

INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY
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SUMMARY OF RESEARCH

The Air Transportation Technology Program at Princeton University, a program emphasizing graduate and undergraduate student research, proceeded along four avenues during the past year:

- Guidance and Control Strategies for Penetration of Microbursts and Wind Shear
- Application of Artificial Intelligence in Flight Control Systems
- Computer-Aided Control System Design
- Effects of Control Saturation on Closed-Loop Stability and Response of Open-Loop-Unstable Aircraft

Areas of investigation relate to guidance and control of commercial transports as well as general aviation aircraft. Interaction between the flight crew and automatic systems is a subject of principal concern.

Recently, it has become apparent that severe downdrafts and resulting high velocity outflows present a significant hazard to aircraft on takeoff and final approach. This condition is called a microburst, and while it often is associated with thunderstorm activity, it also can occur in the vicinity of dissipating convective clouds that produce no rainfall at ground level. Microburst encounter is a rare but extremely dangerous phenomenon that accounts for one or two air carrier accidents and numerous general aviation accidents each year (on average). Conditions are such that an aircraft's performance envelope may be inadequate for safe penetration unless optimal control strategies are known and applied.

While a number of simulation studies have been directed at the problem, there are varied opinions in the flying community regarding the best piloting procedures, and optimal control strategies have only recently been defined. Graduate student Mark Psiaki has undertaken a study of guidance and control strategies for penetration of microbursts when encounter is unavoidable. His initial work shows that simple control laws could greatly reduce an aircraft's response to wind shear. Although the response mechanism is the same, jet transport and general aviation aircraft behave somewhat differently in microbursts; the larger, heavier aircraft are more adversely affected by variations in the

horizontal wind, while the smaller, lighter aircraft have greater difficulty with the downdraft. Our emphasis has shifted to the determination of optimal control strategies for the microburst encounter [1]. The study has begun with the computation of optimal control histories using steepest-descent and second-order gradient algorithms. An envelope of safe flight has been determined for typical jet transport and general aviation aircraft; these results will be documented shortly in Mr. Psiaki's doctoral thesis and in technical papers.

Attention is now being directed at optimal closed-loop control laws for wind shear encounter that could be executed in "real time." [2]. Graduate student Amit Joshi is working in this area. In addition, he will be developing a real-time fixed-based cockpit simulation as an adjunct to this research.

Undetected system failures and/or inadequately defined recovery procedures have contributed to numerous air carrier incidents and accidents. The infamous DC-10 accident at Chicago's O'Hare Airport, in which loss of an engine pod, subsequent loss of subsystems, and asymmetric wing stall led to disaster, provides a prototype for the kind of tragedy that could be averted by intelligent flight control systems. (An intelligent control system is one that uses artificial intelligence concepts, e.g., an expert systems program, to improve performance and fault tolerance.) Although many methods of modern control theory are applicable, the scope of the problem is such that none of the existing theories provides a complete and practical solution to the problem. At the same time, heuristic logic may be applicable, but it has yet to be stated in satisfactory format.

Graduate student David Handelman is developing a knowledge-based reconfigurable flight control system that will be implemented with the Pascal programming language using parallel microprocessors. This expert system could be considered a prototype for a fault-tolerant control system that could be constructed using existing hardware. The knowledge-based flight control system is specified initially and tested using the LISP programming language. When desired logic is determined, the corresponding Pascal code is generated automatically. Details of knowledge base development, expert system logic, and initial evaluations are contained in Ref. 3.

In a parallel effort, graduate student Chien Huang is using LISP to investigate the utility of a string-oriented, recursive logical system in the same role. A principal distinction between this and the previous approach is that flight control code will be modified in response to control system failures. As an adjunct to automatic restructuring of the control system, a tool for computer-aided control system design is being developed. The Control Equation Parser allows conventional state-space expressions to be translated to LISP code, and it executes complex design functions such as the solution of Riccati equations by

calling subroutines written in numerically efficient computer languages such as FORTRAN or Pascal [4].

Maintenance of flight control systems between flights also is a knowledge-intensive task, so it is likely that expert systems can be useful aids to aircraft mechanics. Senior Christopher Loh demonstrated the possibility of translating conventional maintenance and operations manuals for the hydraulic system of a tandem-rotor helicopter into an expert system using LISP [5]. The prototype expert system contains over 250 rules and 150 parameters in a MYCIN-like format, yet it describes only a fraction of the information contained in the manuals.

Whereas most expert system development tools are deductive, requiring the system designer to specify rules to be executed by a computer, inductive knowledge acquisition tools that generate rules from specified scenarios may be more useful in many applications. For example, a skilled pilot might well be able to explain what he or she would do in a given emergency, yet not recognize the rule structure that the actions represent. Graduate student Brenda Belkin has documented an exercise (performed under separate contract) in which an inductive tool was used to define procedures for an in-flight emergency [6].

One of the virtues of highly reliable electronic flight control systems is that an aircraft's stability and response, i.e., its closed-loop flying qualities, can be tailored to the pilot's needs. For reasons of performance and maneuverability, it may be desirable to design the aircraft so that its natural (unaugmented) modes of motion are unstable, with the understanding that the flight control system will provide the necessary stability by deflecting control surfaces to counter potentially divergent motions. Because control surfaces have limitations on their displacements and rates of travel, stability can be restored only within a bounded region about the trim point. If the aircraft's motions exceed the boundaries, the available control forces and moments will not be sufficient to prevent divergence.

Graduate student Prakash Shrivastava developed methods for determining the stability boundaries and control response for systems containing control saturation, and in the process, he was awarded the Ph.D. degree [7]. Analysis was carried out using state-space plots, in which saturation boundaries were represented by straight lines, stability boundaries were seen to be unstable limit cycles or straight lines, stable trajectories approach equilibrium points, and unstable trajectories diverge to infinity. The analysis pertained to systems containing unequal saturation boundaries, as well as those with multiple saturating controls.

In addition, a technical paper describing work completed in earlier years was published during 1986. Reference 8, which summarizes, in part, the Ph.D. research of Aharon Bar-Gill, describes the results of flight experiments to determine the effects of aircraft dynamic characteristics on flying qualities during single-pilot instrument flight.

The FAA/NASA grant supporting student research in air transportation technology has inestimable value in helping educate a new generation of engineers for the aerospace industry, and it is producing research results that are relevant to the continued excellence of aeronautical development in this country.

ANNOTATED BIBLIOGRAPHY OF 1986 PUBLICATIONS

1. Psiaki, M.L., and Stengel, R.F., "Optimal Flight Paths Through Microburst Wind Profiles", AIAA Journal of Aircraft, Vol. 23, No. 8, Aug 1986, pp. 629-635.

The problem of safe microburst wind shear encounter during the approach and climb-out flight phases was addressed using flight path optimization. The purpose was to investigate the physical limits of safe penetration and to determine control strategies that take full advantage of those limits. Optimal trajectories for both jet transport and general aviation aircraft were computed for encounters with idealized and actual microburst profiles. The results demonstrate that limits to control system design rather than to the aircraft's physical performance may be the deciding factor in an aircraft's capability for safe passage through a wide class of microbursts. The best control strategies responded to airspeed loss in an unconventional manner: by raising the nose to maintain lift.

2. Stengel, R.F., "Optimal Control Laws for Microburst Encounter," in Proceedings of the 15th Congress of the International Council of the Aeronautical Sciences, Paper No. ICAS-86-5.6.3, London, Sept 1986, pp. 870-878.

Simplified structures for longitudinal control laws that reduce an aircraft's response to the strong head-tailwind variations associated with microbursts are presented. They are based on non-zero-set-point linear-quadratic regulators that command throttle setting and angle of attack as functions of velocity and flight path angle, and they can incorporate direct measurements of the wind profile if available. Selection of cost functions to be minimized by feedback control has been aided by a prior study of classical control laws and exact nonlinear-optimal flight paths through realistic microburst wind profiles. The resulting optimal control laws have an adaptive, dual-mode structure that can be implemented either in flight-director logic or in an autopilot.

3. Handelman, D.A., and Stengel, R.F., "A Theory for Fault-Tolerant Flight Control Combining Expert System and Analytical Redundancy Concepts," in Proceedings of the 1986 AIAA Guidance, Navigation, and Control Conference, Williamsburg, AIAA Paper No. 86-2092-CP, Aug 1986, pp. 375-384.

This paper presents a theory for rule-based fault-tolerant flight control. The objective is to define methods for designing control systems capable of accommodating a wide range of aircraft failures, including sensor, control, and structural failures. A software architecture is described that integrates quantitative

analytical redundancy techniques and heuristic expert system concepts for the purpose of in-flight, real-time fault tolerance. The resultant controller uses a rule-based expert systems approach to transform the problem of failure accommodation task scheduling and selection into a problem of search. Control system performance under sensor and control failures is demonstrated using linear discrete-time deterministic simulations of a tandem-rotor helicopter's dynamics. It is found that the rule-based control theory can be used to enhance existing redundancy management systems. This approach to control system design also provides inherent parallelism for computational speed, smooth integration of algorithmic and heuristic computation, a search-based decision-making mechanism, straightforward system organization and debugging, and an incremental growth capability.

4. Huang, C.Y., and Stengel, R.F., "A Symbolic Parser for Control Equations," in Proceedings of the Institute of Measurement and Control 2nd Workshop on Computer-Aided Control System Design, Salford, England, July 1986, pp. 7-14.

A computer program for symbolic compilation and numerical simulation of control system design equations has been developed. The Control Equation Parser translates expressions written in standard state-space format into the LISP computer language for evaluation. Vectors and matrices are easily defined, and common operations of linear algebra are readily executed using this program. Numerical solutions can be obtained by executing LISP code or, as in the case of control calculations, by calling FORTRAN subroutines. In combination with a LISP workstation, the program provides a highly interactive tool for assisting in the design of multivariable control systems.

5. Loh, C.T., "A Prototype Maintenance Expert System for the CH-47 Flight Control Hydraulic System," Princeton University Technical Report No. MAE-1751, Apr 1986.

An investigation of the use of artificial intelligence techniques in the maintenance of hydraulic flight control systems was undertaken. A knowledge-based expert system employing situation-action rules (production systems) for diagnosing failures and subsequently identifying faulty devices was developed. The expert system's "inference engine" performs a backward-chaining process via a goal-driven control strategy. Its strategy involves finding rules that demonstrate a given hypothesis, then verify the facts used by the rule. The resulting LISP program, which emulates a small fraction of the procedures contained in maintenance and operations manuals for the CH-47 helicopter, contains over 250 rules for setting over 150 parameters.

6. Belkin, Brenda L., "A Demonstration Expert System for Implementing Emergency Procedures in a High-Performance Fighter Aircraft," Princeton University Report No. MAE-1749, Apr 1986.

A demonstration expert system was developed using a knowledge acquisition tool to simulate the operation of an electronic pilot's assistant. The task selected was the implementation of in-flight emergency procedures for a fighter aircraft. Two modes require the computer to help with routine flight tasks. Two others require the computer to plan and execute procedures for aircraft control autonomously, for instances in which the pilot is incapacitated or is subjected to high workload.

7. Shrivastava, P.C., "Stability Regions of Relaxed Static Stability Aircraft Under Control Saturation Constraints," Princeton University Report No. MAE-1747-T (Ph.D. Thesis), Oct 1986.

General characteristics of closed-loop stability regions for open-loop-unstable linear systems with bounded controls were determined. The shapes and sizes of stability regions were shown to depend on the types of singularities associated with system dynamics, feedback gains, control saturation limits, and command inputs. Analytical expressions were derived in normal-mode coordinates for the stability boundaries. Longitudinal static instability of the aircraft normally forces a single system root to become unstable, creating a saddle-point singularity, while directional static instability results in two unstable (real) roots with a focal point singularity. Stability regions can be characterized as hypercylinders in the state space surrounding the commanded closed-loop equilibrium point. Non-zero command inputs create asymmetry in the saturation effects, usually resulting in a net shrinkage of the stable region. Displacement saturation and rate saturation produce distinct effects, and a combination of the two can be particularly restrictive.

8. Bar-Gill, A., and Stengel, R.F., "Longitudinal Flying Qualities Criteria for Single-Pilot Instrument Flight Operations," AIAA Journal of Aircraft, Vol. 23, No. 2, Feb 1986, pp. 111-117.

Experiments to determine the flying qualities of more than a dozen dynamic configurations were conducted using the variable-stability Avionics Research Aircraft. Particular attention was paid to variations in long-period longitudinal characteristics and their effects on the performance of simulated IFR flights from takeoff through landing. Lift slope had the greatest effect on pilot opinion, workload, and tracking error. Bounds for satisfactory flying qualities were found for three parameters: phugoid mode damping, stick force gradient (with respect to trim airspeed), and pitch/airspeed gradient.

Wind Shear Guidance and Control Aircraft Applications of Machine Intelligence Fixed-Base Simulation

WIND SHEAR GUIDANCE and CONTROL

Classical Control System Design to Reduce
Microburst Response

Flight-Path Optimization to Minimize
Microburst Response

Linear-Quadratic Control System Design to
Approximate Optimal Microburst Response

Significance of Control & Short-Period Lag

Application of Nonlinear Inverse Dynamics in
Closed-Loop Control

AIRCRAFT APPLICATIONS of MACHINE INTELLIGENCE

Functions of a Knowledge-Based Control System

Fault-Tolerant Flight Control Systems

Real-Time Expert System Development

Signal Dependencies, Graphs and Frames

Computer-Aiding for the Pilot

Hydraulic System Failure Diagnosis

FIXED-BASE SIMULATION

Three Aircraft Simulations in Preparation:

Navion

Small Twin-Jet Transport

Twin-Jet Fighter/Attack Aircraft

Single-Person Crew Station

Computer-Generated "Out-the-Window" and
Panel Displays

Silicon Graphics IRIS 3020 Workstation

(UNIX, 68020, Graphics Engine)

IBM PC-AT (PC-DOS, 80286/7)

3 - Multibus Single-Board Computers (80286/7)

"C" Programming Language

Verbex 4000 Voice Recognition System

Ethernet Connection to
Symbolics 3670 LISP Machine