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Computer-Aided Design of Flight Control Systems

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ABSTRACT

A comprehensive computer program for designing and evaluating multidisciplinary aircraft flight control systems is described. The *FlightCAD* program contains a variety of modeling, synthesis, analysis, and simulation alternatives. The program will be used to produce a control design for the *1991 AIAA Controls Design Challenge* (to be completed in 1992). *FlightCAD* ultimately will implement a number of control design techniques; here it uses direct digital synthesis to produce a robust, proportional-integral-filter controller with scheduled linear-quadratic-Gaussian gains and command generator tracking of pilot inputs. The *FlightCAD* design approach is reviewed, and a status report is presented.

INTRODUCTION

Designing flight control systems for modern aircraft continues to be a challenging task: high-performance aircraft are becoming harder to control as a consequence of lighter weight, broader flight envelopes, and increased performance requirements. There has been a transition from inherently stable configurations with relatively rigid airframes and traditional control surfaces to flexible, unstable configurations with multi-function, redundant control surfaces. Flight control systems with mechanical linkages and limited-authority, analog, stability augmentation have been replaced by full-authority, fly-by-wire, digital, command augmentation. The desire for "Level 1" flying qualities throughout the flight envelope leads to coupled, high-gain controllers that excite structural modes and interact with control-actuator dynamics, and there is increasing need to integrate flight controls with engine controls and load-alleviation functions. These are important precursors to *multidisciplinary design*, in which aerodynamic, structural, propulsive, and control functions are considered together.

Currently available computer-aided control system design (CACSD) programs facilitate design in many ways, but they fall short in flight-control-specific features. Factors that must be addressed include:

- flight dynamic modeling
- approximating aerodynamic, structural, propulsive, and control functions
- generating nominal flight paths and flight envelope
- satisfying flying qualities criteria
- adapting to flight condition
- analyzing stability and performance robustness

These capabilities should be accessible in an easily understood, interactive format that is intuitive, comprehensive, and requires little supplemental programming.

The *FlightCAD* computer program is intended to address these needs. It will have broad capabilities for modeling aircraft systems and subsystems, for integrating their coupled effects in simulation, and for designing flight control systems over the entire flight envelope. The program uses a desktop metaphor to organize the design process, with a menu bar, pull-down lists of design functions and alternatives, dialog boxes, and multiple display windows. *FlightCAD* is implemented using features of the NeXT Computer for designing user interfaces, integrating code produced in several programming languages, and multitasking within a UNIX environment.

In the remainder of the paper, the *1991 AIAA Controls Design Challenge* is briefly reviewed, the architecture of *FlightCAD* is outlined, the Challenge Design control logic is presented, and the current status of development is outlined.

1991 AIAA CONTROLS DESIGN CHALLENGE

The *1991 AIAA Controls Design Challenge* presents six-degree-of-freedom dynamic, aerodynamic, and thrust data for a high-performance aircraft in the form of FORTRAN code and written specifications [1]. Its specified goals are to design an automatic digital controller that a) can maintain straight-and-level flight at a specified altitude and Mach number, b) can control normal acceleration, altitude, and Mach number in a constant-g turn, and c) can provide a level acceleration from subsonic to supersonic flight. The Challenge is motivated by many of the factors mentioned above, as well as by practical issues often overlooked in theoretical development. Control design solutions must account for significant nonlinearities, time variations, and uncertainties in aircraft dynamics; limited and imprecise sensors; and control surface dynamics, including displacement and rate limits. Bias errors, scale factor variations, disturbances, and noise effects also must be considered.

OVERVIEW OF *FlightCAD*

FlightCAD is a CACSD program focused on aircraft dynamics, flight control systems, stability, and performance. It is built around a desktop metaphor that features pull-down menus and dialog boxes containing design alternatives, and documents with multiple layers of information. The program runs in the NeXTStep 2.0 environment on a NeXTCube 68040 Computer.

On first startup, *FlightCAD* presents two blank windows, icons of frequently used software "tools," and a menu side-bar (Fig. 1). One window contains a *FlightCAD* document (a *CADdoc*), and the other supports a simple text editor for function entry and revision. The standard NeXT icon dock is modified to display only programs relevant to FlightCAD. The top-level menu items describe *FlightCAD's* functions and features. Several of the items are common to most window-based applications (such as Info and Edit); those that are specific to *FlightCAD* include:

Block Diagram - Define and display the structure and substructures of the system's elements, as depicted in the *CADdoc*.

Model - Build differential equations, algebraic equations, and transfer functions that describe the reference frame, aircraft (including inertial, aerodynamic, propulsive, elastic properties), actuators, sensors, and flight computer.

Design - Compute operating points, trajectories, and flight envelope. Portray nonlinear functions. Synthesize control and estimation logic.

Analyze - Compute time and frequency responses. Evaluate stability and performance. Conduct statistical studies of

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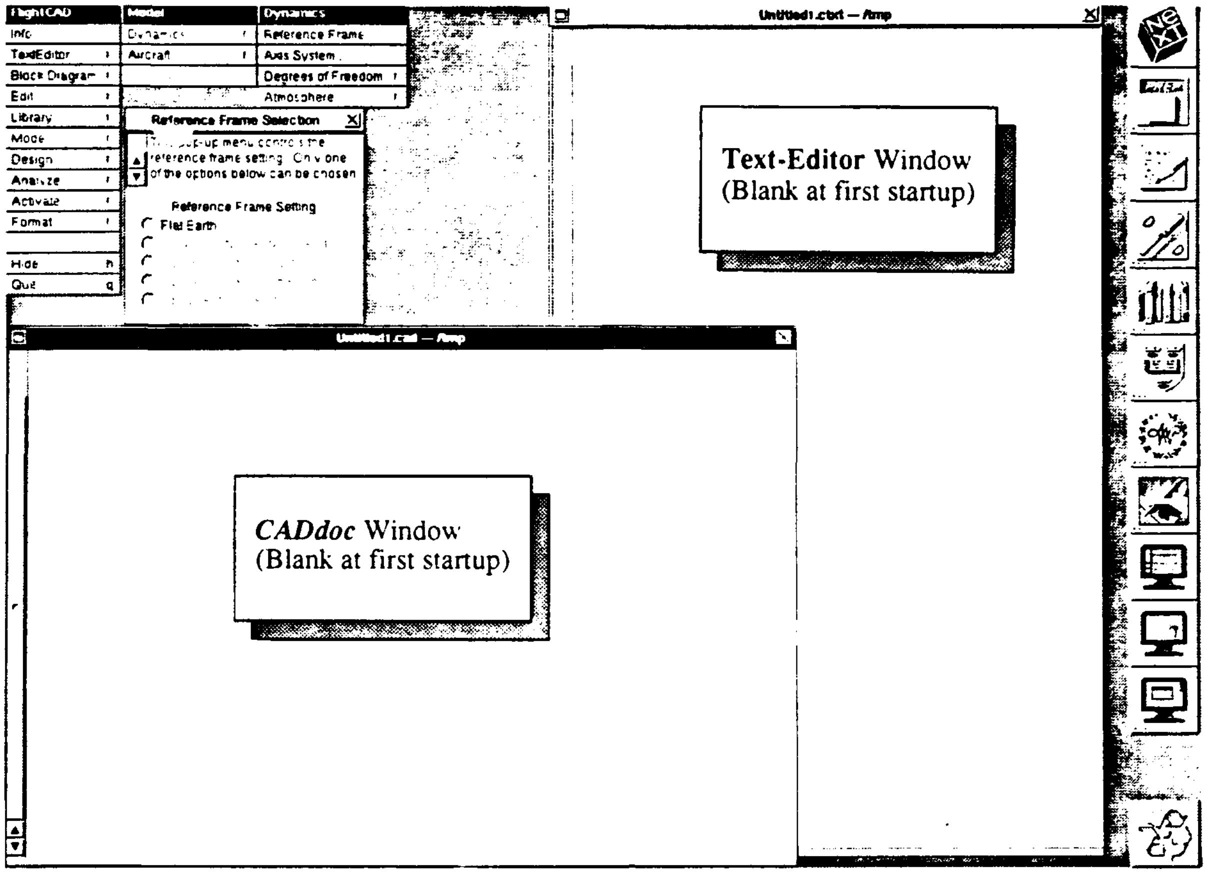

Figure 1. *FlightCAD* at first startup.

computational results, including Stochastic Robustness Analysis.

Activate - List of all open documents. Selecting a name brings that document into the foreground.

Menus and submenus are arranged in a natural hierarchy. In the example (Fig. 2), "Model" is the top-level selection, "Dynamics" is the second-level selection, "Reference Frame" is the third-level selection, and "Flat Earth" has been selected as the dynamic modeling frame of reference. This "point-and-click" process defines the equations of motion to be used for control design and simulation. Most remaining choices can be selected in the same way, and the NeXTStep environment makes adding menu items an easy process.

FlightCAD's focal point is the block diagram. The *FlightCAD* document contains diagrams drawn by the user to represent the system. Each block has several labels that describe its properties (Fig. 3); for example, a given block might have a label, its contents might be stored in a filename, its function may assume continuous- or discrete-time modeling ('CT' or 'DT'), and it might have a number of inputs and outputs. Unknown properties are designated with a question mark. A block can contain a function (and be marked with an 'F'), which can be edited in a text-editor window (Fig. 4), or another block diagram (and be marked with a 'B'), which can be opened and examined in a separate *CADdoc*. In this way, the user can navigate through the existing hierarchy of inner and outer loops. Blocks can be moved, examined and connected with multi-variable links using the menu items. Connections between blocks can carry as many variables as the block(s) have inputs and outputs. All block parameters are easily changed through the appropriate menu items. The *CADdoc* block diagram can be exported as a PostScript picture for inclusion in a written document.

Block diagram templates facilitate system development. Figure 3 represents a typical flight control problem; it contains blocks for actuators, sensors, aircraft dynamics, the environment, and the control logic. This format allows quick development in as much detail as desired. If a given block is not required, its function is set to unity; hence, a control designer could simulate just the plant dynamics at first, then check the effect of pressure or temperature variations, add actuator and sensor dynamics, and finish with a controller that takes all of this into account.

FlightCAD translates the functions represented by block diagrams into C source code. At each step, *FlightCAD* incrementally compiles only those portions of the code that have changed since the last compilation, allowing development to occur in stages. This feature supports rapid prototyping and comparison of competing designs.

FlightCAD contains advanced iteration and search capabilities that enhance modeling, design, and analysis. In any phase, the controller can be evaluated at selected, tabulated, or random points of the operating range space, supporting point designs, designs along (or in the vicinity of) nominal path histories, or designs that span the entire flight envelope. This feature is useful not only during design but in the evaluation phase, when the likelihood of satisfactory stability and performance must be determined.

Control and estimation design algorithms ultimately will include a wide range of alternatives, from classical methods for single-input/single-output systems to modern methods of multi-input/multi-output design; from linear, time-invariant models to nonlinear, time-varying models; and for continuous and sampled-data controllers. Our response to the 1991 AIAA Controls Design Challenge focuses on gain-scheduled, linear-quadratic-Gaussian theory; hence, the associated elements of *FlightCAD*

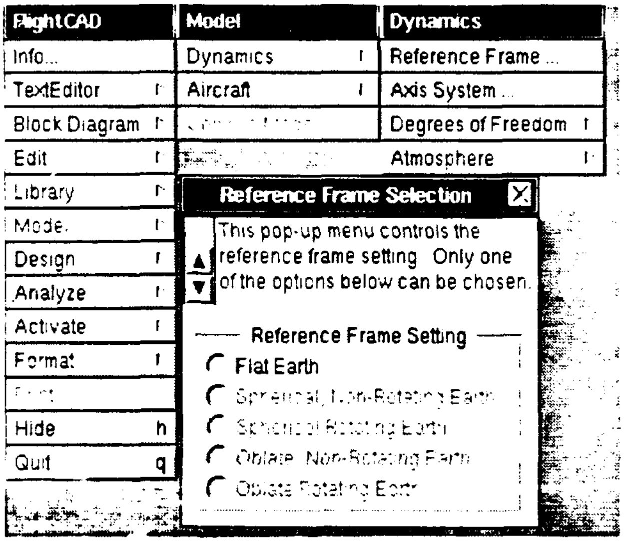

Figure 2. *FlightCAD*'s Menu Structure.

will be developed first. Succeeding efforts will broaden the program's capabilities.

CONTROL DESIGN PHILOSOPHY

Our Challenge Design has a conventional block-diagram structure, as indicated by Figure 3. The *Controller* block contains forward- and feedback-loop elements, and the *Estimator* block contains filters for model-based noise reduction. Feedback elements account for the effects of low-frequency disturbances, high-frequency noise, and plant uncertainty using Proportional-Integral-Filter (PIF) compensation. Forward-loop elements generate the desired state trajectory and corresponding nominal control settings using a Command-Generator-Tracker (CGT) structure. The digital flight control system (DFCS) takes an incremental form to facilitate initialization, interfacing with the nonlinear environment, and switching between command modes. The Estimator block contains a bank of reduced-order filters, with low-pass, complementary, and notch characteristics,

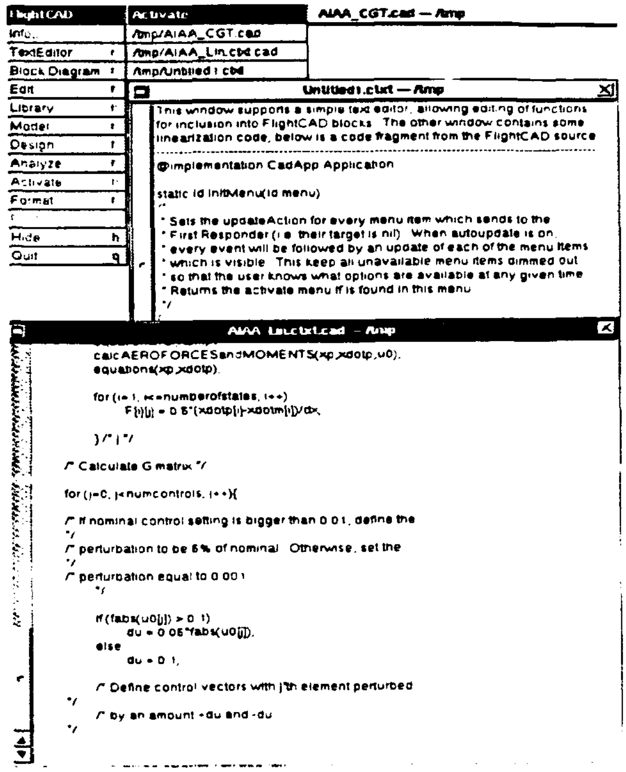

Figure 4. *FlightCAD*'s Editor Windows.

as appropriate. These filters follow a Kalman format, although the implementations are hierarchical and sub-optimal.

The Challenge Design DFCS is based on an evolution that began with the study of coupled, linear, time-invariant dynamic models of a rapidly maneuvering aircraft [2,3] and continued through the development of numerous linear-quadratic-Gaussian (LQG) flight control designs [4-19], seven of which were tested in flight. The dynamics and control of high-performance aircraft were investigated in [2-7], culminating in suggested designs for Type 0 and 1 controllers for an operational Naval aircraft. The

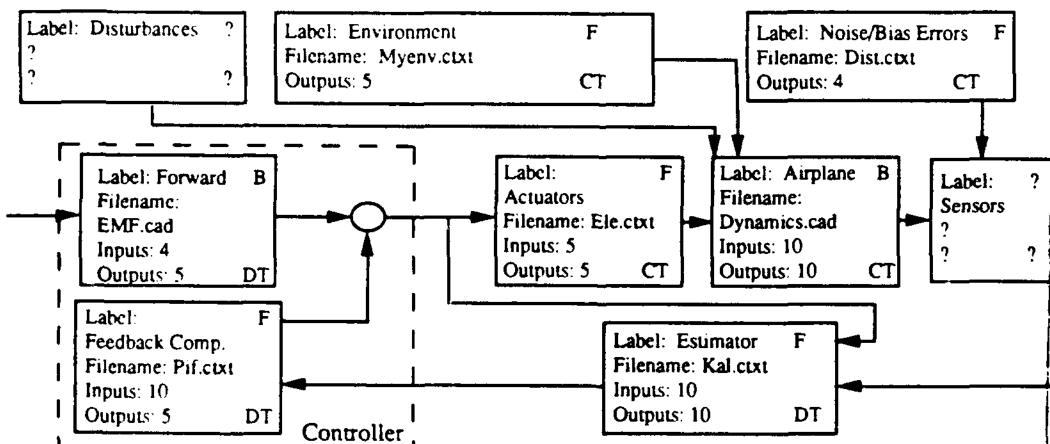

Figure 3. *FlightCAD*'s Block Diagram Template.

PIF control structure was developed for NASA's VTOL Approach and Landing Technology (VALT) Program [8-10], resulting in a successful flight test of adaptive attitude- and velocity-vector command/control laws on an experimental CH-47B helicopter. Six digital control laws were flight-tested on Princeton University's two Navion variable-stability aircraft, demonstrating proportional, proportional-filter (PF), and proportional-integral (PI) linear-quadratic control [11,12], direct side-force control via implicit model following [13], adaptive lateral-directional control to eliminate "wing rock" in fully stalled flight [14], and PIF command augmentation [15,16]. PIF controllers were designed for the B-737 twin-jet transport used in NASA's Advanced Transport Operating Systems (ATOPS) Program [17,18]. The PIF/CGT approach also has been applied in a design study for the X-29 Forward Swept-Wing Demonstrator Aircraft [19].

The Challenge Design extends prior developments in several ways. It uses the PIF/CGT/LQG model to produce fully coupled control of the Challenge Aircraft throughout the design envelope. Control and estimation gains at each of several fixed operating points will be chosen to satisfy military flying qualities specifications with considerable margins in the initial design. These gains then will be adjusted for maximum stability and performance robustness using Stochastic Robustness Analysis [20-22]. Artificial neural networks will be used to adapt control and estimation gains to changing flight condition [23]. The Challenge Design will be developed in the *FlightCAD* environment.

Dynamic Modeling

The aircraft equations of motion are nonlinear ordinary differential equations,

$$\dot{\mathbf{x}}(t) = \mathbf{f}[\mathbf{x}(t),\mathbf{u}(t),\mathbf{w}(t),\mathbf{p}] \qquad (1$$

where $\mathbf{x}(t)$ is the n-dimensional state, $\mathbf{u}(t)$ is the m-dimensional control, $\mathbf{w}(t)$ is an s-dimensional disturbance, and $\mathbf{p}$ is an l-vector of parameters. The rigid-body state for this problem is described by

$$\mathbf{x} = [V \;\; \alpha \;\; q \;\; \theta \;\; h \;\; \beta \;\; r \;\; p \;\; \phi \;\; \psi]^T \qquad (2$$

where (V, α, β) are the airspeed, angle of attack, and sideslip angle components of the air-relative velocity vector, (p, q, r) are components of the body-axis angular-rate vector, (ϕ, θ, ψ) are the Euler angles describing roll, pitch, and yaw attitude, and h is the altitude. The first five components of $\mathbf{x}$ are called *longitudinal variables*, and the second five represent *lateral-directional variables*. The available control effectors are contained in,

$$\mathbf{u} = [\delta E \;\; \delta T \;\; \delta A \;\; \delta R]^T \qquad (3$$

corresponding to symmetric deflection of the left and right elevons (or stabilators), thrust command (to two engines), asymmetric deflection of left and right ailerons, and rudder deflection. The first two control elements have greatest effect on longitudinal variables, while the second two are principally lateral-directional controls. Wind provides the principal disturbance $\mathbf{w}$; it can be expressed as perturbations to (V, α, β).

The state (as well as control and disturbance) is observed through the measurement r-vector,

$$\mathbf{z}(t) = \mathbf{y}(t) + \mathbf{n}(t) = \mathbf{h}[\mathbf{x}(t),\mathbf{u}(t),\mathbf{w}(t)] + \mathbf{n}(t) \qquad (4$$

where $\mathbf{n}(t)$ is an r-dimensional measurement-error vector. The measurement-vector components are,

$$\mathbf{y} = [a_N \;\; a_L \;\; a_S \;\; p \;\; q \;\; r \;\; \psi \;\; \theta \;\; \phi \;\; h_I \;\; M \;\; p_T \;\; p_A \;\; \alpha] \qquad (5$$

(a_N, a_L, a_S) are orthogonal components of acceleration (not measured at the center of mass), (ψ, θ, ϕ) are Euler attitude angles, h_I is inertial altitude, M is Mach number, and (p_T, p_A) are total and ambient pressures.

Linearized models find widespread use in control design. Along a nominal trajectory specified by $\mathbf{x}_0(t)$, $\mathbf{u}_0(t)$, $\mathbf{w}_0(t)$, and $\mathbf{n}_0(t)$ for t in (t_0, t_f), perturbations of the state and observation vectors are governed approximately by linear, time-varying equations,

$$\Delta\dot{\mathbf{x}}(t) = \mathbf{F}(t)\Delta\mathbf{x}(t) + \mathbf{G}(t)\Delta\mathbf{u}(t) + \mathbf{L}(t)\Delta\mathbf{w}(t) \qquad (6$$

$$\Delta\mathbf{z}(t) = \mathbf{H_x}(t)\Delta\mathbf{x}(t) + \mathbf{H_u}(t)\Delta\mathbf{u}(t) + \mathbf{H_w}(t)\Delta\mathbf{w}(t) + \mathbf{n}(t) \quad (7$$

$\mathbf{F}$, $\mathbf{G}$, $\mathbf{L}$, $\mathbf{H_x}$, $\mathbf{H_u}$, and $\mathbf{H_w}$ are conformable Jacobian matrices expressing sensitivities to the perturbation variables, evaluated along the nominal trajectory.

$\mathbf{F}$, $\mathbf{G}$, and $\mathbf{L}$ partition into direct and coupling blocks. The upper-left blocks express longitudinal effects on longitudinal variables, the lower-right blocks express lateral-directional effects on lateral-directional variables, and the off-diagonal blocks induce coupling between the two sets. When the wing span is horizontal, the coupling blocks of an aerodynamically symmetric aircraft are small, as non-zero terms arise only from engine gyroscopic effects. In turning or rolling flight, longitudinal and lateral-directional motions are coupled, so the coupling blocks of $\mathbf{F}$, $\mathbf{G}$, and $\mathbf{L}$ may have significant effect. In a steady pullup, the motions are not coupled, but the lateral-directional blocks are altered from their cruising-flight values.

The state can be propagated between discrete instants of time $(t_k, t_{k+1}, \ldots)$ by,

$$\Delta\mathbf{x}_{k+1} = \mathbf{\Phi}_k\Delta\mathbf{x}_k + \mathbf{\Gamma}_k\Delta\mathbf{u}_k + \mathbf{\Lambda}_k\Delta\mathbf{w}_k \qquad (8$$

and the corresponding measurement perturbations are

$$\Delta\mathbf{z}_k = \mathbf{H}_{\mathbf{x}_k}\Delta\mathbf{x}_k + \mathbf{H}_{\mathbf{u}_k}\Delta\mathbf{u}_k + \mathbf{H}_{\mathbf{w}_k}\Delta\mathbf{w}_k + \mathbf{n}_k \qquad (9$$

The subscript "k" indicates evaluation at t_k. Here, $\mathbf{\Phi}$, $\mathbf{\Gamma}$, and $\mathbf{\Lambda}$ have the same dimensions as $\mathbf{F}$, $\mathbf{G}$, and $\mathbf{L}$ and are derived from the system's state transition properties for a given sampling interval, $\Delta t = t_{k+1} - t_k$. For present purposes, a constant control sampling rate ($= 1/\Delta t$) of 50 per sec appears appropriate, while gain schedules may be updated at a slower rate.

Dynamic Compensation

Control and estimation logic for the nonlinear plant (eq. 1 and 2) can be expressed as a *dynamic compensator*,

$$\Delta\mathbf{u}_k = -\mathbf{C}_k\,\boldsymbol{\xi}_k \qquad (10$$

$$\boldsymbol{\xi}_{k+1} = \mathbf{\Psi}_k\boldsymbol{\xi}_k + \mathbf{\Theta}_k\Delta\mathbf{u}_k + \mathbf{K}_k[\mathbf{z}_k - \mathbf{h}(\hat{\mathbf{x}}_k,\mathbf{u}_k)] \qquad (11$$

$$\boldsymbol{\xi}_k = [\Delta\hat{\mathbf{x}}_k^T \;\; \boldsymbol{\chi}_k^T]^T \qquad (12$$

$$\mathbf{u}_k = \mathbf{u}_{0_k} + \Delta\mathbf{u}_k \qquad (13$$

$$\hat{\mathbf{x}}_k = \mathbf{x}_{0_k} + \Delta\hat{\mathbf{x}}_k \qquad (14$$

This linear, time-varying structure is equivalent to a feedback control law (eq. 10) operating on the internal state estimate $\Delta\hat{\mathbf{x}}$ contained in the $(n + k)$-dimensional $\boldsymbol{\xi}_k$ (eq. 12). $\boldsymbol{\chi}_k$ is a k-vector of compensation components that may include integrals of state elements or an explicit command model to be followed. $\mathbf{C}_k$ and $\mathbf{K}_k$ are selected to provide satisfactory nominal response, and they may vary in time. $\mathbf{\Psi}_k$ and $\mathbf{\Theta}_k$ include nominal values of $\mathbf{\Phi}_k$ and $\mathbf{\Gamma}_k$ plus integrating (i.e., accumulating) or filtering operations associated with $\boldsymbol{\chi}_k$. $\mathbf{C}_k$, $\mathbf{K}_k$, $\mathbf{\Psi}_k$, and $\mathbf{\Theta}_k$ are represented as full-order matrices here, but they may be partitioned, reduced, and simplified in DFCS implementation.

The desired state and corresponding control for the nonlinear plant, $\mathbf{x}_{0_k}$ and $\mathbf{u}_{0_k}$, enter as in eq. 13 and 14, and they can be produced by the Command Generator. The nominal control setting is quite sensitive to parameter variations and disturbance input. The *incremental form control law* eliminates the need to know $\mathbf{u}_{0_k}$ by computing the present control command as a perturbation to the previous command, which implicitly contains the nominal control value:

$$\mathbf{u}_k = \mathbf{u}_{k-1} - (\mathrm{C}_k \xi_k - \mathrm{C}_{k-1} \xi_{k-1}) \tag{15}$$

Proportional-Integral-Filter/Command-Generator Tracker Control

The Proportional-Integral-Filter (PIF) structure augments aircraft dynamics with both the control rate dynamics and command output integration. It allows control displacements and rates to be limited implicitly, and it provides explicit integration of the error between the desired and actual command outputs. The control law is derived using the linearized aircraft model, augmented with equations for control rate and command output integration [16]:

$$\frac{d}{dt}\begin{bmatrix}\Delta\mathbf{x}\\ \Delta\mathbf{u}\\ \Delta\boldsymbol{\xi}\end{bmatrix} = \begin{bmatrix}\mathbf{F} & \mathbf{G} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathbf{H} & \mathbf{D} & \mathbf{0}\end{bmatrix}\begin{bmatrix}\Delta\mathbf{x}\\ \Delta\mathbf{u}\\ \Delta\boldsymbol{\xi}\end{bmatrix} + \begin{bmatrix}\mathbf{0}\\ \mathbf{I}\\ \mathbf{0}\end{bmatrix}\Delta\mathbf{v} \tag{16}$$

The corresponding sampled-data form is,

$$\begin{bmatrix}\Delta\mathbf{x}\\ \Delta\mathbf{u}\\ \Delta\boldsymbol{\xi}\end{bmatrix}_{k+1} = \begin{bmatrix}\boldsymbol{\Phi} & \boldsymbol{\Gamma} & \mathbf{0}\\ \mathbf{0} & \mathbf{I} & \mathbf{0}\\ \boldsymbol{\Phi}_1 & \boldsymbol{\Phi}_2 & \mathbf{I}\end{bmatrix}\begin{bmatrix}\Delta\mathbf{x}\\ \Delta\mathbf{u}\\ \Delta\boldsymbol{\xi}\end{bmatrix}_k + \begin{bmatrix}\boldsymbol{\Gamma}_1\\ \mathbf{I}\Delta t\\ \boldsymbol{\Gamma}_3\end{bmatrix}\Delta\mathbf{v} \tag{17}$$

Equation 16 requires that $\Delta\mathbf{x}$ and $\Delta\mathbf{u}$ be integrated to form $\Delta\boldsymbol{\xi}$ in eq. 17, and a first-order data hold would be needed to obtain $\Delta\mathbf{u}_k$ from $\Delta\mathbf{v}$. Euler integration is used in both cases, and the couplings to $\Delta\mathbf{x}$ and $\Delta\boldsymbol{\xi}$ are eliminated, yielding the following model:

$$\begin{bmatrix}\Delta\tilde{\mathbf{x}}\\ \Delta\tilde{\mathbf{u}}\\ \Delta\tilde{\boldsymbol{\xi}}\end{bmatrix}_{k+1} = \begin{bmatrix}\boldsymbol{\Phi} & \boldsymbol{\Gamma} & \mathbf{0}\\ \mathbf{0} & \mathbf{I} & \mathbf{0}\\ \mathbf{H}\Delta t & \mathbf{D}\Delta t & \mathbf{I}\end{bmatrix}\begin{bmatrix}\Delta\tilde{\mathbf{x}}\\ \Delta\tilde{\mathbf{u}}\\ \Delta\tilde{\boldsymbol{\xi}}\end{bmatrix}_k + \begin{bmatrix}\mathbf{0}\\ \mathbf{I}\Delta t\\ \mathbf{0}\end{bmatrix}\Delta\tilde{\mathbf{v}}_k \tag{18}$$

where $\Delta\tilde{\mathbf{x}}$ is the perturbation from the optimal state history, $\Delta\tilde{\mathbf{u}}$ is the perturbation from the optimal control history, and $\Delta\tilde{\mathbf{v}}$ is the perturbation from the optimal control rate history.

The cost function to be minimized by control is,

$$J = \int_0^{\infty}\left\{\begin{bmatrix}\Delta\tilde{\mathbf{x}}^T & \Delta\tilde{\mathbf{u}}^T & \Delta\boldsymbol{\xi}^T\end{bmatrix}\begin{bmatrix}\mathbf{Q} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{R} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{Q}_\xi\end{bmatrix}\begin{bmatrix}\Delta\tilde{\mathbf{x}}\\ \Delta\tilde{\mathbf{u}}\\ \Delta\boldsymbol{\xi}\end{bmatrix} + \Delta\mathbf{v}^T\mathbf{R}_D\Delta\mathbf{v}\right\}dt \tag{19}$$

where the weighting matrices are chosen to meet implicit model-following goals associated with good handling qualities [24,25]. The resulting sampled-data optimal control law takes the form

$$\Delta\tilde{\mathbf{v}}_{k-1} = \mathbf{C}_1\Delta\tilde{\mathbf{x}} + \mathbf{C}_2\Delta\tilde{\mathbf{u}} + \mathbf{C}_3\Delta\boldsymbol{\xi} \tag{20}$$

$\mathbf{C}_1$, $\mathbf{C}_2$, and $\mathbf{C}_3$ are the solutions to the algebraic Riccati equations associated with the regulator [26].

The desired state trajectory can be propagated by a command generator, which shapes pilot inputs to produce a desirable nominal response. In combination with suitable logic for regulation (e.g., PIF), the controller becomes a command-generator-tracker (CGT). CGT is a form of explicit model following, where a desired set of dynamics is simulated and the actual system is controlled as a function of the error between the two [27]. This approach allows for uncertainty in the plant dynamics (reflected in **F** and **G**) and typically requires high controller gains for close tracking of the generated commands. However, a combination of explicit and implicit model following has been shown to produce satisfactory controllers with modest gains [25]. For the initial design, command-generator logic will be approximated by simpler matrix relationships that achieve satisfactory steady-state response [26]. Additional details of the PIF/CGT controller can be found in [16,18].

State Estimation

The PIF/CGT controller is designed with the assumption of full state feedback. Because all state components are not observed directly and all measurements are subject to noise, bias, and scale factor error, state estimation is needed. In addition to reducing noise effects in all observations, the main goals are to estimate the air-relative velocity components, altitude, and attitude; to estimate biases and scale factors as required; and to provide quantities needed for gain scheduling (see below).

Prior experience [8-11] suggests that several reduced-order filters are preferable to a single full-state estimator. The preliminary estimator suite is as follows: a) Three uncoupled first-order angular-rate filters, b) one velocity vector filter (with accelerometer bias estimate), c) one altitude filter (with altimeter bias estimate), d) one attitude vector filter (possibly using quaternions internally), and e) derivation of gain scheduling parameters.

Gain Scheduling via Neural Networks

Challenge Design DFCS gains will be calculated at operating points throughout the flight envelope, as specified by angle of attack, Mach number, dynamic pressure, and wind-axis roll rate (e.g., [2]). Artificial neural networks provide an exciting new alternative for scheduling these gains because they can generalize nonlinear functions of many variables with little or no prior knowledge of those functions' shapes. Many neural networks receiving current attention are memory-less expressions that approximate functions of the form,

$$\boldsymbol{y} = \boldsymbol{f}(\boldsymbol{x}) \tag{21}$$

where $\boldsymbol{x}$ and $\boldsymbol{y}$ are input and output vectors, and $\boldsymbol{f}(\cdot)$ is the relationship between them. Neural networks can be considered *generalized spline functions* that identify efficient input-output mappings from observations [23]. Rather than approximating eq. 28 by a series, table look-up, or traditional splines, an N-layer neural network represents the function by recursive operations,

$$\mathbf{x}^{(k)} = \mathbf{s}^{(k)}[\mathbf{W}^{(k-1)}\mathbf{x}^{(k-1)}] \triangleq \mathbf{s}^{(k)}[\boldsymbol{\eta}^{(k)}]\text{ , } k = 1 \text{ to } N \tag{22}$$

where $\boldsymbol{y} = \mathbf{x}^{(N)}$ and $\boldsymbol{x} = \mathbf{x}^{(0)}$. $\mathbf{W}^{(k-1)}$ is a matrix of weighting factors determined by the learning process, and $\mathbf{s}^{(k)}[.]$ is an activation-function vector whose elements normally are identical, scalar, nonlinear functions $\sigma_i(\eta_i)$ appearing at each network node:

$$\mathbf{s}^{(k)}[\boldsymbol{\eta}^{(k)}] = [\sigma_1(\eta_1{}^{(k)}) \ldots \sigma_n(\eta_n{}^{(k)})]^T \tag{23}$$

One of the inputs to each layer is a unity threshold element that biases the activation-function output.

The *sigmoid* is commonly used as the artificial neuron, though other functions such as the derivative of the sigmoid or the radial basis function can be used. The sigmoid is a saturating function written as $\sigma(\eta) = 1/(1 + e^{-\eta})$ for output in (0,1). Learning algorithms for the elements of $W^{(k)}$ typically involve either a gradient search or an extended Kalman filter.

In the present application, each gain element will be represented by a neural network with four inputs (the parameters specifying the operating space for gain calculations) and a single hidden layer of four nodes. The networks need not be trained on-line; hence, they do not add an undue amount of complexity. They do, however, provide substantial power for portraying gain schedules efficiently and with small error.

Stochastic Robustness Analysis

Robustness of the Challenge Design DFCS can be assessed in a number of ways. Gain and phase margins provide weak information about the robustness of single-input/single-output systems. They are not reliable indicators of the likelihood that stability and performance goals will be met under parameter uncertainty [28] because parameter variations change the *shape* of the Nyquist contour as well as its gain and phase [26]. Similar notions have been applied to the multi-input/multi-output case through singular-value analysis, but the same Nyquist contour effects occur; hence, a new approach to defining control system robustness is needed.

Stochastic Robustness Analysis is such an approach [20-22]. It is based on the premise that each parameter variation can be modeled by a probability density function, which may be bounded, non-Gaussian, and correlated with other parameters. This probability description can be used to shape the output of a random number generator which, taken with the outputs for all other uncertain parameters, forms a set of parameters for a single evaluation of stability and performance metrics. The metrics are noted, and the process is repeated in a "Monte Carlo" analysis. As the number of trials grows, the tested parameter distributions approach their models, and the probability distributions of the stability and performance metrics are estimated within computable confidence intervals. These estimates are compared with target values to determine whether or not the closed-loop system possesses adequate robustness.

In the present application, we are particularly concerned with maintaining a vanishingly small probability of closed-loop instability, a high probability of satisfactory performance, and a reasonable level of assurance of low turbulence response. The appropriate military specifications for flying qualities and flight control systems will establish target levels for these evaluations.

STATUS OF THE PROJECT

The AIAA Design Challenge model has been translated from FORTRAN to C code and has been compiled on the NeXT Computer. Results from the C version are being compared with those generated by the FORTRAN version. All further development will be based on the C version.

The *FlightCAD* program is operational in part; the user interface is complete, and some of the simulation routines and functions are working. The block diagram manipulation code is not complete and is the major focus of current work. *FlightCAD* can manipulate text documents and compile them, and can open completed *CADdocs*. Block connection and compilation also is on the near-term agenda.

CONCLUSION

A flight control design with proportional-integral-filter structure, command-generator-tracking, linear-quadratic-Gaussian gain calculation, and gain scheduling is proposed as a solution to the AIAA Controls Design Challenge. The design has practical engineering significance, making it suitable for flight test and future application. The control design will be developed with *FlightCAD*, a computer program that presents new paradigms for the multidisciplinary design of future flight control systems.

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