DIGITAL SIMULATION OF V/STOL AIRCRAFT FOR AUTOPILOT RESEARCH

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INTRODUCTION

Research is currently underway at Ames Research Center on developing trajectory control logic for a class of advanced aircraft known as vertical or short takeoff and landing aircraft (V/STOL) (ref. 1). From that work, simulations of such aircraft oriented to autopilot research are introduced as an example of a large-scale system.

The scope of this research is to proceed from basic theory to flight test on at least one research STOL aircraft now at Ames. Work is currently concerned with the augmentor wing jet STOL research aircraft (AWJSRA); this will be the source of some of the details of aircraft models discussed later. Since generalized digital flight-control hardware system (called STOLAND, ref. 2) has been designed for Ames and installed in the AWJSRA, the results of our research can be entered as control logic software in the STOLAND system and flight tested. The research is focused on controlling the vehicle during approach and landing in anticipation of an operational environment of high-density terminal area traffic where tight control over flight paths, both in space and time, is required.

Scale, in this paper, is sensed from the point of view of the autopilot research, that is, the size of the simulation is defined in relation to its use in the research. One measure of size significant to us was the ease with which the simulation could be used as a research tool by one or two persons. Another measure was its complexity as a system to be controlled. A generalized autopilot is a device for controlling the aircraft flight path throughout its flight regime and, as such, necessarily solves the aircraft equations of motion. If that solution is very difficult, then it reflects the complexity of the aircraft itself.

In our research, problems of both size and complexity were encountered and these derive mostly from the nature of the V/STOL aircraft itself. For the class of V/STOL aircraft, several new design elements contribute to problems of size and complexity; they are designed to use both engine power and major changes in structural configuration to augment the aerodynamic forces to achieve low landing speeds, and this results in nonlinear engine and configuration-dependence of aerodynamic modeling data. Often there is also a novel type of engine control not found on conventional aircraft; for example, the engines of the AWJSRA exhaust through a controllable nozzle that can be rotated more than 90°. This control is simple to simulate but adds a great deal of complexity to the flight-control problem.

The appropriate level of detail in simulating the flight dynamics is the rigid body motion of the aircraft which, by itself, is not a large number of degrees of freedom.

Problems of size as a working tool were attacked by use of a hierarchy of simulations that represent the aircraft with increasing completeness of detail in parallel with a corresponding hierarchical development of the autopilot, and also through various partitionings of the system equations. The control problem was also attacked through partitioning to divide it into problems half as large although still difficult to solve.

SYMBOLS

A	matrix mapping angular velocity into Euler attitude rates
A_g, B_g	matrices of wind gust state equations
A, B	matrices of approximate attitude state equation
AT	list atmospheric parameters: density, temperature, pressure, and speed of sound
ATT	(Φ, Θ, Ψ), Euler attitude angles
b	wing span
c	wing cord
C_D, C_Y, C_L	dimensionless coefficients of drag, Y, and lift force
C_J	dimensionless coefficient of equivalent thrust
C_ℓ, C_m, C_n	dimensionless coefficients of roll, pitch, and yaw moments
d_i, d_{mi}	dimensionless gradients of aerodynamic force and moment
E_1, E_2, E_3	transformations for rotations about the i, j, k axes, respectively
fo, f_i, f_{mi}	dimensionless force and moment vectors
F	flap deflection angle
F_B, FA_B, FE_B	forces – total, aerodynamic, engine, respectively, in body axes
I	aircraft inertia matrix in body axes
(I, J, K)	inertial reference frame (runway)
(i_b, j_b, k_b)	body axes reference frame
(i_w, j_w, k_w)	wind axes reference frame

ℓ_E	location of engine in body axes
M	aircraft mass
$\dot{M}_F$	engine fuel flow
M_B, MA_B, ME_B	moments in body axes – total, aerodynamic, and engine moments, respectively
N	noise
Q	dynamic pressure
R_I	position, vector, inertial coordinates
S	wing area
T	engine thrust
TC	equivalent thrust of compressed engine air used to augment aerodynamics
u_i	control variable
UM	moment controls (δ_a, δ_e, δ_R)
UF	force controls (F, δth, ν)
VA	airspeed
VA_B	velocity vector with respect to air mass, body axes components
V_I	inertial velocity, inertial axes components
W_I, WS_I, WG_I	total, steady, gust winds, respectively; inertial axes components
XT	translational motion variables (R_I, V_I, $\dot{V}_I$)
XT_{REF}	translational variables for reference trajectory
XR	rotational motion variables (Φ, Θ, ψ, Ω_B)
α	angle of attack, angle between body axis I_B and velocity vector
β	side-slip angle, angle between velocity vector and aircraft plane of symmetry
δa	aileron deflection angle
δe	elevator deflection angle

δi	angle variable, one of $\beta, \delta_a, \delta_e, \delta_R$
δR	rudder deflection angle
δth	throttle setting
(Φ, Θ, Ψ)	Euler attitude angles; roll, pitch, and heading angles, respectively
μ_j	angular rate variable, one of $\{\dot{\alpha}, \dot{\beta}, \Omega_B\}$
μ^*	nondimensionalizing factor for μ_j
τ	time constant
ΩB	angular velocity, body axes components

Subscripts

B	quantity is a vector given in body axes
C	commanded value of the quantity
EX	extremes of the quantity (maximum or minimum)
I	quantity is a vector given in inertial axes components
W	quantity is a vector given in wind axes components

Superscript

$(')$	time derivative of the quantity

SIMULATION USES IN THE RESEARCH

The digital simulation of the system serves as a tool for both computing and understanding during the process of solving the control problem. First, it contains a reference definition of the aircraft in the form of parameters and model data and functional relationships, as well as algorithmic specifications of the dynamic behavior of the aircraft algorithmically. All aspects of the aircraft influence the autopilot development so that it is advantageous for the researcher to become intimately familiar with the simulation. To promote these uses, the simulations should be easy to access, use, understand, and modify, and its structure should reflect the autopilot researcher's perception of aircraft flight at as many levels as possible. Secondly, aircraft motion is sufficiently complex that the autopilot design begins with ideas based on a simplified view of the aircraft followed by an iterative use of the simulation in which ideas are tested and unforeseen effects uncovered and then fed back into the design. Many effects understood only qualitatively are quantitatively tested. During this process, the autopilot changes frequently while the remainder of the simulation program remains the same so that it will be useful to isolate the autopilot as a plug-in subsystem. Thirdly, the autopilot research from theory to flight test proceeds in stages of ever increasing integration with the complete flight-control problem and a hierarchy of simulations that correspondingly simulate the aircraft in increasing detail is necessary. In the first stage, since we are concerned with trajectory control, only a simplified simulation of the rotational dynamics is necessary. Later, attitude control and navigation is added, which requires simulation of both the translational and rotational degrees of freedom. A final stage of integration with flight hardware, displays, safety, and pilot opinion is required, and a large general purpose, man-in-the-loop laboratory simulation is used in this stage.

The main obstacle to these uses was the size of the available simulations. Although it was to be a tool for autopilot research, the simulation program for V/STOL aircraft with rigid-body dynamics threatened to be much larger than the autopilot program. However, the effort and labor required are proportional to size for a digital program, so it is essential to minimize size, especially in the critical early stages of the research. Much was gained by properly partitioning the simulation and several partitions that have proved advantageous to our work are described. Since these partitions are inevitably motivated by the nature of flight, a description of flight is first given and then the system is defined.

DESCRIPTION OF FLIGHT

The motion of a rigid aircraft can be thought of in terms of its six degrees of freedom, three of which describe the path of the center of gravity through space and three describe the rotational motion of the aircraft about its center of gravity.

The trajectory is defined in some inertial frame. Figure 1 shows a coordinate frame with origin at the touchdown point on the runway. This frame is suitable to describe terminal area approach paths, and it is an inertial frame if a flat earth is assumed. The trajectory is controlled through the aerodynamic and engine forces, which can be described by their body axis components. The body axes are a frame attached to the structure with (i_b,k_b) in the aircraft plane of symmetry (fig. 1). If the velocity vector is maintained in the plane of symmetry, then the aerodynamic forces as well as the engine forces all lie in the plane of symmetry. The aerodynamic force is normally given by its components along and perpendicular to the velocity vector (called drag and lift, respectively). This force vector is located with respect to body axes by the angle of attack, α, and is a strong function of α so that lift force is controlled by controlling α. The other major force is the engine thrust, whose magnitude is controlled by a throttle and, for the AWJSRA, its direction with respect to the body axes is controlled by a rotatable exhaust nozzle. In addition, compressed air from the engine is exhausted through a special flap to augment the aerodynamic lift during landing. Thus, control over the inertial path requires control over the inertial orientation of the plane of symmetry as well as forces in that plane.

The inertial orientation is usually defined by the Euler angles Φ, Θ, and ψ (fig. 2). Control over Φ and ψ provides control over the inertial orientation of the plane of symmetry and control over Θ provides control over the angle of attack and therefore the lift. Control over these attitudes is obtained with the applied moments. For this purpose, small, movable aerodynamic surfaces are found at the extremes of the structure (fig. 2) – ailerons at the wing ends and tail and rudder at the end of the body – which provide control moments about three orthogonal directions. The terms δa, δe, δr refer to surface deflection angles. This location at the structural extremes also minimizes the disturbance forces associated with attitude control and hence minimizes the coupling of attitude controls with the center of gravity motion.

An experienced passenger may have noticed that there is little rotational motion in commercial flights or rather he may have noticed the discomfort when it is otherwise. The attitude is almost always steady or slowly varying, and this characterizes the attitude motion generated with the simulation. There are also small-amplitude variations about this steady motion, typically at high frequency compared to variations in the center-of-gravity motion because the aircraft has inherently faster dynamics and controls in the rotational degrees of freedom than in the linear degrees.

AIRCRAFT SIMULATION – MAIN SUBSYSTEMS

Figure 3 shows a subdivision of the simulation at its broadest level of subsystems and also the input-output relations among them. The autopilot outputs are commands to the six force and moment controls of the aircraft model. The aircraft model calculates the applied engine and aerodynamic forces and moments that are output to the equations of motion section which integrates these equations and calculates environmental parameters (such as winds, density, etc.). State information and environmental data are then fed back to the autopilot and aircraft model. In the process of simulation, the flight evolves by cycling through this loop, where each cycle corresponds to the integration step size used in the numerical integration of the equations of motion.

The principle intent of this modular structure is to minimize the programming labor needed for autopilot research by isolating the equations into blocks according to the frequency with which they will change. The equations of motion subsystems apply to all aircraft and all autopilots. The aircraft model changes rarely as new modeling data are obtained from flight identification, or it changes among groups working on different aircraft. Finally, the autopilot changes most frequently. The labor of plugging in a revised or alternate subsystem is minimized since there are very few interface variables.

Finally, the same structure can be used for all simulations in the anticipated hierarchy of simulations so that the autopilot can be transferred up the hierarchy with a minimum of plug-in labor, including, eventually, the aircraft flight-control system itself. While the interfaces have been minimized, complexity and large size remains internalized in the subsystems, particularly the aircraft model and the autopilot. To consider further partitioning of the system and also to define it, the equations for each of the three main subsystems are reviewed next.

Equations of Motion and Environment Subsystems

Figure 4 shows the equations of motion. Rigid body and flat earth are assumed as is appropriate in our case. These equations exhibit the nature of the dynamics without containing any detail about the aircraft or autopilot, so this subset of system equations will appear for any aircraft or autopilot. Where vectors occur in the notation, a subscript indicates the coordinate frame in which its components are given, for example, R_I is the position vector in inertial coordinates.

The first two equations describe the trajectory in the inertial reference frame. The aircraft forces are assumed given in body axes and must be transformed to the inertial frame. During a simulation run, these are integrated to give the trajectory. The second pair of equations describe the rotational degrees of freedom. The angular acceleration equation is written in body axes because the aircraft matrix, I, is constant in this frame. The applied moments are assumed given in body axes also.

The system dynamics are partitioned later among the translational and rotational degrees of freedom. Attitude enters the trajectory motion through the transformation, T_{IB}, and to the extent that the force F_B depends on variables of the rotational motion, although this is not shown here. The translational degrees enter the rotational motion through M_B only, although this dependence is not yet shown.

Generally, the air mass will be in motion relative to the ground and this enters the problem because the aircraft forces are functions of the velocity relative to the air mass rather than the inertial velocity. The wind is modeled as the sum of a steady component (*WB*) and a gust component (*WG*) generated from a linear system driven by Gaussian distributed noise; this model is frequently used in simulations. Parameters of the atmosphere – density, temperature, pressure, and speed of sound – are also required for calculating aircraft forces and these are generated from an altitude-dependent, standard atmosphere model.

Finally, various functions of the motion must also be calculated in the simulation: the Eular angle transformation and the matrix, A, used in the equations of motion and also the velocity vector with respect to the air mass required by the aircraft model. This vector appears in the model in the form of its spherical coordinates (VA, α, β). Additional quantities used by the aircraft model in general are the dynamic pressure, Q and the angle rates α and β.

This group of equations is the subset of system equations that define the equations of motion subsystem of the simulation. This subsystem appears in any simulation independent of aircraft or autopilot. The inputs to this subsystem are the total aircraft forces and moments in body axes and the aircraft mass, and its outputs are the translational and rotational motion variables, wind, and atmospheric parameters, and various parameters of the velocity vector with respect to the air mass. Figure 5 is a block diagram of this subsystem.

Aircraft Model Subsystems – AWJSRA

The aircraft model subsystem is defined by its equations (fig. 6). This subsystem is the principal source of size and complexity in the simulation and in the control problem so the equations are given in sufficient detail to show these aspects. Where details of a specific aircraft occur, these are taken from the augmentor wing. The function of this subsystem is to calculate the aircraft forces and moments that arise from the engine and from the airflow over the aircraft structure.

Engine– The engine model requires first that sufficient data be stored to define fuel flow, thrust magnitude, and the equivalent augmentation thrust. This last is a fictitious thrust force that measures the amount of compressed engine air exhausted through the trailing edge of the experimental flap of the augmentor wing. The stored functions are nonlinear functions of atmospheric parameters, airspeed, and throttle control. The fuel consumption accounts for slow variations in aircraft mass during flight. The engine dynamics that govern variations in thrust in response to throttle commands are modeled simply as a first-order system. However, engine dynamics are normally quite complex, reflected here in the form of a time constant that changes (depending on whether thrust is increasing or decreasing) and in the form of constraints on the extremes of magnitude, rate, and acceleration of thrust. The nozzle angle dynamics are taken simply as a constant rate. The parameter, C_J, is the dimensionless equivalent thrust and appears as a variable throughout the aerodynamic functions. The factor QS is commonly used throughout aerodynamics to make forces dimensionless. Finally, the engine force is given by the thrust and directed relative to the body axes frame by a unit vector given from the nozzle angle, and the engine moment is given straightforwardly (fig. 6). This description is specialized to the AWJSRA, particularly in the appearance of C_J and ν. The term C_J appears throughout the aerodynamics, and its contribution to modeling complexity is apparent. The nozzle appears only in the very simple manner shown, but it contributes major difficulties to the solution of the control problem, both conceptually and computationally. Engine models for other powered lift aircraft would also have special effects that would increase the complexity, although different in detail.

Actuators— The dynamic response of the aerodynamic control surface deflections to control commands is considered next (fig. 6). The actual hardware by which the pilot or autopilot communicates with these surfaces is a complex sequence of linkages, servomotors, hydraulic actuators, and the surface itself, as defined on an engineering schematic of some kind. However, we are not interested in this level of detail, so an input-output model of the actuator system is identified from its detailed description and the dominating dynamics separated from that and modeled in the simulation as a simple first- or second-order system. The remaining dynamics are much faster than those of the aircraft motion. The remaining features of concern are the limits on surface position and rate, resulting from aerodynamic or servomotor saturation, which are reflected in the control problem as limits on control power.

Aerodynamics— The principal source of size and complexity in our system is the aerodynamic model. Generally, the aerodynamic forces and moments are functions of time histories (up to the present) of motion and control variables. However, almost all flight can be conceived as being small departures from some steady flight condition and this motivates modeling the aerodynamic force as a sum of terms (fig. 6). The leading term, f_O, is the force in steady flight and the remaining terms are superposed independent small effects that account for nonzero values of various motion and control variables. For completeness, the expression is premultiplied by a transformation $E_2(-\alpha)$ from wind axes components in which the aerodynamic force data are usually given, and the factor, QS, that separates the principal dependence of forces on air speed and also makes the vectors in the sum dimensionless.

The leading term, f_O, is a function of α, F, C_J, and altitude, and it accounts for the principal dependence of aerodynamic forces on these variables. Although the $\{f_i\}$ terms are functions of several variables, the principal variations in flight and their difference for zero results from the variable δi, which is one of the angles $\{\beta, \delta a, \delta e, \delta R\}$. These terms are either linear or nearly so in the variable δi. For the controls, their usefulness is closely dependent on their near-linearity. The remaining terms $\{d_i\}$ account for various angular rates $\{\alpha, \beta, r_B\}$, whose effects are modeled as linear and are made dimensionless by the appropriate factor from $\{\mu_j^*\}$. Similar remarks apply to the description of the moments.

The components of the force and moment vectors given in wind axes are individually identified in the working nomenclature as coefficients of drag, Y, and lift forces and as coefficients of roll, pitch, and yaw moments – one coefficient for each component of each vector in the sum. These coefficients are functions of varying degrees of complexity and sufficient data to define all the coefficients in the list are stored in the simulation. The gross properties of this collection of coefficients are examined next.

Aerodynamic coefficients– Figure 7 summarizes in a matrix the coefficients required for the aerodynamic mode. The columns itemize the terms that are summed to form the total force and moment and the rows itemize the wind axes components of each term. The resulting nomenclature of the coefficients thus identifies each contribution to aerodynamic forces and moments by source and by effect – this is the working nomenclature. A large body of classical literature exists which analyzes the origins and consequences to the flight dynamics of each coefficient.

The collection of coefficients divides about evenly into trivial and nontrivial ones. The nontrivial ones vary in complexity from constants to functions of four variables. Much of this complexity is characteristic of powered lift aircraft compared to conventional aircraft, for example, the engine parameter, C_J, appears in most of the coefficients. And parameters such as F, δa, which conventionally have linear additive effects, are now nonlinear and even nonadditive as for F.

In the simulation program, these coefficients are evaluated at each integration step and this constitutes a large part of the computational and storage load in a six-degree-of-freedom simulation. This situation is common to powered lift vehicles, and efficient computational methodology is a significant programming problem that is also reflected as a significant programming problem in the autopilot. The functions are handled by storing tabulated functions that are then interpolated during a simulation run. Figure 8 shows an example – a lift-drag polar that defines the leading force term by mapping values of the three independent variables (α, F, C_j) into values of C_L and C_D. For a conventional aircraft, we would have a single independent variable and therefore a single line on one plot. For the AWJSRA, two additional variables require first additional lines and then additional plots.

Half of the 60 possible coefficients are zero. This reflects the physical symmetry of the aircraft as well as the normal operation of the aircraft with the velocity vector in the plane of symmetry. If the rows and columns of the matrix of the coefficients are shuffled, the structure shown in figure 9 appears. As seen, the system of variables and of force and moment components almost divides into two independent subsystems (referred to as the longitudinal and lateral degrees of freedom), which separates motion in the plane of symmetry from motion lateral to it. If we were to linearize the equations of motion about an unaccelerated flight condition, this decomposition appears throughout the systems of equations, and this has been exploited heavily in the classical development of aircraft control since the small-disturbance behavior of the aircraft can thus be analyzed as two subsystems half the size.

This subdividion is now exploited in the nonlinear simulations, nor in our control problem, where we are interested in the inertial path of the vehicle as much as its local small-perturbation dynamics. It will prove more rewarding in terms of solving the autopilot problem to exploit a division into linear and rotational degrees of freedom. Nevertheless, this shows that there are other partitions of the complete system into loosely coupled subsystems besides the ones to be focussed on here.

Figures 6 through 9 have defined the model of the aircraft forces and moments that result from the engine and aerodynamics. Their interrelationships are exhibited in a block diagram of the aircraft model (fig. 10). The internal blocks correspond to the main subroutines of the digital simulation of this subsystem; the engine is modeled in a single block while the aerodynamic description is divided into three blocks – actuators, forces, and moments.

The input-output relations among these blocks are arranged as two main parallel streams of cause and effect. This divides the calculations into quantities for which significant variations occur slowly or rapidly in time relative to each other. The lower stream contains slowly varying quantities – engine model, aerodynamic forces, and many coefficients of the moment equations which vary slowly with α, F, and C_j. Most calculations of the aircraft model can be separated into this stream. This partitioning is exploited when computation time is critical by carrying out the slow stream at, for example, half the frequency of the fast stream. This has been done in simulations operated in real time, primarily man-in-the-loop simulations. On the one hand, the computation time for a cycle must not exceed the corresponding real time increment being simulated, and that time increment should also be about 10 times the natural frequency of the dynamics being simulated. This partitioning of calculations was used when the computational load required for simulating powered lift vehicles exceeded the computer speed if carried out in a single stream. An alternate solution, also used, is a faster computer. A similar constraint on computational cycle time will occur for the autopilot in flight, and a similar partitioning of the control calculations into subsystems evaluated at different rates can be exploited there as well.

Autopilot– In the simulation of aircraft flight, the motion is always controlled, that is, the values of all controls must somehow be defined to operate the simulation. In the present case, where the simulation is used for autopilot development, experimental autopilot logic fills this role. Although the autopilot is not discussed in detail, it is useful to describe its functioning at a general level since this will motivate a useful partitioning of the aircraft simulation (fig. 11).

The purpose of the autopilot, in general, is to fly some reference path defined, for example, by air traffic control. To do this, the autopilot necessarily solves the equations of motion for the control settings that fly the reference path and corrects any errors from the path.

Figure 11 shows the input information to be the state variables divided into variables of the translational and rotational degrees of freedom, and also wind information and inputs from air traffic control that define the reference trajectory. The outputs are commands to the control actuators, subdivided into force and moment controls.

Internally, the autopilot logic is partitioned into trajectory control and attitude control. The attitude control logic calcualtes the moment control commands that execute attitude and angular velocity commands from the trajectory control logic. The trajectory control logic uses the force controls, UF, to control forces in the plane of symmetry; δth and ν are engine controls and F, the flap deflection angle, controls lift through its dependence on wing configuration. It also uses the attitude control subsystem to control the orientation of the plane of symmetry in inertial space and it uses pitch angle to control aerodynamic force through angle of attack.

The control problem is thus divided into two smaller problems based on a partitioning of the system into translational and rotational degrees of freedom. The trajectory is controlled by large engine and aerodynamic forces that inherently have slower dynamics than the control moments used by the attitude control subsystem. In addition, it is assumed that attitude commands from the trajectory control logic will have only low-frequency variations for the passenger-oriented operations considered here. Thus, for the controlled airplane, the rotational subsystem appears to the translational subsystem as a fast servo insofar as attitude response to attitude commands is concerned. This result can be used to simplify the rotational degrees of freedom and to obtain a relatively small simulation that has proved extremely useful in studying the trajectory control problem (fig. 12).

SIMPLIFIED SIX-DEGREE-OF-FREEDOM SIMULATION

Figure 12 shows the complete system – autopilot, aircraft model, and equations of motion – subdivided into translational and rotational subsystems that separate the trajectory variables and attitude variables. The translational subsystem is affected by the rotational subsystem through the attitude response to attitude commands and through a perturbation force that results from high frequency rotational dynamics and has negligible effect on the trajectory. Because of the faster rotational dynamics, the complete rotational subsystem can be removed and its input-output behavior obtained approximately from a linear second-order system (fig. 12).

Thus the simulation can be partitioned into a half-size simulation to study the trajectory control problem. This has proved an ideal tool, much smaller in size and computation time than the parent six-degree-of-freedom simulation. In fact, the size of the trajectory control logic program is twice that of the remainder of the simulation, which gives a comfortable ratio of the tool size to problem size for this portion of the research. If the complete six-degree-of-freedom simulation were to be used for the trajectory control research, then the reverse would be true, and the control logic program would be outweighed by the rest of the simulation by more than two to one.

HIERARCHY OF SIMULATIONS

Figure 13 shows some aspects of literal size revealed by the hierarchy of simulations. A six-degree-of-freedom simulation was available for our research needs, but the size of this object was a problem, as well as its organization, which was oriented toward general-purpose use with man-in-the-loop simulation. It was large in terms of the number of boxes of FORTRAN cards that could be carried about lightly, or the number of listings that could be spread out on a desk, or the number of sheets of paper required to write down a working definition of the system. In this regard, the report that defines the aircraft model has 96 pages of equations and tabulated function data (ref. 3). These sizes are significant in relation to the desire for easy accessibility, use, understanding, and modification during the critical early stages of the research when the central conceptual problems are solved.

In response to this problem of size, a hierarchy of simulations of increasing size and detail has been assembled or planned. First, the simplified six-degree-of-freedom simulation described in figure 12 is used to develop the trajectory control logic. The shaded and unshaded portions of the bar in figure 13 are the size of the trajectory control logic and the size of the remainder of the simulation, respectively, in feet of FORTRAN cards. Not only is the absolute size of this program quite small, but the size of the research portion of the simulation is twice that of the rest of the simulation program. This is a comfortable working ratio between the size of the tool used and the size of the problem being solved. Although the simulation is very much smaller than the six degrees of freedom, the control problem remains difficult.

The second member of the hierarchy is the six-degree-of-freedom simulation, used for attitude control and navigation studies, as well as for verification of the trajectory control logic in a more detailed simulation of the flight dynamics. This tool is much larger and the ratio of tool size to problem size is less favorable. (One response to tool size is to enlist a specialist to work the tool for you, but at the expense of some loss of familiarity with the system being controlled.)

The third member of the hierarchy of simulations is a large man-in-the-loop laboratory simulation on computers dedicated to such simulations. The added detail included a cockpit, displays, sensors, and also a copy of the STOLAND airborne computer and peripheral equipment that may be used for a thorough evaluation before any flight test. With a simulation of this size, a staff of specialists and assistants who work solely with the simulation is required.

The organizational size itself creates certain problems of inconvenience to the research. The demand for the simulator-STOLAND is sufficiently great that long lead time scheduling or inconvenient working hours become necessary and it is quite possible that an additional simulation, intermediate in size between the second and third members of the hierarchy, will be programmed to minimize the time needed on simulator-STOLAND.

SUMMARY

Simulations of V/STOL aircraft for autopilot research were introduced as an example of a large-scale system. Large, in this case, was perceived in relation to the uses of the simulation, that is, in terms of the research requirement for a simulation that was easy to work with and in terms of the complexity and difficulty of the control problem. Both problems were attacked and at least partially solved through partitioning of the system of equations and hierarchic organization of the system. The various organizations described are listed in figure 14.

First, a hierarchy of simulations was assembled – a sequence of increasingly detailed simulations of the aircraft paralleling a corresponding hierarchic development of the autopilot. The object was to have a digital simulation no larger than necessary at each stage of the research since such factors as ease of access, use, understanding, and modification are all proportional to size.

Second, a modular organization was given to the simulations, which were divided into three main subsystems – the autopilot, the aircraft model, and the equations of motion and environment section. These modules have a minimum of interface variables and provide for plug-in simplicity so

that frequent revisions of the autopilot and occasional changes of aircraft occurring in the research can be made.

Third, the dynamics of the system were subdivided into translational and rotational degrees of freedom, based on the different frequencies at which significant variations in motion variables and control forces and moments occur in the two subsystems. This is the basis of the autopilot partitioning into two smaller control problems. This frequency separation can also be used to satisfy the real-time constraint on the autopilot cycle time should the computational load for powered-lift aircraft prove too large in relation to computer speed. This was also the basis for devising a simplified six-degree-of-freedom simulation by replacing the rotational subsystem with its input-output relation. This has been a very convenient research tool for the trajectory control problem and has permitted a study of that problem independent of the attitude control problem.

Fourth, an alternate partitioning of the aircraft dynamics into longitudinal and lateral degrees of freedom was mentioned. This is used in the classical linearized analysis and separates the dynamics into motion in the plane of symmetry and lateral to it.

Finally, partitioning the aircraft model section into two subsystems whose variations were well separated in frequency permitted these subsystems to be evaluated at different rates during simulation. This has been used in real-time simulations to meet the real-time constraints on computation cycle time, especially for powered lift V/STOL aircraft.

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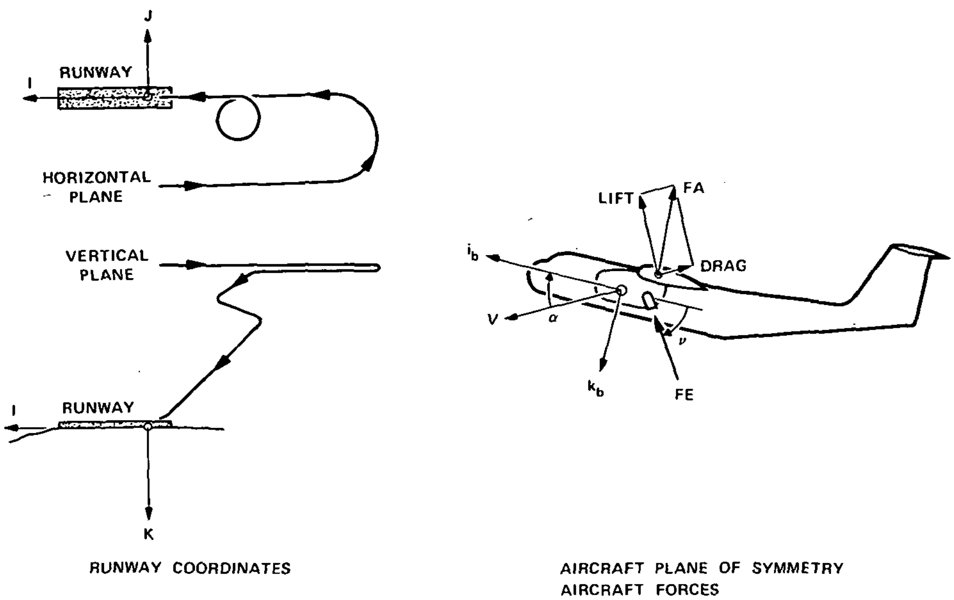


Figure 1.– Translational degrees of freedom.

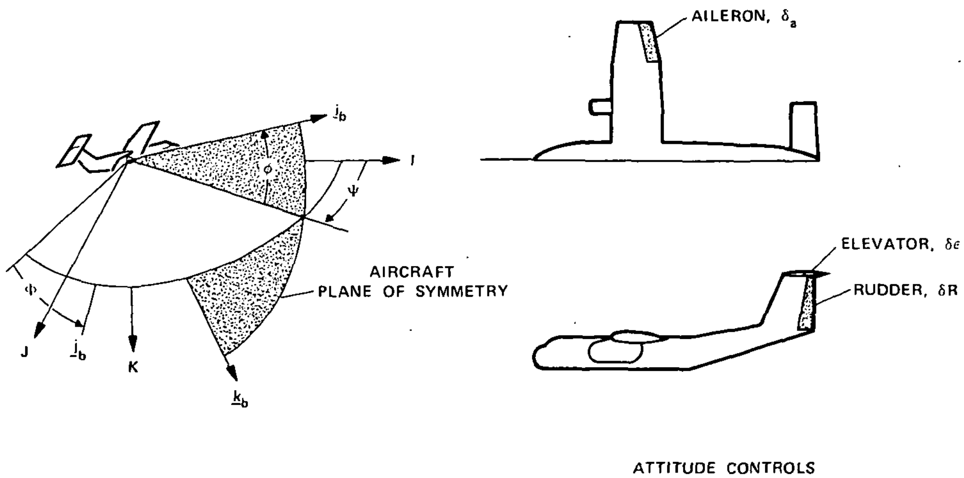
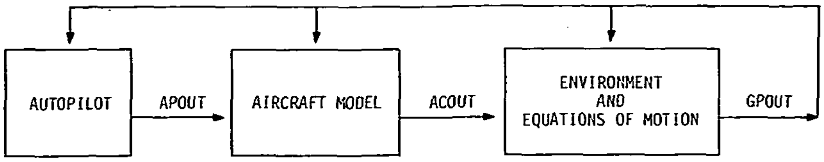


Figure 2.– Rotational degrees of freedom.



APOUT: $(F_c, \delta th_c, \nu_c, \delta a_c, \delta e_c, \delta R_c)$

ACOUT: (M, F_B, M_B)

GPOUT: $(R_I, V_I, \dot{V}_I, (\phi, \theta, \Psi), \Omega_B,$
$W_I, VA, \alpha, \beta, \dot{\alpha}, \dot{\beta}, AT)$

Figure 3.– Block diagram of AWJSRA aircraft simulation.

Translational degrees of freedom: position and velocity:

$$\dot{R}_I = V_I$$

$$\dot{V}_I = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} + T_{IB}(\phi, \theta, \Psi) \frac{1}{m} \Sigma F_B$$

Rotational degrees of freedom: attitude and angular velocity:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\Psi} \end{bmatrix} = A(\phi, \theta, \Psi) \cdot \Omega_B$$

$$\dot{\Omega}_B = I^{-1} \Sigma M_B + I^{-1} \Omega_B \times I \Omega_B$$

Wind velocity:

$$W_I = WS_I(z) + WG_I$$

$$\begin{bmatrix} \dot{WG} \\ \dot{WG} \end{bmatrix}_I = A_g \begin{bmatrix} WG \\ WG \end{bmatrix}_I + B_g N_g \; ; \qquad N_g = (N_x, N_y, N_z) \sim N(0,1)$$

Atmosphere:

$$AT = [\rho(z), T(z), p(z), a(z)]$$

Kinematic functions:

$$T_{IB} = E_1(\phi) E_2(\theta) E_3(\Psi)$$

$$A = \begin{bmatrix} 1 & \sin\phi \tan\theta & \cos\phi \tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix}$$

$$VA_B = T_{BI}(V_I - W_i)$$

(VA, α, β) = spherical coordinates of YA_B

$$Q = \frac{1}{2} \rho V^2$$

$$\dot{\alpha} = d\alpha/dt$$

$$\dot{\beta} = d\beta/dt$$

Figure 4.– Equations of motion – rigid body, flat earth.

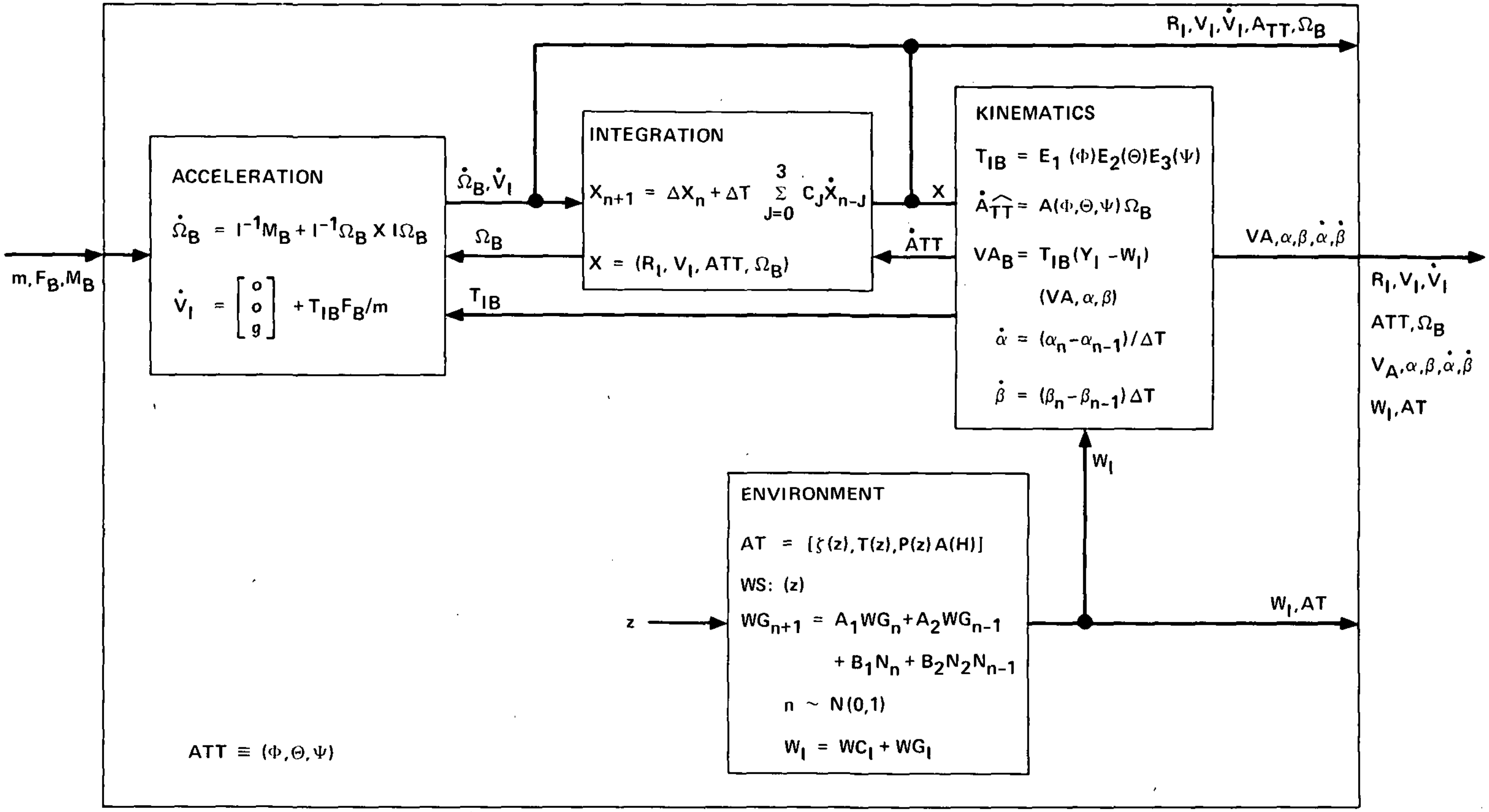


Figure 5.– Block diagram of equations of motion and environment model.

$\Sigma F = FE + FA$

$\Sigma M = ME + MA$

Engine

Stored data: $\dot{M}_F(AT, \delta th)$, $T(AT, VA, \delta th)$, $TC(AT, VA, \delta th)$

$\dot{M} = -\dot{M}_F$ — Constraints: $\{T_{EX}, \dot{T}_{EX}(T), \ddot{T}_{EX}(T, \dot{T})\}$ $\tau(\dot{T})$

$\dot{T} = (\delta th - T)/\tau$

$\dot{\nu} = $ Const, C_ν — Constraints: $\{\nu_{EX}\}$

$C_J = TC/QS$

$FE_B = \underline{i}(\nu)T$

$ME = FE \times \underline{\ell}_E$

Actuators

$\dot{u}_i = [u_{i_c} - u_i]/\tau_i$ — $u_i \epsilon \{\delta a, \delta e, \delta R\}$

Constraints: $\{u_{i_{EX}}, |u_i| max\}$

$|\dot{F}| = $ const, C_F — Constraints: $\{F_{EX}\}$

Aerodynamics

$$FA_B = QSE_2(-\alpha)\left[f_0(z, \alpha, F, G_J) + \Sigma f_i(\delta i, \alpha, F, G_J) + \Sigma d_i(d, F, G_J)\,\frac{\mu j}{\mu_j^*}\right]$$

$$MA_B = QS[\ell]E_2(-\alpha)\left[f_{m_0} + \Sigma f_{m_i} + \Sigma d_{m_i}\,\frac{\mu j}{\mu_j^*}\right]$$

$\delta i \;\epsilon\; \{\beta, \delta a, \delta e, \delta R\}$

$f_i = 0$ for $\delta i = 0$; f_i monotonic in δi

$$\left|\frac{\partial fi}{\partial \delta i}\right| \dot{\delta i}_{max} >> \left|\frac{\delta fi}{\delta \alpha}\right| \dot{\alpha}_{max}, \text{ etc.}$$

$\mu_j \;\epsilon\; \{\dot{\alpha}, \dot{\beta}, \Omega_B\}$

$$\mu_j^* \;\epsilon\; \left\{2\,\frac{VA}{b},\; 2\,\frac{VA}{c}\right\}$$

Stored data: $\left\{C_{D_0}, C_{D_1}, \ldots, C_{y_0}, C_{y_1}, \ldots, C_{L_0}, C_{L_1}, \ldots\right\}$

$\left\{C_{\ell_0}, C_{\ell_1}, \ldots, C_{m_0}, C_{m_1}, \ldots, C_{n_0}, C_{n_1}, \ldots\right\}$

Figure 6.– Aircraft model – AWJSRA.

	Wind axes components	f_o, f_{m_o}	$f_{\delta e}$ $f_{m_{\delta e}}$	$f_{\delta a}$ $f_{m_{\delta a}}$	$f_{\delta R}$ f_{m_β}	f_β f_{m_β}	$d_{\dot\alpha}$ $d_{m_{\dot\alpha}}$	$d_{\dot\beta}$ $d_{m_{\dot\beta}}$	d_p d_{m_p}	d_q d_{m_q}	d_r d_{m_r}
FA	$-l_w \cdot FA$ (drag)	$C_{D_{W_B}}$	0	$\Delta C_{D_{\delta_a}}$	0	0	0	0	0	0	0
	$J_w \cdot FA$ (Y)	0	0	ΔC_{δ_a}	$\Delta C_{y_{\delta_R}}$	$C_{y_\beta} \cdot \beta$	0	$C_{y_{\dot\beta}}$	C_{y_p}	0	C_{y_r}
	$-k_w \cdot FA$ (lift)	$C_{L_{WB}} + \Delta C_{L_T}$	$C_{L_{\delta e}} \cdot \delta e$	$\Delta C_{L_{\delta_a}}$	0	0	$C_{L_{\dot\alpha}}$	0	0	C_{L_q}	0
MA	$lw \cdot MA$ (roll)	0	0	$\Delta C_{\ell_{\delta_a}}$	0	$C_{\ell_\beta} \cdot \beta$	0	$C_{\ell_{\dot\beta}}$	C_{ℓ_p}	0	C_{ℓ_r}
	$Jw \cdot MA$ (pitch)	$C_{m_{WB}} + \Delta C_{m_T}$	$C_{m_\delta} \cdot \delta e$	$\Delta C_{m_{\delta_a}}$	0	0	$C_{m_{\dot\alpha}}$	0	0	C_{m_q}	0
	$Kw \cdot MA$ (yaw)	0	0	$\Delta C_{n_{\delta_a}}$	$\Delta C_{n_{\delta_R}}$	$C_{n_\beta} \cdot \beta$	0	$C_{n_{\dot\beta}}$	C_{n_p}	0	C_{n_r}
	Independent variables	$\alpha, \alpha(t-\tau)$ F, C_J, z	α	δa α, F, C_J	δR	α, F, C_J			α, F, C_J		α, F, C_J

Figure 7.— Aircraft model – aerodynamic force coefficients.

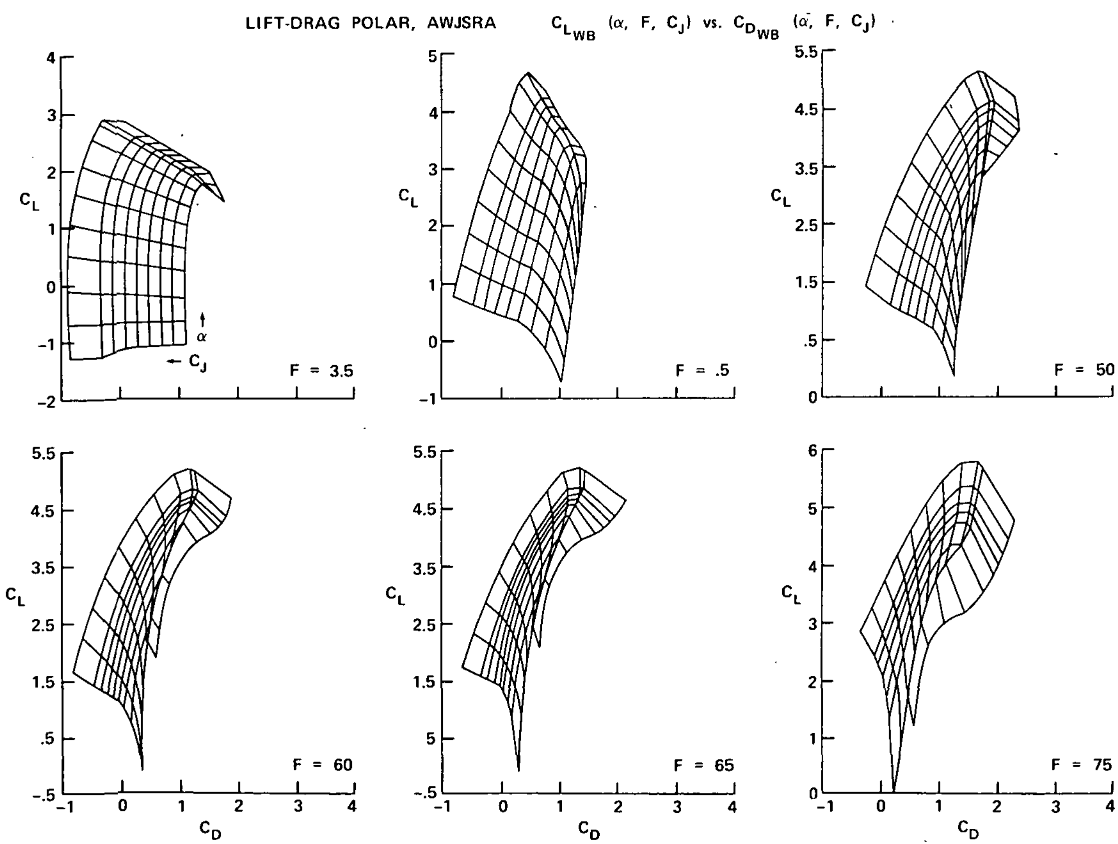


Figure 8.— Lift-drag polar, AWJSRA.

Coefficient	Parameters									
	α, F, C_J	δ_e	α	q	δa	δR	β	$\dot{\beta}$	p	r
(a) Longitudinal										
Drag, $-i_w \cdot FA$	$C_{D_{WB}}$	0	0	0	$\Delta C_{D_{\delta_a}}$					
Pitch, $j_w \cdot MA$	$C_{m_{WB}} + C_{m_T}$	$C_{m_{\delta e}}$ e	$C_{m_{\dot{\alpha}}}$	C_{m_q}	$\Delta C_{m_{\delta_a}}$					
Lift, $-k_w \cdot FA$	$C_{L_{WB}} + \Delta C_{L_T}$	$C_{L_{\delta_e}}$ B	$C_{L_{\dot{\alpha}}}$	C_{L_q}	$\Delta C_{L_{\delta a}}$					
(b) Lateral										
Roll, $i_w \cdot MA$					$\Delta C_{\ell_{\delta a}}$	$\Delta C_{\ell_{\delta R}}$	C_{ℓ_β}	$C_{\ell_{\dot{\beta}}}$	C_{ℓ_p}	C_{ℓ_r}
y, $j_w \cdot F_A$					$\Delta C_{y_{\delta a}}$	$\Delta C_{y_{\delta R}}$	C_{y_β}	$C_{y_{\dot{\beta}}}$	C_{y_p}	C_{y_r}
Yaw, $k_w \cdot MA$					$\Delta C_{n_{\delta a}}$	$\Delta C_{n_{\delta R}}$	C_{n_β}	$C_{n_{\dot{\beta}}}$	C_{n_p}	C_{n_r}

Figure 9.– Aircraft model – coefficients for longitudinal and lateral degrees of freedom.

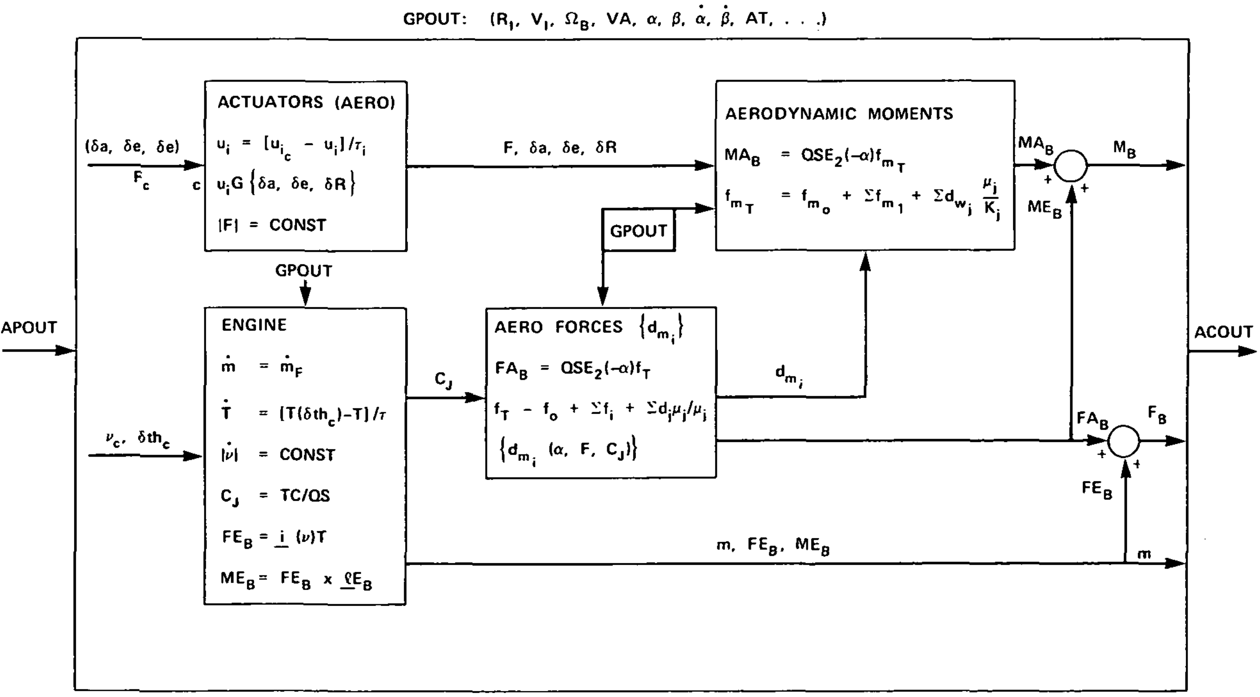


Figure 10.– Block diagram of aircraft model – (AWJSRA).

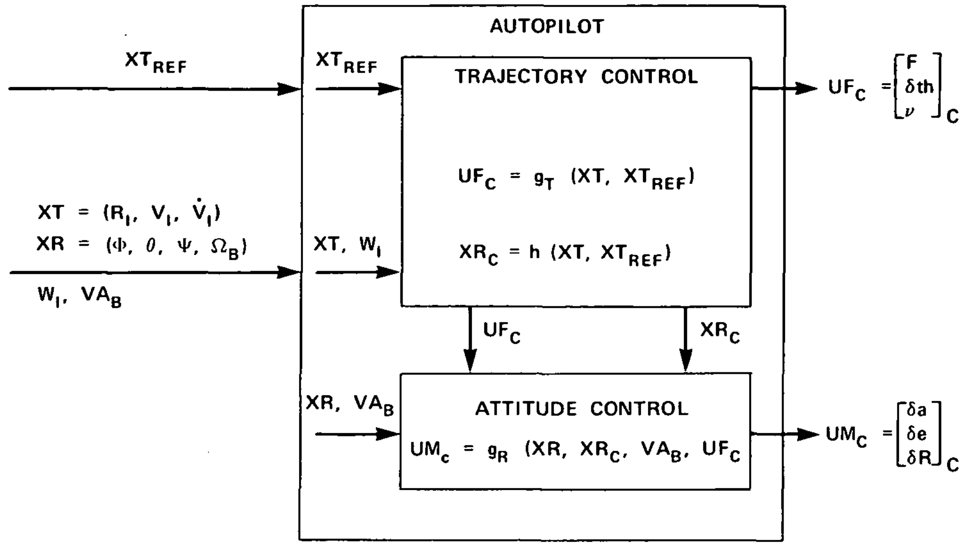


Figure 11.– Block diagram of autopilot.

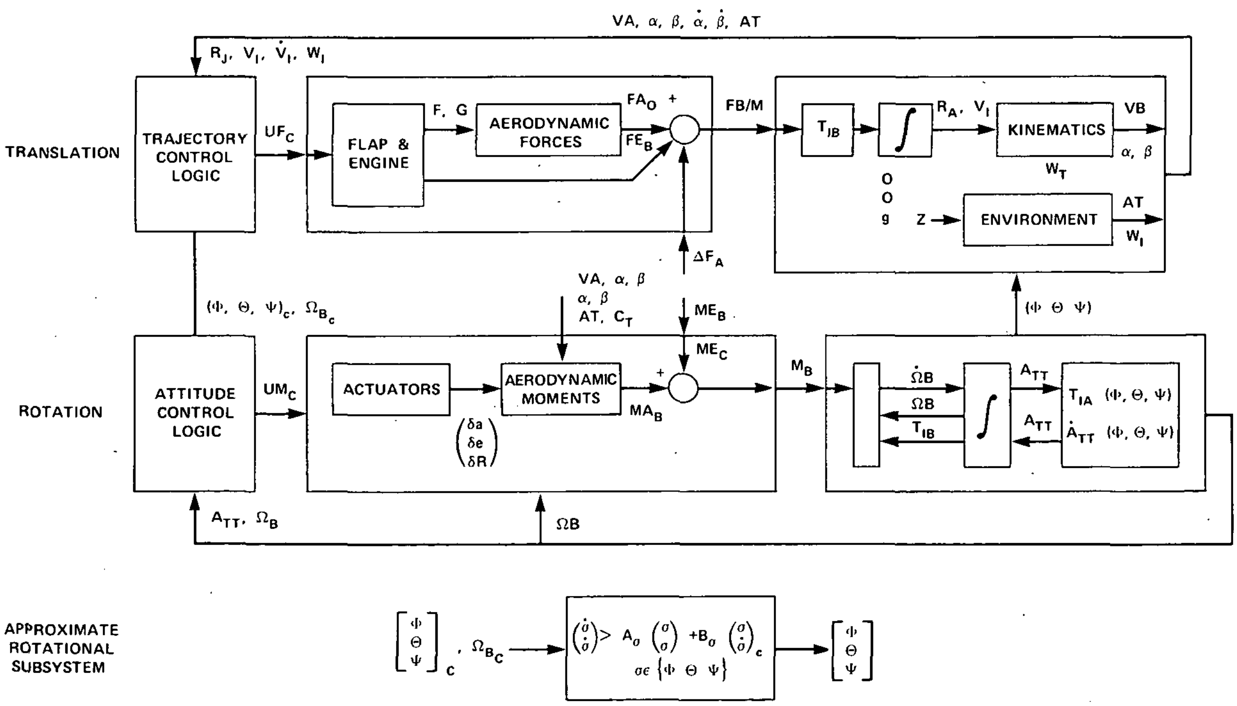


Figure 12.– Subsystems – translational and rotational degrees of freedom.

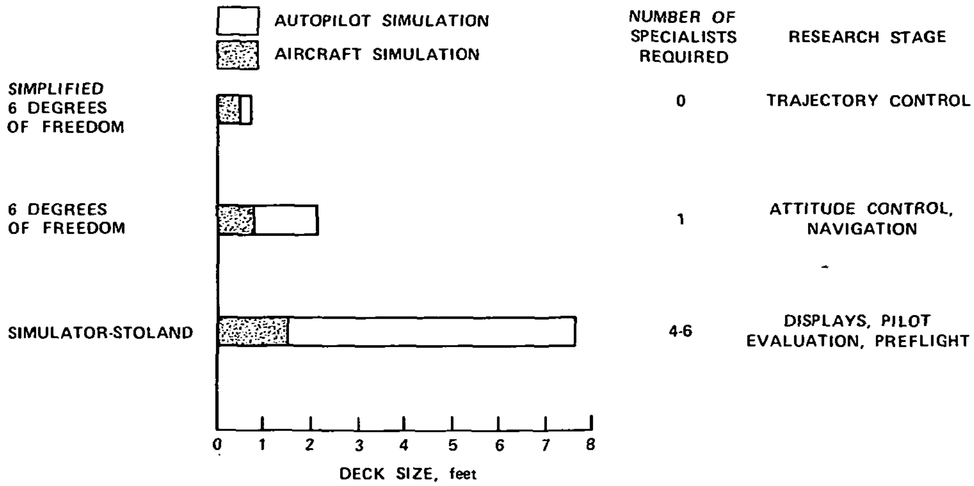


Figure 13.– Hierarchy of simulations.

1.	HIERARCHY OF SIMULATIONS	LIMIT SIZE OF SIMULATIONS
2.	MODULAR ORGANIZATION	PLUG-IN SIMPLICITY FOR AUTOPILOT OR AIRCRAFT CHANGES
3.	TRANSLATIONAL/ROTATIONAL DECOMPOSITION	SUBDIVIDE CONTROL PROBLEM REDUCE COMPUTATION CYCLE TIME SIMPLIFIED SIX-DEGREE-OF-FREEDOM SIMULATION
4.	LONGITUDINAL/LATERAL DECOMPOSITION	SUBDIVIDE LINEARIZED DYNAMICS
5.	AIRCRAFT MODEL "SLOW"/"FAST" CALCULATIONS	REDUCE COMPUTATION CYCLE TIME

Figure 14.– Summary of organizations.