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P- 11

INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY AT PRINCETON UNIVERSITY, 1992-1993

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SUMMARY OF RESEARCH

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

- Flight Control System Robustness
- Microburst Hazards to Aircraft
- Wind Rotor Hazards to Aircraft
- Intelligent Aircraft/Airspace Systems
- Aerospace Optical Communications

This research has resulted in a number of publications, including theses, archival papers, and conference papers. An annotated bibliography of publications that appeared between June 1992 and June 1993 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.

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. Rarely will there be a single "most robust" controller, as design tradeoffs must inevitably be considered. For example, stability, settling time, and control usage all may be of concern; controllers that favor one criterion over the other two have dramatically different characteristics.

Our initial research focused on probabilistic analysis of the stability and performance robustness of given controllers, while more recent research has shifted to designing robust controllers [1-6]. We have demonstrated that classical stability (i.e., gain and phase) margins are not good indicators of robustness, particularly when comparing compensators with different structures. Numerical search is shown to produce robust controllers based on proportional-filter linear-quadratic regulators with implicit model-following.

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 applied.

An expert system for wind shear avoidance that extends the FAA Microburst Windshear Guidelines can account for temporal and spatial variations in the evidence that wind shear is present [7, 8]. 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 extended Kalman filters to develop a head-tailwind profile.

Real-time guidance for the case in which wind shear has been encountered is being investigated. Our emphasis has shifted from optimal strategies for abort and recovery [9] to strategies based on nonlinear-inverse-dynamic controllers [10]. The former approach seeks to minimize a path-following cost function that implicitly maximizes the minimum altitude during an aborted approach to landing. The latter approach prescribes a desired rate of climb once an abort has been declared, then generates the necessary control commands by inverting the aircraft's dynamic model.

The dynamics of a twin-jet transport encountering an intense wind "rotor" have been studied [11]. It was found 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. Conventional linear-quadratic flight control laws can maintain the wing's level through such encounters.

Advanced concepts for air traffic management are being developed by modeling aircraft and air traffic centers as intelligent agents that engage in principled negotiation [12]. Each agent is characterized as a dynamic system that carries out declarative, procedural, and reflexive functions [13]. Principled negotiation entails the proposal of alternative flight plans, evaluation of costs and constraints according to separate and shared interests, and conflict resolution. We are 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.

With growing demands on the radio spectrum, it is likely that currently unused alternatives could play important roles in the *IAAS*. *Optical sensing and communication* could shoulder a significant percentage of the overall load. Of course, there are weather and line-of-sight limitations on optical devices, so they may never be considered the sole means of providing services. From a global or national perspective, however, optical devices may prove useful in off-loading radio frequencies on a regional and/or altitude-dependent basis. The national airspace is rarely (if ever) "socked in" coast-to-coast, and even in areas of cloud cover, there are altitude strata (especially at cruising heights) within which visual line-of-sight is retained over long distances. By definition, very-low-altitude line-of-sight exists in the terminal area for Category I IFR conditions or better. Consequently, there are numerous situations in which precision measurements and high-bandwidth communication could be furnished by optical systems, including transmissions through communications satellites. (Optical systems can be substantially *more precise* and allow much *higher data rates* than radio transmissions.) The *IAAS* would adapt to changing weather and traffic conditions, always maximizing allowable flight operations subject to practical constraints; consequently, on average, airspace capacity could be greatly increased. An annotated bibliography is contained in [14].

In addition to the research noted above, two publications related to the Joint University Program appeared during the reporting period. A book chapter describing an architecture for intelligent flight control was published [15]. Notes and homework assignments for an undergraduate course on aerospace guidance and control were included in a book describing educational applications of the MATLAB programming language [16].

ANNOTATED BIBLIOGRAPHY OF 1992-1993 PUBLICATIONS

1. R. F. Stengel and C. I. Marrison, "Robustness of Solutions to a Benchmark Control Problem," *J. Guidance, Control, and Dynamics*, Vol. 15, No. 5, Sept.-Oct. 1992, pp. 1060-1067.

The robustness of ten solutions to a benchmark control design problem presented at the *1990 American Control Conference* has been evaluated. The ten controllers have second- to eighth-order transfer functions and have been designed using several different methods, including H_∞ optimization, loop transfer recovery, imaginary-axis shifting, constrained optimization, structured covariance, game theory, and the internal model principle. Stochastic Robustness Analysis quantifies the controllers' stability and performance robustness with structured uncertainties in up to six system parameters. The analysis provides insights about system response that are not readily derived from other robustness criteria, and it provides a common ground for judging controllers produced by alternative methods. One important conclusion is that gain and phase margins are not reliable indicators of the probability of instability. Furthermore, parameter variations actually may improve the likelihood of achieving selected performance metrics, as demonstrated by results for the probability of settling-time exceedance.

2. L. R. Ray and R. F. Stengel, "Stochastic Measures of Performance Robustness in Aircraft Control Systems," *J. Guidance, Control, and Dynamics*, Vol. 15, No. 6, Nov.-Dec. 1992, pp. 1381-1387.

Stochastic robustness, a simple technique used to estimate the robustness of linear, time-invariant systems, is applied to a twin-jet transport aircraft control system. Concepts behind stochastic *stability* robustness are extended to stochastic *performance* robustness. Stochastic performance robustness measures based on classical design specifications and measures specific to aircraft handling qualities are introduced. Confidence intervals for comparing two control system designs are presented. Stochastic performance robustness, the use of confidence intervals, and tradeoffs between performance objectives are applied to a twin-jet aircraft example.

3. L. R. Ray and R. F. Stengel, "A Monte Carlo Approach to the Analysis of Control System Robustness," *Automatica*, Vol. 29, No. 1, Jan. 1993, pp. 229-236.

Stochastic robustness, a simple technique used to estimate the stability and performance robustness of linear, time-invariant systems, is described. The scalar *probability of instability* is introduced as a measure of stability

C-2

robustness. Examples are given of stochastic performance robustness measures based on classical time-domain specifications. The relationship between stochastic robustness measures and control system design parameters is discussed. The technique is demonstrated by analyzing an LQG/LTR system designed for a flexible robot arm. It is concluded that the analysis of stochastic robustness offers a good alternative to existing robustness metrics. It has direct bearing on engineering objectives, and it is appropriate for evaluating robust control system synthesis methods currently practiced.

4. L. R. Ray and R. F. Stengel, "Computer-Aided Analysis of Linear Control System Robustness," *Mechatronics*, Vol. 3., No. 1, Jan. 1993, pp. 119-124.

Stochastic robustness is a simple technique used to estimate the stability and performance robustness of linear, time-invariant systems. The use of high-speed graphics workstations and control system design software in stochastic robustness analysis is discussed and demonstrated.

5. C. I. Marrison and R. F. Stengel, "Gain and Phase Margins as Indicators of Robustness," *Proceedings of the 1992 IEEE Regional Control Conference*, New York, July 1992, pp. 5-8.

A Monte Carlo analysis of scalar compensators designed for a benchmark problem shows that there is very little correlation between classical stability margins and the likelihood that plant parameter variations will lead to instability. The principal reason is that parameter variations change the shape of the Nyquist plot as well as the gain and phase margins; hence, the branch of the nominal Nyquist plot or critical frequency that determines stability margins may not be the one that produces instability as parameters vary. This result also calls into question the use of singular values as measures of stability robustness, because transfer-function amplitude ratio is equivalent to the singular value in the scalar case.

6. R. F. Stengel, L. R. Ray, and C. I. Marrison, "Probabilistic Evaluation of Control System Robustness," presented at the *IMA Workshop on Control Theory and Its Applications*, Minneapolis, Oct 1992.

Practical control systems must operate satisfactorily with uncertain variations in plant parameters (i.e., control systems must be *robust*), but there are limits to the degree of robustness that may be considered desirable. Tolerance to parameter variations that never occur is not useful, and it could lead to closed-loop systems whose normal performance has been compromised unnecessarily. A probabilistic definition of robustness based on expected parameter variations is consistent with accepted design principles, and it is readily evaluated by simulation. *Stochastic Robustness Analysis* predicts the effects of likely parameter variations on closed-loop stability and performance through evaluation of commonly accepted criteria. Competing control designs are judged by the likelihood that system response and design metrics will fall within desired bounds. Together with numerical search, probabilistic evaluation is a powerful approach not only for comparing alternative controllers but for designing control systems that satisfy robustness and performance requirements.

7. D. A. Stratton and R. F. Stengel, "Stochastic Prediction Techniques for Wind Shear Hazard Assessment," *J. Guidance, Control, and Dynamics*, Vol. 15, No. 5, Sept.-Oct 1992, pp. 1224-1229.

The threat of low-altitude wind shear has prompted development of aircraft-based sensors that measure winds directly on the aircraft's intended flight path. Measurements from these devices are subject to turbulence inputs and measurement error, as well as to the underlying wind profile. In this paper, stochastic estimators are developed to process on-board doppler sensor measurements, producing optimal estimates of the winds along the path. A stochastic prediction technique is described to predict the hazard to the aircraft from the estimates as well as the level of uncertainty of the hazard prediction. The stochastic prediction technique is demonstrated in a simulated microburst wind shear environment. Use of the technique in a decision-making process is discussed.

8. D. A. Stratton, "Aircraft Guidance for Wind Shear Avoidance: Decision Making Under Uncertainty," Ph. D. Thesis, Princeton University, Department of Mechanical and Aerospace Engineering, Oct. 1992.

Severe low-altitude wind shear poses a significant threat to air transportation safety. Concepts for assisting critical decision making under uncertainty are advanced to promote the avoidance of hazardous weather, particularly microburst wind shear. Computational strategies founded on probability and optimal estimation theories enable flight deck integration of diverse forecasting and detection systems, from airport weather information services to airborne forward-looking wind sensors.

A decision-making policy for wind shear is developed from a comprehensive investigation of microburst phenomenology, its observed characteristics, and its effects on aircraft flight. Existing avoidance guidelines for wind shear are extended to exploit the latest available technology, such as Doppler weather radar and lidar. Theories for probability-based decision making facilitate real-time computer reasoning with dynamic, conflicting data from a wide array of sources. Bayesian neural networks fused with multivariable estimators account for the limited precision, reliability, and timeliness of correlated sensor measurements. Monte Carlo analyses are conducted to refine Kalman filters for forward-looking sensors, with statistical results completing their incorporation into Bayesian reasoning.

Symbolic and numerical processes for a Wind Shear Safety Advisor are implemented and evaluated. A risk assessment model based on empirical and analytical results is used to compare the relevance of available wind shear information sources. Simulations of the risk-assessment model show its insensitivity to parameter variations. Validations of overall Wind Shear Safety Advisor logic illustrate how it conveys beneficial advance warnings in rapidly developing microburst-encounter situations. These results prove that intelligently-integrated detections systems can warn pilots of threatening wind shear sooner, more frequently, and more effectively than isolated systems can.

9. S. S. Mulgund and R. F. Stengel," Optimal Recovery from Microburst Wind Shear," *Proceedings of the AIAA Atmospheric Flight Mechanics Conference*, Hilton Head, Aug. 1992.

The flight path of a twin-jet transport aircraft is optimized in a microburst encounter during approach to landing. The objective is to execute an escape maneuver that maintains safe ground clearance and an adequate stall margin during the climb-out portion of the trajectory. A cost function penalizing rate of climb deviations from a nominal value and the rate of elevator deflection produces qualitatively good results in a variety of microburst encounters. The optimal maneuver is a gradual pitch-up that ceases near the core of the microburst, followed by a slight reduction in pitch attitude in the tailwind area of the microburst. A minimum airspeed constraint in the optimization prevents excessive airspeed loss in very severe microbursts. The aircraft equations of motion include short-period dynamics, so that the optimization solves directly for the control surface deflections required to achieve the optimal flight paths.

10. S. S. Mulgund and R. F. Stengel, "Aircraft Flight Control in Wind Shear Using Partial Dynamic Inversion," *Proceedings of the 1993 American Control Conference*, San Francisco, June 1993, pp. 400-404.

A flight control law based on partial inversion of the longitudinal dynamics of a twin-jet transport aircraft is presented. The controller is partitioned into a slow-time-scale and a fast-time scale to simplify its design. Three types of controllers are developed: airspeed/climb rate, groundspeed/climb rate, and throttle/climb rate. For microburst encounters during approach to landing, it is found that a combination of airspeed and groundspeed regulation is quite effective for controlling the flight path to touchdown. Regulation of groundspeed to a nominal value in the performance-increasing region of the microburst prevents an inadvertent reduction in thrust, while regulation of airspeed to a nominal value in the performance-decreasing area of the microburst prevents excessive airspeed loss. The throttle/climb rate controller is used for aborted-landing encounters. The combination of groundspeed and airspeed control is used until the decision is made to abort the landing, at which point maximum throttle and a specified positive climb rate are commanded.

11. D. R. Spilman, "Dynamic Response and Control of a Jet Transport to a Single-Axis Wind Vortex," M. S. E. Thesis, Princeton University, Department of Mechanical and Aerospace Engineering, Jan. 1993.

The dynamic response and control of a twin-jet transport aircraft encountering a single-axis wind vortex on final approach to landing is investigated. A horizontal wind vortex, or wind rotor, is formed by strong winds that flow over a mountain range and roll up on the leeward side of the mountain, forming a rotating airmass. If proper control action is not taken immediately after encountering a rotor, then severe performance degradation and possible ground impact may result.

A complete six-degree of freedom jet transport aircraft model that includes nonlinear aerodynamic data, unsteady aerodynamic effects, and wind-gradient effects over the aerodynamic surfaces is used to simulate an aircraft-vortex encounter. Dynamic simulations are used to determine the effects of vortex strength, vortex length, lateral entry position, vertical entry position, and encounter incidence angle on the aircraft response parameters. Roll angle and sideslip angle are primary response parameters because they may introduce performance degradation and control hazards. A large induced roll angle results from a co-axial encounter in which the vortex axis is aligned with the flight path and the wind-shear gradient is directly incident over the aircraft wing. An encounter with a rotor oriented at a 60° angle to the flight path produces a severe sideslip angle response which in turn causes a large roll-angle response. In this case the response is highly dependent on the precise initial conditions of the encounter.

Both rudder and aileron controls are useful in alleviating vortex-induced roll; however, rudder control may excite lightly damped Dutch-roll dynamics. A simple lateral-directional linear-quadratic controller that uses rudder to control sideslip and aileron to control roll successfully controls the simulated aircraft through strong wind vortices without exciting unwanted dynamics. In addition to demonstrating the value of using automatic control to reduce the wind vortex hazard, such a control system has benefits beyond its immediate design goals. Because of the similarities between wake vortex flows and mountain-wave vortex flows, the controller may be used to reduce required separation distances at airports. It also may prove superior to a human pilot in preventing catastrophic low-altitude control system failures.

12. R. F. Stengel and J. P. Wangermann, "Air Traffic Management as Principled Negotiation Between Intelligent Agents," presented at the AGARD Guidance and Control Symposium, *Machine Intelligence in Air Traffic Management*, Berlin, May 1993.

Air transportation provides the backbone for passenger transport over moderate to long distances in the U.S. and much of the world, and it is becoming an increasingly important mode for short-range travel and cargo transport as well. There is a growing demand for use of available airspace and a heightened concern for on-time performance. Demand frequently exceeds available capacity of the airspace system, causing flight delays, negative economic impact, and passenger inconvenience [1, 2]. New technologies are emerging that will make flight operations both simpler and more complex. On the one hand, advances hold promise for increasing the productivity, reliability, and safety of the air transportation system. On the other, advances in technology introduce uncertainty, increase human workload (if not properly implemented), increase the potential for dispute, and present new challenges for both certification and day-to-day operations. This paper presents a concept for an *Intelligent Aircraft/Airspace System (IAAS)* that could be a focal point for developing air traffic management in the coming decades. The *IAAS* would integrate the capabilities of all ground-based and airborne components of the system (identified as *Intelligent Agents*) in order to provide increased capacity and maintained or improved safety. *Principled Negotiation* is proposed as a framework for interactions between intelligent agents.

13. R. F. Stengel, "Intelligent Flight Control Systems," presented at the *IMA/RAS Conference on Aerospace Vehicle Dynamics and Control*, Cranfield, UK, Sept. 1992.

The capabilities of flight control systems can be enhanced by designing them to emulate functions of natural intelligence. Intelligent control functions fall in three categories. *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 spontaneous, inner-loop responses for control and estimation. Intelligent flight control systems learn knowledge of the aircraft and its mission and adapt to changes in the flight environment. Cognitive models form an efficient basis for integrating "outer-loop/inner-loop" control functions and for developing robust parallel-processing algorithms.

14. R. F. Stengel, "Aerospace Optical Communications Abstracts," Princeton University, Department of Mechanical and Aerospace Engineering, Princeton, NJ, May 26, 1993.

Over 100 abstracts related to the possible application of optical communication to aircraft were drawn from the AIAA Aerospace Abstracts. The abstracts describe papers published between 1989 and 1983. Although the papers focus primarily on space applications, several address aircraft-to-aircraft and aircraft-to-satellite communications.

15. B. L. Belkin and R. F. Stengel, "AUTOCREW: A Paradigm for Intelligent Flight Control," *An Introduction to Intelligent and Autonomous Control*, P. Antsaklis and K. Passino, ed., Kluwer Academic Publishers, Norwell, MA, 1993, pp. 371-400.

An expert system Pilot-Aid is envisioned to automate many functional and low-level decision-making tasks in future high performance and jet transport aircraft to help alleviate pilot workload. Nine modular rule-based systems, collectively called AUTOCREW, were designed to automate functions and decisions associated with a combat aircraft's subsystems. The knowledge bases were designed individually; areas of cooperation between the knowledge bases were identified, and common information was designated as "shared" information. An interactive graphical simulation testbed was developed to demonstrate and test the cooperating AUTOCREW ensemble's performance. Workload metrics were formulated to quantify AUTOCREW's performance in terms of the ensemble's efforts in assisting the Pilot. The workload metrics give reasonable results for the comparison

of workloads among AUTOCREW's experts, as well as comparative results among task groups within a single knowledge base. The applicability of the methods utilized to design AUTOCREW for other applications is also discussed.

16. R. F. Stengel, "Aerospace Guidance and Control," *Using MATLAB in the Classroom*, Prentice Hall, Englewood Cliffs, 1993, pp. 3-26.

This book chapter presents notes and computer-based assignments for an undergraduate course on aerospace guidance and control. One third of the course is devoted to flight mechanics, another third addresses guidance and control of the flight path, and the remaining third deals with instrumentation for measuring position and motion. The course assignments include computational flight tests with a six-degree-of-freedom simulation of a light aircraft; calculations of stability- and control-derivative matrices, eigenvalues, transfer functions; root locus and Bode plots; and design of flight control systems using classical and linear-quadratic methods.