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INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY AT PRINCETON UNIVERSITY, 1985

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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 five avenues during 1985.

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

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 remain to be defined.

Graduate student Mark Psiaki has undertaken a study of guidance and control strategies for penetration of microbursts when encounter is unavoidable. It has been shown that simple control laws could greatly reduce an aircraft's response to wind shear[1]. 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[2]. The study has begun with the computation of optimal control histories using steepest-descent and second-order gradient algorithms. Once an envelope of safe flight has been determined for a typical jet transport, attention will be directed at a general aviation type, and optimal closed-loop control laws will be investigated. During the past year, a survey paper on the subject was published[3].

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. Although funding for this effort has shifted to another source, results will have direct bearing on air transportation systems, as illustrated by [4]. In a parallel effort, graduate student Chien Huang is using the LISP programming language 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.

Senior Takashi Sensui has begun to apply artificial intelligence principles in the study of air traffic control (Sensui, 1986). Working in the computer language PROLOG, he is designing optimal control logic for terminal area operations.

Prospects for reducing pilot workload through voice inputs to the aircraft are extremely promising, and graduate student Parvada Suntharalingam has completed a short study of the characteristics of a representative system (Suntharalingam, 1985). Using a commercially available system that is capable of recognizing continuous speech and which takes advantage of structured grammars, she demonstrated the effects of the number of training passes on misrecognition and rejection rates. Her results show that the system's errors are not greater than manual input errors of similar information.

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 is developing methods for determining the stability boundaries and control response for systems containing control saturation[5,6]. Analysis is carried out using phase-plane plots, in which saturation and stability boundaries are represented by straight lines, stable trajectories approach equilibrium points, and unstable trajectories diverge to infinity. The analysis pertains to systems containing unequal saturation boundaries, as well as those with multiple saturating controls.

Future control-system engineers will benefit from design procedures that are computer-intensive, and it is important to create computer programs that allow designers to describe and analyze complex systems interactively. Senior Russell Nelson developed a control-system analysis program based on the LISP language mentioned above (Nelson, 1985). Analysis proceeds with classical concepts of transfer-function analysis in a program that can be run on a personal computer.

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 REFERENCES

1. Psiaki, M.L., and Stengel, R.F., "Analysis of Aircraft Control Strategies for Microburst Encounter", AIAA **Journal of Guidance, Control, and Dynamics,** Vol. 8, No. 2, Mar-Apr 1985, pp. 553-559.

   Penetration of a microburst during takeoff or approach is an extreme hazard to aviation, but analysis has indicated that risks could be reduced by improved control strategies. Attenuation of flight path response to microburst inputs by elevator and throttle control was studied for a jet transport and a general aviation aircraft using longitudinal equations of motion, root locus analysis, Bode plots of altitude response to wind inputs, and nonlinear numerical simulation. Energy management relative to the air mass, a pitch-up response to decreasing airspeed, increased phugoid-mode damping, and decreased phugoid natural frequency were shown to improve microburst penetration characteristics. Aircraft stall and throttle saturation were found to be limiting factors in an aircraft's ability to maintain flight path during a microburst encounter.

2. Psiaki, M.L., and Stengel, R.F., "Optimal Flight Paths Through Microburst Wind Profiles", presented at the AIAA 12th Atmospheric Flight Mechanics Conference, Snowmass, CO, AIAA Paper No. 85-1833-CP, Aug 1985.

   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.

3. Stengel, R.F., "Solving the Pilot's Wind-Shear Problem", **Aerospace America,** Vol. 23, No. 3, Mar 1985, pp. 82-85.

   Although aircraft have had to contend with wind variability since the beginning of aviation, the July 1982 crash of Pan American Flight 759 on the outskirts of New Orleans, which killed 153 people, riveted attention on the hazards of flying in wind shear. Microbursts, unusually severe downdrafts accompanied by intense outflows, prove especially hazardous during takeoff or landing. Within a minute or less the aircraft may be subjected to a headwind, then a downdraft, and then a tailwind. Just as the pilot throttles back to arrest ballooning above the nominal path caused by increase airspeed, headwind vanishes and downdraft causes the aircraft to lose lift. Lift is further degraded as the aircraft enters the outflow. A microburst compounded by heavy rain is thought to have caused the crash of Pan Am's Flight 759. The article addesses several aspects of the problem and proposes both short-term and long-term solutions.

4. Handelman, D.A., and Stengel, R.F., "Combining Quantitative and Qualitative Reasoning in Aircraft Failure Diagnosis", presented at the 1985 AIAA Guidance, Navigation, and Control Conference, Snowmass, CO, AIAA Paper No. 85-1905-CP, Aug 1985.

The problem of in-flight failure-origin diagnosis is addressed by combining aspects of analytical redundancy and artificial intelligence theory. The objective is to use a mathematical model of the aircraft's dynamic behavior to supplement the knowledge used for diagnosis. A method is developed whereby qualitative causal information about a dynamic system is drawn from its model. Based on sensitivities of the equations of motion to worst-case failure modes, a measure of the relative capacity of system elements to affect one another is derived. A diagnosis procedure combining problem reduction and backward-chaining ordered search uses this knowledge to reduce a list of elements capable of failure to a relatively small list of elements suspected of failure. Examples illustrate use of the knowledge base and the problem-solving mechanism that has been developed.

5. Shrivastava, P.C., and Stengel, R.F., "Stability Boundaries for Aircraft with Unstable Lateral-Directional Dynamics and Control Saturation", presented at the 1985 AIAA Guidance, Navigation, and Control Conference, Snowmass, Co, AIAA Paper No. 85-1948-CP, Aug 1985.

Aircraft that do not possess inherent (aerodynamic) stability must rely on closed-loop control systems for stable operation. Because there are limits on the deflections of an aircraft's control surfaces, the region of stable operation also is bounded. These boundaries were investigated for a lateral-directional example, in which vertical fin size was inadequate to provide directional stability and where aileron and rudder deflections were subject to saturation. Fourth-order models were used in this study, with flight control logic based upon minimum-control-energy linear-quadratic regulator theory. It was found that the stability boundaries can be described by unstable limit cycles surrounding stable equilibrium points. Variations in regions of stability with gain levels and command inputs are illustrated. Current results suggest guidelines for permissible limits on the open-loop instability of an aircraft's lateral-directional modes.

6. Shrivastava, P.C., and Stengel, R.F., "Regions of Stability with Unequal Saturation Limits and Non-Zero Set Points", presented at the 24th IEEE Conference on Decision and Control, Fort Lauderdale, FL, IEEE Paper No. S-0128, Dec 1985.

Constraints on the magnitudes of control variables limit the region where open-loop unstable systems can be stabilized using feedback control. Variations in regions of stability with unequal control saturation limits and non-zero set points are illustrated for single-input unstable linear systems with one or two unstable eigenvalues. The regions of stability for saddle-point and unstable-node-type singularities increase in one of the saturation limits, but they become invariant when the larger control limit exceeds a certain value; the stability regions vanish for non-zero set points that saturate the controls. The unstable-focus-type singularity exhibits strikingly different characteristics. These results suggest guidelines for obtaining desired stability regions for different types of singularities.

ANNOTATED BIBLIOGRAPHY

1. Nelson, R.F., "Computer Aided Control System Design", Princeton University Independent Work Report, May 1985.

The objectives of this project were to develop an interactive computer program to serve as a tool in the design of control systems and to evaluate the utility of the LISP programming language in this application. An environment of LISP functions that allows the user to define and examine a system characterized in the frequency domain was developed. The program generates a block diagram of a multiloop system, then computes frequency-response characteristics between arbitrary points in the diagram; these can be displayed as Bode or Nyquist plots. The LISP language was found to provide a flexible, interactive tool that could aid the development of large-scale systems.

2. Sensui, Takashi, "Automation of the Terminal Area Air Traffic Control System - Progress Report", Princeton University Independent Work Report, Jan 1986.

The objective of the project is to design logic for a fully automated terminal area control system. Design specifications have been defined, and application of an expert system is discussed. A brief comment concerning the programming of simplified models is included.

3. Suntharalingam, P., "A Test on the Reliability and Performance of the Verbex Series 4000 Voice Recognizer", Internal Memorandum, Princeton University Laboratory for Control and Automation, Sept 1985.

Speech input is becoming an increasingly important form of data entry. The object of this exercise was to test and explore the features of a voice recognition unit that enables communication between human and machine. The unit is speaker-dependent, i.e., it requires training with a given vocabulary as spoken by a single person. The speaker's voice patterns are stored on a solid-state cartridge and are subsequently used as templates for recognition. Two additional features of the unit are its ability to recognize continuous speech (strings of words as opposed to single commands) and its use of structured grammars, in which words of specified classes (subject, predicate, modifier, etc.) must be spoken in a fixed order. Tests were run to determine the voice recognition unit's error rates as functions of machine training level and to determine the relative merits of structured and unstructured grammars. It was found that error rates varied from one speaker to the next; some speakers required more training passes than others to achieve a given level of recognition accuracy. It also was noted that a structured grammar requires less training than an unstructured one to achieve a given accuracy. However, the latter may be preferred for its greater flexibility; with sufficient training, the error rates may be reduced to acceptable levels.