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GENERIC PILOT AND FLIGHT CONTROL MODEL FOR USE IN SIMULATION STUDIES

Eric N. Johnson* and Amy R. Pritchett†

School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0150

ABSTRACT

In developing an aircraft simulation, a number of aircraft dynamic models are available with a range of fidelity. However, many applications of simulation also require a model of the flight control or of the pilot to realize their goals. These models can be difficult to implement using classical control methods and, in the case of flight control systems, may not be publicly available. This paper describes a generic pilot and flight control model suitable for many applications of simulation in research and design. This model may be easily implemented in simulation by using a architecture adapted from adaptive control for inner-loop attitude control, which capitalizes upon the dynamic information known within a simulation to create a stable control behavior. This architecture allows specification of the closed-loop behavior of the aircraft and controller (pilot or autopilot). Specific implementations of inner- and outer-loop control behavior are detailed. Simulation runs with this controller, acting as both a pilot and as a flight control system, are documented.

INTRODUCTION

In developing an aircraft simulation, a number of aircraft dynamic models are available with a range of fidelity.[1,2,3] However, many applications of simulation – including flight deck prototyping and testing, avionics integration, preliminary aircraft design, air traffic control research, and education – also require a model of the autopilot or of the pilot to realize their goals.

Historically, these models of autopilot and pilot behavior are not commonly available in a form that can be easily implemented in a flight simulator. While pilot control behavior has been widely studied and documented,[4,5] the closed-loop invariant behavior associated with piloted control is difficult to implement in a simulation without inverting the aircraft dynamics.

*?Lockheed Martin Assistant Professor of Avionics Integration, Member AIAA.
E-mail: Eric.Johnson@aerospace.gatech.edu

† Assistant Professor, Member AIAA.
E-mail: Amy.Pritchett@isye.gatech.edu

Similar difficulties are also faced in implementing models of flight control system behavior into simulations. Although the general form of the flight control systems' resulting closed-loop behavior may be known, re-creating this behavior with the aircraft dynamics can be difficult, traditionally requiring a significant amount of reverse-engineering to develop an approximate model. Comprehensive, exact models of the flight control system's internal behavior are rare and usually proprietary.

Recent advances in adaptive control allow the desired closed-loop inner-loop dynamics of a combined control system and aircraft to be specified as a reference model.[6] These control architectures use dynamic inversion (created or trained by adaptive elements such as neural nets) to infer the aircraft controls required to follow the closed-loop reference model dynamics.

This paper demonstrates a modification of an adaptive control architecture that allows pilot or flight control system closed-loop inner-loop dynamics to be specified in the control of detailed, non-linear aircraft dynamic models. This modified architecture takes advantage of the exact knowledge about the aircraft available in simulation to eliminate the adaptive elements of the control architecture, providing a simple, generic implementation suitable for many simulations.

While outer-loop control by pilots and flight control systems is not as consistent between aircraft and tasks and inner-loop control, this paper also discusses the general forms of their outer-loop behavior and provides representative outer-loop models of both pilots and flight control systems.

This paper first reviews general models of autoflight systems and of pilot control behavior, including the distinction between inner- and outer-loop control behavior. A control architecture that can be modified from adaptive control to provide a generic model of pilot or flight control is then outlined, and a specific implementation is detailed. Results from several simulation tests are documented. The paper ends with a summary and notation of how these generic models may be improved upon with further development.

MODELS OF PILOT AND FLIGHT CONTROL CLOSED-LOOP BEHAVIOR

As shown in Figure 1, a common and useful representation of aircraft control identifies an inner-loop element that tracks attitude through commands to aircraft control surfaces, and an outer-loop element that generates the attitude commands to the inner-loop element to achieve a specified velocity and altitude. The following sections will review the current state of knowledge of inner- and outer-loop control behavior.

Models of Pilot Control Behavior

The specific linkages between aircraft, inner-loop control element and outer-loop control element shown in Figure 1 mimic pilot control behavior in many tasks.

Pilot outer-loop control behavior is modeled as three outer-loop controllers. Each controller was developed as a model of pilot guidance behavior in each dimension, roll, pitch, and airspeed. The set of four inner-loop controllers takes in the commanded f_c, q_c and T_c from the outer-loop as well as the requirement that $b_c = 0$ for coordinated flight. These four inputs are used by the roll, pitch, thrust and yaw controllers to define the the commands d_a, d_e, d_T and d_r respectively.

This division of inner-loop and outer-loop control is substantiated and reinforced by pilot training and cockpit instrumentation. For example, during instrument flight training pilots are taught that the focus of their 'scan' should be on their artificial horizon to monitor their attitude, supplemented by frequent glances to indications of heading, speed and altitude to reevaluate whether they are tracking the correct attitude or should readjust their desired attitude and engine settings. This scan is supported by a standard cockpit design which places the artificial horizon in the center of the instruments, surrounded by the airspeed, heading indication or directional gyro, and altimeter.

Pilot Inner-Loop Control Behavior Several mathematical pilot models have been developed based on simulator and flight test data. The main difficulty in modeling pilot inner loop control behavior arises from their ability to adapt to changes in the aircraft behavior. A simple but effective representation of this closed-loop behavior for a manual control task is the crossover model where the combined pilot and aircraft in a single control dimension are described by the following transfer function near the crossover frequency by the following open loop transfer function[1,2]:

$$G_{FL}(s) = G_p(s)G_c(s) = \frac{S_p S_c e^{-t_e . s}}{s}$$

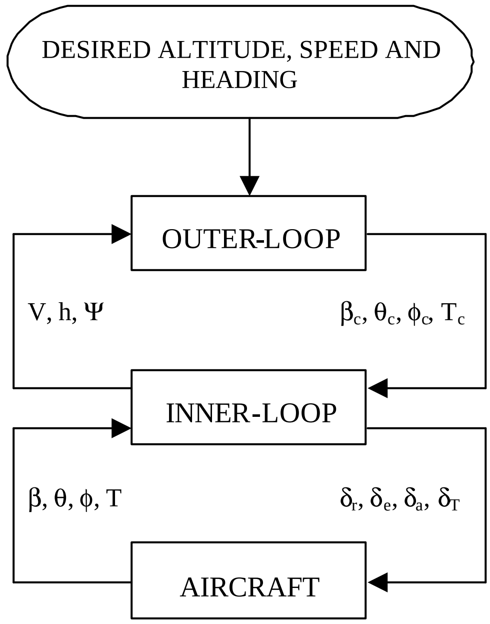

Figure 1 – Generic Control Model Composed of Inner- and Outer-Loop Elements

where: S_p is the pilot gain, S_c is the effective gain of the aircraft dynamics in this control axis in the vicinity of the crossover frequency, and t_e is the pilot's effective time delay. The pilot transfer function is modeled as

$$G_p(s) = \frac{S_p\left(t_L s + 1\right)e^{-t_e . s}}{\left(t_I s + 1\right)}$$

and parameters in the model are adjusted to match the crossover model near the crossover frequency. The plant model here depends on the aircraft and on any stability and control augmentation used in the flight control system. The form of the resulting system will vary, but it is typically desirable to have a first order response of roll input to roll rate and a second order response of pitch control to pitch angle response.

Pilot Outer-Loop Control Behavior Unlike inner-loop control behavior, pilot outer-loop control behavior has not been found to have a consistent form across all pilots and across all piloting tasks. For example, depending on the phase of flight and immediate situation, a pilot may choose to use throttle to control flight path angle (in tracking a glide-slope), vertical speed (in a steep climb or descent), or airspeed (in adjusting speed during cruise). However, the selection of these outer-loop behaviors for a trained pilot is usually rationale and therefore predictable if the proper contextual factors are taken into account.

Models of Flight Control Closed-Loop Behavior

In generating an approximate model of most flight control systems, the distinction shown in Figure 1 between inner- and outer-loop control elements is again appropriate, as they are often separated functionally within the flight control system into attitude control and velocity control. The specific choice of parameters considered by inner- and outer-loop, and controlled by the outer-loop, may vary between systems; for example, one may choose to control attitude, while another may choose to control angle of attack. This differences are largely aircraft specific and tuned to the specific performance requirements, while the overall form is reasonable consistent.

Flight Control System Inner-Loop Control Behavior In designing flight control systems, a common desired closed-loop behavior is a second order response for the two attitude commands (roll and pitch) and for sideslip. The specific mechanisms by which this response is created within the control system varies with the design approach for the controller, the sensor information available to the control system, and the aircraft dynamics.

Flight Control System Outer-Loop Control Behavior As with pilots, several specific forms of outer-loop control may be provided by the flight control system. For example, modern autopilots may have separate modes for altitude hold, flight level change, vertical speed hold (to a commanded altitude) and flight path angle hold (to a commanded altitude). To first order, the general form of these modes of behavior are predictable; each may have specific idiosyncrasies which a model can be tuned to as data is available.

EXTENSIONS FROM ADAPTIVE CONTROL ARCHITECTURES FOR INNER-LOOP CONTROL

Adaptive control architectures now exist that create (within the capabilities of the aircraft dynamics) a consistent closed-loop inner-loop behavior.[6] This consistency is achieved through dynamic inversion of the plant (aircraft) model, which allows the controls to be set directly to values predicted to create the desired behavior. In actual flight, adaptive elements (such as neural nets) are needed to tune the dynamic inversion. In the control architecture described in this section modified for use in simulation, exact knowledge of aircraft dynamic behavior is available and can be used directly, negating the need for an adaptive element.

Each inner loop controller is composed of three components: a reference model, a plant model, and an actuator model. The reference model defines the desired behavior of aircraft and controller (pilot alone, stability augmentation system and pilot, or autopilot). In this study it is chosen to be the crossover model for a human pilot, and a desired second order response to model a production autopilot system. Since the reference model and aircraft dynamics are assumed to be of second order, ? (pseudo-control) is a desired (angular) acceleration of the aircraft. The acceleration desired of the aircraft is:

$$n = n_{rm} + K_P(x - x_{rm}) + K_D(\dot{x} - \dot{x}_{rm}) - \Delta \ .$$

The first term represents the dynamics of the reference model. The second and third terms are feedback terms for any differences between the state and state derivative values actually attained by the aircraft compared to the desired reference model values. The fourth term, model error Δ, is model error as measured in the simulation, and is described below. The input-output relationship of control effect on dynamics is simplified by a single gain $\hat{b}$. Correspondingly, this simple function may be inverted to compute the control command to the aircraft d_{cmd} that will generate the desired dynamic ?.

$$d_{cmd} = (\hat{b})^{-1} n$$

This estimate $\hat{b}$ does not need to be accurate; it need only have the correct sign as the true value. Actual controls are not always those commanded: actuator dynamics and saturation can cause differences between the commanded controls (d_{cmd}) and actual values (d). The difference between actual and commanded controls also causes an estimate of aircraft acceleration ($\hat{n} = \hat{b}d$) to be different from the desired dynamics ?. The difference between the actual dynamics and the desired dynamics defines the hedge signal: $n_h = n - \hat{n}$.[6] The hedge signal represents the increment of the desired dynamics that can not be achieved due to actuator limitations. This hedge dynamics is subtracted from the simulation of the reference model states so that the reference model continues to represent achievable dynamics: $\ddot{x}_{rm} = n_{rm} - n_h$. Model error (?) represents the difference between the actual acceleration of the aircraft and its estimate: $\Delta^+ = \ddot{x} - \hat{n}$. In a controller on an actual vehicle, computation of this model error is difficult as it requires an accurate noise-free measurement of angular acceleration. However, in the simulator, these values are known exactly; because model error is both an input to $\hat{n}$ as well as its output, the values of acceleration and $\hat{n}$ from the previous timestep are used in calculating ?, a reasonable approximation when the time-step is small. The set of equations could also be iterated to converge on the correct values at every update.

IMPLEMENTATION

Inner-Loop

In implementing inner-loop controllers in simulation, the modified control architecture described in the previous section may be used; the specific control behavior is determined by the reference model as selected to model pilot or flight control system.

In modeling a flight control system, a second order response may be specified for the two attitude commands (roll and pitch) and for sideslip. A first order response is specified for thrust. Roll response is typical; this second order response is specified by

$$n_{rm} = w_n^2 (f_{cmd} - f_{rm}) + 2Vw_n (\dot{f}_{cmd} - \dot{f}_{rm})$$

with selected natural frequency and damping ratio as indicated. The remainder of the setup is consistant with that introduced above. The structure is illustrated in Figure 2.

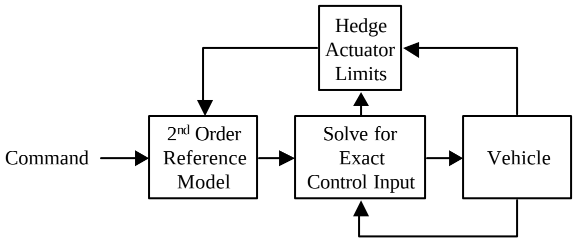

Figure 2 Inner Loop Autopilot Structure for a Single Axis or Channel

In the human pilot model (perhaps in series with a stability augmentation system), the reference model is based on the crossover model. With an ideal stability augmentation, the lead and lag terms of

$$G_p(s) = \frac{S_p (t_L s + 1) e^{-t_e s}}{(t_I s + 1)}$$

(or both) t_L and t_I may be omitted. For roll, the generic stability augmentation system exhibits the desired response

$$\frac{\dot{f}(s)}{u(s)} = \frac{K_p}{(t_p s + 1)}$$

with exact cancellation of all but one rigid body mode, where *u* is the roll input from the pilot. As a result, the crossover pilot model design (for manual control of roll angle) is completed based on the plant model

$$\frac{f(s)}{u(s)} = \frac{K_p}{s(t_p s + 1)}.$$

The specified pitch angle response is similar. This structure is illustrated in Figure 3. The components that make up the generic stability augmentation system model are deliniated.

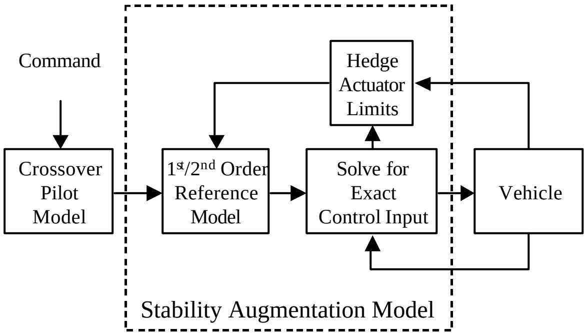

Figure 3 Inner Loop Stability Augmentation System and Pilot Model Structure for a Single Axis

Outer-Loop

Less emphasis is placed on an outer loop generic autopilot or pilot model here, since, noted earlier, several different types of outer-loop control behaviors are common, selected based on contextual factors beyond the scope of traditional dynamic analysis. However, one broadly applicable approach is to provide attitude and thrust commands to the inner loop to achieve a desired velocity, itself based on a desired position. Internal limits are used on attitude commands and possibly velocity commands. This is the approach taken here.

However, to keep the autopilot truly generic, data available only in a simulation is used to adjust these thrust and attitude commands as though an ideal autopilot has been developed. This is accomplished by continually including the error in expected and achieved acceleration in the next attitude and thrust command generation cycle, effectively solving for the attitude and thrust commands needed at every instant to give the desired response – within the limitations of the plant inputs. This is reasonable as an autopilot, flight director, or human pilot model for many applications.

The pitch angle computation is typical. The vertical speed command is determined based on altitude error.

$$VS_{cmd} = \frac{(h_{cmd} - h)}{t_h}$$

which may then be limited. Next, commanded rate of change of vertical speed is determined

$$\dot{VS}_{cmd} = \frac{(VS_{cmd} - VS)}{t_{VS}} - \Delta_{VS}$$

where Δ_{VS} is model error computed below. Now commanded pitch angle is determined based on estimated scale factor, $\hat{b}_{VS}$, which need not be very accurate; in practice the sign needs to be correct and the magnitude within an order or magnitude is sufficient.

$$q_{cmd} = \frac{V\dot{S}_{cmd}}{\hat{b}_{VS}}$$

Pitch angle command is normally limited at this point, either to an arbitrary value or to one based on maximum performance climbs and descents (corresponding to maximum and minimum available thrust). Model error is found based on information from the previous update. Alternatively, these equations could be iterated with the aircraft model to solve for the correct pitch angle command, but in practice this is not necessary.

RESULTS

The proposed generic autopilot and SAS/pilot model was tested utilizing an F-16 model that is available in the literature.[3] This allowed the system to be demonstrated on an aircraft with a large flight envelope and that benefits from stability augmentation.

For the pilot/SAS results, the SAS was a rate command system on pitch and roll, both with a frequency of response of 1 rad/sec. The directional channel was a sideslip-command system with a natural frequency of 3 rad/sec. The pilot model utilized the crossover model form.[4,5]

The autopilot model has a second order response on all three inner loops, with 1 rad/sec undamped natural frequency in roll and pitch, and 3 rad/sec in yaw. The damping ratio was selected to be critical, one, for all loops. The specified thrust response was first order with a time constant of 5 seconds for all cases.

The pitch angle response of both approaches is shown in Figure 4 from brake release to level off at 2000 ft. Pitch angle command is limited to 30 degrees (thrust limitations are not a factor for this time history). The pilot model response differs, and has a significantly larger steady state offset to the ramp input of heading during level off. The elevator angle is shown in Figure 5 for the same responses. Here, the pure time delay in the pilot model is evident when the aircraft rotates for takeoff. The airspeed response is shown in Figure 6.

At 250 KCAS, a step input of heading command is given to exercise the lateral channels. The heading response is shown in Figure 7. The aileron used is given in Figure 8. The roll angle commanded and the result is given in Figure 9.

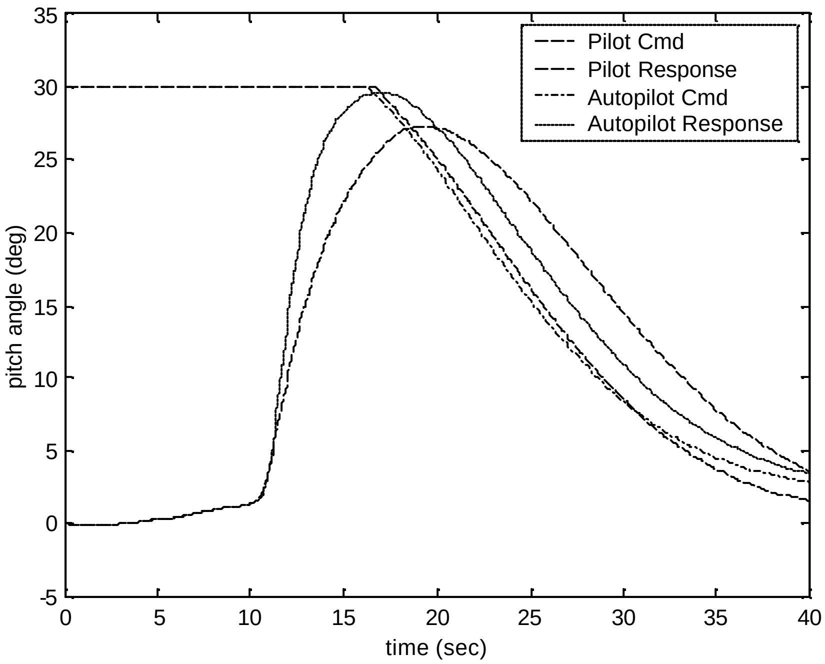

Figure 4 - Pitch attitude response, autopilot model and human pilot model with SAS response, commanded and actual shown, for rotation, takeoff, and level-off at 2000 ft

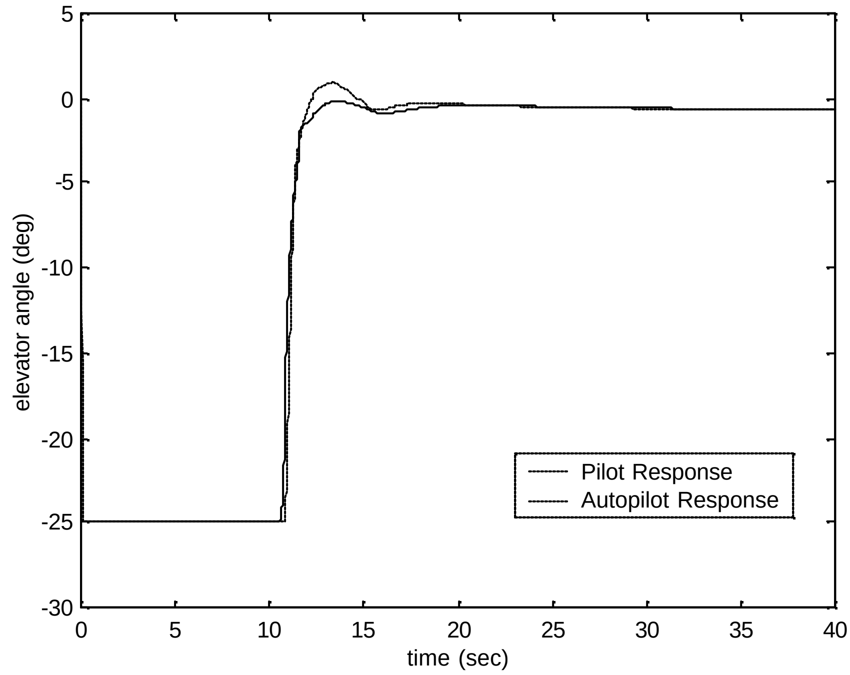

Figure 5 - Elevator time history, for both pilot model with SAS and autopilot model, pure time delay in pilot model is visible just after rotation

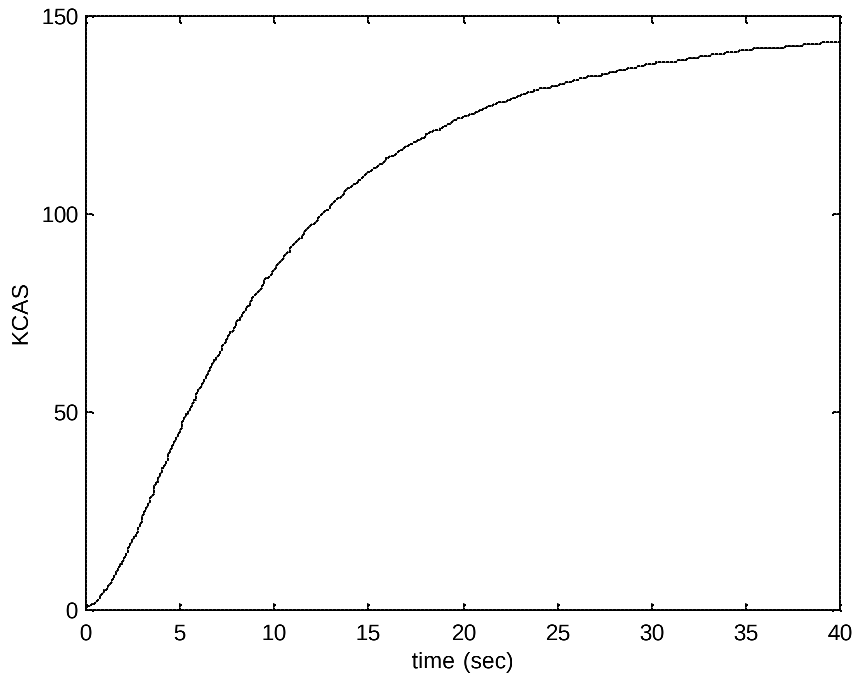

Figure 6 - Airspeed response from brake release, in Knots Calibrated Air Speed (KCAS), response with pilot model and autopilot model are similar

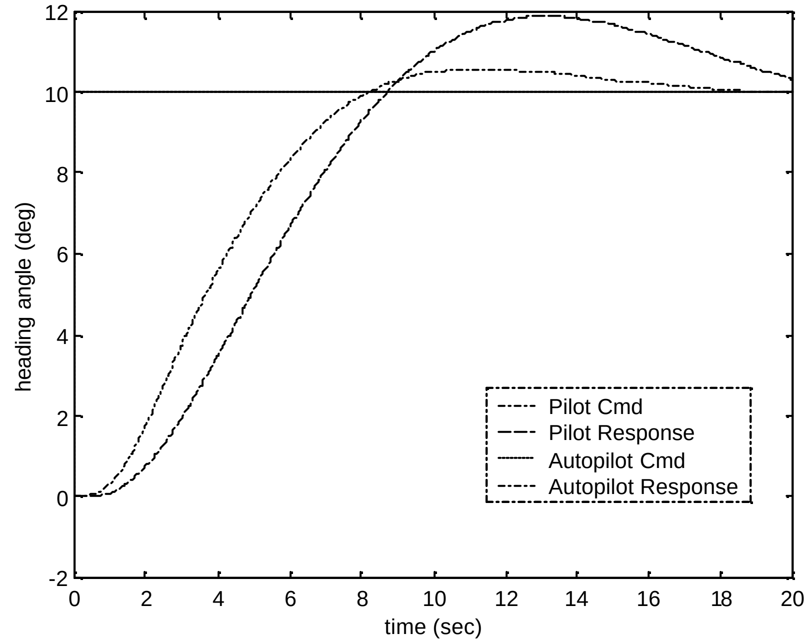

Figure 7 - Heading response for a 10 degree step input of heading command, pilot model response is initially slower

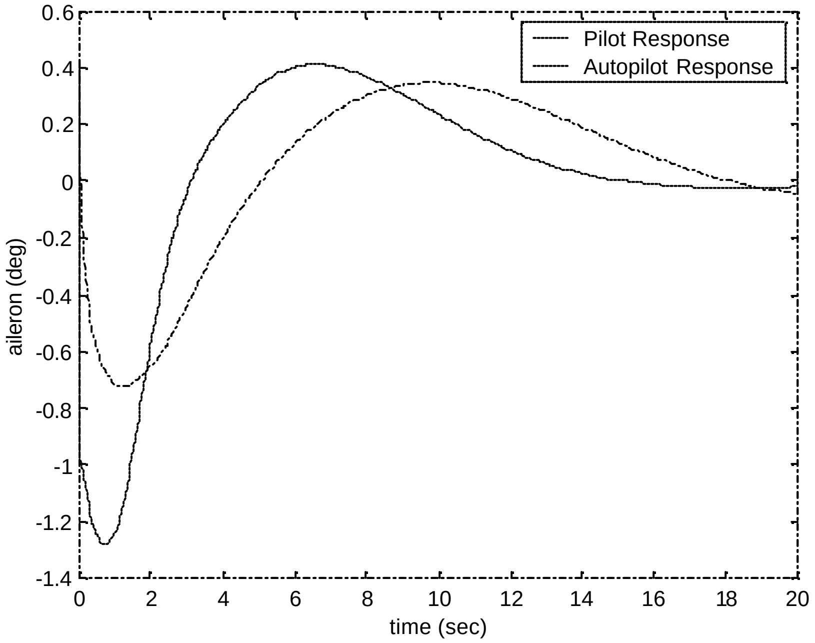

Figure 8 - Aileron time history for 10 degree step input of heading command, for both pilot model with SAS and autopilot model

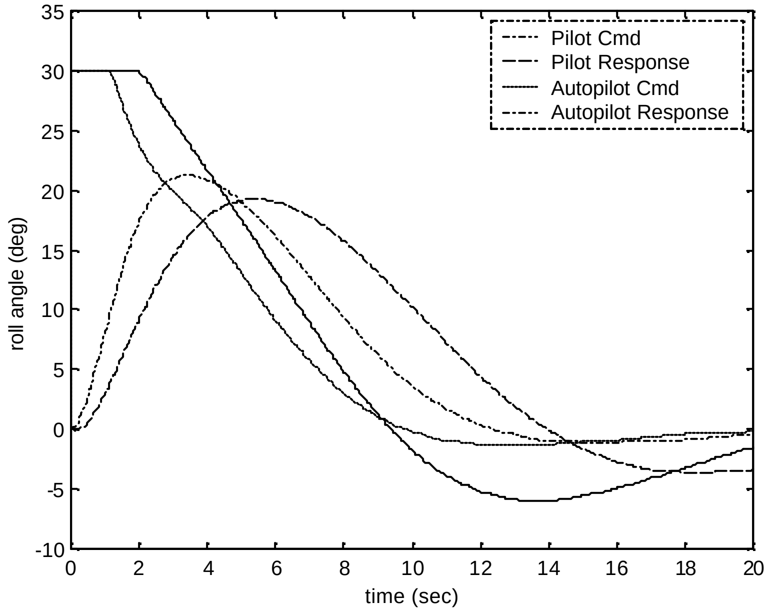

Figure 9 - Roll angle response, commanded and actual, for a 10 degree step input of heading command

CONCLUSIONS

This paper described a generic model of pilot or flight control system behavior suitable for, and easily implemented in, flight simulations. The inner-loop element is modified from adaptive control architectures, and allows a closed-loop behavior to be specified and followed that incorporates the dynamics of the aircraft; this allows for the inclusion of closed-loop behaviors established by models of pilots and by common specifications for flight control systems performance. While outer-loop control behavior is not specified as exactly by models of pilot and flight control system behavior, some general forms were also given here.

The generic model was applied to an aircraft dynamic model with a large flight envelope and requiring stability augmentation. This model was set to enact both pilot and flight control system behavior, and the dynamic responses of trajectory commands were found to behave in the general form expected when under piloted and automatic control.

While not an exact representation of one specific autoflight system – and within the limitations of pilot models – this generic model provides a reasonable, easy-to-implement means of incorporating pilot and flight control system behavior into flight simulation. The fidelity of this representation is suitable for many types of research and design activities, including avionics integration, flight deck design and testing, air traffic control research, and education.

As a further development, the pilot model may be further improved by automating the tuning of its parameters in response to the dynamic characteristics of the aircraft model, as specified in the literature.[4,5]

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