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Dan W. Dorr

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ROTARY-WING AIRCRAFT TERRAIN-FOLLOWING/TERRAIN-AVOIDANCE SYSTEM DEVELOPMENT

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Abstract

NASA Ames Research Center is conducting research to develop an automated Nap-of-the-Earth (NOE) helicopter flight capability for potential application in the U.S. Army light, attack, scout helicopter (LHX) program. As a step toward achieving this goal, NASA is conducting a terrain-following/terrain-avoidance (TF/TA) system concept evaluation using real-time piloted simulation on the vertical motion simulator (VMS) at Ames Research Center. The initial effort for this simulation consisted of optimizing the flightpath generation algorithm with respect to several variable parameters, developing a flightpath controller to precisely position the helicopter along the desired flightpath, and integrating the software for trajectory generation with flightpath control software. The TF/TA flightpath computation takes advantage of the lateral maneuvering capability of the aircraft and uses local terrain features for optimal terrain masking during low level (contour) flight. A math model of a an 18,000-lb-class helicopter, a digital terrain database, the trajectory generation software, and the flightpath controller were all combined to produce an off-line computer simulation of the complete TF/TA system. This simulation will provide data to optimize the system and evaluate its feasibility in preparation for the real-time piloted simulation on the VMS. Initial results indicate that the system is satisfactory for automatic, low level TF/TA helicopter flight.

Introduction

Aircraft that fly into threat areas have a need for low level, maneuvering penetration capability. Terrain-follwing/terrain-avoidance (TF/TA) systems, whether implemented automatically or by flight director guidance commands, can provide this capability, and therefore increase overall mission survivability. Systems currently in use in tactical and strategic fixed-wing aircraft and rotary-wing aircraft have TF capability only. These systems are limited to longitudinal maneuvering in the vertical plane only, while their heading is determined solely by waypoints selected during mission planning. Terrain-following/terrain-avoidance systems, however, produce trajectories requiring simultaneous longitudinal and lateral/directional maneuvering to take maximum advantage of local terrain features for masking.

The U.S. Air Force has conducted simulation evaluations for some TF/TA systems for fixed-wing aircraft.[1,2] These systems were typically designed for high speed flight (above 500 knots), whereas rotary-wing aircraft fly at much lower speeds. Low speed flight (0-100 knots) offers the potential for using TF/TA flightpath solutions which are much closer to the ground, producing better terrain masking. The eventual goal of this research at NASA Ames is to develop a fully automatic Nap-of-the-Earth (NOE) flight capability where the aircraft will be flown at altitudes just above ground level.

Current TF/TA systems are a combination of three basic building blocks. First, the terrain below and in front of the aircraft must be sensed in real-time and put in a digital format to be used to augment prestored Defense Mapping Agency (DMA) data for the area. Next a trajectory generation algorithm determines the optimal path through this terrain. And, finally, a flightpath controller calculates the control inputs to precisely position the aircraft along the desired trajectory. Our work thus far has focused primarily on the latter two tasks, as the technology for terrain sensing, and the blending of stored data with measured data requires further development.

A trajectory generation algorithm, Dynapath, was developed by TAU corporation,[3] and employs a combination of discrete path searching and dynamic programming, while discarding paths that violate constraints to produce the optimal flightpath solution. The navigation reference path is defined by waypoints selected during mission preplanning. Aircraft dynamics are incorporated into the algorithm to determine the tree structure of possible flightpaths, while navigation and maneuvering constraints limit the number of possible paths. Dynapath determines the optimal trajectory by minimizing a cost function which penalizes increasing altitude and lateral deviation from the reference path.

This paper presents work being accomplished to develop a real-time, piloted simulation on the vertical motion simulator (VMS) at NASA Ames. Descriptions of the trajectory generation algorithm and the flightpath controller are given. The software integration of the entire TF/TA system is then discussed. And, finally, real-time simulation requirements and unique features of applying TF/TA systems to helicopter flight are summarized.

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Trajectory Generation Algorithm

The trajectory generation algorithm, and its software implementation are the crux of the entire TF/TA system. The algorithm logic flow and interfaces are shown in Fig. 1. The following discussion gives a description of the Dynapath algorithm.[4]

Dynapath, as implemented here, uses a decoupled procedure in which the lateral solution and vertical solution are determined independently to obtain the optimal flightpath. In this decoupled procedure, the lateral ground track is first determined by assuming that the aircraft can fly perfectly in the vertical set clearance (desired altitude above ground). Then the vertical commands to position the aircraft at the vertical set clearance are computed. An integrated, fully coupled procedure is also available in Dynapath, but the computation time for the decoupled procedure is considerably less.

Dynapath requires several inputs before computing the optimal flightpath. Among these inputs are the following parameters whose values are selected by the user:

Waypoints - Inertial coordinates (x, y), which define straight line segments to be used as the nominal navigation path (reference path).

TF/TA ratio - A constant contained in the cost function which determines the amount of lateral maneuvering versus vertical maneuvering to produce the optimal flightpath.

Maximum lateral deviation - The lateral distance from the reference path beyond which no flightpath solution is allowed.

Vertical set clearance - The altitude above ground level (AGL) which the flighpath solution attempts to maintain. It may be a hard constraint or incorporated into the cost function.

The user also supplies the following aircraft constraints: maximum bank angle, maximum climb angle, maximum dive angle, airspeed, minimum and maximum normal load factor. Other inputs required by Dynapath are digital terrain elevation data and predicted initial aircraft position and velocity.

Determining the optimal flightpath solution first requires that a tree structure of possible flightpaths is constructed. Examining the lateral structure of the decoupled procedure, aircraft bank angle is discretized at 1-sec intervals. Assuming level, coordinated flight, these discrete values of bank angle produce a finite number of possible paths which form a tree structure (Fig. 2). At each successive node of the tree,

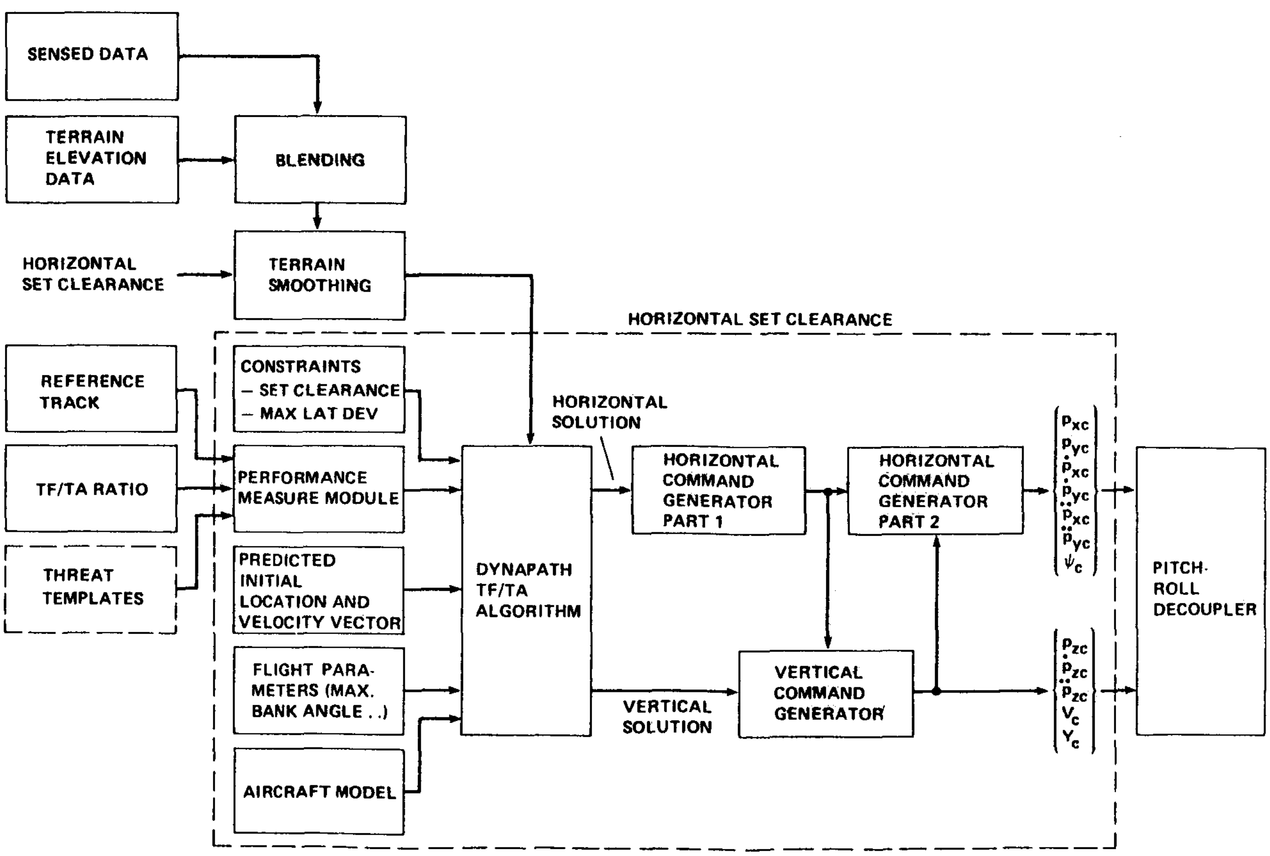

Fig. 1. Dynapath block diagram.

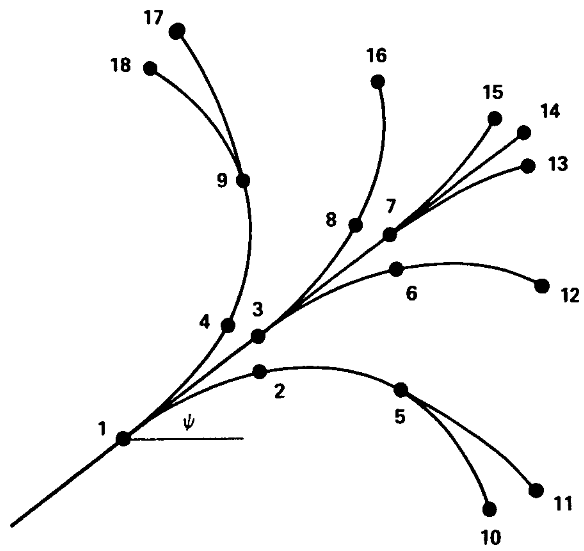

Fig. 2. An example tree with numbered nodes.

pertinent information is stored including (x, y) location and cumulative cost to the node. Each node is checked to see if it violates any constraints (i.e., maximum lateral deviation from the reference path). Branches are discarded if any constraints are violated. After the tree structure of possible paths has propagated through the entire processing patch, the cumulative cost of each surviving branch is compared, and the path with the lowest cost is selected as the optimal flightpath solution. The vertical solution is then obtained similarly using discrete values of pitch control.

The cost function is the performance measure, and for each node, i, the cumulative cost is given by:

$$J = \sum_i (H_i + \omega D_i)$$

where:

H_i = altitude above mean sea level
D_i = lateral distance from reference path
ω = TF/TA ratio
i = current node

This performance measure allows lateral maneuvering to seek the valleys reducing the cost due to H, but excessive lateral maneuvering will increase the cost due to D. The TF/TA ratio blends the two penalties and allows the user to select the desired balance between lateral and vertical maneuvering. Large values of ω produce trajectories which are primarily TF, while very small values of ω will produce primarily TA flightpaths.

The output from Dynapath is a three-dimensional flightpath in an inertial frame. This flightpath is stored in the form of aircraft states (x, y, and z positions velocities, and accelerations) at 1-sec intervals to position the aircraft along the desired trajectory. Based on this stored array of aircraft states, a flightpath controller determines the required helicopter controls, or displays information to the pilot to fly along the optimal trajectory.

The trajectory generation algorithm, was designed to compute guidance for a single patch, where a patch is the area in front of the aircraft's present location. The width of a patch is defined by the maximum lateral deviation, and the length is an input parameter to be selected by the user. While the TF/TA trajectory for a patch is being calculated, the aircraft is flying along a previously computed trajectory. The initial conditions for the current computational patch are predicted based on the preceeding patch. As implemented here, each patch is about 25-sec long and is updated after 5 sec, so successive patches are overlapped. This process gives the system adequate look ahead capability. As the aircraft enters a new patch, the trajectory calculation has been completed and stored. This trajectory is flown while the trajectory for the next path is calculated.

Flightpath Control

The output from the trajectory generation software is the input to the flightpath controller, which determines the control inputs required to keep the aircraft on the optimal trajectory. A high degree of precision is required of the controller because of the close proximity of the aircraft with the ground. The controller implemented here initially follows the design of the McDonnell Aircraft Company in determining the outer loop, body axes controls.[5] Inner loop control laws (for actual helicopter control inputs) were developed for an 18,000-lb-class helicopter using linear quadratic regulator (LQR) design techniques. The control structure is shown in Fig. 3.

The outer loop control structure assumes that the aircraft is in coordinated forward flight. (This is not the case for helicopters flying in a NOE environment, but for TF/TA applications, it is a valid assumption.) First, a transformation from inertial coordinates to path coordinates is performed on the output states from the guidance software, as well as the actual aircraft states. The errors in horizontal and vertical position, velocity, and acceleration are than combined to produce a total horizontal acceleration command and a total vertical acceleration command. The required bank angle, normal load factor, and yaw rate to follow the acceleration commands are then computed, completing outer loop control.

The inner loop control laws must be tailored to a specific aircraft, since they must take into account aircraft response. For the TF/TA system checkout, a nonlinear, math model of an 18,000-lb-class helicopter is being used.[6] Stabililty and

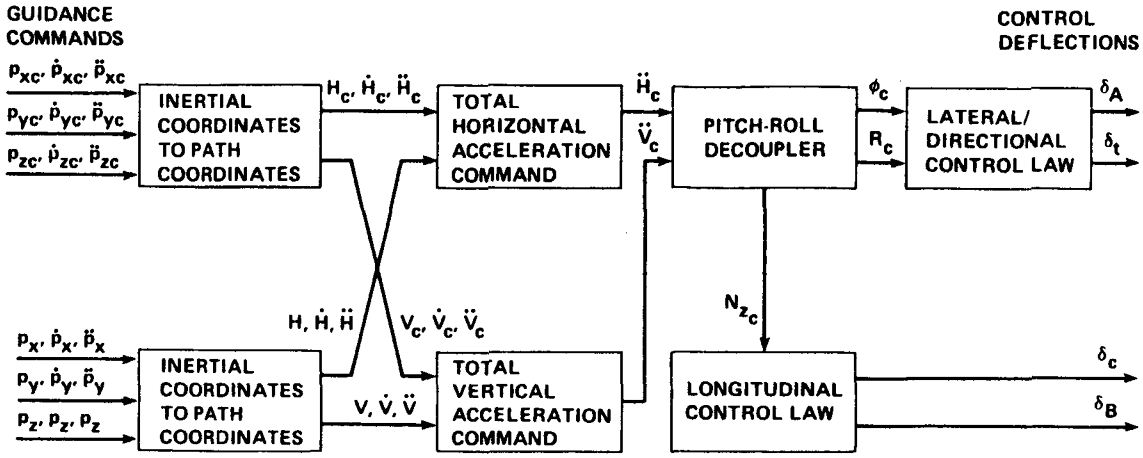

Fig. 3. Flightpath control flow.

control derivatives of the helicopter, at an airspeed of 60 knots, were used with LQR design techniques to determine the optimal state feedback gains for collective, cyclic, and rudder pedal inputs. The decoupled, linear perturbation equations of motion for a helicopter in level flight are[7]

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & X_q & -g \\ Z_u & Z_w & Z_q+u_o & 0 \\ M_u & M_w & M_q & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} X_{\delta_c} & X_{\delta_B} \\ Z_{\delta_c} & Z_{\delta_B} \\ M_{\delta_c} & M_{\delta_B} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_c \\ \delta_B \end{bmatrix} \quad \text{longitudinal}$$

$$\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} Y_v & Y_p & Y_r-u_o & g \\ L'_v & L'_p & L'_r & 0 \\ N'_v & N'_p & N'_r & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ p \\ r \\ \phi \end{bmatrix} + \begin{bmatrix} Y_{\delta_A} & Y_{\delta_t} \\ L'_{\delta} & L'_{\delta} \\ N'_{\delta_A} & N'_{\delta_t} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_A \\ \delta_t \end{bmatrix} \quad \text{lateral/directional}$$

where:

u,v,w	= aircraft body axes velocity components
p,q,r	= aircraft body axes angular velocity components
X_i, Y_i, Z_i	= stability and control derivatives (forces)
L'_i, M_i, N'_i	= stability and control derivatives (moments)
$\delta_c, \delta_B, \delta_A, \delta_t$	= helicopter control inputs
θ, ϕ	= pitch and roll Euler angles
g	= acceleration due to gravity
u_o	= nominal forward velocity (trim speed)

With the decoupled state equations in the above form, a quadratic cost function was defined to minimize the use of controls and the transient response. The optimal state feedback gains for both longitudinal and lateral/directional control were then determined using the method of eigenvector decomposition, which provides a solution to the algebraic Riccati equation.[8] The preliminary design of the inner loop control system was carried out following this method. Since control systems designed using optimal techniques are sometimes quite sensitive to disturbances and errors in system modeling, the response of the entire system will be analyzed in detail to determine if this control is adequate. In the implementation of this inner loop control, the regulator values are provided by the outer loop control.

Terrain Sensor Inputs

For the guidance software to determine the optimal flightpath, digital terrain elevation data must be available for the entire processing patch. This data consists of stored DMA format data which are then updated by aircraft onboard sensors (radar, laser, and infra-red sensors are all possibilities). The state-of-the-art in sensor fusion is not yet at a point where these systems can be used operationally for TF/TA digital terrain representation, and our simulation will not attempt to model terrain data gathering by sensors. Instead, a prestored database which accurately represents the terrain to be flown over (except in a few cases of "unseen objects")is used. In this manner, we assume perfect sensors, and our efforts are focused on guidance and flightpath control.

Creating a file containing the elevation data for a processing patch requires that careful consideration be given to the spacing between data points. As the spacing between data points becomes smaller, the terrain resolution increases, but the data file also increases in size. It takes more time to update larger data files when going from one patch to the next, and more memory is required. Spacing should be chosen based on the desired vertical set clearance and aircraft velocity. At lower airspeeds, the vertical set clearance can be lower, and terrain resolution must be higher. Tests will be conducted at 40 to 100 knots with a vertical-set clearance of 30 to 100 ft using a data spacing of 15 ft. In running the off-line simulation, 15-ft spacing has proved adequate for both terrain resolution and database file handling.

Off-line Simulation

The four major elements of the complete TF/TA system simulation are the digital terrain database, the guidance software, the flightpath controller, and the helicopter model. These elements have been combined on a VAX 11/780 computer for initial checkout and optimization of the combined system prior to real-time simulation. The terrain database is a digitized representation of a terrain board used by the U.S. Air Force in aircraft simulations at Wright-Patterson Air Force Base. The guidance software was run with just the terrain data to evaluate its effectiveness and to adjust parameters so that adequate trajectory solutions for real-time helicopter flight are obtained. Finally, "off the shelf" software for the helicopter math model was implemented along with the preliminary design of the flightpath controller.

The off-line simulation executes in the same sequence that would occur in actual flight. Since the guidance software requires a finite time (about 5 sec presently) to compute the desired trajectory for a new patch, the aircraft states at the start of the patch must be predicted, based on the current aircraft states and the desired trajectory for the current patch. Each time the trajectory for a new patch is computed, the solution is passed to the flightpath controller, which then provides control inputs to the helicopter.

At the present time, the integration of all the system elements is just being completed, and only preliminary results are available. Figure 4 shows a two-dimensional view, looking down at a typical solution of the actual path flown by the helicopter over a sample of terrain. Preliminary results show that the trajectory generation algorithm is seeking the valleys, while maintaining the nominal reference course, and the flightpath controller is providing helicopter control inputs to maintain the desired trajectory. These preliminary results indicate that the guidance and flightpath control software are functioning adequately, but detailed analysis of the integrated system is required before real-time piloted simulation.

Real time Simulation

The real-time piloted simulation will be conducted on the VMS at NASA Ames. The VMS (Fig. 5) provides extensive cockpit motion with

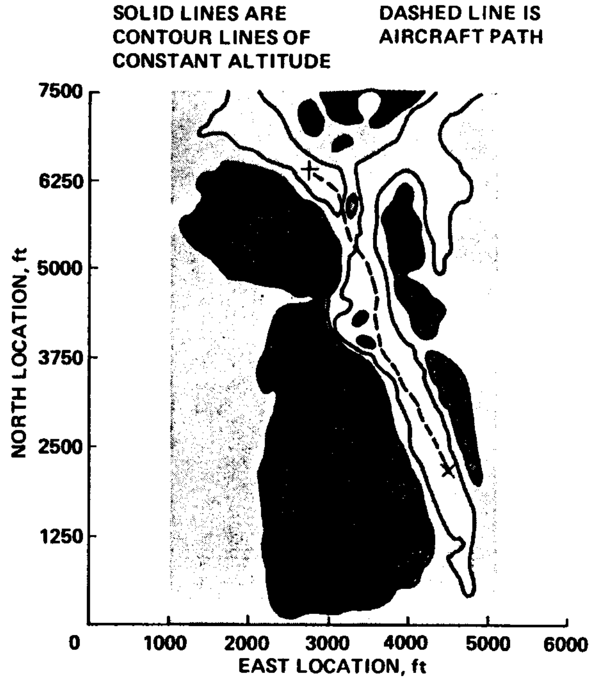

Fig. 4. Actual helicopter flightpath from waypoint A to waypoint B.

six degrees-of-freedom.[9] Pitch, roll, and yaw motion are provided by a six-legged (hexapod) hydraulic actuated system connected to the cab. This system is mounted on a moving platform which allows large vertical (±25 ft) and lateral (±17 ft) movement. The acceleration capability of the VMS is ±1.0 Gs vertically and ±0.5 Gs laterally. The simulation will employ a light weight, single-rotor helicopter model which will execute in a separate computer from the guidance software to maintain a cycle time adequate for real-time flight.

The visual system will consist of a four window display of computer generated imagery (CGI). The CGI database will be similar to Fig. 6, consisting of pyramid-shaped hills with altitudes ranging from 0 to 1000 ft, and some trees and buildings. More hills will be added to the database, however, to provide more interesting flightpath solutions. This database will also be represented in DMA format for the guidance software. In addition to the four-window display, there will be a head-down, moving map display to help the pilot with navigation and a head-up-display (HUD) which will provide guidance to the pilot. The guidance commands will be displayed by either a flight director or a "pathway-in-the-sky" (Fig. 7).

The simulation objectives are to quantitatively and qualitatively evaluate the performance of the guidance and flightpath control functions in real-time flight while varying system parameters. Various courses will be predetermined

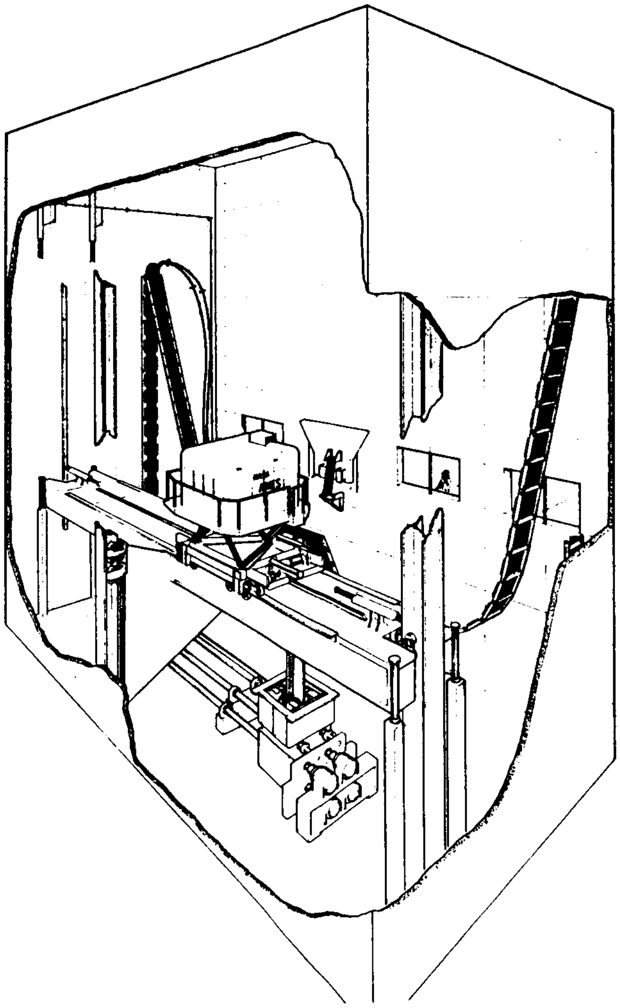

Fig. 5. Vertical motion simulator.

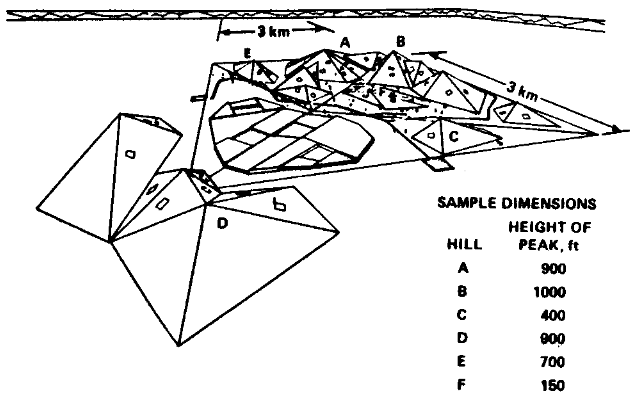

Fig. 6. CGI data base.

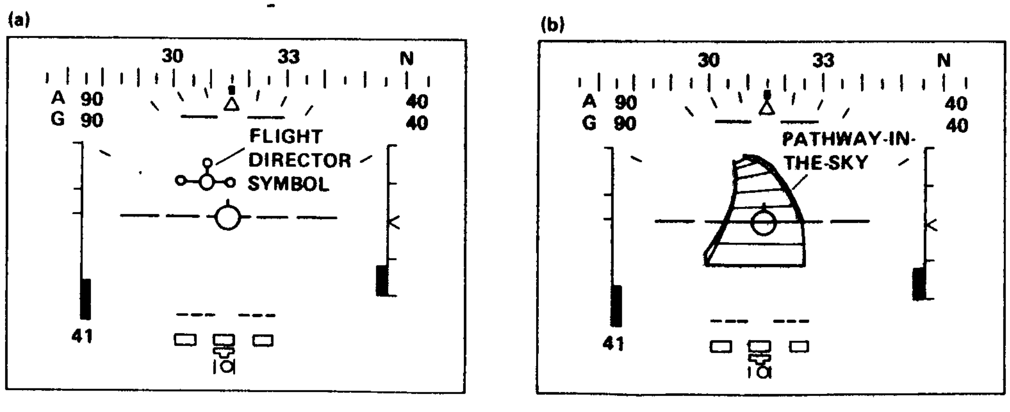

Fig. 7. HUD with a) Flight director guidance, b) Pathway-in-the-sky guidance.

by waypoint selection, and runs at airspeeds of 40 to 100 knots and altitudes from 30 to 100 ft will be conducted. Pilots will fly several runs in three modes: manual flight, manual flight with HUD displayed guidance, and fully automatic flight. During fully automatic flight, the pilot will be monitoring and evaluating the system.

In developing the guidance algorithm and the flightpath control system, constant airspeed forward flight was assumed. This is valid for fixed-wing aircraft and for rotary-wing aircraft in the limited environment of our simulation. Helicopters, however, can slow down to a hover, and even fly backwards, which, in an NOE environment, is sometimes required. For automated NOE flight, the guidance algorithm and flighpath controller will both need to be significantly modified by eliminating the assumption of forward flight at constant airspeed. Also higher resolution in the digital elevation data is required as the helicopter is flown lower and slower. Finally, the aircraft was treated as a point mass in the guidance algorithm development, and while this is adequate for contour flight, the rest of the aircraft must be considered at altitudes near tree level. During the TF/TA simulation, the system will be pushed by flying as low and slow as possible, but there will be a point where the guidance and control solutions are no longer valid. Therefore, a follow-on effort is required in guidance and control development to advance toward automated NOE flight.

Summary

As a step toward automated NOE flight, a TF/TA system for helicopters is being developed using off-line and real-time piloted simulation at NASA Ames. The system incorporates a database of digital terrain elevation data, which, in actual flight, would be updated in real time by aircraft onboard sensors; a guidance algorithm, Dynapath, which computes the optimal path through the terrain; and a flighpath controller, which determines the helicopter control inputs to maintain the optimal trajectory.

The major elements have been combined with a nonlinear model of a helicopter to form an off-line simulation of the complete TF/TA system. This simulation is being used to validate the system concept and to optimize the solutions produced by the guidance software and flightpath controller. Preliminary results from the simulation indicate that the system is functioning adequately; however, detailed performance analysis is required before real-time simulation.

Piloted simulation on the VMS at Ames will be conducted to evaluate the entire TF/TA system in real-time flight while varying input parameters. Pilots will fly over various courses in three modes: manual flight for baseline comparison, manual flight with HUD displayed guidance commands, and fully automatic flight. The NOE environment will be approached in pushing the system by flying low and slow, but modifications in the guidance and control systems will be required for automated NOE flight due to the present restriction of constant-speed forward flight.

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16. Abstract

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