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Four-Dimensional Helical Approach of Aircraft in an Air Traffic Control Environment

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With the advent of digital avionic techniques, it has become possible to plan the integration of computer systems for performing on-line optimization tasks during flight operation. These computers can be used for computing attitude and control strategies by minimizing different cost functions. Digital systems will play an even bigger part on tomorrow's flight deck because of the improved control capabilities. This paper presents the results for a simulation study in which a minicomputer was used for computing four-dimensional flight trajectories in an air traffic control environment. Special interest was given to helical approach for a transport aircraft, in this case a DC-10/30.

Introduction

THIS paper presents the results of a combined analysis and simulation program to determine the effects of helical flight trajectories on transport aircraft during approach and landing. The objectives of the program are to: 1) computerize and optimize the approach and landing procedures; 2) determine whether four-dimensional (4-D) navigation, together with helical approaches, allows a reduction of fuel consumption[1,2]; 3) realize the navigation computer using a microcomputer system; 4) make comparisons of actual flight data with optimal procedures. This computer system is designed for on-line operation, which will enable in-flight system's updating and optimizations.

The system is currently being designed and is partly tested for a DC-10/30 aircraft. Development work is continuing to implement the hard- and software system on a flight simulator in order to test the on-line capabilities under more realistic conditions.

Problem Statement

The task of executing helical maneuvers in the terminal area is clearly a problem of automatic control system synthesis. The fundamental problem is the safe and efficient guidance and control of the aircraft from various points to the runway. In order to reduce the pilot's workload when performing such maneuvers, the guidance and control of the aircraft should be computerized.

This versatile computer system must include the following minimum control possibilities: 1) four-dimensional guidance of aircraft, 2) helical approach, 3) holding, 4) flare, rollout, and go-around, and 5) takeoff.

It is clear that such a computer-controlled system can only function when on-line operation is guaranteed. Due to this restriction, the system must be designed in such a way that at any time, and under all flight conditions, new control strategies may be computed or optimized. On-line operation is required when different system or environmental parameters are changed—for example, during approach, landing, or go-around maneuvers.

On-line optimization, in the sense of minimizing a performance index, requires a computational effort which may become unrealistically large. That is, in order to limit the computing time for solving an optimizing task, special directives for the system's design are necessary, and these can be summarized as follows:

1) The navigation and control system has to be designed as a hierarchical system with task-oriented processors at different levels. The executive program which supervises the computer network can be interrupted by the pilot at any time.

2) The input to the system should be straightforward, unique, and echoed with graphical output.

3) For each selected task, the guidance and control computer system should also generate emergency strategies.

4) Fast system state and control predictions must be included when on-line optimization tasks and system monitoring are to be performed.

5) The computer system should not affect the reliability of the guidance and control system; the executive must continuously monitor the different processors, data flows, and displays in order to detect, annunciate, and display system failures.

As previously stated, a computerized guidance and control, which includes 4-D navigation, helical approaches, computer-controlled flare, rollout, and go-around, requires a very powerful processor system for solving such complex on-line tasks. Installing modern technologies in today's cockpit should primarily enhance aircraft safety by adding new control and monitoring capabilities. This cannot always be guaranteed because sophisticated hard- and software systems tend to become so complex that the efficient on-line tests fail.

In this paper, a modern computerized guidance and control system is proposed. The system is first described, the general concept and philosophy is presented, and hardware systems are also discussed. The proposed guidance and control system has been partly realized and tested, but is, in no way, a commercial product. The primary goal of the entire project is to carry out a feasibility study of this guidance and control problem and to give some proposals for a possible realization.

System Specifications

The basic system configuration is shown in Fig. 1. General computers operating at various levels define the hierarchical system. The master, or executive computer, coordinates and supervises the network. The pilot's interactions are inputs to the executive.

Monitoring Computer

This computer handles the data flow from the various aircraft systems such as autopilots and aircraft-integrated data acquisition systems (AIDS), and continuously tests the

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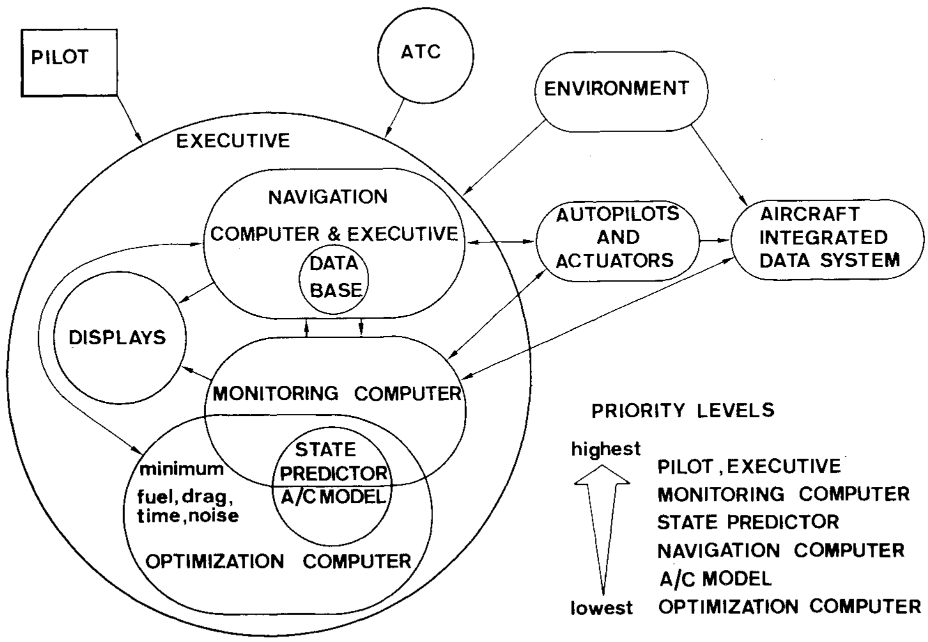

Fig. 1 Block diagram of the computer network.

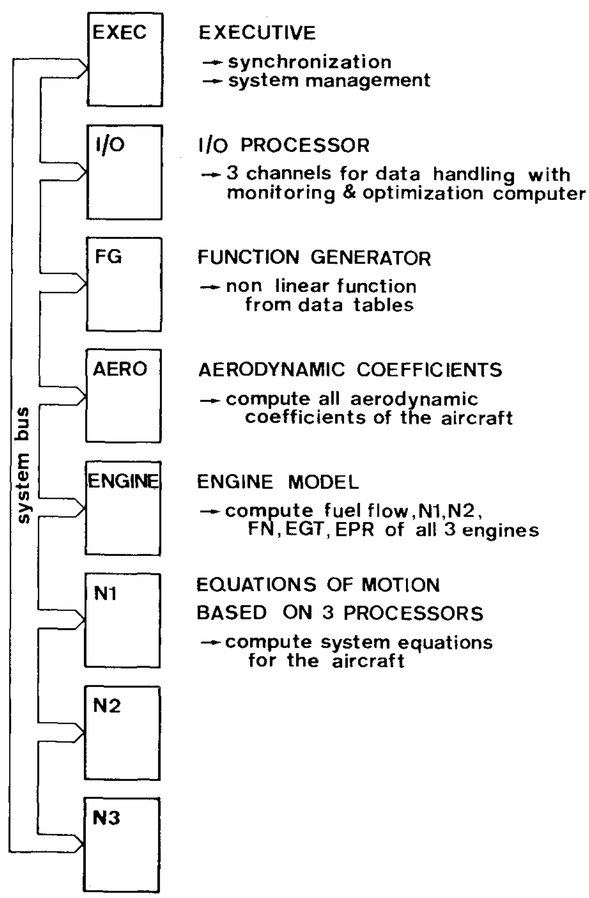

Fig. 2 Basic structure of the microcomputer-based DC-10 model.

current state of the aircraft. The monitoring system is also responsible for failure detection and for attitude, state, and control display.

Aircraft Model

The aircraft model is the heart of the system. This integrated model is called during the optimization of a specific maneuver. With this aircraft model it is possible, at any time and under any environmental conditions, to simulate the state of the aircraft. Also included in this model is a fast state predictor which allows prediction of final conditions—for example, the touchdown point or end values for a given maneuver. The aircraft model is realized with a set of microcomputers. The different microcomputers operate in parallel. This structure is necessary in order to reduce the computing time. The basic structure of the aircraft model is shown in Fig. 2.

The master executive of the model coordinates the different processors. The input/output (I/O) processor can handle up to three high-speed channels for the data flow between the monitoring and the optimization computer. A special computer is used to calculate the different aerodynamic nonlinear functions.

Optimization Computer

This computer generates the different optimal strategies by minimizing a given performance index. It operates in the background under control of the executive computer, and receives its information from the data base and from the monitoring system. During the optimization search, the aircraft model is numerically integrated and the performance index is evaluated at each optimization stage. On-line optimal control policies allow a reduction of operating costs and provide for a more efficient control of the aircraft. This leads to, among other benefits, drag, fuel consumption, and time optimization.

The purpose of this optimization computer is twofold. First, it optimizes the system's performance for a specified steady-state flight condition; for example, the drag optimization along a 4-D flight trajectory. Second, it serves as an on-line controller when new steady-state conditions are required. The nominal or steady-state solutions are precomputed offline and stored in a data base. These precomputed solutions are optimal for given ideal conditions, primarily for a fully operative aircraft, and under known environmental conditions for a specific flight plan.

During the on-line operation, the aircraft, while airborne, is controlled using an optimal state feedback controller. If, during the on-line operation, a new nominal trajectory has to be computed, then a new search for an optimal solution is activated with the last optimal solution as the initial conditions. This strategy guarantees a fast convergence, which means a smaller computational effort.

Navigation Computer

This computer generates the 4-D trajectories for a terminal area and the required command sequences. These commands are then interpreted by the control actuators.

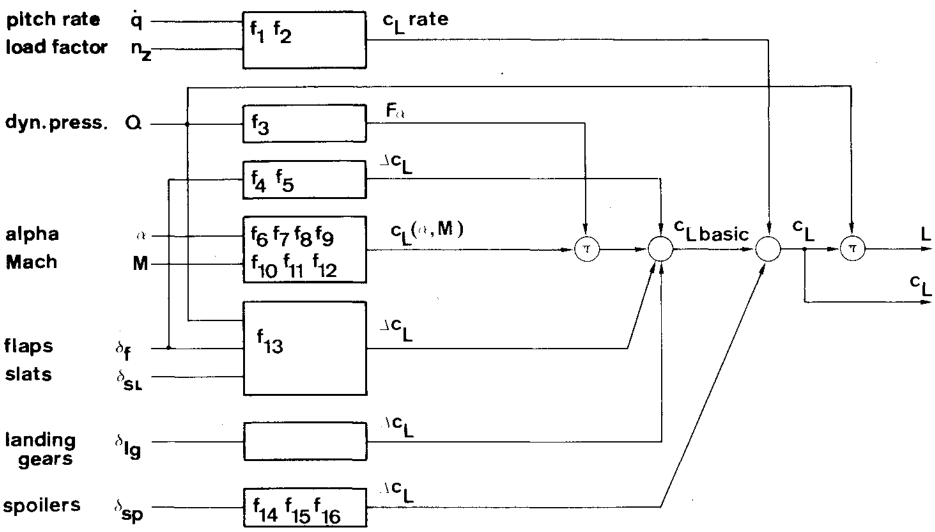

Fig. 3 Block diagram of the lift computer.

A 4-D flight profile consists of a ground track, an altitude, and an associated speed profile which controls the flight time. Different program options provide a great flexibility for the computation of the navigation pattern and of the associated command sequences. This navigation computer is actually realized with a process computer. The program is written in FORTRAN IV. It is planned to implement this navigation software package together with the optimization program on a fast microcomputer system.

The assigned priorities for the various computers in this guidance and control system are specified as follows: 1) executive, 2) monitoring computer, state predictor, 3) navigation computer, aircraft model, and 4) optimization computer.

The Lift Computer as Part of the Aircraft Model

The lift force and the associated lift coefficient were first mechanized on a microcomputer, and this module gives an example of the aircraft modeling problem. The fundamental equation for the lift and drag forces may be written as follows:

Lift

$$L = qS_w(C_L + \Delta C_L)$$

Drag

$$D = qS_w(C_{D_p} + C_{D_i} + C_{D_c})$$

where S_w is the wing reference area, C_L and C_D the lift and drag coefficients, and q the dynamic pressure. The various coefficients may be defined in a simplified way as follows:

$$C_L = C_L(\alpha - \alpha_0)$$

$$C_L = \Sigma \text{ corrective terms}$$

$$C_{D_p} = C_{D_0} + \Sigma \text{ parasite drag coefficients}$$

$$C_{D_i} = \eta C_L^2 \qquad \eta = k/\pi e A\!\!R$$

where e is the Oswald efficiency factor, k is the ground effect drag factor, $A\!\!R$ is the aspect ratio;

$$C_{D_c} = \text{compressibility drag coefficient}$$

and

$$q = \tfrac{1}{2}\rho V^2$$

where ρ is the air density.

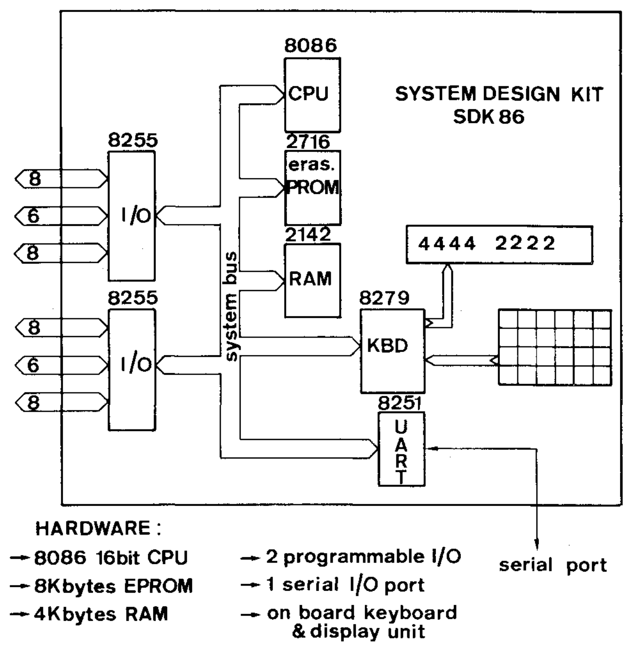

Fig. 4 Hardware configuration of the system design kit computer.

A. Lift Equation

The lift coefficient C_L is a fundamental coefficient of the aircraft, corresponding to the nondimensional lift development by the wing and horizontal tail surface. Additional corrective terms are included in order to take account of the effects of landing gear, wing icing, and variable wing settings such as slats, flaps, ailerons, and spoilers on the lift coefficient. The basic lift coefficient also depends on the angle of attack α, the Mach number M, the effect of the control surfaces, and the environment. The block diagram of the lift coefficient is shown in Fig. 3. The basic lift $C_{L_{\text{basic}}}$ is made from the summation of $C_L(\alpha, M)$, the effect due to wing settings, and landing gear position. Depending on the spoiler's setting, and the rate terms of the equations of motion, the basic coefficient is then corrected. Sixteen nonlinear aerodynamic functions are necessary to evaluate the various terms in the lift equation. These functions are tabulated, and automatically called for the lift calculation. Therefore, 9 inputs and 16 nonlinear functions are necessary to implement the lift computations.

B. Lift Computer

The lift computer uses a 16 bit microcomputer. Every 50 ms the input data are loaded. The values of the nonlinear func-

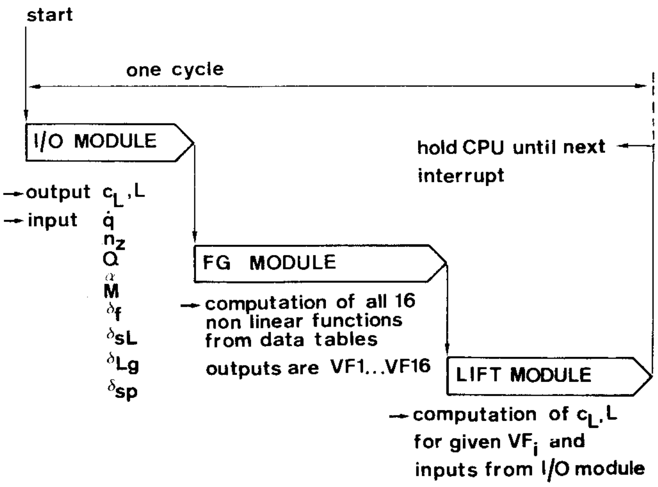

Fig. 5 Lift computer program cycle.

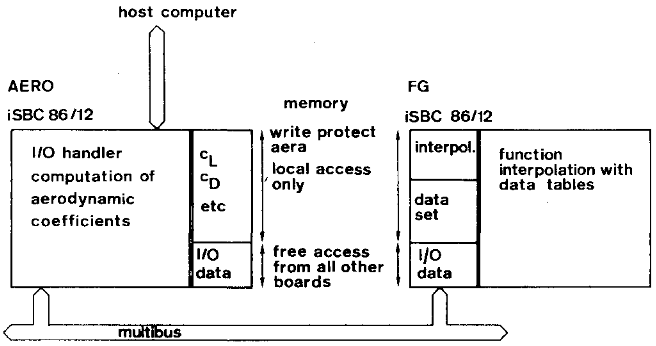

Fig. 6 Hardware configuration of the two-board computer system.

tions are evaluated, the lift force and lift coefficient are computed, and the results transferred to the output channels. The data transfer is byte parallel. Figure 4 shows the hardware configuration of the microcomputer. This hardware consists of a 16-bit central processing unit (CPU), 4 kbyte erasable programmable memory (EPROM), 4 kbyte random access memory (RAM), two programmable I/O ports, and an on-board keyboard controller for software debugging.

Different problems had to be solved while designing the lift computer. Due to the time-critical application, it was necessary to scale all variables; therefore, special software for the basic arithmetic operations $(+,-,*,\div)$ had to be developed.

The software design was done at the assembler level. Special attention was given to optimize the code (use of register-to-register operations, avoiding memory references, etc.).

The program structure is separated into three modules: 1) I/O module for the data transfer, 2) function generator module $(f_1,\ldots,f_{16})$ and 3) lift module (C_L and L).

The timing of one program cycle is shown in Fig. 5, one cycle for the lift computation is 16 ms long, about 20 ms are reserved for the implementation of the drag force, and the drag coefficient, and 14 ms for I/O transfers.

This areodynamic computer calculates lift values for all possible flight conditions of the aircraft.

C. High-Performance System

The following aerodynamic coefficients will also be implemented on the single-board computer: 1) side force coefficient C_y, 2) rolling moment coefficient C_l, 3) yawing moment coefficient C_n, and 4) pitching moment coefficient C_m.

In order to realize this aerodynamic computer, two parallel high-performance microcomputers are necessary. One for the I/O handling with the host computer for the calculation of the different aerodynamic coefficients, and the second for the evaluation of the nonlinear functions. Both computers communicate via a dual port memory and a special common bus controller. Figure 6 describes the system configuration of the two-board aerodynamic computer.

This system description points out the design philosophy. The computer system has a modular structure which allows the designer to organize and optimize the data transfer between the different computers. This structure also provides a better time synchronization for this time-critical microcomputer application.

It is important to emphasize the fact that this design work is primarily research work in the field of computer science, and a test case for a microcomputer application. Efforts are being made to test the system under realistic conditions using a flight simulator. The next section presents a test case of a helical approach and landing at Zürich airport.

The Helical Approach as a Flight Test Example

The navigation and control system was tested during different simulated approach and landing conditions in the terminal area of Zürich airport. The dynamics of the DC-10/30 were simulated on a process computer. In these test examples, different 4-D trajectories were computed and the resulting control commands were then used as control inputs for the simulated DC-10.

The computed trajectories are specified by given way points, the center of the helix, and by the holding pattern. These "fix" points are specified by the air traffic control conditions and by standard flight procedures.

One typical approach is shown in Fig. 7. The initial aircraft altitude and speed are continuously reduced in the helix. The helical flight allows the aircraft to reach the landing conditions with idle power setting, the speed being continuously decelerated on a steep flight path with an optimized lift-to-drag ratio.

Just prior to the instrument landing system (ILS) capture transient, the flight path angle is reduced to the required value, and the aircraft is then stabilized for the final approach. Slats, flaps, and landing gear are automatically set and extended.

If holding is commanded, the navigation computer automatically computes the point HXHD, where the aircraft has to leave the helix. The connection between helix and holding pattern is shown in Fig. 8. The holding pattern is specified by the International Civil Aviation Organization.[3]

These simulated results have shown that such a computerized approach and landing system reduces the workload of the pilots during critical maneuvers such as approach, landing, go-around, or takeoff. The advantages of such cockpit-computer power are so evident that, in the future, digital computers will replace the classical analog techniques. The first simulated results have shown that such digital systems can: 1) compute optimal 4-D flight trajectories in an air traffic control environment; 2) monitor the different maneuvers and precompute emergency situations such as, for example, a go-around; 3) optimize the system's performance; 4) reduce flight time; 5) optimize aircraft drag and fuel consumption; 6) update the nominal control commands when system's failures occur or when environmental conditions change.

The only disadvantage is the required computational effort for optimizing the guidance and control of the aircraft. But with today's technology it is already possible to integrate such a computer system into a cockpit. One concern, however, is the software reliability. It is clear that in such sophisticated computer systems the software is very complicated and, therefore, errors may be difficult to detect. The system must be designed in such a way that different tests are performed in flight. Failures must be detected in a fail-safe manner and automatically displayed. Therefore, it is necessary to design a

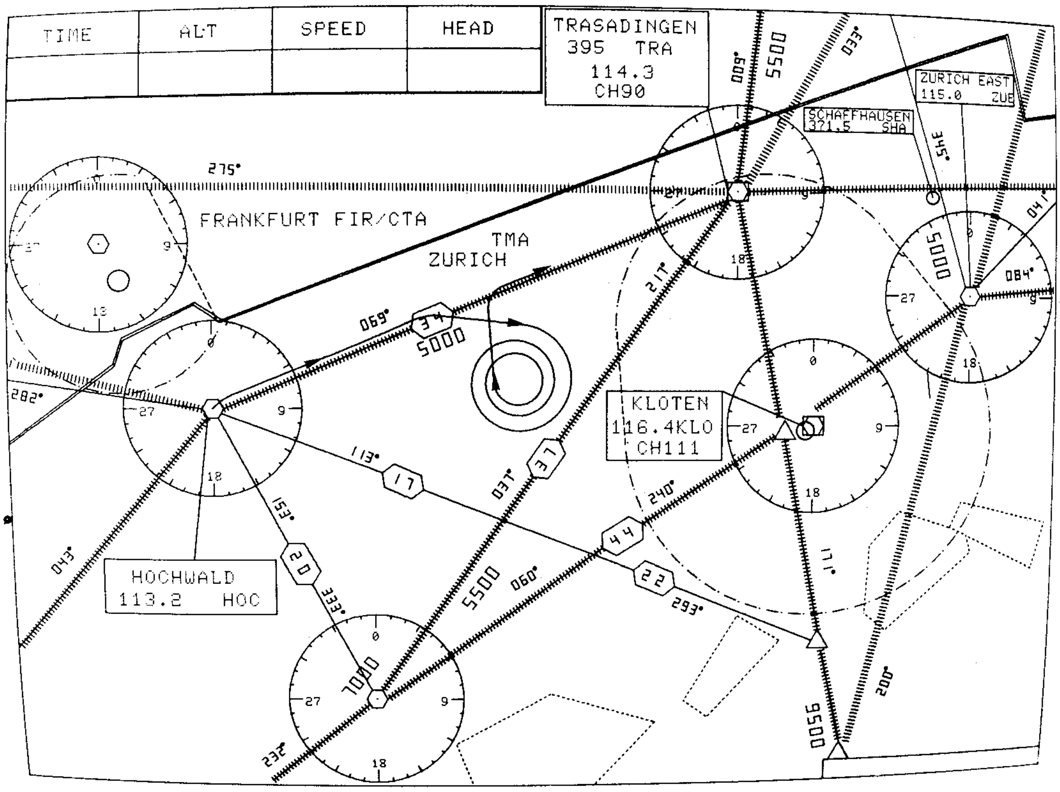

Fig. 7 Simulated helical approach to Zürich airport.

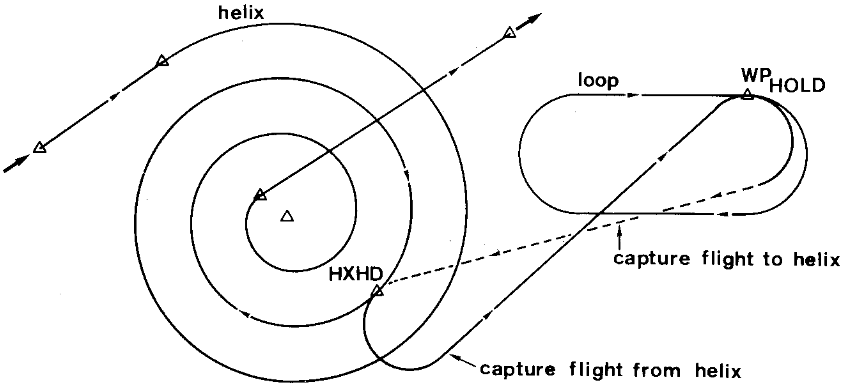

Fig. 8 Helix and holding pattern description.

background monitor and display system to inform the cockpit crew of the current status of the computer guidance and control system; otherwise, it will not be "failsafe."

At the present time, the described navigation and control system has only been tested with a single aircraft. A multiaircraft airport environment must also be considered in order to evaluate the on-line capabilities on each on-board computer system.

Conclusions

In summary, the problem of designing a microcomputer system for optimal guidance and control has been discussed. The general system philosophy and first simulated results have been presented.

At the present time, the aircraft model also includes an engine module which computes the states of all three aircraft engines. On-line tests of the lift, drag, and engine module are currently performed on the flight simulator.

A byproduct of this design work is the evaluation of new cockpit instruments using display and microcomputer technology. Displays and microcomputers offer new interesting possibilities for attitude display, intelligent I/O processing, and system monitoring. To track special maneuvers like helical approaches, new instruments are required. Computer-controlled displays offer more flexibility than the ones actually in use in cockpits. Development work is continuing at various levels to realize the system as described in this paper.

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