JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 17, No. 4, July–August 1994

Intelligent Control Law Tuning for AIAA Controls Design Challenge

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Constrained optimization is used as the basis of the intelligent control law tuning applied to the AIAA Controls Design Challenge. A tuning rule is formulated by translating multiple control system design requirements into a cost function and a set of constraints. During the tuning process, constrained optimization is employed to search for control laws that minimize the cost function subject to the constraints. Simulation results are presented to demonstrate the successful applications of the method.

I. Introduction

ESSENTIALLY, control law design is a multi-objective design task. Automatic flight control systems must meet a variety of tracking error requirements set for decoupled responses, rise times, settling times, overshoots, and steady-state errors. Most control system design methods can be used to achieve these requirements, provided their design parameters, such as gains and filters in the classical control design or weighting matrices in the modern control design, are properly tuned. Nevertheless, the rationale of tuning these design parameters so that the control law can meet its design requirements is vague. Much time is consumed in the tuning effort. In addition, nonlinearities are often ignored in control law designs, because most control law design methods are derived from linear model and linear theory. Such simplification separates the control law design and its verification into two design steps.

In 1990, the AIAA Guidance, Navigation, and Controls Technical Committee formulated a two-year Controls Design Challenge[1] of using state-of-the-art control law design methodologies to develop realistic control laws for a high-performance airplane model. Since then, an airplane model, its subsystems, and the control law performance requirements were established.[1,2] A number of groups[3] have participated in this event.

The author[4] assumed the following. First, there will be many designs based on linear quadratic regulator, eigenstructure assignment, linear quadratic Gaussian, and H_∞ design methods. Other design methods must also be investigated. Second, the control effector functions in the airplane model are quite decoupled. A control law with a simple structure would satisfy the performance requirements. Third, nonlinearities such as actuator rate limits and available control power will not be solved easily by conventional design methods. Fourth, there is a need to tune control laws intelligently to meet design requirements. How to establish an intelligent control law tuning method and apply it to an adequate control law structure for the AIAA Controls Design Challenge is the objective of this paper.

The procedure of intelligent control law tuning is illustrated in Fig. 1. The idea is to replace the engineer's tuning with an automated process that consists of the optimization software and control law design and analysis tools. During application of this method, a tuning rule consisting of a cost function and a set of constraints representing multiple control system design requirements is used. In the tuning process, constrained optimization in conjunction with classical or modern control design methods are applied to tune the control law so that all design requirements can be satisfied. The method is attractive because of its abilities to work directly with design requirements and to include the complete nonlinear plant model in the tuning process. It simply combines the control law design and its verification together. In addition, the intelligence embedded in the optimization algorithms will assist control engineers searching for proper control law.

This paper describes the application of intelligent control law tuning to the AIAA Controls Design Challenge. In Sec. II, the mathematical form of constrained optimization is reviewed with an explanation of how it can be applied to flight control system designs. The control law design approach of a pitch-axis model-following controller and two autopilots is summarized in Sec. III. Airplane control power analysis, control law tunings and implementation, and simulation of various autopilot functions are presented in Sec. IV. Finally, concluding remarks are given in Sec. V.

II. Constrained Optimization in Intelligent Control Law Tuning

A constrained optimization problem[5] is formulated by minimizing $f(x)$ subject to

$$g_j(x) < 0 \qquad j = 1, \ldots, m$$
$$\min x_i < x_i < \max x_i \qquad i = 1, \ldots, n$$

where $f(x)$ is the cost function, $g(x)$ is an m-dimensional constraint function, and x is an n-dimensional vector.

In the flight control system design, elements in x are the design parameters of the selected control law design method. Generally, these elements are bounded. In the classical control design, they are gains and filters.[6] In the modern control design,

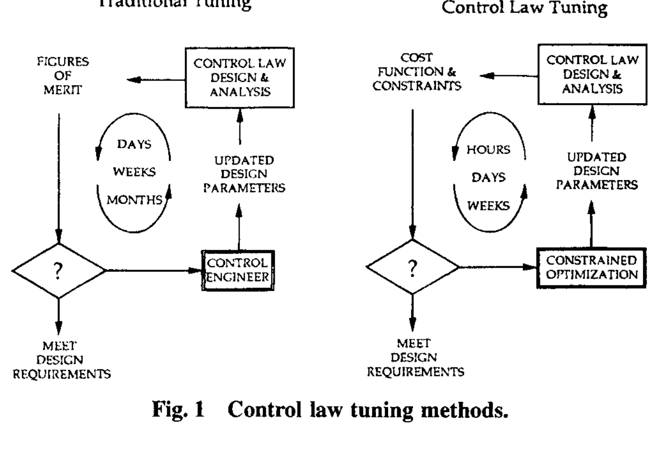

Fig. 1 Control law tuning methods.

Received April 24, 1992; revision received Aug. 19, 1993; accepted for publication Oct. 15, 1993.

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they are weighting matrices in the linear quadratic design[6,7] and desired eigenvalues and eigenvectors in the eigenstructure assignment design.[8]

Cost function and constraints can be figures of merit such as states of plant, trajectory error, frequency response mismatch with respect to low-order equivalent systems, peak transient response, maximum magnitude in frequency response, gain and phase margins, bandwidth, time delay, rise time, settling time, overshoot, steady-state error, and eigenstructure. Generally, these are nonlinear functions.

In this paper, a programming mechanism that executes several program modules in order was applied. Other execution arrangements[4] may also be used, depending on available resources. First, an optimization program was written in Fortran. When this program is executed, it reads cost function and constraints from a data file, calls automated design synthesis[5] (ADS) subroutines with these data, and stores the ADS-updated design parameters into a data file. During each execution, the ADS software either perturbs a design parameter if it is in the process of generating the Jacobian or updates all of the design parameters if the Jacobian is completed. The nonlinear six-DOF simulation program received in the design challenge program package[1] was also modified to include trim, linearization, and some interface capabilities.

Matrix$_x$ was used as the driver to control steps of the tuning process. Its functions include the following: 1) transferring design parameters, ADS flags, cost function, and constraints to the optimization program through a data file; 2) executing the optimization program by using spawn command [\\ . . . in Matrix$_x$]; 3) loading the design parameter data file generated by the optimization program; 4) performing linear control law analysis; 5) executing the six-DOF program; 6) loading the time history data file saved by the six-DOF program; and 7) evaluating cost function and constraints from linear analysis or nonlinear time history. Details are described in the next section.

III. Design Approach

A. Design Goals

The following requirements are extracted from Design Challenge Announcement[1] and are used as the guidelines in this paper. The design goals for an automatic control law or set of control laws that could be implemented in a digital computer onboard an aircraft are 1) straight-and-level flight at a specified altitude and Mach number, and 2) altitude and Mach number control during a 2-*g* turn. The control laws should be evaluated at the following conditions: 1) 9,800 ft and 0.5 Mach, 2) 39,800 ft and 0.6 Mach, 3) 39,800 ft and 1.4 Mach, and 4) 9,800 ft and 0.9 Mach. The successful function of the control laws should be demonstrated by starting at the specified initial conditions and evaluating the response of the aircraft/control system model to a steep ramp input in altitude of +50 ft/s for 4 s. The control laws must hold commanded altitude to within ±50 ft and Mach number to within ±0.01 of the commanded condition. For straight-and-level flight, angle of sideslip must be held to within ±1.0 deg of 0.0 deg, and roll attitude must be maintained to within ±5.0 deg of 0.0 deg. For the turn, the normal acceleration must be held to within ±0.2 *g* of the specified condition, and angle of sideslip must be maintained to within ±2.0 deg of 0.0 deg. Also, the control laws must perform 1) a level acceleration at 30,000 ft starting at 0.5 Mach number and ending at 1.4 Mach number, and 2) a turn from straight-and-level flight at 10,000 ft and 0.8 Mach number to 3.0 *g*.

B. Control Law Structure

To achieve the design goals, a pitch-axis command augmentation system (CAS), an altitude/speed autopilot, and a turn autopilot were designed using the described intelligent control law tuning method. The autopilots are modified from the control law subroutine UCNTRL[1,2] in the given simulation program. Aerodynamic characteristics of the given airplane model indicate that the interaction between longitudinal and lateral/directional axes is small; therefore, the subsystems were designed separately. The control laws were designed at the 11 flight conditions shown in Fig. 2. The block diagram is depicted in Fig. 3. A 50-Hz frame rate was chosen. No specific study was conducted in choosing this frame rate, except that 1) the given simulation program uses this rate, 2) the 50-Hz rate for the control law shown in Fig. 3 is considered fast enough compared to the dynamics of this airplane model, and 3) it is believed that current digital flight computers can meet the throughput requirement of this control law.

C. Pitch-Axis Command Augmentation System

Pitch CAS was designed by using the linear quadratic (LQ) model-following design method.[9] Here, it uses ADS software to tune weighting matrix for the LQ design. With appropriate Matrix$_x$ and VAX/VMS commands, an iterative process is set up as follows:

1) The airplane is trimmed and linearized at a selected flight condition. A three-state airplane short period linear model[10] ($\Delta\alpha$, q, and $\Delta\theta$) for model-following controller design and a five-state linear state-space equation consisting of the airplane longitudinal model (ΔV, $\Delta\alpha$, q, and $\Delta\theta$) and the stabilator actuator model $20/(s + 20)$ for calculating frequency response, phase margin, and maximum actuator rate are created (using the modified six-DOF program).

2) Command-shaping and model equations are set up for model-following design. The shaping filter has the form of $10/(s + 10)$. The typical model transfer functions used here are $(12s + 44)/(s^2 + 6s + 16)$ for pitch rate response and $16/(s^2 + 6s + 16)$ for normal acceleration response. These represent the desired handling qualities.[11] [In Matrix$_x$]

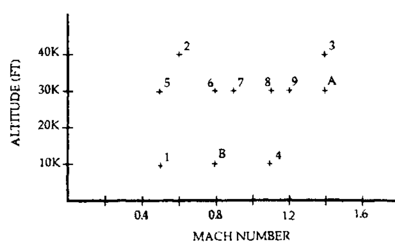
3) Pitch rate and normal acceleration are chosen as the output variables to be weighted in the LQ design. Control weighting is assigned to be unity. The output weightings are the design parameters that will be tuned by the ADS software. Initial values and upper and lower bounds of design parameters are set. [Matrix$_x$: SAVE 'filename' . . .]

4) The constrained optimization program is initialized. [Matrix$_x$: \\RUN OPTI__PROG;]

5) Feedback and feedforward gains in the model-following controller are solved. In Fig. 3, KCAS1, KCAS2, and KCAS3 are the feedback gains for $\Delta\alpha$, q, and $\Delta\theta$, respectively. A filter $10/(s + 10)$ is also implemented in the α path for noise precaution. Feedforward gains are not included in the block diagram because they are used to shape pilot stick input and won't be used in the autopilot evaluation. [Matrix$_x$: LOAD 'filename' to input updated design parameters or Q matrix. [EVAL,KR] = REGULATOR(A,B,Q,R);]

6) A standard equivalent system procedure[11] is applied to evaluate the cost function or frequency response mismatch of the closed-loop system and model transfer functions. [Matrix$_x$: frequency response of closed-loop system and frequency response mismatch.]

7) The phase margin from the loop transfer frequency response where the loop is broken at the actuator is determined. The first constraint is established by subtracting the phase margin from 45 deg. Mathematically, the acceptable constraint has to be negative; practically, the phase margin is demanded to be greater than 45 deg. [In Matrix$_x$]



Flight Condition	Mach Number	Altitude (Ft)
1	0.5	9800
2	0.6	39800
3	1.4	39800
4	0.9	9800
5	0.5	30000
6	0.8	30000
7	0.9	30000
8	1.1	30000
9	1.2	30000
A	1.4	30000
B	0.8	10000

Fig. 2 Flight conditions used in the design.

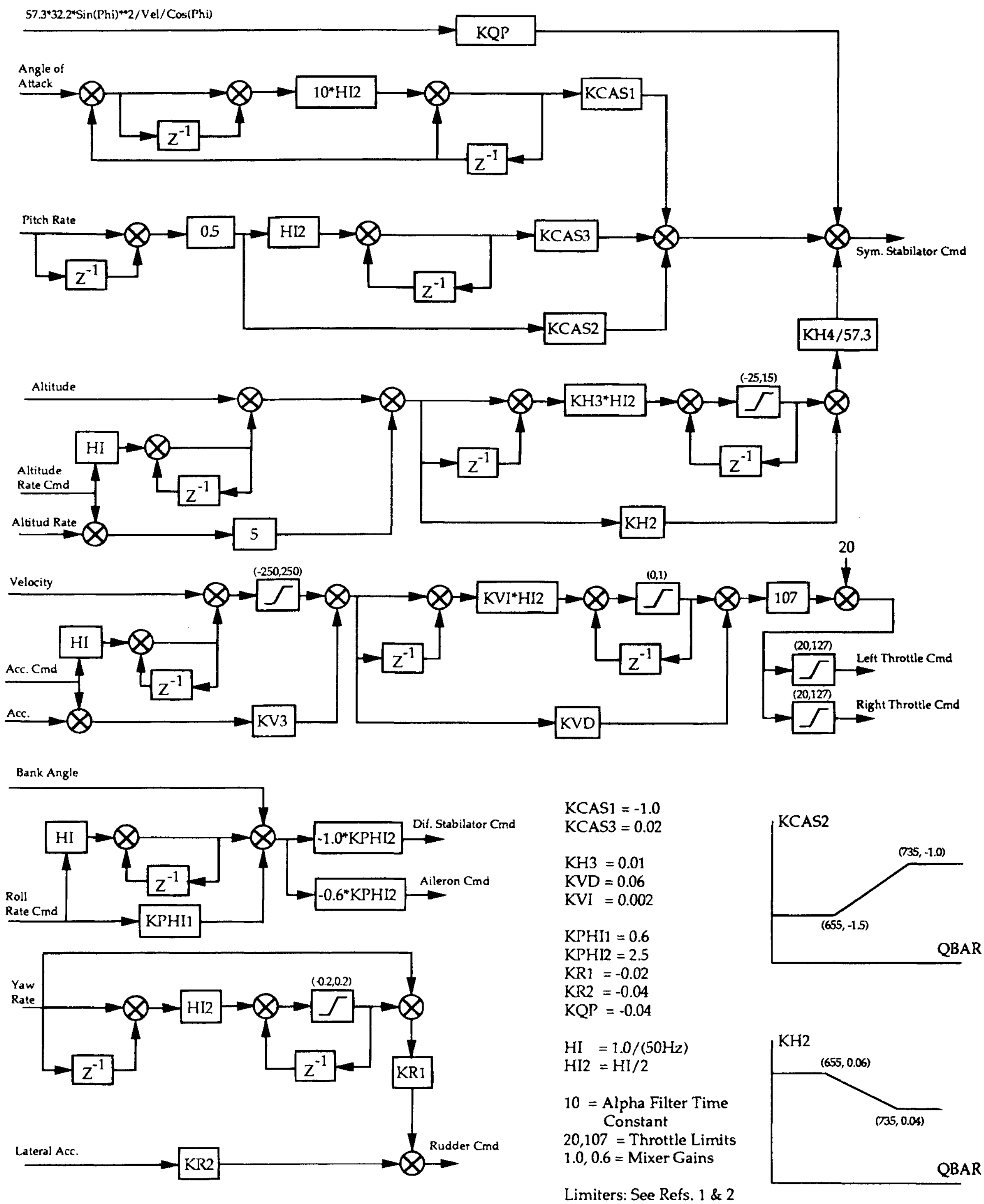


Fig. 3 Control law block diagram.

8) The second constraint is calculated by subtracting 15 deg/s from the maximum absolute value of the actuator rate when a unit step stick command is applied to the closed-loop system. This prevents the saturation of actuator rate limit. [In Matrix_x]

9) The cost function and constraints are saved for the optimization program. If the ADS software observes that the cost function is minimized and the constraints are met, or if the results are satisfied by the engineer, the tuning stops here. Otherwise, the ADS software will update its records, tune design parameters (output weightings in the LQ design) based on the cost function and constraints, and return to step 5. [Matrix_x: SAVE 'filename' cost function and constraints; \\RUN OPTI__PROG]

D. Altitude/Speed Autopilot

The pitch-axis CAS was implemented into the UCNTRL subroutine of the nonlinear six-DOF simulation program. The lateral/directional control law uses its original UCNTRL part. Then, design challenge requirements were used in selecting the maneuver command, cost function, and constraints. A Matrix_x

command file was set up to execute iteratively the optimization program and the six-DOF program, and to evaluate the cost function and constraints from time history data.

1) *Maneuver*: a 10-s simulation, a 50-ft/s altitude rate commanded from 1 to 5 s.

2) *Cost function*: maximum altitude deviation with respect to the altitude command.

3) *Constraints*: 0.01 Mach number, 1-deg sideslip, and 5-deg roll altitude deviations.

4) *Design parameters*: autopilot gains, including KH2, KH3, KVD, and KVI, which are the proportional and integral gains in altitude loop and speed loop, respectively.

E. Turn Autopilot

A process similar to altitude/speed autopilot tuning was applied, after the altitude/speed autopilot was also incorporated into the UCNTRL subroutine.

1) *Maneuver*: a 30-deg/s roll rate commanded from 1 to 3 s for a 2-*g* turn.

2) *Cost function*: sum of roll attitude error with respect to the roll command.

3) *Constraints*: 50-ft altitude, 0.01 Mach number, and 2-deg sideslip deviations.

4) *Design parameters*: autopilot gains including KPHI1, KPHI2, KR1, KR2, and KQP. KPHI1 and KPHI2 are the roll rate and roll attitude error gains; KR1 and KR2 are for yaw axis control; and KQP, a crossfeed for turn coordination.[10]

IV. Design Results

A. Aircraft Control Power Analysis

A simple open-loop control power analysis was conducted to examine the aircraft's altitude/speed control capabilities. At each trim flight condition, the stabilators and throttles are commanded to their maximum positions in the nonlinear six-DOF simulation program. Time history at flight condition 1 is shown in Fig. 4. Subsystem lags and nonlinearities are illustrated in stabilator and thrust responses. The first peak altitude error and the Mach number deviation when this peak altitude error occurs indicate the achievable limits in altitude and speed controls.

Results are summarized in Table 1. It is apparent that the design goals[1] of 50-ft altitude error and 0.01 Mach number error are unachievable at flight conditions 1, 2, and 5 and very difficult to achieve at flight conditions 6 and 7. Obviously, these flight conditions all occur at lower dynamic pressure where the forces and moments generated by aerodynamic control surfaces are relatively weak. Early analysis[4] indicated that these altitude errors and Mach number deviations could be reduced significantly had an ideal actuator model been used (*note*: the rate limit of actuators is 24 deg/s).

B. Control Law Tuning

Key ADS[5] flags used in the tuning are 1) strategy option: ISTRAT=6 (sequential linear programming optimization strategy); 2) optimizer option: IOPT=5 (modified method of feasible directions for constrained minimization); and 3) one-dimensional search option: IONED=7 (find the minimum of a constrained function by first finding bounds and then using polynomial interpolation). ADS guidelines were followed in choosing this set of flags out of hundreds of possible combinations. The main objective is to use the software to find a set of solutions that satisfies design requirements if there is no problem in solution convergence. The same initial values have been used in most cases. Control law tunings generally start to converge within design constraints after 10–15 iterations.

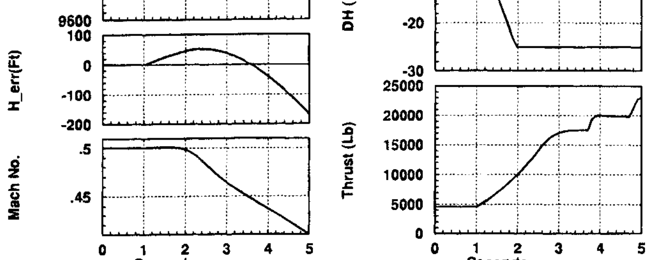


Fig. 4 Altitude and speed control power analysis at flight condition 1 when maximum stabilator deflection and throttle are commanded.

C. UCNTRL Implementation

Although three feedforward gains in the model-following pitch-axis CAS are not used in the autopilot evaluation, there are still 12 control law gains at each of the 11 flight conditions. How to implement these gains into the control law subroutine UCNTRL in order to cover the design envelope practically is not a trivial task. Considerations in gain scheduling include selection of independent variables, number of break points, and methods of data interpolation. Because gains do not vary too much with respect to dynamic pressure (perhaps the autopilot gains were bounded during tuning), a gain unification was performed by adjusting the gains around their mean values while maintaining the autopilot performance.

It is concluded that only two gains must be scheduled as simple functions of dynamic pressure. Therefore, the final control law was implemented into the UCNTRL subroutine with two options, unified gains and original gains at 11 flight conditions. The unified gains are presented in Fig. 3. HI is the sampling period; HI2 is a half of sampling period. These are used in the digitization of integrators. Except for yaw channel, other gains and limits are inherited from the original UCNTRL subroutine. A PC disk containing the new UCNTRL subroutine was also mailed to AIAA.[1]

D. Simulation Results

The unified-gain control law was evaluated by performing the required maneuvers[1] at the relevant flight conditions. Actually, results in maneuvers 1 and 2 that follow are verified during control law tuning.

1. Straight-and-Level Constant Speed Climb

A 50-ft/s climb command was applied from 1 to 5 s. Tracking errors at all 11 flight conditions are listed in Table 2. The results agree with the altitude/speed control power analysis summarized in Table 1.

2. 2-g Constant Speed Level Turn

A 20-s turn maneuver with a 30-deg/s bank commanded from 1 to 3 s was simulated. The command is equivalent to a 60-deg bank or a 2-*g* turn command.[10] Tracking errors are listed in Table 3. Total load factor, which includes thrust effect, was measured at the end of simulation, while mean bank angle was taken from 6 to 20 s. A 2-*g* turn cannot be made at flight conditions 2 and 5 because the stabilators were saturated in an attempt to hold altitude and speed (*note*: the symmetric stabilators are used for pitch control, whereas differential stabilators are used for roll control).[2]

3. 2-g Constant Speed Climbing Turn

This is a combination of maneuvers 1 and 2. Tracking errors are summarized in Table 4. Simulations of using the unified-gain and the original gain control laws at flight condition 4 are shown in Fig. 5. Responses of two control laws are very close.

4. Straight-and-Level Acceleration

Time history of the level acceleration at 30,000 ft is shown in Fig. 6. A maximum acceleration command was applied. It takes 97.6 s to accelerate the airplane from Mach 0.5 to Mach 1.4. The maximum altitude error, 35.9 ft, is within 50 ft. Roll attitude and sideslip stay well within the requirements.

Table 1 Control power analysis to meet a 50-ft/s altitude trajectory

Flight condition	Mach	Altitude	Qbar	$Stab_{trim}$	$Thrtl_{trim}$	ΔH	$\Delta Mach$
1	0.5	9800	236	−2.86	37.4	53.5	0.0136
2	0.6	39800	100	−7.26	113.0	123.1	0.0466
3	1.4	39800	543	−1.55	108.0	41.2	0.0078
4	0.9	9800	761	−0.57	60.1	26.1	0.0061
5	0.5	30000	110	−7.08	78.1	105.0	0.0372
6	0.8	30000	282	−1.51	47.9	48.3	0.0204
7	0.9	30000	356	−1.53	51.0	40.2	0.0164
8	1.1	30000	532	−3.87	91.8	37.7	0.0093
9	1.2	30000	633	−1.86	100.1	38.4	0.0043
A	1.4	30000	862	0.98	111.7	33.2	0.0055
B	0.8	10000	596	0.44	50.6	31.4	0.0059

Table 2 Peak errors during a straight-and-level constant speed climb

Flight condition	ΔH_{max}	$\Delta Mach_{max}$	$\Delta\Phi_{max}$	$\Delta\beta_{max}$
1	55.3	0.0135	0.10	0.10
2	123.1	0.0545	8.40	5.47
3	43.6	0.0079	0.14	0.11
4	25.7	0.0045	0.09	0.03
5	108.1	0.0495	2.98	2.22
6	48.0	0.0207	0.08	0.08
7	39.8	0.0151	0.07	0.05
8	38.8	0.0072	0.10	0.07
9	39.7	0.0066	0.12	0.07
A	35.3	0.0041	0.15	0.11
B	30.7	0.0067	0.07	0.04

Table 3 Peak errors, total load factor, and mean bank angle during a 2-*g* (60-deg) constant speed level turn

Flight condition	ΔH_{max}	$\Delta Mach_{max}$	$\Delta\beta_{max}$	LF_{20s}	$\Delta\Phi_{mean}$
1	27.2	0.0042	0.84	1.91	60.0
2[a]	44.7	0.0644	1.88	1.19	36.2
3	45.7	0.0036	0.68	1.93	59.9
4	13.7	0.0004	0.91	1.91	59.9
5[a]	27.1	0.0071	1.52	1.22	36.7
6	20.7	0.0088	0.56	1.94	59.9
7	12.6	0.0039	0.52	1.94	59.9
8	28.6	0.0023	0.60	1.94	59.9
9	32.5	0.0069	0.66	1.93	59.9
A	19.7	0.0004	0.81	1.91	59.8
B	7.4	0.0006	0.65	1.92	59.9

[a]1.25G (37.0 deg) turn only.

Table 4 Peak errors, total load factor, and mean bank angle during a 2-*g* (60-deg) constant speed climbing turn

Flight condition	ΔH_{max}	$\Delta Mach_{max}$	$\Delta\beta_{max}$	LF_{20s}	$\Delta\Phi_{mean}$
1	62.4	0.0226	3.44	1.91	59.9
2	——	——	——	——	——
3	49.8	0.0095	1.36	1.94	59.8
4	46.8	0.0053	1.17	1.91	59.9
5	——	——	——	——	——
6	51.0	0.0286	3.66	1.94	60.0
7	43.5	0.0153	2.68	1.95	59.9
8	40.9	0.0068	1.41	1.94	59.9
9	43.1	0.0065	1.10	1.94	59.9
A	39.5	0.0034	0.82	1.91	59.8
B	40.5	0.0059	1.32	1.92	59.9

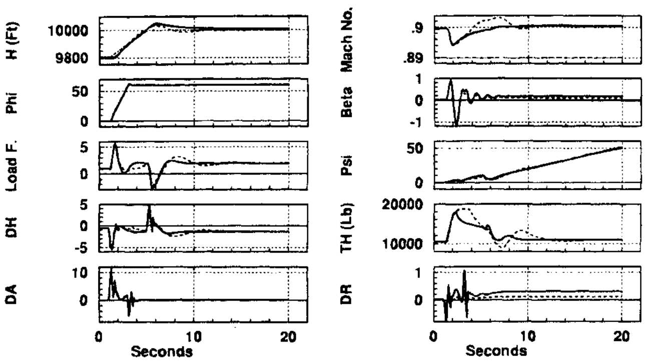


Fig. 5 2-*g* constant speed climbing turn at flight condition 4; solid lines: unified gains, dashed lines: original gains.

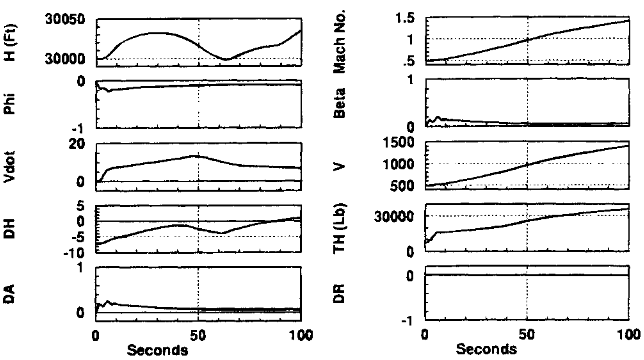


Fig. 6 Straight-and-level acceleration from Mach 0.5 to Mach 1.4.

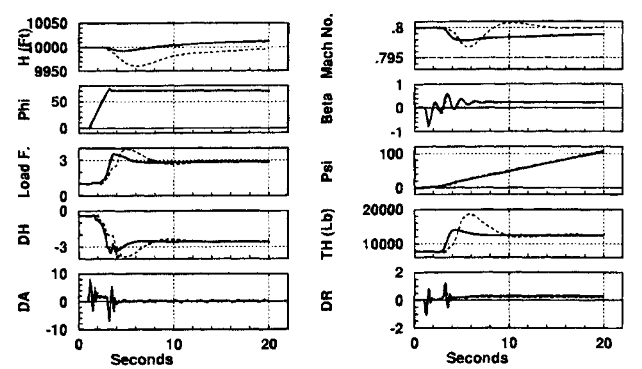


Fig. 7 3-*g* constant speed level turn at flight condition B; solid lines: unified gains, dashed lines: original gains.

*5. 3-*g* Constant Speed Level Turn*

Time history of using both sets of control laws to perform a straight-and-level 3-*g* turn at 0.8 Mach number and 10,000 ft altitude are shown in Fig. 7.For the unified gains, the final load factor is 2.84 *g*, which stays within the required 0.2 *g* of 3 *g*. Mean bank angle from 6 to 20 s is 70.45 deg. Maximum deviations in altitude, Mach number, and sideslip are 11.83 ft, 0.00214, and 0.79 deg, respectively.

V. Conclusions

The idea of intelligent control law tuning is to replace the engineer's tuning with an automated design process that consists of the optimization software and control law design and analysis tools. This method converts control law design to the framework of constrained optimization. It uses intelligent optimization algorithms, specifically the ADS software, to search for control laws that satisfy design requirements. The method works directly with design requirements while using the complete nonlinear model in the tuning process. It was successfully applied to design the control laws for the high-performance airplane model used in the AIAA Controls Design Challenge. Simulation results demonstrate that the control law satisfies design requirements at most flight conditions. The only exceptions are where analysis predicts control power deficiencies exist.

This paper presents an experiment of using intelligent algorithms to aid the control law designs. Similar approaches[3] have been applied by other researchers or engineers. It is believed that many more issues, such as including a variety of design requirements and using other control law structures and design methods, remain to be investigated.

Acknowledgments

The author is very grateful to C. C. Bayley, C. M. Ha, and J. C. Virnig for their helpful discussion and to D. S. Bodden for his encouragement in conducting this study.

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