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NASA/RAE Collaboration on Nonlinear Control Using the F-8C Digital Fly-by-Wire Aircraft

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ABS: Design procedures are reviewed for variable integral control to optimize response (VICTOR) algorithms and results of preliminary flight tests are presented. The F-8C aircraft is operated in the remotely augmented vehicle (RAV) mode, with the control laws implemented as FORTRAN programs on a ground-based computer. Pilot commands and sensor information are telemetered to the ground, where the data are processed to form surface commands which are then telemetered back to the aircraft. The RAV mode represents a singlestring (simplex) system and is therefore vulnerable to a hardover since comparison monitoring is not possible. Hence, extensive

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NASA/RAE COLLABORATION ON NONLINEAR CONTROL USING THE F-8C DIGITAL FLY-BY-WIRE AIRCRAFT*

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SUMMARY

A cooperative advanced digital research experiment (CADRE) was established by the National Aeronautics and Space Administration (NASA) and the Royal Aircraft Establishment (RAE), in which nonlinear control algorithms developed by the RAE were tested on the F-8C digital fly-by-wire (DFBW) aircraft based at the Dryden Flight Research Facility. In the initial phase of the collaboration, some variable-gain algorithms, referred to collectively as variable integral control to optimize response (VICTOR) algorithms, were flight tested. With VICTOR, various measures available within the control system are used to vary gains and time-constants within the closed loop and thereby enhance the control capability of the system, while reducing the adverse effects of sensor noise on the control surfaces. A review of design procedures for VICTOR and results of preliminary flight tests are presented. The F-8C aircraft is operated in the remotely augmented vehicle (RAV) mode, with the control laws implemented as FORTRAN programs on a ground-based computer. Pilot commands and sensor information are telemetered to the ground, where the data are processed to form surface commands which are then telemetered back to the aircraft. The RAV mode represents a single-string (simplex) system and is therefore vulnerable to a hardover since comparison monitoring is not possible. Hence, extensive error checking is conducted on both the ground and airborne computers to prevent the development of potentially hazardous situations. Experience with the RAV monitoring and validation procedures is described.

SYMBOLS

DECL	on-board pitch command, deg
DEP	pitch stick command, deg
DERAV	pitch downlink elevator command, deg
DEUP	pitch uplink elevator command, deg
DRATE	maximum floating limit draft rate, 2.5 deg/sec
DYNP	dynamic pressure, lb/ft^2
G_a	closed-loop gain
G_q	baseline proportional gain
G_{qv}	proportional gain
$G_{\int}$	baseline integral gain
$G_{\hat{\int}v}$	integral gain
K_a	feed-forward gain
M_q	normalized pitching moment derivative due to pitch rate
M_α	normalized pitching moment derivative due to angle of attack
M_η	normalized pitching moment derivative due to elevator deflection
Q,q	pitch rate, deg/sec
q_D	pilot pitch-rate demand, deg/sec
$\dot{q}$	pitch acceleration, deg/sec^2
s	complex frequency variable
T	time delay
V_q	VICTOR pitch-rate gain

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V_θ VICTOR integral pitch-rate gain

Z_α negative of lift force due to angle of attack

Z_η negative of lift force due to elevator deflection

α angle of attack, deg

$\dot{\alpha}$ angle-of-attack rate, deg/sec

δ VICTOR error threshold level

δ_1 second VICTOR error threshold

ε error

ε_V error between pitch-rate response and pilot demand

η elevator deflection from trim position

η_D CADRE elevator command, deg

τ_a lead-time constant for phase advance

τ_N time-constant of noise filter and phase advance

τ_{Nv} time-constant of noise filter

τ_Z time-constant of pilot's filter

τ_{1_ε} VICTOR error lead-time constant

τ_{2_ε} VICTOR error lag-time constant

1. INTRODUCTION

Following discussions in 1979 between RAE and NASA on collaboration in the fields of active control technology and handling qualities, a joint program of nonlinear control was established. In this program, known as the cooperative advanced digital research experiment (CADRE), nonlinear flight-control techniques developed by RAE have been implemented and tested on the F-8C digital fly-by-wire (DFBW) research aircraft based at Ames Research Center's Dryden Flight Research Facility.

The F-8C DFBW aircraft is operated in the remotely augmented vehicle (RAV) mode (Ref. 1), in which control laws are implemented as FORTRAN programs on a ground-based computer; the control loop from the pilot and aircraft sensors to the actuators is completed by two-way telemetry. Since this represents a simplex system, extensive error checking is performed to prevent the development of potentially hazardous situations. Experience gained with the RAV monitoring and validation procedures is described in this paper.

The control concept was initially developed by RAE. F. R. Gill, the principal RAE advocate of nonlinear control concepts, has proposed several novel control concepts offering potential benefits in both control performance and handling qualities (Refs. 2-5). One of these concepts, the variable control to optimize response (VICTOR), has formed the basis of the initial stage of the collaboration.

Although the F-8C DFBW aircraft used for the flight testing is fitted with triplex on-board computers, the RAV mode is used for CADRE. Control laws are implemented in a high-level language (FORTRAN) on a ground-based computer, with the control loop from pilot inputs and aircraft sensors through the computer to the control actuators being completed by two-way telemetry (Fig. 1). The RAV mode is a simplex system and is therefore vulnerable to a hardover, since command voting or comparison is not possible. Hence, extensive error checking is carried out in both the ground and airborne computers and, if an error is detected, control is restored to the on-board system. Further details of the F-8C RAV flight-test technique, including modifications introduced for the CADRE flights, are given in Sec. 3.

With VICTOR, measures available within the control system are used to vary the gains within the closed loop and, hence, to enhance the control capability of the system while reducing the adverse effects of sensor noise on the control actuators. The operation of VICTOR is illustrated in Fig. 2. Normally, as the closed-loop gains increase, the control improves and the noise effects become greater. On the other hand, as the gains decrease, the noise effects decrease, but the control also becomes less effective. The VICTOR method overcomes this conflict by allowing the gain to vary as a function of error signals within the system, so that the gains increase when control is required as a result of pilot input or external disturbance, but are allowed to reduce to a much lower level once the control requirement has been satisfied. The design and operation of a variable-gain algorithm, known as VICTOR-E, implemented for a pitch-rate-to-elevator controller as part of CADRE, is described in Sec. 2.

Initial flight tests of the variable-gain control laws commenced early in 1982; they are described in Sec. 4. The principal aim of the flight tests was to establish whether a variable-gain controller could offer improved control performance over a linear baseline system, and whether any adverse handling problems were introduced by the rapidly varying gain. The task chosen for this assessment was an air-to-air tracking task, with the F-8C aircraft required to track an accompanying chase aircraft through a pushover/pull-up maneuver. These tests have demonstrated that a variable-gain controller can be designed to give improved control performance while maintaining acceptable handling qualities. In addition, the flight tests have shown that modifications introduced into the RAV system software for the CADRE tests have been successful in allowing the assessment of the nonlinear control laws without undue restriction on the maneuver envelope of the aircraft. Finally, enhancements to the VICTOR control law and the introduction of other nonlinear control techniques into the CADRE program are discussed in the light of experience with the initial flights.

2. DESIGN OF THE VARIABLE-GAIN CONTROLLER[1]

The general structure of the CADRE nonlinear pitch-rate controller is shown in Fig. 3. The controller consists of two parallel loops: a baseline loop with fixed gains to provide a datum; and a higher-bandwidth VICTOR loop, the contribution from which is governed by the variable-gain algorithm. This parallel structure of the VICTOR and baseline loops embodies part of the concept of class A/B control architecture (Refs. 6, 7). The class A system is that needed to keep the aircraft flying, and the class B system combines with A to provide high performance. In this case, when the system errors are small, the class B (VICTOR) gains are reduced to zero; but once a significant error caused by pilot demand or external disturbance is detected, the gains in the class B system are allowed to increase rapidly to drive the error toward zero.

The CADRE control laws were developed in two stages: the initial design of the baseline and nonlinear control laws by RAE (Refs. 8, 9), using a simplified model of the F-8C short-period dynamics; and the simulation and assessment of the control laws at Dryden using a full six-degree-of-freedom model of the aircraft, together with the introduction of modifications to the RAV system software needed to ensure flight safety (see Sec. 3).

The first stage of the design was performed at RAE, using the computer-based control systems design package, TSIM (Refs. 10, 11). The major part of the design exercise was carried out using a continuous representation of the system, but a discrete implementation was also simulated and the characteristics checked as the design progressed. In addition, real-time engineer-in-the-loop simulations were used to check the system performance for a simple tracking task. Finally, the CADRE control laws were converted to difference-equation form and specified as a set of FORTRAN subroutines for the RAV ground computer. The CADRE control-law subroutines were then evaluated by NASA, and some modifications were introduced, as specified in Ref. 12.

This paper includes a summary of the principal design criteria and constraints, including the aircraft and actuator dynamics (Sec. 2.1), time delay (Sec. 2.2), and command prefilter (Sec. 2.3). The baseline system parameters are defined in Sec. 2.4, and the design of the VICTOR-E algorithm is discussed in Secs. 2.5 and 2.6. The final CADRE software includes eight combinations of parameters defining a range of control-law options; these are summarized in Sec. 2.7. The implementation of the control laws as FORTRAN subroutines is described in Sec. 2.8.

2.1 Aircraft Model

The pitch-rate controllers were designed for a fixed flight condition with a Mach number of 0.67 and an altitude of 6100 m. The short-period dynamics of the F-8C were modeled by linearized second-order equations of the form

$$\begin{bmatrix} \dot{q} \\ \dot{\alpha} \end{bmatrix} = \begin{bmatrix} M_q & M_\alpha \\ 1 & Z_\alpha \end{bmatrix} \begin{bmatrix} q \\ \alpha \end{bmatrix} + \begin{bmatrix} M_\eta \\ Z_\eta \end{bmatrix} \eta$$

where q is pitch rate, α is angle of attack, and η is elevator deflection from trim position.

The values of the normalized derivatives (such as M_q and M_α) were taken from the linearized six-degree-of-freedom data given in Ref. 13.

The primary and secondary actuators were represented by the first- and second-order transfer functions, $1/(1 + 0.08s)$ and $3969/(s^2 + 88s + 3969)$, respectively.

As noted previously, an important effect of the F-8C RAV facility is the time delay introduced by the telemetry link hardware and the ground computer. In the early design stages the delay was represented by the continuous second-order approximation

$$e^{-Ts} \approx \frac{12 - 6Ts + T^2s^2}{12 + 6Ts + T^2s^2}$$

where T is the delay time.

A total delay of 50 msec was assumed for the system design, but the initial flight tests indicate that the total delay in the RAV mode is about 100 msec, which leads to some reduction in the damping of the systems (see Sec. 4).

2.2 Command Prefilter and Feed-Forward

The initial design goal for the system response to a pilot demand was that the pitch-rate response to a step input on the stick should be rapid and exhibit as small an overshoot as possible. Normally, if no prefilter is included, the aircraft zero causes a large overshoot in pitch-rate response to a step input. To alleviate this effect, a command prefilter of the form $(1 + \tau_a s)/(1 + \tau_z s)$ is introduced. For a second-order model, the aircraft zero time-constant τ_z is given, in terms of normalized derivatives, by

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$$\tau_z = \frac{M_\eta}{M_\alpha Z_\eta - M_\eta Z_\alpha}$$

For the design flight condition, $\tau_z = 1.02$.

The value of the lead-time constant, τ_a, allows some control over the size of the pitch-rate overshoot. For $\tau_a = 0$, simulations showed that the response was too slow for accurate tracking. On the other hand, as τ_a approaches τ_z, the lag is effectively canceled, which leads to an increasing tendency to overshoot. Air-to-air tracking at long distance (≈300 m) requires accurate control of pitch attitude through dead-beat pitch-rate response, whereas when the target is close, height errors play a more important part in the task, and hence there is an increasing emphasis on faster normal acceleration response. Therefore, the original dead-beat rate-response goal was changed for close tracking. Because of the inherent lag between pitch rate and normal acceleration response to an elevator input, more rapid normal acceleration requires an increased pitch-rate overshoot, with a consequent increase in the lead-time constant, τ_a. Two values of τ_a were included as options in the final software specification (Ref. 12) (also see Sec. 2.7):

$$\tau_a = 0.2 \quad \text{for distant tracking (>150 m)}$$

$$\tau_a = 0.6 \quad \text{for close tracking (<150 m)}$$

If no integral term is included in the control system, Gill (Ref. 4) shows that a feed-forward of the pilot demand with gain K_a will lead to a steady-state error of zero. For a second-order aircraft model, the feed-forward gain K_a, of Fig. 4, can be expressed in terms of normalized derivatives as

$$K_a = \frac{Z_\alpha M_q - M_\alpha}{Z_\alpha M_\eta - M_\alpha Z_\eta} = 0.62$$

for the design flight condition. Although the baseline controller includes an integral term, which will itself act to reduce the steady-state error to zero, the integral acts relatively slowly, and it has been found advantageous to retain the feed-forward element.

2.3 Baseline Loop Parameters

The selection of the gain values, G_q and G_θ, and the time-constant, τ_N, is considered in detail in Ref. 8. It should be noted that for convenience, the proportional and integral gains are scaled by a factor related to the elevator effectiveness, $G_a = 1/M_\eta$ (which is equal to 0.087 at the design flight condition), so that the total gains for the proportional and integral loops are given by G_aG_q and G_aG_θ, respectively (Fig. 4). The primary design criterion was to maintain a damping level of about 0.5 on the short-period mode, while making the response speed as rapid as possible and keeping noise effects on the elevator at a reasonable level. The values selected were as follows:

Time-constant:	$\tau_N = 0.033$ sec
Proportional gain:	$G_q = 3.6$
Integral gain:	$G_\theta = 4.15$

2.4 Design of VICTOR-E Algorithm

Design guidelines for the structure and implementation of variable-gain control laws are currently under investigation at RAE. In particular, Gill has evolved several strategies for gain variation, which are described in detail in Refs. 4 and 5. One feature that stands out from this work is that in order to derive the full benefit of a high-gain system, the variable gain must be increased rapidly once the decision has been made that control is required. Hence, for the variable-gain algorithm described here (VICTOR-E), the starting point for gain variation in the VICTOR control loop is a straightforward on/off switch controlled by an error threshold. In other words, given an error ε and a threshold level δ, the system is switched to a higher gain when $\varepsilon \geq \delta$ and is switched back to a lower gain when $\varepsilon < \delta$. Some modifications have been introduced to this criterion to reduce the effects of switching transients, but VICTOR-E remains intrinsically a switching algorithm.

To retain reasonable levels of damping, the higher gain of the VICTOR system must be associated with a greater bandwidth. In the single-loop VICTOR systems described by Gill (Refs. 4, 5), the noise filter time-constants (and hence the bandwidth of the system) are slaved to the gain variation. As noted earlier, however, an important feature of the VICTOR-E implementation is the parallel structure (Fig. 3), in which the variable-gain elements are confined to a separate loop. One advantage of this parallel architecture is that the wider bandwidth of the VICTOR loop can remain fixed, with the contribution of this loop being controlled by the gain term alone, and, hence, the need for filter time-constant variation is removed.

The structure of the VICTOR control-loop includes variable proportional and "leaky" integral control in addition to fixed-phase advance and noise filter elements. The overall gains are varied by means of VICTOR gearings V_q and V_θ, which are in the range of 0 to 1 (for VICTOR-E, V_q is set equal to V_θ), and the maximum gains of the VICTOR loop are set by parameters G_{qV} and $G_{\theta V}$. For the design case, the integral gain $G_{\theta V}$ is set to zero, and the proportional gain G_{qV} is set to 3.6 (equal to the value of G_q in the baseline loop). The time-constant of the noise filter and phase elements in the VICTOR loop advance, τ_{NV}, is set to 0.0125. Other values of these parameters are, however, included in the eight systems selected for flight (see Sec. 2.7).

2.5 Operation of VICTOR-E

The VICTOR-E algorithm operates by means of an error signal ε_V, which controls the V_q gearing ($0 \le V_q \le 1$). To ensure that V_q responds quickly to the pilot's stick movements, ε_V is based on the difference between the pitch-rate response q and the pilot demand q_D. The error is then filtered and washed out to eliminate noise and steady-state components, finally yielding the VICTOR error ε_V, defined by

$$\varepsilon_V = \left| (q - q_D) \left(\frac{\tau_{1_\varepsilon} s}{1 + \tau_{1_\varepsilon} s} \right) \left(\frac{1}{1 + \tau_{2_\varepsilon} s} \right) \right|$$

Time-constant values of $\tau_{1_\varepsilon} = 10$ and $\tau_{2_\varepsilon} = 0.05$ have produced satisfactory control behavior. Initially, the VICTOR gearing was increased by switching V_q from 0 to 1 when the error threshold δ was exceeded. To smooth out differences in control behavior experienced when pilot demand is close to the threshold, however, a second threshold, δ_1, was introduced so that when ε_V is increasing and $\delta \le \varepsilon_V \le \delta_1$, then $V_q = (\varepsilon_V - \delta)/(\delta_1 - \delta)$.

When the control demand has been satisfied and the error is reduced to a low level, the VICTOR algorithm must take account of this and reduce V_q toward zero. Gill (Refs. 4, 5) finds that the response is sensitive to the rate of reduction of the gain, and that it is important to ensure that the gain is not reduced too rapidly. Hence, if ε_V is decreasing, the maximum value of V_q is held until $\varepsilon_V < \delta$, after which V_q is reduced to zero linearly with time. A ramp decay time of 2 sec has proved to be suitable.

The operation of the VICTOR-E algorithm is illustrated in Fig. 5, using the results from simulation studies for a 0.1-sec lagged-step pilot input of 1 deg/sec. It should be noted that in the example shown, ε_V does not reach a high enough level to force V_q to its limiting value of unity.

2.6 Parameter Combinations for Flight Tests

Following simulation of the CADRE control laws at RAE and NASA, eight combinations of parameters were identified as possible candidates for flight testing. These eight functions can be commanded from a mode-panel on the ground; they allow the control law on the RAV system to be changed without leaving real time (see Sec. 3). The eight combinations comprise four basic systems, with two values of the lead-time constant on the pilot's prefilter, $\tau_a = 0.2$ or 0.6, specified for each (see Sec. 2.3). The basic systems are as follows.

1. Baseline: Here the proportional and integral gains in the VICTOR loop G_{qV}, $G_{\theta V}$ are set to zero, leaving only the baseline loop in operation. Even though the VICTOR loop is ineffective, the gearing V_q continues to vary and can be used as an indication of system performance (see Sec. 4). The baseline systems are numbered 5 and 6 with $\tau_a = 0.2$ and 0.6, respectively.

2. VICTOR (design gain): For this case, the VICTOR proportional gain G_{qV} is set at 3.6, with the integral gain $G_{\theta V}$ again set at zero. This corresponds to the design case described in Ref. 9 and is intended to give an enhanced control performance over that of the baseline system. These systems are denoted by 1 and 2, corresponding to $\tau_a = 0.2$ and 0.6, respectively.

3. VICTOR (half design gain): Here, G_{qV} is set at 1.8, which represents half the design value of 3.6. This case was included to allow G_{qV} to be increased progressively from zero to the design value. Systems 3 and 4 refer to this controller with $\tau_a = 0.2$ and 0.6, respectively.

4. VICTOR (emulation of baseline): For this case, the baseline system is degraded by halving the gains G_q and G_θ and allowing the VICTOR gains G_{qV} and $G_{\theta V}$ to make up the deficit. The VICTOR noise filter time-constant τ_{NV} is reset to the baseline value τ_V. Systems 7 and 8 correspond to $\tau_a = 0.2$ and 0.6, respectively.

2.7 Implementation of Control Laws in FORTRAN

The control laws described previously in this section have been converted to difference-equation form and specified as a set of subroutines written in standard FORTRAN IV. One of the principal aims of the software design was to produce well-commented, easy-to-follow coding, to ensure that the programs comprised an exact definition of the computing task to be performed. The development of the difference equations used in the software is described in more detail in Refs. 14 and 15. The structure of the software is shown in Fig. 6. Different versions of the coding are given in Refs. 8, 9, and 12, but each version is referred to by a unique one- or two-letter identifier xx. With reference to Fig. 6, each version contains three subroutines:

1. The initialization routine, QINIxx, is called once before engagement to set up the system parameters (gains and filter coefficients, etc.) and to initialize the filters.

2. The control program, QCONxx, takes in pitch rate and longitudinal stick position and generates an elevator demand signal. To minimize computing time delays from input to output, this routine performs only as much of each filter calculation as is needed to produce the output.

3. The filter completion routine, QFILxx, completes the filter calculations ready for the next input sample.

3. RAV SYSTEM OVERVIEW

The F-8C DFBW aircraft contains a triply redundant, full-authority, digital fly-by-wire flight-control system with provisions for accepting single-string (simplex) control-surface commands from a ground-based computer while in a special remotely augmented vehicle (RAV) mode. This mode allows advanced control concepts, such as the CADRE control laws, to be programmed into the ground-based computer. The necessary data are transmitted to the ground and the computer commands are transmitted back to the aircraft, as shown earlier in Fig. 1. The RAV mode is selectable by the pilot. It is a single-string (simplex) system; therefore, if there is any failure, the system automatically switches or can be manually switched back to the on-board digital SAS mode. The CADRE RAV mode allows implementation and changes to the CADRE control laws, which are written in FORTRAN, without disrupting the integrity of the on-board flight system.

In addition to programming the control laws in the ground-based computer, the development and flight qualification of the CADRE system involved an effort in system development. Significant changes and improvements were required for the existing ground and airborne software, Ref. 1, for the CADRE program. Additional failure-detection and identification methods were required for maneuvering flight. An effort was made from the start to develop a failure management strategy that would allow full elevator authority during maneuvering while allowing no failure in the F-8C RAV system to compromise either the fail-operational integrity of the triplex on-board systems, or the flight safety of the aircraft.

Monitoring command software was used for both the simulator testing and during flight. This allowed significant time saving during evaluation, verification, validation, and during flight testing.

Although the rigorous flight qualification standards developed in previous RAV experiments were used, modifications were made in the testing techniques and the procedures to meet the unique requirements of the CADRE system.

3.1 CADRE RAV System

The CADRE RAV system involved mechanization and implementation of various ground and airborne hardware, as well as software interfaces. The primary elements of the hardware used in the F-8C RAV facility are shown in Fig. 7; they are divided between ground systems and airborne systems.

The process starts with parameters being downlinked, including aircraft sensor signals and pilot commands. These signals are received at the telemetry-receiving station and are passed to a downlink telemetry computer which performs the required subframe decommutation and discrete processing of the downlink data. It also formats a data buffer for access by the control-law computer. The downlink data are then interfaced to the CADRE computational algorithms in the control-law computer. An additional computer interface, shown in Fig. 7, is to an external mode-control box. This provides a flexible change to the CADRE control laws between the eight different control algorithms.

The function of the CADRE control-law computer is first to compute the CADRE control algorithms. Secondary functions are real-time input/output computation, fault detection, and ground preflight testing. The program structure has two primary segments. One is a real-time segment which is synchronized to the uplink encoder and operates at an 18.75-msec frame rate. It contains all elements for the eight CADRE control-law configurations, logic for switching between control laws, and the set of failure detection and isolation algorithms that is discussed in Sec. 2. In addition, it contains the input and output routines required for the reformatting of the downlink and uplink parameters and the discrete interface to the mode-control box. The other segment of the program structure is the non-real-time or background segment. All initialization functions and several display routines are processed in this segment. The display routines, which are formatted for a CRT terminal, were designed for ground checkout and testing. In addition, the CRT terminal interface allows selected control system parameters, for example, G_{QV}, to be changed during flight, if desired. The display routines permit the easy monitoring of many of the hardware-to-software interface parameters, internal control variables and states, and failure detection functions. The ground computer software also contains a preflight module that is divided into static checks and a maximum/minimum dynamic check. The CADRE preflight is a monitor-only program; therefore, it can be used during flight if desired. Hard copies may be obtained of not only the preflight tests but of any of the CRT displays.

The CADRE control-law uplink commands are formatted as four 16-bit words of command information and operate on an 18.75-msec frame rate. Each command word contains 10 bits of proportional information; the remaining six bits are used for discrete uplink signals which provide for ground-commanded RAV disengagement. Although the RAV program uplinks the four words *pitch command*, *roll command*, *yaw command*, and *flap command*, the CADRE system only uses the pitch command. The uplink decoder outputs the four digital uplink words, which are then interfaced to the on-board flight-control system. The RAV commands are also sent to the on-board instrumentation system and transmitted via the downlink telemetry for monitoring in ground-based facilities during flight. The CADRE RAV system interface to the on-board flight system was designed to be an independent, pilot-selectable mode. Special care was taken to ensure that the operation of the CADRE RAV mode did not compromise the overall redundancy management and failure strategies of the DFBW flight systems. Therefore, the RAV on-board computer software mechanization included a series of logic statements specifying the conditions for the engagement and disengagement of the CADRE RAV mode; these are discussed in detail in Sec. 3.2.

In addition to pilot selection of the CADRE control modes, all of the engagement conditions had to be satisfied before the CADRE RAV mode became suitable for flight testing. The CADRE system was automatically disengaged, and control was transferred to the on-board SAS, if any of the disengage conditions appeared. In addition, the RAV on-board software contained functions that provided transient-free mode engagement, and command-rate reasonability checks. The on-board computer software was also modified to include command authority floating limits and ultimate g limits. This allows full elevator authority for maneuvering flight, which was needed for CADRE flight-test evaluation, while providing additional on-board protection.

The authority limits and rate-check thresholds were all chosen to ensure that aircraft transients were acceptable in the event of a worse-case hardover failure.

3.2 Failure Detection and Identification

The CADRE experiment was designed using a single-string (simplex) RAV system; therefore, redundancy management algorithms commonly used for multiple systems were impossible. Although a previous RAV system had successfully been developed (Ref. 1), it was not a full-authority system and did not require some of the additional concepts developed for this program. The primary features of the CADRE RAV mode-failure-detection system are (1) continuous rate-check testing of the uplink and downlink signals every minor cycle by both the flight and ground computers; (2) inhibition of RAV engagement until certain criteria are satisfied for both computer systems; (3) a wrap test that compares the RAV uplink command with itself sent back on a downlink word; (4) use of a floating window command limiter in the flight computer; and (5) imposition of a g envelope boundary for RAV operation. If a hard failure is declared by either computer system, a RAV downmode automatically occurs whereby the RAV command is faded to the on-board command in 2 sec. The particular cause of the RAV downmode is immediately identified and displayed in real time for downmodes originating from the ground computer. Piloted action is required to activate the RAV failure display code for RAV disconnects originating in the flight computer, and that information is then relayed to the flight controller. The failure detection tests and RAV limiting restrictions will now be discussed.

Ground computer— There are 11 tests for failure monitoring:

1. RAV engagement bias
2. DEUP rate check
3. Stick/trim opposition
4. Wrap test
5. DEP downlink rate check
6. Q downlink rate check
7. DECL downlink rate check
8. DERAV downlink rate check
9. DYNP downlink rate check
10. Downlink telemetry computer fail
11. CADRE control-law computer fail

Failure identification is displayed in real time both on a strip chart and on a light display on the mode-control panel. Since the RAV mode is susceptible to data spikes caused by temporary loss of the telemetry signal, a hard failure is not declared unless a threshold has been exceeded for n or more consecutive iterations. Once a RAV downmode is commanded, the error must be reset before another RAV attempt is made. Each test will now be described.

Before RAV engagement, the CADRE command is compared with the current SAS command. The difference between the two must be 5° or less, otherwise an engagement bias error is declared that inhibits the RAV mode from engagement. Any command difference less than 5° is added to the CADRE command which then forms the RAV uplink command (DEUP). This bias then becomes fixed upon a successful RAV engagement..

Rate-check testing is performed on the CADRE RAV uplink signals. If the command rate exceeds the rate-check limit, the current command is replaced with the previous one and a counter starts incrementing. As long as this condition exists the RAV command remains frozen until the counter limit is reached and a RAV downmode is declared. If the RAV command becomes less than the rate-check value before the counter limit is reached, the RAV command is allowed to update to the new value, and the counter is reset to zero.

A test is performed that determines whether the trim command is in the same direction as the stick displacement. If the stick deflection exceeds the threshold, and a trim command is in opposition, a counter starts incrementing. When the counter limit is reached, a RAV downmode is declared.

A wrap test performs a closed-loop check of the RAV uplink command with itself which is sent back on a downlink channel. If the difference between these signals exceeds a given tolerance, a counter starts incrementing. When the counter limit is reached, a RAV downmode is commanded.

The proportional downlink words are rate-checked in their raw PCM format form before they are converted to engineering units. If the rate of change exceeds the tolerance level, the previously passed signal replaces the current one and a counter starts incrementing. As long as this condition exists, the passed signal remains frozen until the counter reaches a limit, at which time a RAV downmode is commanded. If the input signal becomes less than the tolerance before the counter limit has been reached, the new signal will be passed through, and the counter will be reset to zero.

The discrete downlink word is tested in a different way. For any discrete change to be recognized it must exist for at least three consecutive iterations; if not, the change is ignored, although no RAV downmode will result. This logic produces a two-sample delay for all discrete changes.

The downlink telemetry computer that first receives the downlink signals is tested in the following way. The computer expects to receive fresh downlink data at a rate of 200 sps, and when it does, a counter is incremented. If the counter fails to advance for five consecutive iterations, a RAV downmode is commanded.

The control-law computer is tested for failures by use of an external hardware watchdog timer. Each time the real-time loop begins execution, a pulse is sent to a timer. Failure to receive another pulse within about 20 msec causes a time out and a RAV downmode will be commanded through hardware.

Flight computer— There are 15 conditions that must be satisfied by the flight computer in order to engage the RAV mode and to stay in that mode. These conditions are as follows:

Not in SAS mode	Not SAS, surface and flap-rate check
Surface rate check	Autopilot engaged
Not SAS and surface rate check	Autopilot disconnect
Engage tolerance failed	Sensor failed
Flap-engage tolerance failed	Uplink failed
Flap rate check	Low-g limit exceeded
Not SAS and flap-rate check	High-g limit exceeded
Surface and flap-rate check	

The display codes are accessible to the pilot upon his request to execute the RAV failure display code program. The major failure testing will now be discussed.

A RAV engage tolerance test is first performed. It looks at the current RAV uplink command and compares it with the present on-board command. They must be within 1° for this test to pass, otherwise a RAV inhibit error will be set to prevent an engagement.

Once the RAV mode has been engaged, the command is rate checked. This test is similar to that of the RAV rate-check test which is done in the ground computer. If the rate of change of the RAV command exceeds 50°/sec, the current RAV command is replaced with the previous one until the counter reaches the limit of 3. When this situation occurs, a RAV downmode is declared from the airborne computer.

A floating window command limiter was added to the airborne software for the CADRE RAV program as a final test to prevent an undetected hardover just below the rate check from coming through to the surface directly. This limiter is illustrated in Fig. 8. Initially, the window is centered at ±3° about the current RAV command. Command rates up to 50°/sec are allowed within the 6° window. The window continuously tries to stay centered on the RAV command, but is only allowed to drift at a maximum rate of 2.5°/sec. Eventually, the RAV command will be rate-limited to the drift rate value until the command rate is decreased or reversed and the window is allowed to recenter as shown in the figure. A rate-limit signal is telemetered to the control room during the flight test whenever the RAV command is rate-limited.

The floating limiter, in combination with the rate-check testing that is resident in the triply redundant on-board systems, provides protection for a full-authority, single-string (simplex), ground-based control system. However, because of other safety considerations, RAV operation at the outer airplane g limits was deemed undesirable. Therefore, a g envelope limit for RAV operation was also added to the airborne system. These limits were set at +5 and -2 g's. If these limits are exceeded, an automatic RAV downmode will result.

3.3 RAV Software Development

Simulation— The CADRE control laws were developed by RAE and supplied to NASA DFRF. The simulation developments at NASA DFRF were performed in two principal stages. The first stage involved development of a real-time, all-digital simulation of the CADRE system — a duplication of the system developed by RAE. Data supplied by RAE were used to validate the simulation. This allowed for consistency checking between results and provided a timely method for evaluating modifications to individual control system filters or combinations of filters for selected inputs.

The second stage was the major simulation effort; it consisted of a CADRE simulation using the F-8C DFBW iron-bird simulation facility (Fig. 9). The iron-bird simulation consists of a decommissioned F-8C aircraft with the following equipment: triplex primary digital system; triplex analog computer bypass; a full set of flight actuators; triplex electrical buses with batteries; triplex hydraulic system; operable auxiliary aircraft systems; and operable cockpit instruments.

The iron bird interfaces with a nonlinear simulation of the F-8C aerodynamics which uses actual surface positions as inputs. The RAV ground computers were used as elements of the total CADRE simulation. The uplink and downlink hardware interfaces were simulated in the simulation computer, and the control laws were implemented on the same type of ground computer that was used during flight.

The iron-bird facility was the key element in the system verification, validation, and flight qualification.

CADRE software verification— The CADRE software verification tests were designed to insure compliance with the software specification. The verification process, which included element-by-element verification, required written procedural descriptions and produced hard-copy test results. All dynamic elements, such as filters, were exercised in a dynamic environment, and responses were compared with independent computer responses based on the desired characteristics. All path combinations of the CADRE control laws were executed. Each test was accompanied by a written verification test report that is under software control management. These reports contain descriptions of test, objective, setup, results, and conclusions.

A comprehensive software configuration control policy was developed based on the previous RAV experience (Ref. 1). Procedures were implemented to govern the verification test requirements, software changes, discrepancy reporting and reconciliation, software manufacture and loading, and documentation requirements.

Not only were written verification tests and results required, as discussed above, but all program changes also required the same documentation. Before the implementation of any program change, approval had to be given by a software control board.

CADRE configuration validation— The overall CADRE system configuration testing was designed to qualify the CADRE ground and vehicle systems and to insure proper system operation. The analysis and validation of the basic system design and mechanization initially used the iron-bird simulation. This facility was used to verify the proper control-law implementation through static and dynamic response tests and through extensive piloted evaluation. The RAV ground computer was used as elements of the total simulation, and the uplink and downlink hardware interfaces were simulated. The RAV simulation ground and on-board software interfaces were identical to those of the actual aircraft and ground facilities, and the software developed and validated in the CADRE system simulation was used during the CADRE flight operation.

Qualification testing— A series of failure-mode demonstration tests was conducted to insure proper system response to any critical fault. These tests were first conducted on the F-8 iron-bird simulator, then a subset of these tests was repeated during aircraft/ground facility systems tests. In addition, an integrated closed-loop preflight of the total CADRE system was accomplished in which all CADRE input and output parameters were checked both statically and dynamically. As a final step in the flight qualification process, the RAV system operational parameters were monitored during a sequence of flight tests in which the CADRE control laws were operating open-loop. These open-loop monitoring flight tests verified RAV uplink and downlink communication links, telemetry signal strength, and the ground and aircraft synchronization strategies.

4. FLIGHT TESTS

Flight tests of the VICTOR variable-gain control laws commenced in February 1982. The main objective of the tests was to establish whether the variable-gain controller could offer improved control performance over that of a fixed-gain baseline system and whether any adverse handling problems were introduced by the rapidly varying gains. In addition, a comparison has also been made between the baseline controller and a variable-gain system, designed to reproduce, rather than improve, the performance of the baseline. The task used for this assessment has been an air-to-air tracking task, in which the F-8C pilot is required to track an accompanying chase aircraft through a pushover/pull-up maneuver. Details of the maneuver and other test procedures are given in Sec. 4.1. No direct measurement of the accuracy of tracking is available, but indirect indications are obtained from recordings of the system activity and from pilot ratings of the different controllers. These results are presented in Sec. 4.2.

The initial flight tests have highlighted the need for some enhancements of the current variable-gain control laws. Improvements planned include the provision of gain scheduling with dynamic pressure to widen the flight envelope, and the introduction of a rate-limiting term in the variable-gain logic to alleviate the effects of transient, rapid increases in gain, which can lead to the RAV rate limit being exceeded and to a consequent RAV downmode. Following this, it is proposed that three further concepts that have been studied at RAE be introduced into the CADRE control laws. These are (1) overshoot control (Ref. 5), in which the damping properties of the control loop are adjusted during the response to prevent undesirable overshoots; (2) a nonlinear command prefilter (Ref. 16), which is designed to give good response for both target acquisition and tracking; and (3) the self-adaptive technique, INFAIR (Ref. 17), in which the parameters of the command prefilter are adjusted to maintain invariant control response across the flight envelope. Some of these developments are discussed in Sec. 4.3.

4.1 Test Procedure

During the CADRE flight-test program, the F-8C takes off and climbs to the design conditions, normally Mach 0.6 and an altitude of 6100 m, with the on-board stability augmentation system (SAS) engaged in pitch, roll, and yaw. After trimming the aircraft, the pilot engages the RAV pitch mode, thus allowing the longitudinal control to be provided by the experimental CADRE control laws on the RAV ground computer.

The initial tests included testing of the eight CADRE control modes and the longitudinal SAS mode under the following conditions:

1. Nose-up and nose-down pitch pulses input by the pilot
2. Steps input by ground control
3. Rapid climb and descent between 5500 and 6700 m
4. 3-g windup turn

These tasks were used primarily to allow both the pilot and flight-test personnel to evaluate the control-law performance from a stability standpoint before the pilot rated its ability to perform the required task.

The major part of the flight test has been devoted to an evaluation of the CADRE controller for an air-to-air tracking task in which the F-8C pilot attempts to track the accompanying chase aircraft through a maneuver. In this maneuver, the pilot of a target aircraft rolls into a stabilized 3-g turn while endeavoring to keep the designed altitude and speed condition, but allowing altitude loss, if necessary. After turning 180°, the target pilot unloads the aircraft, reverses the direction of roll and pulls a stabilized 3 g's in the opposite direction, again through 180°. A tracking distance of about 300 m has been used to allow assessment of low overshoot CADRE controllers 1, 3, 5, and 7.

For this tracking task, the F-8C pilot was asked to assign a Cooper-Harper pilot rating (Ref. 18); this rating, as well as any other pilot comments on the system, was recorded. In general, the pilot was not told which CADRE controller was in operation. On the flight instruction card, the different controllers were simply referred to as modes A, B, C, etc., with the relationship to the CADRE controllers (1 to 8) known only to the flight-test engineers. This enabled the inclusion of repeat points to establish whether the pilot rating changed during the course of a flight.

Although more complex tracking tasks have been attempted, they have usually led to a RAV downmode because of the elevator rate of g-limit checks. It is possible that the inclusion of a rate-limit controller and gain scheduling (Sec. 4.4) within the CADRE control laws will allow the more complex tracking tasks to be achieved.

4.2 Flight Results

The initial flight tests concentrated on the tracking tasks described in Sec. 4.1, with the target aircraft at a range of about 300 m. The control laws that are designed for the task are modes 1, 3, 5, and 7. For these modes the lead-time constant on the pilot's prefilter is set at 0.2, giving a relatively low overshoot (Sec. 2.3). The controller, with $\tau_a = 0.6$ (cases 2, 4, 6, and 8), giving an overshoot in pitch rate have also been flown for this task, but have usually been given lower ratings. A summary of the ratings of two pilots (pilots A and B) for the eight CADRE controllers defined in Sec. 2.7, together with the on-board SAS system, is given in Table 1. The ratings in the table are for two particular flights but they are representative of ratings assigned after all five flights to date. The SAS mode uses washed out pitch-rate feedback to improve the short-period damping; since it is implemented on the on-board system, no additional RAV time delay is involved.

From Table 1, it can be seen that the pilots have consistently rated the mid-gain VICTOR system (mode 3) higher than the other CADRE controllers. Some basis for this rating can be found in Fig. 10 where flight records for the tracking maneuver for case 5 (baseline) and case 3 are compared. First, from the pilot input traces of Fig. 10a, it can be seen that the pilots were able to reproduce the maneuver very accurately, in that the variation of pitch-rate demand with time is virtually identical for the two modes. The low-amplitude, high-frequency bursts on the elevator demand signal for mode 3 of Fig. 10b show the influence of the VICTOR loop in widening the bandwidth of the controller. That the extra bandwidth is significant can be judged from the pilot ratings and a comparison of the VICTOR gearing (VQ) time histories of Fig. 10c. The activity of the VICTOR gearing is a convenient measure of how well the control demand is being satisfied, since the gearing increases toward unity when the difference between demand and response exceeds a prescribed threshold. In the traces of Fig. 10c, the VICTOR gearing is below one for a considerably greater part of the maneuver in case 3 than in case 5, indicating the greater degree of control afforded by the VICTOR controller.

Further observations of the different controllers in the tracking task and pilot comments about them are summarized below.

1. Baseline system (case 5): Generally, the baseline pitch-rate controller was rated slightly better than the on-board SAS controller. Control was precise and stable, but the initial response to a stick input was thought to be rather slow. The pilot rating was 4 to 5.

2. High-gain VICTOR system (case 1): There were stability problems with the design case (case 1) of VICTOR. In particular, the short-period mode was poorly damped and any attempt to use this controller for tracking led to a rate limit and a RAV downmode. The inadequate damping for this case was due to the time delay in flight, which has been estimated at about 100 msec. This was greater than the 50-msec delay used in the original design. It is anticipated that the performance of this controller will be improved by the introduction of rate limit and overshoot control elements. These are discussed in Sec. 4.3. No pilot ratings were given because of the stability problems.

3. Mid-gain VICTOR system (case 3): In general, this controller was preferred for the tracking task, giving precise control with at most one overshoot. A consistent pilot rating of 3 was obtained and flight traces indicate that the error between demand and response was usually smaller than with the other systems, with the result that the VICTOR loop was active for less time (see Fig. 10). One test has been performed with gain between the mid- and high-gain system, cases 3 and 1. Indications are that there is an improvement in pilot rating from 3 to 2 for small increments in maximum variable gain ($G_{qv} = 2.2$). This may imply that an optimal value of G_{qv} may be determined, given the present system.

4. VICTOR emulation of baseline (case 7): The pilot rating for this case was similar to that for the baseline (case 5). Nevertheless, the pilots could detect a difference between the two controllers, in that case 7 was thought to give less precise control, with slightly lower damping than the baseline. (In fact, the damping levels for cases 7 and 5 are the same; therefore, the perception of lower damping levels may be the start of a PIO as the pilot reacts to the controller breaking out from the low-gain condition.) Flights are planned with different values of the threshold, which will give further information on this effect.

5. System with pitch-rate overshoot (cases 2, 4, 6, and 8): These systems were designed for tracking at a range of under 150 m, but have been assessed in the 300-m tracking task. It can be seen from Table 1 that the pilot ratings are less consistent and more adverse for their controllers than the low overshoot modes. Pilot comments would seem to show some influence of the time delay in that the systems appeared to give very little reaction initially followed by a sudden rapid response which did not find favor with the pilots. For close-range tracking, this effect may not be so pronounced, since the task is governed by height changes which tend to lag the pitch-attitude changes. These will be evaluated in future flight tests, using a simulated refueling task.

5. FURTHER DEVELOPMENTS

Enhancements to the CADRE controller to be introduced in the near future are described below. These are concerned with gain scheduling, rate-limit control, and the reduction of overshoots.

5.1 Gain Scheduling

The CADRE controllers were designed for a fixed flight condition (Mach 0.67 at 6100 m). During the pushover/pull-up tracking maneuver, the pilots experienced some difficulty in maintaining the design conditions, with the result that as Mach number increased or altitude decreased, some loss of stability was experienced. To overcome this problem, the closed-loop gains are to be scheduled with the reciprocal of the measured dynamic pressure q, so that as altitude decreases or Mach number increases, the gains will reduce and stability will be restored. A scheduling relationship for the closed-loop gain G_a and for the feed-forward gain K_a (Fig. 4), has been selected and is being incorporated in the CADRE software.

5.2 Rate-Limit Control

One of the safety checks incorporated in the RAV system ensures that control reverts to the on-board system should the demand to the elevator exceed a certain rate (Sec. 3). This has proved a limiting factor in testing some of the CADRE controllers, particularly the high-gain VICTOR systems (1 and 2). Further design studies have shown that the high rate of change within the VICTOR loop is due mainly to the rapid increase in the gearing V_q associated with an increase in control demand. In fact, the successful operation of the variable-gain controller is not significantly affected by these high rates and hence a form of rate-limit control can be introduced with little or no performance penalty. In Ref. 19, several alternative rate-limiting strategies are compared for both fixed- and variable-gain controllers. The schemes proposed are based on continuous representations of the control system and require an estimation of the extent to which the rate-limit is exceeded, so that the effective gain can be reduced by using an appropriate feedback whenever rate limiting is imminent. However, for an implementation such as that used in CADRE, a relationship between the variable gearing V_q and the demanded control rate exists, so that the rate of control can be limited by adjusting V_q directly.

5.3 Overshoot Reduction

A nonlinear technique for reducing the magnitude of response overshoots has been proposed recently (Ref. 5). It is based on the argument that when the control is reducing, the magnitude and rate of change of this error can be used to predict a possible overshoot. In such a case, an additional control term can be introduced to increase the effective damping. The dramatic effect of such a term is shown in Fig. 11, where the technique is applied to the high-gain VICTOR system (case 1) with a time delay of 100 msec. It can be seen that the undesirable oscillatory response is much reduced, without a significant effect on the initial rate of response when the overshoot control term is introduced. It is expected that the influence of the time delay will be crucial in this application, with an effect not only on the damping of the system but also on the timing of the overshoot control term. Figure 11 also illustrates the effect of rate-limit control, with the onset of the overshoot control switch held back to ensure that the elevator demand rate does not exceed 50°/sec.

5.4 F-8C RAV Facility

One current constraint associated with the RAV facility is the time delay introduced by the telemetry communication with the ground-based computer. The RAV system mechanization for future programs will have significantly less delay. Improvements in the uplink hardware systems provide at least a tenfold increase in system bandwidth, as well as an uplink and downlink synchronization capability. These features will allow the RAV time delay to be reduced to a minimum.

6. CONCLUDING REMARKS

A major benefit of the NASA Dryden F-8C remotely augmented vehicle (RAV) facility is a reduction in the resources required to implement experimental control laws in the flight-test program, since the safeguards built into the facility obviate the need to produce flight-critical, high-integrity software. Furthermore, the control-law software is written in a high-level language (FORTRAN) and the structure and logic are, therefore, readily understood by the engineers and scientists working on the program. Additional safeguards introduced to the RAV facility for the NASA/RAE CADRE program have proved very successful in widening the maneuver envelope of the aircraft, while maintaining a low level of uncommanded reversions to the on-board system.

The additional time delay associated with the current RAV facility did influence both the stability and handling assessment of the experimental control laws. Nevertheless, meaningful results can be obtained by comparing the behavior of different control laws when the time delay is present.

The initial stage of the CADRE program has successfully illustrated the potential of variable-gain control laws, which allow the closed-loop gains to rise transiently to levels that would not be desirable for continuous operation owing to excessive noise-induced actuator activity. As a result of experience gained during the first stage of flight experiments, the introduction of improvements to the variable-gain control laws and the inclusion of further nonlinear techniques developed by RAE are planned in the near future.

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TABLE 1. SUMMARY OF PILOT RATINGS FOR AIR-TO-AIR TRACKING TASK

System	Description	Rating	
		Pilot A	Pilot B
On board			
SAS	Stability augmentation system; no time delay	5-6	5
Low overshoot controllers			
Baseline	CADRE baseline controller	4	5
VICTOR	High-gain variable-gain controller	--	--
VICTOR	Mid-gain variable-gain controller	3	3
VICTOR	Variable-gain simulation of baseline	4	5
Higher overshoot controllers			
Baseline	CADRE baseline controller	4	7
VICTOR	High-gain variable-gain controller	--	--
VICTOR	Mid-gain variable-gain controller	4	5
VICTOR	Variable-gain simulation of baseline	4-5	10

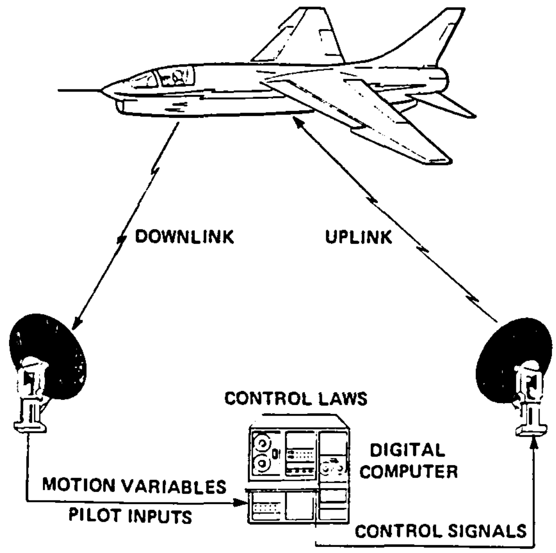


Fig. 1. F-8C DFBW RAV flight test technique.

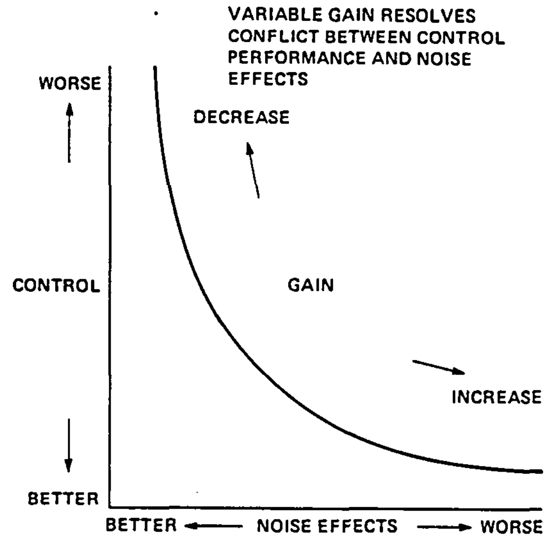


Fig. 2. VICTOR nonlinear control policy.

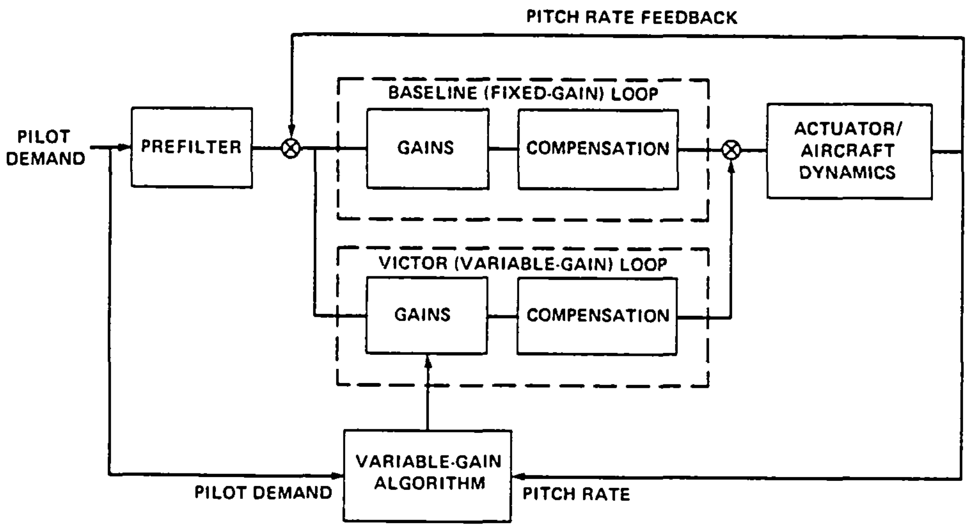


Fig. 3. General structure of RAE nonlinear pitch-rate controller.

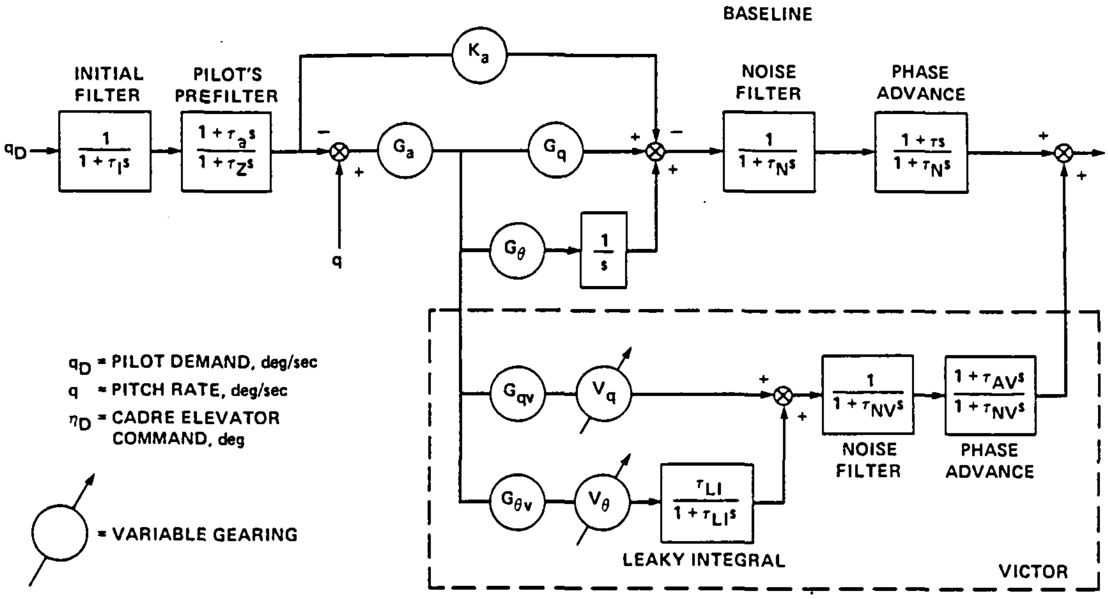


Fig. 4. Baseline plus VICTOR-E pitch-rate controller.

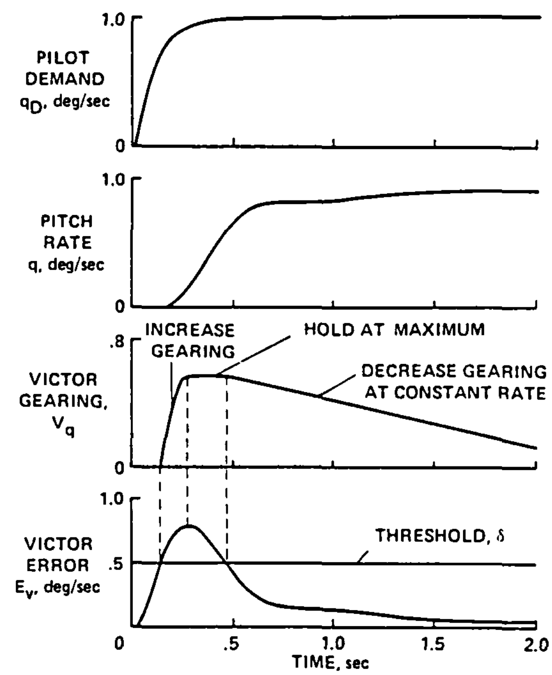


Fig. 5. Operation of VICTOR-E algorithm.

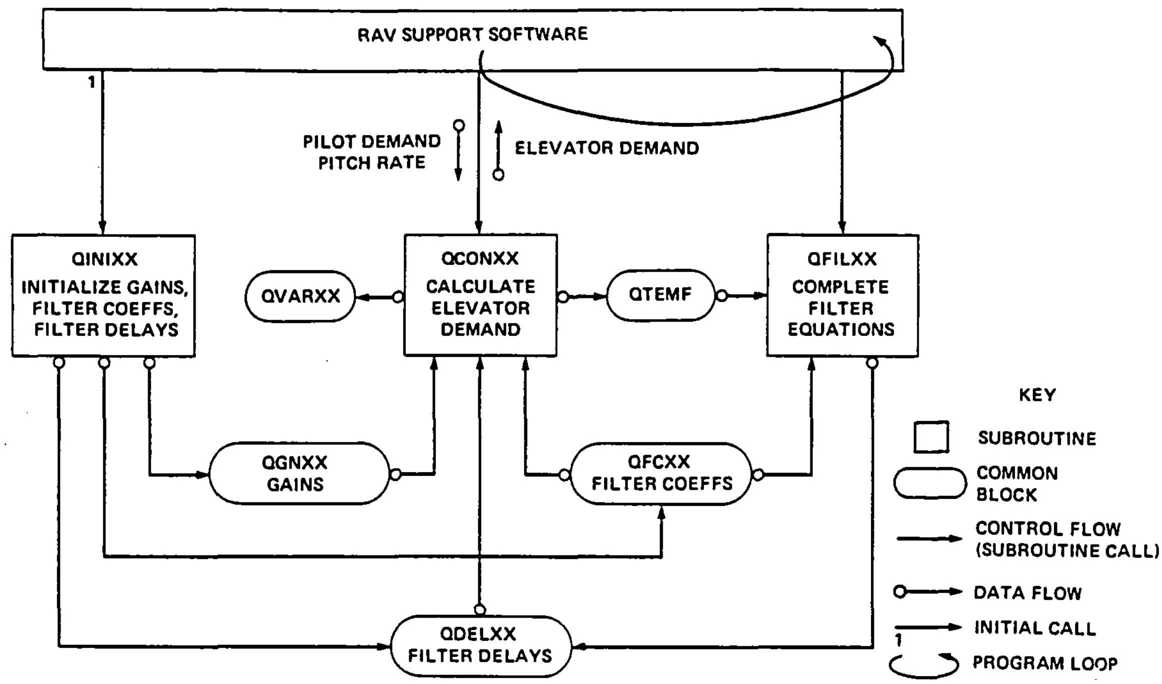


Fig. 6. Software structure for CADRE control laws.

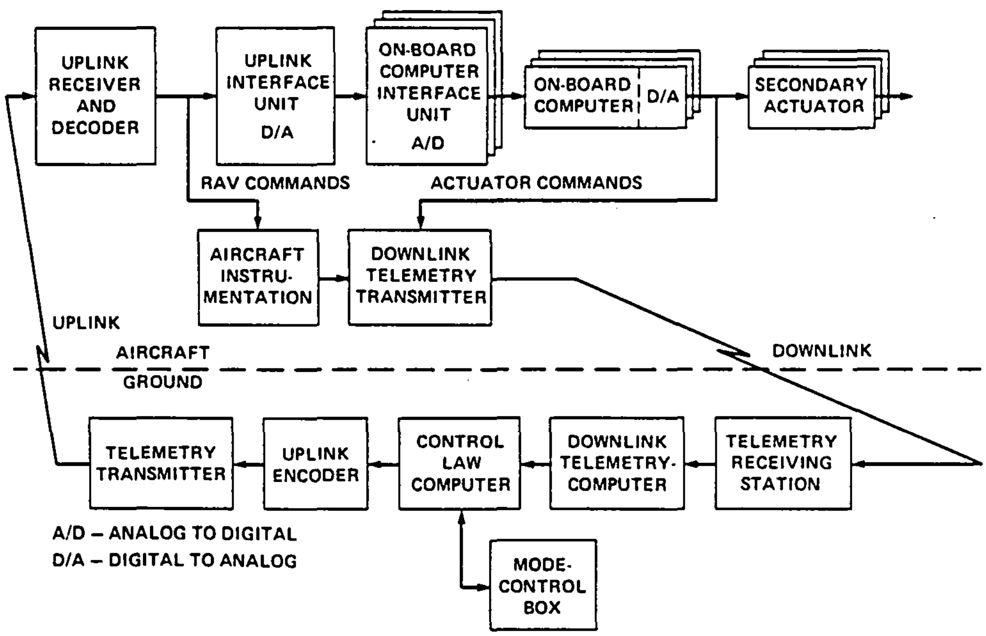


Fig. 7. Primary hardware elements of RAV system.

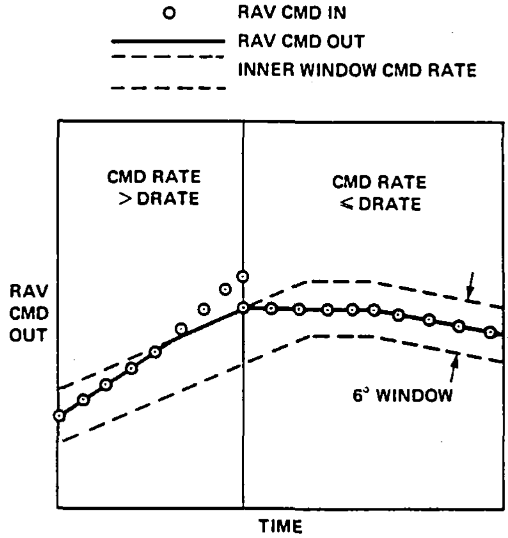


Fig. 8. F-8C DFBW floating RAV limiter.

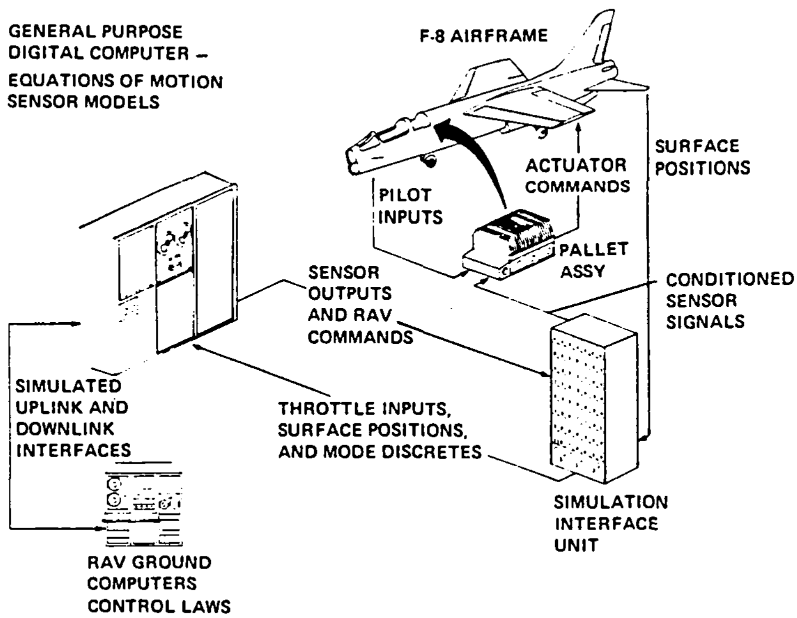
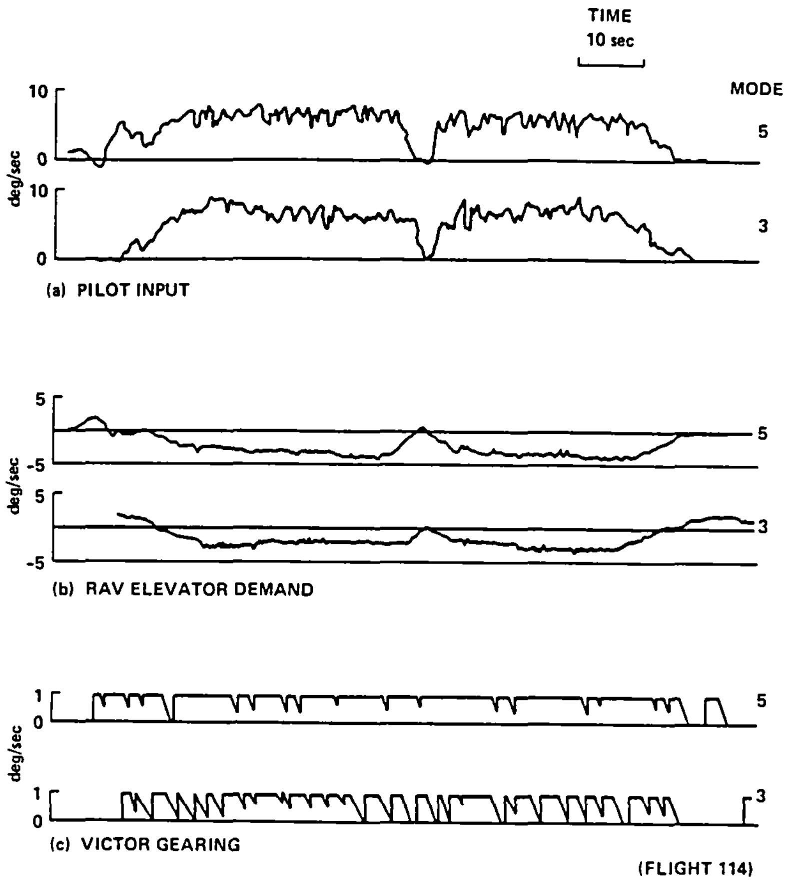


Fig. 9. F-8C DFBW iron-bird simulation facility configured for RAV system testing.



CONTROL MODE: BASELINE, PILOT RATING (4)
CONTROL MODE: MID-GAIN VICTOR, PILOT RATING (3)

Fig. 10. Flight traces for baseline and mid-gain VICTOR systems.

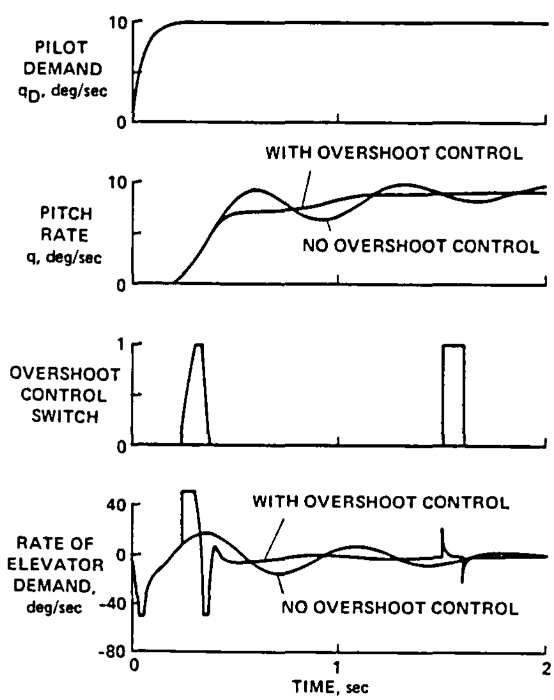


Fig. 11. Effect of overshoot control.

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16. Abstract

A cooperative advanced digital research experiment (CADRE) was established by the National Aeronautics and Space Administration (NASA) and the Royal Aircraft Establishment (RAE), in which non-linear control algorithms developed by the RAE were tested on the F-8C digital fly-by-wire (DFBW) aircraft based at the Dryden Flight Research Facility. In the initial phase of the collaboration, some variable-gain algorithms, referred to collectively as variable integral control to optimize response (VICTOR) algorithms, were flight tested. With VICTOR, various measures available within the control system are used to vary gains and time-constants within the closed loop and thereby enhance the control cpability of the system, while reducing the adverse effects of sensor noise on the control surfaces. A review of design procedures for VICTOR and results of preliminary flight tests are presented. The F-8C aircraft is operated in the remotely augmented vehicle (RAV) mode, with the control laws implemented as FORTRAN programs on a ground-based computer. Pilot commands and sensor information are telemetered to the ground, where the data are processed to form surface commands which are then telemetered back to the aircraft. The RAV mode represents a single-string (simplex) system and is therefore vulnerable to a hardover since comparison monitoring is not possible. Hence, extensive error checking is conducted on both the ground and airborne computers to prevent the development of potentially hazardous situations. Experience with the RAV monitoring and validation procedures is described.

17. Key Words (Suggested by Author(s))
Nonlinear control
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