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DESIGN AND TEST OF FLIGHT CONTROL LAWS FOR THE KAMAN BURRO UNMANNED AERIAL VEHICLE

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ABSTRACT

A flight control system was developed for an unmanned vehicle based on the Kaman K-MAX helicopter. The initial design was based on an 8-DOF linear state-space aircraft model extracted from flight test data. The aircraft dynamics were combined with estimated sensor and actuator dynamics, around which the control law architecture was developed. The baseline control system gains were tuned using optimization software to meet a selection of applicable performance and handling-quality specifications. Real-time evaluation of the control laws was accomplished on a desktop simulation. Flight test of the resulting control laws revealed discrepancies between the model and the aircraft; the model was updated with accurate sensor and actuator dynamics identified from flight-test data. After re-tuning the control system gains, the aircraft performance closely matched prediction.

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INTRODUCTION

BURRO program / mission

Kaman Aerospace is developing an unmanned version of the K-MAX "aerial truck" (Figure 1.) Under contract to the Marine Corps Warfighting Lab, an autonomous K-MAX will demonstrate Broad-area Unmanned Responsive Re-supply Operations (BURRO)[1] capability for supporting Marines deployed ashore. With a slung-load payload capacity equal to its 6,000-pound (2720 Kg) weight, the K-MAX BURRO UAV will be capable of quickly delivering large amounts of supplies and equipment to troops without risking a pilot's life.

This paper focuses on the initial development of a flight control system for the BURRO Phase 1 flight demonstrations. In Phase 1, a ground operator commands the aircraft, and a safety pilot is present aboard; flight is limited to the hover/low-speed flight regime, without an external load. The work was performed under a Cooperative Research and Development Agreement (CRDA) between Kaman Aerospace and the Army/NASA Rotorcraft Division at Ames Research Center. Follow-on work is underway to expand the flight envelope to include hover with a slung load and forward flight, both with and without a slung load.

Turning the K-MAX into a UAV presents a particular challenge – the aircraft has an unstable roll

mode at 0.63 rad/sec, with a time-to-double of 2.4 sec; this forms a lower bound on the control system bandwidth. Combined with a mission profile that places the aircraft in close proximity to personnel, naval ships, and terrain, these characteristics dictate a comparatively high bandwidth control system capable of accurately maintaining aircraft position and attitude.

Figure 1. Kaman K-MAX helicopter

BURRO development strategy

Because the BURRO demonstrator aircraft was required to be developed in a very short time span and for a low cost, Kaman Aerospace used many existing assets. This approach resulted in the use of an electromechanical actuator system originally developed for UH-1 drones, modified for the BURRO application. Similarly, the sensor package and flight control computer are the same as those used in the development of Kaman's SH-2G(A).

To keep development time to a minimum, Kaman chose the latest software tools available. Several UAV and manned aircraft development programs have shown that the use of such tools can dramatically reduce the time required to bring a vehicle from concept to flightworthy aircraft.[2,3,4] The Army/NASA Rotorcraft Division at NASA Ames Research Center has assembled a set of cooperative design and evaluation tools under the COntrol and Simulation Technologies for Autonomous Rotorcraft (COSTAR) initiative. The COSTAR tools include:

- CIFER® (Comprehensive Identification from FrEquency Responses)[5], used to extract linear state-space models from flight-test time history data.
- CONDUIT (the CONtrol Designer's Unified InTerface)[6], which provides a graphical environment for control system modeling, evaluation, and optimization.
- RIPTIDE (Real-time Interactive Prototype Technology Integration / Development Environment)[7], a desktop flight simulation and control system testing tool.

The COSTAR tools were used extensively in the K-MAX BURRO program, and their use is highlighted where applicable.

AIRCRAFT MODELING

Prior to designing the BURRO flight control system, an accurate model of the aircraft dynamics was required. This entailed modeling the basic airframe, the attitude, attitude rate, altitude and translational rate sensors, and the control actuators.

First, piloted frequency sweeps were flown using an unaugmented K-MAX. Colbourne, Tomashofski and Tischler used the CIFER® software package to identify an eight degree-of-freedom linearized state-space model of the helicopter dynamics from the flight data.[1] The model included rotor dynamic inflow and coning states. Figure 2 (from Reference 1) compares the CIFER®-identified on-axis roll response to flight data; the results for the other responses are similarly good matches.

The identified model was verified in the time domain by comparing model doublet responses to flight data. The model matched the aircraft response very well, as seen in the roll and pitch responses to a roll control input shown in Figure 3 (also from Reference 1.)

The sensor dynamics were then modeled as equivalent time delays using second-order Pade approximations. The delays used were based on the sensor manufacturers' specifications. Bench-test frequency sweeps of the actuators were processed using CIFER® to obtain second-order transfer function models of the actuator dynamics.

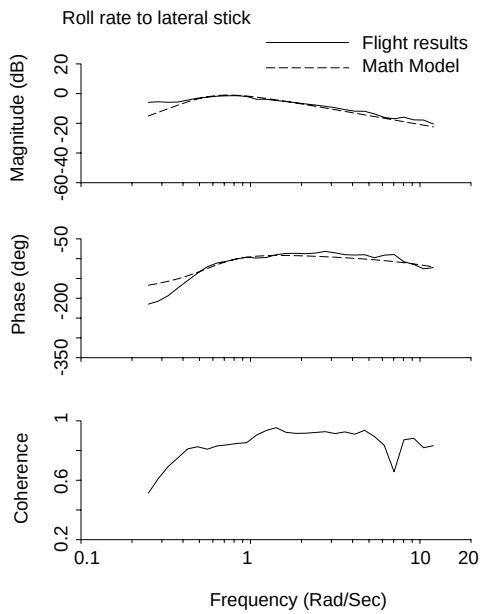


Figure 2. CIFER-identified roll rate response

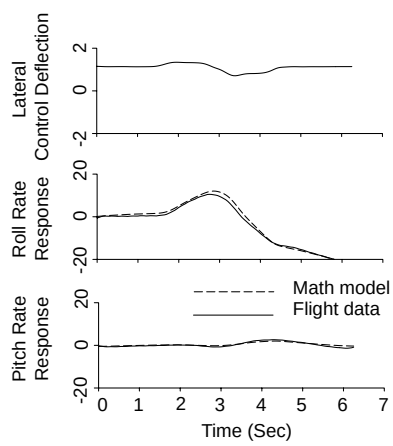


Figure 3. Time-domain verification of CIFER® model

All the elements of the aircraft model were then assembled into a Simulink® block diagram within the CONDUIT environment. The resulting model provided a basis from which to design the flight control system.

CONTROL LAW DEVELOPMENT

The flight control system (FCS) modes were selected based on the BURRO system specification requirements for autonomous guidance and navigation, combined with ground operator control during the terminal phases of flight. Earth-referenced Translational Rate Command (TRC), with Altitude Rate Command/Altitude Hold and Heading Command/Heading Hold are used as the basic control modes. These modes will be used by the autonomous guidance and navigation software as well as for the ground operator's direct control of the aircraft. An Attitude Command/Attitude Hold (ACAH) mode is available, at least in the demonstration vehicle, for ground operator use in precision control of the aircraft.

Control system architecture

The control system architecture was designed to implement the selected FCS modes. The basic control system layout consists of outer loops for the TRC function and inner loops for stability and attitude control (Figure 4.) A simple control system architecture was desired to facilitate later manual implementation in flight-worthy C code. Therefore, proportional-integral-derivative (PID) controllers (Figure 5) for each of the primary axes provide the stabilization and attitude control functions. For each of the longitudinal and lateral channels, the TRC controller is implemented with a P-I scheme (Figure 6), whose output is fed to the attitude controller. The PID/PI scheme allows classical control design methods to be used and provides insight into the function of each of the gains in the system.

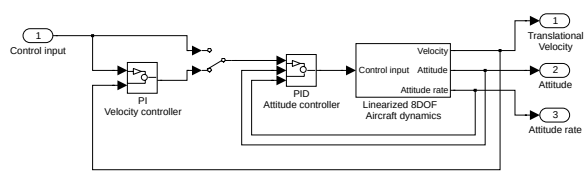


Figure 4. Control scheme

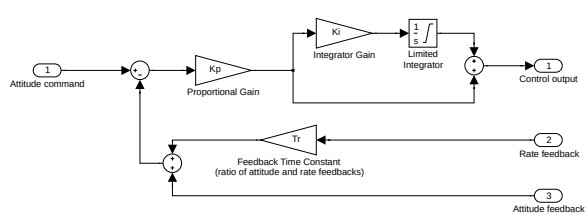


Figure 5. PID attitude controller

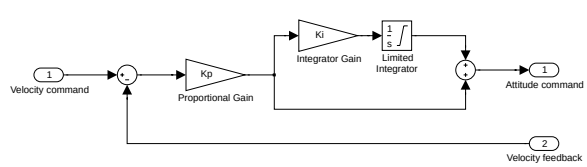


Figure 6. PI velocity controller

Preliminary values for the control system gains were calculated using classical design methods, from the 8-DOF CIFER-identified state-space model. The gains were chosen to achieve at least 45 degrees of phase margin and greater than 6 dB of gain margin. For the desired stability margins, with the crossover frequency ω_c occurring at the point of maximum phase, the system's total equivalent time delay, τ_{SL}, can be used to estimate the maximum achievable crossover frequency of the control system[8] via the formula

$$\omega_c = \frac{0.37}{\tau_{SL}}. \tag{1}$$

If the closed-loop bandwidth ω_{BW} is defined as the lowest frequency at which the augmented vehicle exhibits 45 degrees of phase margin or 6 dB of gain margin, then $\omega_{BW} \approx \omega_c$. An equivalent time delay of τ_{SL} = 0.095 sec was found, based on the Simulink® models of the aircraft, actuator and sensor dynamics. This value of τ_{SL} predicts an achievable bandwidth of ω_{BW} = 3.9 rad/sec, which is within the 2 – 4 rad/sec ω_{BW} range suggested for light rotorcraft with ACAH response characteristics.[9]

Because translational rate response equivalent rise time (where $T_{\dot{x}_{eq}}$ occurs when $\dot{x} = 0.632\dot{x}_{ss}$) faster than 2.5 sec produces an objectionably abrupt attitude response,[10] the outer-loop gains were selected to place crossover at around 0.4 rad/sec.

Only the roll-to-pedal response exhibits a large amount of coupling, due to the K-MAX's synchropter rotor configuration. A simple crossfeed gain provided satisfactory decoupling at frequencies above the control system bandwidth. The required gain corresponds to the ratio of the control derivatives, $K_{cf} = -L_{\delta\ pedal}/L_{\delta\ lat.\ stick}$ = -0.48.

Tuning in CONDUIT

The CONtrol Designer's Unified Interface (CONDUIT) provides a single, graphical, interactive environment for the development, evaluation and automated tuning of flight control systems. CONDUIT makes use of aircraft/control system models built in either the MATLAB / Simulink® or MatrixX / SystemBuild® graphical block-diagram tools. Key to the optimization function of CONDUIT is the graphical representation of specifications. A broad selection of time- and frequency-domain specifications encompassing performance and handling-quality requirements are included with the CONDUIT software, and users are provided with tools for constructing and modifying specifications to their own needs. A set of specifications is selected to constrain an aircraft/control system model; the control system engineer chooses control system gains to use as variable design parameters. The CONDUIT optimization engine then attempts to tune the design parameters to satisfy the set of specifications. If the basic requirements of all specifications can be achieved, CONDUIT proceeds to tune the design parameters to minimize a designated subset of the specifications.

The Simulink® aircraft model was updated for use in CONDUIT by adding nonlinear effects such as rate and saturation limits to the actuators, and output limits to the control system integrators. CONDUIT-specific switches were added to allow broken-loop stability analysis. Finally, the PID controller gains in the Simulink® model were designated to be tunable CONDUIT design parameters. A higher-level view of the lateral controller model, shown in Figure 7, illustrates the complexity of the system.

Selection of Specifications

To evaluate and tune the performance of the K-MAX BURRO, a set of handling-quality, performance, and stability specifications were selected from the built-in CONDUIT libraries. While the K-MAX BURRO is nominally an unmanned vehicle, a safety pilot will be on board the aircraft throughout the demonstration program. Also, the aircraft is not a purpose-built UAV – the dynamic components and airframe were designed from the beginning to operate within the usual bounds imposed upon a manned vehicle. Finally, it is anticipated that a ground operator will be in command of the aircraft during near-earth operations. Thus, handling qualities consistent with manned VTOL vehicles were selected to avoid situations wherein the control system's commands might be contrary to those expected by the safety pilot, or might exceed the normal operating parameters of the vehicle.

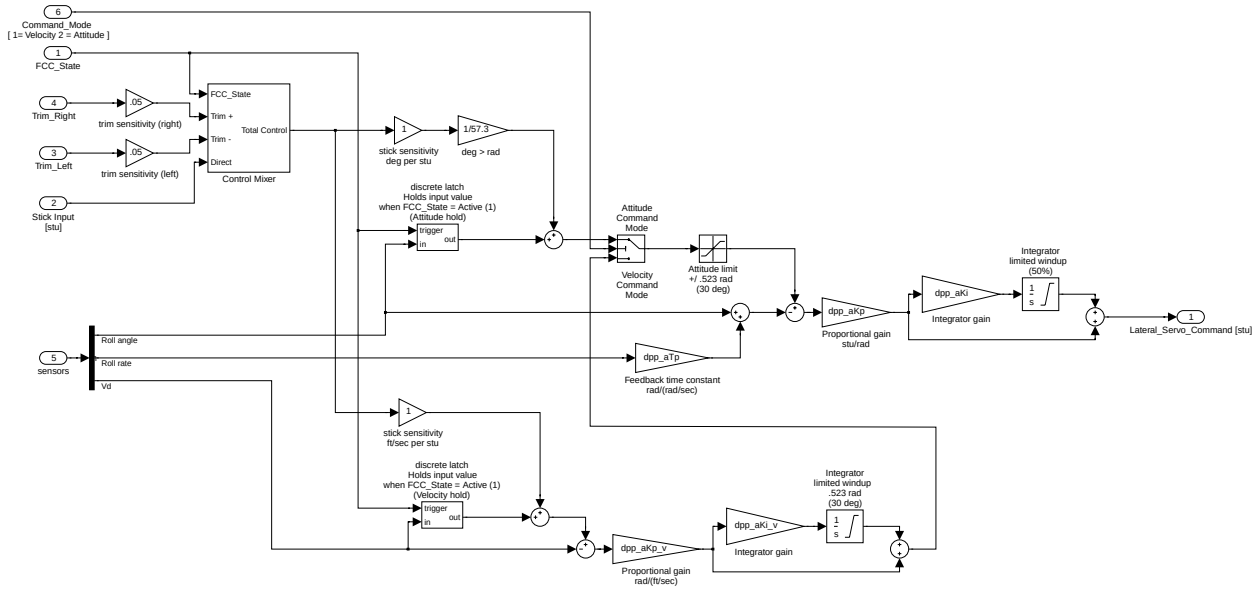


Figure 7. Simulink® model of lateral controller

Within CONDUIT, specifications are presented graphically, as shown in the example of Figure 8. Aircraft time and frequency responses are processed to extract information pertinent to the specification, which is then plotted on the graphical figure. Three levels of performance are shown as bounded regions. The Level 1 region represents satisfactory performance, while Level 2 results are considered to be in need of improvement. Level 3 results are deemed so deficient that improvement is mandatory. A brief description of each specification and the rationale for its selection follows.

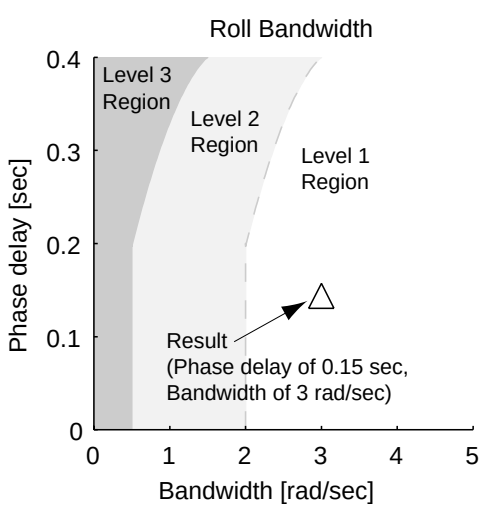
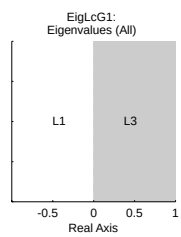


Figure 8. Example of CONDUIT specification

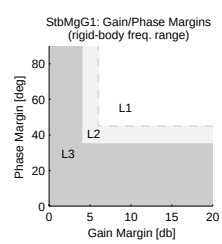
Two types of specification were used to ensure a stable aircraft:

- <u>Eigenvalue Location</u>



This specification constrains all eigenvalues of the system to lie in the left half of the s-plane, thereby ensuring stability of the aircraft. The real component of the right-most eigenvalue is evaluated.

- <u>Stability Margins per MIL-F-9490</u>



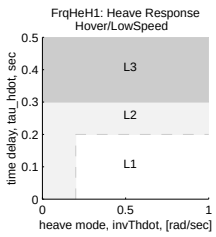
The stability margin specification requires 45 deg of phase margin and 6 dB of gain margin, within the rigid-body frequency range of 0.1 to 40 rad/sec. The specification is based on the broken-loop response and is therefore imposed upon each control channel.

Several specifications were chosen to drive the choice of gains towards values that would produce good handling qualities. For initial concept demonstration, the ground operator will not be exposed to adverse or

distracting conditions. Therefore, the specifications (taken primarily from Aeronautical Design Standard 33D, "Handling Qualities Requirements for Military Rotorcraft")[11] were selected to represent non-aggressive tasks with operator attention fully directed to control of the aircraft.

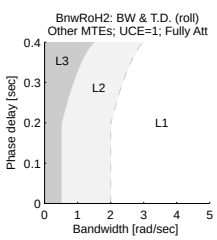
The chosen handling-qualities specifications were:

- Heave Response per ADS-33D



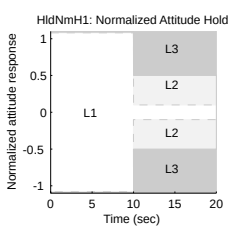
The vertical rate response to collective stick inputs is fit to a first-order low-order equivalent system, from which the characteristic parameters (the inverse time constant $\frac{1}{T_{\dot{h}}}$ and the equivalent time delay $\tau_{\dot{h}}$) are found. The specification requires that the heave response meet the ADS-33D handling quality levels.

- Bandwidth and Phase Delay per ADS-33D



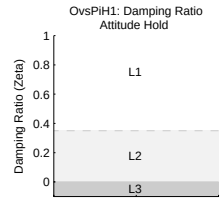
The closed-loop attitude response is required to meet the ADS-33D limits. The ADS-33D criteria for fully-attended operations were used.

- Normalized Attitude Hold per ADS-33D



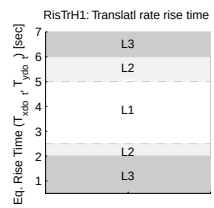
The attitude response to a disturbance (injected into the control system just downstream of the actuators) must fall within the specified envelope. The specification ensures that the control system retains good disturbance-rejection qualities, even as the system gains are reduced.

- Damping Ratio per ADS-33D



A damping ratio of at least 0.35 must be maintained, as calculated from the time response to a step control input.

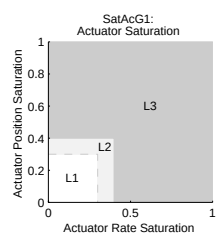
- Translational Rate Rise Time per ADS-33D



The rise time of the translational rate response to a step control input must be greater than 2.5 sec and less than 5 sec. This requirement is intended to avoid objectionably fast attitude changes, while keeping attitude-command-like short-term response of the aircraft.

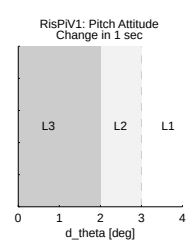
Two specifications were selected to evaluate performance of the system. These specifications were applied to each of the four control channels. They were:

- Actuator Saturation



Position and rate of the control actuators are not allowed to saturate for more than 30% of the duration of a response to an aggressive control input.

- Attitude Rise Time

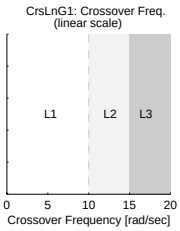


To ensure that control authority is maintained, the attitude change produced within one second of a step control input is required to be above a certain value.

After meeting the Level 1 requirements of all specifications, CONDUIT proceeds to minimize any that are defined as "objectives". Two such specifications were included for each of the four control

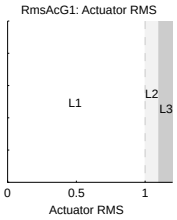
channels. These specifications were also grouped to form a single "summed objective", such that minimization would be performed on the sum of the component objectives. This ensures that the best possible performance will be extracted from each component of the grouped objectives, rather than attempting to minimize the single worst objective. The objective specifications are:

- Crossover Frequency



The broken-loop crossover frequency of the system is minimized by CONDUIT's optimization engine after all other constraints have been satisfied. This keeps the activity of the control system at the minimum level required to meet the performance, stability and handling-quality requirements.

- Actuator Position RMS



The RMS position of the actuators, normalized by the maximum position of the stick and the actuators' full travel, is minimized by the CONDUIT optimization engine after satisfaction of all other requirements. Minimizing the RMS position effectively reduces saturation and actuator sizing requirements as much as possible; an additional benefit is the reduction of component fatigue.[12]

Evaluation and Tuning

First, CONDUIT was used to evaluate the performance of the aircraft with the classically-derived preliminary gain values. The aircraft was stabilized, with adequate stability margins; as seen in Figure 9 for the lateral channel, the crossover frequency was approximately at the value predicted using Equation 1. However, at this crossover frequency the actuator activity and saturation were excessive.

Next, the control system gains were tuned using CONDUIT. CONDUIT was able to tune the design parameters to meet the Level 1 requirements of all specifications. Further tuning was able to minimize the Actuator Position RMS and Crossover Frequency specifications.

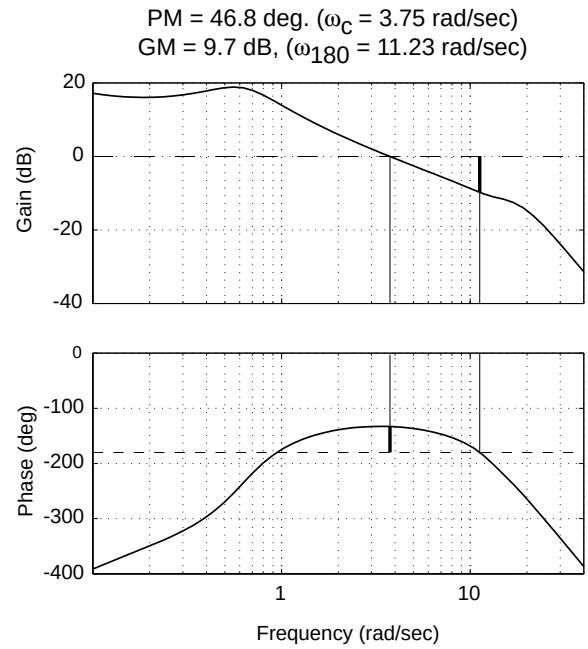


Figure 9. Baseline lateral stability margins

RIPTIDE evaluation

Prior to flight testing the CONDUIT-tuned control laws, the Simulink® aircraft model was tested in the RIPTIDE desktop simulation environment (Figure 10.) Evaluation of the control laws in RIPTIDE provides a quick piloted assessment of the behavior of the aircraft. It is especially useful for identifying problems arising from nonlinear effects, such as those due to control mode switching. Testing of the K-MAX BURRO allowed tuning of trim rates and control authority, and uncovered an error in mode-switching logic. Without RIPTIDE, these changes would have required significant test time in the aircraft.

FLIGHT TEST

Testing of the aircraft with the CONDUIT-tuned control laws commenced in January 2000. Initial flights demonstrated a considerable deviation in the aircraft behavior from that predicted by the CONDUIT model and RIPTIDE simulation, exhibiting unstable roll oscillations. An example is shown in Figure 11.

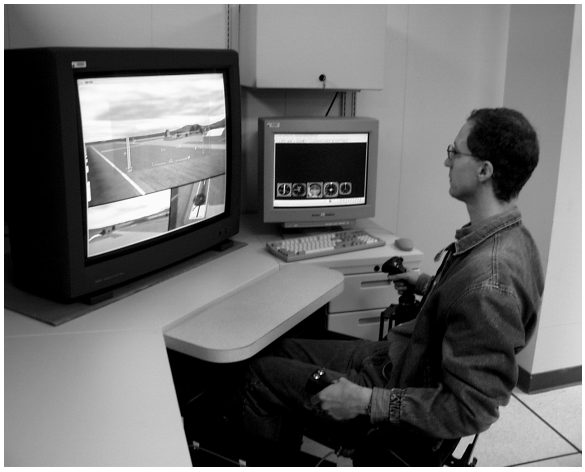


Figure 10. Control law evaluation using RIPTIDE

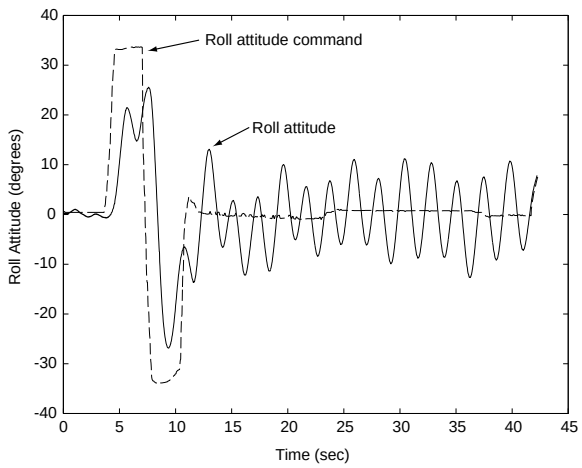


Figure 11. Oscillatory roll response during initial flight testing

To identify the source of the instability, longitudinal and lateral doublets were flown, and CIFER® was used to extract frequency responses at various points in the control system. This process allowed accurate identification of the sensor and actuator dynamics, as installed in the aircraft. Significantly, the equivalent time delay of these components was over 200% greater than originally modeled – a comparison of the component contributions is shown in Table 1. The increased actuator delay was due to a difference in performance as installed in the vehicle, versus the bench-test; the manufacturer's estimates for sensor delay were optimistic. The delay attributed to the computer, which runs at 50 Hz, was initially based on 1/2 frame for zero-order hold plus an additional 1/2 frame of computational delay. These estimates proved to be considerably below the delays encountered in flight test. Finally, the initial FCS design assumed that the sensor data would not require any filtering, while during flight test it was found that considerable low-pass filtering of the attitude rate was required. Using the updated value of τ_{SL} = 0.290 sec in Equation 1, the predicted achievable control system bandwidth was reduced to 1.27 rad/sec. This value is well below the recommended range and would be considered Level 2 in a piloted aircraft.

Table 1. Comparison of estimated and actual delay

Component	Estimated Delay (ms)	Actual Delay (ms)
Actuators	50	107
Sensors	25	53
Computer	20	40
Filters	0	90
TOTAL	**95**	**290**

Model updated

A decided advantage to using COSTAR's CIFER® and CONDUIT tools lies in their capability to rapidly re-tune the control system gains as components of the aircraft and control system are changed or whose properties become better known. The new sensor, filter and actuator dynamics were incorporated into the Simulink® block diagram, and the model was evaluated in CONDUIT. With the updated components, the model predictions matched the flight test data; the model response was oscillatory at the same 0.4 Hz frequency seen in the aircraft (Figure 12.)

Gains re-tuned using CONDUIT

Next, the gains were re-tuned to accommodate the updated dynamics. With the added time delay, the system becomes very highly constrained in pitch and roll – as compared to the lateral broken-loop responses of the XV-15 tiltrotor and the SH-2F Sea Sprite helicopter in Figure 13, the aircraft is conditionally stable over a very narrow frequency range. At low frequency, this is due to unstable rigid-body dynamic modes. At higher frequency, the large amounts of delay cause a rapid phase roll-off. While conditional stability (e.g. both a gain increase margin and a gain

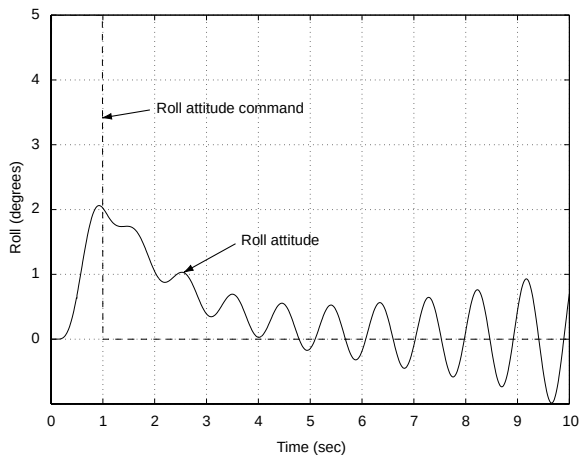


Figure 12. CONDUIT model roll response

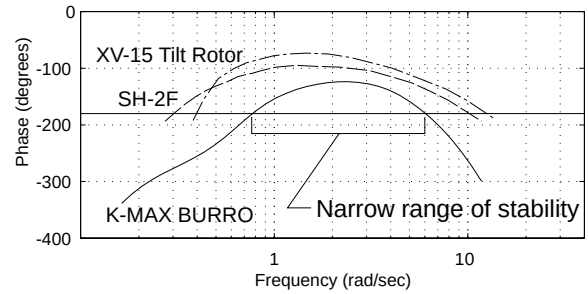


Figure 13. Comparison of lateral broken-loop phase responses

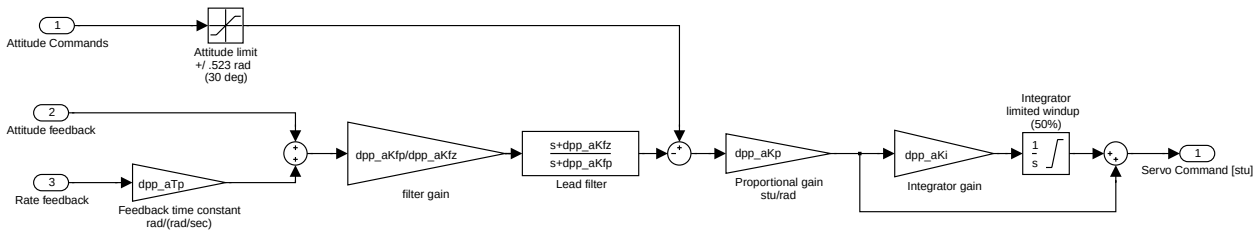


Figure 14. Roll attitude controller with added lead filter

reduction margin) is typical for hovering aircraft, the K-MAX BURRO has an unusually narrow frequency range over which it is stable. Above 6 rad/sec, or below 0.8 rad/sec, the aircraft is laterally unstable. To maintain reasonable phase margin, the crossover frequency should be greater than 1.4 rad/sec (approximately twice the minimum stable frequency.) The aircraft also has a lightly-damped mode at 6 rad/sec that is not captured by the 8-DOF model; adequate suppression of this mode requires that crossover be a factor of three lower, i.e. below 2.0 rad/sec. The characteristics of the pitch axis are similar. Note that the 1.27 rad/sec crossover based on the high-frequency dynamics using Equation 1 is below the crossover frequency desired to stabilize the 0.63 rad/sec mode. To allow some increase in the crossover frequency, lead filters were added to the pitch and roll attitude control architecture, as shown in Figure 14. This allows an increase in ω_C by sacrificing gain margin relative to the design rules of Equation 1. The lead filter pole and zero were designated as CONDUIT-tunable design parameters, to allow CONDUIT to trade off gain margin for increased phase margin in the region of crossover.

As seen in the broken-loop roll response of Figure 15, CONDUIT successfully tuned the control system gains to optimize the stability of the aircraft. The predicted roll attitude time response is shown in Figure 16. All of the resulting specifications are shown in Figure 17. While the collective, pedal, and TRC margins were solidly Level 1, the best attainable lateral and longitudinal ACAH stability margins were Level 2. To achieve even Level 2 stability margins with the updated dynamics, CONDUIT allowed some of the other specifications to degrade – control system bandwidth, pitch attitude damping, and pitch and roll attitude response time all dropped into the Level 2 region; yaw attitude response time deteriorated to Level 3.

Flight test with updated gains

The K-MAX BURRO flight control software was updated with the new CONDUIT-tuned gains. The roll response in ACAH mode, shown in Figure 18, is smooth and stable, although the

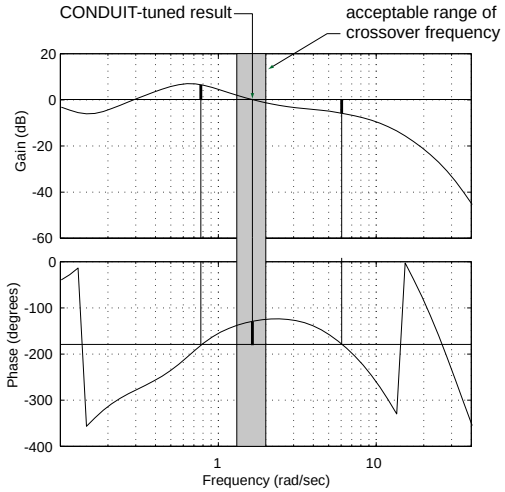


Figure 15. CONDUIT-tuned broken-loop lateral response

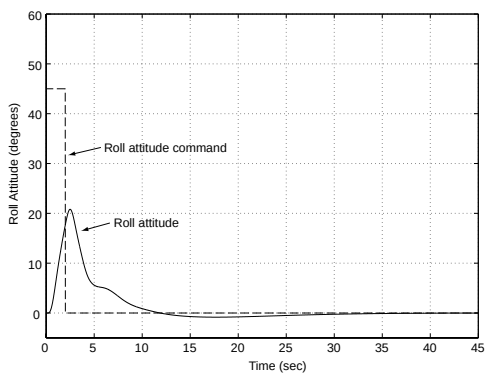


Figure 16. Improved CONDUIT model roll response

response is somewhat sluggish as indicated by the low bandwidth, and the unmodeled 1-Hz mode is not completely suppressed. The flight test response agrees well with the CONDUIT model prediction of Figure 16. Responses in other control axes are similar. Ground operator experience commanding the aircraft in ACAH mode demonstrated that the low ACAH margins resulted in high operator workload, while TRC operation proved easier, but afforded less precision.

CURRENT ACTIVITY

Following a successful demonstration of the Build 1 K-MAX BURRO to the Marine Corps Warfighting Lab, work is proceeding on control law design for hovering flight with an external slung load. Development of the 10-DOF equations of motion and CIFER identification of the loaded aircraft are complete,[1] and CONDUIT tuning of the control system is currently in progress. Similar work is being conducted for forward flight conditions. Turn coordination, automatic ascent and descent profiles, and waypoint navigation functions are in development at Kaman Aerospace.

CONCLUSIONS

Extensive use of advanced control system design tools allowed the Kaman/Ames team to build a successful system in a six-month period. Several key points emerged from this project:

- Application of the COSTAR design and evaluation tools significantly reduces development time. The tools facilitated rapid aircraft and component model identification, FCS design, gain tuning and desktop simulation.
- The design space for the K-MAX BURRO UAV is very limited. CONDUIT was able to extract additional performance within the limitations of the design, tuning 23 design parameters against 33 specification requirements.
- A key driver of the control system performance was accurate knowledge and modeling of high-frequency component dynamics. CIFER® proved useful for identification of unknown or inaccurate elements of the system.
- Equivalent time delay provides an accurate prediction of achievable system performance, and should be used early in the development cycle to assess the feasibility of achieving mission goals with proposed hardware.
- Increased phase margin would improve performance; this could be accomplished by reducing the total delay in the system, or by providing phase lead through an architecture change. Both avenues are being investigated.

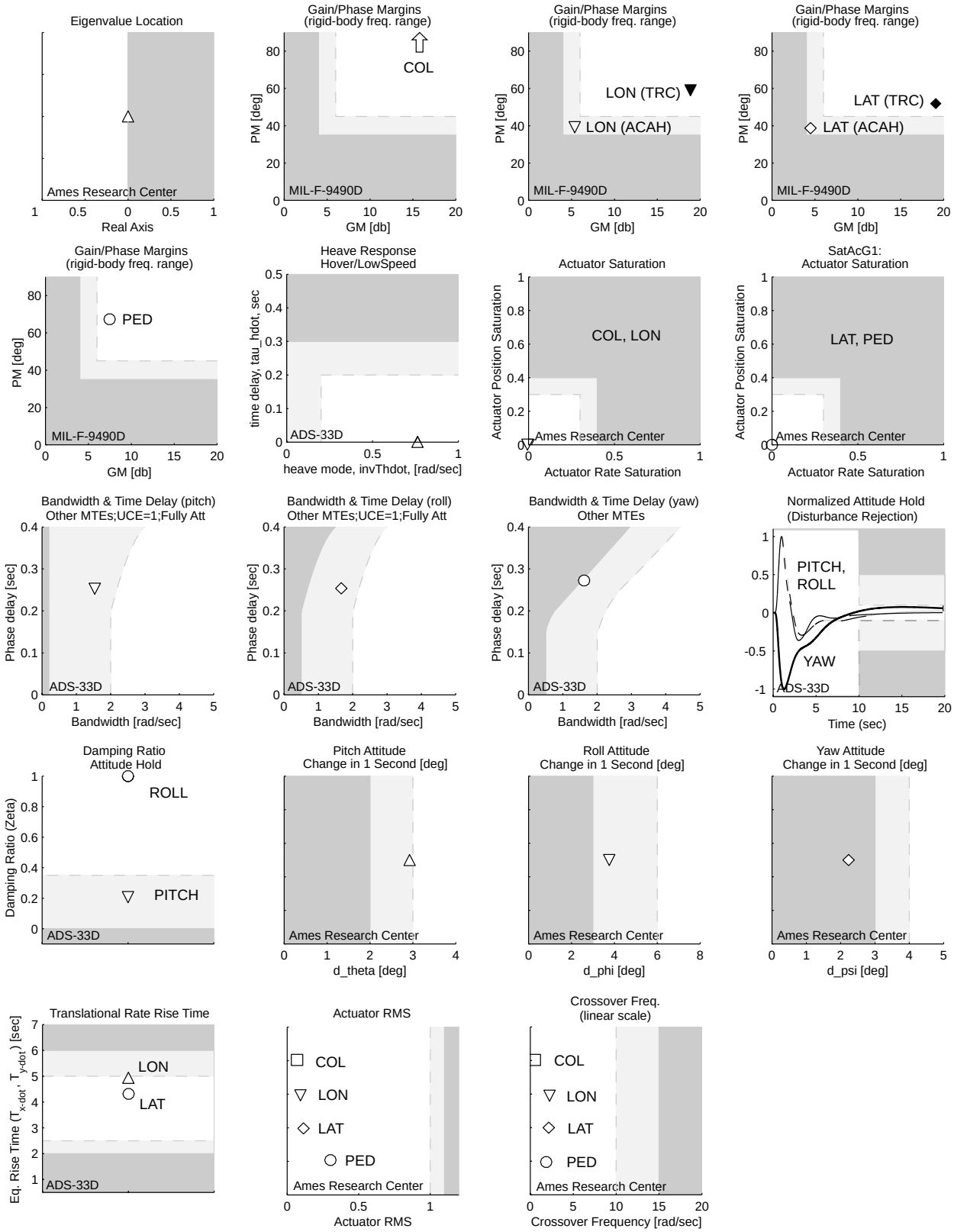


Figure 17. Specifications showing CONDUIT-tuned results

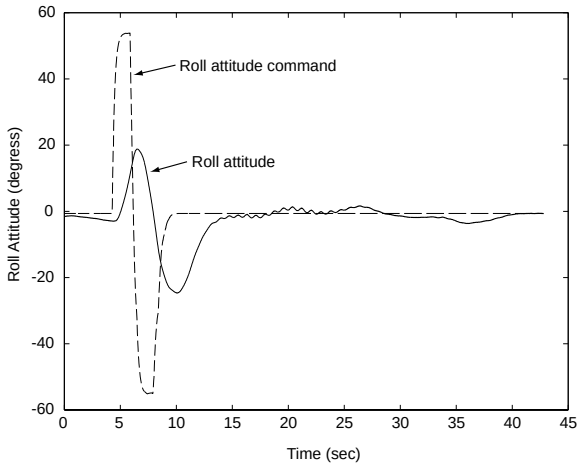


Figure 18. Improved flight-test roll response

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