FUTURE ASPECTS OF SUPERSONIC TRANSPORT NAVIGATION

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ABSTRACT

Requirements studies have been completed and a five-year program plan has been developed for research leading to the technology required for an advanced supersonic transport integrated avionics system. The study results, long-range plan, and work presently underway in the specific areas of navigation and guidance are presented. The goal of this work is eventually to integrate the best available navigation and guidance mechanisms in a hybrid fashion which makes most effective use of each. The most important constituent tasks being pursued are a passive navigation and traffic control satellite system, use of inertially derived translation information to improve significantly the all-weather landing capability, flight test varification monitoring tests helpful to strapdown system design, sensor level redundancy concepts in strapdown inertial navigation systems, fuel-optimum climb trajectory studies, and laser gyro research for aircraft applications.

INTRODUCTION

The Electronics Research Center (ERC) in Cambridge, Massachusetts, was founded on the premise that electronics is an "essential element in every aspect of aerospace flight." Since all supersonic aircraft are espected to contain electronic equipment primarily for navigation, guidance, control, and communications, it was logical to direct ERC to devote some of its electronics research efforts toward supersonic aviation applications.

The first step was a study phase made between November 1966 and March 1967 to determine the requirements and critical research problems associated with achieving a total integrated avionics system for an advanced supersonic transport (ASST) class of aircraft. Separate studies with a variety of contractors were performed in the areas of guidance and navigation; flight control, display, and all-weather landing; communications; power generation, conditioning, and distribution; flight instrumentation and measurements; hazard avoidance; information processing; and overall system and reliability research. Only the guidance and navigation aspects of these studies will be treated in this manuscript.

NAVIGATION AND GUIDANCE REQUIREMENTS STUDY RESULTS[1]

Table I typifies the definition of the adjective "advanced" in extrapolating from the Boeing 2707 configuration to the ASST characteristics for the 1975-1985 era.

TABLE I
ASST CHARACTERISTICS

Range	6000 nm
Cruise speed	3.2 Mach
Cruise altitude	70-85,000 ft
Ramp weight	710,700 lb
Takeoff weight	700,000 lb
Cruise $(L/D)_{max}$	10
Cruise specific impulse (partial after burning)	2500 sec
Landing weight	385,000 lb

It represents a reasonable evolution toward a slightly larger, higher performance vehicle with extended range. In most cases, however, the conclusions and recommendations of the requirements study would not have been altered significantly if the prototype B-2707 or the Concorde configuration had been used throughout as the model for the study. Much more important were the assumptions made regarding the operational environment that would exist in this future era. These were set forth as the following important observations:

(1) One of the most critical problems in ASST (and SST) operations is its interface with the environment, and, in particular, air traffic control (ATC). To achieve fully the inherent economies in ASST operation, significant improvements in the ATC concepts and equipments will have to be implemented. In particular, these improvements are related to the automation in the ATC procedures, a single control center for North Atlantic routes, a capability for world-wide aircraft surveillance and communication system, and hence a greater airline freedom in the selection and assignment of specific airlanes for most economical source-to-destination flights. Similarly, the air traffic control in the terminal areas should be automated and new, all-weather landing systems implemented to reduce or eliminate the delays in holding patterns.

(2) An immediate implication of the advanced ATC systems is a much greater freedom in the selection of flight profiles, and a subsequent requirement to follow such profiles with precision in assigned air-time space. The selected profiles will not only provide most economical source-to-destination flight, but also generate

the optimum climb and descent profiles within the sonic-boom and noise-abatement constraints. To achieve the required flight precision at ASST speeds, the aircraft guidance and steering functions will have to be automated.

(3) Finally, a high degree of automation thus achieved should not detract (in fact, add to it) from the flight safety requirements. The required flight safety and precision will have to be implemented by careful selection of equipments, redundancy concepts, failure detection techniques, and backup modes. Furthermore, the crew, now assigned the overall system operation surveillance and performance evaluation responsibilities, will have to be provided with display and control equipments and functions that are consistent with their new role.

Within the context of the above observations, the major requirements study conclusions are listed below:

(1) A world-wide system of airline communication and surveillance will be essential for the ASST era. This system can only be implemented (when one considers the economics and geo-political environment) by utilizing satellites. An immediate extension of this idea is that a world-wide radio navigation capability can be incorporated into such a system with relatively small incremental cost (less than, for example, a world-wide Loran, or possibly, even Omega, in which the user equipment costs for ASST would be excessive).

(2) From the purely inherent accuracy point of view, present inertial navigation systems can meet the predicted ASST requirements. In fact, it is possible to reduce the inertial equipment costs significantly by proper mixing of the data from a lower accuracy inertial system with the navigation satellite data.

(3) The redundancy techniques in inertial navigators presently considered for SST are costly and represent the major navigation system weakness. New techniques of instrument level redundancies would significantly improve the system economics (increased dispatch probabilities) while possibly reducing the cost. Feasibility of these techniques was demonstrated in this report and several tradeoff areas were developed. However, the performance (accuracy) is yet to be demonstrated.

(4) Some level of flight automation for ASST will be essential to meet the anticipated flight path constraints for ATC and sonic-boom limit, and, just as

importantly, to relieve the crew from routine tasks so that they can perform efficiently in an ASST environment.

(5) The most critical flight phase for ASST is landing and take-off under all-weather conditions (including Category IIIc conditions). The present operational instrument landing system (ILS) will not provide the required capability. However, advanced ILS equipments (such as the one being tested by NAFEC) are available and will provide the required performance for ASST. Landing safety and performance can be significantly improved if ILS data are used in conjunction with the inertial data to provide completely automatic approach, flare-out, and runway deceleration under all visibility conditions. Such a system could also be used for automatic go-around and reacquisition of the ILS beams.

(6) For primary (self-contained) navigation for the ASST, inertial systems provide greater accuracy, higher reliability (present and potentially), and competitive cost compared to high quality doppler navigators. Furthermore, to achieve the required heading reference precision (minutes of arc), a doppler system would need an inertial quality heading reference. Complex stellar-inertial systems are not justified for the required ASST performance since the flight durations are only of the order of 2 to 3 hours.

(7) The required Category III capability for ASST can only be achieved if taxiing aids are developed in such a manner that the pilot can automatically or manually steer the airplane from the runway to the terminal area. Such taxiing aids are presently being investigated by several organizations.

NASA/ERC FIVE-YEAR RESEARCH PROGRAM

In response to the recommendations of the Navigation and Guidance Requirements Study,[1] as well as all other available information sources, a five-year research program was formulated. This plan, of course, is not all-inclusive, but tends naturally to emphasize those areas which benefit most from the personal talents, expected results of other on-going programs, and budget limitations at NASA/ERC.

The basic underlying philosophy of the research is to provide two primary, but completely independent, navigation mechanisms of the same order of performance, both capable of the required mission precision, and both available for the full duration of flight, i.e., a passive navigation satellite and an inertial navigation system (INS) If these two independent navigation measurement mechanisms can consistently agree with each other, then a great deal of flight crew confidence will be established. The crew will then be more willing to fly actually against a third answer that is the best estimate of the two measurements combined in hybrid fashion. If either the navigation satellite or the inertial navigation system cannot be developed to the point of compatible capability, then a certain degree of crew confidence will be compromised by going to a hybrid configuration just to satisfy the mission requirements.

In the terminal area, the existing, special-purpose navigation aids will be used to improve navigation precision, but emphasis will be put on hybridizing these subsystems with the INS as the high-frequency, on-board reference required for expediting precision, time-constrained trajectories to help alleviate terminal area conjestion.

The major elements of the five-year research program are presented below.

Inertial-Navigation-Satellite Navigation System Test

Of all the potential world-wide-coverage navigation aid systems, the navigation satellite shows the greatest promise for fulfilling the enroute navigation requirements for the ASST. The present navigation control satellite system studies being carried on at NASA/ERC[2] will develop the basic user and satellite equipment requirements and establish the navigation satellite system configuration. The design goal of this study effort is a position accuracy of the order of 0.1 n.m. one sigma, with a measurement available at least once every 16 seconds. This degree of precision and the improvement potential of another order of magnitude using relative navigation techniques in localized areas suggest that the navigation satellite will be useful well into terminal area operations, probably to the point of ILS beam capture.

While the satellite navigation system is being tested at supersonic transport speeds and altitudes, hopefully enough preliminary work will have been done to hybridize the discrete independent navigation measurements of the satellite with the continuous, high-frequency, independent navigation measurement achieved by the on-board inertial system to produce a single best estimate of position that will command a high degree of flight crew confidence.

Inertially Aided All-Weather Landing Capability

The most critical flight phase for the ASST is landing and take-off under all-weather conditions. Landing safety and performance can be significantly improved if ILS data are used in conjunction with inertial data to provide completely automatic approach, flare-out, and runway deceleration under all visibility conditions.[1]

Preliminary simulation results of a study underway at the M.I.T. Instrumentation Laboratory[3] indicate a potential performance improvement in excess of two orders of magnitude, i.e., final touchdown 0.26 foot from the runway centerline instead of 35.0 feet for the typical lateral control situation simulated. This preliminary work will be extended under NASA/ERC sponsorship to include the effects of inertial system errors, beam bending statistical errors, structural dynamic considerations, and autopilot error sources. The study will make estimates of the computation, displays, and interfaces required to prepare a test aircraft for flight test of the basic concepts.

The primary difference between the classical approach to the automatic landing problem and this new inertially aided approach resides in the intelligent use of the inertially derived translational information of velocity and acceleration relative to the ground or glide slope and localizer planes. Of all the various ASST research tasks underway at NASA/ERC, this particular one is probably most likely to be timely enough and significant enough to affect the Boeing SST prototype directly.

Improved Reliability of Inertial Navigation Systems

All future trends of supersonic transport navigation indicate increased reliance on the inertial navigation system for continuously available, high-frequency navigation information. Fuel optimum climb, cruise and descent profiles; minimum time terminal area maneuvers; inertially aided all weather landing; rapid preprogrammed response to hazard avoidance cues or possible emergency conditions; and the automatic flight management concept,[4] in general, are future concepts which rely heavily on the existence of an inertial navigation system in the aircraft. This demand will continuously boost the reliability requirements on the INS function to the point where it might conceivably become a safety-of-flight-item.

The vendor competition to develop, deliver, and maintain highly reliable 1-nmph gimballed inertial measurement units (IMU) for the airframe manufacturers will continue to be a vigorous activity for many years to come. It is expected that every effort will be made to improve the reliability of each component and inertial sensor of these IMU's. In most cases, however, the electromechanical components typified by the gyros will remain the pacing reliability problem. Because of the self-sustaining momentum that already exists in the development of the 1-nmph gimballed IMU category of the system, NASA/ERC has chosen to look several years to the future for different and perhaps more promising advanced concepts and technologies.

Triplication of the IMU's and other elements of the total INS, together with flight crew management of the information generated, will probably remain as a reasonable state-of-the-art approach toward higher system level reliability. But as was stated earlier, a conclusion of the requirements study[1] was that "the redundancy techniques in inertial navigators presently considered for SST are costly and represent the major navigation system weakness. New techniques of instrument level redundancies would significantly improve the (dispatch probabilities) and safety while possible reducing the cost."

For example, a strapdown INS containing 6 gyros and 6 accelerometers (a total of 12 inertial sensors) on a single block has been shown to have a mean time between flight cancellation (MTBFC) that is more than twice the (MTBFC) for an INS containing 3 gimballed IMU's consisting of 3 gyros and 3 accelerometers each (a total of 18 inertial sensors). In short, a sensor level redundant INS in this case is twice as reliable for only about two-thirds the cost of a system level redundant INS.

In principle, redundant sensor inertial navigation systems can be implemented either in a gimballed or strapdown system. However, the use of multiple inertial instruments (six gyros and six accelerometers, for example) on a single platform penalizes the mechanical, thermal, and electrical design of the gimballed system to the point of questionable practicality. The failure detection, diagnosis, and rejection of faulty information would also have to be almost instantaneous to avoid degradation of the true inertial reference stored physically by the stable member of a redundant-sensor-gimballed system. Redundant-sensor strapdown mechanizations, however, are very reasonable and, in fact, have always been one of the more promising advantages of strapdown systems.

NASA/ERC is presently heavily engaged in strapdown inertial system research on many fronts. Of particular interest in view of the above discussion is the fact that a six-gyro, six-accelerometer strapdown system is in the process of being built. The object of building this system is to be able to demonstrate with working hardware the numerous redundant-sensor-system concepts which analysts typically assume to be mechanizable. This experimental system will serve as a valuable testbed for a long series of redundant-sensor-system experiments.

Among the concepts that will eventually be tested are both hard and soft (performance) failure detection, different levels of self diagnosis complexity, reconfiguration of the use of valid sensor information in response to diagnosis, generation of redundant system level answers that contain one answer that will always be independent of the next possible failure, self-repair of soft failures by long-term continuous observation and recalibration, and toleration for a sequence of as many as four separate sensor failures before flight cancellation.

Laser Gyro Research

Demonstration of the improved reliability potential of sensor level redundancy is not enough to make strapdown inertial navigation systems attractive for aircraft applications. Ideally they must be capable of 1-nmph performance and be significantly less expensive than gimballed systems. The ring laser gyro is being given careful consideration as a good candidate for being the key to the fulfillment of these ideals. Design goals of on-going development programs are expected to achieve long-term stabilities and drift rates consistent with the required performance within the next few months. Much more work is still required to make these instruments commonplace, but they are ideal for strapdown application, are highly insensitive to translational vibration environments, and should cost between $2 and $4 thousand each, less than one quarter of their single-degree-of-freedom floated instrument counterparts.

Strapdown INS Flight Test Verification

Strapdown system technology does not enjoy the familiarity and wealth of past experience supporting gimballed system technology. Completely self-contained strapdown inertial navigation systems do exist, however, as typified by the flight verification test of the Honeywell Sign III system that will be carried out at Holloman Air Force Base during the first few months of next year. These tests will verify many of the basic design principles underlying strapdown system technology.

Aircraft Environment Tests

In an attempt to improve the design of strapdown systems for aircraft environments, a specially tailored vibration monitoring instrument package and data recorder will be built and flown on a variety of aircraft to determine six-degree-of-freedom vibrations against the same time reference to determine the presence of coning motion, one of the more serious environments for error propagation in strapdown systems. This particular required form of data does not exist. One of the most important goals of this supporting program is to determine accurately the typical preflight aircraft environment which has direct influence on the design of preflight self-calibration and self-alignment techniques so important to inertial system performance. Of course, redundant sensor systems have the extra potential of being ideally suited for optimal filtering schemes which are most fruitful in proportion to the designer's knowledge of the likely environment. This is another requirement for the presently unavailable data.

Ultra Precise Gimballed Inertial Systems

There is a third approach which is in direct competition with the triplicated 1-nmph gimballed INS concept and the redundant sensor strapdown INS/navigation satellites in hybrid concept. This concept is compatible with a NASA/ERC-sponsored instrument development program, being run in another area of the M.I.T. Instrumentation Laboratory. The performance of the instruments under development would accommodate the concept of autonomous, unaided inertial navigation flights from departure all the way to destination ILS beam capture. Some preliminary thinking has been directed toward this approach but factors such as the exorbitant cost of a single system, questionable reliability if only one system is used, and state department regulations concerning export of precision INS equipment cloud the picture for this concept at the present time.

OTHER ASPECTS OF THE FIVE-YEAR RESEARCH PLAN

The areas of activity described thus far are presently in progress as part of NASA/ERC's FY '68 research activity. Other areas of ASST activity that are of significant interest, but as yet have not been started for a variety of reasons, are presented below.

Multifunction navigation concepts and the implied computation requirements for combining very high frequency omnirange (VOR), distance measuring equipment (DME), barometric altitude and INS information for departure and terminal area navigation constitutes one activity; barometric altitude, passive navigation satellite, and INS for enroute navigation is another study area which should begin next year. Hybrid precision altimetry and air data sensing using static pressure, the dynamics of the vertical channel of the inertial system and the airborne radar altimeter will provide a complementary, multifunction, vertical channel navigation capability.

Performance assessment of new automatic guidance concepts and compatible ATC procedures represents another area of effort that has been temporarily deferred. Emphasis thus far has been on generating the analysis tool required to develop and assess fuel optimum climb-to-cruise-condition profiles. A great deal of important work needs to be done in this area to take full advantage of the inherent performance capability of the supersonic transport. Time saving terminal area maneuvering guidance functions which take advantage of the INS-supplied true ground speed is another resource that should be tapped.

CONCLUSIONS

Research leading toward the technology required for the navigation and guidance aspects of an advanced supersonic transport integrated avionics system has begun in a few critical areas. More time is needed before the true merits of the approach can be evaluated and before the actual fruits of the work can be incorporated into certified flight systems.

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