

Design and Flight Testing of Digital Direct Side-Force Control Laws

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Three-input/three-output command augmentation control laws have been designed and tested in flight using Princeton's Variable-Response Research Aircraft. Controllers were based upon algebraic model-following, a fast and efficient method of direct digital synthesis for advanced control modes. Pilot opinions of several command modes and controller-to-command pairings are presented in this paper. Flat turns, lateral translation, and roll control were investigated. Of the command modes tested, foot pedals-to-yaw rate, lateral stick-to-roll rate, and thumb lever-to-sideslip angle provided the best overall ratings.

Introduction

WITH conventional controls, the pilot's influence on an aircraft's flight path is complex. Cockpit control motions are transformed from elevator/aileron positions through angular accelerations and attitudes to lift modulation and orientation, finally producing vertical and horizontal forces that accelerate the flight path. For the past decade, there has been considerable interest in the possibilities for improving flight path control by direct command of lift and side force. Added control surfaces would produce the necessary forces, allowing linear and angular motions to be decoupled or "re-coupled" in ways that may be advantageous for differing piloting tasks. Control-Configured-Vehicle (CCV) command modes are designed with these objectives in mind.

In the lateral-directional case, aileron, rudder, and side-force panel deflections can be blended to achieve flat turn, wings-level sideslip, fuselage pointing, and conventional rolling motions. However, while the unconventional command modes may improve pilot performance for some tasks, they may degrade it for others. Furthermore, pilot acceptance of unfamiliar responses must be addressed; cues that contradict the pilot's training can be uncomfortable and disorienting, at best requiring a period of learning and adaptation, and at worst preventing satisfactory control.

An earlier study indicated that pilots place high value on natural response to conventional control inputs in the approach and landing.¹ Two pilots evaluated various interconnects of side-force and conventional control deflections as well as separate side-force control in Princeton's Variable-Response Research Aircraft (VRA), shown in Fig. 1. They preferred separate side-force control because it required a minimum readjustment in piloting style and because the response to all controls was predictable. The VRA's dynamics were unaugmented in these tests, and an analog fly-by-wire system was used for control. Although Ref. 1 illustrated how to achieve open-loop decoupling of the steady-state responses, the configurations tested in flight possessed varying degrees of coupled response. In the interim, attention was directed to digital control design and implementation, as well as to pilot opinions of associated flying qualities.²⁻⁶

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The present paper reports on a recent VRA program in which closed-loop digital control was used to provide a range of stability and response characteristics with coordinated deflections of ailerons, rudder, and side-force panels. Digital CCV control laws were developed using an algebraic model-following technique whose gain computation is considerably simpler than that of the linear-quadratic (LQ) regulator (although the control structure is identical) and which incorporates the concepts of quasi-steady equilibrium presented in Refs. 5 and 6. In all cases, the pilots used foot pedals, lateral stick, and thumb lever for control inputs; however, the command variables assigned to each controller varied among modes. (For example, a constant foot pedal deflection would be interpreted as a constant yaw rate command in one mode and as a constant sideslip command in another.) Flight test results are discussed after presenting details of control law design and implementation.

Digital Control Law Development

Aircraft Model

The discussion of model development follows Ref. 5. Lateral-directional motions of an aircraft can be described by the fourth-order linear differential equation

$$\Delta \dot{x} = F \Delta x + G \Delta u \quad (1)$$

The state vector, Δx , represents perturbations in yaw rate (Δr), sideslip angle ($\Delta \beta$), roll rate (Δp), and roll angle ($\Delta \phi$):

$$\Delta x = (\Delta r \ \Delta \beta \ \Delta p \ \Delta \phi)^T \quad (2)$$

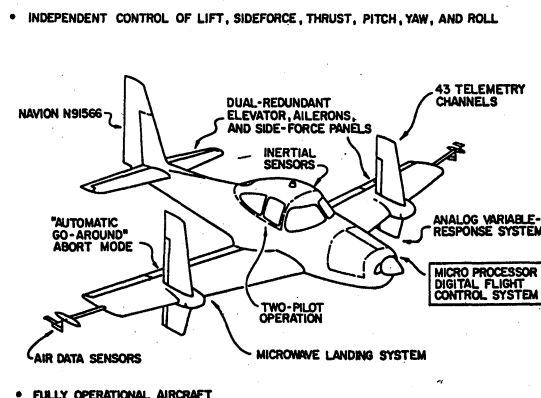


Fig. 1 Variable-response research aircraft (VRA).

The VRA can be controlled independently in all six degrees of freedom, as it is equipped with direct-lift and direct-side-force surfaces in addition to its conventional controls. Longitudinal motions were not a subject for study (although they were controlled by the pilot in flight); hence, the control vector Δu considered here represents perturbations in rudder angle ($\Delta\delta R$), side-force panel angle ($\Delta\delta SF$), and aileron angle ($\Delta\delta A$):

$$\Delta u = [\Delta\delta R \ \Delta\delta SF \ \Delta\delta A]^T \quad (3)$$

The corresponding stability and control matrices, F and G , are defined as:

$$F = \begin{bmatrix} N_r & N_\beta & N_p & 0 \\ -1 & Y_\beta/V & 0 & g/V \\ L_r & L_\beta & L_p & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (4)$$

$$G = \begin{bmatrix} N_{\delta R} & N_{\delta SF} & N_{\delta A} \\ Y_{\delta R}/V & Y_{\delta SF}/V & Y_{\delta A}/V \\ L_{\delta R} & L_{\delta SF} & L_{\delta A} \\ 0 & 0 & 0 \end{bmatrix} \quad (5)$$

Taking straight-and-level flight with an indicated airspeed of 105 knots as the nominal flight condition, the numerical values of the VRA's lateral-directional matrices were represented as⁷

$$F = \begin{bmatrix} -0.75 & 5.3 & -0.26 & 0.0 \\ -1.0 & -0.4 & 0.0 & 0.181 \\ 1.16 & -11.5 & -6.5 & 0.0 \\ 0.0 & 0.0 & 1.0 & 0.0 \end{bmatrix} \quad (6)$$

$$G = \begin{bmatrix} -6.1 & 2.1 & -0.222 \\ 0.0935 & 0.38 & 0.0 \\ 0.6 & 0.0 & 21.0 \\ 0.0 & 0.0 & 0.0 \end{bmatrix} \quad (7)$$

(All angles are measured in radians or degrees.)

Direct digital synthesis was used to design the command augmentation control laws, so it was necessary to define the discrete-time equivalent of Eq. (1)

$$\Delta x_{k+1} = \Phi \Delta x_k + \Gamma \Delta u_k \quad (8)$$

Under the assumption that the controls are held constant between periodic sampling instants, t_k , the outputs of this recursive difference equation are identical to the integration of Eq. (1) when Φ and Γ are chosen as

$$\Phi = e^{FT} = I + FT + (FT)^2/2 + \dots \quad (9)$$

$$\Gamma = \Phi^T [I - FT/2 + (FT)^2/6 - \dots] G \quad (10)$$

where I is the identity matrix. Therefore, Eq. (8) is a suitable model of aircraft dynamics for control design.

Equilibrium Response

A constant command input, Δy^* , specifies equilibrium values of the state and control vectors, Δx^* and Δu^* ,

collectively known as the regulator set point. Perturbations from the set point are described by,

$$\Delta \tilde{x}(t) = \Delta x(t) - \Delta x^*(t) \quad (11)$$

$$\Delta \tilde{u}(t) = \Delta u(t) - \Delta u^*(t) \quad (12)$$

Assuming that the pilot's commands can be interpreted as some linear combination of the state and control, a constant pilot command should result in constant state and control vectors:

$$\Delta y^* = H_x \Delta x^* + H_u \Delta u^* \quad (13)$$

H_x and H_u define the command relationship, and the dimensions of Δy and Δu are assumed to be equal. At equilibrium, $\Delta x_{k+1} = \Delta x_k$, so the combined solution of Eqs. (8) and (13)

$$\begin{bmatrix} (\Phi - I) & \Gamma \\ H_x & H_u \end{bmatrix} \begin{bmatrix} \Delta x^* \\ \Delta u^* \end{bmatrix} \triangleq W \begin{bmatrix} \Delta x^* \\ \Delta u^* \end{bmatrix} = \begin{bmatrix} 0 \\ \Delta y^* \end{bmatrix} \quad (14)$$

leads to a direct solution for Δx^* and Δu^* in terms of Δy^* :

$$\begin{bmatrix} \Delta x^* \\ \Delta u^* \end{bmatrix} = W^{-1} \begin{bmatrix} 0 \\ \Delta y^* \end{bmatrix} \triangleq S \begin{bmatrix} 0 \\ \Delta y^* \end{bmatrix} \quad (15)$$

or

$$\Delta x^* = S_{11}(0) + S_{12} \Delta y^* \quad (16)$$

$$\Delta u^* = S_{21}(0) + S_{22} \Delta y^* \quad (17)$$

As long as W is nonsingular, the partitions of S are:

$$S_{11} = (\Phi - I)^{-1} (-\Gamma S_{21} + I) \quad (18)$$

$$S_{12} = -(\Phi - I)^{-1} \Gamma S_{22} \quad (19)$$

$$S_{21} = -S_{22} H_x (\Phi - I)^{-1} \quad (20)$$

$$S_{22} = [-H_x (\Phi - I)^{-1} \Gamma + H_u]^{-1} \quad (21)$$

S does not exist when the state vector contains a pure integral of the command variable.⁶ By definition, the integral cannot be constant when the command is a nonzero constant. The problem can be solved by defining a quasi-steady equilibrium for a reduced-order system, treating the integral state as a forcing term that grows continuously as long as the command is constant. Equations (8) and (13) are partitioned as

$$\begin{bmatrix} \Delta x_1 \\ \Delta x_2 \end{bmatrix}_{k+1} = \begin{bmatrix} \Phi_1 & \Phi_2^I \\ \Phi_2^I & I \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \end{bmatrix}_k + \begin{bmatrix} \Gamma_1 \\ 0 \end{bmatrix} \Delta u_k \quad (22)$$

$$\Delta y^* = [H_{x_1} \ H_{x_2}] \begin{bmatrix} \Delta x_1^* \\ \Delta x_2^* \end{bmatrix} + H_u \Delta u^* \quad (23)$$

Δx_1 is the reduced-order state, and Δx_2 is the integral state. Neglecting possible $\Delta \dot{x}_1^*$ effects, the quasi-steady equilibrium is

$$\begin{bmatrix} \Delta x_1^* \\ \Delta u^* \end{bmatrix} = \begin{bmatrix} (\Phi_1 - I) \Gamma_1 \\ H_{x_1} \ H_u \end{bmatrix}^{-1} \begin{bmatrix} -\Phi_2^I \Delta x_2^* \\ \Delta y^* - H_{x_2} \Delta x_2^* \end{bmatrix}_k \\ = S' \begin{bmatrix} -\Phi_2^I \Delta x_2^* \\ \Delta y^* - H_{x_2} \Delta x_2^* \end{bmatrix}_k \quad (24)$$

and the integral state Δx_{2k} is propagated by

$$\Delta x_{2k}^* = \Delta x_{2k-I}^* + \Phi_I^* \Delta x_{1k-I}^* \quad (25)$$

For fourth-order, lateral-directional dynamics, the most likely cause of singular equilibrium is roll rate command, because roll angle is retained as a state variable. If roll angle is commanded instead, the equilibrium is nonsingular, because steady $\Delta\phi$ implies zero Δp . Yaw rate command is nonsingular because yaw angle does not appear in the fourth-order equations; however, if a fifth-order model including yaw angle perturbations were considered, yaw rate command would be singular.

Algebraic Model-Following

As shown in Ref. 8, a simple algebraic manipulation specifies the control law when a state-space model for the desired closed-loop system exists and when the conditions for "perfect" model-following are satisfied. Given the continuous-time model with zero set point

$$\dot{\Delta x}_M(t) = F_M \Delta x_M(t) + G_M \Delta u_M(t) \quad (26)$$

where Δx_M and Δu_M have the same dimensions as Δx and Δu and where $\Delta x_M(0) = \Delta x(0)$, the analog control law,

$$\begin{aligned} \Delta U(t) &= G^{\#} [(F_M - F) \Delta x(t) + G_M \Delta u_M(t)] \\ &\triangleq C_B \Delta x(t) + C_F \Delta u_M(t) \end{aligned} \quad (27)$$

provides perfect model-following if

$$(GG^{\#} - I)(F_M - F) = 0 \quad (28)$$

The control law provides model-following implicitly, making the system output behave like the model output without actually implementing the model in the control structure. $G^{\#}$ represents the left pseudo inverse of G and is defined as

$$G^{\#} = (G^T G)^{-1} G^T \quad (29)$$

As long as F_M takes the same form as F , i.e., the bottom row is [0010] [Eq. (4)], the closed-loop control need affect only the top three rows of F . In general, this requires three independent controls; hence, adding side-force control allows the perfect model-following capability that could not be obtained using only rudder and ailerons.

A digital model-following controller can be formed,

$$\begin{aligned} \Delta u_k &= \Gamma^{\#} [(\Phi_M - \Phi) \Delta x_k + \Gamma_M \Delta u_{Mk}] \\ &\triangleq C_B \Delta x_k + C_{FM} \Delta u_{Mk} \end{aligned} \quad (30)$$

where Φ_M and Γ_M are defined as in Eqs. (9) and (10). If

$$(\Gamma \Gamma^{\#} - I)(\Phi_M - \Phi) = 0 \quad (31)$$

then Eq. (30) provides perfect model-following at the sampling instants for the discrete-time case. To first order, satisfying Eq. (28) implies satisfaction of Eq. (31).

Digital regulation about a non-zero set point ($\Delta x^*, \Delta u^*$) could be provided by Eq. (30) using the (\sim) variables:

$$\Delta \tilde{u}_k = C_B \Delta \tilde{x}_k + C_{FM} \Delta \tilde{u}_{Mk} \quad (32)$$

from Eqs. (11) and (12),

$$\Delta u_k = \Delta u_k^* + C_B (\Delta x_k - \Delta x_k^*) + C_{FM} (\Delta u_{Mk} - \Delta u_{Mk}^*) \quad (33)$$

Two approaches can be followed. The pilot's input, Δy^* , can be used to define Δx^* and Δu^* , and C_{FM} can be considered

zero by design. For nonsingular equilibrium, Δx^* and Δu^* are specified by Eqs. (16) and (17); therefore, the control law is

$$\Delta u_k = (S_{22} - C_B S_{12}) \Delta y_k^* + C_B \Delta x_k \triangleq C_F \Delta y_k^* + C_B \Delta x_k \quad (34)$$

An identical effect can be achieved through appropriate choice of Γ_M (and, therefore, of C_{FM}), with the separate Δu_k^* taken to be zero.

For singular equilibrium, Eqs. (24) and (25) specify Δx_1^* , Δu^* , and Δx_2^* , so the control law is

$$\begin{aligned} \Delta u_k &= (S'_{22} - C_I S'_{12}) \Delta y_k^* + C_B \Delta x_k \\ &+ [(C_I S'_{11} - S'_{21}) \Phi_I^* - C_2] \Delta x_{2k}^* \end{aligned} \quad (35a)$$

where C_B is partitioned as $[C_I C_2]$ to be conformable with Δx_1^* and Δx_2^* . This can be written as

$$\Delta u_k = C_F \Delta y_k^* + C_B \Delta x_k + C_I \Delta x_{2k}^* \quad (35b)$$

By comparison with Ref. 5, the algebraic model-following control laws [(Eq. (34) or Eq. (35) plus Eq. (25)] are seen to have the same structures as the corresponding LQ regulators.

Command Vectors and Controller-Command Pairings

The choice of command variables and their assignment to cockpit control devices are important elements of CCV flight control design. They govern both the naturalness and the utility of the aircraft's response to control. The notion of "control harmony" can be applied to this process: the feet, hands, and thumbs can provide commands for essentially independent objectives, but poor choices of command variables and controller-command pairings could prevent effective control.

It is useful to review two interrelated aspects of CCV control design, although they may appear obvious. The first is that decoupling responses may do away with beneficial as well as adverse coupling, so it may be desirable to reintroduce a certain degree of coupling in the commands. The second is that more than one CCV command mode can be provided simultaneously. For example, flat turn and sidestep and conventional rolling modes can be contained in a single control law.

As an example of both good and bad features that can result, consider the following command vector:

$$\Delta y^* = [\Delta r^* \Delta \beta^* \Delta p^*]^T \quad (36)$$

The flat turn can be achieved by commanding Δr with zero $\Delta \beta$ and Δp . The sidestep results from commanding $\Delta \beta$ with zero Δr and Δp . Roll rate is achieved by commanding Δp , but the aircraft's response is not conventional with zero Δr and $\Delta \beta$ because lack of yaw rate indicates that there is no turning of the velocity vector. In a coordinated turn,

$$\Delta r^* = \frac{g}{V} \Delta \phi^* \quad (37)$$

and $\Delta \phi^*$ is the integral of Δp^* . Consequently, a *secondary command* to yaw rate that is proportional to the desired roll angle (either the integral of Δp^* or a direct roll angle command) is needed to achieve conventional rolling response.

The pilot could provide the secondary command manually, but a better solution would be to modify the command vector definition. Using Eq. (23), the above examples would become,

$$\Delta y^* \triangleq [H_{x_1} H_{x_2}] \begin{bmatrix} \Delta x_1^* \\ \Delta x_2^* \end{bmatrix} \quad (38a)$$

or

$$\begin{bmatrix} \Delta y_1^* \\ \Delta y_2^* \\ \Delta y_3^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & -g/V \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta r^* \\ \Delta \beta^* \\ \Delta p^* \\ \Delta \phi^* \end{bmatrix} \quad (38b)$$

with singular roll rate command and from Eq. (13)

$$\Delta y^* \triangleq H_x \Delta x^* \quad (39a)$$

or,

$$\begin{bmatrix} \Delta y_1^* \\ \Delta y_2^* \\ \Delta y_3^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & -g/V \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta r^* \\ \Delta \beta^* \\ \Delta p^* \\ \Delta \phi^* \end{bmatrix} \quad (39b)$$

with nonsingular roll angle command.

A fuselage pointing mode with constant lateral flight path angle $\Delta \xi$ also would require a secondary command. Since

$$\Delta \xi = \Delta \psi + \Delta \beta \quad (40)$$

where $\Delta \psi$ is the yaw (or heading) angle perturbation, a yaw angle command should be accompanied by a negative sideslip angle command. The dynamic equation and state vector [Eq. (1) and (2)] would be augmented to include $\Delta \psi$, and singular or nonsingular command vectors would be defined as in the rolling example.

Once command vectors have been defined, the problem of which cockpit controller should direct which command motion remains. Prior studies indicate varying opinions as to which controller-command pairings are best. Reference 1 found that pilots preferred uncoupled thumb lever side-force command, as mentioned earlier. Foot pedals were used to achieve the flat turn in Ref. 9, while side force was geared to the lateral control wheel for the approach-and-landing simulations of Ref. 10. A throttle-mounted controller was used to command sideslip in Ref. 11, with pedals commanding the flat turn and lateral stick commanding roll. Pilots preferred to use foot pedals for all of the advanced command modes reported in Ref. 12; a thumb switch was

considered useful only for precise pointing adjustments in the flat turn mode.

Although a number of possible controller-command pairings were considered, as reported in Ref. 7, only those configurations listed in Table 1 were tested in flight. In this list, foot pedals, thumb lever, and lateral stick are identified as $\Delta \delta P$, $\Delta \delta T$, and $\Delta \delta S$, respectively. Where there is more than one mode number for a single command vector, model dynamics have been modified as described in a later section. Note that the pilot had to coordinate turns in all but the last pairing.

Model Dynamics and Response

The model dynamics used for control system design can be chosen independently from the command vectors. Consequently, it is possible to have decoupled equilibrium response and coupled transient response (or vice versa) in the closed-loop CCV controller. Because this degree of design freedom is not possible with conventional controls, the guidance provided by Ref. 13 is minimal, and the development of flying qualities criteria for aircraft with CCV command modes is an area of active research.¹⁴

The present paper provides flying qualities¹ evaluation of five dynamic configurations in concert with four controller-command pairings. The nominal steady-state response characteristics of the modes are indicated by Table 1, and the modal characteristics of response are defined by the eigenvalues and eigenvectors listed below. These configurations are representative of CCV modes but do not provide exhaustive coverage of the range of possible parameters.

Initial flight tests illustrated the need for a type of dynamic coupling that normally is taken for granted. Several of the decoupled models originally were defined with stable real roots and zero "directional stability" (N_β). While the aircraft was controllable, its heading wandered when left unattended, forcing the pilot to exert positive control over this "nuisance motion." The models' N_β were set at near-nominal VRA values for the remainder of the flights.

The model eigenvalues, λ_i , and the two largest eigenvector components for each mode are summarized in Table 2. While a conventional aircraft possesses a lightly damped oscillatory Dutch roll mode (ω_{n1} , ξ_1) and real roll and spiral modes (λ_3 and λ_4), none of the design models was entirely conventional. The Dutch roll mode was either heavily damped or real (λ_1, λ_2), and several of the configurations had heavily damped roll-spiral oscillations (ω_{n2} , ξ_2). As shown in Ref. 7, all modes had virtually deadbeat response, i.e., overshoot of 10% or less, of the commanded variables. The principal dynamic coupling was between Δr and $\Delta \beta$ (as a consequence of the models' N_β) and between Δp and $\Delta \phi$ (due to their integral relationship). The mode 2, 3, and 4 models contained the VRA's g/V term in $F(2,2)$, which was zero for the other configurations; therefore, a steady roll rate command caused a steadily increasing $\Delta \beta$ perturbation (proportional to $\Delta \phi$).

Roll angle commands for modes 6-8 were accompanied by secondary yaw rate commands. Because $\Delta \phi$ and Δr were basically uncoupled in the design models, each had a different step response rise time. These configurations also contained L_ϕ terms, which induced the roll-spiral oscillations.

Table 1 Controller-command pairings

Controller	$\Delta \delta P$	$\Delta \delta T$	$\Delta \delta S$
Mode no.	Command		
1,2	Δr	$\Delta \beta$	Δp
3	$\Delta \beta$	Δr	Δp
4	$\Delta \beta$	Δp	Δr
6,7,8	Δr	$\Delta \beta$	$\Delta \phi^a$

^aPlus secondary Δr command

Table 2 Eigenvalues and eigenvectors of the CCV design models

Mode no.	Eigenvalues and [eigenvector components], rad or rad/s			
	λ_1 (ω_{n1})	λ_2 (ξ_1)	λ_3 (ω_{n2})	λ_4 (ξ_2)
1	-9.3 [r, β]	-2.7 [β , r]	-10.0 [p, ϕ]	0.0 [ϕ]
2,3,4	-9.3 [r, β]	-1.6 [β , r]	-6.5 [p, ϕ]	0.0 [ϕ , β]
6	-5.0 [r, -]	-2.0 [r, β]	(3.6) [p, ϕ]	(0.7) -
7	(2.4) [r, β]	(0.8) -	(4.0) [p, ϕ]	(1.0) -
8	(2.1) [r, β]	(1.0) -	(2.0) [r, p]	(1.0) -

Flight Control Implementation

The primary tasks of the microprocessor-based digital flight control system (Micro-DFCS) were to accept analog information from aircraft sensors (including the evaluation pilot's controls), to calculate the control laws, and to send analog commands to the VRA control effectors at periodic instants in time. The model 2 Micro-DFCS consisted of a flight control computer unit (FCCU) and a control-display unit (CDU).⁷ The FCCU contained six Multibus boards for analog input, analog output, central processing, arithmetic processing, main memory storage, and backup memory storage. Although the Z-80A central processor used 8-bit data words, all mathematical operations used 32-bit floating-point format. Analog inputs and outputs were quantized at the 12-bit level. The hand-held CDU allowed the safety pilot, who also served as in-flight test conductor, to command and monitor the Micro-DFCS.

The flight control computer program (CAS-6) contained three sets of routines.⁷ The executive routines provided initialization, CDU interface, and memory check. The utility routines included data conversion, error detection, status driver, math driver, mode change, timer/sampling rate selection, variable pure delay, variable output quantization, and output limiting. The flight control routines provided mode set up for each mode change and interrupt service at each control sampling instant. The executive routines required 433 bytes of memory, while the utility routines were stored in 2412 bytes. The remaining 3288 bytes of CAS-6 contained the flight control routines. All coding was done using assembly language. CAS-6 service routines typically required 20 ms for a computation frame. The nominal sampling rate was 10 per s. Calculations required 5 ms per control surface, plus 5 ms for input and output. The integrator for singular-equilibrium control [Eq. (35)] was not implemented; this had no effect on the response for nonsingular command variables ($\Delta r, \Delta \beta, \Delta \phi$), and its effect on Δp command response would be seen only after a period of several seconds.

Prior to flight test, CAS-6 was tested in a hybrid simulation, which consisted of the Micro-DFCS plus an EAI TR-48 analog computer. The Micro-DFCS executed the CAS-6 control laws; the analog computer simulated VRA lateral-directional dynamics. The hybrid simulation provided an opportunity to verify digital simulation results, and it allowed system tests to be conducted prior to installing the Micro-DFCS in the VRA.

Flight Testing Results

The CCV controllers were evaluated in flight tests of the VRA using telemetry records of system response and opinions of test pilots. In addition to step responses, the telemetry data documented typical time histories during the landing approach, as well as during air-to-ground tracking.⁷ Engineering and research pilots provided commentary and numerical opinion ratings.¹⁵ (The opinion scale runs from 1 to 10, with 1 being the best.)

A number of factors contributed to differences in flight records and previously simulated results, including differences between actual VRA dynamics and the linear mathematical model used in design, actuator dynamics,

turbulence, sensor errors, analog filtering of selected signals, sampling delay of pilot inputs, and telemetry scaling uncertainties. Nevertheless, the expected response characteristics generally were validated by flight testing, i.e., the simulated and achieved time histories were very nearly the same. As an example, the side-force panels have an effective bandwidth of about 3 Hz, which was not modeled in the design process. A 5-deg sideslip angle command in mode 1 calls for a peak $\Delta \delta S^F$ of 22 deg in simulation, but only 10 deg was realized in flight. In spite of this, the $\Delta \beta$ and Δr traces were very nearly the same in both cases. The secondary command for turn coordination does not appear to have functioned in the mode 7 response. Turbulence response of the VRA sideslip vanes contributed to occasional erratic behavior.

The landing approach flights could be separated into three phases: 180-deg turn from downwind leg to final approach (TF), final approach using an aircraft carrier landing mirror for guidance (FA), and maintaining runway centerline past the threshold (MC). The task typically was accomplished with a coordinated banked turn, a flat turn for final approach alignment, and lateral translation while maintaining the centerline. It was determined that the flat turn was not suitable for the 180-deg turn. The lateral acceleration was uncomfortable; the conventional banked turn aided the pilot in visual acquisition of the approach path. The sidestep maneuver had limited value until crossing the runway threshold, when it became useful for nulling lateral velocity, particularly in a crosswind condition.

The research pilot's ratings for five of the modes and the engineering pilot's rating for a single mode are contained in Table 3. Numerical ratings for each mode are averaged from two runs (except as noted), and comments are summarized below.

Mode 2's uncoordinated roll rate command mode was found to be "odd;" foot pedal usage was "tough," and "not likeable on final." Thumb lever command of β was "OK," "dandy, but a bit sensitive." Mode 3's lack of roll coordination was not liked. It was awkward learning to "center the ball with the thumb (lever)," but the pilot was "happy to keep the wings level on approach and use the thumb." "Foot pedal input sends the ball out." This created a conflict in heading and lateral velocity control during centerline tracking. Mode 4 assigned all commands to the wrong controllers. The pilot was unable to learn the new techniques required for control in just two runs: "only way to fly is feet on the floor, roll level then thumb off, then fly turn stick—crazy!" Mode 2 was the closest to natural command-controller pairings and received the best rating of the three; however, the lack of turn coordination precluded satisfactory pilot ratings.

The roll-attitude command configurations were easy to control. For mode 6, the engineering pilot found the "gain on β too high, otherwise good type of control," with uncomfortable ride quality in turbulence. The yaw rate command was "not much help." The research pilot found mode 7's roll command "no advantage on turn, OK on final." The sidestep was "handy," and the wings-level turn was "OK, but no great shakes." Comments on mode 8 were similar; the mode possessed a "nice coordinated turn," but "adverse yaw" was associated with the sidestep. As has been found in many previous studies, the pilot did not like to hold roll attitude with the stick for long periods of time.

Both pilots were sensitive to thumb lever dynamics and output. Initially, the lever was lightly damped, had little natural centering, and was prone to thumb slippage. Direct commands often were found to be too abrupt. Adding a damper, centering spring, sandpaper surface, and low-pass output filter improved the utility of the lever.

Air-to-ground tracking with modes 1, 2, and 8 was investigated briefly. A rudimentary fixed sight was used to maintain track on landmarks at ranges of two to five miles.

Table 3 Pilot ratings of the landing approach task

Mode no.	TF	FA	MC
2	4.75	3.5	3.25
3	5.0	4.75	5.75
4	6.5	7.5	7.75
6 ^a	3.2	3.5	3.0
7	5.0	3.75	3.5
8	3.5	3.75	4.0

^a 3 runs, engineering pilot

The pilots preferred rolling to turn at long range, using the flat turn and sidestep only at short range.

Conclusion

Algebraic model-following provides a simple and effective method of designing CCV control laws when the conditions for perfect model-following are satisfied. Command variables, equilibrium response, and modal dynamics can be chosen independently, allowing substantial flexibility in design. Flight test results showed that careful consideration should be given to providing beneficial coupling, including the use of secondary command variables and feedback that gives the aircraft classical dynamic properties. Pilots attach great importance to natural, predictable response with a minimum requirement for positive control of "nuisance motions." The flight test results reported here tend to confirm this, but a systematic flight investigation of CCV model parameters remains for the future.

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