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FEEDBACK CONTROL LAWS FOR HIGHLY MANEUVERABLE AIRCRAFT

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FEEDBACK CONTROL LAWS FOR HIGHLY MANEUVERABLE AIRCRAFT

Annual Report for the Period February 1, 1993 to January 31, 1994

During the first half of the year, we concentrated our efforts on completing the design of control laws for the longitudinal axis of the HARV. During the second half of the year we concentrated on the synthesis of control laws for the lateral - directional axes.

Our longitudinal control law design efforts can be briefly summarized as follows. We developed longitudinal control laws for the HARV using μ synthesis design techniques coupled with dynamic inversion. An inner loop dynamic inversion controller was used to simplify the system dynamics by eliminating the aerodynamic nonlinearities and inertial cross coupling. Models of the errors resulting from uncertainties in the principal longitudinal aerodynamic terms were developed and included in the model of the HARV with the inner loop dynamic inversion controller. This resulted in an inner loop transfer function model which was an integrator with the modeling errors characterized as uncertainties in gain and phase. Outer loop controllers were then designed using μ synthesis to provide robustness to these modeling errors and give desired response to pilot inputs. Both pitch rate and angle of attack command following systems were designed.

The concept of time - scale separation was used in the design of the angle of attack command system. The outer loop controller required no scheduling since the response of inner loop system was essentially invariant with changes in flight conditions. This invariance of the outer loop controller is due to the design of the inner loop controller. The longitudinal dynamic response of the aircraft was excellent over a wide range of angles of attack. The longitudinal controller design studies described above comprised Jacob Reiner's Ph.D thesis which was

completed in July of 1993. The thesis resulted in three conference papers and two journal papers, one which has been accepted pending revisions by the *Journal of Guidance Control and Dynamics* and one of which will be submitted to *Automatica* .

Although two control effectors, elevators and longitudinal thrust vectoring, were used in the longitudinal control studies, the design problem was essentially single-input/ single-output. The lateral-directional control problem is multivariable. The inputs are pilot lateral stick and pedal commands and the outputs are roll rate about the velocity vector and side slip angle. The control effectors are ailerons, rudder deflection, and lateral thrust vectoring vane deflection.

We have accomplished the following tasks for the lateral-directional controllers:

1. We have designed both inner and outer loop dynamic inversion controllers.

2. We have derived an error model based on a linearized perturbation model of the inner loop system.

3. We have used classical techniques to design controllers for the inner loop system linearized by dynamics inversion. These controllers act to control roll rate and Dutch roll response.

4. We have implemented the inner loop dynamic inversion and classical controllers on the 6 DOF simulation.

5. We have developed a lateral - directional control allocation scheme based on minimizing required control effort.

We are now working on the design of μ controllers for the inner loop system. The general philosophy of design is the same as for the longitudinal control laws. Dynamic inversion is used to cancel the aerodynamic and inertial cross coupling torques about the pitch, roll

3

and yaw axes. Pseudo controls are used to generate commands to the actual control effectors which are ailerons, rudder and lateral thrust vector vane deflection. The inputs to the inner loop controller are the roll and yaw rate commands and the outputs are the roll and yaw rates so that a 2x2 transfer matrix relates the inputs and outputs. Ideally this matrix would be diagonal with the non - zero terms integrators. The effects of uncertainties in the aerodynamics will result in incomplete cancellation of the system dynamics by the dynamic inversion control laws. Models of the errors resulting from uncertainties in the aerodynamics have been developed and incorporated in the error models as linear fractional transformations. These error models will be used in the design of the robust, outer loop μ control laws.

Our work for the third year will include the following topics:

1. Incorporation of an algorithm for maintaining directionality of the control torque in case of control saturation.

2. Design of outer loop control laws using μ synthesis.

3. Evaluation stability and performance robustness of control laws using real and complex uncertainty models.

4. Evaluation of performance of the integrated lateral-directional and longitudinal μ/dynamic inversion controllers using nonlinear computer simulations.

If we command an angular rate which cannot be achieved and some of the control surfaces saturate, we will not achieve rotation about the desired axis. This is due to the torque vector not being oriented properly. This can be remedied by reducing the actuator commands in such a way that the proper direction of the torque vector is maintained even if its magnitude is not as large as desired. This was not an issue in the case of the longitudinal control design since the direction of the pitching torque vector is always perpendicular to the plane of symmetry of the aircraft. It is an issue in lateral - directional control however and will be addressed in the third years research.

Emphasis will be placed on maintaining lateral - directional handling

4

qualities while minimizing side slip and lateral acceleration during extreme maneuvers. The longitudinal control law will result in pilot longitudinal stick input commanding pitch rate command at low angles of attack and angle of attack at higher angles of attack. Lateral pilot stick input will command roll rate about the velocity vector and pilot pedal inputs will command side slip angle. Since rapid response is required, the weightings on angular acceleration will be relaxed as compared with our previous studies.

In previous designs we have used an implicit modeling following design in which the weighted difference between the output of the aircraft and the handling quality model was minimized. This error was not a feedback variable. In an independent study of helicopter flight control systems, we have developed an explicit model following technique in which the pilot commands are input to the handling quality models and the difference between the appropriate helicopter outputs and the outputs of the handling quality models are minimized using μ synthesis. These errors are feedback variables. This approach gives improved response compared with the implicit method. The frequency separation between high and low frequency modes in helicopter is not large. This is the same situation that we find in aircraft at high angles of attack. The explicit model following approach will be investigated to determine if it yields better performance.

In previous studies we did not use the full complement of sensors available. In this study we will us all sensors and we will incorporate weightings on the sensors so that the control laws will optimize the use of the sensors based on their accuracy and frequency response characteristics.

Robustness will be determined by structured singular value analyses in which errors are modeled as real or complex depending on their physical nature. Variations in aerodynamic coefficients, for example, will be represented by real perturbations in the coefficients of the equations of motion. Other errors, such as high frequency dynamics and sensor errors, will be represented as complex functions as they are dynamic in nature and can be modeled as transfer functions

We have shown in our previous work that linear analyses can be very useful but are not adequate to determine important quantities such as

peak acceleration and side slip during extreme maneuvers. Thus we will test our control laws using nonlinear simulations. Maneuvers such as velocity vector rolls and turns at high angles of attack will be emphasized.

Personnel

The personnel involved in the study will be Professors Balas and Garrard, Mr. Zadok Hogui and Ms. Laura Weyer. Mr. Hogui is a Ph.D candidate in the Department of Aerospace Engineering and Mechanics at the University of Minnesota. He is an Israeli citizen and has an B.S. and a M.S. from the Technion in Aerospace Engineering. Mr. Hogui has approximately ten years experience in the Israeli Aerospace Industry. He has been working on our project since the spring of 1993 and is now fully capable of running and modifying the HARV simulation. Ms Weyer is a U. S. citizen who completed her B. S. in Aerospace Engineering and Mechanics at the University of Minnesota in the spring of 1993. She is currently pursuing her M. S. She has worked with Professor Balas in software development in the past.

Publications Resulting From the Grant

Jacob Reiner, Gary J. Balas, and William L. Garrard, "Design of a Flight Control System for a Highly Maneuverable Aircraft Using Robust Dynamic Inversion," accepted pending revision in *Journal of Guidance Control and Dynamics*, 1994.

Jacob Reiner, Gary J. Balas, and William L. Garrard, "Design of Flight Control System Using Robust Dynamic Inversion with Time Scale Separation," submitted to *Automatica*, 1994.

Gary J. Balas, William L. Garrard, and Jacob Reiner, "Robust Dynamic Inversion Control Laws for Aircraft Control," AIAA Paper No. 92 - 4329 AIAA Guidance, Navigation and Control Conference, Hilton Head, South Carolina, August 1992.

Gary J. Balas, Jacob Reiner, William L. Garrard, "Design of a Flight Control System for a Highly Maneuverable Aircraft Using μ Synthesis,"

AIAA Guidance Navigation and Control Conference, August 1993, Monterey, California

Gary J. Balas, Jacob Reiner, William L. Garrard, "Design of a Flight Control System for a Highly Maneuverable Aircraft Using Robust Dynamic Inversion," AIAA Guidance Navigation and Control Conference, August 1994, Phoenix, Arizona

Degrees Awarded as a Result of the Grant

PhD in Aerospace Engineering University of Minnesota, Jacob Reiner, *Control Design for Aircraft Using Robust Dynamic Inversion Technique*, July 1993.