Effect of Radar Disturbances on Ground-Controlled Precision-Landing Delivery

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This study examined the effect of radar disturbances on time-controlled precision-landing delivery. A simulation was developed and tested which models an aircraft on a four-dimensional navigation terminal approach. Trained pilots flew a nominal approach in a fixed-base cockpit simulator following timed delivery commands from an initial fix to a final approach fix. During the flight, position information was estimated from noisy radar observations. Three phases of testing were conducted to quantify the accuracy of a timed delivery algorithm with modifications in the flight commands. In all cases, timed delivery was performed with great accuracy, while keeping pilot workload at a low level.

Introduction of Background Material

THE current Automated Radar Terminal System provides a monitoring function which was unheard of with previous systems. However, this is not sufficient in view of increasing air traffic. More improvements are needed in the exchange of information between the ground controller and the aircraft. The proposed upgraded Air Traffic Control System will provide better data acquisition, communications service, and increased automation. Future systems should be capable of providing more complete automation in terms of command generation and delivery. These systems are called strategic navigation or four-dimensional navigation.

The principle of these systems is to assign a route-time profile to each aircraft, thus providing good management of energy, space, and runways. This method utilizes a fixed airspace structure with a variable flight path to de-randomize aircraft runway arrival time. The method favored by the Federal Aviation Administration consists of ground computation of heading, altitude, and airspeed commands which are broadcast to the aircraft via digital data-link. These commands can be either visually displayed for manual operation by the pilot or, at some future time, directly tied into the aircraft automated systems.

The purpose of this study was to simulate the flight of an aircraft on a terminal approach in a four-dimensional navigation environment using discrete control commands. During the flight, position information was estimated from noisy radar observations. Speed was estimated from these observations and was used in a timed delivery algorithm to determine when to issue commands to the aircraft. Time control precision was experimentally determined in the presence of the radar disturbance, and the accuracy of the four-dimensional navigation task in the presence of this uncertainty was quantified.

A number of studies have previously been conducted to determine fix-to-fix and runway arrival time accuracy. These studies neglected the effect of wind and assumed perfect radar position information. For this reason, a comprehensive model for these two effects was developed.

Wind Model

A wind model was developed which divided the atmosphere into three regions; a surface layer extending from the surface to an altitude of 300 ft, a boundary layer extending up to about 2000 ft for moderate wind conditions, and the free atmosphere which encompassed that space above the boundary layer and below 10,000 ft. The altitudes encountered in this simulation ranged from 2000-6000 ft. Since flight was not required beyond the final approach fix, the entire flight was performed in the free atmosphere. The wind in this region was a mean wind with wind magnitude and direction a function of altitude and surface wind. Wind sheer and veering rate were assumed constant and provided variable magnitude and direction for a free atmospheric wind. A detailed description of the wind model is provided by Malherbe.[1]

Radar Model

Radar position error is a function of performance for any particular radar. This position error is characterized by standard deviations in range and bearing for each observation of the radar. These standard deviations give an approximate aircraft position.

The radar model reproduced radar noise by assuming the noise to be Gaussian white noise. A random number generator[2] was utilized to provide a noisy aircraft position after standard deviations in range and bearing were known. A multiplicative process was used, since it provided random numbers using very little computation time. This process generated twenty uniformally distributed numbers which were summed, averaged, and biased to provide a Gaussian distribution with a mean value of zero.

Three different radar systems were tested along with an error-free case. The least accurate radar tested was the current airport surveillance radar, which had an error with standard deviations in range and bearing equal to 250 ft and 0.25 deg.[3] The second radar system was characterized by standard deviations of 110 ft and 0.14 deg. This performance was theorized for current radar equipment with an improved digital quantizer added to the radar processing equipment. The third radar system was the Discrete Address Beacon System which is currently being tested. The system has demonstrated unpublished test results of 30 ft and 0.035 deg for standard deviations of error. An error-free case was included to provide a baseline for comparison.

Simulation Facility

The aircraft simulation facility consisted of an Adage computer and a fully instrumented fixed-base cockpit

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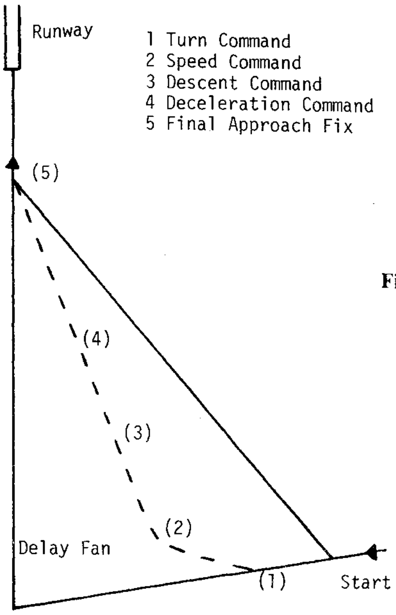

Fig. 1 Approach geometry.

simulator representative of a Boeing 707. The Adage computer simulated the aircraft dynamics, performed all necessary command calculations, and generated the flight instruments on a cathode ray tube using a vector generator.

Approach Geometry

The approach geometry for a four-dimensional navigation scheme must provide flexibility in the time domain and be consistent with enroute and terrain limitations in the area of the airport. For this reason, a single delay fan approach was developed and tested. This delay fan allowed for a maximum delay of 5 min using both path and speed controls. The nominal flight path was in the center of the delay fan, so the arrival time could be shifted ± 150 s.

The approach geometry is shown in Fig. 1. In a multiple aircraft case, aircraft would be assigned a left or right pattern, dependent upon their arrival heading and time. Separation could thus be accomplished by time, altitude, and pattern. The limiting case, in terms of aircraft proximity, occurs when one aircraft is at the final approach fix. The minimum mileage separation for 60-s time interval arrival is 2.9 miles, and for 72-s time interval is 3.65 miles.

Implementing Delivery Commands

The four-dimensional navigation profile included four computer-generated commands, which are represented in Fig. 1. The aircraft simulation started 5 naut. miles from the delay fan at 6000 ft and 220 knots indicated airspeed. The scheduled arrival time at the final approach fix was 486 s.

In order to issue a turn command at the proper point, the computer used runtime, present aircraft position, and a forecast wind. The turn command (1) was issued at a point that would allow a standard rate turn to the commanded course. At this time, the aircraft was about 20 miles from the radar facility and tracking transverse to the radar site. A small error in bearing could advance or delay the turn command. For this reason, a fine tuning airspeed command (2) was issued immediately after completion of the turn.

The descent command (3) was issued at a fixed time, and allowed for the 5 s of pilot delay time after the command was issued, a 2000 ft/min rate of descent, and 5 s to level-off at 2000 ft. After the level-off was completed, the distance and time to the final approach fix was computed every 4 s to determine when to issue the deceleration command (4). The deceleration rate was 2 knots/s, and the commanded airspeed during this phase decreased at this rate. At the conclusion of the deceleration, the aircraft stabilized at 160 knots to the final approach fix (5).

During the entire approach, the wind was compensated with the commands. A forecast wind was used for the turn and airspeed commands. Actual along-course wind was used for the deceleration command.

Commands were transmitted to the aircraft via digital datalink, and were displayed in a small window below the attitude indicator. Command markers on the airspeed indicator, altimeter, vertical velocity indicator, and horizontal situation indicator displayed all command information.

Experimentation and Results

Introduction

The objective of the experimentation phase was to evaluate the system geometry just described. To accomplish this objective, eight pilots were recruited to fly the simulation.

The experimentation took on three distinct phases. Phase 1 used closed-loop speed control during the final portion of the approach. Phase 2 was a simplified configuration deleting the closed-loop speed control, and Phase 3 was a further simplified three-command delivery program. Although the geometry and the overall conduct of flying the terminal approaches were unchanged, the method of delivery was altered to find the most accurate system consistent with pilot workload.

Phase 1 – Closed-Loop Speed Control

Phase 1 included closed-loop speed control during the last 60 s prior to arrival at the final approach fix. It was postulated that this would provide last minute corrections and would improve delivery accuracy. Although the deceleration command was issued at a variable time, it took into effect a fixed rate of deceleration. It was thought that this deceleration would cause errors, since rates are more difficult to maintain than fixed parameters. The programmed rate of deceleration was 2 knots/s, and this schedule was displayed on the airspeed indicator with a moving airspeed command marker.

Once the deceleration to 160 knots was completed, the computer would compute a wind-corrected airspeed every 4 s, based on estimated aircraft position. The result would be displayed on the airspeed indicator. Airspeed limits during this phase were 130 and 220 knots. The stall speed of the aircraft was about 106 knots and a safety margin was added to prevent flying very close to a stall. Also, the aircraft power response was in a region of reversed operation at this low airspeed. This means that it took more power to fly slower. Because of this fact, the workload at low speed was considerably higher. The 220-knot limitation was a structural one, as this speed produced the maximum allowable amount of dynamic pressure on the flaps.

The commanded airspeed displayed on the airspeed indicator would correct to an on-time arrival at the final approach fix. Without radar error, estimated and actual aircraft position were the same, and the commanded airspeed would be stable if actual and commanded airspeed were the same. If the actual airspeed were higher than commanded, the next 4-s computation would correct for this and display a lower commanded airspeed.

With a radar error, the display was quite different. Since the radar errors were Gaussian, the commanded airspeed would be at a different airspeed after each computation. No smoothing algorithm was employed. The pilots were briefed on this and told to smooth these commands themselves. The difference between two successive commanded airspeeds increased with an increase in radar error. Closed-loop speed control was terminated when the aircraft reached a position within a half mile from the final approach fix.

Tests

The eight instrument rated pilots were briefed on the system geometry and display information available to them. They were also told the overall objective of the testing program, as well as the methods used by the timed delivery algorithm. They were then trained in the simulator until they showed a similar proficiency with the aircraft. The training took between one and eight practice terminal approaches and was dependent upon pilot instrument flying experience.

Each pilot then flew four approaches with the same wind profile and varying amounts of radar error. The four radar cases were each flown twice to provide additional data points for analysis. After the first four approaches, the pilots were given a break. The order of the approaches was systematically varied so that with eight subjects every combination of order was tested. These measures were taken to exclude the effects of increased learning and of fatigue from the results.

Results

All approaches were flown successfully and the greatest arrival time error was 9 s late. The earliest arrival was 6 s early. Of the 64 approaches, 9 had early arrivals, 49 had late arrivals, and 6 approaches were on time. The overall average arrival time error was 1.88 s late.

The average miss time without radar error was 1.56 s. This compares well with Morgenstern,[4] who used a similar system geometry and arrived at 1.7 s. The average miss times with radar error were 2.38 s for the Discrete Address Beacon System, 2.75 s for the improved digital quantizer, and 3.44 s for current airport surveillance radar. No data exist for comparison. A plot of arrival time error vs radar error for this phase is shown by the Phase 1 curve in Fig. 2.

Phase 2 – Simplified Configuration

Since the arrival time errors from the Phase 1 testing were acceptable even with the least accurate radar, there was no need to improve the delivery algorithm. However, the question arose as to whether or not a simplified approach would yield similar results. It was decided that the closed-loop speed control portion of the approach should be deleted. This was the portion of the approach where the pilot workload, although still acceptable, was at its highest point, especially with a large radar error where smoothing the commanded airspeed was time-consuming. It was felt that by deleting the closed-loop speed control, more pilot attention could be devoted to maintaining course and altitude.

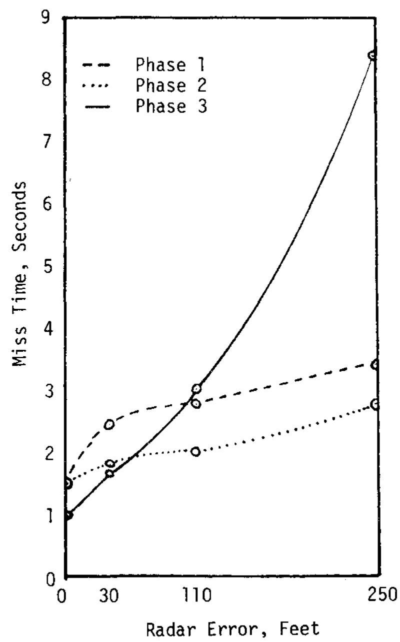

Fig. 2. Results.

The simulation was changed to allow for a constant speed final portion and four of the pilots were retested. Again the order was scrambled, and all possible combinations were flown to eliminate the learning and fatigue factors from the results.

Results

All approaches were flown successfully and the greatest arrival time error was 5 s late. The earliest arrival time was 2 s early. All approaches had some error. The overall average arrival time error was 2 s late.

The average miss time without radar error was 1.5 s. The average miss times with radar error were 1.75, 2.0, and 2.75 s.

A plot of the arrival time error vs radar error for this phase is shown by the Phase 2 curve in Fig. 2. The arrival time errors for Phase 1 and Phase 2 are quite similar. It appears that the Phase 2 system is more accurate in terms of delivery accuracy, but this may be due to increased learning on the part of the subjects. In any case, the two methods are very close in terms of accuracy and the Phase 2 testing was considerably easier to fly.

Phase 3 – Three Command Timed Delivery Program

Because of the results in the Phase 2 tests, the incentive to further simplify the approach was quite strong. Since the turn, descent, and deceleration commands were integral to the approach, the only possible simplification was to eliminate the speed command immediately following the turn. Initially, this command was designed to correct for the lateral tracking error of the radar and any deviation from a standard rate turn performed by the pilot. A greater arrival time error was expected, but the increase caused by the deletion of the command was not known.

There were three changes implemented to accomplish this goal. The first change was the deletion of the airspeed command. Second, the scheduled arrival time was delayed and the interval of time for the command was increased from 30 to 60 s. Previously, the deceleration command could only be given 15 s early or late. This caused a shorter time at 160 knots, but this was judged to be acceptable since flight at 160 knots was called for on final approach. This increased flexibility was needed for any errors acquired between the turn and the deceleration command. Third, the portion of the program which determined when to issue the deceleration command was changed slightly to bias the arrivals so that they would have a zero mean for multiple aircraft. During the Phase 1 and Phase 2 tests, the aircraft, on the average, arrived 2 s late.

Results

With these changes, the simulation was flown twelve times by the author. Each radar error was flown three times. All approaches were flown successfully and the greatest arrival time error was 9 s late. The earliest arrival was 2 s early. Of the 12 approaches, 2 were early, 7 were late, and 3 were on time.

The average miss time without radar error was 1 s. The miss times with radar error were 1.66, 3.0, and 8.33 s. A plot of the arrival time error vs radar error for this phase is shown by the Phase 3 curve in Fig. 2. The arrival time error increases with an increase in radar error and the function is nearly linear.

Conclusions

The results of the experimentation were very encouraging. A functional relationship between radar error and runway arrival time error was found. This relationship appears to be nearly linear and arrival time error was surprisingly small. With the use of four-dimensional navigation techniques, fix-to-fix navigation can be performed with great accuracy, even in the terminal area. All this can be accomplished while keeping pilot workload at a low level. The three alternative methods for achieving delivery accuracy performed within acceptable limits.

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