↓	↓	(h)x			
3	30.→-30.	0.	↓	↓	↓	↓	↓	↓	↓	↓	↓		(h)x		
4	0.	-30.→30.	↓	↓	↓	↓	↓	↓	↓	↓	↓			x	
5	↓	-30.→30.	↓	↓	↓	↓	↓	↓	↓	↓	↓	(d)x			
6	↓	-30.→30.	↓	↓	↓	↓	↓	↓	↓	↓	↓		dx		
7	↓	0.	-2.→2.	↓	↓	↓	↓	↓	↓	↓	↓				x
8	↓	↓	0.	-20.→60.	↓	0	↓	↓	↓	↓	↓	x			
9	↓	↓	↓	-20.→60.	↓	0	↓	↓	↓	↓	↓		x		
10	30.→-30.	30.→-30.	↓	0.	↓	1	↓	↓	↓	↓	↓	x			
11	↓	↓	↓	↓	↓	1	↓	↓	↓	↓	↓		x		
12	↓	↓	↓	↓	↓	1	↓	0	↓	↓	↓	x			
13	↓	↓	↓	↓	↓	1	↓	0	↓	↓	↓		x		
14	0.	0.	↓	18.→32.	↓	0	0	1	0	0	0	x			
15	↓	0.	↓	↓	↓	↓	↓	↓	↓	↓	↓		x		
16	↓	-25.	↓	↓	↓	↓	↓	↓	↓	↓	↓	x			
17	↓	-25.	↓	↓	↓	↓	↓	↓	↓	↓	↓		x		
18	↓	+25.	↓	↓	↓	↓	↓	↓	↓	↓	↓	x			
19	↓	+25.	↓	↓	↓	↓	↓	↓	↓	↓	↓		x		
20	-30.→30.	-25	↓	↓	↓	↓	↓	↓	↓	↓	↓	x			

Table 2-3. Concluded.

Run No.	INPUTS			FEEDBACK		CONFIGURATION SWITCHES						OUTPUTS			
	δ_{SP} (deg.)	δ_{SR} (deg.)	δ_{PED} (in.)	α (deg.)	$\dot{\psi}$ (°/sec.)	ISWPRG(k), k = 1→6, 0=Closed 1=Open						$\delta_{S_L}^{**}$	$\delta_{S_R}^{**}$	δ_a	δ_r
						1	2	3*	4	5	6				
21	-30.→30.	-25	0.	18.→32.	0.	0	0	1	0	0	0		x		
22		25.										x			
23		25.											x		
24		-25.										x			
25		-25											x		
26		25.						0				x			
27		25.						0					x		
28	0.	0.						1						x	
29		-25.		5.→30.										x	
30		25.		5.→30.										x	
31		-25.		-30.→60.							1				x
32		25.		0.→20.						1	0				x
33		25.		0.→60.						0					x
34		25.→-25.		0.→60.											x
35		25.→-25.		0.→60.											x
36		-25.		15.→30.		1		0				x			
37		-25.											x		
38		25.										x			
39													x		
40															

* Priority switch: 0 (PITCH), 1 (ROLL)

** h: average, d: differential

for various settings of roll stick input at a fixed value of α_L (0°) in the roll priority configuration (10 and 11) and in the pitch priority configuration (12 and 13).

Other examples are: runs 28 through 30 which check the effect of α_L changes on δ_a at various settings of the roll stick input, and runs 31 through 33 which check the effect of α_L changes on δ_r for roll stick inputs, aileron inputs, and a combination of these two.

All forty of the tests defined in Table 2-3 were conducted. The results indicated that the F-18 drop-model control law software operates as expected in its real-time, integrated environment.

3.0 F-18 DROP-MODEL, DEDICATED, ANALOG CONTROL SYSTEM SIMULATOR

The systems development contract specified that RTI would design, fabricate, and validate a dedicated analog hardware implementation of the F-18 drop-model control laws concurrently with the work associated with the digital CSS. This analog hardware implementation, referred to in this report as the analog control system simulator (ACSS), was to be integrated with the drop-model instrumentation van and held as an operationally-ready backup to the digital CSS. The rationale for this effort was simple: to have an operational backup system in case that unforeseen technical difficulties were encountered during the development and/or usage of the digital CSS.

The purpose of this section is to present an overview of the F-18 drop-model analog control system simulator (ACSS). The section begins with a discussion of the operational requirements of the ACSS. The following subsection describes the design philosophy and the realization of the ACSS. The section concludes with a general discussion of the performance of the ACSS in its operational environment, i.e., integrated with the drop-model instrumentation van. A more detailed description of the ACSS is presented in Volumes V and VI of this report.

3.1 Operational Requirements

The operational requirements for the dedicated ACSS are, in general, similar to those of the digital CSS, i.e., the analog simulator must provide an accurate simulation of the F-18 drop-model control laws with a certain degree of built-in programmability. In this context, programmability refers to the capability of accomodating reasonable changes in the values of the parameters of the control laws without having to resort to circuit modifications.

The specification of an overall (input-to-output) level of accuracy in a complex analog simulation such as the one under consideration is not a straight forward task because different modules using the same basic components in various configurations produce different measures of accuracy. Furthermore, the numerous internal feedback loops and channel interconnects compound the problem. Nonetheless, an overall accuracy range of 0.5% to 1%

of full scale was specified for the F-18 drop-model ACSS. This range was arrived at based on the experience derived from previous analog control system simulators used in the drop-model facility and on the capabilities of standard, off-the-shelf analog hardware.

Another important operational requirement is system "programmability". This capability enhances the hard-wired analog simulation into one which, albeit dedicated, has the flexibility to accomodate a reasonable range of parameter variations. There are, however, practical limits to this requirement since the more control is provided over the setting of parameter values, the more complex and hence less reliable, the simulation becomes. Based on this consideration, it was specified that the ACSS would provide control over the setting of each system parameter that would result in a ±50% variability about the nominal values specified by the Government.

Certain peculiarities of the F-18 drop-model control laws and of the drop-model facility created other operational requirements for the ACSS. Thus, for example, the ACSS must be configurable to accommodate the various possible combinations of channel interconnections in the control laws. The ACSS must also provide two modes of operation, normal and spin; and a "programmable" interface module to compensate for day-to-day variations in the slope and offset of the downlinked feedback parameter (α).

3.2 System Design

The design of the ACSS for the F-18 drop-model control laws was based on a philosophy of providing access to the largest number of system variables and control over each system parameter. Another philosophical feature of the design was to incorporate maximum amplitude scaling throughout the simulation.

These guidelines provide a number of practical benefits. First, it facilitates system testing, diagnosis, and checkout; second, it provides flexibility in the setting of system parameters (gains, limits, schedules, et al.); third, it enhances signal-to-noise ratios throughout the simulation; and fourth, it guarantees operation of the simulation within the linear region of its constituitive elements.

The F-18 drop-model control laws simulated in the dedicated ACSS are the same as those shown in Figures 2-3 (a and b) of the previous section. Just as in the case of the digital CSS, the first step in the design of the ACSS was to decompose the channels of the control laws into a set of elementary transfer functions. The transfer functions identified were: fixed gain (01), mechanical gearing (02), fixed limiter (03), function generator (04), deadband (05), first order lag filter (06), scheduled gain (07), and scheduled limiter (08).

The design of the ACSS uses conventional operational amplifier circuit techniques to generate this set of elementary transfer functions. Extreme care was exercised in the application of these circuits to ensure the elimination of diode errors (bias and round-off), the precise simulation of break points and hard limits, and the maintenance of at worst a 1% of full scale accuracy level throughout the simulation. These design features were obtained at the expense of an increase in component count over that of a less precise design.

The design approach also stressed modularity and easy access to I/O variables and internal system variables. The set of elementary transfer functions needed for each control law channel (pitch, roll, and yaw) were selectively integrated into modules (cards). The groupings were defined based on the commonality of the application of the selected elementary transfer functions. A signal routing strategy was also adopted that would provide unrestricted access to the input and output variables of the system as well as to most of the internal variables of the simulation. The intent of this approach was to facilitate the monitoring and maintenance of the ACSS.

Another goal of the design approach was to provide a simple means of control over every parameter of the simulation and over the configuration of the simulation. This was accomplished by associating each parameter (except τ_{SRI} in the yaw channel) with a readily accessible control potentiometer and by making the configuration of the ACSS a function of the setting of manually controlled switches.

3.3 System Realization

The realization of the ACSS for the F-18 drop-model control laws is shown in Figure 3-1. This figure shows that the ACSS is built into a standard size cabinet with a rack adaptor that converts it into a drawer which

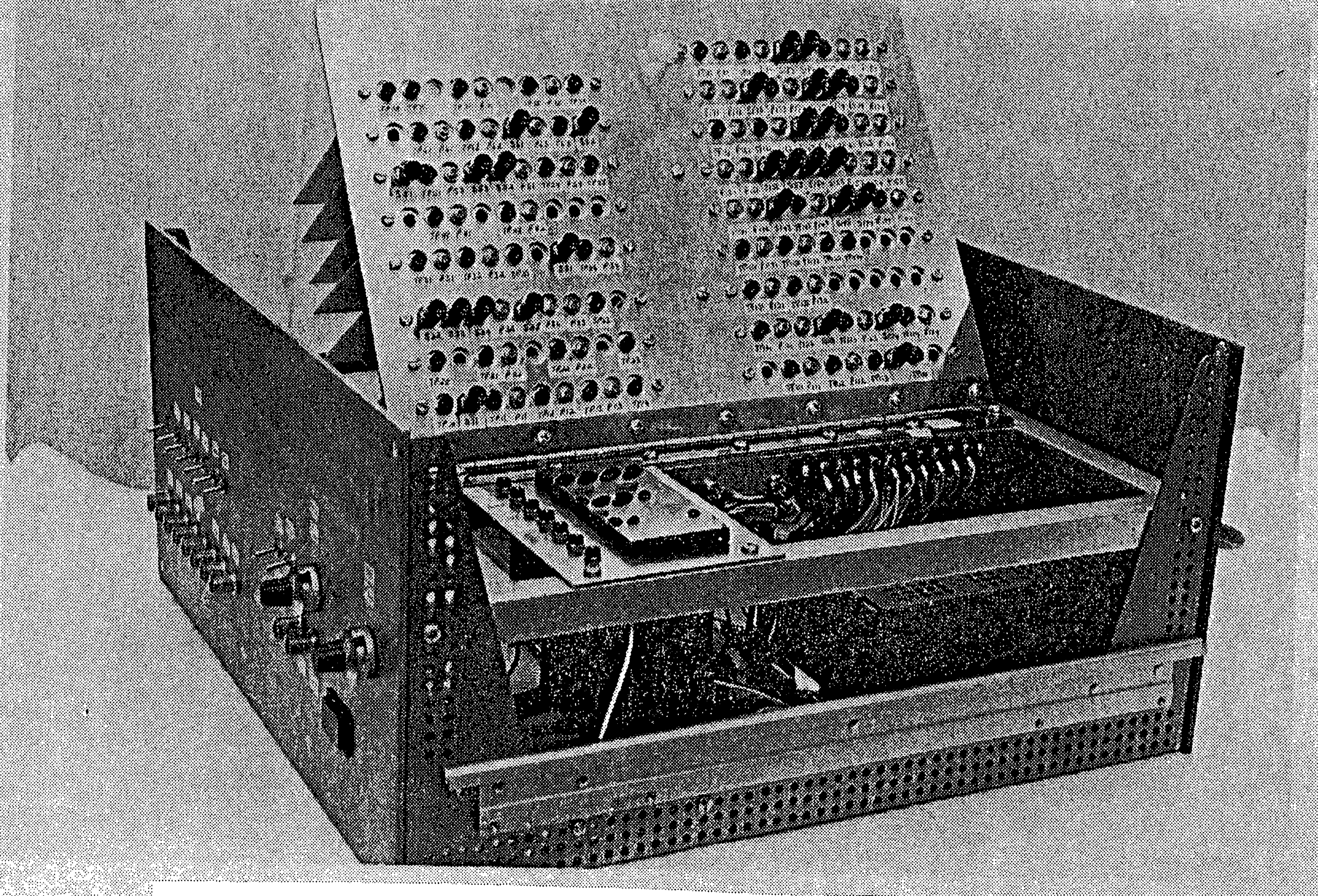


Figure 3-1. Realization of the F-18 drop-model analog control system simulator.

fits in one of the relay racks of the drop-model instrumentation van at LRC.

The ACSS receives its power and system inputs through the rear panel of the cabinet (not visible in Figure 3-1). The ACSS also provides its system outputs through this rear panel. The pilot inputs (δ_{SP}, δ_{SR}, and δ_{PED}) and other utility inputs (spin mode pulse, et al.) arrive from the interface box via an input cable which mates with an input cable plug located on the rear panel. Other system inputs (α_{FB}, α_{SEL}, and α_{CAL}) arrive from their respective sources via individual cables which mate with individual BNC connectors on the rear panel. The simulation outputs (δ_{S_R}, δ_{S_L}, δ_a, and δ_r) leave the ACSS for the interface box via the output cable which mates with an output plug located on the rear panel.

The system inputs and outputs are available on individual BNC connectors located on the front panel of the ACSS (see Figure 3-1). Both the feedback α (α_{FB}) and the conditioned* α (α_{COND}) are also available through BNC connectors on the front panel. The system power on/off button is also located in the front panel. There are nine switches on the front panel which are labelled 1 through 9 and which are grouped in two groups (switch numbers 1-7 on the left side and 8-9 on the right side).

The left side group contains the ACSS configuration switches. The up position of these switches takes a particular variable or function out of the simulation whereas the down position puts them in. Switch No. 1 is a spare; switch No. 2 controls the presence/absence of δ_{h_α} in the simulation; switch No. 3 controls the aileron to rudder interconnect; switch No. 5 controls the rudder pedal to differential tail interconnect; switch No. 6 controls the rudder pedal to aileron interconnect; switch No. 7 controls the roll stick to rudder interconnect; and, switch No. 4 controls the priority under which the differential tail deflections get generated. For switch No. 4 the up position sets the system into roll priority whereas the down position sets the system into pitch priority.

The right side group controls the source of α feedback into the simulation. Switch No. 8 connects the simulation to a zero voltage level (α_0) in

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* α_{COND} is the signal resulting from adjustments in the slope and offset of the α_{FB} signal.

the up position and to the normal α source (α_{FB}) in the down position and switch No. 9 does a similar selection but between a calibration value of α (α_{CAL}) in the up position and the normal α source (α_{FB}) in the down position.

The internal layout of the ACSS can also be seen in Figure 3-1. The right hand side is occupied, from back to front, by a DC power supply, a relay board, and a digital voltmeter. The left hand side is occupied by a hinged panel to which the circuit cards (modules) that realize the analog simulation are screwed.

The ± 15 VDC power supply provides the simulation with a local source of regulated DC voltage. A companion attenuator board contains circuitry that provide other DC voltage levels (-10, +3, and -1) which are useful in the simulation.

The relay board contains eight relays. Seven of these relays are activated by the spin mode signal generated by a ψ magnitude and duration detector in the interface box. The spin mode relays control the operation of the spin mode switches throughout the simulation. The other relay is activated by the α_{SEL} signal provided by the pilot. This relay controls the operation of the switch that connects the simulation to either α_{FB} or α_{CAL}.

The digital voltmeter (DVM) provides the ACSS with a self-contained capability to measure voltage levels throughout the simulation. It is included to facilitate system troubleshooting and parameter setting.

The hinged panel has in its underside the sixteen (16) cards in which the simulation of the F-18 drop-model control laws is realized. The discrete elements (operational amplifiers, multipliers, resistors, capacitors, et al.) in each card are hardwired. The interconnections between cards are also hardwired. Associated with each card of the simulation, there is a set of clearly identified potentiometers, test points, and switches on the hinged panel which in conjunction with the DVM greatly facilitate system testing and the setting of parameter values. Besides the fact that there is sufficient spacing between cards to allow access to circuit points not available on the hinged panel, each card is removable from the hinged panel by simply breaking the electrical connections with associated card(s) and unscrewing it from the hinged panel.

The realization of the simulation for the F-18 drop-model control laws is shown in detail in the block diagrams of Figures 3-2, 3-3 and 3-4. The Figure 3-2 shows the realization of the pitch and differential tail channels; the Figure 3-3 shows the realization of the roll channel; and the Figure 3-4 shows the realization of the yaw channel.

The pitch, differential tail, and roll channels are incorporated in nine (9) cards (P-1, P-2, P-3, P-3A,....., P-8). The yaw channel is incorporated in seven (7) cards (Y-1, Y-2, ..., Y-7). The functional assignment(s) to each card is clearly shown in the three figures. There is an additional card, not included in the chassis, which plugs into the δ_{S_R} and δ_{S_L} BNC connectors of the front panel to calculate the average (δ_h) and differential (δ_d) horizontal tail deflections. This card is to be used during system development tests only.

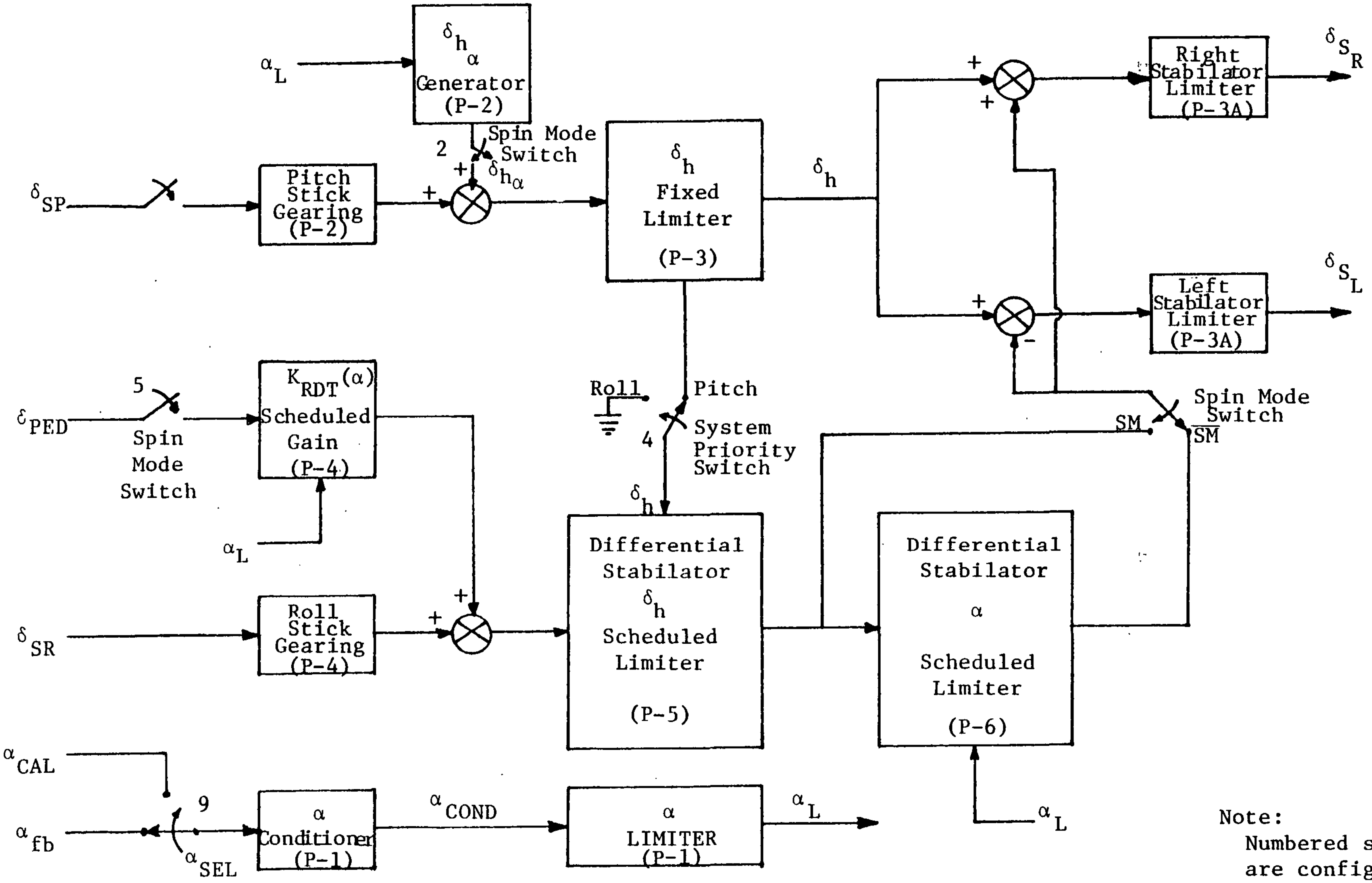
All switches used in the simulation are also identified and classified in these figures (see Table 2-2 of section 2.1.2 for a comparison with the switches defined in the original block diagram). The number next to the configuration switches correspond to the number of the particular switch on the front panel. Note that switch No. 2, controlling δ_{h_α}, is both a configuration switch and a spin mode switch. Also note that besides switch No. 2 none of the spin mode switches are available on the front panel.

It should be noted that although the ACSS has been realized with a modal capability (based on the spin-mode relay controlled switches), there are no plans at the present time to use this capability. Instead, the detection of a spin condition will switch-out the ACSS (disconnect its inputs to the interface box) and go into a direct mode through the interface box.

3.4 System Integration and Performance

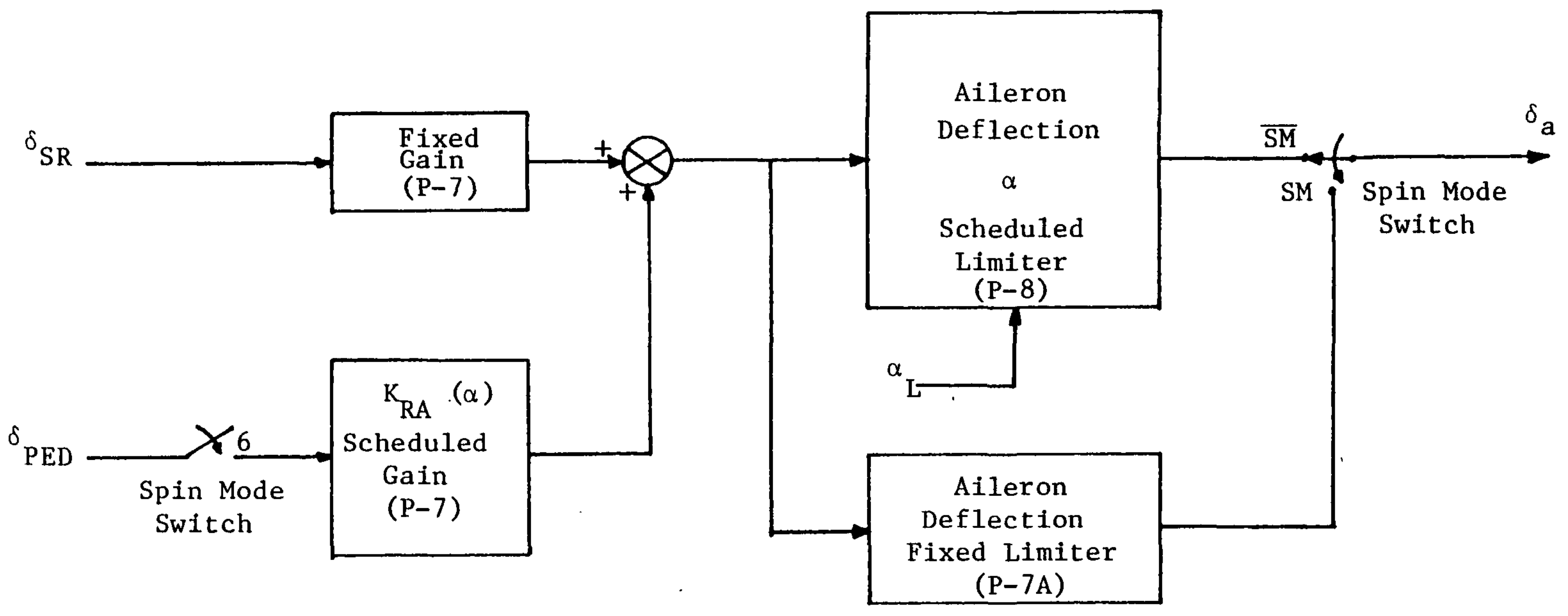
The ACSS was designed, fabricated, and validated at RTI over a period of twelve months. Tests were conducted at every step of the fabrication process to ensure the correctness and accuracy of the design.

First, each realization of the elementary functions was tested and its performance was documented. Next, simular tests were conducted for each card in a stand alone configuration. Next, each channel of the control laws was tested in the various configurations that each one of them could take. Finally, the entire system was subjected to a series of I/O tests for the



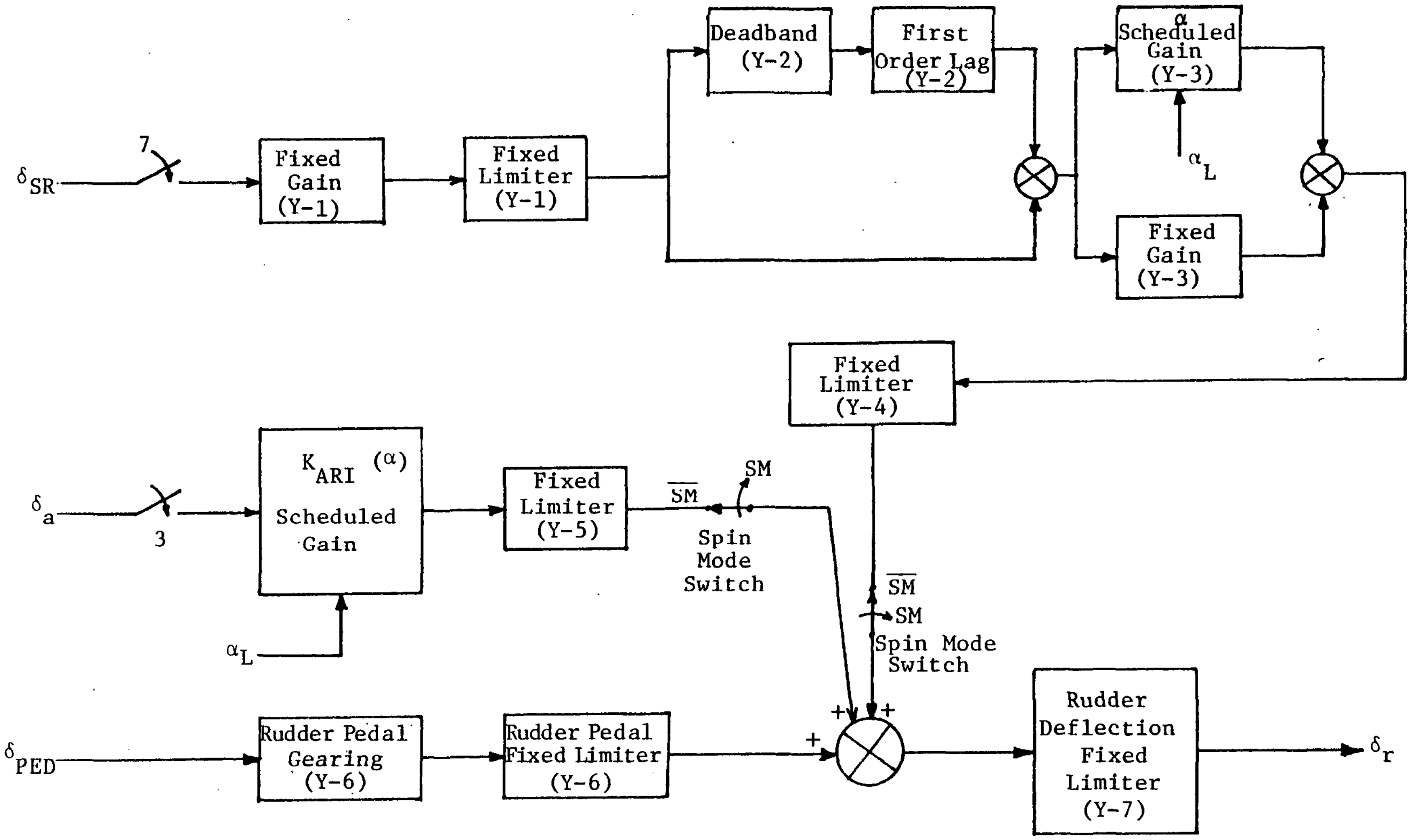
Note:
Numbered switches
are configuration
switches.

Figure 3-2. Block diagram of the F-18 drop-model ACSS (pitch and differential tail channels).



Note:
Numbered switches
are configuration
switches.

Figure 3-3. Block diagram of the F-18 drop-model ACSS (roll channel).



Note: Numbered switches are configuration switches.

Fibure 3-4. Block diagram of the F-18 drop-model ACSS (yaw channel).

purpose of verifying the compliance of the ACSS operation with the established needs of the real time application. All of the above tests certified the proper operation of the ACSS in a stand-alone, laboratory environment.

The analog CSS was then transferred to NASA-LRC where it was integrated with the drop model instrumentation van (NASA trailer NA1044) that supports the stall/spin research facility. The system took its place in one of the relay racks existing in the instrumentation van (immediately below the interface box). A block diagram of the F-18 drop-model ACSS integrated with the drop-model, stall/spin research facility is presented in Figure 3-5.

A more detailed description of the interactions between the ACSS and the instruments of the instrumentation van is illustrated in Figure 3-6. This configuration is basically similar to that of the integration of the digital CSS. There is an input cable that carries the pilot inputs (δ_{SP}, δ_{SR}, and δ_{PED}) and the spin mode signal from the interface box to the ACSS. There is also an output cable that carries the outputs of the simulation (δ_{S_R}, δ_{S_L}, δ_a, and δ_r) from the ACSS to the interface box. There are three other individual inputs to the ACSS: α_{SEL}, α_{FB}, and α_{CAL}. The $\dot{\psi}$ and AGC (RF_Q in the figure) signals are fed from the downlink telemetry to the interface box where they are used to monitor the system for the existence of a spin and a downlink dropout respectively. Note that the ACSS does not require synchronization with the interface box (the uplink telemetry encoder) as in the case of the digital CSS.

Once integrated with the instrumentation van, the analog CSS was subjected to a series of acceptance tests to determine the characteristics of its operation in its true operational environment. The tests defined in Table 2-3 of section 2.3 were run with the ACSS in the loop. The results certified the correct operation of the ACSS for the F-18 drop-model control laws.

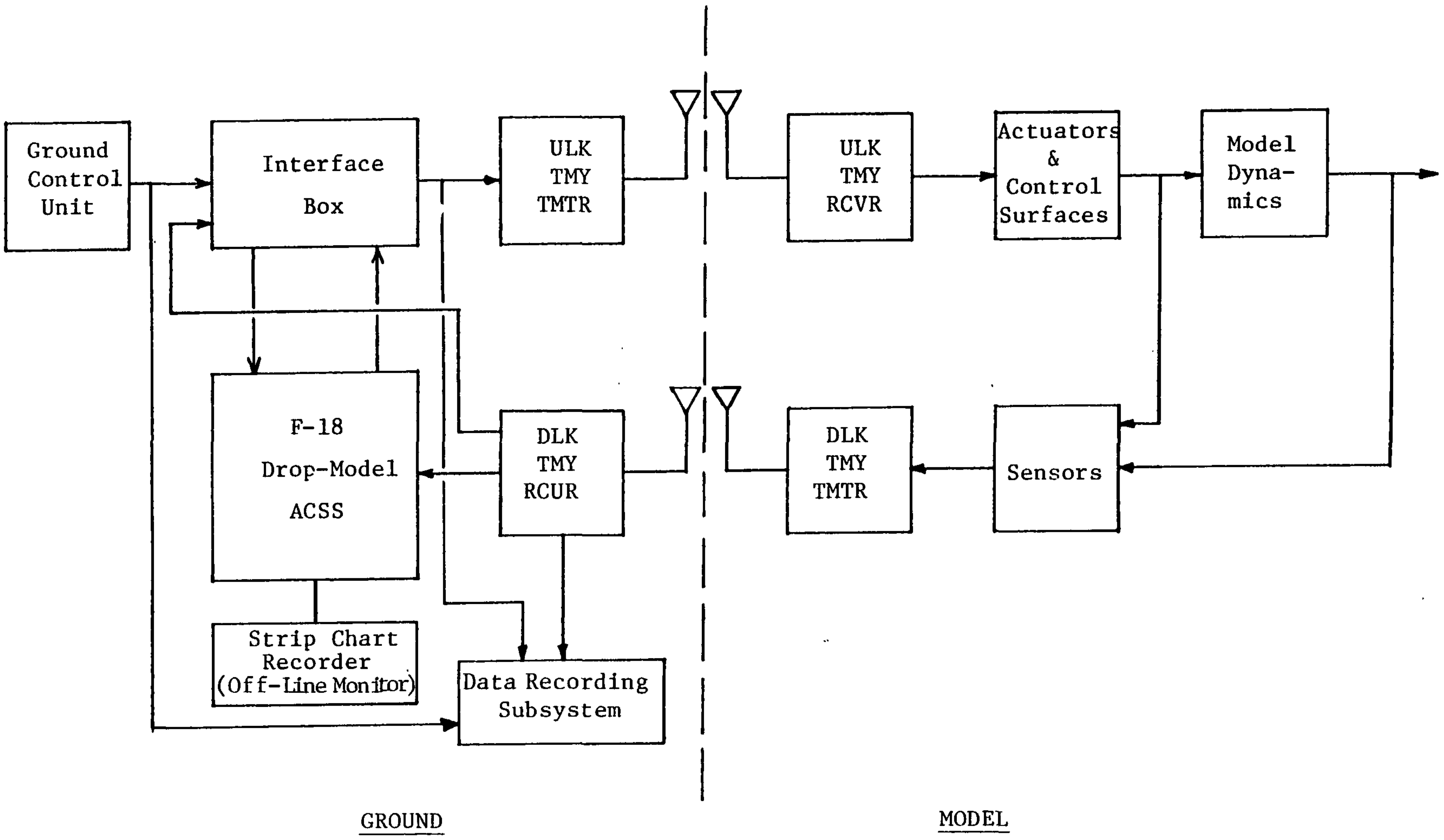


Figure 3-5. Block diagram of the drop-model, stall/spin research facility with the F-18 drop-model ACSS.

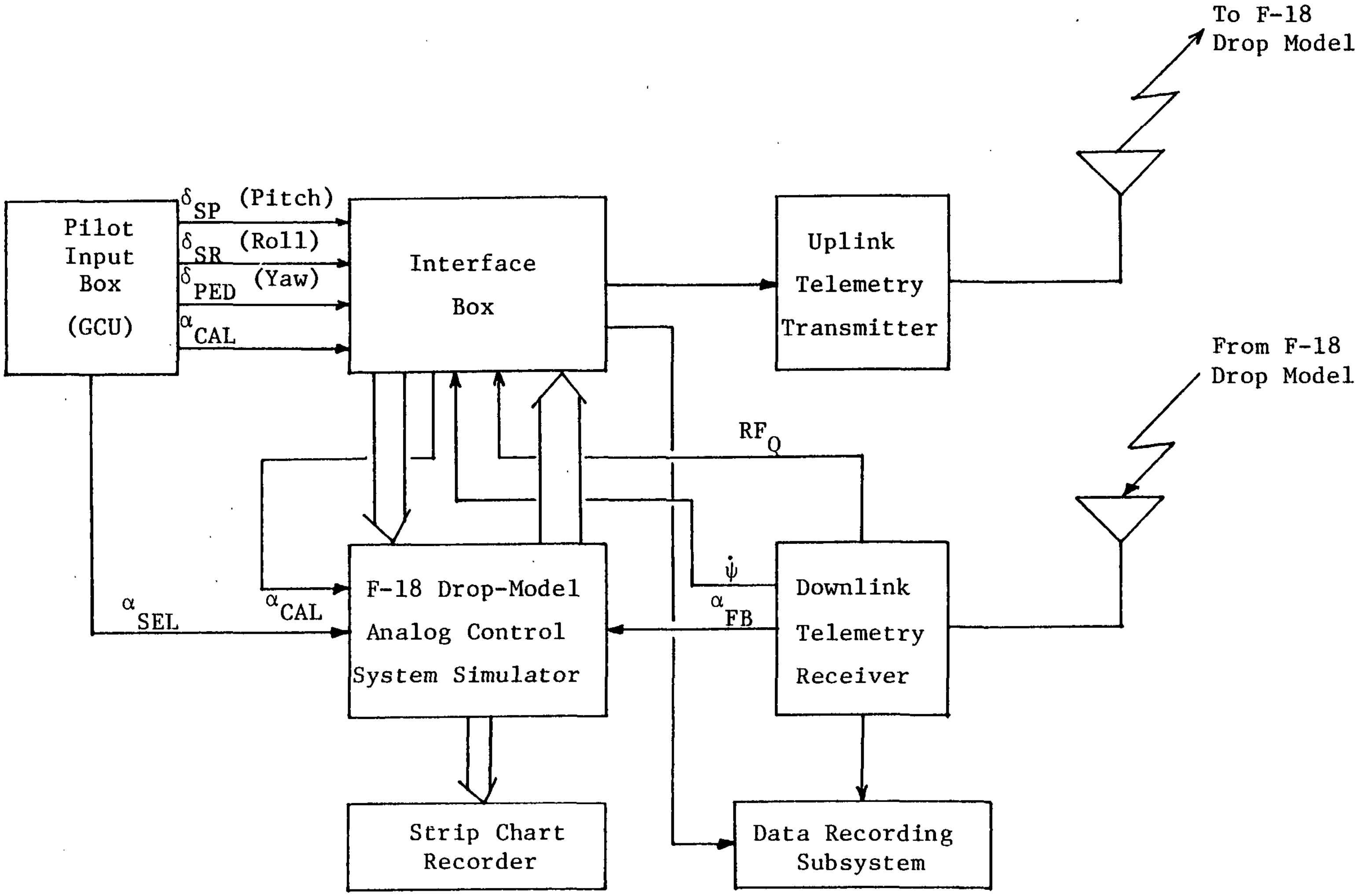


Figure 3-6. Block diagram of the upgraded stall/spin research facility configured to support the F-18 drop-model tests (ACSS).

4.0 STATUS OF THE DROP-MODEL, STALL/SPIN RESEARCH FACILITY

As a result of the work performed under this contract and other related efforts conducted at NASA-LRC by FID personnel with some collaboration from RTI, the capabilities and operational quality of the drop-model, stall/spin research facility has been greatly enhanced. The tasks described in this report have yielded a partially upgraded facility (with respect to the complete set of recommendations given in reference 1) that has a ground-based, programmable, digital control system simulator; a command telemetry link with higher resolution and greater accuracy; a data telemetry link with improved characteristics; capabilities for the on-line monitoring of overall system performance; and the capability for the automatic bypass of the control system simulator as a function of the results of the monitoring tests. The facility also has an operationally-ready, dedicated, F-18 drop-model analog control system simulator to back up the digital control system simulator during the F-18 drop-model program.

The digital CSS gives the facility a powerful and flexible capability of simulating sophisticated control laws which are becoming typical of advanced high performance aircraft. It does this by providing the user with a library of control law modules from which a particular control law can be easily configured.

4.1 Additional Capabilities

The work performed by FID personnel will be documented by them in the near future. The most important aspect of this work has been the upgrading of the FM/FM up and down telemetry links. Other efforts have been directed toward the modification of the command PPM encoder; the design, fabrication, and installation of the $\dot{\psi}$ and AGC magnitude detector and timer; and the design, fabrication, and installation of the automatic CSS bypass circuit.

The uplink telemetry is now an L-band (18.045 MHz) system with its transmitter antenna mounted on a flat plate on the tracker of the ground control unit. The transmitter antenna is actually an array of discrete elements with a variety of phase polarization schemes available.

The downlink telemetry is now an L-band (14.956 MHz) system with a transmitter power adjustable from 2 to 5 watts. The transmitter antenna is made up of an array of discrete elements mounted on a PC board arranged to produce a vertically polarized signal pattern. There are fifteen (15) individual channels plus one channel available for frequency multiplexing. The receiver antenna is colocated with the uplink transmitter antenna on the tracker of the ground control unit.

Performance tests on both telemetry links have not been performed yet but preliminary tests have indicated substantial improvements over the performance of the previous configuration. The results of the performance tests will be included in the system documentation referred to above.

The PPM uplink encoder was modified to increase its resolution from 8 bits to 12 bits. The modification consisted essentially of the substitution of the 8-bit A/D converter by a 12-bit A/D converter and the substitution of the 2.25 MHz crystal oscillator (clock) by a 4.5 MHz crystal oscillator. The encoder was also modified to operate in one of two possible synchronization schemes depending on the setting of a manual switch located in the interface box. In the internal sync position of this switch, the encoder operation is controlled by a digital CSS-generated synchronization pulse whereas in the external sync position of this switch, the encoder operates under the control of its own clock.

The modifications to the uplink encoder board are summarized in Figure 4-1. Note that the manually controlled switch is also controlled by a relay which will change the switch position from internal to external in the event of a transition in system operation from the digital CSS mode to bypass mode.

The yaw rate ($\dot{\psi}$) magnitude detector and timer is a special purpose circuitry that detects the entry into or recovery from a spin by the model being tested. The spin mode detector was incorporated into the interface box of the instrumentation van specifically to support the operation of the system with the F-18 drop-model ACSS in the loop since the digital CSS has its own software-based spin mode detector. When a spin entry condition is detected, the output of the spin mode detector activates a bank of relays in the interface box that switch the ACSS out of the loop and places the interface box in the direct mode. Also under a spin entry condition, the output of the spin mode detector activates the spin mode relays of the ACSS which are responsible for switching the simulated control laws from normal mode to spin mode. The output of the spin mode detector has the reverse

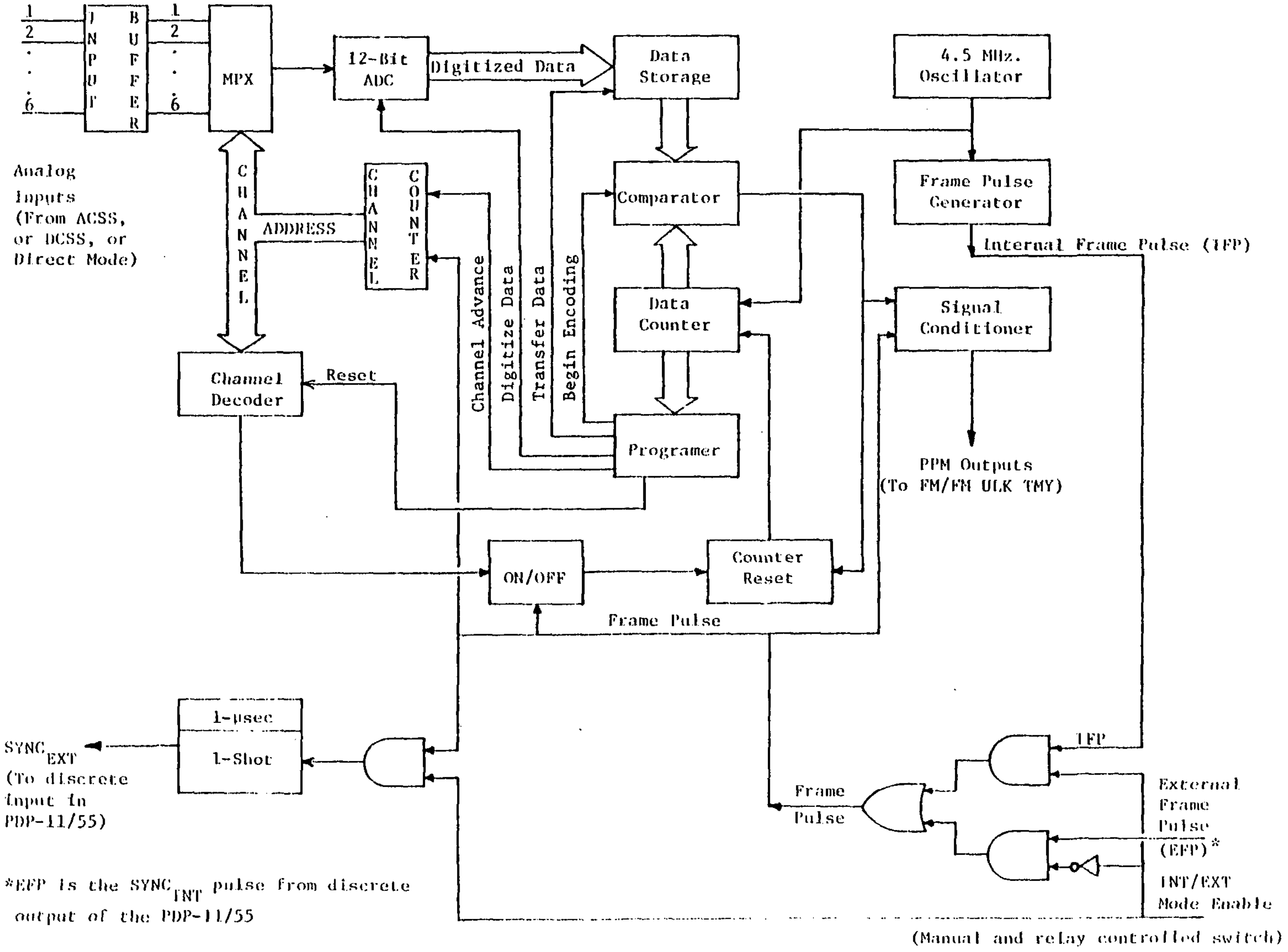


Figure 4-1. Modified uplink PPM encoder block diagram.

effect on both accounts when a spin recovery is detected.

A block diagram of the implementation of the spin mode detector is presented in Figure 4-2. The detector essentially consists of two branches, one to detect the spin entry conditions and the other to detect the spin recovery condition.

The spin entry branch consists of a comparator that detects when $|\dot{\psi}|$ exceeds a preset value (87.5 °/sec at the present time) and a timer (an integrator-comparator combination) that detects when $|\dot{\psi}|$ has exceeded the threshold magnitude for more than a preset amount of time (2 seconds at the present time). When both of these conditions are met, the output of the spin entry branch goes high and activates the bank of relays that switch the ACSS out of the loop.

The spin recovery branch basically consists of the same arrangements of building blocks. The magnitude comparator detects when $|\dot{\psi}|$ is less than a preset value (37.5 °/sec at the present time) and the timer detects when $|\dot{\psi}|$ has been below this threshold magnitude for more than a preset amount of time (2 seconds at the present time). When both of these conditions are met, the output of the spin entry goes high and its inverted version deactivates the bank of relays which in turn switch the ACSS back into the loop.

It should be noted that the output of the spin mode detector is also routed to the ACSS as the spin mode signal that activates the spin-mode relays in the ACSS. These relays, it will be recalled, operate the spin-mode switches of the ACSS which are responsible for switching the simulated control laws from the normal mode to the spin mode. This modal capability of the ACSS is an option which at the present time is not going to be used. If, however, this option is ever used, provisions must be made at the interface box to disable the effect of the spin mode detector output on the bank of relays that switch the ACSS out of the loop.

The downlink telemetry dropout detector was also incorporated in the interface box of the instrumentation van to support the operation of the system with the ACSS in the loop since the digital CSS has its own software-based downlink dropout detector. However, as shown in the block diagram of Figure 4-3, this hardware detector in the interface box is essential to the operation of the software-based detector of the digital CSS.

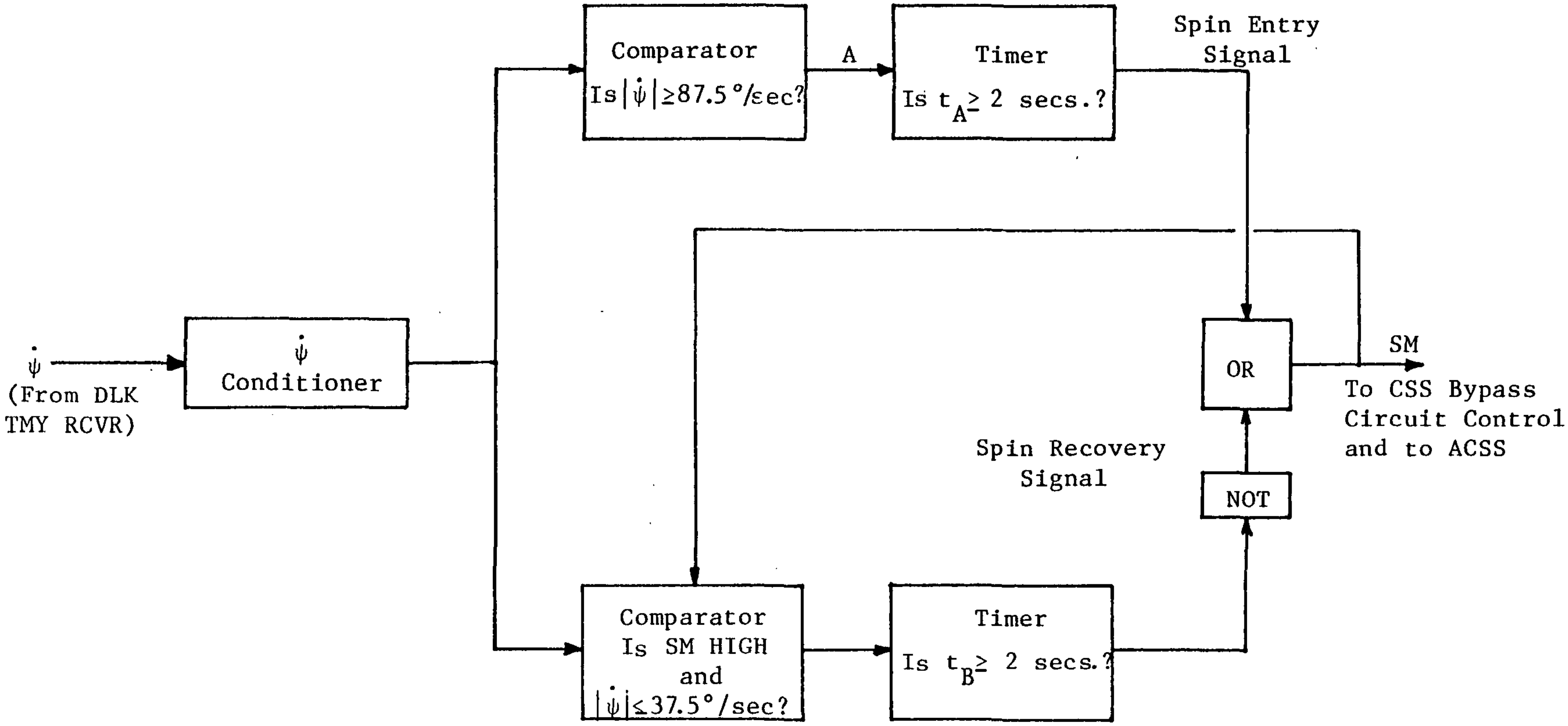
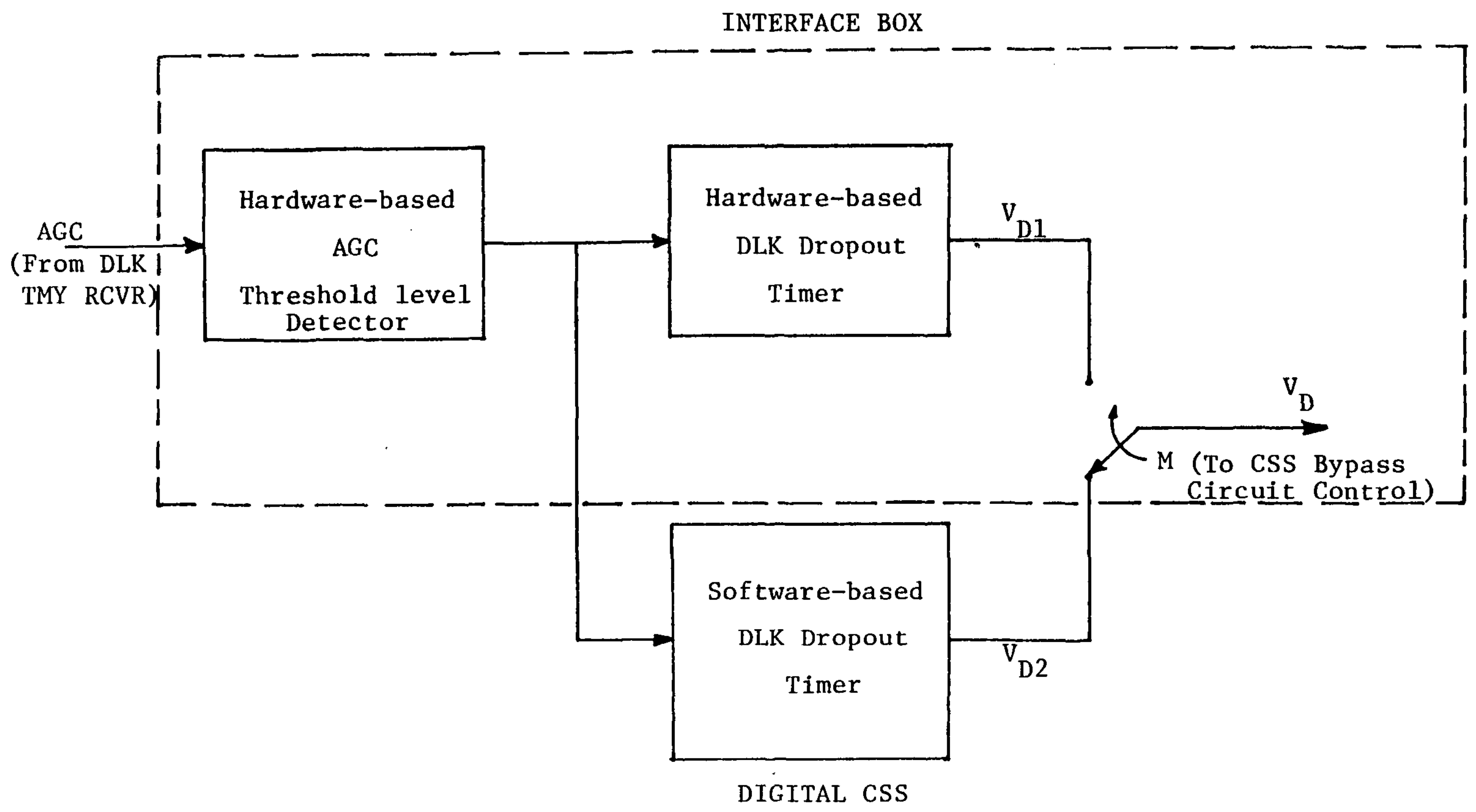


Figure 4-2. Block diagram of the spin mode detector.



Note: M is manual control.

Figure 4-3. Block diagram of the downlink telemetry dropout detectors of the facility.

The hardware-based downlink telemetry detector consists of a threshold level detector which monitors the level of the AGC voltage from the downlink telemetry receiver. The level detector outputs a TTL-compatible level as soon as and for as long as the AGC voltage exceeds a preset level (presently set at -8 volts). The output of the threshold detector feeds into a hardware dropout timer in the interface box and also into a software-based dropout timer (via a discrete input of the digital computer) in the digital CSS.

The hardware dropout timer detects when the excedence of the threshold level has existed for more than a preset amount of time (presently set at 500 msec). When this condition exists, the output of the timer goes high indicating that a downlink dropout has existed for a period of time which is longer than a specified tolerable downlink dropout period. If, in addition, the manually operated switch of Figure 4-3 is set to position A, the output of the timer activates the bank of relays that switch the ACSS out of the loop.

The software-based dropout timer operates identically to the hardware dropout timer. When the switch in Figure 4-3 is set to the D position, the output of the software-based dropout timer controls (via the bank of relays in the interface box) whether or not the digital CSS is switched out of the loop.

There is, however, one important difference between the operation of the two downlink dropout detectors. When the ACSS is in the loop, recovery from an excesively long downlink dropout can switch the ACSS back into the loop (the bank of relays are deactivated). When the digital CSS is in the loop, recovery from an excessively long downlink dropout does not switch the digital CSS back into the loop. This is so because once the output of the software-based detector goes high, it remains high regardless of the condition of its input. This implementation is the result of a decision to stay in the direct mode once an excessively long dropout has been detected while operating with the digital CSS in the loop.

The automatic CSS bypass circuit was incorporated in the interface box of the instrumentation van to provide the capability of disconnecting automatically either of the CSS's being used in a particular test and going into a direct mode. The direct mode of operation is one in which the pilot inputs (δ_{SP}, δ_{SR}, and δ_{PED}) are passed on to the uplink telemetry encoder directly through an open loop control law similar to the spin-mode control law of the CSS's, i.e., one in which all functions of α are eliminated.

The Figure 4-4 provides a graphical description of the operation of this circuit. The select switch actually represents a set of switches each one of which is allocated to an individual output. The position of these switches are automatically controlled by the condition of a bank of relays (also shown in the figure). These relays are opened or closed as a function of the results of a number of system performance monitoring tests. The select switches are manually overridden by a mode selector switch already existing in the front panel of the interface box.

The system conditions that activate the bank of relays to cause the system to go into the direct mode are a spin mode entry and an excessively long downlink dropout (V_{D1} or V_{D2} in Figure 4-3). There are other inputs that control these relays. These come from a pilot switch located in the ground control unit and a test switch located in the instrumentation van.

4.2 Latest Version of the F-18 Drop-Model Flight Control System

The flight control system* (FCS) of the F-18 drop-model has undergone a substantial evolution during the performance of the work described in this report. The modifications to the FCS that marked this evolution were incorporated into the digital and analog CSS's as the work progressed and, consequently, the analog and digital CSS's delivered to LRC contained the latest version of the FCS, "REV C", that had been defined at that time.

Since the conclusion of the work described in this report up to this point, the manufacturer of the F-18 aircraft has made extensive additions and modifications to the flight control system. These changes have a direct impact on the NASA/LRC F-18 drop-model program and, because of the complexity of the changes and the schedule under which NASA/LRC is operating in this program, RTI has been asked to incorporate the latest version of the F-18 drop-model FCS (referred to as "REV D") into both the analog and digital CSS's.

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*In this report the terms control laws and flight control system are used interchangeably.

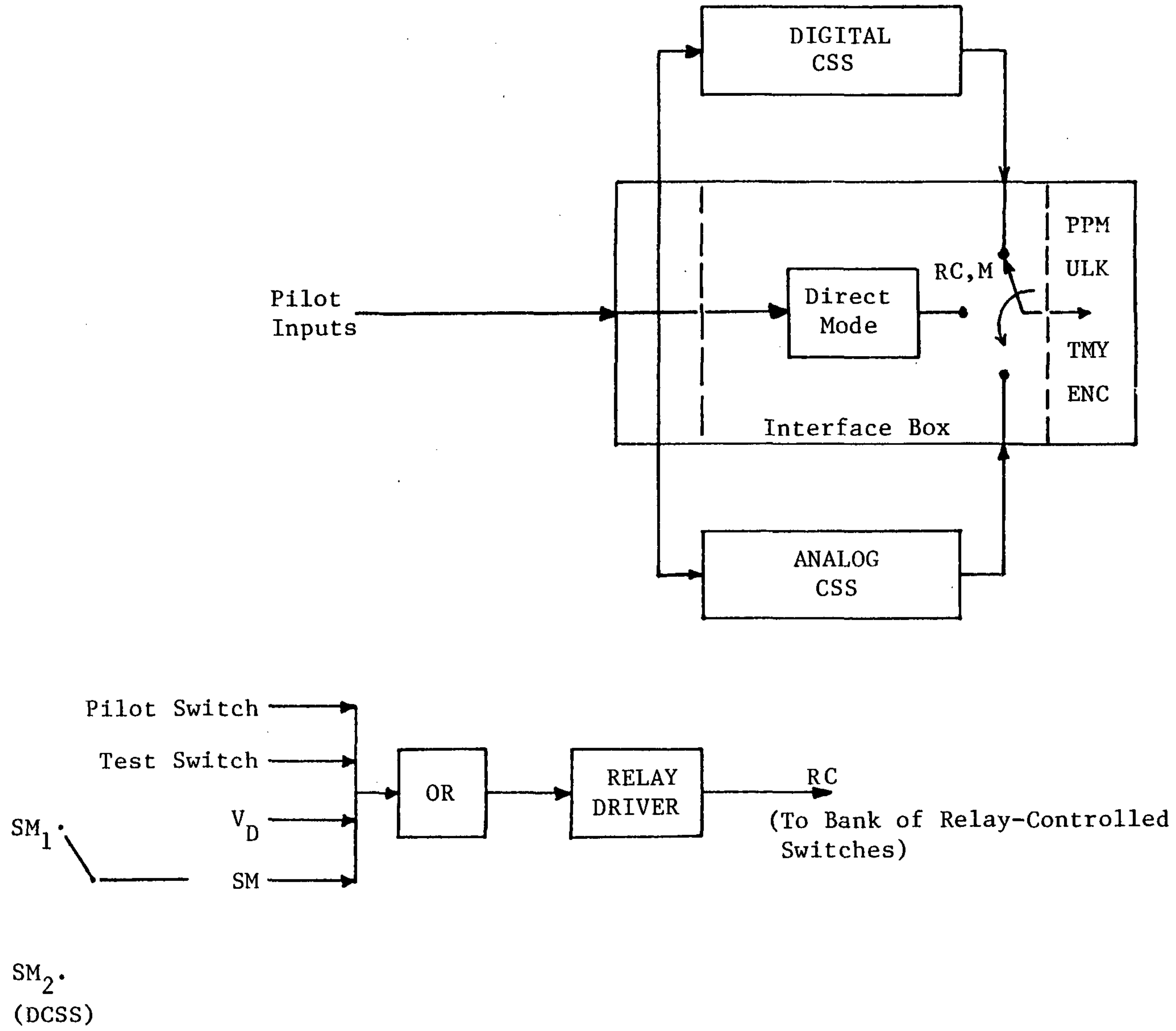


Figure 4-4. Block diagram of automatic CSS bypass circuit.

Notes:
RC, relay control
M, manual control

The latest version of the F-18 drop-model FCS (or control laws) is described in the block diagrams of Figures 4-5 and 4-6. Figure 4-5 describes the pitch and roll channels whereas Figure 4-6 describes the yaw channel. Table 4-1 provides a definition of the symbols used in REV D of the F-18 drop-model FCS. A comparison of Figures 4-5 and 4-6 with Figures 2-3a and 2-3b, respectively shows that the changes leading to REV D impact on all three channels of the F-18 drop-model FCS. Table 4-1 is simply an enhancement of Table 2-1 to incorporate the new symbols used in REV D.

REV D of the F-18 drop-model control laws calls for additional modules to provide a gain-scheduled (versus α), washout path for pitch rate (q) to affect stabilator deflections; an authority limit for the outputs of the new αq limiter system; an authority limit for the differential stabilator signals in the spin mode; and an α-scheduled gain in the rudder pedal to rudder path. It is also necessary to incorporate substantial modifications to existing scheduled and fixed gains.

The upgraded F-18 drop-model control laws (REV D) will be fully incorporated into the digital CSS. On the other hand, only a subset of the changes leading from REV C to REV D will be incorporated in the analog CSS. This compromise in the analog CSS is the result of its limited expansion capability.

The changes needed to update the control laws in the digital and analog CSS's are described below. The details of the implementation of REV D in the digital CSS are documented in an addendum to the digital CSS documentation. The details of the implementation of the compromise form of REV D in the analog CSS are documented in an addendum to the analog CSS documentation.

4.2.1 Digital CSS version. - The additions and modifications needed to upgrade the existing version (REV C) of the control laws into the latest version (REV D) of the control laws in the digital CSS are as follows:

Pitch channel:

1. Add a washout, α-scheduled path for a pitch rate (q) limiter on stabilator deflection.
2. Modify the breakpoints and maximum gain value of the angle of attack (α)-limiter function generator.
3. Add an authority limit to the resultant αq limiter system.
4. Modify stick to stabilator gearing ($K_{\delta_{SP}}$).

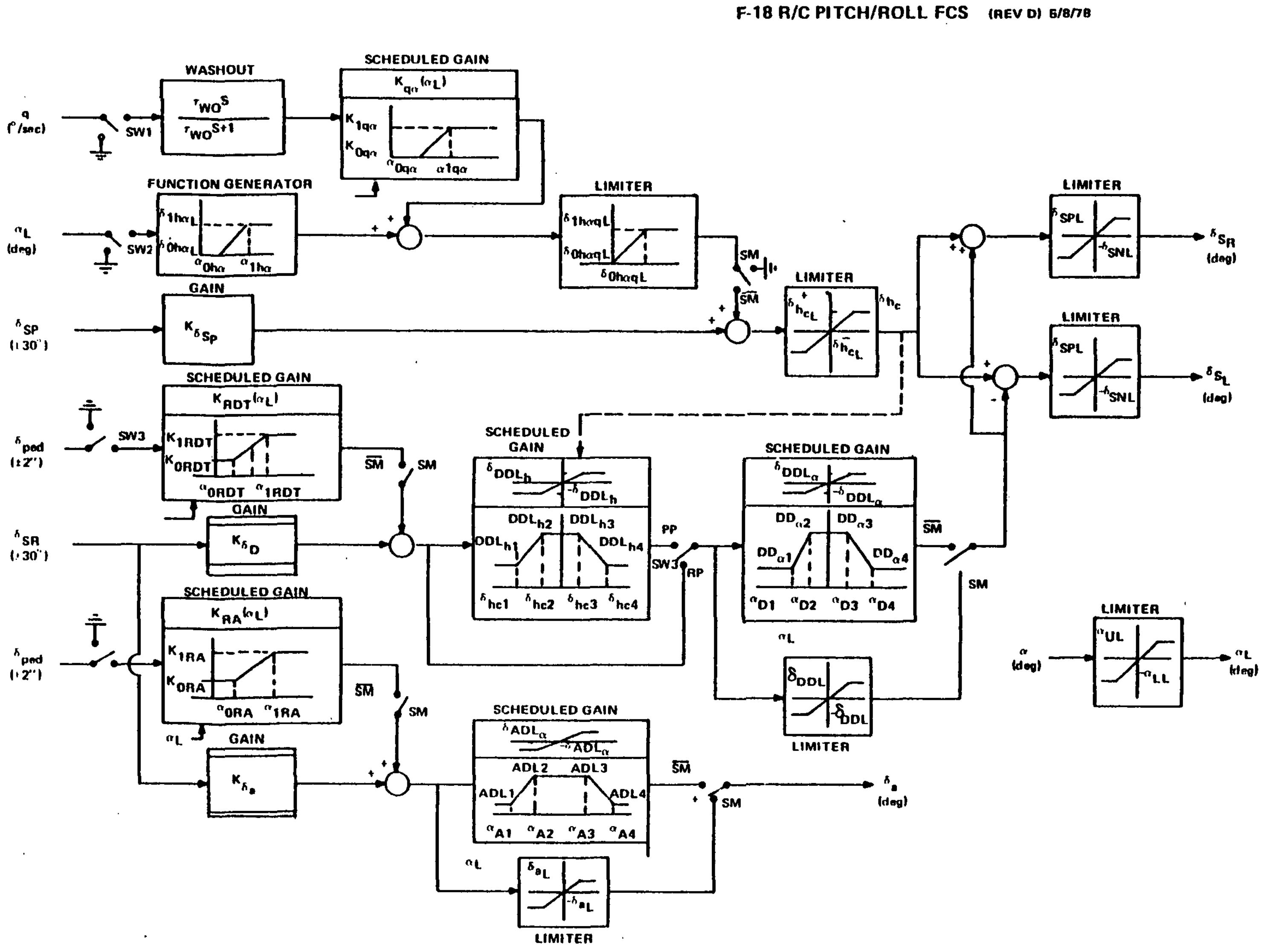


Figure 4-5. Pitch and roll channels of REV D of the F-18 drop model control laws.

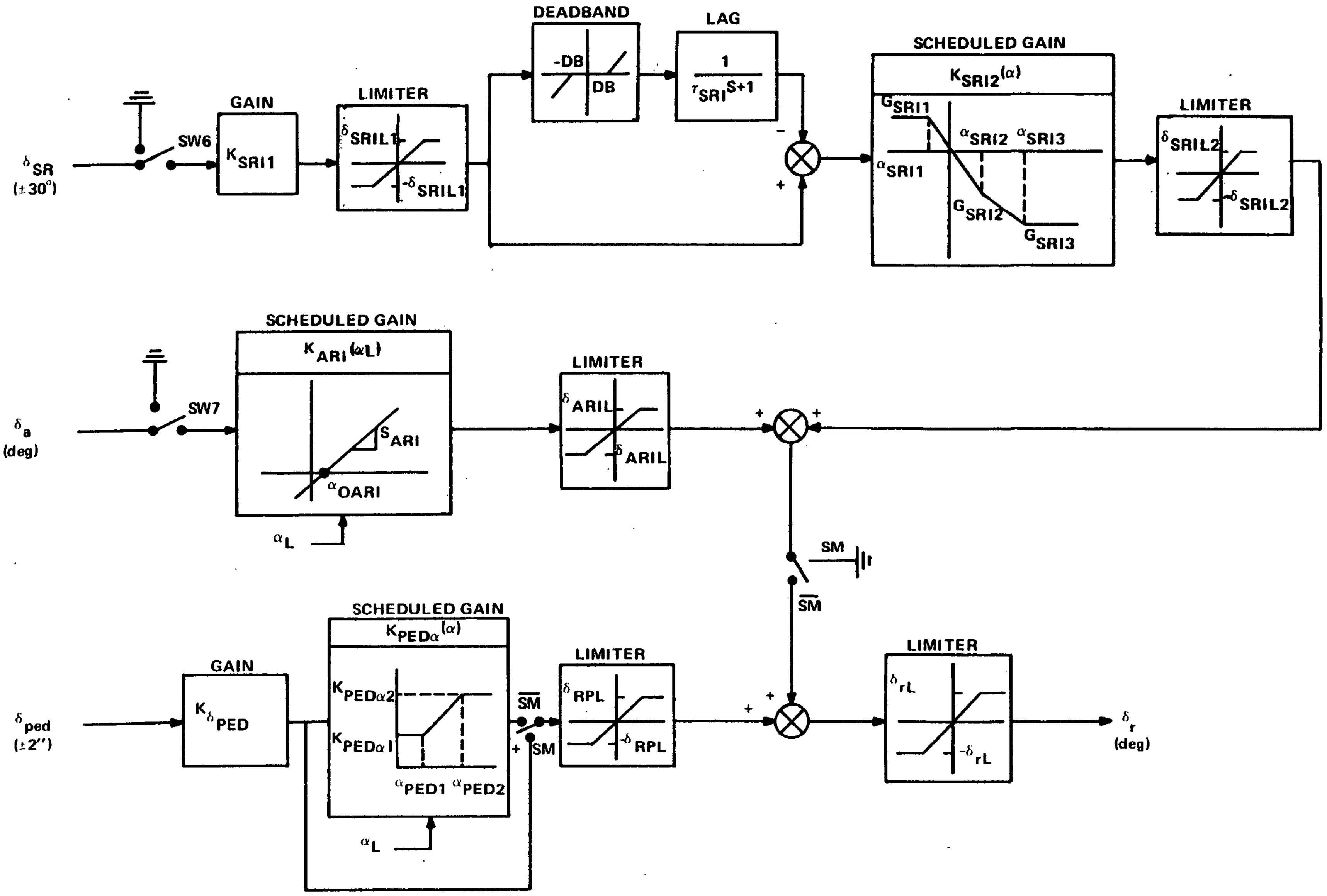


Figure 4-6. Yaw channel of REV D of the F-18 drop-model control laws.

Table 4-1. DEFINITION OF SYMBOLS USED IN THE F-18 CONTROL LAWS (REV-D).

SYMBOL	UNITS	DEFINITION
δ_{SP}	deg.	pitch stick deflection, positive for aft deflection.
δ_{SR}	deg.	roll stick deflection, positive for right deflection.
δ_{PED}	in.	pedal deflection, positive for right pedal down.
α_{FB}	deg.	measured angle of attack
α_{CAL}	deg.	calibrated angle of attack
$\dot{\Psi}$	deg./sec.	measured yaw rate
q	deg./sec.	measured pitch rate
δ_{S_R}	deg.	right stabilator deflection, positive for trailing edge down.
δ_{S_L}	deg.	left stabilator deflection, positive for trailing edge down.
δ_a	deg.	aileron deflection, positive for left roll (right aileron down).
δ_r	deg.	rudder deflection, positive for trailing edge left.
δ_h	deg.	symmetric stabilator deflection.
δ_D	deg.	differential stabilator deflection.
r_{ASM}	deg./sec.	yaw rate limit to activate spin mode.
r_{DSM}	deg./sec.	yaw rate limit to deactivate spin mode.
Δt_{ASM}	sec.	time lag to activate spin mode.
Δt_{DSM}	sec.	time lag to deactivate spin mode.
α_{UL}	deg.	upper limit for measured alpha limiter
α_{LL}	deg.	lower limit for measured alpha limiter
α_L	deg.	limited measured angle of attack

Table 4-1. CONTINUED.

SYMBOL	UNITS	DEFINITION
τ_{WO}	sec.	pitch rate washout time constant
$K_{q\alpha}(\alpha_L)$	sec.	α-scheduled pitch rate gain
$\alpha_{iq\alpha}$	deg.	breakpoints for pitch rate gain
$K_{iq\alpha}$	sec.	breakpoint values of $K_{q\alpha}$
δ_{hq}	deg.	q-generated stabilator deflection input
$\delta_{h\alpha}$	deg.	α-generated stabilator deflection input
$\alpha_{ih\alpha}$	deg.	breakpoints for the α-scheduled stabilator input generator
$\delta_{ih\alpha}$	deg.	breakpoint values of $\delta_{h\alpha}$
$\delta_{h\alpha q}$	deg.	αq system output authority limit
$\delta_{ih\alpha qL}$	deg.	breakpoint values of $\delta_{h\alpha q}$
$K_{\delta_{SP}}$	deg./deg.	pitch stick to stabilator gearing
δ^+_{hcL} δ^-_{hcL}	deg.	positive and negative symmetric stabilator command limits
δ_{hc}	deg.	symmetric stabilator deflection command
$K_{RDT}(\alpha_L)$	deg./in.	α-scheduled rudder to differential tail (RDT) interconnect gain
α_{iRDT}	deg.	breakpoints for the RDT gain
K_{iRDT}	deg./in.	breakpoints values for K_{RDT}
K_{δ_D}	deg./deg.	roll stick to differential stabilator gearing
$\delta_{DDL_{h_c}}$	deg.	differential stabilator deflection limit scheduled as a function of symmetric stabilator deflection command
$\delta_{h_{ci}}$	deg.	breakpoints for $\delta_{DDL_{hc}}$
$DDL_{h_{ci}}$	deg.	breakpoint values of $\delta_{DDL_{hc}}$

Table 4-1. CONTINUED.

SYMBOL	UNITS	DEFINITION
δ_{DDL_α}	deg.	α-scheduled differential stabilator deflection limit
α_{Di}	deg.	breakpoints for δ_{DDL_α}
DDL_{α_i}	deg.	breakpoint values of δ_{DDL_α}
δ_{DDL}	deg.	differential stabilator deflection limit (in SM)
δ_{SPL}	deg.	positive stabilator deflection limit.
δ_{SNL}	deg.	negative stabilator deflection limit.
$K_{RA}(\alpha_L)$	deg./in.	α-scheduled rudder to aileron interconnect gain
α_{iRA}	deg.	breakpoints for K_{RA}
K_{iRA}	deg./in.	breakpoint values of K_{RA}
K_{δ_a}	deg./deg.	roll stick to aileron gearing
δ_{ADL_α}	deg.	α-scheduled aileron deflection limit
α_{A_i}	deg.	breakpoints for δ_{ADL_α}
ADL_i	deg.	breakpoint values of δ_{ADL_α}
δ_{aL}	deg.	aileron deflection limit (in SM)
K_{SRI_1}	deg./deg.	roll stick to rudder (SRI) gain
δ_{SRIL_1}	deg.	roll stick to rudder (SRI) signal limit
DB	deg.	SRI deadband
τ_{SRI}	deg.	SRI lag time constant
$K_{SRI_2}(\alpha_L)$	deg./deg.	α-scheduled SRI gain
α_{SRI_i}	deg.	breakpoints for K_{SRI_2}
G_{SRI_i}	deg./deg.	breakpoint values for K_{SRI_2}

Table 4-1. CONCLUDED.

SYMBOL	UNITS	DEFINITION
δ_{SRIL_2}	deg.	SRI output authority limit
K_{ARI}	deg./deg.	α-scheduled aileron to rudder interconnect (ARI)
S_{ARI}	deg./deg.	slope of K_{ARI} function
$\alpha_{0_{ARI}}$	deg.	α bias in K_{ARI} gain schedule
δ_{ARIL}	deg.	ARI authority limit
$K_{\delta_{PED}}$	deg./in.	pedal deflection to rudder gearing
$K_{PED_\alpha}(\alpha_L)$	deg./deg.	α-scheduled rudder command gain
α_{PED_i}	deg.	breakpoints for K_{PED_α}
$K_{PED_{\alpha i}}$	deg./deg.	breakpoint values for K_{PED_α}
δ_{RPL}	deg.	pilot rudder authority limit
δ_{r_L}	deg.	rudder deflection limit

Roll Channel:

1. Modify stick to differential stabilator (δ_D) gearing (K_{δ_D}) and stick to aileron gearing (K_{δ_a}).

2. Modify the form and break points of the gain-scheduled (versus α) limiters in the differential stabilator and aileron paths.

3. Modify the break points of the α-scheduled gains in the rudder pedal to δ_D and δ_a paths.

4. Add authority limit to the differential stabilator in the spin mode (SM).

Yaw Channel

1. Modify rudder pedal to rudder gearing ($K_{\delta_{PED}}$).

2. Add α-scheduled gain into rudder pedal to rudder path (K_{PED_α}).

3. Modify SRI gain (K_{SRI_1}).

4. Eliminate the static SRI gain (K_{SRI_2}).

5. Modify the form and break points of the α-scheduled SRI gain (K_{SRI_3}).

6. Modify the SRI output authority limit (S_{SRIL_2}).

4.2.2 Analog CSS version - The additions and modifications needed to upgrade the existing version (REV C) of the control laws into the compromise version of REV D in the analog CSS are as follows:

Pitch Channel:

No change from present configuration

Roll Channel:

1. Modify stick to differential stabilator (δ_D) gearing (K_{δ_D}) and stick to aileron gearing (K_{δ_a}).

2. Modify the break points of the gain-scheduled (versus α) limiters in the differential stabilator and aileron paths.

3. Modify the break points of the α-scheduled gains in the rudder pedal to δ_D and δ_a paths.

Yaw Channel:

1. Modify rudder pedal to rudder gearing ($K_{\delta_{PED}}$).
2. Add α-scheduled gain into rudder pedal to rudder path (K_{PED_α}).
3. Modify SRI gain (K_{SRI_1}).
4. Eliminate the static SRI gain (K_{SRI_2}).
5. Modify the break points of the α-scheduled SRI gain (K_{SRI_3}).
6. Modify the SRI output authority limit (δ_{SRIL_2}).
7. Eliminate the ARI path.

4.3 Development Road Map

The impact of the work described in this report on the overall upgrading of the NASA-LRC drop-model, stall/spin research facility can be best understood by referring to Figure 4-7. This figure summarizes the step by step procedure recommended for the upgrading of the facility in the systems analysis report (see reference 1), i.e., this figure is a development road map.

The solid blocks in Figure 4-7 represent the tasks already accomplished whereas the broken line blocks represent the tasks that remain to be done. Although the incorporation of the digital CSS represents a tremendous improvement to the capabilities of the facility, there are a number of essential tasks that must be done before the facility is completely upgraded. The most important of these remaining tasks are:

- Identification of miniature servoactuators (preferably electromechanic) of sufficient bandwidth and power to actuate the control surfaces of the models within the constraints of size, high actuation rates, and extreme aerodynamic loads.

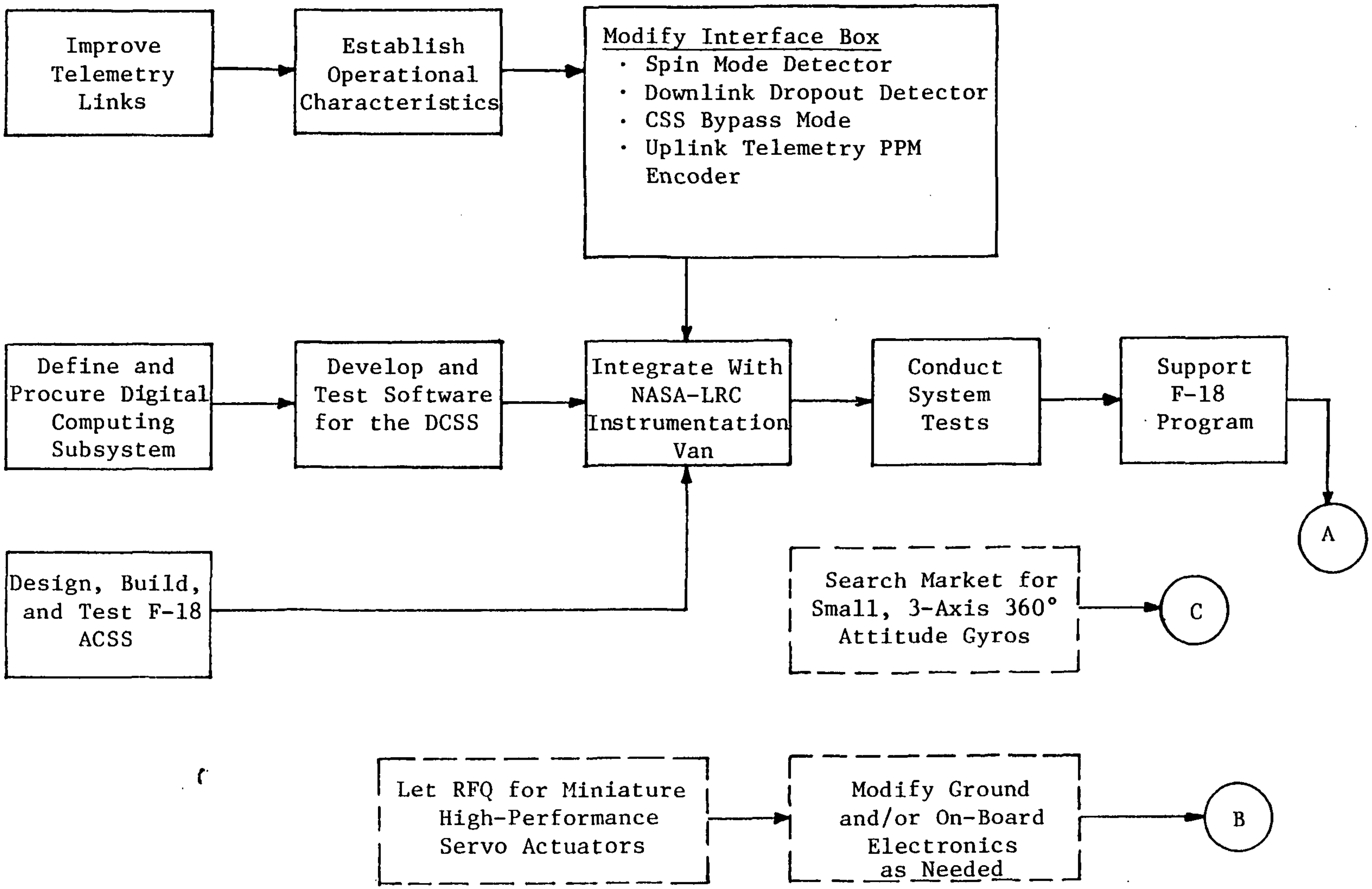
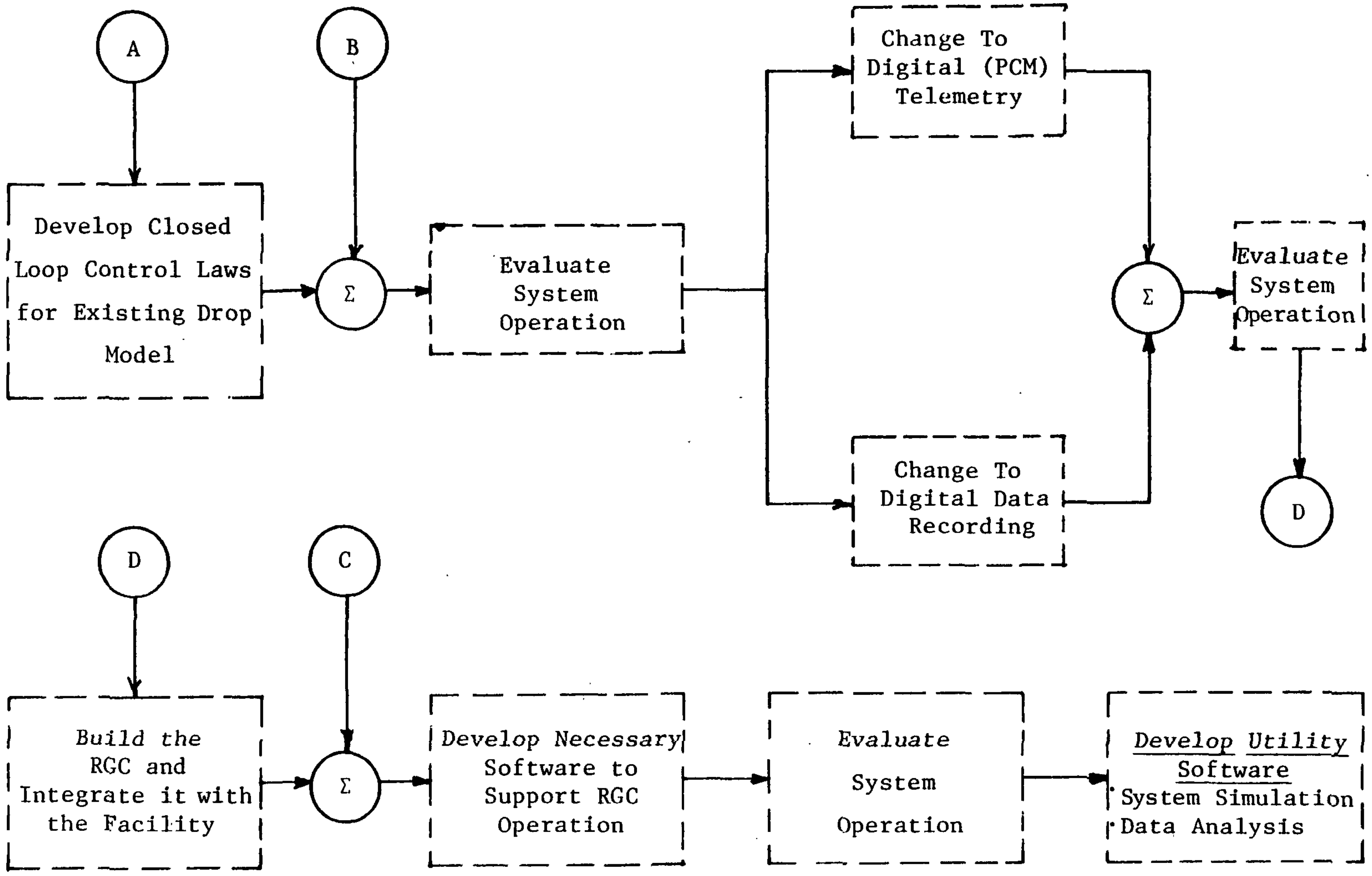


Figure 4-7. Development road map for the upgrading of the drop-model, stall/spin research facility.



Note: RGC, remote ground cockpit.

Figure 4-7. Concluded.

- Search for a small, three-axis, 360°, attitude angle sensor to provide directly sensed attitude information to the pilot of the model in an instrument panel of a remote ground cockpit allowing the pilot to fly the model without direct visual reference to the model.
- If the search for a suitable attitude angle sensor fails, develop a method to derive the attitude angles on the ground from downlinked angular rates that is insensitive to downlink telemetry dropouts.
- Develop a system simulation to be used in testing new control laws and in pilot training.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The development of the ground-based, digital CSS constitutes an important step towards the upgrading of the NASA-LRC drop-model, stall/spin research facility. The incorporation of this simulator into the facility has given it the basic capability of supporting drop-model programs of aircraft with sophisticated closed loop control laws by simply decomposing them into a set of elementary transfer functions and configuring each channel of the control laws from a set of control law modules available in the digital CSS.

The work performed by FID personnel, with RTI's collaboration in some instances, has enhanced the operational quality of some of the elements of the facility. The uplink telemetry PPM encoder now has an increased channel resolution (12 bits) and can operate either synchronized to the digital computer or synchronized locally as before. The improvements to the downlink transmitter power (ranging from 2 to 5 watts), the downlink transmitter antenna design, and to the downlink receiver antenna design and directivity will more than likely show, when tested, that the downlink dropout problem has been substantially decreased.

The hardware "programmable" spin mode detector and downlink dropout detector and their associated CSS-bypass switching circuit have added a new dimension to the online monitoring of the system performance. The interface box and the digital CSS can "decide" automatically when to switch into the bypass mode (direct mode) based on the occurrence of certain preset conditions (see Section 4.0).

As system personnel become familiar with the computational power and flexibility of the digital CSS, the need for an operationally-ready, backup, analog control system simulator (such as the F-18 drop-model ACSS developed under this contract) will no longer exist. The acceptance of the digital CSS by system personnel has been such that RTI is led to believe that the F-18 drop-model program may be the last such program for which a dedicated analog CSS is developed.

There are, however, a few major tasks remaining to be done before this facility is completely upgraded and capable of fully supporting drop-model programs of aircraft with wide bandwidth control systems. The sluggish response of the present servoactuators precludes their use in support of aircraft models with wide bandwidth control system. The lack of a direct means of sensing the models' attitude angles poses severe problems to the precise control of the models from a remote ground cockpit without direct visual contact with the models.

It is recommended therefore, that the upgrading process be continued with orderly emphasis in the following areas:

1) Search for suitable, high performance, miniature servoactuators (preferably electromechanical) for the control surfaces of the models.
2) Determine the availability of a suitable three-axis, 360°, altitude angle sensor.
3) If this search fails, develop and evaluate the performance of the ground derivation of the altitude angles based on the model's angular rates and ground augmentation.
4) Develop a comprehensive, real-time simulation of the system.

The last recommendation is intended as a tool to be used in the testing of newly developed control laws and the training of the pilot of the model. It should not be viewed as an essential requirement but rather as a design and training aid.

REFERENCES

1. Montoya, R. J., and A. R. Jai: Systems Analyses of a Stall/Spin Research Facility Using Remotely Controlled/Augmented Aircraft Models. NASA CR-145182, May 1977.
2. Anon: PDP11 Peripherals Handbook. Digital Equipment Corporation, 1976.