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INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY AT PRINCETON UNIVERSITY, 1991-1992

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SUMMARY OF RESEARCH

The Air Transportation Research Program at Princeton University proceeded along six avenues during the past year:

- Intelligent Flight Control
- Computer-Aided Control System Design
- Neural Networks for Flight Control
- Stochastic Robustness of Flight Control Systems
- Microburst Hazards to Aircraft
- Fundamental Dynamics of Atmospheric Flight

This research has resulted in a number of publications, including archival papers and conference papers. An annotated bibliography of publications that appeared between June 1991 and June 1992 appears at the end of this report. The research that these papers describe was supported in whole or in part by the Joint University Program, including work that was completed prior to the reporting period.

Human pilots traditionally have provided the intelligence to fly manned aircraft in numerous ways, from applying manual dexterity through informed planning and coordination of missions. As aircraft characteristics have changed, and more importantly as the technology has allowed, an increasing share of the aircraft's intelligent operation has relied on proper functioning of electro-mechanical sensors, computers, and actuators. It has become possible to apply machine intelligence to flight control.

It can be argued that any degree of feedback from sensed motions to control actions instills intelligent behavior because control actions are shaped by knowledge of the system's response. In a contemporary context, intelligent flight control has come to represent even more ambitious plans to

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- make aircraft less dependent on proper human actions for mission completion,
- enhance the mission capability of aircraft,
- improve performance by learning from experience,
- increase the reliability and safety of flight, and
- lower the cost and weight of aircraft systems.

The goal of Ref. 1 is to present concepts for intelligent flight control in the contemporary context, and it forms a basis for future research to be conducted in this program. Control functions are distinguished according to a cognitive/biological hierarchy that is bounded on one end by *declarative functions*, which typically involve decision-making, and on the other by *reflexive functions*, which are more-or-less spontaneous reactions to external or internal stimuli.

In a classical flight control context, declarative functions are performed by the control system's *outer loops*, and reflexive functions are performed by its *inner loops*. We may also define an intermediate level of *procedural functions*, which -- like reflexive functions -- have well-defined input-output characteristics but of a more complicated structure. Traditional design principles suggest that the outer-loop functions should be dedicated to low-bandwidth, large-amplitude control commands, while the inner-loop functions should have high bandwidths and relatively lower-amplitude actions. There is a logical progression from the sweeping, flexible alternatives associated with satisfying mission goals to more local concerns for stability and regulation about a desired path or equilibrium condition.

We have begun to examine the application of these concepts to advanced systems for air traffic management. Graduate student John Wangermann is setting the groundwork for an Intelligent Aircraft/Airspace System (IAAS). The goal is to identify means by which ground-based and airborne flight management systems can cooperate to produce a net gain in the efficiency and robustness of air transportation.

Earlier research focused on intelligent failure-tolerant control, resulting in a journal paper that appeared during the reporting period [2]. Failure-tolerant control systems can be characterized as robust, reconfigurable, or some combination of the two. A controlled system that retains satisfactory performance in the presence of variations from an assumed model without changes in the control system's structure or parameters is said to be *robust*. The degree of failure that can be accommodated by a fixed control structure is more restricted than that of a variable control structure. If the control system's structure or parameters can be altered in response to system failure, it is said to be *reconfigurable*. In the latter case, the control system detects, identifies, and isolates failures, and it modifies control laws to maintain acceptable performance. A reconfigurable, failure-tolerant control system must be robust enough to preclude controlled system failure while adaptation is taking place.

Graduate student Subrata Sircar has begun to examine concepts for the next generation of computer-aided flight control system design through development of a comprehensive computer program called *FlightCAD* [3], and graduate student Frank Stoner is continuing this research. The program contains a variety of modeling, synthesis, simulation, and evaluation alternatives. It is organized around a desktop metaphor that takes advantage of unique capabilities of the NeXT Computer. A direct digital synthesis technique is employed; it will produce a proportional-integral-filter controller with scheduled linear-quadratic-Gaussian gains. Tight following of pilot commands will be assured by a forward-loop command generator tracker, and the controller will be sufficiently robust to account for specified levels of parameter uncertainty. A principal feature of the control design package is the enhanced ability to iterate and search during the modeling, design, and analysis process.

We are investigating the use of neural networks for system identification and adaptive control. We envision an aerodynamic model that spans the entire flight envelope of an aircraft, including post-stall and spinning regions. The model contains six neural networks with multiple inputs and scalar outputs, three for force coefficients and three for moment coefficients (for example, the pitch moment network takes the form $C_m = g(\mathbf{x},\mathbf{u})$, where $\mathbf{x}$ represents the state and $\mathbf{u}$ the control). If input variables are not restricted to those having plausible aerodynamic effect, false correlations may be created in the network; hence, attitude Euler angles and horizontal position should be neglected, while physically meaningful terms like elevator deflection, angle of attack, pitch rate, Mach number, and dynamic pressure should be included.

Neural networks can be trained using backpropagation or extended Kalman filtering. Backpropagation typically involves a gradient search that minimizes the mean-square output error between desired and network outputs. Search rate can be modified by adding momentum or conjugate-gradient terms to the algorithm. Learning speed and accuracy can be further improved using an extended Kalman filter. If the network has a scalar output, the extended Kalman filter minimizes the fit error between the training hypersurface and that produced by the network. In an examination of the nonlinear aerodynamics of a twin-jet transport aircraft, graduate student

Dennis Linse has found that the fit error can be dramatically reduced by considering the *gradients* of the surfaces as well [4]. The relative significance given to function and derivative error during training can be adjusted through the measurement-error covariance matrix used in filter design.

Control system robustness is defined as the ability to maintain satisfactory stability or performance characteristics in the presence of all conceivable system parameter variations. While assured robustness may be viewed as an alternative to gain adaptation or scheduling to accommodate known parameter variations, more often it is seen as protection against uncertainties in plant specification. Consequently, a statistical description of control system robustness is consistent with what may be known about the structure and parameters of the plant's dynamic model. Graduate student Laura Ryan Ray completed her Ph.D. thesis on this topic and co-authored a number of related papers, the most recent of which is Ref. 5. Graduate student Chris Marrison has applied *Stochastic Robustness Analysis* to ten controllers designed in response to the 1990 American Control Conference Benchmark Control Problem challenge, and he has extended the analysis approach to develop a search procedure that synthesizes controllers with superior robustness [6]. A particular finding is that there is no single "most robust" controller, as design tradeoffs must inevitably be considered. In the present case, stability, settling time, and control usage all are of concern; controllers that favor one criterion over the other two have dramatically different characteristics.

Severe downdrafts and resulting high velocity outflows caused by microbursts present a significant hazard to aircraft on takeoff and final approach. *Microbursts*, which are often associated with thunderstorm activity, 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.

Our current wind shear research focuses on avoiding wind shear during transport aircraft operations, as well as on developing cockpit strategies for wind shear recovery. Graduate student Alex Stratton has developed an expert system for wind shear avoidance that extends the FAA Microburst Windshear Guidelines to account for temporal and spatial variations in the evidence that wind shear is present [7-9]. A Bayesian Belief Network relates information gathered from many sources to determine the probability of encountering a microburst on the intended flight path. Measurements made by a look-ahead sensor (e.g., Doppler radar or lidar) are processed by a bank of extended Kalman filters to develop a head-tailwind profile estimate that helps determine the likelihood of hazardous microburst encounter.

Graduate student Sandeep Mulgund is investigating alternatives for real-time guidance for the case in which wind shear encounter has not been avoided. He has compared optimal (constant) target-pitch-angle guidance with time-varying optimal control histories for a propeller-driven commuter-type aircraft. Results show the significant differences between best target pitch angles for head-tailwind shear and downdraft encounters. (Although the best single angle of attack for wind shear encounter is essentially the same for equivalent horizontal shears and vertical downdrafts, the corresponding pitch angles are decidedly different.) Time-varying optimal control produces additional altitude margin, which could make the difference between escape and impact in critical encounters. (See ref. 10.)

Graduate student Darin Spilman has analyzed the dynamics of a twin-jet transport encountering an intense wind "rotor", finding that a physically realizable rotor could roll the aircraft to inverted attitude if left unopposed by lateral control. Similarly, unopposed full rudder deflection could invert the aircraft in its landing configuration. This analysis will provide a better understanding of possible hazards to aircraft during the approach phase.

Elements of an aircraft's phugoid motion, the long-period interchange of kinetic and potential energy, were presented in a technical comment [11]. This comment clarified the effects of thrust sensitivity to airspeed on the mode, with particular attention to supersonic flight. It also was noted that pitching moment/speed sensitivity is likely to have an effect of comparable magnitude and should not be neglected.

An archival paper describing research conducted by Brenda Belkin appeared during the reporting period [12]. In her M.S.E. thesis, Ms. Belkin used the paradigm of a hypothetical aircraft crew to facilitate the assignment of tasks, rules, and data within parallel knowledge bases. Ms. Belkin was the recipient of the 1990 William E. Jackson Award of the Radio Technical Commission for Aeronautics for her thesis.

ANNOTATED BIBLIOGRAPHY OF 1991-1992 PUBLICATIONS

1. R. F. Stengel, Toward Intelligent Flight Control, presented at the AGARD Guidance and Control Panel Workshop, *Stability in Aerospace Systems*, Toulouse, France, June 1992.

Flight control systems can benefit by being designed to emulate functions of natural intelligence. Intelligent control functions fall in three categories: declarative, procedural, and reflexive. Declarative actions involve decision-making, providing models for system monitoring, goal planning, and system/scenario identification. Procedural actions concern skilled behavior and have parallels in guidance, navigation, and adaptation. Reflexive actions are more-or-less spontaneous and are similar to inner-loop control and estimation. Intelligent flight control systems will contain a hierarchy of expert systems, procedural algorithms, and computational neural networks, each expanding on prior functions to improve mission capability, to increase the reliability and safety of flight, and to ease pilot workload.

2. R. F. Stengel, Intelligent Failure-Tolerant Control, *IEEE Control Systems Magazine*, Vol. 11, No. 4, June 1991, pp. 14-23.

An overview of failure-tolerant control is presented, beginning with robust control, progressing through parallel and analytical redundancy, and ending with rule-based systems and artificial neural networks. By design or implementation, failure-tolerant control systems are "intelligent" systems. All failure-tolerant systems require some degree of robustness to protect against catastrophic failure; failure tolerance often can be improved by adaptivity in decision-making and control, as well as by redundancy in measurement and actuation. Reliability, maintainability, and survivability can be enhanced by failure tolerance, although each objective poses different goals for control system design. Artificial intelligence concepts are helpful for integrating and codifying failure-tolerant control systems, not as alternatives but as adjuncts to conventional design methods.

3. R. F. Stengel and S. Sircar, Computer-Aided Design of Flight Control Systems, *Proceedings of the 1991 AIAA Guidance, Navigation, and Control Conference*, New Orleans, Aug. 1991, pp. 677-683.

A comprehensive computer program for designing and evaluating multidisciplinary aircraft flight control systems is described. The *FlightCAD* program contains a variety of modeling, synthesis, analysis, and simulation alternatives. *FlightCAD* ultimately will implement a number of control design techniques; here it uses direct digital synthesis to produce a robust, proportional-integral-filter controller with scheduled linear-quadratic-Gaussian gains and command generator tracking of pilot inputs. The *FlightCAD* design approach is reviewed, and a status report is presented.

4. D. Linse and R. F. Stengel, Identification of Aerodynamic Coefficients Using Computational Neural Networks, *AIAA 30th Aerospace Sciences Meeting*, AIAA Paper No. 92-0172, Reno, Jan. 1992.

Precise, smooth aerodynamic models are required for implementing adaptive, nonlinear control strategies. Accurate representations of aerodynamic coefficients can be generated for the complete flight envelope by combining computational neural network models with an Estimation-Before-Modeling paradigm for on-line training. A novel method of incorporating first-partial-derivative information is employed to estimate the weights in individual feedforward networks for each coefficient. The method is demonstrated by generating a model of the normal force coefficient of a twin-jet transport aircraft from simulated flight data, and promising results are obtained.

5. L. R. Ray and R. F. Stengel, Application of Stochastic Robustness to Aircraft Control, *J. Guidance, Control, and Dynamics*, Vol. 14, No. 6, Nov.-Dec. 1991, pp. 1251-1259.

Stochastic robustness, a simple numerical procedure for estimating the stability robustness of linear, time-invariant systems, is applied to a forward-swept-wing aircraft control system. Based on Monte Carlo evaluation of the system's closed-loop eigenvalues, this analysis approach introduces the *probability of instability* as a scalar stability robustness measure. The related *stochastic root locus* provides insight into robustness characteristics of the closed-loop system. Three linear-quadratic controllers of increasing robustness are chosen to demonstrate the use of stochastic robustness to analyze and compare control designs. Examples are presented illustrating the use of stochastic robustness analysis to address the effects of actuator dynamics and unmodeled dynamics on the stability robustness of the forward-swept-wing aircraft.

6. R. F. Stengel and C. I. Marrison, Stochastic Robustness Synthesis for a Benchmark Problem, *Proceedings of the 1992 American Control Conference*, Chicago, June 1992, pp. 2421-2422.

Stochastic Robustness Analysis guides the synthesis of robust LQG regulators for a Benchmark Control Problem. Probabilities of exceeding allowable design limits, including stability, settling time, and control usage, are estimated by Monte Carlo evaluation. Robust, low-gain compensators that fulfill objectives are designed by numerically minimizing quadratic functions of these probabilities. The method is straightforward and makes use of uncomplicated design principles.

7. D. A. Stratton and R. F. Stengel, Probabilistic Reasoning for Intelligent Wind Shear Avoidance, *J. Guidance, Control, and Dynamics*, Vol. 15, No. 1, Jan.-Feb. 1992, pp. 247-254.

Avoiding severe wind shear challenges the ability of flight crews, as it involves assessing risk from uncertain evidence. A computerized intelligent cockpit aid can increase flight crew awareness of wind shear, improving avoidance decisions. A primary task in the development of such a cockpit aid is providing a means of assessing risk from evidence of wind shear from sources with varying reliability. The Federal Aviation Administration's Windshear Training Aid provides guidelines for assessing the risk of wind shear encounter from meteorological evidence. Use of these guidelines in the cockpit is complicated by uncertainty surrounding meteorological knowledge of wind shear. Bayesian network representation is discussed as a means of modeling this uncertain knowledge in a computer. A probabilistic model of the Windshear Training Aid guidelines using Bayesian network representation is presented. This model combines evidence from sources of varying reliability and incorporates results from meteorological studies of wind shear. The probabilistic model can provide flight crews with meaningful estimates of risk to aid their decisions, using evidence from a variety of sources and a base of meteorological knowledge.

8. D. A. Stratton and R. F. Stengel, Robust Kalman Filter Design for Predictive Wind Shear Detection, *Proceedings of the 1991 AIAA Guidance, Navigation, and Control Conference*, New Orleans, Aug. 1991, pp. 1549-1556.

Severe, low-altitude wind shear is a threat to aviation safety. Airborne sensors under development measure the radial component of wind along a line directly in front of an aircraft. In this paper, optimal estimation theory is used to define a detection algorithm to warn of hazardous wind shear from these sensors. To achieve robustness, a wind shear detection algorithm must distinguish threatening wind shear from less hazardous gustiness, despite variations in wind shear structure. This paper presents statistical analysis methods to refine wind shear detection algorithm robustness. Computational methods predict the ability to warn of severe wind shear and avoid false warning. Comparative capability of the detection algorithm as a function of

its design parameters is determined, identifying designs that provide robust detection of severe wind shear.

9. D. A. Stratton and R. F. Stengel, Real-Time Decision Aiding: An Application to Wind Shear Avoidance, *AIAA 30th Aerospace Sciences Meeting*, Reno, AIAA Paper No. 92-0290, Jan. 1992.

Modern control theory and artificial intelligence are applied to the Wind Shear Safety Advisor, a conceptual airborne advisory system to help flight crews avoid or survive encounters with hazardous low-altitude wind shear. Numerical and symbolic processes fuse diverse, time-varying data from ground-based and airborne measurements. Simulated wind-shear-encounter scenarios illustrate the need to consider a variety of factors for optimal decision reliability. Simulations show the potential for effectively integrating available information, highlighting the benefits of the computational techniques employed.

10. S. Mulgund and R. F. Stengel, Target Pitch Angle for the Microburst Escape Maneuver, *AIAA 30th Aerospace Sciences Meeting*, Reno, AIAA Paper No. 92-0730, Jan. 1992.

Commuter and general aviation aircraft face no less a threat from microburst wind shear than do large jet transports, yet most studies of wind shear encounter have neglected them. The effects of microburst wind shear on a propeller-driven commuter aircraft are considered here. Recovery performance of a commuter-type aircraft in a microburst encounter is examined using a constant-pitch-attitude strategy and flight-path optimization. The goals are to identify a suitable target pitch angle for the escape maneuver and to determine the nature of an optimal escape maneuver for commuter aircraft. The results demonstrate that the pitch attitude that maximizes climb rate in a wind shear is strongly dependent on whether the shear is predominantly a downdraft or a horizontal shear. Simulated recoveries show that the optimal constant pitch angle depends on the altitude of encounter, the strength of the microburst, and the initial position of the aircraft relative to the microburst core. In severe wind shear encounters at very low altitude, best results are obtained at relatively low pitch angle. Excessively high target pitch angles subject the aircraft to prolonged periods near stall. Flight path optimization demonstrates that maximum ground clearance is obtained by maintaining a low pitch attitude early in the encounter followed by a gradual pitch-up that ceases when the aircraft exits the wind shear.

11. R. F. Stengel, Comments on "Effect of Thrust/Speed Dependence on Long-Period Dynamics in Supersonic Flight," *J. Guidance, Control, and Dynamics*, Vol. 15, No. 3, May-June 1992, pp. 795-797.

The referenced paper discusses effects of speed-dependent variations in thrust on the long-period motions of aircraft in supersonic flight. Its principal contribution is the demonstration of effects that a complex pair of zeros have on speed-to-throttle feedback. It is concluded that there are fundamental differences between thrust/speed effects in sub- and supersonic flight. The purpose of this comment is to show that thrust/speed effects are indeed small but not zero in supersonic flight and that this is a kinematic effect of increasing speed rather than an aerodynamic effect of Mach number. In the process, a simplified analytical model is offered for further study. Furthermore, it is noted that pitching moment/speed sensitivity due to thrust-axis offset is likely to have important long-period effects even when the direct thrust/speed effects are small.

12. B. L. Belkin and R. F. Stengel, Systematic Methods for Knowledge Acquisition and Expert System Development, *IEEE Aerospace and Electronic Systems Magazine*, Vol. 6, No. 6, June 1991, pp. 3-11.

Nine interacting rule-based systems collectively called AUTOCREW were designed to automate functions and decisions associated with a combat aircraft's subsystems. The organization of tasks within each system is described; performance metrics were developed to evaluate the workload of each rule base and to assess the cooperation between rule bases. Each AUTOCREW subsystem is composed of several expert systems that perform specific tasks. The NAVIGATOR was analyzed in detail to understand the difficulties involved in designing the system and to identify the tools and methodologies that ease development.